SEISMIC REFRACTION ON THE GREEN VALLEY AND HAYWARD FAULTS,
SAN FRANCISCO BAY AREA, CA

A University Thesis Presented to the Faculty
of
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In Partial Fulfillment
of the Requirements for the Degree
Master of Science in Geology

By
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Abstract

In this study I used seismic refraction techniques to investigate two sites on active right-lateral strike-slip fault zones in the San Francisco Bay Area. I designed detailed refraction surveys near Mason Road on the Green Valley fault and at Tyson’s Lagoon on the Hayward fault. The Mason Road site has geomorphic expression of classic linear valleys with offset stream channels, and the primary geophysical targets are buried paleochannels that can serve as piercing points to determine fault offset. The Tyson’s Lagoon site is a pull-apart basin between parallel strands of a right stepover in the southern Hayward fault, and the geophysical target is a suspected boundary between Holocene silts and Pleistocene gravels that could characterize the recent structural development of the fault.

At both sites ample comparative data are available to make informed conclusions from seismic refraction velocity models. At Mason Road I have access to Cone Penetrometer Test (CPT) logs, ground-penetrating radar (GPR) surveys, and hand auger sampling. The final velocity models processed at this site reveal definite channel features at 3-8 m depths, and show velocity contrast at the same depths as a contact that CPT data indicates between Holocene flood deposits and Pleistocene alluvium. The seismic refraction models suggest that the Green Valley fault diverge from the mapped trace by as much as 10 m at this site, and there is also evidence for a slight vertical component of fault motion. Trench excavation at Mason Road will occur within the next few years, and these refraction models may help in optimally locating proposed trenches.
At Tyson’s Lagoon I have access to extensive trench logs, CPT soundings, and borehole logs. The final refraction models processed at this site reveal a layer boundary that dips north, and correlates with depths proposed by CPT and borehole data to be a Pleistocene gravel surface. None of the trenches in Tyson’s Lagoon were excavated deep enough to see this contact, nor was there physical evidence of a theoretical cross-fault transferring slip from the western trace to the eastern trace of the Hayward fault. Seismic refraction models apparently image the Holocene-Pleistocene contact at 7-12 m depths in the pond, and appear to image a cross-fault feature oriented at an acute angle to the main fault traces. Future rail transportation construction at the site will likely benefit from the characterization of this subsurface contact and its implications in paleoseismic studies of the Hayward fault.

This research involved the use of seismic refraction in conjunction with many other sets of complementary data (GPR, CPT, trenching, borehole, and auger) to further explore the near-surface in support of ongoing paleoseismologic investigations. GPR often provides a high resolution subsurface image, while seismic refraction is less susceptible to cultural disturbances and provides better depth control. We must continue to refine this process of employing geophysical techniques (seismic and GPR) together with site-specific physical data. This research has aided in 1) determining optimal locations for proposed trenches, 2) correlating geophysical data with ground-truth data (trench, CPT, borehole), and ultimately 3) developing “virtual trenching” methods that use geophysical techniques to extend real trenches beyond their actual length and depth dimensions.
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Preface

This thesis introduces general concepts and objectives first, and then covers basic data collection techniques and methodologies. Chapters Three and Four discuss each site independently, and are followed by concluding statements and recommendations for future work. Within the site-specific sections detailing data processing and results, figures depict each step of the modeling process for all lines. In the appropriate appendices I arranged complete sets of first break picks, traveltime curves, and velocity models in the same order they are discussed within the text. Composite figures of final velocity models appear in the text, but separate high resolution models appear in the appropriate appendix.

At the Mason Road site (discussed in Chapter Three), I make several references to locations of Cone Penetrometer Test (CPT) logs. The original placement of proposed CPT points formed a broad T-shape at the site, and could be used as a landmark for the design of both seismic refraction lines and ground penetrating radar (GPR) lines. In January 2004 there were 15 CPT stakes at the site, placed 30 m apart, with CPT stake 3 at the intersection of the T-shape. Not all of the CPT stake locations were actually logged by the CPT truck, but I retained these locations and numbering system to help orient both GPR and seismic lines during data collection. Within the text, if a location refers to an observed CPT log, then it is termed as CPT# (e.g. CPT3 or CPT15). If a location refers to a CPT stake # (e.g. CPT stake 2 or CPT stake 5), then that location is only a staked landmark and no CPT data was collected.
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I owe thanks to the many individuals who became involved with this body of work. Dr. James Lienkaemper from the USGS shared his knowledge on possible sites for geophysical investigation during a meeting in December 2003 and has continued to heavily support this work since then. My sincere appreciation goes to those at the Mason Road site who allowed such open access and were so friendly: Bill Yarbrough, landowner and President of B&L Properties and Solano Development; and Sylverio Castaneda of Castaneda Brothers Produce. The Alameda County Public Works Agency was very helpful in allowing access to the Tyson’s Lagoon site. To my friend and fellow graduate student, Sam Heller, I am truly grateful for the help you gave me in starting and continuing this research, and for all of those early mornings and long days collecting data at both field sites. I could not have collected such large amounts of data without energetic and loyal field assistants such as Stephanie Davi, Tasha Storm, Dan Rybczynski, and Carson Hackett. Thanks to the following individuals for providing valuable supporting data and figures: Dave Ponce of the USGS for generating the aeromagnetic raster images and basemaps; Tom Noce of the USGS for collecting and sharing CPT data at the Mason Road site; and Bala Balakrishnan of Fugro West for sharing CPT data at the Tyson’s Lagoon site. I will forever be grateful for the knowledge, support, and guidance that the CSUEB Geology Department faculty and staff granted me on a daily basis. Heartfelt thanks to all of the instructors who molded me into a geologist: Dr. Mitch Craig, Dr. Luther Strayer, Dr. Jeff Seitz, Dr. Dietz Warnke, Dr. Ivano Aiello, and Pat Drumm. Thanks also to Phil Garbutt for sharing his expertise and
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Chapter One:
Introduction, Previous Work, Data Collection and Methodologies

Introduction

The Green Valley fault and the Hayward fault are both NW trending right-lateral strike-slip faults that belong to the broad San Andreas fault system (Frizzell and Brown, 1976). Both faults are active, and have experienced steady creep rates throughout at least the past century (Galehouse and Lienkaemper, 2003; Lienkaemper et al., 1991; Frizzell and Brown, 1976). Lienkaemper and Borchardt (1996) suggest that the Hayward fault has a Holocene slip rate of approximately 9 mm/yr, but since the creep rate averages only 4.6 mm/yr over its length since 1868, the fault is probably locked at depth and has the potential for a major earthquake in the near future (Galehouse and Lienkaemper, 2003). Evidence from a single historical earthquake and three paleoearthquakes during the past 500 years suggests that the southern segment of the Hayward fault has a mean recurrence interval of 130 ± 40 yr (Lienkaemper et al., 2002). Since the last major earthquake on the Hayward fault was in 1868, these data suggest that a large earthquake is likely to occur within the next few decades. However, more recent research (Lienkaemper et al., 2005) suggests a mean recurrence interval of 176 ± 15 yr over the past 1800 years, which is based on ten events. It is important to realize that both of these mean recurrence intervals are well-constrained only as average values, and that the actual variation between individual recurrence times may exceed a century (i.e. a 270 yr recurrence interval cannot be ruled out by the current data; Lienkaemper et al., 2002).
Historically, the Green Valley fault has only had earthquakes of M3.9 and lower (Frizzell and Brown, 1976), but has a creep rate of 4.4 mm/yr (Galehouse and Lienkaemper, 2003). The Green Valley fault is part of a larger fault system that includes the Calaveras and Concord-Green Valley fault zones (see Figure 1), which form a pattern.
of en echelon steps from Hollister to Napa. Previous studies suggest that both the Calaveras-Concord-Green Valley fault zone and the Hayward-Rogers Creek-Healdsburg-Maacama fault zone have the potential for M7 earthquakes, but not all traces of the faults are well defined (Slemmons and Chung, 1982). Locating these fault traces and characterizing slip events on them is important to the San Francisco Bay area where further development and construction are inevitable. A Bay Area Rapid Transit (BART) extension is planned from the Fremont Station south to Warm Springs, and many new housing developments are being built in the valleys adjacent to the Green Valley fault near the Mason Road site. Both sites provided opportunities to conduct geophysical investigations in areas with multiple sets of ground-truth data for comparison.

In this study I used seismic refraction investigations to develop velocity models of the subsurface along the Green Valley and Hayward fault zones. In developing these models, I used ground penetrating radar (GPR) data, trench logs, and cone penetrometer test (CPT) logs to constrain solutions and guide interpretations. Seismic refraction as utilized in this study provided information about the subsurface to depths of 20 m with good depth control, whereas GPR augmented this data with higher resolution at shallower depths of 0-10 m. CPT data provides detailed one-dimensional logs of physical properties to depths of 25 m (within this study), and trenching allows direct visual inspection and physical investigation to 3-4 m depths. GPR is sensitive to cultural artifacts such as metal, conductive wire, and surface changes such as shallow excavations, concrete, or pavement. Seismic refraction is less susceptible to these cultural artifacts, several of which are present at both sites investigated in this study.
Borehole logs, CPT logs, and trench logs can corroborate conclusions derived from GPR and seismic refraction models.

**Previous Work**

Creep along faults in the San Francisco Bay area has been monitored for nearly 40 years (Galehouse and Lienkaemper, 2003). Many of the faults in the San Francisco Bay region are active and have enough surface expression for current creep rates to be established. Current creep rates, together with displacement measurements and magnitudes of historic earthquakes on these faults, are used to assess earthquake hazards. Most recently, trenches have been excavated and logged along the Hayward fault at Tule Pond in Fremont (Lienkaemper *et al.*, 2002). Also on the Hayward fault, numerous trenches have been logged in the vicinity of the Fremont Central Park (Lienkaemper *et al.*, 2002; Borchardt, 1990; Woodward-Clyde & Associates, 1970), just SE of Tyson’s Lagoon and Tule Pond. Cai, McMechan and Fisher (1996) recorded two short (~20 m), high frequency (100 MHz) GPR lines at Fremont Central Park trench sites.

On the Green Valley fault, creep measurements were made near Red Top Road from 1984-1999, as part of a larger study (Galehouse and Lienkaemper, 2003). Frizzell and Brown (1976) investigated the 30 km length of the Green Valley fault, noting observable offset in two manmade features: a 0.25 m offset in a fence built prior to 1862, and a 0.28 m ± 0.01 m offset in a power line built in 1922. The creep measurements by Galehouse and Lienkaemper (2003) over a 15 yr period yielded an overall average creep rate of 4.4 mm/yr. Logistical problems in 1999 prevented further acquisition of reliable measurements. Baldwin and Koehler (2004) logged two trenches at Lopes Ranch on the
southern segment of the Green Valley fault. Additional trenches have been excavated on the northern segment of the fault in Cordelia (Baldwin and Koehler, 2004).

At one of the sites studied in the present work, herein referred to as the Mason Road site, J. Lienkaemper of the United States Geological Survey (USGS) conducted a topographic survey using a differential global positioning system (GPS) and produced a topographic map of the site with a .25 m contour interval. S. Heller and I assisted with GPS field data acquisition. A USGS CPT truck, operated by T.E. Noce, also visited the site in Spring 2004 and logged 12 CPT holes.
Chapter Two:

Data Collection and Methodology

Seismic refraction data were recorded with a Geometrics Geode 24-channel seismograph, using 14 Hz vertical geophones. For every line recorded in this study, I used the following recording parameters: 24 geophones, sledgehammer on plate source, seven shots per line, five stacks per shot. Geophone spacing varied from 2.5-5 m. An example of this recording geometry can be seen in Figure 2. Before designing the final survey geometry, I processed the data from a reconnaissance line recorded at the Mason Road site in March 2004. In these data, the sledgehammer source provided enough energy for distinct first arrivals at the farthest offsets, and the data yielded valid velocity models. In processing the data from each refraction line I used Geometrics SeisImager.

![Diagram of seismic refraction line](image)

Figure 2: Example layout for a seismic refraction line with 24 geophones, 2 m geophone spacing, and 3 shots evenly spaced (two end-on shots and one split-spread shot).
software to pick first arrivals and solve for velocity models. I used two different methods in determining velocity models: time-term and tomographic inversion. For the time-term inversion, I assigned layers to the traveltime data, and then generated two-dimensional, two- and three-layer velocity models. For the tomographic inversion, I specified an initial velocity model equivalent to the time-term solution described above, and ran several iterations. During each iteration, the velocity model is updated, theoretical traveltimes are recalculated and compared with observed times to determine the error. For each model I ran 20 iterations, ensuring that the error decreased to a minimum level. The tomographic inversion method provided a more complex velocity model than the model derived from time-term inversion alone.

For a more detailed understanding of seismic refraction surveying and processing methods, a basic geophysics textbook will suffice (e.g. Keary et al., 2002; Robinson and Çoruh, 1988). In this section I will briefly review the general concepts that lead from data collection to velocity and subsurface modeling. Because we use an artificial source, seismic refraction is considered an “active” method of geophysical investigation. Seismic waves travel through materials at a velocity dependent upon material properties. See Appendix A for examples of typical seismic velocities. When recording a seismic refraction line, we generate a seismic source signal at a known time and location, and use sensors placed in specific positions to record how the resulting seismic waves travel through subsurface materials. More specifically we determine how those waves are refracted and return to the surface as they encounter one or more material contrasts between layers of sediment or rock. By deploying the seismic source at several different
points along the line, we can use the principle of reciprocity to assure that the recorded traveltimes are accurate and can account for unusual geologic structure (e.g. dipping beds or any other structure that is not parallel to the surface). Reciprocity assumes that traveltimes in one direction (i.e. from A to B) should match traveltimes in the opposite direction (i.e. from B to A), and checking the agreement between the two can provide a measure of the reliability of a solution model.

When designing the surveys at each location, I wanted to ensure good coverage of the area, overlap of data lines, and proximity to areas with existing data (CPT logs, GPR lines, trenches, and boreholes). At the Tyson’s Lagoon site, thick vegetation along with seasonal flooding made it difficult to use a rectangular grid system of seismic lines. I collected three intersecting refraction lines roughly forming a triangle within the pond. The longest line (TY-1) ran parallel to a USGS trench excavated a few months prior. The other two lines provided adequate coverage of the middle of the pond, one parallel to the western trace of the fault and the other running diagonally to connect all lines in a triangular shape. The Mason Road site was level and clear of obstructions, making it possible to design a simple rectangular grid system of 11 lines, five oriented E-W and six oriented N-S, superimposed on the suspected trace of the Green Valley fault. Each of the survey geometries is discussed in more detail within the second and third chapters of this text.
Chapter Three:
Green Valley Fault at Mason Road

Site Selection

The Mason Road site provided an opportunity to test near-surface geophysical techniques in an area where multiple types of data were available for comparison. The USGS plans to excavate a trench on the Green Valley fault, and this thesis work could assist with initial site investigations at Mason Road. In the vicinity of the site, there is geomorphic expression of classic fault features such as linear valleys and vegetation, and apparently offset stream channels. The suspected trace of the Green Valley fault strikes approximately N-S through a parcel of land on Mason Road now being used for farming (corn, squash, and tomatillos). The level, open land made shallow geophysical investigation both logistically easy and relatively free from cultural obstruction. I had access to the site during the winter, spring, and early summer months, and the USGS converted one central stake point (referred to as CPT3) into a groundwater-monitoring hole that went undisturbed for the last 18 months. This central stake allowed for easy reoccupation of points at the site on subsequent visits without the use of a differential GPS.

Initial investigation by aerial photo reveals a remarkable offset drainage channel near the study area (Figure 3), yet further investigation discloses that this channel has been redirected for irrigation purposes (J.J. Lienkaemper, personal communication, 2004). Lienkaemper mapped a grouping of en echelon fractures in the paved portion of Mason Road that line up with the suspected trace of the fault (Figure 4). Since the
unaltered portion of the drainage has a near E-W orientation, there could be buried paleochannels which have been offset by the fault. These are believed to be late Pleistocene in age (J.J. Lienkaemper, personal communication, 2004). GPR lines recorded at this site indicate channel feature at depths of ~3 m, but their age has yet to be established. Using seismic refraction along with previous work may help to place proposed trenches and give an approximation of what will be found in those trenches. Furthermore, the surface expression of the Green Valley fault is poorly constrained in this
area. Since this is a creeping fault, surface expressions such as en echelon cracks will help us locate the fault but cannot tell us very much about recurrence interval or paleoseismologic activity. Trenching will ultimately provide the most detailed information on the shallow structure of the fault. Any supporting data, constraining the location of features the trench is targeting (i.e. fault traces or paleochannels), are helpful for strategic placement of that trench.

Figure 4: In March 2005 recent rainwater pools in the fractured portion of this paved road. Fractures run en echelon across the width of the road (white arrows). Field site is 2-300 m south of this photo. Inset photo from February 2004 GPS topographic survey.

**Geologic and Geophysical Setting**

The Mason Road site is situated inside of Green Valley of Solano County California, approximately 3 km NW of Cordelia Junction, California. Green Valley is a
linear valley trending NW to SE. The bedrock is Pliocene Sonoma Volcanics, that are covered in most of the valley by Quaternary alluvium or landslide deposits (Wagner and Bortugno, 1982). One small hill adjacent to the site has outcropping Sonoma Volcanics, from which I collected two fist-sized hand samples. The samples were weathered aphanitic basalt with 1-3 mm vesicles, matching Wagner and Bortugno’s (1982) description of Sonoma Volcanics.

The unnamed 10-12 m wide drainage that borders the site to the west cuts into alluvium creating vertically banking walls ~3 m high. In some locations sandy point bars have developed. A bedload of coarse gravel indicates that the drainage can be high energy at times (Figure 5). Based on the characteristics of this drainage, any buried paleochannels are likely to have a similar size and character.

Baldwin and Koehler (2004) excavated trenches on the Green Valley fault at Lopes Ranch Creek (approximately 13 km S-SE of the Mason Road site). These trenches revealed paleochannels approximately 2 m wide and 1 m deep, buried under 3-4 m of alluvium, and provide another analog of what might be found at the Mason Road site.

Modern day use of the land in Green Valley includes extensive agriculture (vegetable farming and vineyards) on the valley floor, bordered by several housing developments in the adjacent hills. Green Valley Creek runs NE-SW through the center of the valley, but the courses of several smaller drainages on the west side of the valley have been diverted over time for irrigation. A ~400 m long levee has been constructed on the west side of the valley within 500m SW of the Mason Road site. Much of the Quaternary alluvium filling the valley has been leveled out for farming.
The Green Valley fault is associated with a larger fault system comprising the Calaveras and Concord-Green Valley fault zones. The Green Valley fault lies between the Cordelia fault, located to the east, and the West Napa fault, located to the west, both of which have had Holocene displacement (Bortugno, 1982). Previous studies suggest that the Calaveras-Concord-Green Valley fault zone has the potential for a M7 earthquake (Slemmons and Chung, 1982), and a M5.4 earthquake occurred on the southern segment of the Green Valley fault in 1955 (Baldwin and Koehler, 2004). More
than 70 earthquakes, magnitudes M1 to M4, were recorded with epicenters along the Green Valley fault during a six-year period from 1968 to 1974 (Frizzell and Brown, 1976).

The most recent estimate of creep rate on the Green Valley fault is ~4.4 mm/yr (Galehouse and Lienkaemper, 2003). Both the creep rate and the earthquake potential have the eventual consequence of creating property damage and future land/human hazards. Massive landslide deposits also characterize this part of the San Francisco Bay Area. Quaternary alluvium and landslide deposits blanket many of the valleys in this region, including the Green Valley (Wagner and Bortugno, 1982).

Strike-slip motion along the length of the Green Valley fault has placed Pliocene Sonoma Volcanics against both Eocene Markley Sandstone and Lower Cretaceous-Upper Jurassic Great Valley Sequence (Wagner and Bortugno, 1982). On a regional scale, the fault can be identified with aeromagnetic data. Figure 6 shows a high-resolution aeromagnetic survey of approximately 500 km$^2$, centered on the Mason Road site. The figure shows residual total magnetic intensity recorded at 1000 m altitude with flight lines spaced ~536 m apart (USGS, 1992). A magnetic high of up to 80 nT can be matched with the geologic map to reveal that this magnetic anomaly represents Sonoma Volcanics. It is not surprising that the magnetic anomaly plots further east of the suspected surface trace of the Green Valley fault, since Sonoma Volcanics occur on both sides of the fault in this location.
Figure 6: Red lines are faults (Jennings et al., 1977), blue line is coastline around Suisun Bay, white circles are seismicity, Mason Road site within bold black box (aeromagnetic values from USGS, 1992).

Frizzell and Brown (1976) described the Sonoma Volcanics further south, towards Suisun Bay, as dipping west on the east side of the fault, with the Great Valley Sequence on the west side of the fault. Since the Green Valley fault has strike-slip...
motion and Sonoma Volcanics is bedrock on both sides of the fault, it may be difficult to geophysically image the fault surface at the Mason Road site. The geologic setting on other segments of the Green Valley fault are more conducive to geophysical exploration due to the fact that they juxtapose two different lithologies against each other. The Mason Road site is along a segment of the fault that is not defined, and any information about near surface structure will aid in future geologic study, such as trenching. Furthermore, at the Mason Road site the main objective of this study was to identify and locate paleochannels that can be used in future paleoseismic investigations.

**Background Data**

**Groundwater Levels**

Throughout 2004, we monitored groundwater levels at the Mason Road site. The depth to the water table is an important factor to consider for trenching plans, but it provides another line of evidence in interpreting seismic refraction and GPR data. The graph at Figure 7 shows the depth to groundwater from March through October 2004. This site is located on a farm and is under nearly constant irrigation during the dry seasons. Although a high water table is not convenient for trenching operations, it makes seismic refraction data cleaner and sometimes easier to interpret. Seismic P-waves propagate more efficiently through saturated soil or rock layers. The water table is associated with an increase in P-wave velocity that may be interpreted erroneously as a boundary between stratigraphically distinct layers.
Reconnaissance Seismic Refraction

In March 2004, I collected data from a seismic refraction test line at the Mason Road site. This reconnaissance line, named GV-0, was parallel to the Green Valley fault, running N-S from CPT stake 11 to CPT13 on the west side of the fault (Figure 11). The geophone spacing was 2 m, for a total line length of 46 m. Figure 8 shows the three-layer velocity model determined from this line. The top layer of this model is most likely unsaturated soil, the second layer is saturated soil, and the third layer is more consolidated alluvium or weathered Sonoma Volcanics. Unweathered volcanic rocks may have P-wave velocities as high as 5.5-6.5 km/s (Reynolds, 1997).
Cone Penetrometer Testing

In March 2004, T. Noce of the USGS performed CPT soundings at several locations at the Mason Road site. The interpreted CPT logs are in Appendix B. The difference in tip resistance of the cone pushing through the subsurface can serve as an approximation of relative compaction and hardness, and other material and geophysical properties (Noce and Holzer, 2003). In seismic surveying the generalization can be made that harder and more compact materials will have faster velocities, therefore the CPT data can be used as an empirical validation for geophysical models. The CPT data collected at the Mason Road site indicate that there is shallow bedrock at CPT15, at just 1-2 m depth, while alluvial deposits apparently extend to a depth of 25 m at CPT3 (T.E. Noce and J.J. Lienkaemper, written communication, 2004). The CPT data suggest a contact at 5-8 m depth between Holocene or latest Pleistocene flood and channel deposits and Pleistocene alluvium (Lienkaemper, written communication, 2004; see Appendix B). The difference in material properties detected by CPT could be a refractor surface that would show up in
seismic refraction lines, such as the surface seen at 5-6 m depth in the reconnaissance seismic refraction line GV-0.

**Ground Penetrating Radar**

Several GPR lines have been recorded at the Mason Road site using 50 MHz antennae (Craig et al., 2004). Six 180 m long N-S lines were spaced 20 m apart, and three 120 m long E-W lines were spaced 90 m apart. Two of the N-S (fault-parallel) lines show channel structures at shallow (<5 m) depths (Figures 9 and 10). Line M3 shows one channel feature and line M7 shows three. The diffraction at 120 m along line M7 is caused by the groundwater monitoring well surrounded by metal stakes located at CPT3.

![Figure 9: 50 MHz GPR Line M3 runs approximately 160 m N-S, 70 m west of and parallel to the Green Valley fault at the Mason Road site. Interpreted paleochannel structure is highlighted in yellow (modified from Craig et al., 2004).](image-url)
Seismic Refraction Survey Design and Data Collection

Site conditions at Mason Road warranted a simple grid design for the complete seismic refraction survey (see Figure 11). I designed the survey to get complete coverage of the whole field site, while maximizing the amount of data collected coincident with existing CPT and GPR data. Since the seismic data were clean and usable from the reconnaissance line GV-0, I used 5 m geophone spacing on the lines (the maximum spacing possible with the spread cable), which provides a spread length of 115 m. I placed the E-W lines to cross the inferred trace of the Green Valley fault. The N-S lines were 235 m in length, which required running two lines end-to-end and merging the data before processing. Following the numbering system of GPR lines recorded in May 2004, I numbered the refraction lines the same where they coincided. The N-S lines are assigned odd numbers, and E-W lines are even-numbered. If there was no corresponding GPR line, then I incremented the number or augmented the line name with a “b” (i.e. refraction line GV-3b is a N-S line between GPR lines M3 and M5).
Figure 11: Mason Road site survey design with mapped portions of refraction lines as the actual data coverage area (i.e. geophone 1 through geophone 24). Topography shown in 0.25 m increments (modified from J.J. Lienkaemper, written communication, 2004)
With the exception of two of the lines, refraction lines were 115 m long, with geophone spacing of 5 m, seven shots per line, five stacks per shot, and a sledgehammer on metal plate source. Due to the proximity of a residence at the northern end of the site, the northern segment of line GV-3b includes only 19 geophones and five shots, and the northernmost shot on line GV-7 is offset only 19 m from the last geophone (as opposed to 32.5 m in other lines).

During February and March 2005 I recorded a grid of eleven seismic refraction lines. In this region February and March are typically rainy months. In 2005 rainfall was especially high, causing a very shallow (<1 m deep) water table at the Mason Road site during the time of most of the data acquisition. This resulted in good seismic data quality and reduced possible confusion of the water table with any deeper (5-10 m) lithologic boundaries. Field conditions were moist and muddy, and by the time seismic data were recorded, all crops had been harvested. Since the central CPT stake (CPT3) was still in place, re-occupation of the stake positions from a year prior was very easy. Although the data were collected over the course of two months, the field conditions made reoccupation easy and accurate because old geophone and sledgehammer impressions remained in the mud at each successive visit.

**Data Processing and Results**

Appendix C contains figures showing first-break picks, traveltime curves, and velocity model solutions for each of the refraction lines collected at Mason Road. I used Geometrics *SeisImager* software to pick the first arrival times. The data from this site were clean with little noise, and I only occasionally had to delete a trace due to noise. I
assigned layers along traveltime curves and solved a simple velocity model using time-term inversion. Time-term solutions are limited to a maximum of three layers. I also derived velocity models using the tomography method. The tomography method requires an initial velocity model (for which I used my simple time-term solution) and performs an inversion to create a more detailed velocity model with a grid size determined by the number of geophones, the number and placement of shots, and a user-defined number for the time axis (in my models, the grid size was 30 by 10 cells). I ran the tomography procedure on each model, using the default system parameters, and arrived at fairly consistent results for each of the refraction lines. The SeisImager software records the RMS error (matrix inversion error, or root mean square) for each solution, measured in units of time. A low RMS error provides a measure of the reliability of each velocity model solution. An RMS error below 1.5 ms is considered generally acceptable (Geometrics, 2003). Subsurface structures that have anything other than planar-horizontal patterns can sometimes result in a high RMS error, and any solution with an error above 1.5 ms should be carefully considered before interpretation. RMS error in my final velocity models ranged from 1.57 ms to 3.67 ms (Table 1), and I attribute these slightly high values to complicated subsurface structure.

Each of the time-term solutions had similar material velocity values, and only varied slightly in the geometry of velocity models. There were no steeply-dipping surfaces detected in the data, but there were several concave-up lens features that may be channel features. Recall from the survey geometry that all E-W lines cross the inferred trace of the Green Valley fault at ~80 m from the origin of the line, near geophone 10.
Table 1: RMS error values for velocity models at Mason Road site.

<table>
<thead>
<tr>
<th>Line Name</th>
<th>Time-Term Model RMS Error</th>
<th>Tomographic Inversion Model RMS Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>GV-2</td>
<td>1.26 ms</td>
<td>3.67 ms</td>
</tr>
<tr>
<td>GV-2b</td>
<td>1.68 ms</td>
<td>2.16 ms</td>
</tr>
<tr>
<td>GV-4</td>
<td>1.36 ms</td>
<td>2.11 ms</td>
</tr>
<tr>
<td>GV-4b</td>
<td>1.45 ms</td>
<td>2.44 ms</td>
</tr>
<tr>
<td>GV-6</td>
<td>1.66 ms</td>
<td>2.87 ms</td>
</tr>
<tr>
<td>GV-3b</td>
<td>1.49 ms</td>
<td>2.21 ms</td>
</tr>
<tr>
<td>GV-7</td>
<td>1.05 ms</td>
<td>1.97 ms</td>
</tr>
<tr>
<td>GV-13</td>
<td>1.20 ms</td>
<td>1.57 ms</td>
</tr>
</tbody>
</table>

**Line GV-2**

Line GV-2 is an E-W line at the south end of the survey, and crosses CPT13 at geophone 16. The time-term inversion model had an RMS error of 1.26 ms. There was a large velocity contrast between 0.2 km/s and 1.8 km/s at ~3 m. For the tomographic inversion model, RMS error increased to 2.69 ms. The tomographic solution (Appendix C-8) shows a fairly constant velocity of 0.3 km/s down to ~3 m depth underlain by a zone of gradual velocity increase to ~1.4 km/s at ~7 m depth, and a maximum of ~1.7 km/s at the base of the 15 m thick model. The refractor surfaces bow upward within the 7-10 m depths, just west of the center of the line (~120 m on x-axis). There seems to be little or no evidence of the fault at the 80 m mark along the x-axis, but the deeper velocity contours dip more steeply to the east near the eastern end of the line.
**Line GV-2b**

Line GV-2b is parallel to GV-2, located 30 m to the north. Geophone 16 coincides with CPT12. The time-term solution yielded a 1.68 ms RMS error and a two-layer model with a velocity contrast between 0.2 km/s and 1.8 km/s at ~3 m depth. The tomographic inversion had a 2.16 ms RMS error. The tomographic solution (Appendix C-13) shows fairly constant velocity of 0.3 km/s down to ~2.5 m depth underlain by a gradual velocity increase to ~1.5 km/s at ~8 m depth, and finally ~1.7 km/s below. The section with gradually increasing velocity has fairly horizontal velocity contours, but the highest velocity (~1.7 km/s) contour, at ~10 m depth, has a slight bulge upward at ~125 m along the line. Then, near the eastern end of the line, the deepest, highest velocity contours dip more steeply to the east. The increase in dip is slightly further to the west than in line GV-2. The suspected trace of the Green Valley fault should still be located at ~80 m along the x-axis, and there may be some expression of a fault feature where the higher velocity layers begin to dip more steeply to the east.

**Line GV-4**

Line GV-4 is an E-W line parallel to and 60 m north of line GV-2b. Geophone 16 shared its position with CPT10, and the inferred trace of the fault crosses the model at 80 m along the x axis. Using time-term inversion, the solution had an RMS error of 1.36 ms and a distinct velocity contrast between 0.2 km/s and 1.7 km/s at ~3 m. Tomographic inversion had an RMS error of 2.11 ms. The tomographic solution (Appendix C-18) shows a fairly constant velocity of 0.2 km/s down to ~2 m depth underlain by a zone of gradually increasing velocities to ~1.2 km/s at ~5-10 m depth, and finally ~1.7 km/s to
the base of the 15 m thick model. The deepest refractor surfaces bow upward within the 5 m to 10 m depths, just west of the center of the line (between 90 m and 135 m on the x-axis). The highest velocity contours again dip steeply to the east, and this dipping feature has moved further west than was seen in lines GV-2 and GV-2b. The persistence of this dipping feature may in fact be an expression of the Green Valley fault surface.

**Line GV-4b**

Line GV-4b runs E-W in conjunction with the E-W line formed by CPT1 through CPT6. Geophone 16 (at 110 m along the x-axis) is in the same location as CPT 3, the crossing point of the t-shape formed by CPT stakes, and the groundwater monitoring station. Time-term inversion yielded an RMS error of 1.45 ms, and a clear velocity contrast from 0.3 km/s to 1.7 km/s at ~6 m depth. The tomographic inversion yields a 2.87 ms RMS error. The detailed model (Appendix C-23) shows very constant velocity of 0.3 km/s down to ~3 m depth underlain by a gradual velocity increase to ~1.3 km/s at ~8 m depth, and finally ~1.6 km/s below to the base of the 15 m deep model. From the surface to depths of 8 m there are no lateral variations in velocity. Below depths of 8 m on the east side of the line, velocity contours dip to the east and correspond to the same feature in all other E-W lines. This dipping feature is most likely the fault trace. It has not shifted any more to the west as discussed between lines GV-2, GV-2b and GV-4. The fault trace should still cross the refraction line at 80 m on the x-axis (as mapped by J.J. Lienkaemper, written communication, 2004), but based on this model I would shift the inferred fault trace about 10 m to the west of the position shown in Figure 11.
Line GV-6

Line GV-6 is the northernmost of the five E-W lines. At geophone 16, line GV-6 crosses CPT8, and the suspected fault trace crosses the x-axis at ~80 m. The time-term inversion had an RMS error of 1.66 ms, with a two-layer solution showing a strong velocity contrast between 0.3 km/s and 1.6 km/s at a depth of ~6 m. Tomographic inversion had an RMS error of 2.87 ms. The tomographic model (Appendix C-28) shows a very flat-bottomed constant velocity of 0.3 km/s down to ~4 m depth underlain by a gradual velocity increase to ~1.2 km/s at ~8-9 m depth, and finally ~1.6 km/s to 15 m depth at the base of the model. The deepest refractor surfaces bow upward very slightly within the 8-10 m depths, close to the center of the line (between 90 m and 110 m on the x-axis) and again on the far east side of the line. The east-dipping feature seen on all of the other E-W lines has shallowed in this model, and is only slightly expressed at approximately 90 m along the x-axis and at 8-12 m depth.

Line GV-3b

Line GV-3b (merged from the two lines GV-3bs and GV-3bn) runs N-S, 60 m west and parallel to the suspected trace of the Green Valley fault. The total length of the line is 210 m, slightly shorter than the other N-S lines because the northern end of the line abuts residential property. The geophone placed furthest south is 30 m to the west of CPT13 and perpendicular to the N-S line connecting CPT stakes. The time-term inversion had an RMS error of 1.49 ms and a distinct velocity contrast between 0.1 km/s and 1.7 km/s at ~2 m depth. The tomographic inversion RMS error increases to 2.21 ms, and the model (Appendix C-33) yields a fairly constant velocity zone of 0.3 km/s to a
depth of ~3 m on the south end and ~5 m on the north end. Velocity increases from 0.4
km/s to 1.3 km/s between the 4-5 m depth on the south side and the 5-10 m depth on the
north side. Below this zone of high velocity gradient, the base of the model has a
velocity of ~1.6 km/s. There are two, possibly three, features in the model that allude to
paleochannel structure because they are lenses of middle-velocity in the model. These
lens shapes appear at ~5-6 m depths, and at ~80 m, ~130 m, and 185-245 m along the x-
axis. Two of these lens features are 15-20 m wide, and the feature furthest north is
greater than 40 m wide.

Line GV-7

Line GV-7 (merging lines GV-7s and GV-7n) is probably the most useful of all of
the refraction lines in this survey. It is the N-S line that crosses on top of many of the
CPT stakes, and is in the same location as GPR line M7 (the line with the most
paleochannel features). This line is parallel to and 30 m west of the suspected trace of the
Green Valley fault. The time-term inversion model had an RMS error of 1.05 ms, and
showed a strong velocity contrast between 0.3 km/s and 1.7 km/s at ~3 m depth. The
tomographic inversion had an RMS error of 1.97 ms. This tomographic model
(Appendix C-38) shows a fairly constant velocity zone of ~0.3 km/s at 0-3 m depth on
the south side and 0-4 m depth on the north side. Below this top layer, the velocities
gradually increase from ~0.4 km/s to ~1.4 km/s between depths of 3-5 m on the south
side and 5-10 m on the north side. The deepest and highest velocity contour is ~1.7 km/s
at a depth of 6 m on the south side and 13 m on the north side. There are three, possibly
four, lens-shaped low velocity zones in the model that may be buried paleochannels.
Along the x-axis, these features are located at ~45-65 m, ~110 m, ~155-195 m, and ~235-260 m.

**Line GV-13**

Line GV-13 (merged from GV-13s and GV-13n) is the only line completely on the west side of the Green Valley fault trace. This line is 265 m in length, and is in line with the geophone 22 position on all E-W lines (i.e. 140 m on the x-axis of all E-W lines). CPT stake 5 is in the same location as 185 m on the x-axis of line GV-13. The time-term inversion model had an RMS error of 1.2 ms, and solved for three distinct velocity layers. The top layer is 0.1 km/s to a depth of ~2 m, the middle layer is 0.7 km/s down to ~7 m, and the bottom layer is 1.7 km/s to the base of the 35 m deep model. Tomographic inversion yields an RMS error of 1.57 ms. In the tomographic model (Appendix C-43) the top layer is a constant velocity of ~0.2 km/s down to ~1 m depth, underlain by a section of gradually increasing velocity from ~0.3 km/s to ~1.3 km/s between 2-7 m on the south side and 2-11 m on the north side. Below this gradually increasing velocity section, the deepest and highest velocity layers are ~1.7 km/s down to the base of the 15 m deep model. On the north side of the line, the middle velocity layers get thicker and the contours have a broad lens shape approximately 50 m wide and at ~5-10 m depth (between 195 m and 245 m on the x-axis). This may correlate with the other large lens-shaped features on the north sides of lines GV-3b and GV-7, may represent either a natural or human-engineered drainage that has since been buried to make way for farming on this field.
Hand-Auger Data

In April 2005 we hand-augered an apparent channel location interpreted from the north end of GPR line M7 (see Figures 10 and 11). Figure 12 shows the hand-auger equipment and representative soil samples we collected. This feature is approximately 50 m from the proposed USGS trench location. We augered to a total depth of 3.0 m,

Figure 12: April 2005 hand auger sampling at location of paleochannel feature detected by GPR line M7. Representative soil samples at bottom of photo.
collecting soil samples every 30 cm. At depths of 2.7-3.0 m, we encountered several rounded cobbles within soils that contained fine sand and were rich with mica flakes. The largest clast found was a rounded volcanic cobble, ~3 cm length on its longest axis. These observations are consistent with the presence of a shallow channel, as interpreted from the GPR and seismic refraction data. In February 2004, while placing the groundwater monitoring well at CPT3, hand-auger samples were collected to depths of 3.75 m. The GPR line did not indicate any channel features at this location, and the hand-auger soil samples revealed nearly continuous sandy-clay and brown sandy silt, with carbonate nodules forming at 3.0 and 3.75 m depths. Based on the 2004 and 2005 hand-auger samples, channel sediments are not present at CPT3 down to 3.75 m depth, but there may be channel sediments ~40 m north of CPT3, at ~3 m depth, as imaged on the north ends of GPR line M7 and seismic refraction line GV-7.

**Discussion**

From the geologic setting I know that local bedrock at the Mason Road site is Sonoma Volcanics. Judging from the depth of the CPT soundings and the corresponding depth conversions in the seismic refraction models, the deepest velocity contour detected in the refraction data is not likely to be bedrock. Future seismic reflection data collected at this site would be useful in determining depth to bedrock underneath all of the Quaternary alluvium in Green Valley. The deepest velocity contrast detected by seismic refraction therefore must be more compacted and older alluvium, probably the Holocene-Pleistocene contact inferred by CPT data interpretation. The shape of the deepest
velocity contrast detected in line GV-7 suggests the presence of paleochannel features, and matches with GPR results and possibly augering data.

The most representative data in the whole survey is line GV-7, not only because it has a low RMS error but also because it can be correlated with CPT and GPR data. I have taken the CPT soundings from holes 8, 3, 10, 12, and 13 and draped the tip resistance curves over the refraction velocity model for GV-7 and the GPR data line M7 (Figure 13). The CPT data suggest a transition at 5-7 m depth from Holocene or latest Pleistocene flood and channel fill to Pleistocene alluvium below (T.E. Noce and J.J. Lienkaemper, written communication, 2004). The velocity contrast between 1.4 km/s and 1.7 km/s approximately coincides with the Holocene-Pleistocene contact as interpreted from the CPT data. This contrast was not detected in the GPR data. In many

Figure 13: The tomographic inversion model from seismic line GV-7 in background in color. Draped on top of the model are GPR line M7 with paleochannel interpretations (dark grey shading) and CPT tip resistance curves. White dashed line is interpreted Holocene-Pleistocene contact (GPR modified from Craig et al., 2004; CPT data from T.E. Noce and J.J. Lienkaemper, unpublished, 2004).
areas between CPT points, the refraction model can fill in the gaps in the interpreted subsurface structure. Unfortunately none of the CPT points coincided with the most apparent channel features seen in the GPR lines. CPT positions might have been sited more strategically had all of the GPR lines been collected and interpreted prior to CPT data collection.

An east-dipping feature at approximately the same location in all E-W refraction lines may validate the suspected creeping trace of the Green Valley fault, as mapped by Lienkaemper (written communication, 2004). This inferred fault trace in the refraction models nearly lines up with the en echelon cracks found on the paved portion of Mason Road just north of the site, but the geometry of the fault feature indicates that the mapped trace may need to be adjusted by as much as 10 m east and west (Figure 14). This fault feature in the seismic refraction models also may indicate that at this location the Green Valley fault has a slight vertical component of slip. Comparison of the N-S lines corroborates this conclusion, as the highest velocity contours deepen in line GV-13 on the east side of the fault (Figure 15).

The USGS trenching planned at this site will provide a more comprehensive set of data to confirm or refute my results. The final results of GPR, CPT, and refraction data will all be used to better locate proposed trenches at the Mason Road site. If the trenches expose paleochannels at the same locations as identified by geophysical data, then my interpretations will be validated. The ultimate goal will be to better characterize this unconstrained portion of the Green Valley fault.
Figure 14: E-W velocity models in relation to the mapped trace of the Green Valley fault. The grey dashed line is the adjusted trace of the fault based on the east-dipping velocity contours in each model.
Figure 15: N-S velocity models in relation to the mapped trace of the Green Valley fault. View looking SW. Yellow dashed lines indicate inferred channel features.
Chapter Four:
Hayward Fault at Tyson’s Lagoon

Site Selection

I chose the Tyson’s Lagoon site because it provided an opportunity to conduct a near-surface geophysical investigation on a creeping section of the Hayward fault where numerous sets of site-specific data were available for comparison. This site is in the town of Fremont, California, within one city block of the Fremont BART station. The Hayward fault has created classic sag pond geomorphology within a right stepover of the fault. High sedimentation rates provide a preservation mechanism for paleoseismic features within pond sediments. Tyson’s Lagoon straddles either side of Walnut Avenue, and is sometimes referred to as Tule Pond. The most recent trenches excavated in this area have been SE of Walnut Avenue within Tyson’s Lagoon. Unfortunately, the trenches logged thus far have not been deep enough to expose the entire Holocene evolution of this stepover structure within the Hayward fault, and any more subsurface information that can be gained will be useful in many ways. Figure 16 shows an aerial photo of the City of Fremont with the larger portion of Tyson’s Lagoon north of Walnut Avenue labeled. Within Figure 16, the portion of the pond south of Walnut Avenue is herein referred to as the Tyson’s Lagoon site.
Figure 16: Tyson’s Lagoon site with two traces of the Hayward fault indicated by red lines, and the shape of the sag pond prior to modern disturbance outlined in white (modified from J.J. Lienkaemper, written communication, 2005).
Many public-domain geologic studies regarding the site have been published, in part because BART is planning an extension project to extend rail transportation further south. Several earlier site investigations were completed in preparation of the initial construction of the Fremont BART station. If the extension project goes through, then the train tracks will cross over the Hayward fault twice. BART must design for ongoing creep, future earthquake slip, complex surface rupture, and the increased strong ground motions and liquefaction failures, all of which may be expected at this site.

Access to the site was seasonal due to the flooding of the pond during the winter months, and large clumps of tules (bulrush plants) impede surveying and data collection. Designing a simple rectangular grid of seismic refraction lines was impractical, but the site was attractive due to the amount of existing data with which to compare results.

**Geologic and Geophysical Setting**

Tyson’s Lagoon is a sediment-filled depression, or sag pond, aligned in a NW/SE direction along a right stepover in the southern segment of the Hayward fault. The dominant feature in the region is the Hayward fault itself, which on a large scale places upper Jurassic, lower Cretaceous Franciscan Complex mélangé to the SW against Cretaceous and Tertiary marine sediments to the NE (Wagner *et al*., 1991). Quaternary sediments have placed a thin coating over older formations that are only occasionally exposed in outcrop among hills to the east. The Hayward fault runs along the western margin of the East Bay Hills from the Warm Springs District of Fremont to the San Pablo Bay. The fault is over 80 km in length, and is a dextral strike-slip fault with a minor component (0.5-0.6 mm/yr) of vertical slip (Lienkaemper *et al*., 1991; Lienkaemper and
Borchardt, 1996). Recent magnetic and gravity evidence suggests that the ancestral surface of the Hayward fault is dipping east and may be in some complex manner linked to other faults in the area at depth (Ponce et al., 2003). Nevertheless, Tyson’s Lagoon collects Holocene alluvial soils of clay, silt, sand, and gravel (Cooper-Clark & Associates, 1968). A rapid sedimentation rate inside the sag pond provides an excellent setting for paleoseismic study of both aseismic creep and coseismic slip along the Hayward fault.

As discussed in the introduction of this study, a likely mean recurrence interval for major earthquake events on the southern segment of the Hayward fault is $176 \pm 15$ yr over the past 1800 years (Lienkaemper et al., 2005). Creep rate associated with the Hayward fault in Fremont is most recently estimated at 5-9 mm/yr, but for a few years after the Loma Prieta earthquake of 1989 creep rates were dramatically less than the decade prior, and are slowly increasing again with time (Lienkaemper et al., 2001). Slip rate along the entire length of the fault is approximately 9 mm/yr, at least since the 1868 earthquake and possibly throughout Holocene time (Lienkaemper et al., 1991). In an M7 earthquake along the southern segment of the Hayward fault, the Tyson’s Lagoon site might experience lateral displacement between 0.3 and 1.4 m, and as much as 0.2 m vertical displacement (Kelson, 2003).

Aeromagnetic and gravity surveys along the Hayward fault revealed the orientation and extent of the San Leandro Gabbro buried underneath alluvium of the flat bay region west of the fault (Ponce et al., 2003). The bedrock at the Tyson’s Lagoon site is buried deep under these alluvial sediments, but Figure 17 shows a distinct magnetic
Figure 17: Aeromagnetic anomalies in Fremont area. Red lines are faults (Jennings et al., 1977), black line is current trace of Hayward fault (Lienkaemper, 1992), blue line is coastline, white circles are seismicity, Tyson’s Lagoon site within bold black box (aeromagnetic values from USGS, 1996).

Field anomaly of up to 80 nT in between the eastern and western traces of the Hayward fault, north of Tyson’s Lagoon. This anomaly reflects an extension of the dense San
Leandro gabbro body, and is in line with the sag pond at Tyson’s Lagoon (D.A. Ponce, personal communication, 2005). Flights recording this magnetic data were flown with line spacing of ~540 m at an average altitude of 270 m (USGS, 1996).

**Background Data**

**Trenching**

More than a dozen trenches have been excavated at the Tyson’s Lagoon site in the last three decades. Not one of these trenches has gone deep enough to expose pond sediments older than Holocene age. One of the most detailed and documented trenches that correspond with this study is trench 00A (Lienkaemper *et al*., 2002). Logs from this and later trenches show evidence for nine prehistoric earthquakes over the past 1800 years, and constrain their ages and the average recurrence time (Lienkaemper *et al*., 2005). The oldest carbon dating ages gained from sediments in trench 00A were a shell at ~1 m depth from $3840\pm40$ years before present, and two charcoal pieces in the deepest part of the trench from ~3650 years before present (Lienkaemper *et al*., 2002). Four distinct event horizons were logged in trench 00A, from the most recent 1868 earthquake on the Hayward fault (event E1) to event E4 ranging over 200 or 300 years from A.D. 1360-1580 (Lienkaemper *et al*., 2002).

More recent work to constrain dates and events within trenches at Tyson’s Lagoon confirms that all event horizons and theoretical ages of deposition are younger than 2000 years before present (J.J. Lienkaemper, unpublished data, 2005). The most recent trench excavated at this site is a USGS trench logged in 2004, named 04A. This trench spans over 100 m distance in the pond, parallel to and just inside the pond from
Walnut Avenue. Trench 04A revealed many very horizontal soil layers down to the deepest portion of the trench, at ~3.5 m depth.

**Borehole Logs**

Prior to construction of the Fremont BART stations, several dozen observation well borings were drilled to depths ranging from a few meters to more than 74 m (Cooper-Clark & Associates, 1968). Two of these borings were situated at the end of the BART line, just north of Walnut Avenue, one on either side of the western trace of the Hayward fault at Tyson’s Lagoon. Borehole 40 was inside the pond on the east side of the western fault trace and logged the upper boundary of a thick gravel layer at ~40 ft (~12 m) depth. Borehole 41 was outside the pond on the west side of the western fault trace, and logged what is likely the same upper boundary of a thick gravel layer at only 13 ft (~4 m) depth. This surface is vertically offset from outside to inside the pond, based on the two borehole logs that straddle the western trace of the Hayward fault. At the contact between softer alluvium and harder gravel, the standard penetration tester (SPT) blow count increased from 10 to 37 blows/ft in borehole 40 and from 5 to 36 blows/ft in borehole 41. This dramatic increase in blow count indicates a hardness contrast that should provide a strong refractor surface for seismic refraction lines.

**Cone Penetrometer Testing**

During a 2002 site investigation at Tyson’s Lagoon, Fugro West, Inc. conducted CPT soundings along Walnut Avenue near the western boundary of the site. When compared with previous borehole logs, the CPT data corroborated an inferred contact between Holocene and Pleistocene sediments. This boundary was detected at shallow
depths (~3 m) on the west side of the western fault trace, and much greater depths (14-15 m) on the east side within the sag pond (Kelson, 2003). The Holocene-Pleistocene contact is evidently the same boundary logged in 1968 borings as a contact between sandy clays/silts and the deeper thick gravels. Since this contact showed is so distinct in CPT soundings, seismic refraction surveys should detect it as a continuous refractor surface. A modified summary of CPT data collected by Fugro West in 2002 can be found at Appendix D. Note that these CPT soundings were collected along the sidewalk on Walnut Avenue, and the ground surface inside Tyson’s Lagoon is ~3 m lower than the ground surface on the sidewalk. Adjusting for this elevation difference, the depth from surface to the suspected Holocene-Pleistocene boundary within Tyson’s Lagoon should be approximately 13-14 m.

**Seismic Refraction Survey Design and Data Collection**

Site conditions at Tyson’s Lagoon prevented a simple grid design as was used along the Mason Road site on the Green Valley fault. While extensive trenching at Tyson’s Lagoon provides a great deal of subsurface data, it limits the amount of unaltered shallow subsurface with which to conduct detailed geophysical study. I placed seismic refraction lines close enough to existing trench logs to permit data correlation, but not so close that they could be affected by excavated, repacked, and filled holes that were several meters deep and up to a meter wide. Seasonal flooding of the sag pond and extensive growth of large tule (bulrush) plants also complicated my survey design. Seasonal flooding limits survey time to summer months, but sometimes extend as late as
October. The growth of tule plants makes it difficult to layout a survey line and plant geophones properly.

In October 2004, I collected three seismic refraction lines. The first line, TY-1, ran parallel to Walnut Avenue, in between the two traces of the Hayward fault, trending 33°, with 4 m geophone spacing, and a total data area length of 92 m. The second line, TY-2, was south of TY-1, fully inside of the pond, and lined up with a benchmark placed on the scarp of the western fault trace. TY-2 had 3 m geophone spacing, with a sledgehammer on rubber plate source and seven evenly spaced shots. I used a rubber plate instead of a metal plate because the ground was saturated and muddy, and field observation indicated that the rubber plate provided better waveform data than the metal plate. The total data area length of TY-2 was 69 m. The third line, TY-3, connected the first two lines on their SW ends, and ran parallel to and east of the western strand of the Hayward fault. The two coinciding points of the three lines occur at (1) Tyson 1 geophone 2 with TY-3 geophone 23, and (2) TY-2 geophone 2 with TY-3 geophone 3. TY-3 had 2.5 m geophone spacing, for a total data area length of 57.5 m. I used a sledgehammer on rubber plate source for the same reasons as stated with TY-2, and had seven evenly spaced shots along the line. The geometry of these three lines, in relation to the fault trace, Walnut Avenue, trench 04A, and CPT soundings can be seen in Figure 18.

Site conditions in October 2004 were ideal for seismic refraction. The pond was not yet flooded, but the ground was fully saturated and would certainly begin to flood at the next onset of rain. As discussed previously, the groundwater surface can act as a
Figure 18: Seismic refraction survey design at Tyson’s Lagoon with mapped portions of the refraction lines showing actual data coverage area (i.e. geophone 1 through geophone 24). CPT locations are along the Walnut Avenue sidewalk (modified from J.J. Lienkaemper, written communication, 2005).
refractor in data lines and needs to be accounted for during data interpretation. R. Bainer (1982) noted seasonal variations in a previous seismic refraction study conducted approximately 500 m south of Tyson’s Lagoon. Since the groundwater close to the surface, seismic refraction data were easier to interpret, and the energy from each shot experienced less attenuation along the line.

The BART station is located just on the NW side of Walnut Avenue with fairly constant car, bus, and train traffic. I collected data on each of two weekend days in the early morning hours to avoid as much traffic as possible. Even during these dawn hours there was a significant amount of low frequency noise in the waveform data that presented a challenge when picking first arrivals. Any time a bus drove past, or idled at a nearby intersection, there was constant noise on the line with high enough amplitude to overshadow any sledgehammer shot data. Future surveys planned at this site should take into consideration bus/train schedules and should be conducted during the least busy parts of these schedules.

**Data Processing and Results**

Waveform data from all three lines at Tyson’s Lagoon were very noisy. For all three of the lines, consisting of 21 shot gathers, I tested low-cut, high-cut, and bandpass filters. In all cases I found that filtering could reduce noise, but generally degraded the quality of the refracted arrivals in the process. In general, filtering did not harm the direct arrivals, but almost always degraded the refracted arrivals.

Appendix E contains screen images of first break picks, traveltime curves, and corresponding velocity models for each of the refraction lines collected at Tyson’s
Lagoon. Once I picked the first breaks, I assigned layers along traveltime curves and used time-term inversion to determine a layered velocity model. The simple time-term model resolves a maximum of three layers, so I used tomographic inversion methods to create more detailed velocity models. For seismic refraction lines at this site, I used the same processing strategy already discussed in Chapter 2 from the Mason Road site.

Recall that the RMS error provides a value for the reliability of the velocity model, and that 1.5 ms or less is generally considered acceptable (Geometrics, 2003). In the three refraction lines at this site, my final velocity model RMS errors ranged from 1.75 ms to 3.15 ms (Table 2). I attribute these high error values to subsurface material structure that is complicated with fault traces and the disturbed remnants of past trenching.

Table 2: RMS error values for velocity models at Tyson’s Lagoon site.

<table>
<thead>
<tr>
<th>Line Name</th>
<th>Time-Term Model RMS Error</th>
<th>Tomographic Inversion Model RMS Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>TY-1</td>
<td>3.65 ms</td>
<td>2.69 ms</td>
</tr>
<tr>
<td>TY-2</td>
<td>2.16 ms</td>
<td>3.15 ms</td>
</tr>
<tr>
<td>TY-3</td>
<td>1.15 ms</td>
<td>1.75 ms</td>
</tr>
</tbody>
</table>

**Line TY-1**

TY-1 is a NE-SW line that parallels Walnut Avenue and USGS trench 04A. The time-term inversion yielded an RMS error of 3.65 ms, showing a two-layer model with a distinct velocity contrast between 0.3 km/s and 1.8 km/s at ~9 m, shallowing slightly on the NE side. With tomographic inversion, the RMS error was 2.69 ms, and the detailed model (Appendix E-5) shows fairly constant velocity of 0.3 km/s down to ~5m depth
underlain by velocity contours gradually increasing to ~1.5 km/s at ~9 m depth, and finally ~1.8 km/s below to the base of the 15 m deep model. The refractor surfaces bow downward within the 5 m to 10 m depths, just NE of the center of the line, suggesting this is the deepest portion of the pond as it formed. Another possible explanation for this concave-up feature is that there is a cross-fault at depth allowing slip to transfer between the western and eastern traces of this section of the fault.

**Line TY-2**

TY-2 is a line slightly parallel to TY-1, but further inside the pond and angled in a slightly more N-S orientation. The time-term inversion model had a 2.16 ms RMS error and a clear velocity contrast between 0.3 km/s and 2.0 km/s at ~8 m. The tomographic inversion model had an RMS error of 3.15 ms. The tomographic model (Appendix E-10) shows a constant velocity of 0.3 km/s down to ~5m depth underlain by velocity contours increasing to ~1.5 km/s at ~12 m depth, and finally ~1.9 km/s to the bottom of the 15 m deep model. There is a slight deepening of the bottom layers towards the center of the line from approximately 12 m to 17 m depth. The broad deepening feature in the higher velocities (41-81 m on the model’s x-axis) may represent an oblique view, and therefore an apparent width, of the cross-fault structure suspected in refraction line TY-1.

**Line TY-3**

TY-3 is a NW-SE line that parallels the western side of Tyson’s Lagoon and also parallels the western trace of the Hayward fault. The time-term inversion had an RMS error of 1.15 ms and a two-layer model with a distinct velocity contrast between 0.3 km/s and 1.9 km/s at ~8 m. The tomographic inversion RMS error was 1.75 ms. This
tomographic model (Appendix E-15) shows a constant velocity of 0.3 km/s down to ~5m depth underlain by velocities gradually increasing to ~1.5 km/s at ~12 m depth, and finally ~1.8 km/s below to the base of the 15 m deep model. The portion of the model with gradually increasing velocities (between 5 m and 12 m depth) thickens significantly on the NW side of the line (closer to Walnut Avenue). On this side of the line, the top layer with 0.3 km/s velocity only extends to ~4 m depth and the zone with largest gradient (increasing velocity up to 1.5 km/s) extends to >15 m depth. The highest velocity, deepest layer (~1.8 km/s) underlies this thickened section at ~12 m depth on the SE side, but deepens towards the NW below the base of the model. This thickening northward portion of the velocity model correlates with the morphology of the sag pond. The larger, deeper portion of Tyson’s Lagoon is to the north, now partially filled by the construction of Walnut Avenue and a parking lot for the BART station.

Discussion

Data from previous work indicates that there is a Holocene-Pleistocene boundary at depth in Tyson’s Lagoon. The depths of a velocity contrast in seismic refraction lines at this same location seem to match conclusions from previous studies (Kelson, 2003; Cooper-Clark & Associates, 1968). If sedimentation rates in the pond have remained relatively constant, I can used carbon-dated trench samples (Lienkaemper et al., 2002; J.J. Lienkaemper, unpublished data, 2005) to extrapolate about 2000 years of time for every ~3 m of depth. The depth of the suspected Pleistocene gravel surface can be projected to ~18 m on the NW end of refraction line TY-3, so an approximation of age/depth would be ~12,000 years before present (latest Pleistocene).
The transition to a velocity of ~1.8 km/s in the models is most likely the Holocene-Pleistocene boundary inferred by CPT data. Shallow sand and gravels (<2 km depth) can have seismic P-wave velocities from 0.4 km/s to 2.3 km/s (Reynolds, 1997), so a velocity of 1.8 km/s is within this range. Neither the western trace nor the eastern trace of the Hayward fault can be derived from the velocity models, mainly because the fault was on the far edge of lines TY-1 and TY-2. There is a strong possibility of a cross-fault detected in line TY-1, and obliquely in line TY-2. The acute angle of this cross-fault to the two traces of the Hayward fault is consistent with the theory of Riedel shearing in strike-slip fault zones (Tchalenko, 1970). Previous site investigations theorized the existence of a cross-fault in this portion of the releasing bend (Kelson, 2003), but there was no direct geophysical evidence. Line TY-3 provides the most sensible model of the suspected Holocene-Pleistocene contact surface, and confirms that the surface is dipping north into the deeper portion of the pond.

TY-3 is the most representative data not only because it has a low RMS error but also because it can be correlated with CPT data. The CPT data inferred a transition at ~15 m (adjusted) depth from Holocene clay/silt to Pleistocene gravels below (Kelson, 2003). The NW side of the line models the deepest and highest velocity layer at <15 m depth, approximating the adjusted depth of the CPT data. Nevertheless, there is a distinct velocity contrast at depth in refraction line TY-3 that correlates with CPT data and nearby
Figure 19: Composite of seismic refraction lines at the Tyson’s Lagoon site in relation to the western trace of the Hayward fault. Cross-fault feature marked with dashed red line. borehole logs. This deepest refractor in the tomographic inversion model is most likely the contact between Holocene silty sag pond deposits and Pleistocene alluvium gravels.
The refraction models from lines TY-1 and TY-2 appear to image a cross-fault feature, akin to a Riedel shear, that would explain how this section of the Hayward fault transfers slip from the western trace to the eastern trace. Figure 19 shows a composite of the three seismic refraction lines in relation to the western trace of the Hayward fault, and labels the cross-fault feature as well as the suspected Pleistocene gravel contact. The tomographic inversion model for line TY-1 images the cross-fault feature best, and the fact that it has not been discovered before now can be explained by its depth. All trenches at this site are rather shallow (<4 m deep), their depth being limited by the water table within the pond. The possible cross-fault zone seen in refraction line TY-1, and perhaps seen obliquely in TY-2, is imaged at depths between 5-15 m, and appears to be ~20-30 m wide.

Knowing more about the Pleistocene gravel contact surface can help in future paleoseismology studies along the Hayward fault. Deeper excavation through either borehole or trench can reveal dateable fault features and possibly more information about the timing of the opening of the sage pond. Since none of the trenches in the area can be excavated deep enough to expose this Holocene-Pleistocene contact, geophysical techniques may be able to bridge the gap between well-documented trenches and scattered boreholes and CPT soundings.
Chapter Five:

Concluding Statements

Geophysical methods can be used in concert with more traditional geologic site investigations to better characterize subsurface structure in fault zone settings. At the Mason Road site along the Green Valley fault, I conducted a seismic refraction survey that indicates the presence of paleochannel features and provides depth control for those same features detected in GPR surveys. I also determined the apparent location of the fault trace and identified a possible vertical component of fault motion. At Tyson’s Lagoon I interpreted the presence of a cross-fault feature as well as a material contrast that may be the Holocene-Pleistocene contact. This information may contribute to future paleoseismologic investigations of the Hayward fault. Interpreting conclusive results at each of these two sites would not have been possible without supporting data, such as CPT soundings, trench logs, borehole logs, and GPR lines.

Trenching is a very useful tool in paleoseismology and engineering site investigations, but at the same time it is very costly. Geophysical investigations such as seismic refraction and GPR are less expensive, quicker, and can facilitate deliberate trench excavation once a more detailed site investigation is warranted. Seismic refraction can also bridge the gap between shallow trenches and scattered CPT and borehole logs. I designed the seismic refraction surveys to identify and locate three-dimensional subsurface features that may be difficult to characterize using more traditional one-dimensional or two-dimensional investigations. Future geologic site investigations should make full use of geophysical techniques to (1) determine optimal locations for
proposed trenches, (2) create a complete geologic picture with ground truth data (trench, CPT, borehole), and (3) conduct “virtual” trenching to extend real trenches beyond their original length and depth dimensions.
Chapter Six:

Future Work

Green Valley Fault

As previously stated in Chapter Four, the USGS is planning to trench the Mason Road site, generally in the same location as my grid of seismic refraction lines. The logs from these trenches will be helpful in evaluating the usefulness of seismic refraction for detecting near-surface alluvial stratigraphy and siting trenches. According to current plans, a trench will be excavated at a depth of 5-8 m (J.J. Lienkaemper, personal communication, 2004). The target of the trenching will be the base of any late Pleistocene paleochannels, so that they may be oriented, characterized, and materials dated (J.J. Lienkaemper, personal communication, 2004).

Based on seismic velocity models obtained through the present work, I believe that a near-surface geophysical investigation using seismic reflection would be useful. Seismic reflection lines collected in the same locations as CPT logs and refraction and GPR surveys could strengthen any conclusions about channel shapes, locations, and depths. Seismic reflection lines oriented in an E-W direction, crossing the suspected fault trace, may be able to better define the subsurface fault structure.

Baldwin and Koehler (2004) studied a site further SE along the Green Valley fault, and south of the Interstate 80 highway, at Lopes Ranch Creek. This site provides an excellent location for geophysical study because there is a definite material contrast across the trace of the fault. On the west side of the fault are marine sediments of the Lower Cretaceous – Upper Jurassic Great Valley Sequence, while on the east side of the
fault are rocks of the Sonoma Volcanics (Wagner and Bortugno, 1982). Trenching operations are fairly extensive at this site, and those trench logs are published and readily available. Paleochannels were logged in these trenches at depths less than 5 m, so a full suite of geophysical investigations would most likely result in useful data (GPR, seismic refraction, and seismic reflection). Conducting a geophysical study at this site would be another way to refine methods for site investigations and improve the link between geophysics and more traditional engineering geology site investigations.

**Hayward Fault**

Since my seismic refraction lines may have detected the Holocene-Pleistocene contact at the very bottom limit of reliability, it seems appropriate to follow up this work with a geophysical study with greater penetration. Seismic reflection surveying would probably be useful in solving more detailed models of the subsurface in Tyson’s Lagoon. Reflection lines collected in the same locations as CPT soundings and refraction surveys could strengthen any conclusions about the Holocene-Pleistocene contact surface and its structure inside the sag pond. A high-resolution reflection survey may also be able to detail paleoseismic event surfaces, verify the existence of a possible cross-fault feature in the center of the pond, and extend the knowledge of Hayward fault earthquake history.

Preliminary seismic refraction lines collected at the Fremont Central Park site, south of Tyson’s Lagoon and adjacent to Lake Elizabeth, yielded data that were inadequate for processing velocity models. However, extensive trenching, borehole logging, seismic refraction, and GPR surveys have been completed at the site (Lienkaemper *et al.*, 2002; Borchardt, 1990; Woodward-Clyde & Associates, 1970;
Bainer, 1982; Cai et al., 1996). With prior planning to avoid data compromise by cultural noise, a detailed seismic refraction survey at the Fremont Central Park site could be very useful in better characterizing the geologic and geophysical setting of the Hayward fault.

**Alternate Seismic Sources**

In April 2005, after all seismic refraction data were collected for this work, we tested the difference between using a sledgehammer source and a Betsy seisgun (also called a buffalo gun). This device is a pipe and firing pin used to fire blank small-arms ammunition (shotgun) cartridges into the ground. The advantage of using small-arms ammunition is that it provides a source with a higher frequency content and significantly more energy than the sledgehammer. We placed a survey line at the Mason Road site in the same location as line GV-7. The geophones were spaced at 3 m intervals, and the sledgehammer shots had five stacks per shot while the Betsy seisgun had only one stack. The difference between these two sources can be seen in Figure 20. First breaks in the waveform data using the seisgun are much more distinct than in the sledgehammer waveform data. Furthermore, the direct wave traces are much easier to pick out in the seisgun data. For seismic refraction surveys at sites with low frequency cultural noise, such as Tyson’s Lagoon or the Fremont Central Park, I would highly recommend using the seisgun for the source. Although there may be concern from using small-arms ammunition in an urban area, the actual noise from firing the seisgun is indistinguishable from the noise from hitting a metal plate with a sledgehammer.
Figure 20: Waveform data from both the sledgehammer source (a) and the Betsy seisgun source (b) for the same shot location on the same line. Data collected at the Mason Road site, April 2005.
References


Bortugno, E.J., 1982, Map showing recency of faulting, Santa Rosa Quadrangle, 1:250,000: California Department of Conservation, Division of Mines and Geology.


Wagner, D.L., and E.J. Bortugno, 1982, Geologic map of the Santa Rosa Quadrangle, California, 1:250,000: California Department of Conservation, Division of Mines and Geology.


## Appendix A

Seismic P-Wave Velocities in Various Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Seismic P-Wave Velocities*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>330 m/s</td>
</tr>
<tr>
<td>Water</td>
<td>1450-1530 m/s</td>
</tr>
<tr>
<td>Soil</td>
<td>100-500 m/s</td>
</tr>
<tr>
<td>Disturbed soil</td>
<td>180-335 m/s</td>
</tr>
<tr>
<td>Sand (dry, loose)</td>
<td>200-1000 m/s</td>
</tr>
<tr>
<td>Sand (water saturated, loose)</td>
<td>1500-2000 m/s</td>
</tr>
<tr>
<td>Sand and gravel (near surface)</td>
<td>400-2300 m/s</td>
</tr>
<tr>
<td>Sand and gravel (~2 km depth)</td>
<td>3000-3500 m/s</td>
</tr>
<tr>
<td>Clay</td>
<td>1000-2500 m/s</td>
</tr>
<tr>
<td>Floodplain alluvium</td>
<td>1800-2200 m/s</td>
</tr>
<tr>
<td>Basalt</td>
<td>5500-6500 m/s</td>
</tr>
</tbody>
</table>

* Compiled from Reynolds (1997)
Appendix B

Cone Penetrometer Testing at Mason Road Site

B-1: E-W line of CPT logs at the Mason Road site (modified from T.E. Noce and J.J. Lienkaemper, unpublished, 2004)
Appendix C

Mason Road First Break Picks, Traveltime Curves, and Velocity Models

C-1: First break picks, line GV-0. Waveform data from shot 4.

C-2: Traveltime curves, line GV-0.
C-3: Velocity model, line GV-0.

C-5: Traveltime curves, line GV-2.

C-6: Time-Term inversion, line GV-2.
C-7: Tomographic inversion with raypaths, line GV-2.

C-8: Tomographic inversion, final velocity model, line GV-2.

C-10: Traveltime curves, line GV-2b.
C-11: Time-Term inversion, line GV-2b.

C-12: Tomographic inversion with raypaths, line GV-2b.
C-13: Tomographic inversion, final velocity model, line GV-2b.

C-15: Traveltime curves, line GV-4.

C-16: Time-Term inversion, line GV-4.
C-17: Tomographic inversion with raypaths, line GV-4.

C-18: Tomographic inversion, final velocity model, line GV-4.

C-20: Traveltime curves, line GV-4b.
C-21: Time-Term inversion, line GV-4b.

C-22: Tomographic inversion with raypaths, line GV-4b.
C-23: Tomographic inversion, final velocity model, line GV-4b.

C-25: Traveltime curves, line GV-6.

C-26: Time-Term inversion, line GV-6.
C-27: Tomographic inversion with raypaths, line GV-6.

C-28: Tomographic inversion, final velocity model, line GV-6.
C-29: First break picks, line GV-3b. Waveform data from shots 4 and 11. Shot 4 is in blue and shot 11 is in black.

C-30: Traveltime curves, line GV-3b.
C-31: Time-Term inversion, line GV-3b.

C-32: Tomographic inversion with raypaths, line GV-3b.

C-33: Tomographic inversion, final velocity model, line GV-3b.
C-34: First break picks, line GV-7. Waveform data from shots 4 and 11. Shot 4 is in blue and shot 11 is in black.

C-35: Traveltime curves, line GV-7.
C-36: Time-Term inversion, line GV-7.

C-37: Tomographic inversion with raypaths, line GV-7.
C-38: Tomographic inversion, final velocity model, line GV-7.


Appendix D

Cone Penetrometer Testing at Tyson’s Lagoon Site

CPT sounding data (Fugro West, written communication, 2005). Tip resistance (Qt in MPa) vs. depth (m), with subsurface geology interpreted in yellow (Kelson, 2003).
Appendix E

Tyson’s Lagoon First Break Picks, Traveltime Curves, and Velocity Models

E-2: Traveltime curves, line TY-1.

E-3: Time-Term inversion, line TY-1.
E-4: Tomographic inversion with raypaths, line TY-1.

E-5: Tomographic inversion, final velocity model, line TY-1.

E-7: Traveltime curves, line TY-2.
E-8: Time-Term inversion, line TY-2.

E-9: Tomographic inversion with raypaths, line TY-2.
E-10: Tomographic inversion, final velocity model, line TY-2.

E-12: Traveltime curves, line TY-3.

E-14: Tomographic inversion with raypaths, line TY-3.

E-15: Tomographic inversion, final velocity model, line TY-3.