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# Geologic and geotechnical characterization for liquefaction-induced deformation

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GEOLOGIC AND GEOTECHNICAL CHARACTERIZATION FOR

LIQUEFACTION-INDUCED DEFORMATION


A Thesis

Presented to

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San José State University


In Partial Fulfillment

Of the Requirements for the Degree

Master of Science


by

Anne M. Rosinski

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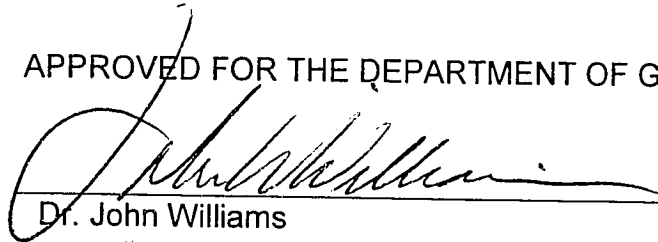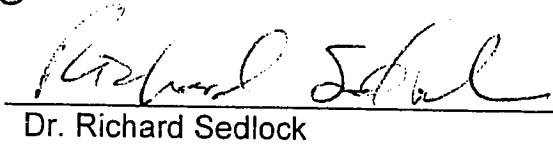
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ABSTRACT

# GEOLOGIC AND GEOTECHNICAL CHARACTERIZATION FOR LIQUEFACTION-INDUCED DEFORMATION

By Anne M. Rosinski

The focus of this research is to provide a geotechnical and geologic characterization of the tectonically active northern Santa Clara Valley, California. This characterization is combined with new models for predicting strain to develop 1:24,000-scale hazard maps based on laboratory testing and improved understanding of processes that affect prediction of surface deformation resulting from liquefaction.

Qualitative geologic information and quantitative geotechnical boring log information are linked together; each layer in each boring is assigned a geologic map unit designation thereby, expanding the description of each geologic unit to include quantifiable geotechnical characteristics. Maps produced in this study group geologic map units with similar amounts of estimated volumetric and shear strain. The maps produced in this study reveal that late Holocene deposits are likely to experience the greatest liquefaction-induced strain, whereas older deposits are likely to experience significantly less horizontal and vertical strain in future earthquakes.

# ACKNOWLEDGMENTS

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# INTRODUCTION

## Purpose of Study

Geotechnical and geologic characterization of sedimentary deposits in the northern Santa Clara Valley, California is the goal of this research. Interpretation of the Holocene-late Pleistocene boundary in the subsurface and characterization of sediment in the Santa Clara Valley is conducted and used to produce regional (1:24,000-scale) hazard maps based on predicted surface deformation resulting from liquefaction. Any attempt to produce maps of future liquefaction-induced deformation must take into account the nature and variability of geologic deposits in the area to be mapped. This task is complicated by the limited subsurface data (geotechnical boring logs) that are generally available in most areas. In this study, 668 boring logs are used to characterize the geology of the northern Santa Clara Valley (Plate 1). Maps of liquefaction-induced deformation based upon the geotechnical and geologic characterization of the sediment in the northern Santa Clara Valley can be used to supplement classical liquefaction susceptibility or liquefaction potential maps. In addition, deformation potential maps may provide information to serve emergency response planning, mitigation prioritization, and assessments of vulnerability of lifeline systems.

In the past, predictions of liquefaction potential have identified areas expected to experience earthquake-induced ground failure such as the maps showing Zones of Required Investigation for Liquefaction produced by the

California Geological Survey (CGS). Construction on artificial fill over San Francisco Bay mud (afbm) in the Marina district in San Francisco resulted in tremendous structural damage and the loss of several lives following the 1989 Loma Prieta earthquake (Harris and Egan 1992), and this damage is an illustration of liquefaction-induced ground failure. Although the cause of ground deformation was well understood, predictions of estimated amounts of ground deformation were not available at the time of the earthquake.

Geologic and Geotechnical Characterization of Holocene to Late Pleistocene Sedimentary Deposits

Knowledge of the distribution of layered cohesionless sediment deposits such as gravel, sand, and silt is an important element for mapping the liquefaction hazard in a given area (Martin and Lew 1999). Most liquefaction-hazard maps are based on an evaluation of sediment type and the likelihood that materials will liquefy, or that liquefaction will be "triggered" during future earthquakes. Typically, categories of very high to low or very low are assigned to each Quaternary geologic map polygon. Deviations from a one-to-one correspondence between Quaternary map unit and liquefaction susceptibility category are typically based on differences across the region in depth to ground water and expected levels of earthquake ground shaking (Knudsen et al. 2004). Geotechnical information is collected during sub-surface investigations for liquefaction analysis using the Simplified Seed Procedure (Seed and Idriss 1971)

and plotted on a map. The final stage of the mapping process involves comparing the results of the susceptibility analysis with the outcome of the triggering analysis performed on the geotechnical boring data. Saturated, liquefiable sediments deposited in areas where ground shaking is expected from earthquakes on nearby active faults are mapped as areas with the potential for liquefaction.

The susceptibility of a soil to liquefaction is commonly examined in the context of a criteria matrix that accounts for the qualitative characteristics of a soil such as age of the deposit and environment of deposition. Descriptive features of the sediment, such as particle size, which may be unique to a particular setting, can be used as keys to recognize liquefaction susceptibility in other similar environments. In addition, quantifiable geotechnical characteristics such as density and grain size distribution are reviewed. The range of values for quantitative characteristics for which liquefaction is known to occur can be established and used as a basis for comparison with measurement of quantitative data collected from other sites.

When a geologic investigation is carried out, the study of the geologic environment is conducted independently of the measurement of the geotechnical parameters. Geotechnical parameters are considered in relation to the Unified Soils Classification System (USCS) designation assigned to the layer in which the measurement was taken. The USCS only describes the physical properties of each layer and considers each layer as existing independently of the layers

above and below it. It is common in geologic investigations that, after the geotechnical properties have been measured, the data are analyzed using the Simplified Seed Procedure (Seed and Idriss 1971). As a consequence, the geotechnical properties become separated from geologic context responsible for their development.

The goal of this research is to combine both types of data to take advantage of both the qualitative and quantitative factors that contribute to liquefaction susceptibility in order to develop a more detailed picture of the liquefaction-induced deformation potential of the region. In this study, 668 boring logs and recent Quaternary mapping by Witter et al. (2006) are used to characterize the geology of the northern Santa Clara Valley. Qualitative geologic information and quantitative geotechnical boring log information are linked together; each layer in each boring is assigned a geologic map unit designation, thereby expanding the description of each geologic unit, and the quantifiable geotechnical characteristics are further inferred to apply to every occurrence of each geologic unit even where not tested by borings.

## Liquefaction-Induced Deformation Hazard Analysis

Advance knowledge of where liquefaction-induced ground deformation is likely to occur may provide an opportunity to retrofit structures prior to a damaging, large-scale earthquake (Fig. 1). Most previous efforts to map potential liquefaction-induced deformation on a regional scale have been based

on predictions of lateral spread displacements (e.g. Youd and Jones 1993). To

formulate a more complete picture of hazards due to liquefaction-induced ground

deformation, the geologic characterization developed in this research may in the



Figure 1. "Loma Prieta, California, Earthquake October 17, 1989. Structures damaged in the Marina District of San Francisco. The first story of this three-story building was damaged because of liquefaction; the second story collapsed. What is seen is the third story." Figure 24B, U.S. Geological Survey Circular 1045. Image file: /htmllib/batch88/batch88j/batch88z/batch88/pla00049.jpg

future be used in combination with new models for predicting liquefaction-

induced strain (Wu 2002; Wu and Seed 2004) to develop regional maps of

liquefaction-induced volumetric and shear strain (Knudsen et al. 2004).

BACKGROUND

Previous Studies

This research follows earlier research conducted for the City of San Jose by Cooper, Clark & Associates (1974) and Falls (1988). In addition to data collected by the California Geological Survey, the present research uses the same data from the city of San Jose used by both Cooper, Clark & Associates and Falls, and relies on the Simplified Seed procedure (Seed and Idriss 1971) to analyze the data to determine where liquefaction is likely to occur. Cooper, Clark & Associates and Falls both estimated liquefaction potential based upon analysis of factors contributing to liquefaction susceptibility combined with an investigation of opportunity for the material in each individual boring to liquefy. The present study estimates liquefaction potential using the Simplified Seed procedure (Seed and Idriss 1971) to calculate the soil resistance to liquefaction (Cyclic Resisting Ratio, CRR) which is then compared to calculated earthquake driving forces (Cyclic Stress Ratio, CSR). Like the report produced for the City of San Jose by Cooper, Clark & Associates, the present research includes maps showing the distribution and potential for earthquake-induced ground failure. However, the hazard maps produced by Cooper, Clark & Associates are based on qualitative data, namely the susceptibility ranking of each geologic map unit, and not on quantitative analysis of liquefaction-induced deformation performed for specific

bore hole locations. In addition, the boundaries on the maps produced by Cooper, Clark & Associates do not follow geologic contacts.

Liquefaction

Estimates of liquefaction potential are the result of analysis of a combination of factors (CGS 1997). In order for liquefaction to occur, susceptible, saturated, unconsolidated, granular material must be present (CGS 1997). In addition, opportunity, i.e. cyclic loading from a nearby active fault source (faults that have ruptured in the last 11,000 years; CGS 2007 ) must be possible. The result of cyclic loading of saturated, unconsolidated, granular material can be the fluidization of sediment. When earthquake shaking occurs, grains shift into a denser configuration by rearranging to fill in void spaces, which may be occupied by water. As the volume of void space available for water to occupy decreases, water pressure increases. As densification continues, pore space decreases to the point that water pressure rapidly passes a critical threshold and water is expelled from the void spaces. As water is expelled, it forces sediment grains apart, resulting in liquefaction.

Regional geology and depositional environment influence the development of characteristics of a particular sedimentary deposit. In fluvial environments for example, uplift and erosion contribute source material that is deposited downstream, and the type of unconsolidated granular material in sediment plays a key role in liquefaction. Sphericity and roundness affect the

efficiency of grain packing, which in turn influences the volume of void space that can be occupied by water. Composition of the material influences whether or not the soil will behave plastically. Clay-sized quartz particles are liquefiable because they are non-plastic and under earthquake loading will behave as a cohesionless material (Seed et al. 2003; Boulanger and Idriss 2006). Gravelly soil, although liable to liquefy, generally has larger pore spaces and therefore is better able to attenuate pore pressure. In addition, due to the energy required to transport larger particles, gravelly material, unlike finer-grained material, tends not to be deposited loosely (Seed et al. 2003).

Study Area

The study area, located in the southern San Francisco Bay region of northern California, includes approximately 390 square kilometers in the northern Santa Clara Valley (Plate 1). The study area includes the Milpitas, San Jose East, San Jose West and portions of Calaveras Reservoir 7.5-minute quadrangles. The majority of the study area is heavily urbanized. The City of San Jose covers a large percentage of northern Santa Clara Valley, and portions of the cities of Alviso, Campbell, Los Gatos, Milpitas, Santa Clara, Saratoga, and Sunnyvale are also included.

The northern end of the study area along the margin of San Francisco Bay is occupied by salt evaporation ponds and associated levees. The San Jose International Airport is located in the north-central part of the study area.

Numerous fluvial systems flow through the northern Santa Clara Valley. The two largest systems are Guadalupe River and Coyote Creek. Guadalupe River is supplied by Saratoga, San Tomas Aquinas, Calabazas and Los Gatos creeks, all of which originate outside the study area in the Santa Cruz Mountains to the west. Coyote Creek is supplied by Berryessa, Penitencia, Tularcitos, Scott, Arroyo de los Coches, Piedmont, Calara, Miguelita, Silver, Babb and Thompson creeks, all of which originate in the Diablo Range to the east (Plate 1).

Six major freeways and several smaller arterial roadways cross the study area. Northwest-trending U.S. Highway 101 (Bayshore Freeway) connects the northern Santa Clara Valley to the San Francisco Peninsula, and northeast-trending Interstate 680 closely parallels the foothills of the Diablo Range and connects the northern Santa Clara Valley to major cities along the east side of San Francisco Bay. State Highway 17/ Interstate 880 extends southward in the western portion of the study area. Trending roughly east-west, State Highway 237 and Interstate 280 span the northern portion of the study area.


Geologic and Geomorphic Setting

The northwest-trending, northern Santa Clara Valley, part of the Coast Range geomorphic province, is situated between the Santa Cruz Mountains to the west outside the study area and the Diablo Range to the east. Outside of the study area, the northern Santa Clara Valley is bordered on the west by the San Andreas fault, and within the study area, on the east by the Hayward and

Calaveras faults. There are 27, primarily non-marine, Quaternary and pre-Quaternary bedrock map units in the northern Santa Clara Valley study area (Table 1 and Plate 1). The margins of the northern Santa Clara Valley are asymmetrically framed by broad alluvial fans that slope gently northward toward San Francisco Bay. Along the west and southwest sides of the valley, at the base of the Santa Cruz Mountains, latest Pleistocene alluvial fans (Qpf) are overlain by thin Holocene alluvial fan deposits (Qhf) (Witter et al. 2006). Along the east and northeast sides of the valley, at the base of the Diablo Range, latest Pleistocene (Qpf) and Holocene alluvial fans (Qhf) are smaller than fans on the west side of the valley, and only minor levees (Qhl) have developed. Holocene alluvial fans generally are composed of poorly sorted mixtures of gravel, sand, silt, and clay. At the upstream end of the alluvial fans, where gradients are steeper, fan deposits typically are composed of coarse-grained material (Qhf), and grade into finer-grained material (Qhff) downstream. Where the fans terminate at the edge of San Francisco Bay, fine-grained material transitions into Holocene fine grained alluvial fan-estuarine complex deposits (Qhfe), Holocene San Francisco Bay Mud (Qhbm) and artificial fill (af) over Bay Mud (afbm). Down the northwest-trending axis of the valley, both Guadalupe River and Coyote Creek contain Holocene stream channel deposits (Qhc), and artificial channel (ac) deposits, and are flanked by Holocene alluvial fan levee deposits (Qhl) and Holocene stream terrace deposits (Qht). Artificial fill (af) is associated with large-scale transportation infrastructure, including highways and railroads, such as the

TABLE 1. QUATERNARY GEOLOGIC MAP UNITS (Modified from Knudsen et al. 2000)

| | Environment of deposition | | Environment of deposition |
|---|---|---|---|
| **Modern** | | | |
| af | Artificial fill | gq | Gravel quarry |
| afbm | Artificial fill over Bay Mud | ac | Artificial stream channel |
| alf | Artificial fill, levee | Qhc | Modern stream channel |
| **Latest Holocene** | | | |
| Qhfy | Alluvial fan | Qhty | Stream terrace |
| Qhly | Alluvial fan levee | | |
| **Holocene** | | | |
| Qhbm | San Francisco Bay mud | Qhff | Alluvial fan, fine facies |
| Qhb | Basin | Qhl | Alluvial fan levee deposits |
| Qhfe | Fine grained alluvial fan-estuarine complex | Qht | Stream terrace |
| Qhf | Alluvial fan | Qha | Alluvium, undifferentiated |
| **Latest Pleistocene to Holocene** | | | |
| Qf | Alluvial fan | Qt | Stream terrace |
| Ql | Alluvial fan levee | Qa | Alluvium, undifferentiated |
| **Latest Pleistocene** | | | |
| Qpb | Basin | Qpa | Alluvium, undifferentiated |
| Qpf | Alluvial fan | | |
| **Early to late Pleistocene** | | | |
| Qof | Alluvial fan | Qoa | Alluvium, undifferentiated |
| **Pre-Quaternary** | | | |
| br | Bedrock | | |

interchange for U.S. Route 101 with Interstate Routes 280 and 680 near the center of the study area.

Bedrock geology in the vicinity of the study area is divided into individual, fault-bounded structural blocks recognized on the basis of differing stratigraphic sequences and geologic histories (Wentworth et al. 1999). Rocks from the Silver Creek, Alum Rock and Mt. Hamilton blocks are within the four quadrangles included in the study area. At the southeastern end of the study area, rocks of the Franciscan Complex (KJf) are juxtaposed against Jurassic rocks of the Coast Range Ophiolite (Jsp) along a low-angle thrust fault in the Silver Creek structural block (Wentworth et al. 1999). Rocks of the Silver Creek block are found along

the hills drained by Silver Creek and in the vicinity of Yerba Buena Ridge. The

Alum Rock block, composed of Jurassic to Quaternary age rocks, is exposed

along the eastern margin of the northern Santa Clara Valley. The Alum Rock

block is separated from the Mt. Hamilton block to the east by the Calaveras fault

and from the Silver Creek block to the south by a concealed fault (Wentworth et

al. 1999). Cretaceous and Jurassic rocks of the Eastern Belt of the Franciscan

Complex are exposed in the northeast portion of the study area.


Seismicity

The study area is the northern Santa Clara Valley. The San Andreas fault

system lies to the west just outside the study area, and the Calaveras and the

southern end of the Hayward fault systems are mapped in the north east margins

of the study area (Plate 1). Among the more significant historic earthquakes in

the region are the M7.0 Hayward earthquake of October 21, 1868 (Berkeley

Seismological Laboratory, http://seismo.berkeley.edu/faq/1868_0.html), the M7.9

San Francisco earthquake of April 18, 1906, and the $M_W$ 6.9 Loma Prieta

earthquake of October 17, 1989. Each of these earthquakes caused

liquefaction-induced ground failure(s) in the northern Santa Clara Valley.

The level of seismic excitation used for this study is the level of peak

ground acceleration (PGA) with a 10% probability of being exceeded over a 50-

year period. The statewide probabilistic seismic hazard analysis (Peterson et al.

1996) indicates that peak ground accelerations with a 10% probability of being

exceeded in 50 years are expected to range from about 0.5 g near the margin of San Francisco Bay to about 0.8 g in the foothills of the Diablo Range at the northeast corner of the study area (Peterson et al. 1996). Deaggregation of the seismic hazard model yields the magnitude and distance of the earthquake that contributes most to the probabilistic estimate of ground motion at a particular location. The deaggregation indicates that the seismic hazard in the southwest part of the study area is dominated by a $M_W7.9$ earthquake on the San Andreas fault at a distance ranging from about 18 to 24 km (CGS 2002). The seismic hazard in the northeast part of the study area is dominated by a $M_W7.1$ earthquake on the Hayward fault at a distance ranging from about 2 to 7 km (CGS 2001). The hazard in the southeast part of the map area is dominated by a $M_W6.4$ earthquake on the southeast extension of the Hayward fault system at a distance of about 7 km (CGS 2000).

Subsidence

Subsidence due to ground-water withdrawal is well documented in the northern Santa Clara Valley. The alluvial fill in the northern Santa Clara Valley consists primarily of Pliocene to Holocene deposits up to approximately 300 m thick, with sand and gravel more prevalent on alluvial fans that line the margins, transitioning to silt and clay toward the San Francisco Bay (Poland 1984). In the early part of the last century, ground-water withdrawal was primarily for agricultural use; however, by the middle of the last century agriculture in the

valley declined while urban development increased the demand on municipal

water supplies (Poland 1971). As ground-water levels decreased, the effective

overburden pressure on the water-bearing sediments increased, causing

compaction and land subsidence. Most of the subsidence in the northern Santa

Clara Valley was accommodated by compaction of fine grained sediment

(Ingebritsen and Jones 1999).

Between approximately 1915 and 1967, as much as 2.4 m of subsidence

occurred, and overall, approximately 260 km$^2$ subsided more than 1 m within

the limits of the study area (Poland 1984) (Fig. 2). Careful monitoring and

management of the basin, including importation of surface water, has led to the

recovery of small amounts of subsidence. The Santa Clara Valley Water District

has observed an increasing number of artesian wells, which reflects rising

ground-water levels (Seena Hoose, SCVWD, oral communication 2000).

Within the study area, historical ground water levels range from less than

approximately 3.5 m below land surface near the San Francisco Bay to

approximately 10-25 m throughout the rest of the study area (CGS 2004). As

ground-water levels rise, vertical effective stress is reduced, causing regional

uplift (Schmidt and Bürgmann 2002). InSAR time-series data record net uplift

in the study area averaging approximately 15-20 mm and as high as

approximately 40 mm on the east side of the south end of Coyote Creek

between 1992 and 1998 (Schmidt and Bürgmann 2002). The InSAR data also

show that uplift in
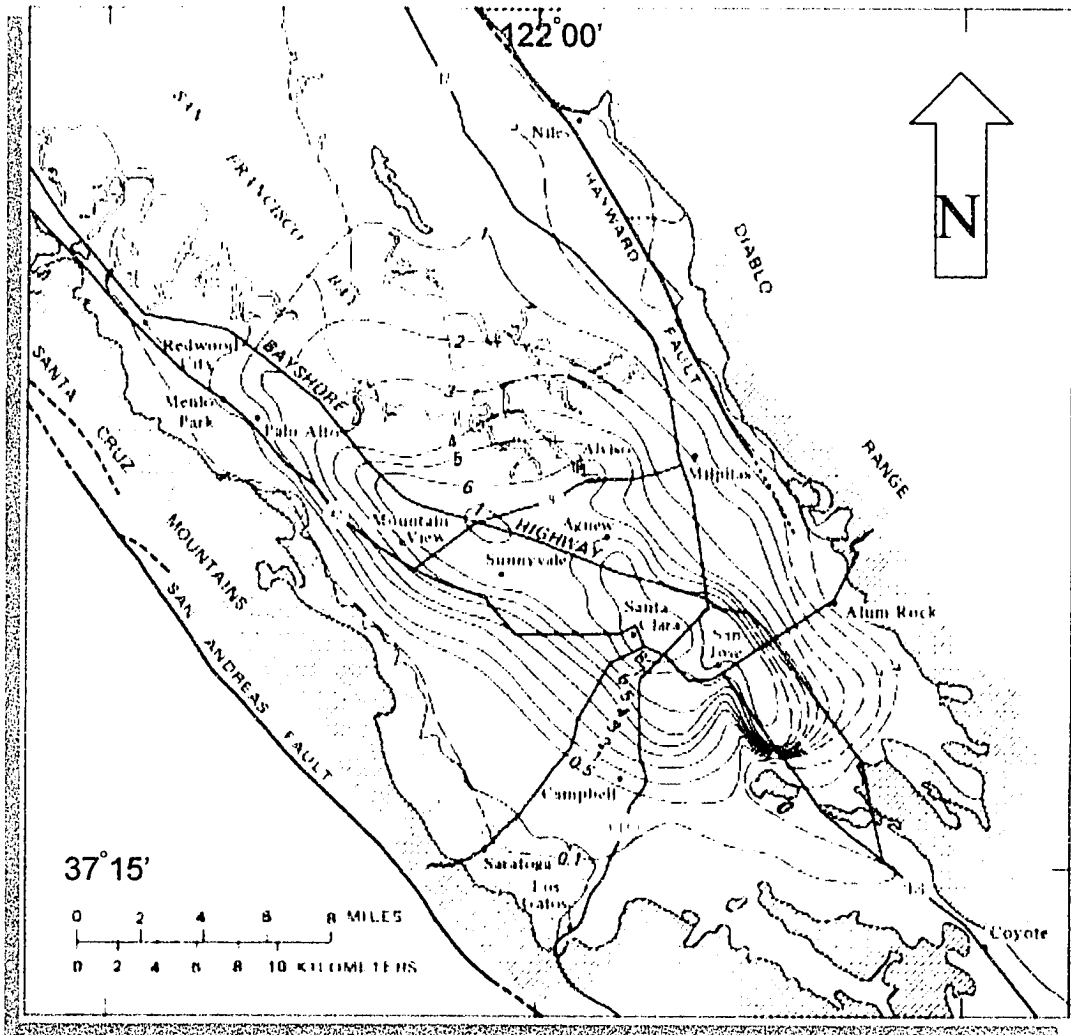
Figure 2. Subsidence in the Santa Clara Valley, California (after Poland 1969).

Alluvium and bay

Santa Clara Formation
*Semiconsolidated
deposits*

Consolidated rocks
*Undifferentiated igneous,
metamorphic, and
consolidated sedimentary
rocks*

Fault
*Dashed where approximate;
dotted where concealed*

———————— *0.1*————————

Line of equal subsidence
*Interval 1, 0.5 and 0.1 foot; dashed where poorly
controlled. Compiled from leveling of U.S. Coast and
Geodetic Survey in May-September 1934, February-
March 1967, and intervening releveling*

Multiply by 0.304 to convert to meters

the Santa Clara Valley is a seasonal phenomenon (Schmidt and Bürgmann 2002).

<u>Historical Liquefaction</u>

Ground failure associated with the 1868 Hayward, 1906 San Francisco, and 1989 Loma Prieta earthquakes includes sand boils, disturbed wells, settlement, lateral spread, stream-bank failure and ground cracks (Youd and Hoose 1978). The majority of ground-failure phenomena observed in the study area caused by the 1868, 1906 and 1989 earthquakes is concentrated in the northern half of the study area near the margin of the San Francisco Bay, where ground water levels are typically within 3-4 m of ground surface (Plate 2).

Ground failure associated with the 1868 Hayward earthquake includes lateral spreading and sand boils. Lateral spreading was observed at station 149 (Knudsen et al. 2000) (Plate 2). Accounts of lateral spread describe the banks of Coyote Creek being "shaken together" and cracks with water pouring out along the bay side of the creek (Youd and Hoose 1978). Sand boils were observed at station 149 as well (Knudsen et al. 2000). Reports of sand boils relate that cracks flowed with water for 48 hours following the earthquake, and water spurted "...to the height of several feet" (Youd and Hoose 1978).

Reported ground failure associated with the 1906 San Francisco earthquake was more varied and more widespread than that associated with the 1868 Hayward earthquake, and included stream bank land sliding, lateral

spreading, ground settlement, ground cracks, sand boils and disturbed wells. Lateral spread was observed at stations 148, 149, 150 and 155 (Knudsen et al. 2000). Reports of lateral spread at station 148 relate that "...two rows of trees in an orchard had parted off and slid into the slough" (Youd and Hoose 1978). At station 149, reports of lateral spread include descriptions of a bridge that "...was shifted on its concrete supports, the two ends moving in opposite directions" and "...cracks on both sides of the Coyote River at intervals all the way to San Jose" (Youd and Hoose 1978). At station 150, it was reported that fissures were observed near a ranch house and that .3 m (1 foot) of "downthrow" was measured on the east side of the fracture (Youd and Hoose 1978). Finally, at station 155, it was reported that "heave of the land" occurred "in a northwesterly direction 1.3 m (4 feet) from its original position" (Youd and Hoose 1978).

Ground settlement as a result of the 1906 San Francisco earthquake was documented at stations 148, 149, 150, 151 and 152 (Knudsen et al. 2000). At station 148, settlement was observed along the train tracks leading out of the north end of the town of Alviso, and a well casing was driven out of the ground (Youd and Hoose 1978). At station 149, reports of ground settlement describe the west side of a 3.7-m-diameter pool being lifted higher than the east side of the pool (Youd and Hoose 1978). Details of settlement are sparse for stations 150 and 151; however, it was documented that at these stations a ranch house settled slightly on its northwest side, and that there was a "slump in soft ground"

respectively (Youd and Hoose 1978). Finally, at station 152, settlement occurred in front of the principal hotel in Alviso (Youd and Hoose 1978).

The 1906 San Francisco earthquake caused sand boils to occur at numerous locations, including stations 148, 149, 150, 151 and 153. (Knudsen et al. 2000). A report of sand boils for station 148 notes that "cracks formed from which muddy and sandy water flowed" (Youd and Hoose 1978). A report of sand boils associated with station 149 notes that "water flowed from cracks in the yard and piled up sand .15 m (6 inches) on both sides" and also record "many craterlets of sand" (Youd and Hoose 1978). Further, a report of sand boils associated with station 150 recounts that "considerable sand was brought up by water flowing from the cracks" in an orchard (Youd and Hoose 1978). At station 151, it was reported that "cracks in the vicinity of Milpitas flowed artesian water for 48 hours after the shock" (Youd and Hoose 1978). Finally, at station 153, a report of sand boils describes water spouting into the air "to the height of several feet" (Youd and Hoose 1978).

Miscellaneous effects of ground failure associated with the 1906 San Francisco earthquake include reports of disturbed wells at stations 148, 155 and 158 (Knudsen et al. 2000). The report of a disturbed well at station 148 records that prior to the earthquake the well in question "required a wind-mill to pump the water. At the time of the earthquake the casing was driven .6 m (2 feet) out of the ground, wrecking the pump, and since that time the well has been flowing under a heavy pressure" (Youd and Hoose 1978). At station 155, it was reported

that, "On the farm of Mr. Fox, 4.8 km (3 mi.) north of San Jose, the water pipe of an artesian well was broken off 18.2 m (60 ft.) below the surface and carried by the heave of the land in a northwesterly direction 1.3 m (4 ft.) from its original position" (Youd and Hoose 1978). Finally, at station 158, "water and mud in many instances are reported as having spurted from the artesian wells, but in a few days they resumed their normal condition" (Youd and Hoose 1978).

Ground failure associated with the Loma Prieta earthquake of 1989 was limited in scope compared to the earthquakes of 1868 and 1906; however, lateral spread and settlement were observed. At station 51E, south of San Jose Municipal Airport, "minor lateral spreading" and settlement caused "minor cracking" along a frontage road (Seed and Harder 1990). In addition, at station 51D approximately 1 km north of San Jose Municipal Airport, "minor settlement" of a tower foundation was observed (Seed and Harder 1990). Finally, settlement was observed at station 51B in Alviso in the approach fills of the Gold Street Bridge (Tinsley et al. 1998).

The absence of ground failure in areas that are susceptible to liquefaction is also important because, among other reasons, non-failure can provide information about shaking intensity. Reports of the absence of ground failure associated with the 1906 earthquake in the study area are recorded for stations 156 and 157 (Knudsen et al. 2000). No ground failure was reported at station 156 "between Coyote Creek and the mountains" (Youd and Hoose 1978). At station 157, south of State Highway 280 in the vicinity of W. William Street, no

damage was reported at San Jose Water Works or the city's gas mains (Youd and Hoose 1978). Further, following the 1989 Loma Prieta earthquake at station 51C, the absence of liquefaction was reported "from the shoreline of the bay to State Highway 237" (Tinsley et al. 1998) where numerous instances had been reported following the 1868 and 1906 earthquakes at station 149 (Youd and Hoose 1978).

METHODS

Data from geotechnical boring logs were used to characterize the geotechnical properties of the geologic units mapped in the northern Santa Clara Valley for the purpose of evaluating the liquefaction-induced ground deformation hazard of each geologic unit. All of the layers in each boring log were reviewed, and each layer was assigned to a geologic map unit. While completing this task, particular attention was paid to identifying a change with depth in the measurable geotechnical properties of sediment. After each layer in each boring was assigned a geologic map unit, liquefaction potential analysis was performed on each of the layers in each boring. Liquefaction potential analysis for each layer was calculated deterministically using the methods of Youd et al. (2001) and probabilistically using the methods originally developed by Seed and Idriss (1971) and modified by Seed et al. (2003). The liquefaction analysis was carried out using a program developed by the California Geological Survey (Unpublished). Finally, using the Cyclic Stress Ratio (CSR) and corrected penetration test results produced by the liquefaction analysis, post-liquefaction deformation potential analysis was performed on all saturated layers composed of liquefiable textures for which penetration test data are available, and the total amount of potential volumetric and shear strain for each boring was summed using the methods of Wu et al. 2004 (volumetric strain) and Wu 2002 (shear strain).

These geotechnical properties infer the position and shape of a three-dimensional surface at shallow depth that can be broadly characterized as a boundary between shallower low-density materials and deeper higher-density materials. In many areas, this surface probably coincides with the top of the Pleistocene section, i.e., with a specific stratigraphic surface. However, in other areas evidence indicates that the density boundary does not coincide with the top of the Pleistocene. The focus of this paper is the density boundary defined by geotechnical properties, but for convenience the boundary is often referred to as the top of the Pleistocene.

Data Collection

To assess the potential for liquefaction-induced ground failure, an understanding of this area's late Quaternary history and deposits was developed by interpreting logs of geotechnical borings and relating the stratigraphy depicted in the borings to geologic map units. The information collected and used to interpret the geologic setting in this project includes: (a) detailed Quaternary geological map for the northern Santa Clara Valley area produced at 1:24,000 scale by Witter et al. (2006), (b) 668 geotechnical borings, (c) probabilistic earthquake shaking information, and (d) ground-water levels. Data used in this study are from the Milpitas, Calaveras Reservoir, San Jose East and San Jose West 7.5-minute quadrangles (Plate 1). The boring data were collected from local government files and entered into a Geographic Information System during

previous seismic hazard mapping efforts conducted by the California Geological Survey (http://gmw.consrv.ca.gov/shmp/index.htm).

The boring logs collected for this study range in depth from 3.1 to 45.7 m (10 to 150 feet), with 40% reaching a depth of 12.2 m (40 feet) or more. In a study like this in which only existing geotechnical borings are used, the quality of the borehole data varies. The logs should provide thorough documentation of how and where each boring was advanced. Of primary importance on the boring log is the penetration test data, which are standard data needed when calculating liquefaction potential. Laboratory studies of texture, grain-size distribution and fines content (FC) provide information needed in several of the methods used to estimate liquefaction-induced deformation. Data are stored in a database according to whether the information was measured, calculated or assigned for a sample or layer, or summed for the boring as a whole (Appendix 1).

## Assignment of Geologic Map Units to Each Boring Layer

Layers in each boring were assigned to a geologic map unit based on both the descriptive geologic characteristics and the geotechnical properties of the material encountered and recorded on individual boring logs. Effort was first placed on determining whether layers are Pleistocene or Holocene in age. The Pleistocene surface is important because most researchers believe that sediment greater than 11,000 years old is unlikely to liquefy.

The study area includes two major drainages discharging into the San

Francisco Bay and is characterized by unconsolidated sedimentary deposits that are highly variable, both vertically and laterally, over short distances. Because the data used in this study consist of boring logs collected from a variety of outside sources, and no new data were collected, dating of samples was not possible. Further, no attempt was made to locate age-dated soil samples from outside sources. Logs collected for this study are from borings distributed randomly across the study area, and the separation between borings is large (typically >300 m) compared to layer thickness (85% < 3 m thick), making it difficult to correlate discontinuous layers between borings.

Ideally, the same class of data would be available for every layer in every boring. But, because the same data were not available for every layer in every boring, the most important type of information reviewed was the penetration test data, because it may be used as a proxy for the density of the layer. Contrasts in penetration resistance are particularly important for identifying the boundary between the Holocene and latest Pleistocene. As sediment ages and becomes more lithified, the density of the sediment increases, and the increase in density is reflected in a higher penetration resistance (Powers et al. 1992; Hitchcock and Helley 2000, 2003).

Penetration resistance also was reviewed in the context of the lithologic description recorded for each layer. Lithologic descriptions that include words such as "organics," "roots," or "carbonaceous" may also indicate the presence of a buried late Pleistocene soil horizon. As sea level rose at the end of the latest

Pleistocene the depositional environment of the northern Santa Clara Valley changed. In the study area the change in depositional environment is preserved in some borings as a textural change at the inferred boundary between the late Pleistocene and Holocene (Hitchcock and Helley 2000, 2003). Other researchers have interpreted the "top of Pleistocene" to represent a former land surface that existed prior to the rise of seawater through the Golden Gate at the beginning of the Holocene (Helley and Lajoie 1979; Atwater, Hedel and Helley 1977).

In the northern Santa Clara Valley, repeated fluctuations in the depth of groundwater due to the influence of the nearby San Francisco Bay may cause sediment to consolidate, resulting in higher penetration resistance.

In some borings, it is easier to discriminate one geologic unit from another based upon the texture of the sediment layers sampled in the boring. For instance, silt (ML) is a fine-grained material that is a component of many of the geologic units found in the map area, such as Holocene alluvial fan levee deposits (Qhl) and Holocene alluvial fan deposits (Qhf). Each geologic map unit represents a different depositional environment; however, silt contained in different units may be described on different boring logs using similar terms such as "fine, brown, medium stiff, moist". By carefully reviewing the textural composition of a given layer in the context of the other layers in the boring in which it is sampled as well as in the context of surrounding borings, it may be possible to discern the geologic setting in which the sediment was deposited, and

ultimately, the geologic unit to which the sediment belongs. Table 2 lists criteria

that are compared to assign layers to specific geologic units. It is important to

note that some of the descriptive characteristics listed in Table 2 may not be

noted in the description of every sediment layer on a boring log; however, several

layers together may display a combination of characteristics that make it possible

to interpret the geologic setting for a series of layers.

TABLE 2. CRITERIA FOR ASSIGNING LAYERS TO GEOLOGIC MAP UNITS (Clahan et al. 2002)

Are there features that suggest the presence of a soil (rootlets, caliche, and pedogenesis)?

Are there regionally correlatable discontinuities?

Is there a change in penetration resistance within/between layers in borings?

Are regionally identifiable units (e.g. Merritt Sand, Bay Mud) present?

Does the color change (mottling, oxidation at the Top of Pleistocene)?

Does the texture change (grain size, gradation, sorting) laterally and/or vertically?

For example, in boring 000051_00142 (Appendix 1), layers 1 through 4 are

composed primarily of silt, clay, and fine-grained sand, and are interpreted as

geologic unit Holocene alluvial fan levee deposits (Qhl). According to Helley and

Wesling, (1989) "levee deposits are loose, moderately to well sorted sand, silt

and clay." In contrast, although the textures of layers 5 through 8 in boring

000051_00142 are similar to the textures of layers 1 through 4 (sand, silt and

clay), layer 8 contains gravel, and the descriptions for layers 5 and 8 include

modifying phrases such as "discontinuous sand lenses" and "interbedded

streaks of sand" respectively. Layers 5 through 8 in boring 000051_00142 are interpreted as geologic unit Holocene alluvial fan deposits (Qhf) rather than Qhl because according to Witter et al. (2006), Qhf consists of "sand, gravel, silt and clay, and is moderately to poorly sorted, and moderately to poorly bedded." The subtle change in the textural composition and continuity of bedding between layers 1 through 4 and layers 5 through 8 is interpreted to be the result of a change in depositional environment, and therefore layers 1 through 4 are interpreted as belonging to a different geologic map unit than layers 5 through 8.

Due to the paucity of useful descriptive terminology on boring logs, it is difficult to differentiate among Holocene or latest Pleistocene sub-units in most cases. In many cases the shallowest sub-surface layers are assigned to the geologic map unit mapped at the ground surface on the Quaternary map produced by Witter et al. (2006). However, in some borings an effort was made to identify sub-units for subsurface layers. In addition to the criteria listed in Table 2, for borings advanced into artificial fill, levee deposits (alf), the elevation of the top of the levee was compared to the elevation of the natural ground surface adjacent to the artificial levee. All layers in the boring with appropriate physical properties and with elevation equal to or below the elevation of the natural ground surface, but above the layers identified as Pleistocene (where present), were assigned to the geologic map unit upon which the levee was constructed.

In addition, an effort was made to recognize borings where the geologic unit assigned to the uppermost layer in a boring was different from the geologic

unit(s) assigned to underlying layers in the same boring, especially for borings located near a geologic contact. Because it is common for sedimentary layers of adjacent geologic units to interfinger, an attempt was made to determine whether subsurface layers in borings near geologic contacts should be assigned to the geologic unit mapped at the surface of the boring, or assigned to the geologic unit in contact with the geologic unit mapped at the surface of the boring. The boring log was reviewed and differences in the characteristics of sedimentary layers including penetration resistance, color, grain size, and lithology were used to determine to which geologic unit a layer should be assigned. For example, boring 2009B1 (Plate 1) near the intersection of Senter Road and Phelan Avenue on the San Jose East quadrangle, is located near the geologic contact between Holocene stream terrace deposits (Qht) and Holocene alluvial fan levee deposits (Qhl). Layers 1 (clay) and 2 (poorly sorted sand) are interpreted to belong to geologic map unit Qht, the unit mapped at the surface on the Quaternary geologic map used for this project, whereas layers 3 through 6 (silt, clay, silty sand, and clay respectively) are interpreted to belong to geologic map unit Qhl. Witter et al. (2006) describe Qht deposits as including sand, gravel, silt, and minor clay. However, Helley and Wesling (1989) describe Qhl deposits as including moderately to well-sorted sand, silt, and clay. Layers 2 through 6 are described as fine-grained silty sand, silt, or clay with no mention of coarser material.

The following criteria were used as keys to identify layers of different ages

in the northern Santa Clara Valley:

## Modern

Where not specifically noted on boring logs, artificial fill deposits (af), artificial fill over Bay Mud (afbm), and artificial fill, levee (alf) are identified where the layer description on the boring log indicates the presence of man-made historical debris such as bits of glass or broken concrete typically in a well-sorted matrix (Witter et al. 2006). Commonly, modern deposits are tan to light brown (Witter et al. 2006). In addition, the location of the boring may help identify the presence of fill deposits. Large-scale infrastructure such as bridges and major highways commonly require placement of fill during construction, and therefore, borings in the vicinity of infrastructure often encounter fill deposits. Layers that are not composed of fill but are considered Modern, including artificial stream channel (ac) and modern stream channel (Qhc), are most easily identified based upon their geographic location in existing streams. The median penetration resistance was calculated for each of the geologic map units and the median penetration resistance of all the Modern deposits in the northern Santa Clara Valley ranged from 6 to 11 blows per foot.

## Latest Holocene

Youngest Holocene deposits are typically unconsolidated, very loose to loose granular deposits, or very soft to soft, fine-grained deposits (Witter et al. 2006). Youngest Holocene deposits are most easily identified based upon their geographic location adjacent to existing streams. Layers that are identified as Youngest Holocene include alluvial fan (Qhfy), alluvial fan levee (Qhly), and stream terrace (Qhty) deposits. The median penetration resistance was calculated for each of the geologic map units and the median penetration resistance of all the Holocene deposits in the northern Santa Clara Valley ranged from 6 to 11 blows per foot.

## Holocene

Holocene deposits tend to be slightly consolidated clay, silt, and fine sand, as well as mixtures of slightly consolidated sand, silt and clay (Witter et al. 2006). Holocene deposits are most easily identified based upon their geographic location in the distal areas of active fans and downstream portions of active fluvial systems. Layers identified as Holocene include San Francisco Bay mud (Qhbm), basin (Qhb), and stream terrace (Qht) deposits, and deposits associated with alluvial fan environments including fine grained alluvial fan estuarine complex (Qhfe), alluvial fan (Qhf), alluvial fan fine facies (Qhff), and alluvial fan levee (Qhl) deposits. The median penetration resistance was calculated for each of the geologic

map units and the median penetration resistance of all the Holocene deposits in the northern Santa Clara Valley ranged from 4 to 25 blows per foot.

### Pleistocene

Pleistocene deposits of a given texture, such as silt, have a higher density than those of the same texture in a younger deposit. Pleistocene deposits are typically mapped at the surface in the proximal portions of alluvial fans located along the margins of the Santa Clara Valley, and are commonly dissected by Holocene stream channels. It is not uncommon to note a coarsening-upward sequence in Pleistocene sediment within a single boring, although the coarsening-upward sequence, if present, may be subtle, such as a transition from clay to sandy silt. Where only a single source is contributing sediment to a portion of the study area it may be possible to discern a sediment sequence or layer that marks the change from latest Pleistocene to Holocene. Because there are many source areas contributing sediment to the northern Santa Clara Valley, particularly toward the downstream axis of the study area, unique sedimentary sequences, if present, are most likely to be observed in borings at the margins of the valley where streams from single source areas emanate from the base of either the Santa Cruz Mountains on the western margin of the valley, or along the base of the Diablo Range on the eastern margin of the valley. Sediment from a single source may be identified by the consistent use of descriptive terminology such as "gray-brown silty gravel" regardless of when or by whom the subsurface investigation was conducted. Layers identified as Pleistocene include late Pleistocene to Holocene alluvial fan (Qf), Late Pleistocene to Holocene alluvial fan levee (Ql), Late Pleistocene to Holocene stream terrace (Qt), Late Pleistocene to Holocene alluvium, undifferentiated (Qa), Late Pleistocene basin (Qpb), alluvial fan (Qpf), Late Pleistocene alluvium, undifferentiated (Qpa), Early to middle Pleistocene undifferentiated alluvium (Qoa) and Early to middle Pleistocene alluvial fan (Qof). The median penetration resistance was calculated for each of the geologic map units and the median penetration resistance of all the latest Pleistocene sediment in the northern Santa Clara Valley ranged from 8 to 28 blows per foot.

Cross sections were constructed after each layer was initially assigned to a geologic map unit. Borings were critically reviewed in the context of surrounding borings, with particular attention paid to differences in density as measured by blow count values and lateral and vertical textural changes

observed in layers at similar depths, and in some cases, the name of the geologic map unit assigned to a particular layer was revised. Plate 3 is a cross section constructed along the northern edge of the study area. The process of scrutinizing layer descriptions in the context of layers in surrounding borings as they appear on cross sections and then revising the name of the geologic unit assigned to each layer was repeated numerous times. Cross sections were constructed both parallel and normal to the northwest-trending axis of the study area. Borings that appear on more than one cross section were reviewed to ensure consistency in assignment.

On Plate 3, the top of Pleistocene is depicted as a solid line through the top of the shallowest layer identified as latest Pleistocene and as a queried dashed line at the estimated depth of the top-of-Pleistocene surface through borings in which Pleistocene is uncertain or not identified. For example, at the east end of the cross section in Plate 3, the top-of-Pleistocene surface is identified in borings 000057_00138 and 000057_00121, but not in boring 000057_00140. The surface is projected through the middle of layer 3 in boring 000057_00140 because that is the expected depth based on the known depth to Pleistocene in the adjacent borings. For shallow borings, such as those at the west end of the cross section, the top-of-Pleistocene surface is projected as a queried dashed line below the boring at the depth at which Pleistocene might be expected.

The top-of-Pleistocene surface may be identified based upon different

criteria in different borings. In boring 000057_00100 on Plate 3, it is inferred based on an increase in penetration resistance and a coarsening-upwards sequence of layers 8, 7, and 6, recorded as a change from clay in layer 8 to sand in overlying layers 6 and 7. In contrast, for boring 000057_00139, the top-of-Pleistocene surface is inferred from an increase in penetration resistance with depth for layers with the same USCS classification. Clay layer 3 in boring 000057_00139 has penetration resistance values of 39 and 33 blows per foot; however, clay layer 5 in the same boring has a penetration resistance of 61 blows per foot, and the log states that the sediment is "very hard below 7 feet." Further, it should be noted that the characteristics that are used to identify the top-of-Pleistocene surface in the northern Santa Clara Valley may not be valid for other regions of the valley or elsewhere. The characteristics that are used to identify the top-of-Pleistocene surface may vary from region to region based on factors such as number and type of source areas, regional tectonics, climate, and depositional environment.

After each layer was assigned to a geologic map unit, a contour map showing the elevation of the top of the Pleistocene was constructed. The contours on the map were constructed through the elevation of the top of the uppermost layer in each boring identified as latest Pleistocene. The contour map was reviewed to make sure that the surface depicted by the map was consistent with a land surface that would be expected to develop during a period of low sea level. Remnants of Pleistocene fans exposed along the margins of the present-

day northern Santa Clara Valley were compared to the contour surface constructed using the elevations of the top of the Pleistocene as interpreted from boring logs. The exposed surfaces of Pleistocene fans are places where the elevation of the top of the Pleistocene is known with confidence and can be used as control points when constructing a contour. In particular, borings that caused contour lines to be deflected or drawn in a manner inconsistent with the expected land surface were reviewed and reinterpreted in the context of surrounding borings, and the emerging contour surface of the elevation of the top of Pleistocene was subsequently revised.

During the late Pleistocene, sea level is interpreted to have been as much as 130 m below the current level, resulting in a prolonged period of subaerial exposure, weathering and consolidation (Helley and Lajoie 1979). As sea level dropped, the center of the basin that was once filled with water became exposed. The period at the end of the Pleistocene when sediment was exposed allowed for the development of a distinct pedogenic horizon that has been identified in excavations by Hitchcock and Helley (2003) as defined by a marked increase in density as well as identifiable changes in color and texture.

## Liquefaction Analysis

To perform liquefaction analysis, information from individual boring logs was entered into a database without modification (whenever possible). However in some cases, professional judgment was necessary to clarify information

recorded on the log. In particular, the quality of the standard penetration test (SPT) varies considerably from one boring and operator to the next. Non-SPT values add additional variation to liquefaction analysis. Recorded blow counts for non-SPT sampling, where the sampler diameter, hammer weight, drop distance, and energy delivery differ from those specified for an SPT are converted to SPT-equivalent blow count values, when appropriate.

To characterize the quality of each SPT value, each penetration test compiled in the database was ranked from 1 to 29 (CGS unpublished) based upon how closely the sampling matches ASTM D1586-99 standards (ASTM 1999) and whether or not the recorded blow counts can reasonably approximate those of an SPT. For example, a penetration test for which the diameter of the sampler is not known is assigned a quality ranking of 13 if the blow counts have been converted to the SPT equivalent. Penetration tests with a quality ranking lower than 12 were not used (Appendix 2) (CGS unpublished). Where no analysis of laboratory fines content is provided for layers with liquefiable textures, a default (fc) for liquefiable materials was assigned based upon the Unified Soil Classification System (USCS) designation for the layer (Table 3). Similarly, if unit weight data are not provided on the boring logs, then values for each layer based on the layer's soil type must be assumed (Appendix 3) (CGS unpublished). The actual and converted SPT blow counts are normalized using a common reference effective overburden pressure of 1 atmosphere (approximately 1 ton per square foot), and a hammer efficiency of 60% using a method described by

Seed and Idriss (1971, 1982, with updates by Seed, Idriss and Arango 1983,

1985; Seed and De Alba 1986; and Seed and Harder 1990) and updated

according to the

TABLE 3. FINES CONTENT (FC) ASSIGNED TO SAMPLES WITH LIQUEFIABLE TEXTURES FOR WHICH NO
TEXTURAL DATA WERE PROVIDED ON BORING LOGS (Knudsen et al. 2004)

| | Curve used in triggering evaluation[†] | FC used in $(N_1)_{60,cs}$ calculation [‡] |
|---|---|---|
| Standard/conforming USCS categories | | |
| GW, GP, SW, SP | SD | 2.5 |
| GW-GM, GW-GC, GP-GC, SW-SM, SW-SC, SP-SM, SP-SC | SM | 8.5 |
| GM, SM | SM | 24 |
| GC-GM, SC-SM | ML | 30 |
| GC, SC, ML | ML | 35 |
| Other non-USCS categories found on boring logs [§] | | |
| GP-SP, GW-GP, SW-SP "cobbles & boulders", "gravel", "gravel and sand", "sand" | SD | 2.5 |
| "artificial fill", "soil" | SM | 12 |
| GP-SM, SM-SP | SM | 14 |
| SC-SP, SC-GP | SM | 19 |
| GM-SM, "alluvium", "loess" | SM | 24 |
| ML-SM, SM-SC | ML | 30 |
| ML-CL, SC-CL, SC-ML, SM-CL, SM-ML | ML | 35 |

† curve assigned for use in Simplified Procedure triggering analysis (SD- 5%, SM - 15%, ML - 35% fines content)
‡ fines content in percent assigned (when no laboratory textural data are available) for use in calculating $(N_1)_{60,cs}$
§ soil descriptions found on boring logs that do not conform with USCS categories; these categories are not
recommended for use in logging borings

recommendations of Youd et al. (2001) and Seed et al. (2003). This normalized

blow count is referred to as $(N_1)_{60}$. Some of the methods for evaluating the

susceptibility of deposits to liquefaction and the potential for deformation include

adjusting the $(N_1)_{60}$ value for the fines content of the sample; this adjusted "clean-

sand equivalent" value is referred to as $(N_1)_{60,cs}$. Finally, the liquefaction

potential of each layer in every boring is evaluated deterministically using the

methods of Youd et al. (2001) and probabilistically using the methods of Seed et

al. (2003).

The deterministic model proposed by Seed et al. (1984, 1985) uses SPT-

based correlations. With minor modifications proposed by the NCEER Working

Group (NCEER 1997; Youd et al. 2001), this correlation is one of the most widely

accepted correlations that is still used in practice (Fig. 3) (Cetin et al. 2004).

Figure 3 shows the relationship between the standard penetration test $(N_1)_{60}$

measured for a soil, with respect to intensity of cyclic loading, expressed as a

magnitude-weighted equivalent uniform cyclic stress ratio $(CSR_{eq})$ approximating

earthquakes with magnitudes of 7.5 (Cetin et al. 2004).

The cyclic stress ratio for a soil layer is calculated by using the equation

developed by Seed and Idriss (1971).


$$CSR = .65(a_{max}/g) \, (\sigma_{vo}/ \, \sigma'_{vo}) \, r_d \hspace{2cm} \text{(equation 1)}$$

CSR = Cyclic Stress Ratio
$a_{max}$ = Peak horizontal ground acceleration
g = acceleration of gravity
$\sigma_{vo}$ = vertical overburden stress
$\sigma'_{vo}$= vertical overburden stress minus pore pressure
$r_d$ = non-linear shear mass participation factor minus stress reduction
        coefficient to account for flexibility in the soil


Peak horizontal ground acceleration $(a_{max})$ is derived from the statewide

probabilistic seismic hazard evaluation released cooperatively by the California

Department of Conservation, California Geological Survey, and the U.S.

Geological Survey (Petersen et al. 1996).

In contrast, probabilistic models include data from a growing set of field

observed liquefaction case history data from earthquakes that have occurred

since 1984 (Seed et al. 2003). The term probabilistic refers to "triggering" of

liquefaction, not the consequences (resulting from deformation). Probabilistic
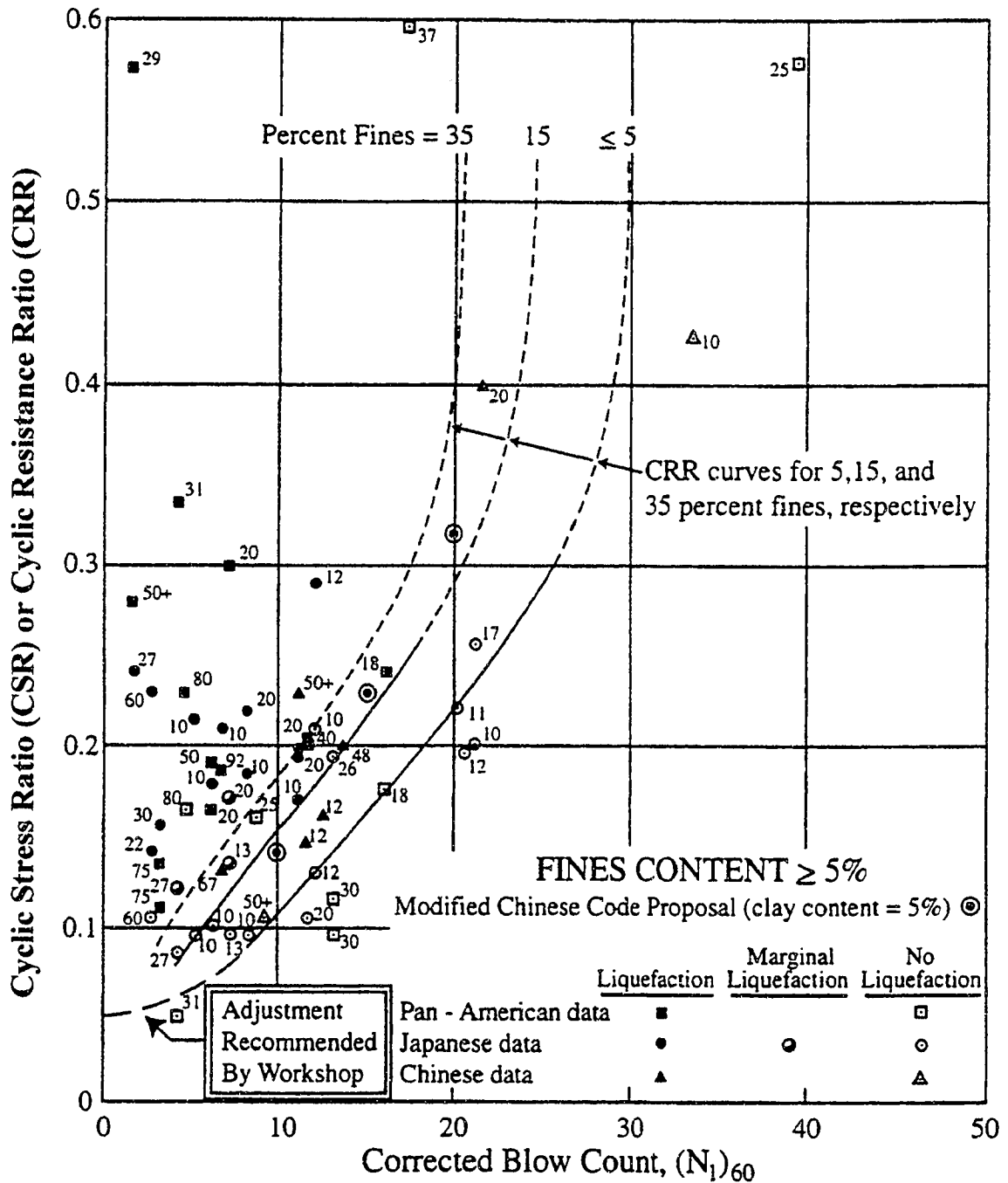
Figure 3. Deterministic correlation for evaluation of liquefaction potential. The chart shows CRR curves for clean sand (5% fines), silty sand (15% fines), and silt (35% fines). Given a corrected blow count value [$(N_1)_{60}$] from a valid penetration test and the fines content of the soil, the CRR value is read off the y-axis (Seed et al. 1984; Youd et al. 2001).

charts (Fig. 4) commonly are plotted with the deterministic curves derived by

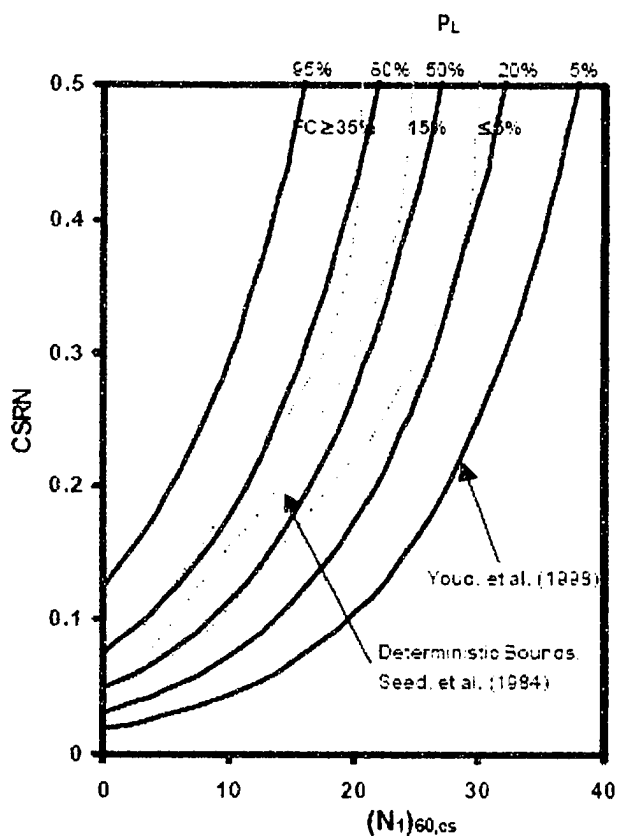Seed et al. (1984) from Figure 3.



Figure 4. Probabilistic correlation for evaluation of liquefaction
potential (Youd et al. 1997). This chart shows probability of
liquefaction curves plotted in same space as deterministic correlations
of Seed et al. (1984).

To use the chart in Figure 3, the corrected SPT value is plotted in the CSR

- $(N_1)_{60}$ space and then the results are reviewed to see whether the point falls to

the left or right of the appropriate empirically determined curve. The liquefaction

curves are calibrated for liquefiable textures that describe clean sand (5% fines),

silty sands (15% fines) and silt (35% fines). Similarly, to use the chart in Figure 4

the corrected SPT values are plotted in the CSR - $(N_1)_{60}$ space and then the

results are reviewed to see whether the point falls to the left or right of the

appropriate curve denoting probability of liquefaction. The Factor of Safety

against liquefaction (FS), an estimate of whether liquefaction will occur, is the

ratio of a soil's resistance to liquefaction (CRR), to the cyclic seismic loading

imposed on the soil (CSR) (Seed and Idriss 1982):

$$Factor\ of\ Safety = CRR/CSR \qquad (equation\ 2)$$

The CGS liquefaction analysis program calculates a FS for each geotechnical

sample where blow counts were collected. Typically, multiple samples are

collected for each borehole. The program then independently calculates a FS for

each non-clay layer that includes at least one penetration test using the minimum

$(N_1)_{60}$ value for that layer. The minimum FS value of the layers penetrated by the

borehole is used to evaluate the liquefaction potential for each borehole location.

The reliability of FS values varies according to the quality of the geotechnical

data (CGS 2006).

The liquefaction potential index (LPI) defined by Iwasaki et al. (1982)

provides an estimate of the severity of liquefaction at a specific location. The

purpose is not to predict the occurrence of liquefaction, but rather to indicate the

potential for ground failure manifested by occurrences of sand boils or other

similar phenomena as a result of liquefaction. The LPI calculation takes into

account the thickness of the liquefied layer, the proximity of the liquefied layer to the ground surface, and the degree to which the Factor of Safety for a particular boring is less than 1.0 (Iwasaki et al. 1982). The calculation requires a maximum depth of 20 m. LPI values calculated for borings that penetrate the subsurface to a depth shallower than the required depth are considered minimum values.

## Deformation Analysis For Level-Ground Conditions

Two classes of methods for estimating quantities of post-liquefaction ground deformation, both of which are typically used in site investigations, not in regional mapping, are (1) empirical predictions of lateral spread displacements, and (2) predictions of volumetric and shear strains (Knudsen et al. 2004) (Fig. 5). This study deals only with predictions of volumetric and shear strain, which can be predicted using either semi-empirical formulations or numerical simulations. Semi-empirical methods for predicting shear and volumetric strain are based on a growing set of laboratory data and improved understanding of processes; some of these methods have been calibrated against the growing database of historical ground failure case histories. Probabilistic liquefaction triggering analysis and analysis of volumetric strain for non-saturated soils also may be incorporated into these methods. The major disadvantages of applying the semi-empirical methods to estimate shear and volumetric strain are that these methods require detailed geotechnical data (for best results laboratory data
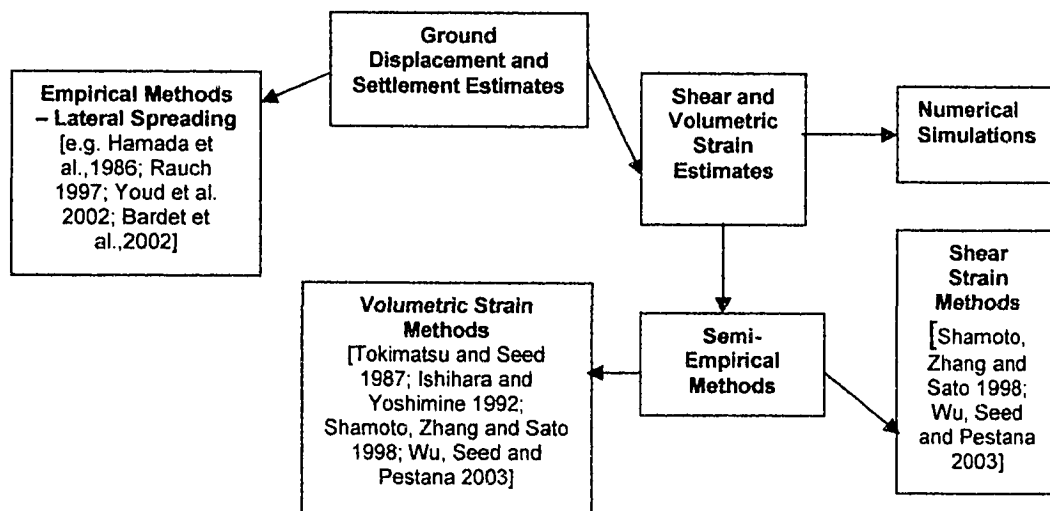
Figure 5. Methods of predicting liquefaction-induced deformation (Knudsen et al., 2004)

are used) that can be expensive to collect (Knudsen et al. 2004).

The methods of Wu (2002), Wu and Seed (2004), and Wu et al. (2003) are based on laboratory testing, specifically cyclic simple shear testing of undrained samples of fully saturated sand. Wu (2002) conducted tests using Monterey No. 0/30 sand, with strain measured at 15 cycles (approximating an M 7.5 earthquake), pressures of 40kPa, 80kPa, and 180kPa, and relative densities ranging from 35% to 80%. The results of the testing show that measured strain (for level ground conditions) falls within the ranges predicted by the limiting strain charts formulated by Tokimatsu and Seed (1987). Among the benefits of this method is that, in addition to providing an estimate of probability of liquefaction (P_L), it includes updates to previously developed tools including a new nonlinear

shear mass participation factor ($R_d$) and new fines correction factor ($C_{fines}$) (Knudsen et al. 2004).

There are four steps required to apply the method of Wu (2002) and Wu et al. (2003): (1) evaluate liquefaction susceptibility for each saturated layer as described earlier in this section; (2) use the values of $(N_1)_{60, cs}$ and CSR estimated in step one in conjunction with a new family of curves (Fig. 6) to estimate the post-liquefaction reconsolidation volumetric strain (settlement) of each saturated, liquefiable layer; (3) calculate volumetric compression of non-saturated sandy layers according to the procedures of Tokimatsu and Seed (1987); and (4) sum the volumetric changes of all saturated and unsaturated soil layers. The new procedure was shown by Wu and Seed (2004) to perform well for a suite of field performance case histories with small to moderate ground settlements.

Wu (2002) also proposed a new pragmatic chart (Fig. 7) for prediction of limiting shear strain (displacement). This chart, however, is preliminary because it has yet to be thoroughly calibrated against field performance case histories, so it may be updated or modified in the future.

The methods for estimating volumetric strain yield results that can be thought of as "predicted" or as "within-a-factor-of-two," whereas the relationships used to estimate future shear strain should be thought of as "limiting" or "potential" values (Knudsen et al. 2004). Because shear strain amplitude
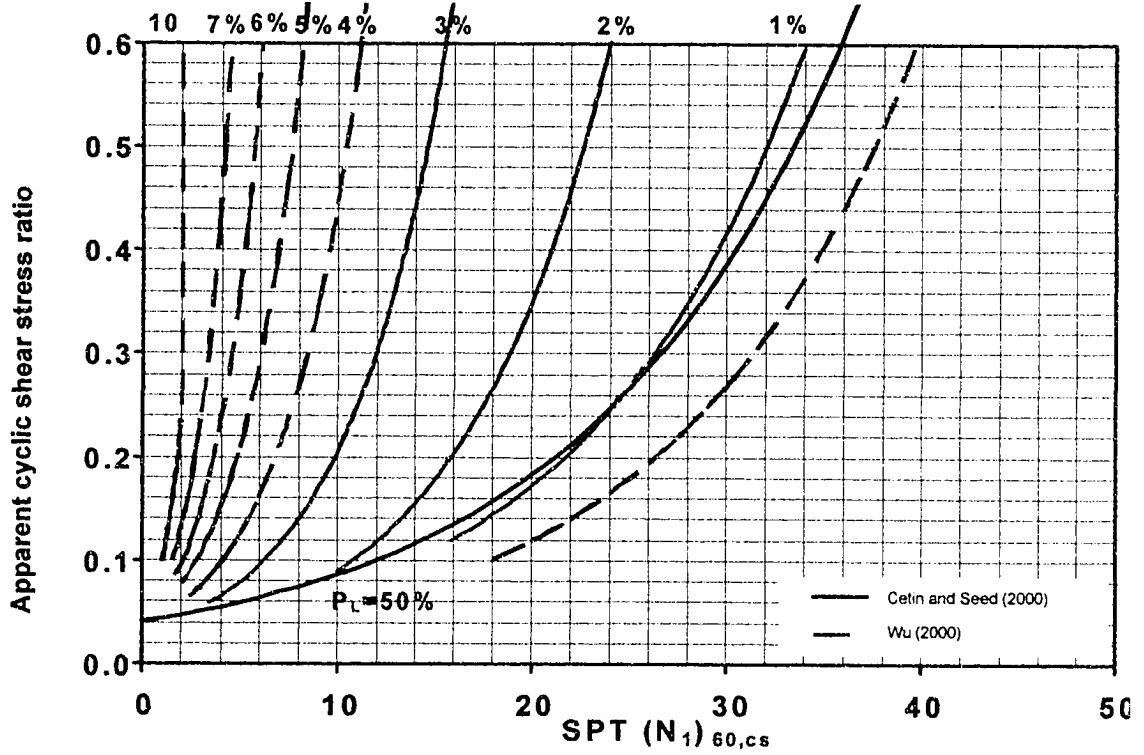
Figure 6. Proposed correlations between CSR, $(N_1)_{60,cs}$ and reconsolidation volumetric strain (Wu et al. 2003).
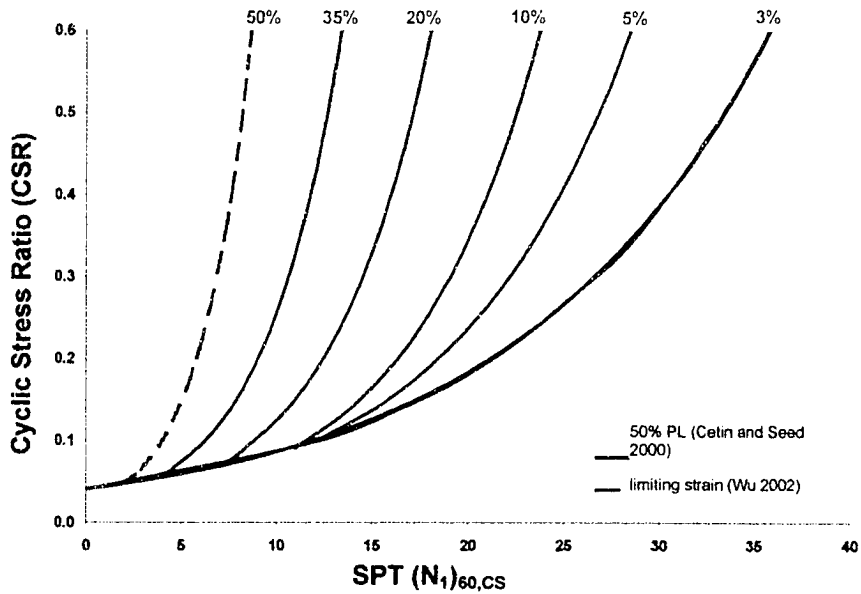


Figure 7. Proposed correlations between CSR, $(N_1)_{60,cs}$ and limiting shear strain (Wu et al. 2003).

continues to accumulate in liquefied sands under constant shear load conditions, liquefaction-induced shear strain is uniquely defined by selection of a pre-determined number of cycles (Knudsen et al. 2004). For the Wu (2002) method, liquefaction-induced limiting shear strain is defined as the single amplitude shear strain at the 15th loading cycle, which is the approximate number of uniform loading cycles in a typical $M_w$ 7.5 earthquake.

Finally, the potential volumetric and shear strain that can be expected in deposits from different geologic environments and of different ages is characterized using the results of the post-liquefaction deformation analysis. The predicted strain of individual geologic map units is estimated by multiplying the calculated strain (for each combination of CSR and corrected penetration resistance) by the thickness of each layer containing saturated sediment with liquefiable textures and then summing the calculated deformation amounts for all of the layers for each map unit.

Deformation potential calculations are carried out only for layers with liquefiable textures (Table 3) and are then summed over the entire length of the boring. A value of zero is assigned to a layer for which either (1) the particular combination of N-value and CSR for that layer does not result in measurable strain, or (2) the particular combination of N-value and CSR for the layer results in measurable strain but the liquefiable textures in the layer are not saturated. The depths to first-encountered unconfined ground water were plotted onto a map of the project area and contoured to constrain the estimate of historically

shallowest ground water. An anticipated high ground-water level is estimated based on historical ground-water data. In areas where ground water is either currently near-surface or could return to near-surface levels within a land-use planning interval of 50 years, CGS constructs regional contour maps that depict these levels (CGS 2006). A null value means that either no liquefiable textures are present and/or that no penetration test data are available, and therefore strain could not be calculated. Thus, where data are not available, calculated values must be considered minima.

# RESULTS

Each layer in each of the 668 boring logs was assigned to Quaternary map units and used to characterize the geology of the northern Santa Clara Valley and interpret the Holocene-late Pleistocene boundary in the subsurface. The geotechnical data were grouped and analyzed with respect to the geologic map unit to which each layer was assigned, and with respect to the age of the geologic unit mapped at the surface of each boring.

Trends in the data revealed during the analysis, such as an increase or decrease in a given geotechnical parameter interpreted as the result of an increase or decrease in the age of sediment, are used to validate the methods used in this project. For instance, penetration resistance is expected to increase as a result of increasing age because the sediment has been subjected to consolidation for a longer period of time. If the results of the analysis do not conform to the expected outcome, it may be an indication that errors were made in the interpretation and assignment of the layers in the borings to a particular geologic map unit.

A range of geotechnical parameters is recorded and calculated for each of the layers within each boring and for the boring as a whole. The liquefaction potential of each layer is evaluated deterministically using the methods of Youd et al. (2001) and probabilistically using the methods of Seed et al. (2003). Other parameters calculated for each layer include factor of safety (FS) and probability

of liquefaction ($P_L$). Parameters calculated for each boring include the thickness of sediment with liquefiable textures, the thickness of saturated liquefiable sediment, and the liquefaction potential index (LPI). The results of the various analyses are used to create maps of liquefaction-induced deformation based upon the geotechnical and geologic characterization of the sediments in the northern Santa Clara Valley.

## Nearest Neighbor Statistics

A geostatistical approach is adopted to evaluate the variability in sediment properties from boring to boring. Figure 8 uses the $T_{15}$ parameter, a parameter introduced by Youd, Hansen and Bartlett (2002) and Bardet et al. (2002) in their lateral spread predictive models, to describe the thickness of saturated sediment with liquefiable textures and penetration resistance values of less than 15. In a setting with "layer cake" geology, $T_{15}$ values should be similar from boring to boring. Figure 8 shows that 900 m is the maximum distance for which there is a relationship between adjacent borings (in the $T_{15}$ parameter) (Knudsen et al. 2004). However, the median separation distance between any two borings in the study area is approximately 1,044 m. This means that caution is warranted for estimates of geotechnical and geologic properties made for areas that are more than 900 m from the nearest boring and between borings more than 900 m apart. The conclusion that can be drawn from this information is that a greater density

of borings would improve understanding of the geologic variability in this area
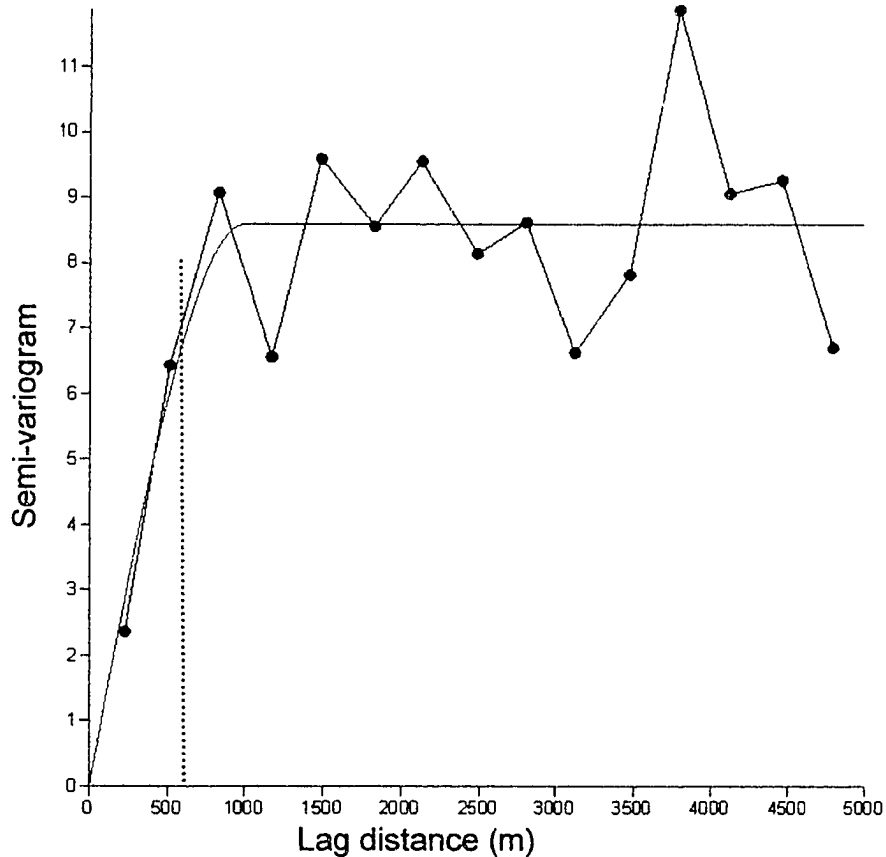
(Knudsen et al. 2004).



Figure 8. Nearest neighbor semi-variogram. Semi variance is a measure of the degree of spatial dependence between samples (Clark and Harper 2000). A semi-variogram measures the variance between data as a function of distance. The maximum separation distance for borings in the study area for which there is a relationship between adjacent borings is approximately 900 m (Knudsen et al. 2004).

## Pleistocene Surface Elevation Map (Interpreted)

As mentioned at the outset of the Methods section, the geotechnical

properties of materials in the borings were used to infer a three-dimensional

surface that broadly defines a boundary based on density differences. For the purposes of this study, that surface is generally interpreted as the Holocene-Pleistocene boundary (Plate 4). However, evidence indicates that the two surfaces do not coincide in some areas. In any event, for the purposes of liquefaction hazard mapping, it is more important to identify the change in the geotechnical properties of sediment than the age of sediment.

It was possible to identify a change in the measurable geotechnical properties of sediment such as penetration resistance in 215 of 668 borings used in this study. Approximately 272 borings penetrate to significant depths in the center of the valley where the Pleistocene surface is deepest, so contours in the center of the valley are constructed with much less confidence than those near the valley edges. It appears that during the late Pleistocene a significant volume of the Santa Clara Valley was drained by one primary source oriented roughly parallel to the present day location of Coyote Creek, or that two large streams were flowing parallel and in close proximity to one another like Guadalupe River and Coyote Creek are today.

Mapping the elevation at which the change in the penetration resistance of sediment occurs results in the depiction of a surface that is a reasonable representation of a natural land surface. The surface depicted on the map suggests an environment where the land surface was stable for a period of time long enough for it to begin to be incised by numerous small drainages, and depicts a surface that closely resembles the topography of the modern land

surface. Dates obtained for sediment in eight deep wells in the northern Santa Clara Valley collected by Carl Wentworth and John Tinsley of the USGS indicate that the elevation of the top of Pleistocene based on dates is somewhat lower than the surface depicted on Plate 4 (Carl Wentworth oral communication 2007) indicating imperfect correlation of geotechnical and stratigraphic boundaries. Wentworth (oral communication 2007) notes that "the latest pulse of sedimentation started before the end of the Pleistocene, and therefore, one may argue that the geotechnical boundary coincides with the top of the Pleistocene".

Liquefiable Textures

Table 4 shows that for many of the geologic map units fewer than half of

TABLE 4. PERCENTAGE OF EACH GEOLOGIC MAP UNIT
WITH TEXTURES THAT ARE POTENTIALLY LIQUEFIABLE

| | Number of layers | | Layer thickness | |
|---|---|---|---|---|
| Geologic map unit | # of layers | % of layers with liquefiable texture (%) | Cumulative thickness of all layers (m) | % of total with liquefiable textures |
| af | 223 | 26 | 329 | 14 |
| alf | 11 | 55 | 21 | 57 |
| Qhc | 20 | 65 | 53 | 55 |
| Qhfy | 46 | 22 | 78 | 13 |
| Qhly | 169 | 37 | 323 | 28 |
| Qhty | 87 | 44 | 129 | 31 |
| Qhbm | 29 | 7 | 51 | 9 |
| Qhb | 17 | 18 | 35 | 7 |
| Qhfe | 103 | 31 | 160 | 18 |
| Qhf | 1700 | 47 | 2925 | 42 |
| Qhff | 267 | 14 | 488 | 10 |
| Qhl | 357 | 53 | 611 | 48 |
| Qht | 8 | 88 | 8 | 92 |
| Qf | 116 | 46 | 415 | 37 |
| Ql | 12 | 50 | 17 | 39 |
| Qt | 2 | 100 | 2 | 100 |
| Qpf | 561 | 59 | 1304 | 58 |

See Table 1 for geologic map unit definitions, units are listed in order of increasing age

the sediment layers described on the compiled boring logs are coarse enough to liquefy. Calculations of liquefaction-induced strain are made only for the layers with granular textures (thus not USCS classes CL, CH, MH, ML-CL, OH, OL, Pt) because fine-grained soils are not expected to liquefy. Map units that are expected to be fine grained (e.g. Qhb – Holocene basin deposits, Qhff – Holocene alluvial fan, fine facies, Qhbm – Holocene Bay mud) all consist of more than 80 to 85% fine sediment.

## $(N_1)_{60,cs}$ Factor of Safety, and Cyclic Resistance Ratio

Table 5 shows several trends are evident. (1) $(N_1)_{60,cs}$ values for sediment with liquefiable textures are generally low; in most cases the median values are less than 15, a value previous researchers have considered an upper bound for sediment likely to experience large-scale liquefaction-related deformation. (2) The method of Youd et al. (2001) results in median $(N_1)_{60,cs}$ values that tend to be 2 to 3 blows/ft higher than the values calculated using the method of Seed et al. (2003). The methods of Youd et al. (2001) and Seed et al. (2003) are identical except in the input value for the non-linear shear mass participation factor ($r_d$).The non-linear shear mass participation factor is used to account for the fact that a column of soil does not act like a rigid body, so the peak shear stress calculated using equation 1 decreases with depth (Cetin and Seed 2000). The stress reduction coefficient $r_d$ is a function of site stratigraphy, soil properties, and the characteristics of the "input" motions (excitations). By definition, it has a value of 1.0 at the ground surface (Cetin and Seed 2000). The methods of Seed et al.

(2003) use improved correlations for estimation of $r_d$ as calculated by Cetin and

Seed (2000). Cetin and Seed (2000) performed 2,153 seismic site response

analyses to examine the change in $r_d$ for a range of site conditions and ground

motion excitation characteristics (Seed et al. 2003). Cetin and Seed (2000)

found that the $r_d$ suggested by Seed and Idriss (1971) (and used by Youd et al.,

TABLE 5. FINES CORRECTED PENETRATION RESISTANCE, FACTOR OF SAFETY AND CYCLIC RESISTANCE RATIO (SUMMARIZED BY LAYER FOR ALL GEOLOGIC MAP UNITS)

| Geologic map unit | Penetration Resistance $(N_1)_{60,cs}$ | | | | Factor of Safety (only liquefiable textures) | | | | Cyclic Resistance Ratio (CRR) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | All textures (including fines) | | Only liquefiable textures | | | | | | | | |
| | # of layers | median [Seed et al., 2003] | median [Youd et al., 2001] | % of layers | median [Seed et al., 2003] | # of FS values | mean FS | median FS | mean | median | standard deviation |
| af | 48 | 10.4 | 13.1 | 63 | 11.9 | 42 | 0.7 | 0.3 | 0.27 | 0.15 | 0.29 |
| alf | 5 | 6.3 | 9.8 | 75 | 8.5 | 5 | 0.2 | 0.2 | 0.12 | 0.09 | 0.05 |
| Qhc | 11 | 11.2 | 11.6 | 100 | 11.2 | 11 | 0.5 | 0.4 | 0.36 | 0.23 | 0.36 |
| Qhfy | 7 | 11.1 | 14.8 | 100 | 11.1 | 7 | 0.6 | 0.4 | 0.16 | 0.17 | 0.04 |
| Qhly | 54 | 6.5 | 9.5 | 95 | 6.5 | 51 | 0.4 | 0.3 | 0.21 | 0.17 | 0.19 |
| Qhty | 28 | 7.0 | 9.4 | 100 | 7.0 | 27 | 0.3 | 0.2 | 0.20 | 0.15 | 0.19 |
| Qhbm | 1 | 8.5 | 12.1 | 0 | na | na | na | na | na | na | na |
| Qhb | 4 | 6.2 | 9.7 | 50 | 7.9 | 4 | 0.2 | 0.2 | 0.15 | 0.15 | na |
| Qhfe | 15 | 4.8 | 7.9 | 100 | 4.8 | 15 | 0.2 | 0.2 | 0.18 | 0.12 | 0.24 |
| Qhf | 598 | 11.2 | 14.2 | 89 | 11.6 | 553 | 0.5 | 0.3 | 0.35 | 0.20 | 0.33 |
| Qhff | 35 | 8.7 | 12.3 | 55 | 9.5 | 31 | 0.4 | 0.3 | 0.24 | 0.18 | 0.24 |
| Qhl | 137 | 10.3 | 13.8 | 90 | 10.3 | 135 | 0.4 | 0.3 | 0.27 | 0.17 | 0.27 |
| Qht | 4 | 28.9 | 31.1 | 100 | 25.3 | 4 | 1.0 | 1.2 | 1.00 | 1.00 | na |
| Qf | 41 | 10.8 | 13.6 | 100 | 10.8 | 40 | 0.4 | 0.3 | 0.23 | 0.22 | 0.17 |
| Ql | 4 | 8.5 | 12.1 | 100 | 8.5 | 4 | 0.2 | 0.2 | 0.15 | 0.14 | |
| Qt | 2 | 26.3 | 28.8 | 100 | 26.3 | 2 | 0.7 | 0.7 | na | na | na |
| Qpf | 227 | 19.2 | 21.5 | 93 | 19.8 | 222 | 0.9 | 0.7 | 0.56 | 0.35 | 0.39 |

See Table 1 for unit definitions. Units are listed in order of increasing age. Textures that are not subject to liquefaction include CL, CH, MH, ML-CL, OH, OL, Pt.

2001) underestimates the degree to which $r_d$ may vary with changes in site conditions and ground motion characteristics, and results in overestimates of $r_d$ between depths of 10 and 50 feet, the depth range for which liquefaction potential is calculated (Seed et al. 2003). It is likely that the difference in $r_d$ values accounts for the difference in corrected blow count values. (3) The median factor of safety (FS) value for most geologic map units is much less than 1. Where the FS value is less than 1, layers with potentially liquefiable textures are prone to liquefaction when subjected to a level of shaking that has only a 10% probability of being exceeded in 50 years. However, it is important to remember that a significant fraction of the sediment in the study area is composed of fine-grained materials – materials that are too fine to be likely to liquefy. For instance, Table 5 shows that the median FS value for latest Holocene alluvial fan deposits (Qhfy) is 0.17. However, Table 4 shows that only 22% out of a total of 46 layers, and only 13% out of the total thickness of 78 meters of sediment, are composed of liquefiable textures. This means that although the composition of Qhfy includes sediment that is liquefiable, the relative abundance of the liquefiable fraction of Qhfy is low.

Figure 9 summarizes some of the geologic characteristics of the liquefiable deposits found in the study area. Because geologic characteristics are often complex and difficult to model, data distributions are frequently non-ideal, although some interpretation is possible. Figure 9 illustrates a range of measured penetration resistance values for layers as grouped according to age

for latest Holocene (Qhfy, Qhly, Qhty, and Qhfe), Holocene (Qhb, Qhc, Qhf, Qhff,

Qhl, and Qht) and latest Pleistocene (Qf, Ql, Qt, and Qpf) ages. The x axis
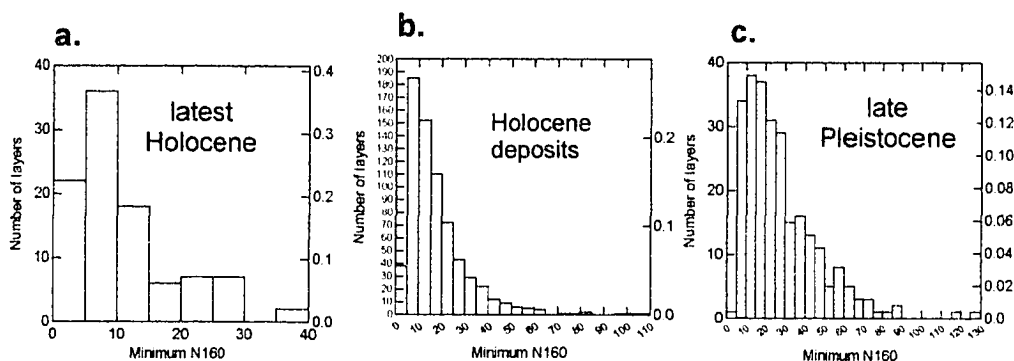


Figure 9. Histograms of penetration resistance (by layer, only liquefiable textures are included). From a. Latest Holocene [number of layers = 98, mean=11.5, median=8.9]; b. Holocene deposits [number of layers = 693, mean=17.7, median=14.1]; and c. Latest Pleistocene deposits [number of layers = 255, mean=28, median=23].

records the minimum penetration resistance of each layer, and the y axis records

the number of layers for each $(N_1)_{60}$ value. Late Pleistocene layers (Fig. 9c) have

the highest penetration resistance, with a median value of 23, followed by

Holocene (Fig. 9b) layers with a median value of 14.1, and latest Holocene

deposits (Fig. 9a) with a median value of 8.9. The overall increase in density

with increasing age of the deposit is likely a reflection of the fact that older

deposits have been subjected to compaction and lithification processes longer.

Plate 5 shows histograms of all penetration resistance measurements

(from layers with liquefiable textures) collected for this research. Each layer has

been assigned a geologic map unit based on interpretation of the stratigraphy

depicted in the boring logs as described above. The histograms for map units for

which there are a sufficient number of samples (e.g. Qhly, Qhfe, Qhf, Qhl) suggest that $(N_1)_{60,cs}$ populations are not normally distributed, but are more likely to be log-normally distributed. There appears to be a general trend of increasing penetration resistance with increasing age of deposits, as observed in Table 5. A "box and whisker" plot of these same data (Fig. 10) shows that the properties of the map units overlap. The results depicted on Figure 10 underscore an important point: if the methods used in this research are to be applied in other geographic regions, the minimum number of borings necessary to produce meaningful results will vary based upon the complexity of the geology of the region under investigation.

Liquefaction Potential Index

LPI has been calculated for all borings in the study area with saturated, loose, granular deposits for which penetration test data are available. Figure 11 shows that many geologic map units have calculated median LPI values in the range of 10 to 15. Toprak and Holzer (2001) found that the surface manifestation of liquefaction-induced deformation is 93% for LPI values of near 15 and 58% for values near 5. Because sediment becomes increasingly resistant to liquefaction with age, LPI should decrease with increasing age. However, calculated LPI values for Holocene and late Pleistocene deposits in this study do not follow the expected trend. The reason for this difference may be that the LPI parameter expresses only the probability of surface manifestations of liquefaction and not
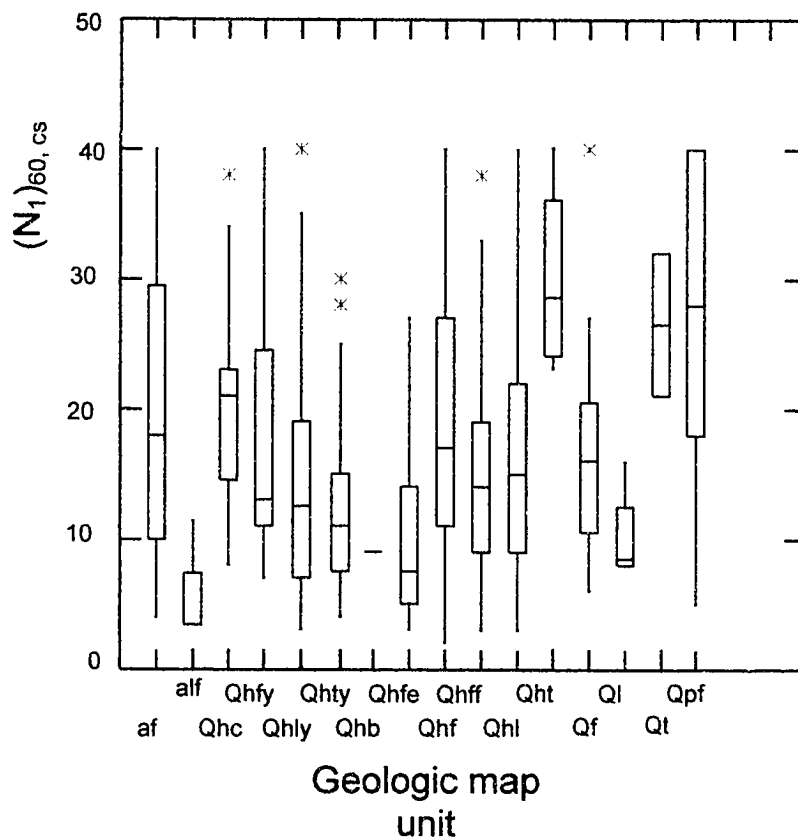
Figure 10. Box and whisker plot of fines corrected penetration resistance measurements for every layer in the project geotechnical boring database. The length of the box shows inter-quartile range (the median of the upper part of the data minus the median of the lower part of the data) and larger box lengths indicate greater variability in the data set; the line through the box shows the median value. The "whiskers" show the overall range of the data. Outliers in the data set are represented by stars at either end of the whiskers. Geologic map units are listed in order of increasing age from left to right.
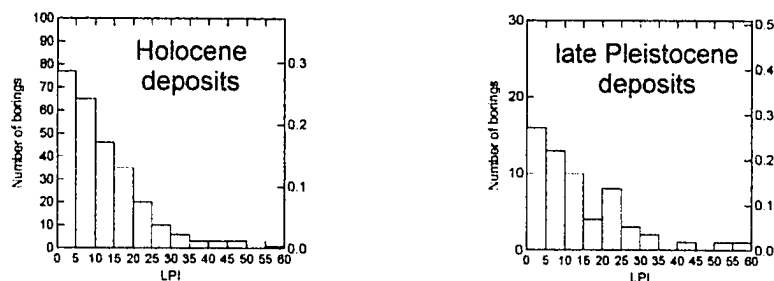
Figure 11. Liquefaction Potential Index calculated for borings aggregated to the representative age of the majority of deposits (Holocene or Late Pleistocene) in the boring; Holocene deposits [number of borings = 269, median = 9.6], Late Pleistocene deposits [number of borings = 59, median = 10.4].

magnitudes of deformation. Toprak and Holzer (2003) noted that pockets of potentially liquefiable material that are not laterally continuous might yield a high LPI value but no surface manifestations of liquefaction, whereas a thin but widely distributed potentially liquefiable layer that is deeply buried might yield a low LPI yet produce significant liquefaction-related surface features. Sedimentary deposits in the northern Santa Clara Valley are highly variable both laterally and vertically over a short distance. It is possible that sediment that is identified as late Pleistocene contains discontinuous lenses of potentially liquefiable material, that are not likely to produce deformation features at the ground surface.

Deviation from expected results may also be due to the fact that not all of the borings in this study reach the minimum required depth of 20 m (Iwasaki et al.1982) and/or that more data are needed.

## Estimating Strain for Each Geologic Map Unit

Table 6 summarizes data generated by the methods of Wu et al. (2004) (volumetric strain) and Wu (2002) (limiting shear strain) liquefaction-induced ground deformation models used in this study. The table shows strain calculations for borings grouped according to surficial geologic map unit.

TABLE 6. CALCULATED VOLUMETRIC AND LIMITING SHEAR STRAIN ALONG WITH SETTLEMENT AND HORIZONTAL DISPLACEMENT FOR BORINGS INITIATED IN EACH GEOLOGIC MAP UNIT

|  | # | Volumetric strain (%) | | | Settlement (meters) | | | Shear strain (%) | | | Displacement (meters) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  | μ | med | σ | μ | med | σ | μ | med | σ | μ | med | σ |
| afbm | 6 | 4.5 | 4.8 | 0.6 | 0.1 | 0.1 | 0.1 | 42.1 | 43.0 | 5.4 | 1.2 | 1.0 | 0.7 |
| alf | 24 | 3.1 | 3.0 | 1.7 | 0.1 | 0.1 | 0.2 | 26.5 | 27.1 | 16.8 | 1.0 | 0.5 | 1.3 |
| ac | 2 | 2.7 | 2.7 | 0.9 | 0.2 | 0.2 | 0.1 | 26.8 | 26.8 | 9.0 | 1.9 | 1.9 | 1.5 |
| Qhc | 3 | 1.0 | 0.5 | 1.3 | 0.0 | 0.0 | 0.1 | 7.9 | 0.0 | 13.7 | 0.4 | 0.0 | 0.6 |
| Qhfy | 21 | 3.1 | 3.0 | 1.4 | 0.1 | 0.1 | 0.1 | 28.6 | 27.2 | 15.6 | 0.9 | 0.7 | 0.7 |
| Qhly | 28 | 2.7 | 2.9 | 1.6 | 0.1 | 0.1 | 0.1 | 24.9 | 24.2 | 17.7 | 1.1 | 0.8 | 1.2 |
| Qhty | 18 | 3.2 | 3.2 | 1.3 | 0.1 | 0.1 | 0.1 | 30.0 | 27.5 | 16.0 | 0.9 | 0.8 | 0.7 |
| Qhfe | 11 | 4.2 | 4.1 | 2.0 | 0.2 | 0.1 | 0.2 | 33.8 | 30.3 | 15.1 | 1.6 | 1.1 | 1.4 |
| Qhf | 183 | 1.4 | 0.8 | 1.7 | 0.0 | 0.0 | 0.1 | 11.7 | 0.6 | 16.3 | 0.3 | 0.0 | 0.8 |
| Qhff | 72 | 2.2 | 2.1 | 1.6 | 0.1 | 0.0 | 0.1 | 18.9 | 14.7 | 16.8 | 0.5 | 0.3 | 0.7 |
| Qhl | 87 | 2.4 | 2.6 | 1.8 | 0.1 | 0.0 | 0.1 | 21.7 | 20.9 | 17.9 | 0.6 | 0.4 | 0.7 |
| Qht | 4 | 2.3 | 2.3 | 1.5 | 0.2 | 0.2 | 0.1 | 20.1 | 19.3 | 15.4 | 1.6 | 1.5 | 1.5 |
| Qf | 6 | 1.2 | 1.3 | 0.8 | 0.0 | 0.0 | 0.0 | 5.3 | 6.1 | 4.8 | 0.1 | 0.0 | 0.1 |
| Qt | 1 | 0.9 | -- | -- | 0.1 | - | - | 1.0 | -- | -- | 0.2 | - | - |
| Qpf | 23 | 0.2 | 0.0 | 0.4 | 0.0 | 0.0 | 0.0 | 0.5 | 0.0 | 1.3 | 0.0 | 0.0 | 0.1 |

"Predicted" volumetric strain is calculated and shown here using the Wu et al. (2004) approach. This method assumes nearly level ground and, based on comparison with case studies yields estimates that should be within a factor of two of future settlement.

See Table 1 for listing of names of geologic map units.

"Limiting" shear strain is calculated and shown here using the preliminary correlations by Wu (2002). This method assumes nearly level ground and yields estimates that should be considered maxima.

# - number of borings; μ mean; med – median; σ - standard deviation.

To estimate amounts of volumetric strain or limiting shear strain, the calculated strain is multiplied by the thickness of saturated sediment with potentially liquefiable textures. Table 6 reveals that there is an inverse correlation between the age of the deposit mapped at the ground surface and estimated strain – generally, the younger the deposit the larger the estimated strain. The younger deposits (e.g. the late Holocene units Qhfy, Qhly, Qhty and

Qhfe) generally are less dense and thus more susceptible to liquefaction triggering and the subsequent deformation. As noted in the methods section, the methods for estimating volumetric strain yield results that can be thought of as "predicted" or as "within-a-factor-of-two," whereas the relationships used to estimate future shear strain should be thought of as "limiting" or "potential" values.

The median strain values for each geologic map unit are grouped into five categories (ranging from Very Low to High) according to the median strain value for all borings that penetrate a given geologic unit at the ground surface. Plates 6 and 7 show where these units occur at the land surface. The colored dots on each map represent the locations of borings for which strain was calculated, where the color of each dot correlates to the total amount of strain for all layers composed of saturated, liquefiable textures summed for the entire length of each boring. The higher values of both volumetric and shear strain tend to be located adjacent to Guadalupe River and Coyote Creek (the two largest water courses in the study area), and where these water courses discharge into the San Francisco Bay. Areas adjacent to active water courses where thick accumulations of loose, saturated and granular material are more susceptible to liquefaction (Witter et al. 2006) appear to have a correspondingly higher susceptibility to liquefaction-induced strain. In contrast, older sediment that has been subjected to consolidation over a longer period of time is less susceptible to liquefaction

(Witter et al. 2006) and appears to have a correspondingly lower susceptibility to liquefaction-induced strain.

On Plates 6 and 7, the geologic map unit artificial fill over Bay Mud (afbm) is assigned to the category with the highest median strain value. Clay is not considered a liquefiable texture because cohesive fines such as clays (a primary component of mud) do not liquefy during undrained cyclic loading, i.e., earthquake shaking (Boulanger and Idriss 2004). However, because fill associated with afbm is less likely to be engineered and in many locations was dredged from sandy areas (Witter et al. 2006), even though the unit includes a high percentage of clay, the liquefaction susceptibility of afbm is considered Very High and the potential for liquefaction-induced strain for afbm is likely to be high as well.

Strain results summed for all saturated, liquefiable textures for which penetration test data are available in each boring suggest that for borings near Guadalupe River and Coyote Creek there is limited agreement between the amount of volumetric or limiting shear strain per boring and median strain value for the geologic map unit in which the boring is located. However, overall it appears that borings located near Guadalupe River and Coyote Creek tend to have the highest strain values (categories High, Moderate-High, and Moderate) regardless of whether or not the amount of strain for an individual boring falls into the same strain category as the map unit in which it is located.

Figures 12 and 13 show the number of individual borings assigned to each

strain category that plot in the correspondingly colored polygon representing the same amount of deformation on the strain maps. Of the 668 borings reviewed for this research, percent strain was summed for 489 borings that record penetration test data and contain layers composed of saturated, liquefiable textures. Figures 12 and 13 show that a small number of the borings plot within the map polygon that represents the same strain category. Figures 14 and 15 show the percent of borings that plot within the map polygon that represents the same strain category, as well as the percent of borings that plot within the polygon with the next higher and lower strain category. The relatively low correlation between mapped strain category and the strain category for each individual boring is most likely due to the fact that sedimentary deposits in the map area vary vertically and laterally over a short distance. Variability in distribution of sedimentary deposits results in variation in susceptibility to liquefaction, and subsequent liquefaction-induced strain.

The purpose of this study is to try to understand how well the range of variability in strain that is likely to occur within a given geologic map unit may be predicted by the environment in which the sediment was deposited. For instance, distal fan areas such as Holocene alluvial fan, fine facies (Qhff) are typically low-energy environments characterized by deposition of fine sediments such as silts and clays. The relative percent of silt and clay sampled in multiple boring advanced into Qhff sediment may vary. One boring may include a larger

Number of borings that plot in map polygon with corresponding volumetric strain value (%)
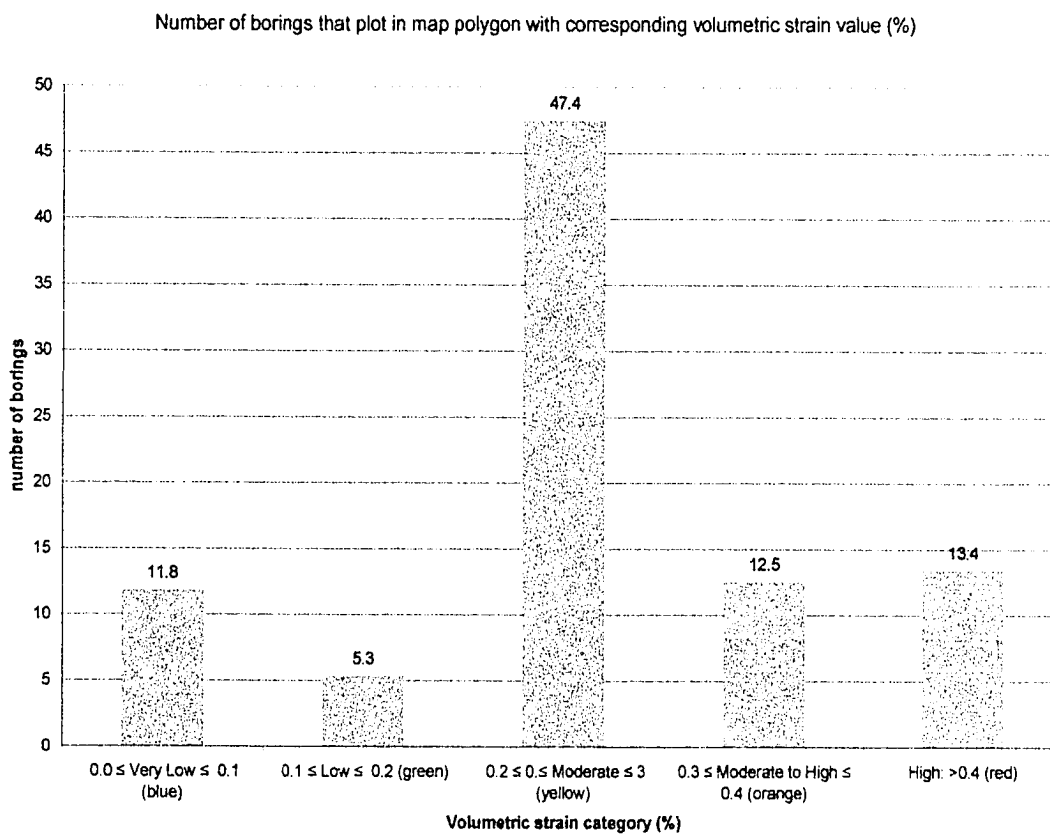


Figure 12: Histogram showing the number of borings that plot in the map polygon with the corresponding volumetric strain (%). The color noted on the x axis corresponds to the strain category for the dots and the shaded polygons on the map.

Number of borings that plot in map polygon with corresponding shear strain value (%)
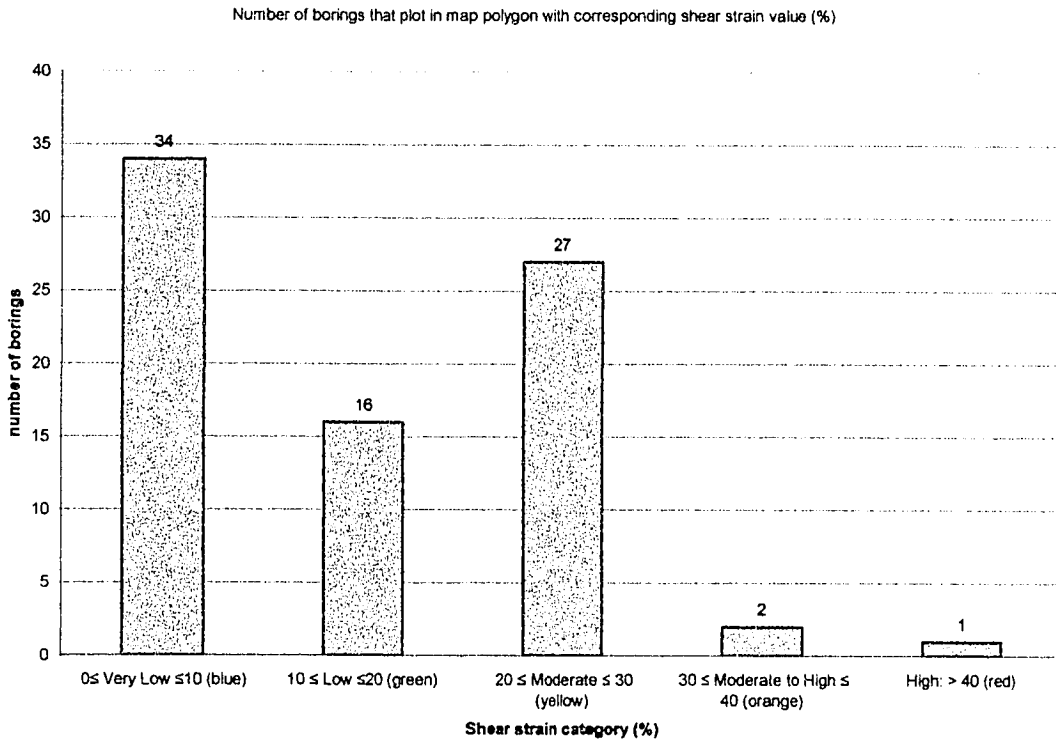


Figure 13: Histogram showing the number of borings that plot in the map polygon with the corresponding shear strain (%). The color noted on the x axis corresponds to the strain category for the dots and the shaded polygons on the map.

**Percent of borings that plot In polygon with same volumetric strain value, polygon with next higer volumetric strain value, and polygon with next lower volumetric strain value**



□ Percent of borings that plot in next lower volumetric strain category (%)

■ Percent of borings that plot in next higher volumetric strain category (%)

□ Percent of borings that plot in polygon with corresponding volumetric strain value (%)
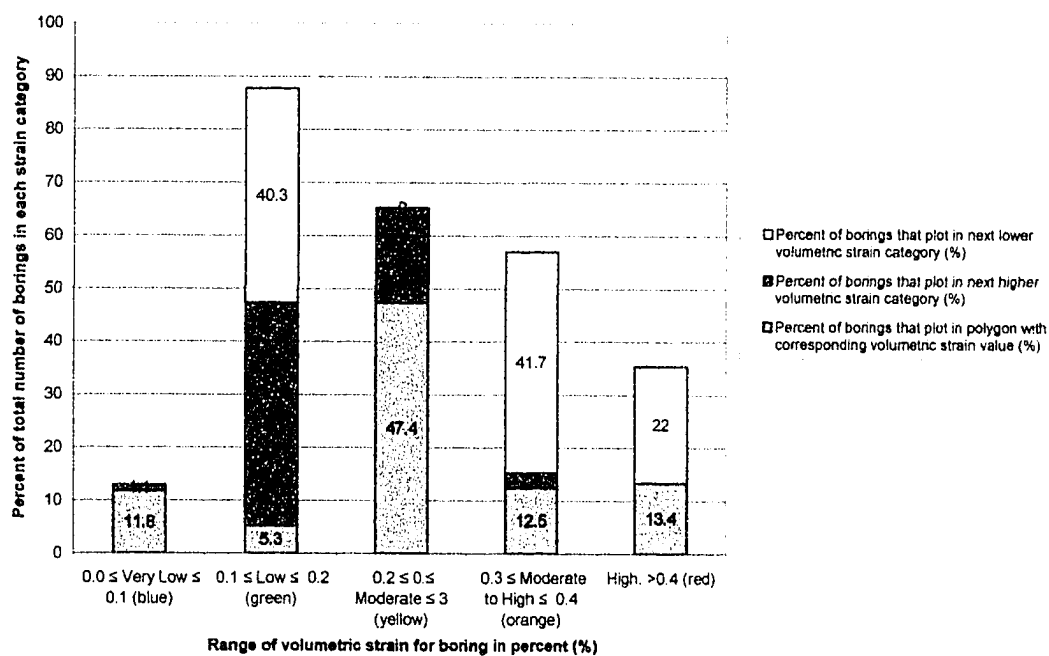
Figure 14: Histogram showing the percent of borings that plot in the map polygon with the corresponding volumetric strain (%) as well as the polygon with the next higher and lower volumetric strain category. The color noted on the x axis corresponds to the strain category for the dots and the shaded polygons on the map.

Percent of borings that plot in polygon with same shear strain value, polygon with next higer shear strain value, and polygon with next lower shear strain value
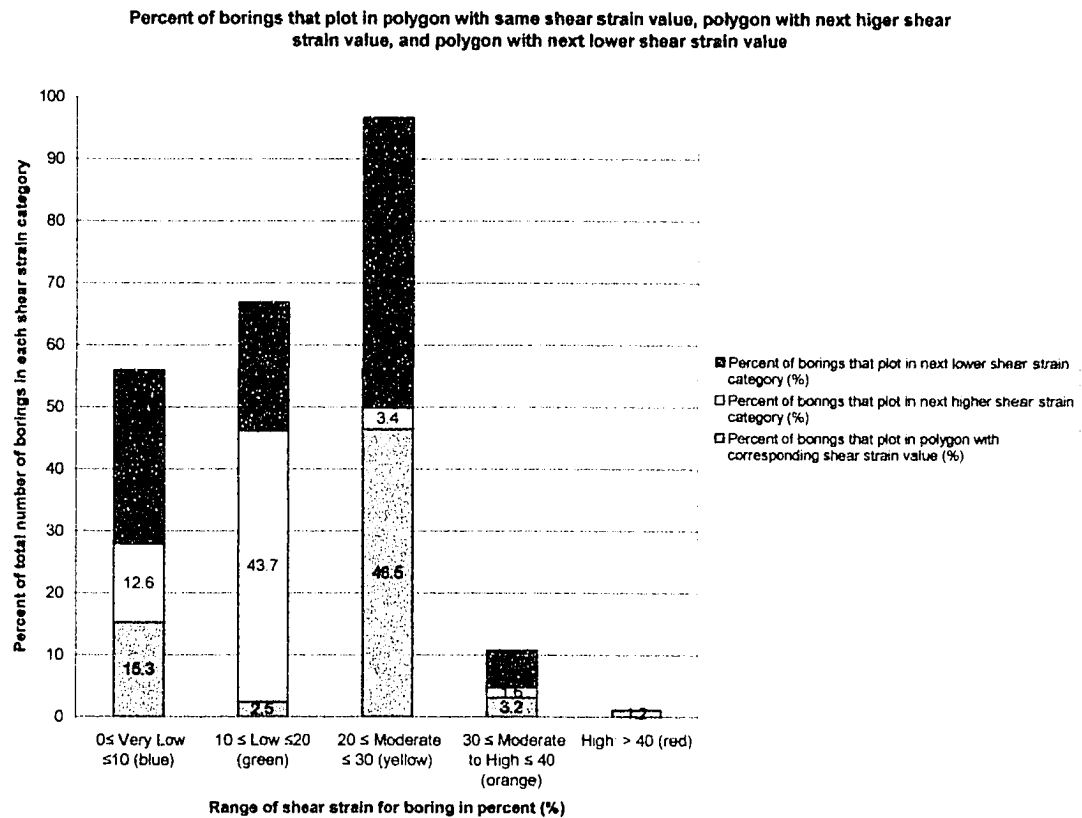


Figure 15: Histogram showing the percent of borings that plot in the map polygon with the corresponding shear strain (%) as well as the polygon with the next higher and lower shear strain category. The color noted on the x axis corresponds to the strain category for the dots and the shaded polygons on the map.

percentage of silt and therefore be relatively more susceptible to liquefaction and likely to experience a relatively greater amount of strain compared to other nearby borings in Qhff with more clay. However, even though the liquefaction susceptibility and subsequent strain may vary for adjacent borings, overall the range of variability will be limited because the type of sediment deposited in Qhff is limited by the low-energy depositional processes that operate in that environment. Geotechnical data recorded on boring logs such as penetration

resistance provide quantifiable data that can be used to calculate liquefaction

potential and the potential for liquefaction-induced strain. Grouping the geologic

map units according to the median strain value for all of the borings that

penetrate that unit allows for the production of a regional-scale map that

illustrates characteristic liquefaction-induced strain based on specific geologic

environment. The boundaries of the strain polygons correspond to boundaries of

geologic map units, and Plates 6 and 7 show that environments with the highest

predicted amounts of strain are nearest to higher-energy stream environments

where young, loose, coarser-grained sediments are deposited.


Observed vs. Predicted Deformation

Because it was not possible to calibrate deformation predicted by this

study using primary data (in-situ measurements from preserved historical ground

failure features), an attempt to calibrate results using descriptions of historical

ground failure from the 1868 Hayward, 1906 San Francisco and 1989 Loma

Prieta earthquakes was conducted instead. Accounts of ground deformation

compiled by Youd and Hoose (1978) include descriptions with quantified

estimates of ground failure.

An attempt was made to compare the amounts of liquefaction-induced

ground deformation predicted using data compiled in this study with measured

amounts of historical deformation within the study area caused by the 1868, 1906

and 1989 earthquakes. In the fall of 2003, William Lettis and Associates, Inc.

excavated a 93-m-long trench at Cilker Orchards, just west of Coyote Creek,

approximately 4 km south of San Francisco Bay (Thompson et al. 2004). The

purpose of their study was to investigate whether lateral spreads occur

repeatedly in the same location. Youd and Hoose (1978) compiled several

accounts of lateral spread adjacent, and in close proximity, to Coyote Creek in

the vicinity of the trench, including fissures, offset rows of trees in the adjacent

orchards, and settlement caused by both the 1868 Hayward and 1906 San

Francisco earthquakes. Unfortunately reconstruction of a levee adjacent to

Coyote Creek in 1993 made it impossible to locate a trench in the area where the

majority of ground failure features were reported. Only two small sand dikes (3-5

mm wide) were visible in the trench, and they did not provide enough information

to calibrate the results of this study.

These written accounts were reviewed and a table containing an estimate

of the type of ground failure to occur at each site (displacement or settlement)

and the amount of deformation that occurred at each site was compiled

(Appendix 4). After each site was located, the estimated amount of predicted

ground failure was compared to the observed amount of ground failure within

each geologic map unit. For settlement, the predicted amount exceeds the

observed amount of ground failure, while for displacement the observed amounts

of ground failure are somewhat higher than predicted. Although there are many

reports of earthquake-induced ground failure following the 1906 earthquake,

some features are not well documented. Youd and Hoose caution that "most

post-earthquake investigative efforts were applied to assessing the extent of structural and other damage or tracing out ruptured faults; hence notations concerning ground failures are commonly of incidental nature," e.g., no distinction is made between ground failures due to liquefaction and those caused by deformation of soft clay.

CONCLUSIONS

The surface elevation of the boundary that is interpreted as the top of the Pleistocene shows a central topographic low aligned down the center of the northern Santa Clara Valley that corresponds to the present-day location of Guadalupe River and Coyote Creek. Identification of this paleo-land surface is accomplished through an iterative process that includes collecting and reviewing geotechnical data recorded on boring logs and constructing cross sections through the study area. The most important type of information reviewed was the penetration test data because it may be used as a proxy for the density of the layer. As sediment ages and lithifies, its density and penetration resistance increase. The top of the Pleistocene was inferred from penetration test data, laboratory test results including grain size analysis, moisture content, and dry density, and descriptive comments that mention changes in color, lateral and vertical textural changes, or presence of organic matter. All borings that contained layers interpreted as Pleistocene were plotted and a contour map was constructed. Borings that caused contour lines to be deflected or drawn in a manner inconsistent with the expected land surface were reviewed and reinterpreted in the context of surrounding borings, and the emerging contour surface of the elevation of the top of Pleistocene was subsequently revised. The contours delineating the center of the northern Santa Clara Valley are constructed with much less confidence than those along the margins of the

valley. Holocene sediment increases in thickness both toward the center of the northern Santa Clara Valley and downstream. Most of the geotechnical borings used in this study are not deep enough to penetrate the Pleistocene surface in the center of the study area.

The following conclusions are reached about sediment layers described in geotechnical boring logs collected in the northern Santa Clara Valley: 1) fewer than half of the sediment layers described are coarse enough to liquefy, whether analyzed by the total number of layers or the total boring length assigned to each map unit; 2) the median corrected penetration resistance $((N_1)_{60,cs})$ value for sediment with liquefiable textures in most cases is less than 15, a value previous researchers have considered an upper bound for sediment likely to experience large-scale liquefaction-related deformation; 3) the method of Youd et al. (2001) results in median $(N_1)_{60,cs}$ values that tend to be 2 to 3 blows/ft higher than the values calculated using the method of Seed et al. (2003); 4) where the Factor of Safety value is less than 1, layers with granular textures are prone to liquefaction when subjected to a level of shaking that has only a 10% probability of being exceeded in 50 years, although a high percentage of the sediment in the study area consists of fine-grained materials that probably are too fine to liquefy; 5) liquefaction potential index values for younger deposits tend to be lower than for older deposits; and 6) the maximum distance for which there is a relationship between adjacent borings is approximately 900 m, while the median separation distance between any two borings in the study area is approximately 1,044 m,

indicating that additional data are required to adequately characterize geologic variability in the northern Santa Clara Valley.

Because the descriptions for sediment layers on boring logs often lack sufficient detail, it is often not possible to distinguish sub-units for sub-surface layers. For the purposes of liquefaction and liquefaction-induced deformation analysis it is sufficient to identify the paleo-land surface boundary, or the depth at which the sediments are sufficiently dense that they will not liquefy.

The northern Santa Clara Valley is characterized by the highly variable nature of its late Quaternary geology. This variability makes it difficult to differentiate areas likely to experience large liquefaction-related deformation from areas with less hazard. Resolution of this problem might occur with the acquisition of additional geotechnical boring data. The data available for this project (668 boring logs) do not include a uniform number of borings from every potentially liquefiable geologic map unit. Geotechnical data recorded on boring logs such as penetration resistance, fines content, or USCS classification provide quantifiable data that can be used to calculate liquefaction potential and the potential for liquefaction-induced strain. Grouping the geologic map units according to the median strain value for all of the borings that penetrate that unit allows for the production of a regional-scale map that illustrates characteristic liquefaction-induced strain based on specific geologic environment.

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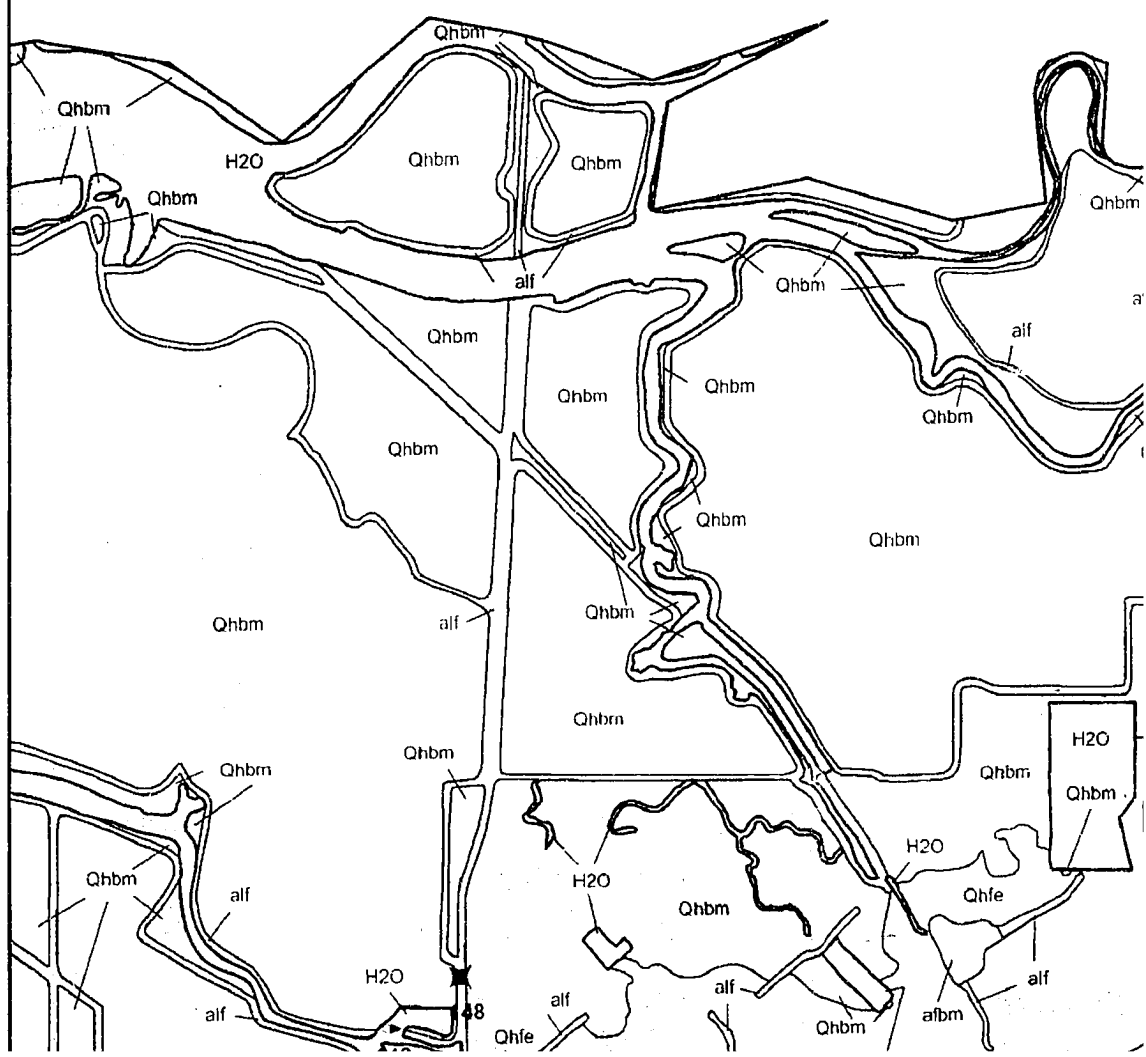
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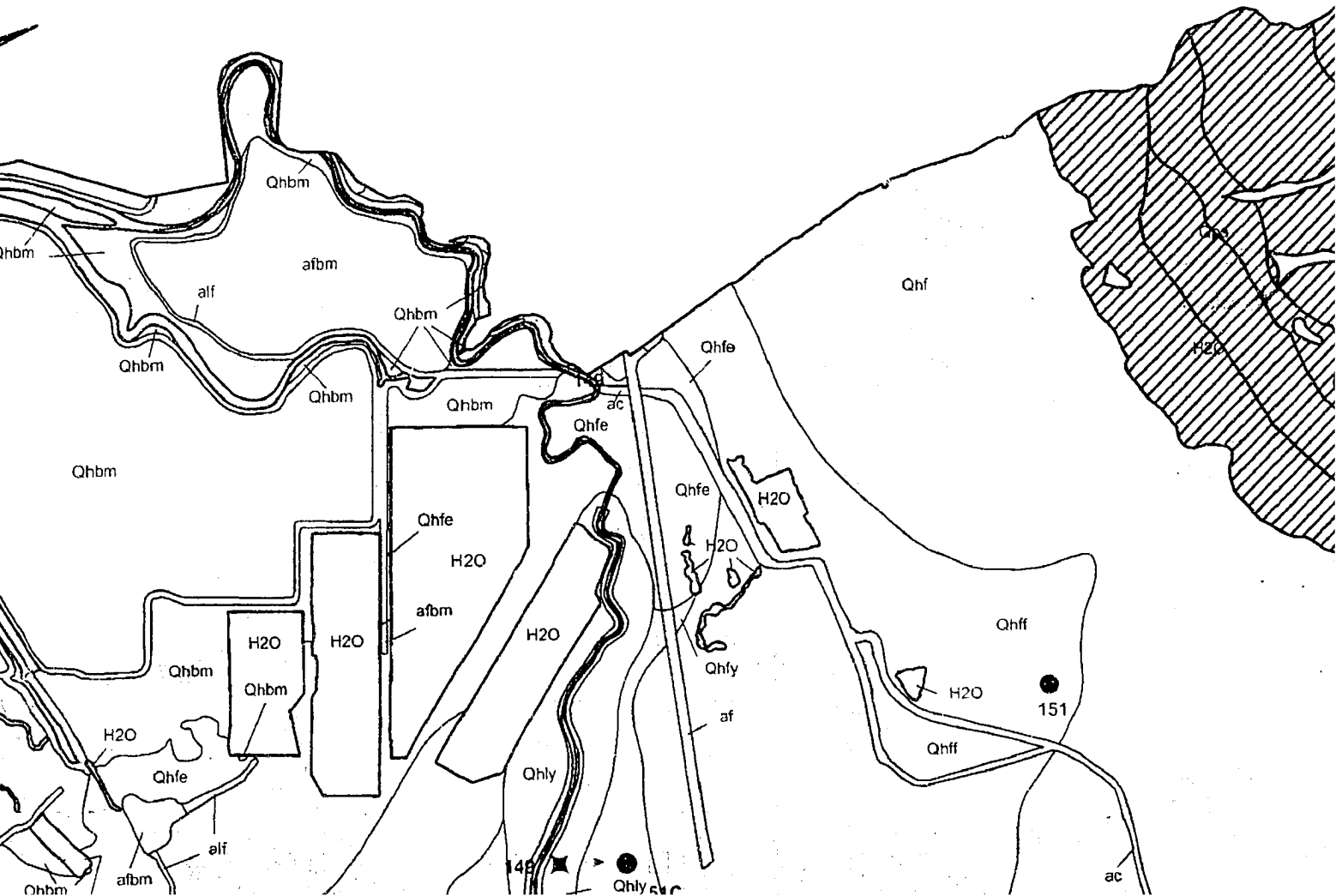
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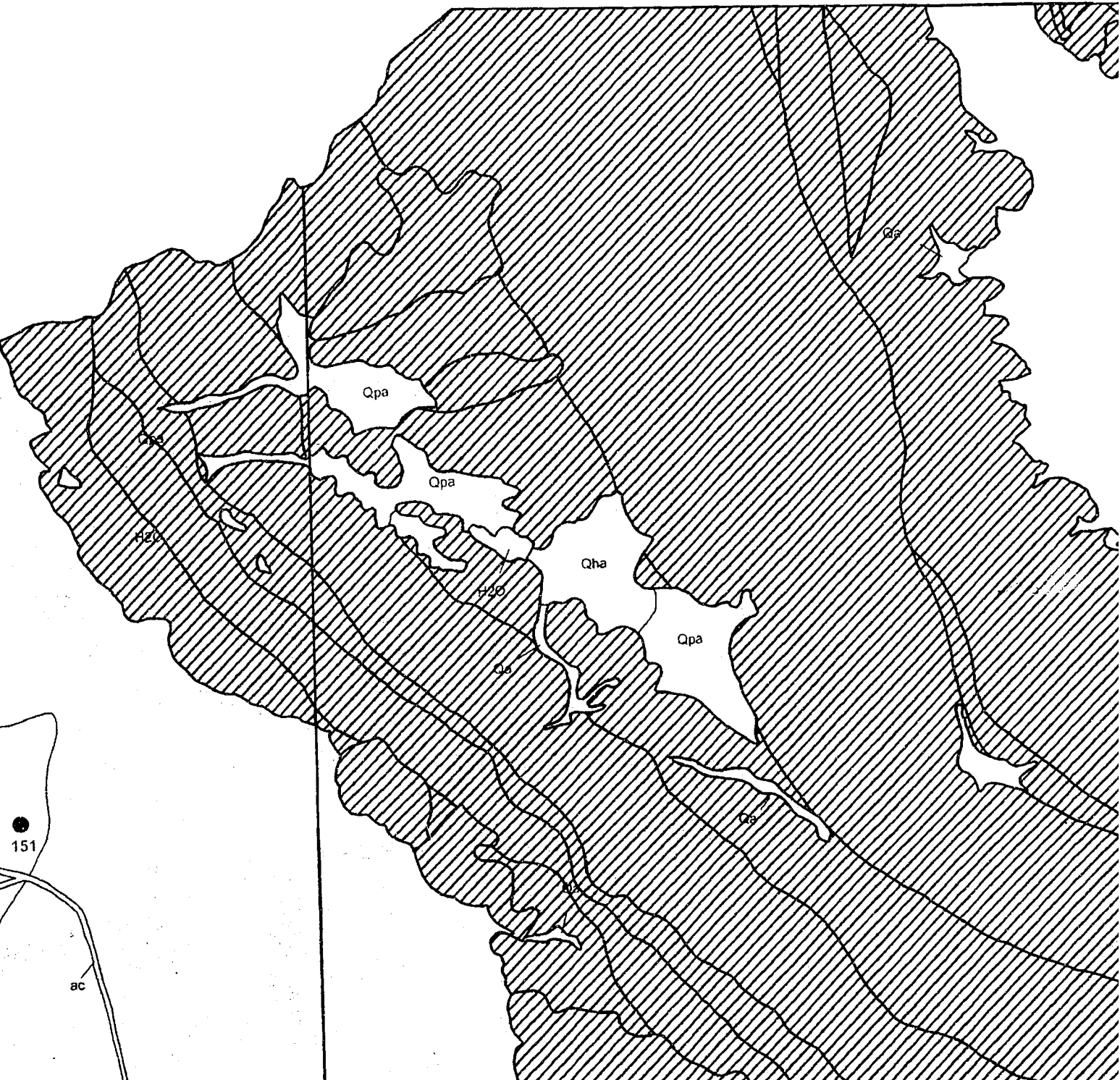
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I6Q_2B10

I6Q_1B12

M5Q_1B22

Qhf

M6Q_1B9

Qhfe

K6Q_2B1

K6Q_1B10

J6Q_2B25

N6Q_1B11

dc

M6Q_2B5

Qhfe

K6Q_1B1

J6Q_1B1

J7Q_2P2

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N7Q_1B3

Qhfe

K7Q_1B9

H2O

L7Q_1B6

J7Q_2B17

Qhfe

H2O

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N7Q_2B2

H2O

M7Q_1B3

O7Q_1B4

O7Q_2B1

J7Q_1B19

Qhff

afbm

H2O

H2O

H2O

18Q_3B2

J7Q_1B4

Qhfy

H2O

af

Qhff

A8Q_2B1

18Q_2B4

J8Q_2B7

37302B2

Qhly

M8Q_3B1

A8Q_1

18Q_1B

J8Q_1B12

M8Q_2B1

M8Q_1B3

M9Q_1B1

# UDY AREA



Hayward Fault Zone

Qa

H2O

Qpa

Qha

H2O

Qpa

Qa

Qha

Qoa

2B1

A8Q 1B3

121° 45'

37° 30'

H2O

Qha

Qoa

Qoa

Diablo Range

Cal

Qhly
18Q_1 3Q_1B12 M8Q_2B1 M8Q_3B1 37302B2 A8Q_1B3
9Q_4 M8Q_1B3
Qhly M9Q_1B3 ac N9Q_B5
1B6 Qhff I9Q_2B26 L9Q_1B1 M9Q_2B10 N9Q_2B3
H9Q_2B7 I9Q_5B3 QhffL9Q_2B8
I9Q_P6 J9Q_B3
I9Q_3B1 J9Q_3B1 A9Q_2B1
I9Q_3B8 H9Q_3B8 I9Q_4B2 Qhfy A9Q_1B22
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H10Q_1B9 37474B1
B2 H10Q_2B10 Qhfy 10Q_1B18 N10Q_2B3 B10Q
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H10Q_4B16 Qhff K10Q_1B2 L10Q_1B1 O11Q_B1
Q_1B17 J11Q_5B5 11Q_1B7
J11Q_4B L11Q_1B2 M11Q_1B4 O11Q_2B2
10Q_2B18 I11Q_2B Qhl Qhf
H11Q_1B10 J11Q_2B1 N11Q_1B1 O12Q_B1
1Q_3B19 I11Q_3P41 11Q_6F17
H11Q_4B21 I11Q_4F5 M12Q_3B2
J11Q_7 0 M12Q_1EB1 O12Q_1B1
Qhfy alf L12Q_2 1
N12Q_1EB3
Qhly L12Q_1B3
H12Q_1EB1 K12Q_1B M12Q_2B10 Qhf
Qhly EB16 N13Q_2EB1
H12Q_2EB10 Qhty
12Q_3EB11 N13Q_1EB3
H13Q_2EB12 I13Q_1EB7 M13Q_1EB2
B8 K13Q_1B3 Qhl 37296B4
Qhff af A13Q_1B1
Q_WB08 J13Q_1B1 Qhly
Qhly I14Q_1B1 N14Q_1B5
VB0 H14Q_2B10 J14Q_1B1
6WB1 J14Q_1B1 L14Q_1EB5
H14Q_3EB13 K14Q_1B2 af M14Q_1EB1
14Q_4WB alf
H14Q_4EB14 J14Q_2B6 M15Q_1EB12
H14Q_1B1 L15Q_1 Qhly
3WB13 af Qhly
I15Q_1B1 Qhty
ac L15Q_6EW Qhc
Q_EB Qhf L15Q_5EW6 L15Q_3EW2 Qhly
H15Q_2EB16 J15Q_1B2 L15Q_4EW5 Qhl
15Q_4WB14 L15Q_2B 1 Qhl
H1Q_1B2 1298B9
1Q_1B51 Qhl
af 767B1 37490B1 1307B2 Qhly Qhf
10Q_3EB1 Qhly 1695B3
alf 1249B1 Qhf
1Q_2B4 766B4 Qhf
Qhly Qhly Qhly
J2Q_2WB15 740B1 Qhc
1EB1 J2Q_1EB2 af 1083B1 73 B1 Qhf
alf af N2Q_1B4
H2Q_2B2 37119B CC1
Qhf M2Q_1E B1 706B1 af 714B1
K2Q_1WB Qhf 713B1

Coyote Creek
Guadalupe

Calaveras Fault Zone

F1Q_2EB1   F2_7EB2

F1Q_1EB1

H2Q_1EB1

Qhf

F2Q_2EB2

H2Q_2B2

D2Q_1B1

E2Q_1B4

F2Q_1B1

Qhff

ac

E2Q_2EB1

G2Q_1B2

D2Q_2B1

G3Q_2B3

A3Q_2B2 Qhf

F3Q_5B4

G3Q_1B1

H3Q_2EB2

F3Q_6B1

F3Q_2B1

H3Q_3EB1

G3Q_3B1

A3Q_1B4

C3Q_2EB2

F3Q_1B1

H3Q_1EB1

I3Q_2B1

C3Q_1B2

C_Q_4B1

D3Q_1B1

F3Q_4EB3

H3Q_4EB1

C3Q_3EB3

I3Q_1B

ac

F3Q_1B3

G4Q_3B2  G4Q_5EB2  H4Q_2P1

Qhf

af

G4Q_1B9C

H4Q_4B3

H4Q_3B4

C5Q_2EB7  Qhf

F_Q_1B4

G4Q_4EB2

5Q_1B4

C5Q_5B2

D5Q_1B2

E4Q_1D_2

G4Q_2B9B

H_Q_5B1

H4Q_1B6

I4Q_1B1

A5Q_3B1

B5Q_1B2

C5Q_4E

C5Q_1B3

F4Q_2B2

5Q_1B1

Qhf

ac

F5Q_2B

H5Q_1EB3

37127B

5Q_2B2

C5Q_3S6

H5Q_2EB1

F5Q_2B1

E5Q_1B9A

Qhf

E6Q_1DH2

E6Q_1B

1433B10

I6Q_1B1

B7Q_1B1   C7Q_1B1

E7Q_1B

1433B13

37173B4

Qhl

A7Q_1B1

D7Q_2DH1

F7Q_2EB1

D7Q_1B2

521B2

F7Q_3B1

519B1

37210b4

2417B2

1023B3

F7Q_1B2

1009B1

37188B3

B8Q_1B1

37215B1

1189EB

Qhf

G8Q_1EB1

HS00409_43B

447B1

1758B6

1504B5

1388B1

401B8

1128B1

1618B1

128B0

Qhf

D9Q_1EB1

Qhl

37136EB1   1245B

B10Q_1B1

Qhl

Guadalupe River

Qhly
J2Q_2WB15
766B4
1249B1  1430EB1  Qhty
2Q_2B4
J2Q_1EB2
740B1
H2Q_1EB1
af
alf
1083B1  737B1  1321B1
N2Q_1B4
72B1
Qhff
af
37119BVCC1
Qhl
H2Q_2B2
Qhly
Qhf
M2Q_1EB1
706B1  Qhl  713B1  af  714B1
K2Q_1WB16
af
37102BH1
Qhff
K3Q_1WB17
Qhly
Qhly
H3Q_2EB2
Qhl
H3Q_1EB1  I3Q_2B1
Qhly
ac
279B2
1771EB
H3Q_4EB1
Qhl
I3Q_1B1
H4Q_2P1
Qhf
37130B1
632B4
Q_4B3
H4Q_3B4
630B1
635B3
2328B
H5Q_5B1  H4Q_1B6  I4Q_1B1
631B1  633B3  Qhl
37128B4  1449B4
1531B1
Qhl
1304B1  620B1  Qhf
Q_1EB3  37127B8
1361B2
1304B4
H5Q_2EB1
1292B2
1087EB3
588B1  608B1  Qhl
L5Q_1EB3
Qhl
37312B2  Qhl
1526EB11
541B1  568B1  1250B8  1194B1
807B1
1587B3
I6Q_1B1  1587B2
37282B2
37173B4  Qhl
37274B9  37290B8  3721B1
541B1
1537B1  Qhf
2161B1  Qhf
37279B15
A7Q_3MV
37321B2
Qhf  1959B1
1177B1  A7Q_1MV
1075EB2  37267B3
B7Q
L7Q_1B1
37255B7  Qhl  3742B5
189EB  Qhc
1145B1
37260B1
1758B6  472B2  468B1  1071B1
HS00409_43B10  451B2
gg  Qhl  336B2  552B1  Qhl
1210B1  Qhl  ac
416B1
1128B1  388B1  394B1  36IB1
1128B6  Qhl  Qhc
gg
Qhc  37419B
Qhf
1018EB4
37136EB1  1245B3  3143B1
1245B1  1313B1
245B8  Ohty
Qhf  Qhf

753B1

769B3

2060E

Qhty

Qhc

750EB5

703B7

751B2

Qpf

2008B1

1180B5

1321B1

Qht

713B1

af

714B1

710B1

37291B2

711B3  712B3

37102MH1

Qhty  Qhl

ac

2125B1

685B6

Qhff

37289B2

1749EB7

Qhf

681EB2

1607B2

772B1  Qhc

37123B2

670B1

2020B1

37287B10

ac

1771EB2

1747B2

653B2

Qhff

645B1

648B5

632B4

653B1

Qhff

639B3

Qhl

635B3

834B3

37222B4  Qhff

37286B4

618B6

629B3

2328B1

Qhl

1858B1

Qhf

1141B1

37285B2

37352R1B1

1176B4  Qhl

1574B8

Qht

37284B1

37142B9

Qhff

594B2

af

807B1

1367B39

2595B1

H2

37283B4

Qhl

575DH3

Qhb

37282B2

Qht

37280B8  37281B1

2036B1A  2868B1

Qhl

538B1

1077B1

1651B1

79B15

Qhf

503B4  1652B2

532B2

1124B2

Qht  538B4

233B3

276B1

1765EB1

1103EB4

495EB1  488EB2

A7Q_2MW37  B7Q_2MW4

505B1

Qhf

1959B1

A7Q_1MW36

B7Q_1MW35

Qht

2302DH1

594B2

502B1

476B1

3795B4

2003B1

Qhty

487BG

Qhl

1220B1

Qht

1181B5

1145B1

1543B1

1402EB1

Qhty

1344EB2

1690B2

461B9  1283B5

1775TB1

Qht

555B1  Qhl

Qht

404B2

476B1

Qhty

Qhl

361B1

Qhf

37218B3

37415B1

354B1

Qhl

366B7

Qhf

359B2

2240B1

362B3

Qpf

2008B1

1180B5

2B3

1749FB7

Qhf

72B1  Qhc

Qhff
645B1

Qhf

639B3

618B6

628B  Qhf  2284B1

Qhf

Qhf

1176B4  Qhf

Qhf

B2

H2O

594B2  af

H2O  af

2596B

Qhb  Qhb  595B5

1652B1

1077B  1651B1

503B4

165  B2

532B2

1765EB1  1103EB4

Qhf  438EB2

495EB1

3795B4

1050B3

Qhf

Qhf
1518B4

2028B5

1280EB2  Qf  2084B3

439B1

Qhff

428B1

Qhf

37218B3

Qhf  Qf

366B7

359B2

Qoa

58  ac

604B1  583B6

58 B11  966B20

Qpf

549B6

Qhf

34B1

10  B3

2192B2

397B2

Qpf

Qhf

1936B3

Qpf

2352B1

B

Qht

Qhc

37° 15'

122° 00

Milpitas base map prepared by the U. S. Geological Survey , 1961, photorevised19
Calaveras Reservoir base map prepared by the U. S. Geological Survey, 1961, pho
San Jose East base map prepared by the U. S. Geological Survey, 1961, photorevi
San Jose West base map prepared by the U. S. Geological Survey, 1961, photorev

Quaternary Geologic maps of the Milpitas, Calaveras Reservoir, San Jose East and
modified from Witter et al. (2006)

Legend

Qhc

3741B

2240B1

Qhc

1245B1  1245B3
245B8
Qhf

354B1
Qhty

1313B1

Qhf

1820B1

37361B

N110_1B1

Qhf

ac
B
Qhf

2O

Qhty

37133B1

Qhl

Qhl

Qhl

295B4
37416B6
Qhff

286 4
Qhf

Qhff

1659B3
Qhl

455EB1

Qhl

2 3B1

2426B1

Qhl

235B3
Qhty

Qpf

Qhc
Qpf

Qhl

Qhty
2 1
Qhl 51 Qhty
2698B3

Qpf

J14Q_1B1

1308B1

Qhty 270
H2O

Qhc

1673EB4

Qhf

Qhty

Qhty  3741

3750 B3

H2O

Qhf
ac

Qhf

H2O
1510B1
Qhty

1123EB7
Qpf

166 B1

98B1

3748 B1
Qhf

1420EB

Qh
Qhty

Qhty

# Index Map of the North

N
W
S

# Northern Santa Clara Valley, California

Qhf
Qoa
354B1
Qht
366B7
Qhf
359B2
362B3
Qht
Qhc
2240B1
ac
Qhty
7361B7
1327EB1
1029B3
1008B1
af
2310B4A
1485B7
Qhty
af
H2O
Qhty
Qhl
1416B4
H2O
1906B6
311B2
Qhc
1432B1
H2O
2676B1
Qhty
Qhf
295B4
1987B1
Qhl
37416B6
H2O
Qhff
Qhc
1659B3
270B1
Qhty
253B1
244B4
145DH2
Qhl
Qhl
Qhff
1925B1
2206B3
Onf
235B3
37441B1
1530B1
Qhf
253B3
Qhc
Qhl
2404B1
Qhty
H2O
251B1
H2O
2698B3
Qhf
225B1
2708B1
Qhc
37414FB1
1578B1
1560B3
Qhty
37414G
Qhf
H2O
199B3
1693B1
1510B1
37484B2
1773EB3
Qhly
98B1
153B1
Qhff
60B1
Qhc
Qhl
Qhty

**N / W / E / S** (compass rose)

0 — 1 (scale bar)

Milpitas

Qhf

Qoa

36283

ac

Qhc

2224B2

Qha

Qpf

1221B1    1065B2
              Qf

H2O

Qha

H2O

H2O

H2O

Qha

Qhc

Qht

Qht

H2O

Qha

Qhc

Qht

Qhty

Qhc

Qht

Qhty

Qht

Qhf

Qnf

Qht

Qht

1925B1

Qhf

236B3    Qht

Qhl

2404B1

214B6

2708B1

1578B1    3734B3    Qhl

Qhl

Qhty

Qhf

Qhf    2104B10    1953B1    H2O

199B3    1683B1    Qhtv

Qhtv

af    H2O    Qhty    Qht

37° 15'

121° 45'

# California

```
0        1        2        3        4        5
|_____|_____|_____|_____|_____|
        Kilometers
```

| Milpitas | Calaveras Reservoir |
| --- | --- |

37° 15'

122° 00

Milpitas base map prepared by the U. S. Geological Survey , 1961, photorevised19
Calaveras Reservoir base map prepared by the U. S. Geological Survey, 1961, pho
San Jose East base map prepared by the U. S. Geological Survey, 1961, photorevi
San Jose West base map prepared by the U. S. Geological Survey, 1961, photorev

Quaternary Geologic maps of the Milpitas, Calaveras Reservoir, San Jose East and
modified from Witter et al. (2006)

Legend

| | |
|---|---|
| • | Borehole location |
| I6Q_1B1 | Boring name |
| ▬▬▬ | Section line location |
| THESIS XSEC | Section line label |
| ——— | Geologic map unit boundary |
| Qhff | Geologic map unit name (see Table 1 in text for explanation) |
| ▨ | bedrock |
| ▬▬▬ | Faults |
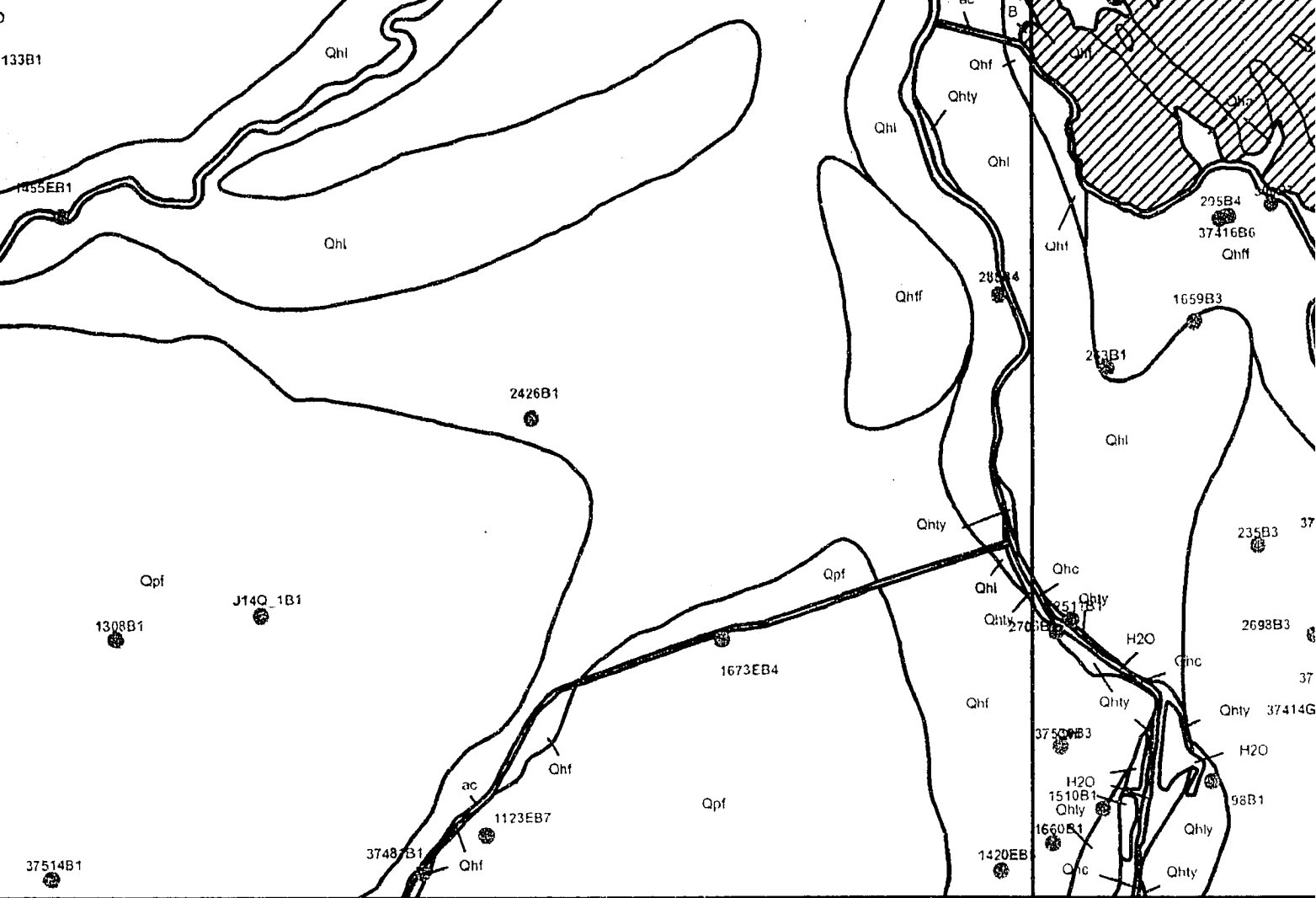
**Index Map of the North**

1980.
...otorevised 1980.
...vised 1980.
...evised 1980.

...d San Jose West Quadrangles

N
W — S

# nern Santa Clara Valley, California

Qhf
H2O
1906B6
2676B1
1432B1
Qhty
Qht
1987B1
Qhc
Qhty
Qht
H2O
Qhty
Qht
Qhf
270B1
244B4
Qhl
Qnl
245DH1
ac
Qhff
Qhf
1925B1
236B3
Qht
37441B1
2206B3
254B3
Qhf
1530B1
Qhf
Qhl
Qhf
H2O
2404B1
21B6
Qhf
225D1
2708B1
37414FB1
1578B1
37343B3
Qnl
514G
Qhl
37484B2
204B1
199B3
1953B1
1773EB3
Qhf
2104B10
193B1
Qhf
1683B1
H2O
Qhl
Qhff

0          1          2
K

E

| Milpitas | Calaveras Reservoir |
|---|---|
| San Jose West | San Jose Ea |

Qht
H2O
Qhc
Qhfy
Qhf
Qht
Qhl
Qht
Qhf
Qht
Qhl
Qhl
Qhty
Qhty
Qhty
Qhf
H2O
af
H2O
Qhty
Qhf

1925B1
25?B5
2404B1
236B3
2?4B6
2708?1
1578B1
37318B3
2104B10
1953B1
199B3
1683B1

37° 15'

121° 45'

# California

| 0 | 1 | 2 | 3 | 4 | 5 |

**Kilometers**
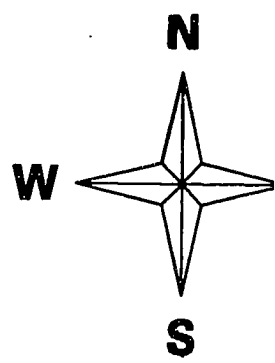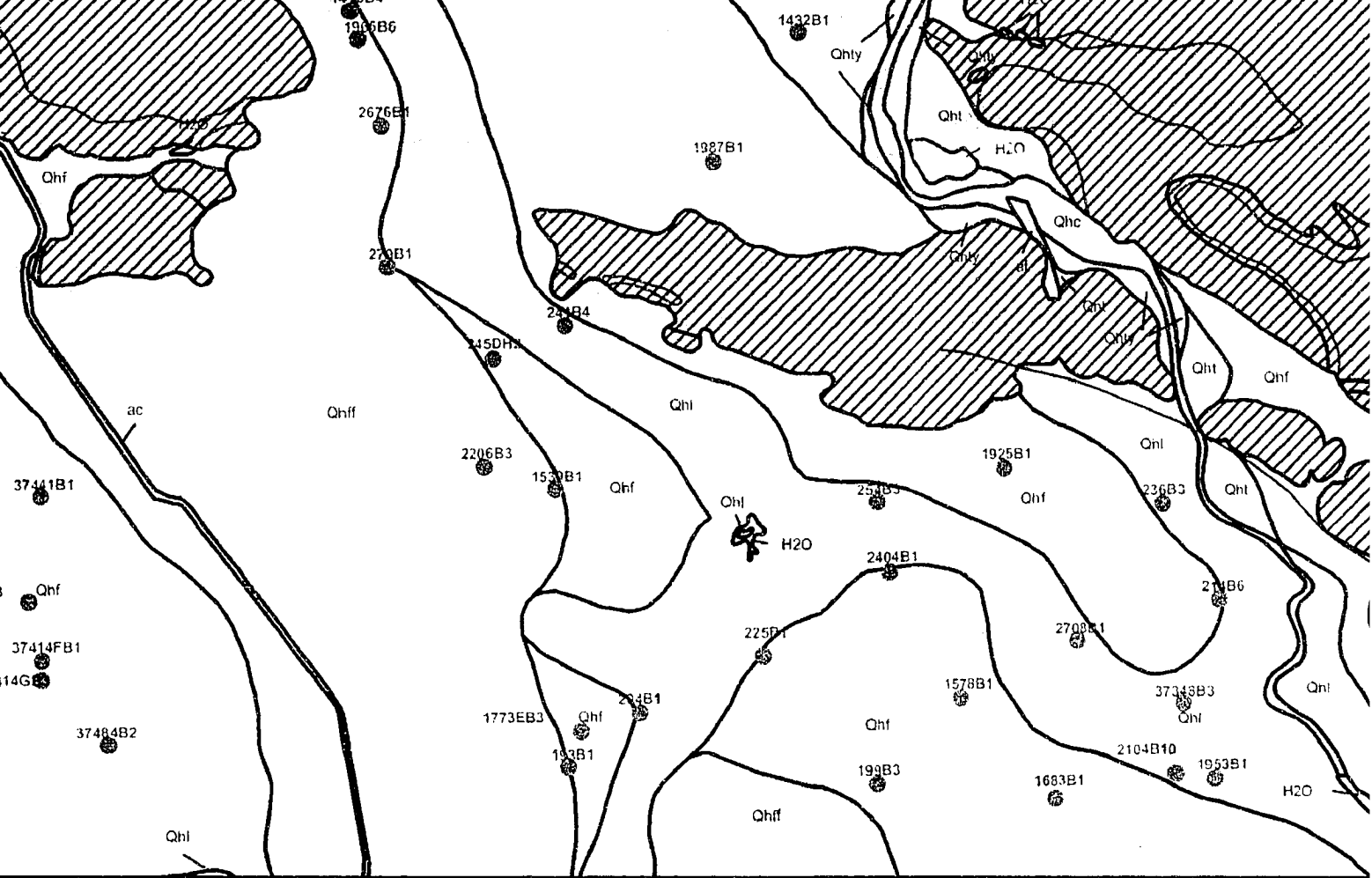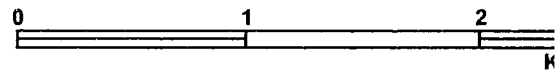
| Milpitas | Calaveras Reservoir |
|----------|---------------------|
| San Jose West | San Jose East |
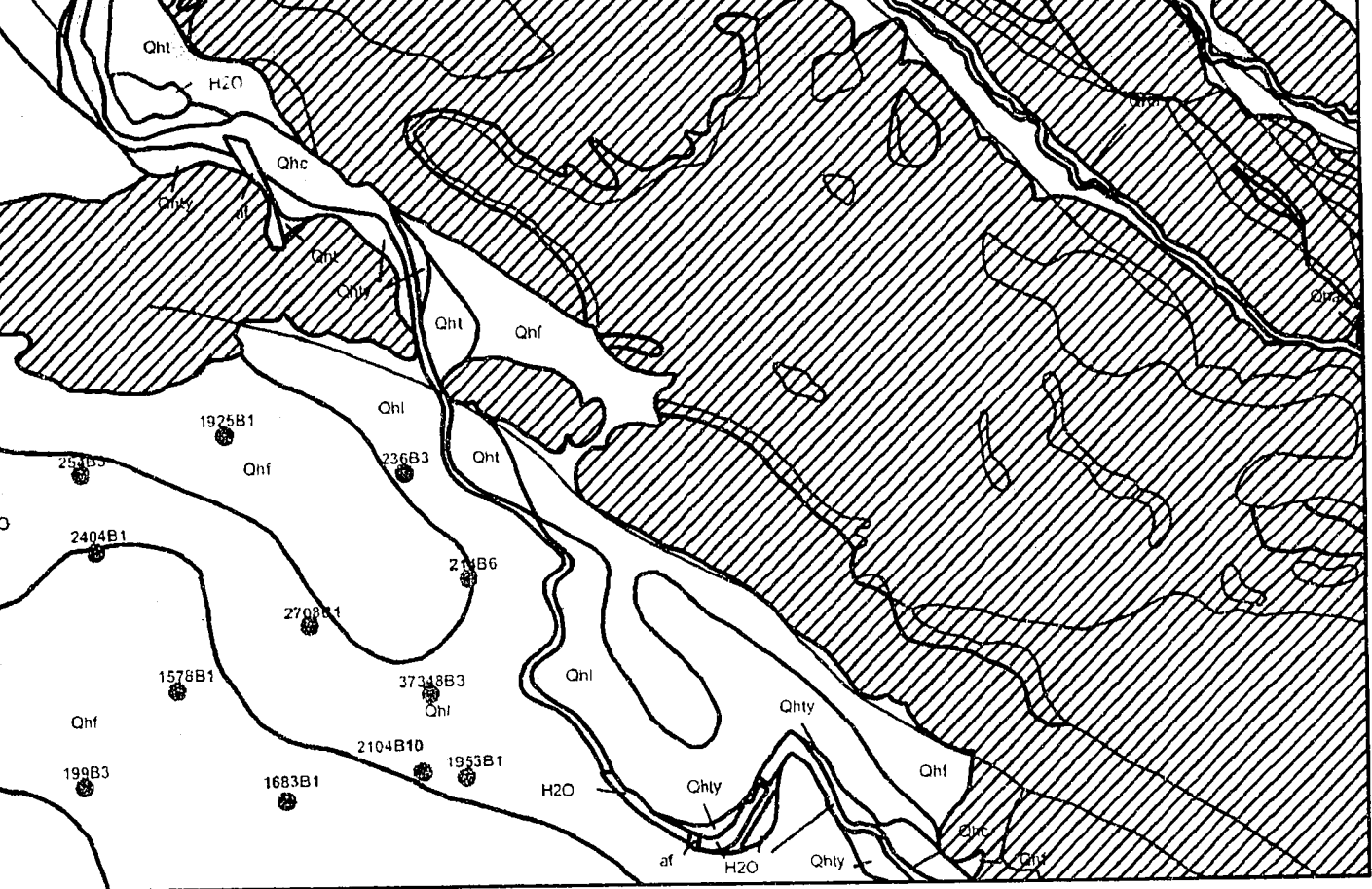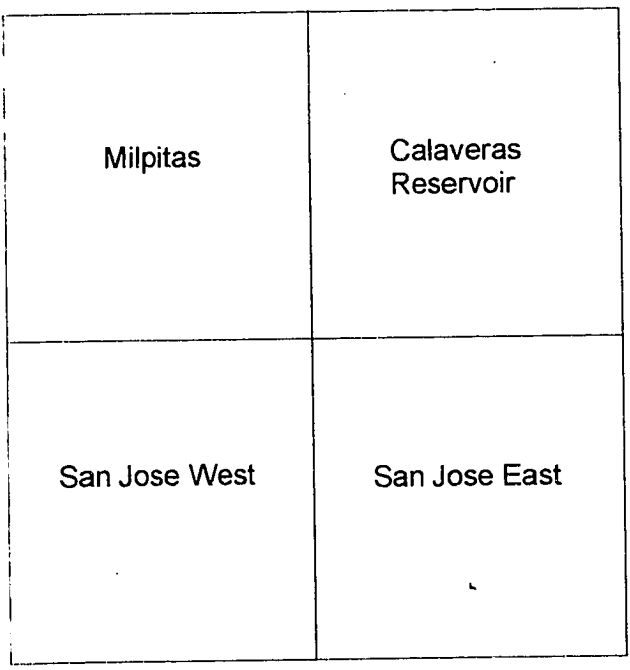
THESIS PLATE 1 - Index Map
Anne Rosinski

# NOTE TO USERS

Oversize maps and charts are microfilmed in sections in the following manner:

# LEFT TO RIGHT, TOP TO BOTTOM, WITH SMALL OVERLAPS

This reproduction is the best copy available.

N

Qhbm

Qhbm

H2O

Qhbm

Qhbm

Qhbm

Qhbm

Qhbm

alf

Qhbm

Qhbm

Qhbm

Qhbm

alf

Qhbm

Qhbm

Qhbm

Qhbm

Qhbm

Qhbm

alf

Qhbm

H2O

Qhbm

Qhbm

Qhbm

alf

Qhbm

H2O

Qhbm

H2O

alf

Qhbm

Qhfe

Qhbm

alf

alf

alf

H2O

Qhbm

alf

48

alf

Qhfe

Qhbm

afbm

Qhbm

Qhbm

afbm

alf

Qhbm

Qhbm

Qhbm

Qhbm

Qhbm

Qhbm

ac

Qhfe

Qhf

Qhfe

Qhfe

H2O

Qhfe

H2O

H2O

afbm

H2O

H2O

H2O

H2O

Qhbm

Qhbm

Qhfy

Qhff

af

H2O

151

H2O

Qhfe

Qhbm

Qhff

H2O

Qhly

ac

alf

148

afbm

Qhbm

Qhly

ac

Qa

Qpa

Qpa

Qpa

H2O

Qha

Qa

Qpa

Qa

Qa

151

ac

**A**

121° 45'

37° 30'

H2O

Qa

Qa

Qha

Qoa

Qoa

Qa

Qoa

Qhbm    Qhfe    Qhly

alf    alf    Qhfe    alf

H2O    alf    Qhbm    afbm    Qhff

148    alf    Qhfe    H2O

148    Qhfe    Qhff    149

alf    afbm    Qhfe    Qhfy    Qhly

Qhbm    152    149

alf    Qhbm    af    Qhfy    151    149    150    Qhf

Qhbm    51B    af    Qhff    Qhfy

alf    afbm    148 Qhty

alf    Qhbm    Qhff

alf    Qhbm    af

H2O    Qhff    Qhfe    Qhff    alf

af    Qhff    H2O    Qhc    Qhfy

H2O    alf    Qhc    Qhty

af    Qhty

Qhfy    Qhff    Qhty

152

H2O    Qhty

**Guadalupe River**

Qhff    Qhff    Qhff

alf    alf    H2O    Qhly    Qhly

Qhff    Qhff    alf    alf

ac    Qhfy    51D

Qhfy    Qhff    ac

Qhf    ac    Qhf    af

Qhc    Qhff    alf

Qhf    Qhf    Qhc

Qhff

Qhff    Qhff    Qhf

Qhff

ac

Qhly

Qhly 5 C

Qhff

ac

150 149

151

Qhfy

Qhf

Qhly

149

Qhl

Qhf

Qhc

alf

alf

Qhly

Qhf

Qhly

Qhty

ac

153

Qhf

af

Qhly

Qhl

Qhf

af

af

Qhty

af

Qhly

Qhly

155 Qhc

Qhty

Qhf

Qhl

Qhly

Qhf

Qhl

Qhly

Qhly

Qhf

Qhc

Qhl

Coyote Creek

af

Qhl

af

Qhf

Qhc

149

Qhly

alf

Qhly

Qhf

Qhl

alf

af

Qhly

af

af

af

Qhly

Qhf

Qhf

No ground failure repo

ac

af

Qhty

Qhl

Qhff

Qhly

Qhc

Qhc

f

Qhc

Qhf

Qr

Qhf

Qhf

Qoa

Qa

B

Qa

Qhf

Qpf

Qhf

Qpf

Qhc

Qhf

B

Qa

Qpf

Qhf

Qhf

Qpf

Qhf

186

ground failure reported along the length of this line

Qhff

Qhf

Qhf

Qhf

ac

Qhff

alf

Qht

ac

Qhf

af

Qhf

Qhf

Qhl

ac

Qhl

Qht

Qhl

Qhc

Qhl

gq

Qhf

gq

Qht

Qhf

Qhl

Qhl

Qhf

Qhf

H2O

Qhl

Qhc

Qhc

alf

af

Qhly

Qhf

af

af

af

Qhly

51E

ac

Qhly

Qhff

Qhl

**Creek**

af

Qhl

Qhl

Qhty

Qhl

**No ground failure rep**

ac

Qhff

Qhl

153

Qhl

Qhf

Qht

Qhl

Qht

Qhl

Qht

Qhf

Qhf

Qhf

157

Qht

Qhl

Qhc

Qhl

158

Qht

Qhl

Qhl

Qhff

Qhl

gq

Qhl

Qhf

ac

Qhl

Qhf

Qhc

gq

Qhc

Qhf

Qhc

Qhf

Qhty

Qhf

Qhl

Qhl

ac

B

Qhf

Qhl

Qhty

Qhl

ground failure reported along the length of this line

Qhff
Qhc
Qhf
Qpf
ac
Qhf
Qhff
Qhf
Qhff
Qhl
Qhf
Qhl
Qhff
Qhf
Qhl
H2O
af
af
H2O
Qhb
Qhb
Qhf
Qhff
Qhl
Qhf
Qht
Qhf
Of
Qht
Qhty
Qhf
Qht
Qf
Qht
Qhff
Qhty
Qpf
Qhff
Qht
H2O
Qhty
Qhf
Qoa
Qhf
ac
Qht
Qhty
Qht
Qhc
H2O
Qht
af
Qhty
af
H2O
Qhty
Qhc
H2O
H2O
Qhty

Qhf

Qhc

ac

Qhf

Qhf

Qpf

Qhf

Qa

Qhl

Qhl

H2O

H2O

af

af

Qpf

Qhb

Qhb

Qhf

Qpf

Qhf

Qf

Qpf

Qhf

Qf

Qhl

Qf

Qhff

Qpf

Qhf

H2O

Qhf

Qhf

Qoa

Qht

Qpf

Qhc

ac

Qhl

Qpf

Qhc

Qha

Qhf

H2O

Qpf

Qhty

af

af

H2O

H2O

Qf

Qhty

Qhty

Qhc

H2O

Qha

Qhty

Qha

Qhc

Qhc

Qhty

Qhc

Qhc

Qht

H2O

Qpf

Qhc

Qht

Qhf

H2O

Qht

Qht

Qht

Qht

Qhty

Qpf

Qht

H2O

Qpf

Qa

Qht

Qhf

Qht

Qa

Qhf

Qa

Qhty

Qhc

Qht

Qpf

Cht

Qht1

Qhty

Qpf

Qht1

Qt

37° 15'

122° 00'    Milpitas base map prepared by the U. S. Geological Survey, 1961, photorevised 1980.
Calaveras Reservoir base map prepared by the U. S. Geological Survey, 1961, photorevised 1980.
San Jose East base map prepared by the U. S. Geological Survey, 1961, photorevised 1980.
San Jose West base map prepared by the U. S. Geological Survey, 1961, photorevised 1980.

**REFERENCE:**
Quaternary geologic maps of the Milpitas, Calaveras Reservoir. San Jose East and San Jose West
Quadrangles modified after Witter et al., (2006)

Historical ground failure data from Youd and Hoose, 1978; Tinsley, 1998; Knudsen et al., 2000.

| Milpitas | Calaveras Reservoir |
|---|---|
| San Jose West | San Jose East |
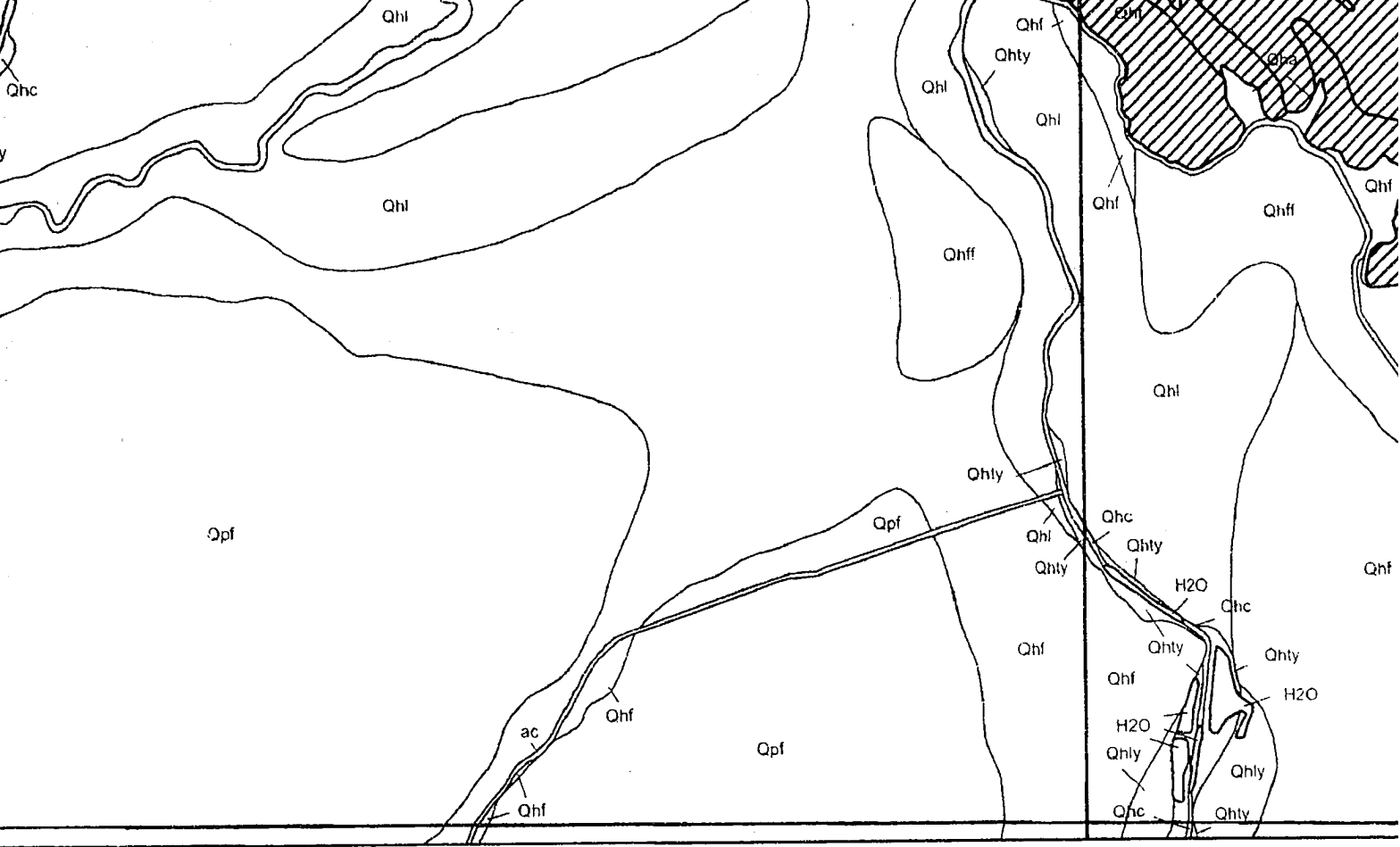
THESIS PLATE 2 - Historical Ground Failure, Anne Rosinski, 2007

Qhc

Qhl

Qhty

Qhl

Qhl

Qhl

Qhf

Qhff

Qhff

Qhl

Qpf

Qpf

Qhly

Qhc

Qhl

Qhty

Qhty

H2O

Qhc

Qhf

Qhf

Qhty

Qhf

Qhty

Qhf

H2O

Qhf

ac

H2O

Qhly

Qhf

Qhly

Qhc

Qhty

Qhf

# Historical Ground Failur

**Scale**

0      1      2      3      4

**Kilometers**

**N**

**W** — **E**

**S**
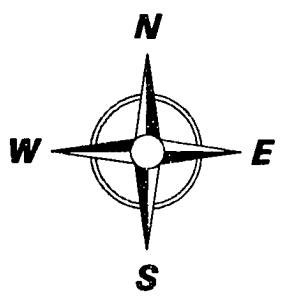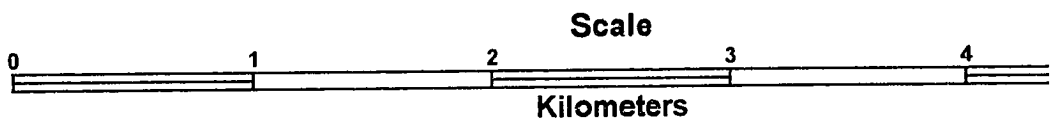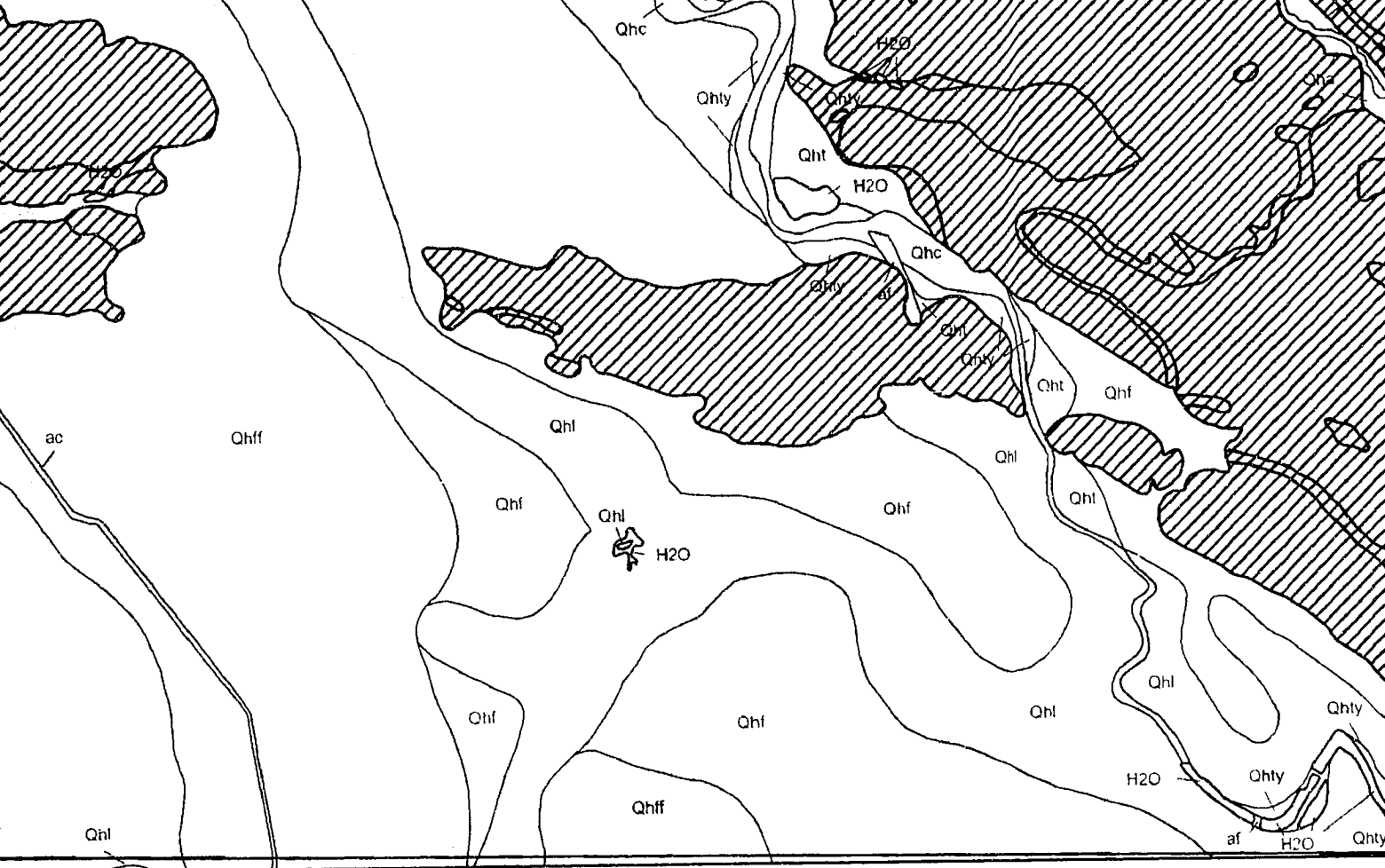
**Legend**

— Geologic map unit boundary

148  Ground failure site number (see Appe

Absence of ground failure reported

▲ Disturbed well

► Lateral spread

● Sand boil

✖ Settlement

Qhff  Geologic map unit (see Table 1 in te

H2O

Bedrock

Qhc

Qhty

Qht

H2O

H2O

Qhc

Qhty

af

Qht

Qhf

Qhl

Qhl

Qhf

Qhl

Qhl

Qhl

Qhl

Qhty

Qhf

Qhff

Qhl

H2O

H2O

Qhty

Qhty

af   H2O   Qhty

Qha

Qha

121° 45'

37° 15'
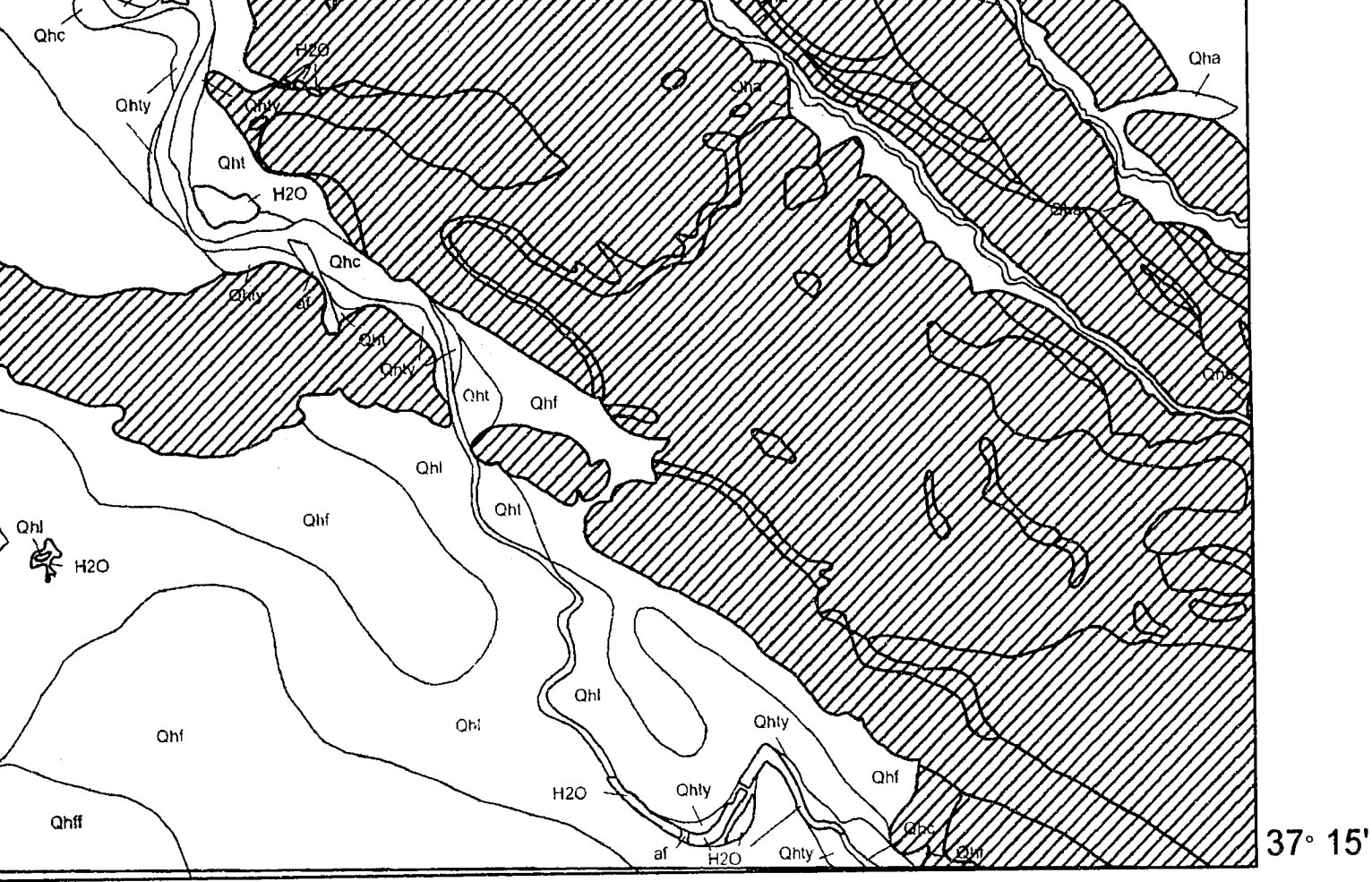
## Legend

——— Geologic map unit boundary

148    Ground failure site number (see Appendix 4 for details)

Absence of ground failure reported

▲    Disturbed well

►    Lateral spread

●    Sand boil

✖    Settlement

Qhff    Geologic map unit (see Table 1 in text for explanation)

H2O

Bedrock

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WEST

19.630655,34.7525

tion in feet
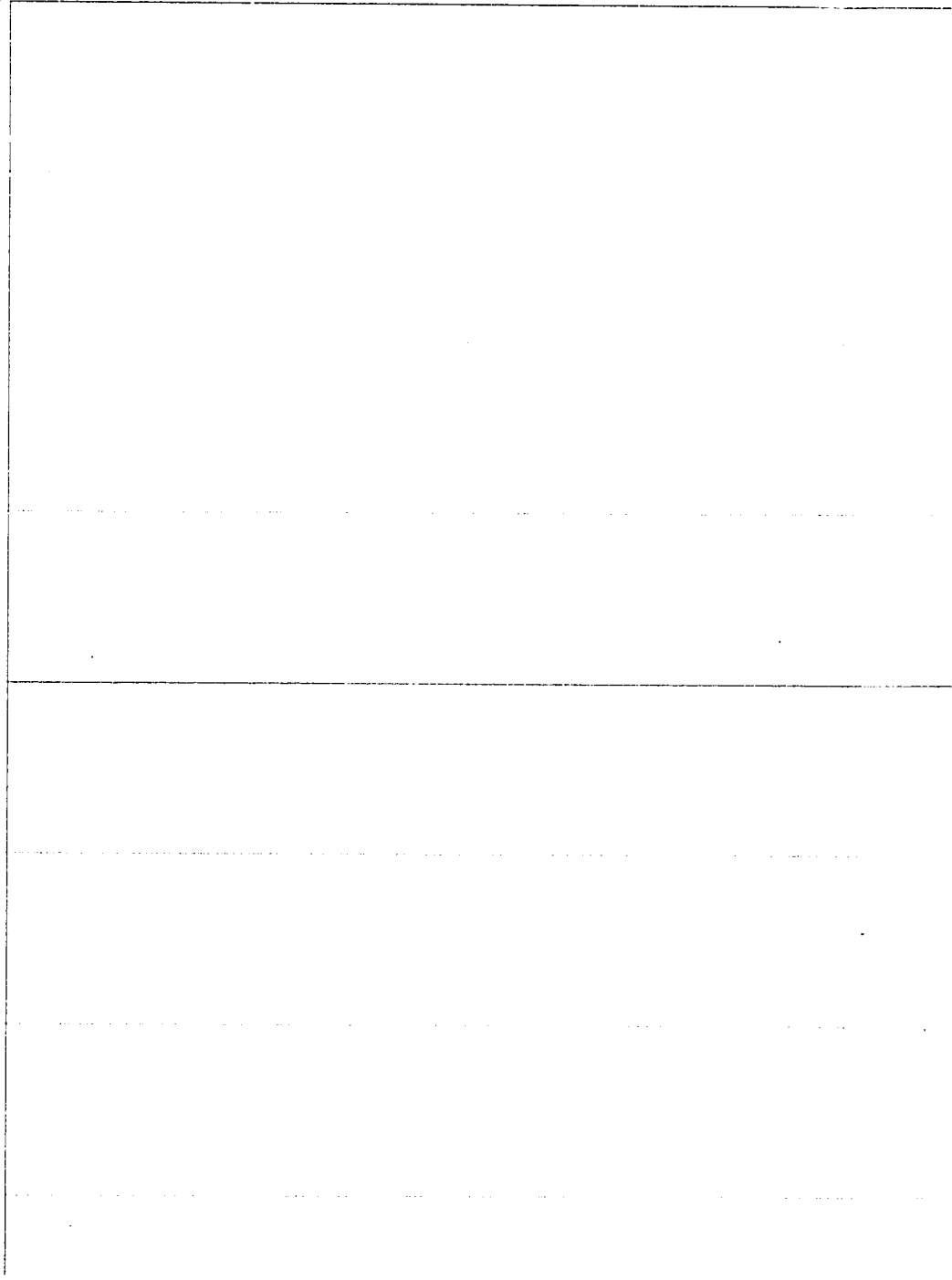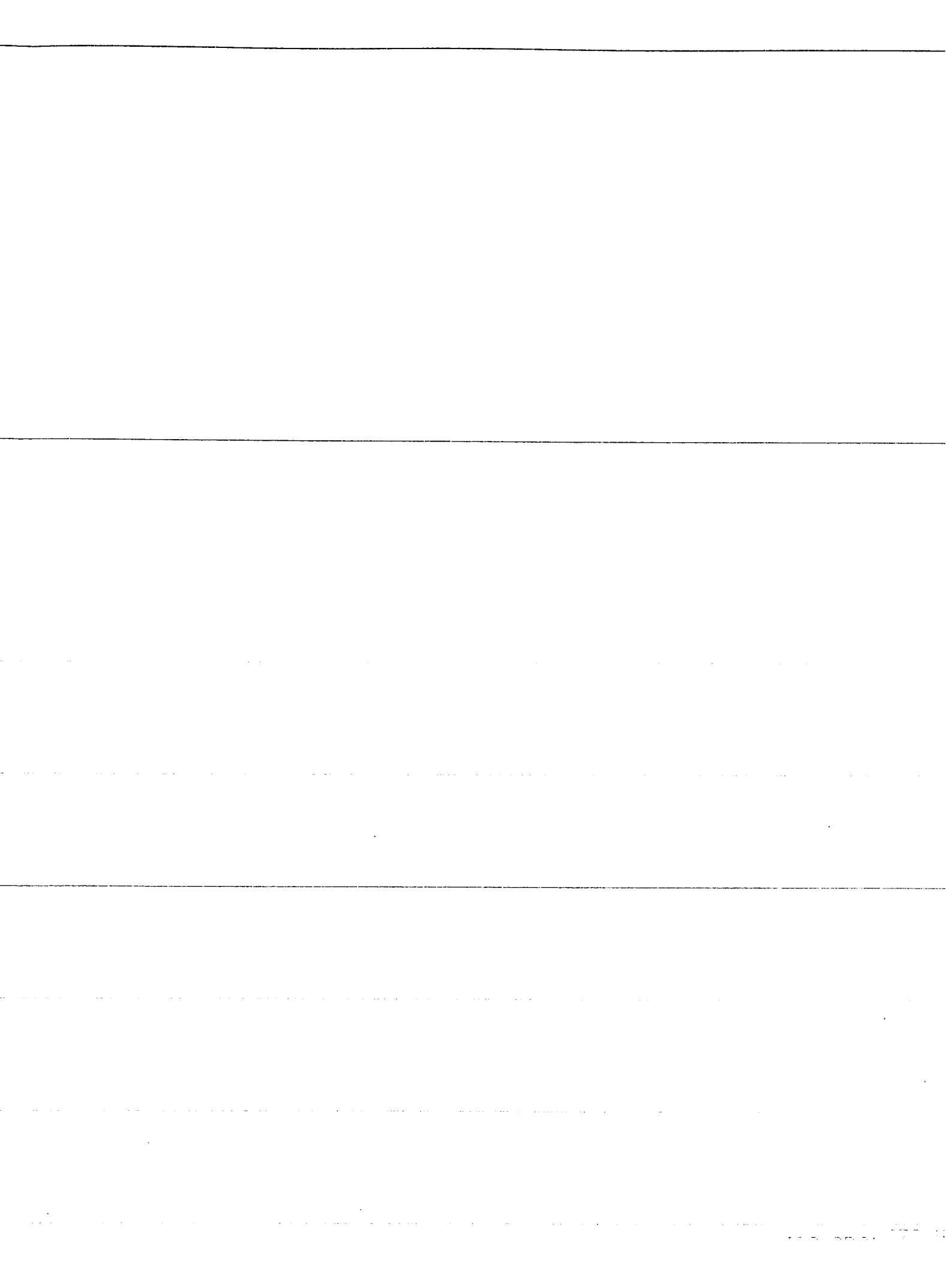
Coyote Creek

Highway 880

Southern Pacific Rail Road

Approximate ground surface elevation
Note that borings are projected to
cross section line, and therefore, the
top of the boring may not correspond to
ground surface.

Southern Pacific Rail Road

North Main Street

N160-20 N160-17
DD107
N160-22
DD117  Qhf
N160-20  CH

af
CL

af
CL
af
N160-8  ML-CL
DD100
G200-68 N160-11
N160-13
N160-10

Qhf
CL

af
CL

N160-11  Qhf
CL

N160-54 N160-46

N160-39 N160-33

N160-63

N160-61 N160-60

N160-61

af
CL

17
07
23
17
20

Qhf
CH

Qhf
CL

af
CL

Qhf
CL

N160-8
DD80

N160-15

af
CL-CH N160-17 N160-14

N160-24 N160-21

Qhf
CL

N160-8

Qhf
CH

N160-15 N160-13

Qhf

N160-15 N160-13

N160-3
DD88

Qpf
CL

of
GP
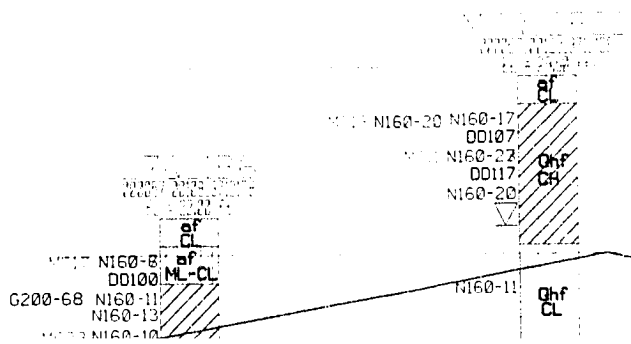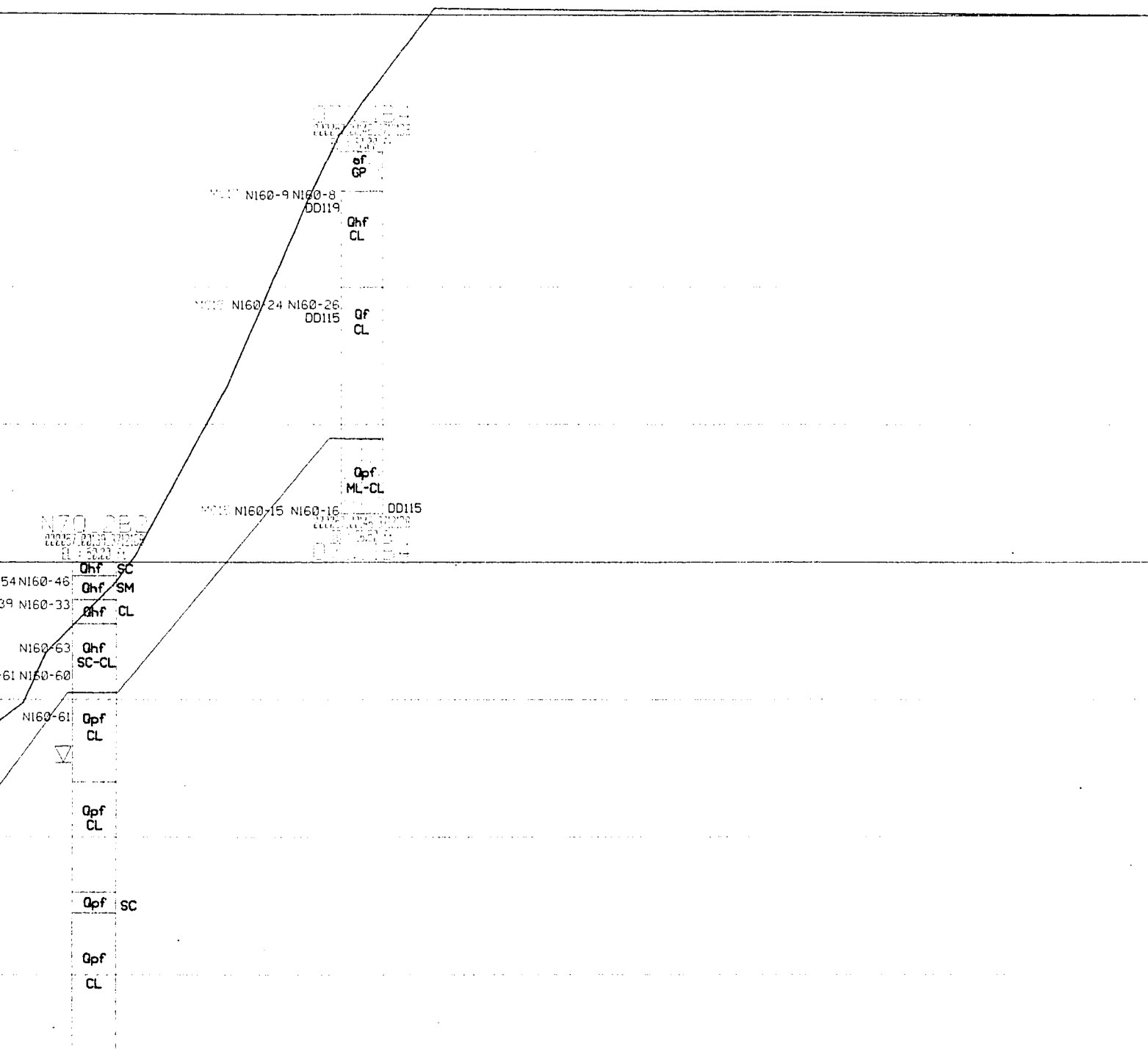
N160-9 N160-8
DD119

Qhf
CL

N160-24 N160-26
DD115

Qf
CL

Qpf
ML-CL

N160-15 N160-16 DD115

Qhf SC

54 N160-46 Qhf SM

39 N160-33 Qhf CL

N160-63 Qhf
SC-CL

61 N160-60

N160-61 Qpf
CL

Qpf
CL

Qpf SC

Qpf
CL

EAST

Elevation

N160-13 N160-13
DD110

**of
CL**

N160-17 **of**
DD113 **CL-ML**

N160-17
DD120

N160-30
DD113

N160-2
DD109

N160-26
DD111

N160-28
DD112

N160-1
DD105

N160-32
DD113

N160-6 **Qhly**
DD98 **CL-ML**

N160-
DD98

N160-19
DD118

**Qhly
CH**

N160-9
DD97

N160-
DD9

N160-6 **Qhfe
DD82 CL-ML**

N160-14

**Qhly
CL-CH**

N160-1
DD10

N160-19

N160-14

N160-

N160-7 **Qhly. SM**

N160-1

? ? ?

af
CL-ML

af
CL-ML N160-29
DD122

af
ML-CL

N160-31
DD114

N160-23
DD106

Qhly
CL N160-14

DD106

N160-13
DD107

Qhly
CL

Qhly
ML N160-11
DD112

Qhf SM N160-7

af
SP

af
CL

Qhly
CL

Qhf
CL N160-6
DD89

N160-15 N160-13
DD110

Qhfy
CL

N160-11
DD86

Qhff CL

Qhly
SM N160-10

N160-22

Qhff
CL

N160-10
DD94

Qhly
CH

Qhly
CL

G200-40

N160-13
DD108

N160-8
DD105

Qhf
CL

N160-12

Qhfy N160-15
CL DD105

Qhly
CL-CH

N160-12

N160-24

N160-13 DD90

N160-9

Qhf
CL

Qhly
CL

Qhf
SC N160-5

Qhff
CL

G200-38

N160-10
DD99

Qpf
SW-SP

N160-5

G200-40

N160-20
DD115

Qhf
SP-SM N160-9

N160-46
DD111

Qpf
SW-SP

G200-8

Qpf
CL N160-17

N160-9

Qpf
CL

N160-8

DD107
N160-23 Qhf
DD117 CH
N160-20

af
CL
af
N160-8 af
DD100 ML-CL
G200-68 N160-11
N160-13
N160-10
DD100 Qhf
CH
N160-11 Qhf
CL

N160-30 Qhf
DD119 SC
G200-20

N160-7 Qhf
DD107 SC-CL
G200-52

N160-19 Qhf
G200-60 CL

N160-13 Qhf
DD120 SC
G200-26

N160-14
DD115

N160-15 Qhf
DD115 CL

Qpf
CL

N160-12

N160-10
G200-60

N160-8
DD112

DD111

N160-12 Qpf
DD116 SC
G200-33

N160-7

Qpf
CL

Top of Pleistocene inferred f

(actual stratigraphic boundary

| | |
|---|---|
| 212757,222223,3/1209 | Official Boring Name |
| 73 18 | Alternate Boring Name |
| TD 41.52 ft | Total depth of boring |
| **Qhfy** | Stratigraphic Unit - See Appendix 1 for layer description |
| **ML** | Lithology (USCS) |
| N160-11 | Penetration Resistance |
| M113 | Moisture Content (%) |
| DD136 | Dry Density (pounds per cubic foot) |
| G200-38 | Grain Size Analysis (percent of silt and clay particles finer than 0.074 m |
| ▽ | Water Level Measured In Boring |
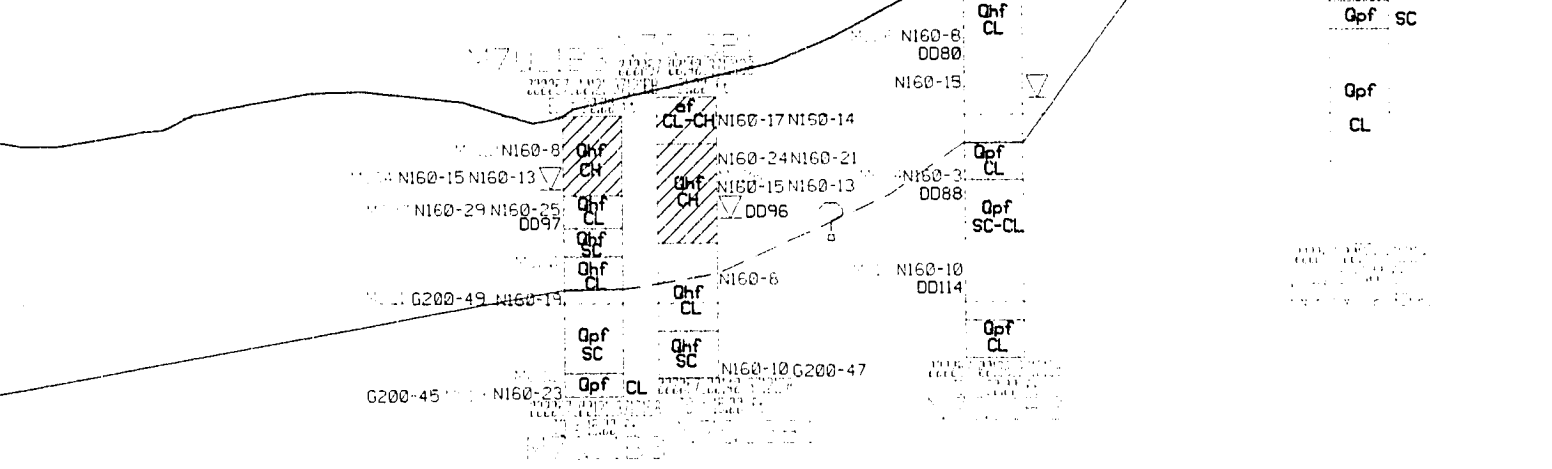
N160-8 Qhf CL

Qpf SC

N160-8 DD80

N160-15

Qpf CL

Qf CL-CH N160-17 N160-14

N160-8 Qhf CH

N160-15 N160-13

N160-29 N160-25 DD97

Qhf CL

Qhf SC

Qhf CL

N160-24 N160-21

Qhf CH

N160-15 N160-13 DD96

Qpf CL

N160-3 DD88

Qpf SC-CL

G200-49 N160-19

Qhf CL

N160-6

N160-10 DD114

Qpf CL

Qpf SC

Qhf SC

N160-10 G200-47

G200-45 N160-23 Qpf CL

from geotechnical properties

ry may differ)

Feet

et

THESIS PLATE 3 — Cross
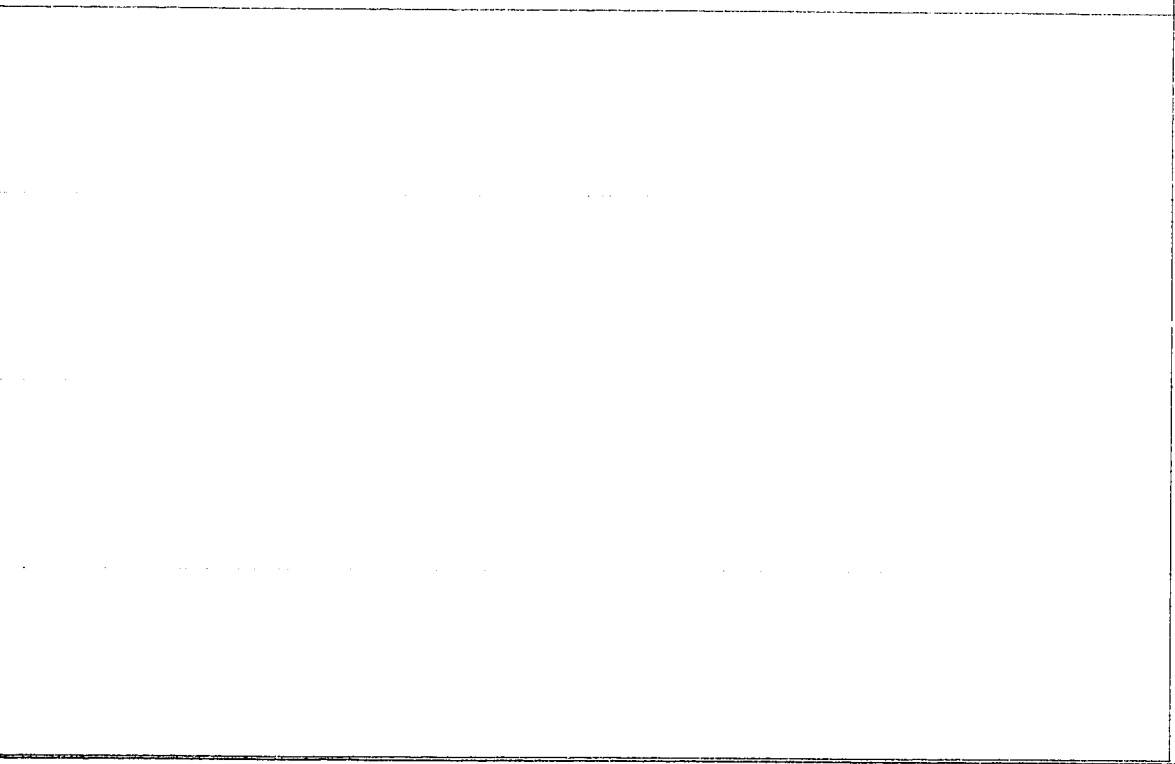
SIS PLATE 3 — Cross Section

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GUADALUPE R

RIVER

CREEK

20
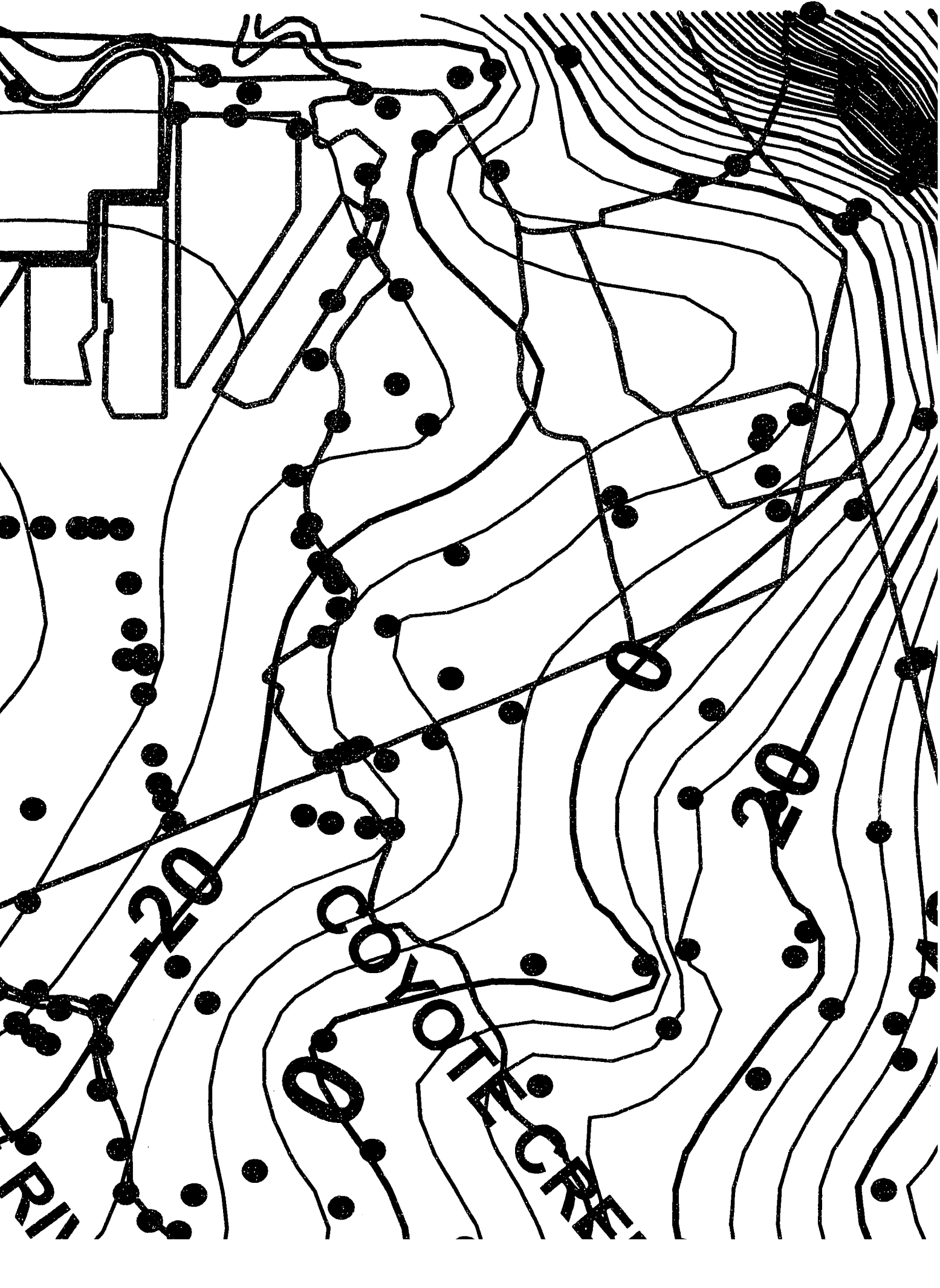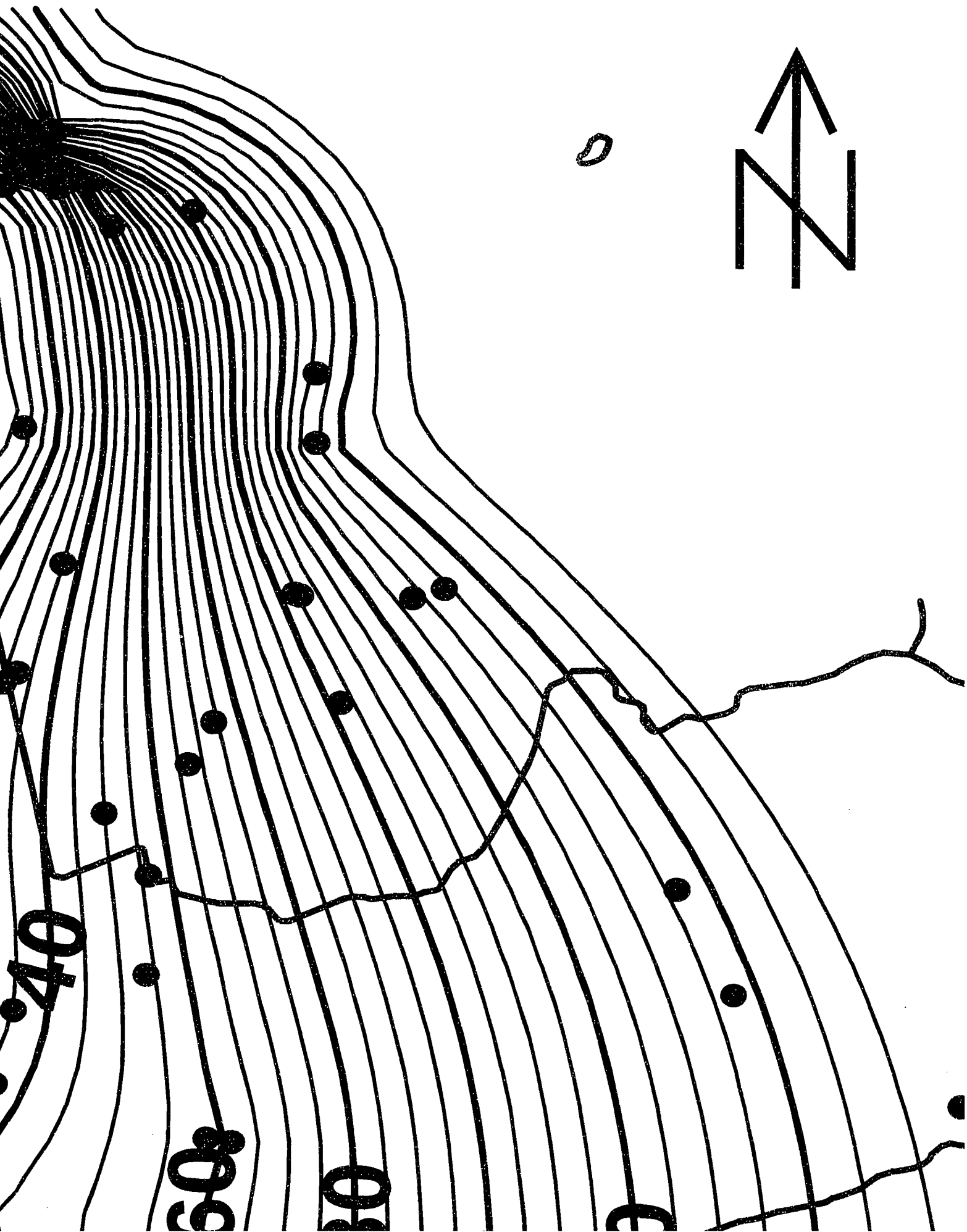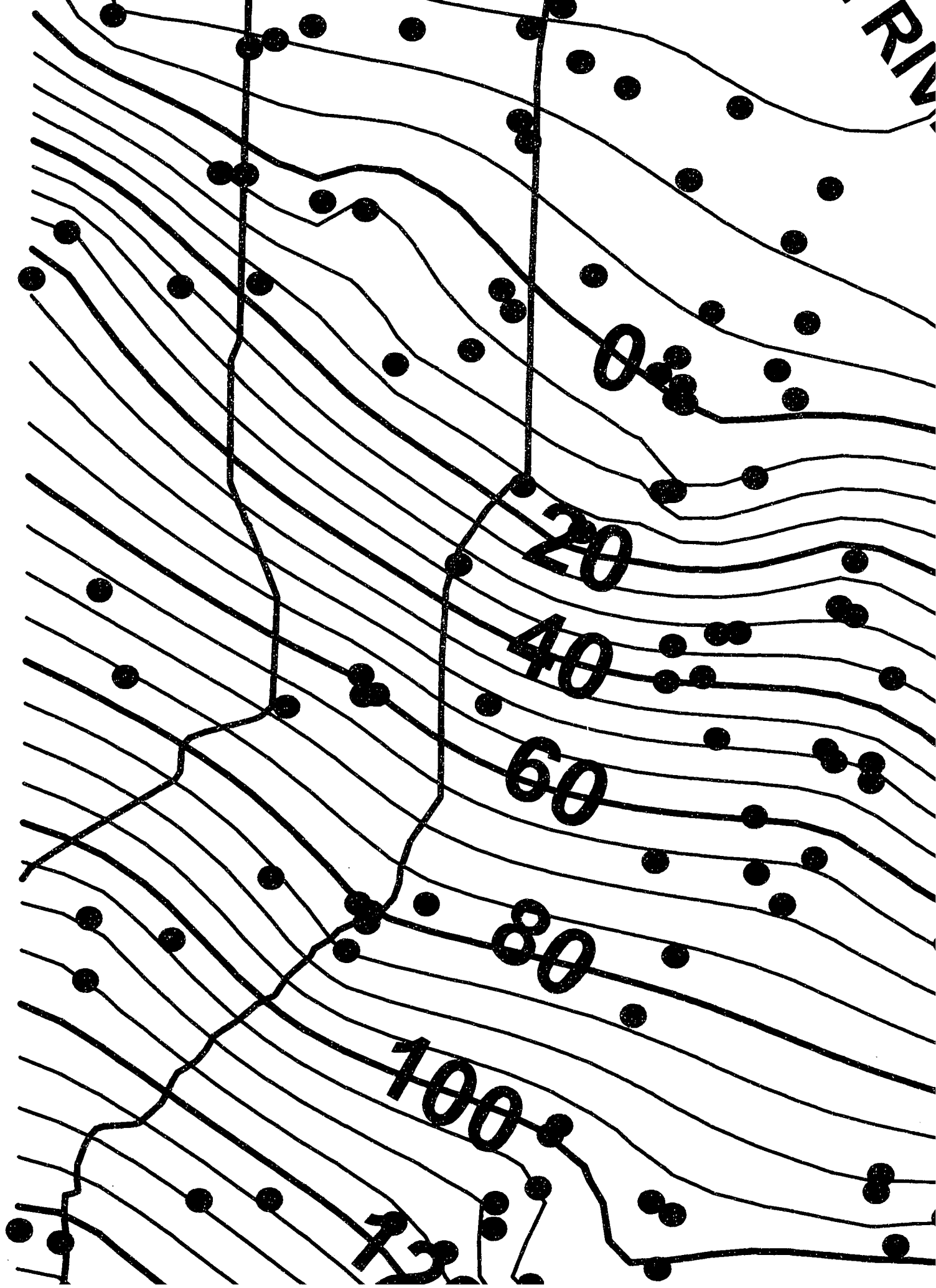
120

# SCALE IN KILOMETERS

0     1     2
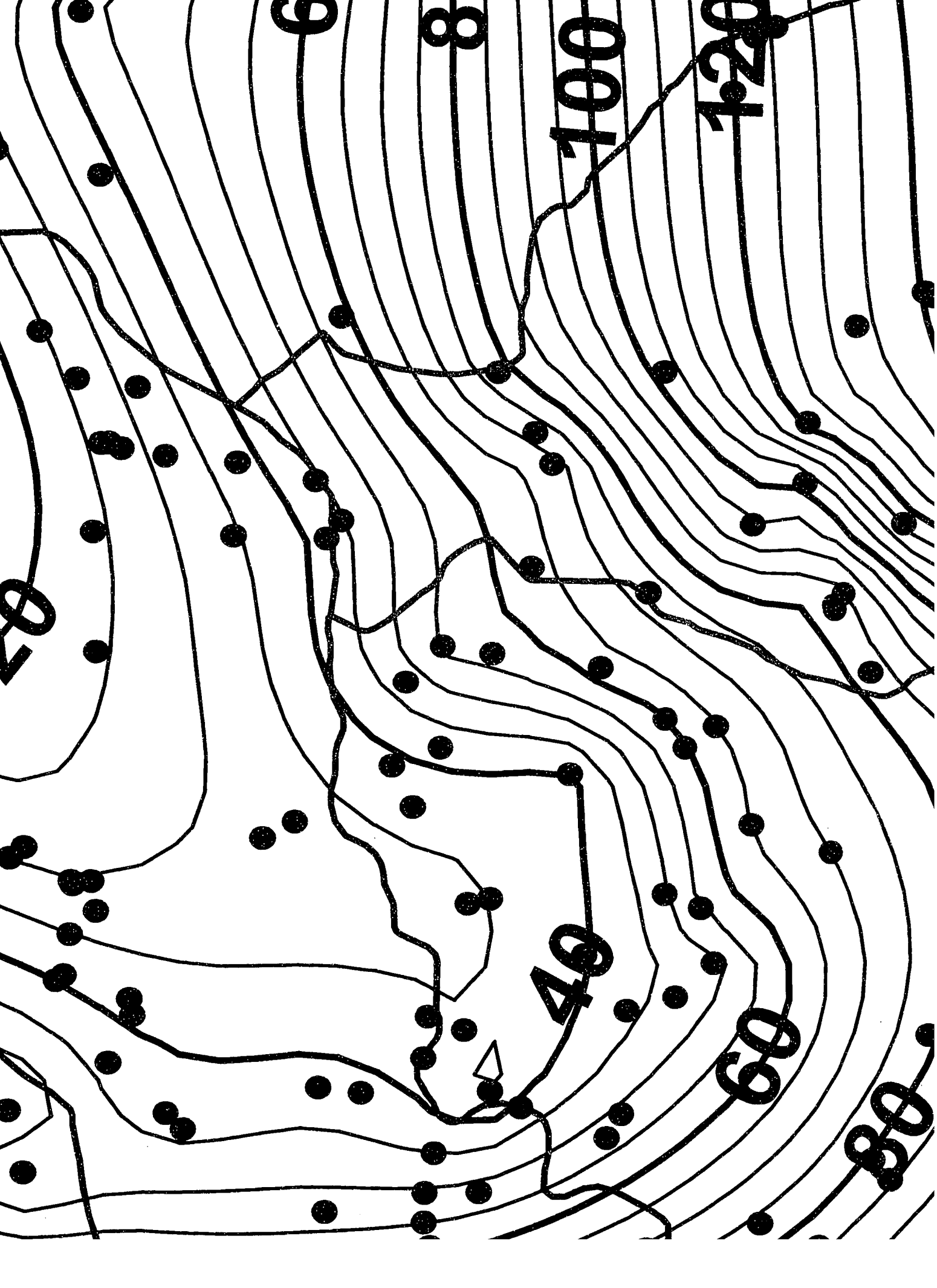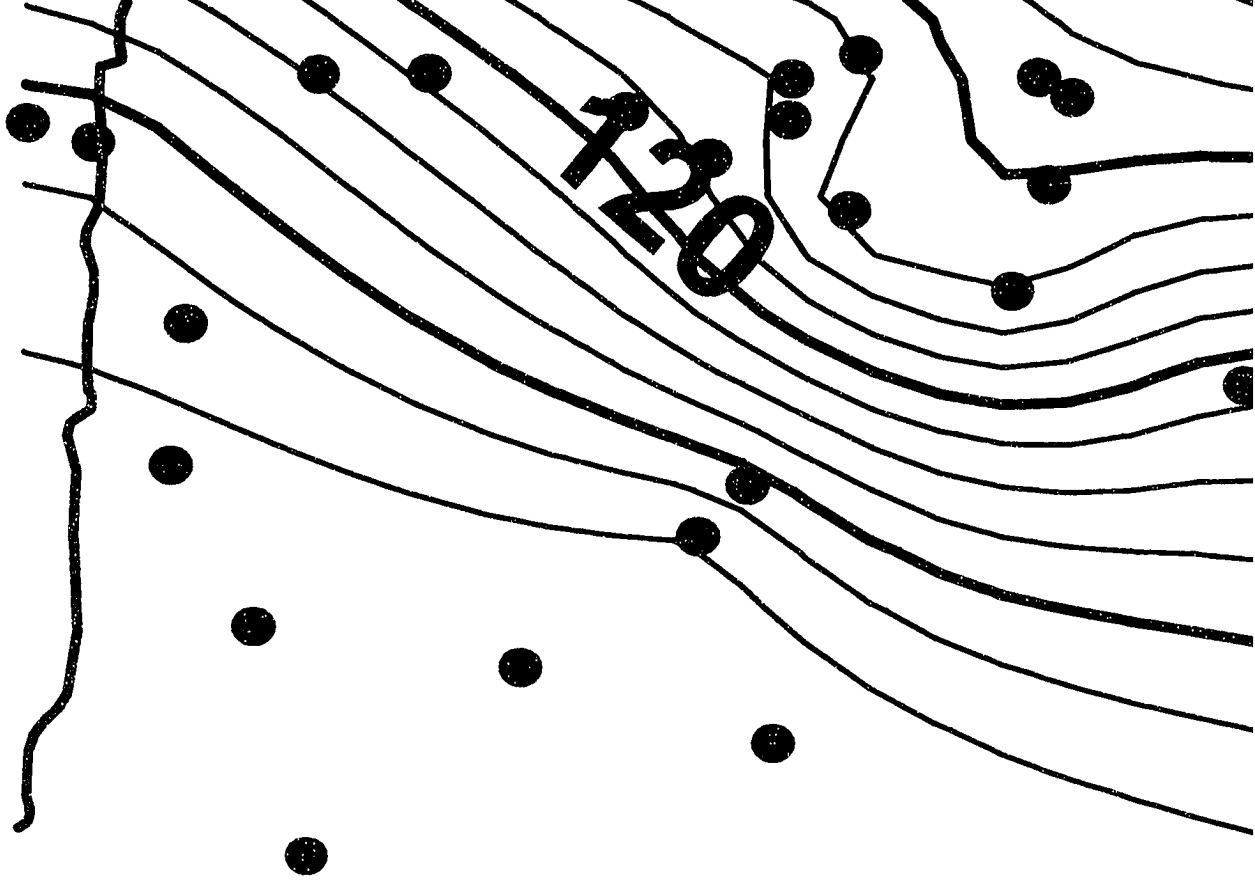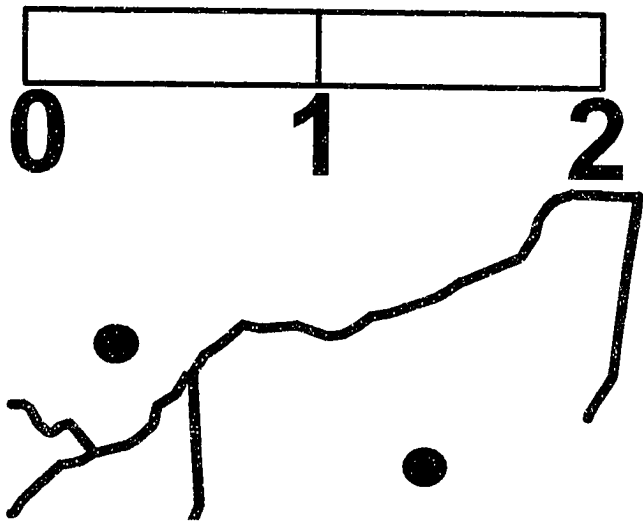
● GEOTECHNICAL BORING
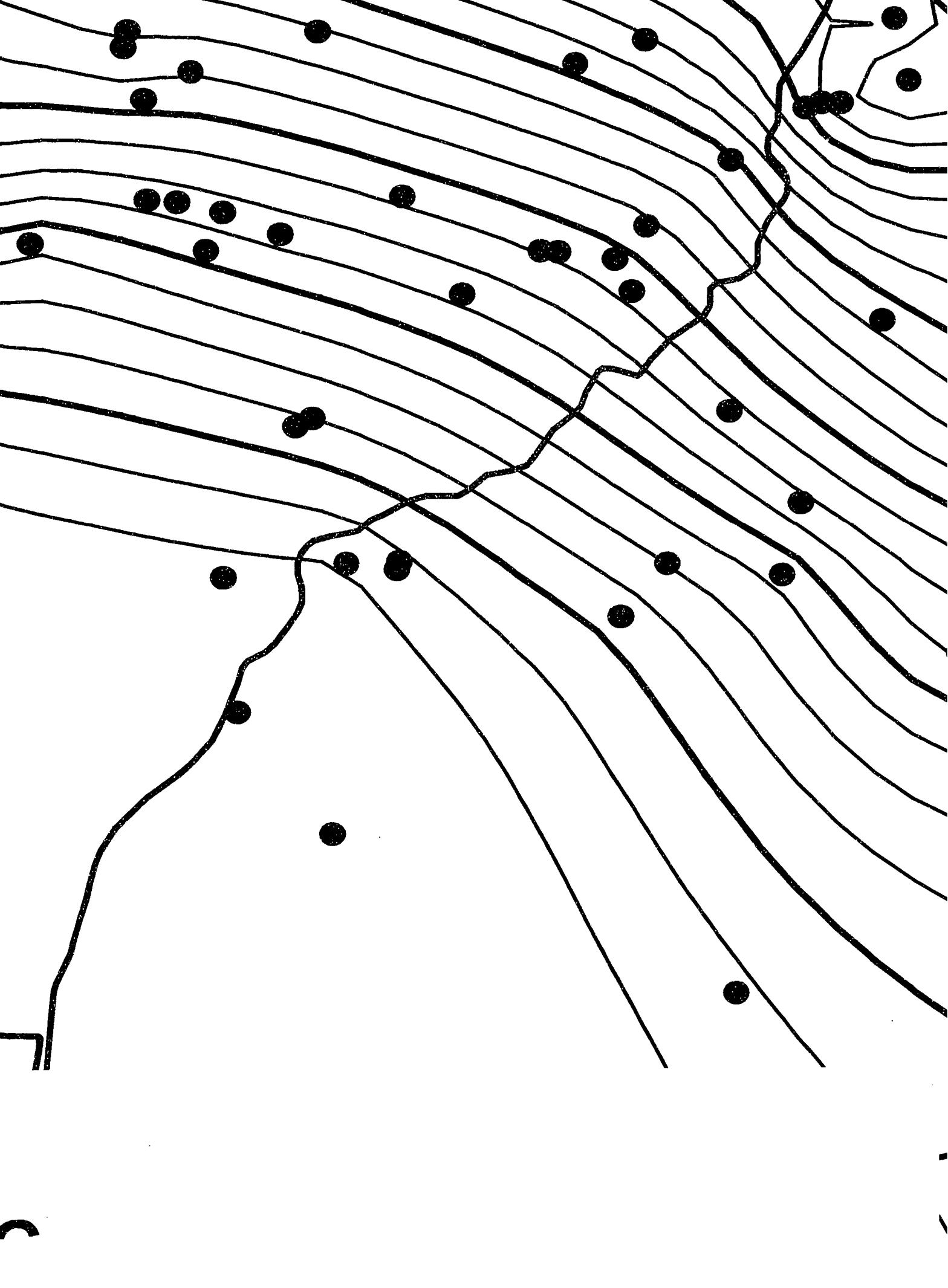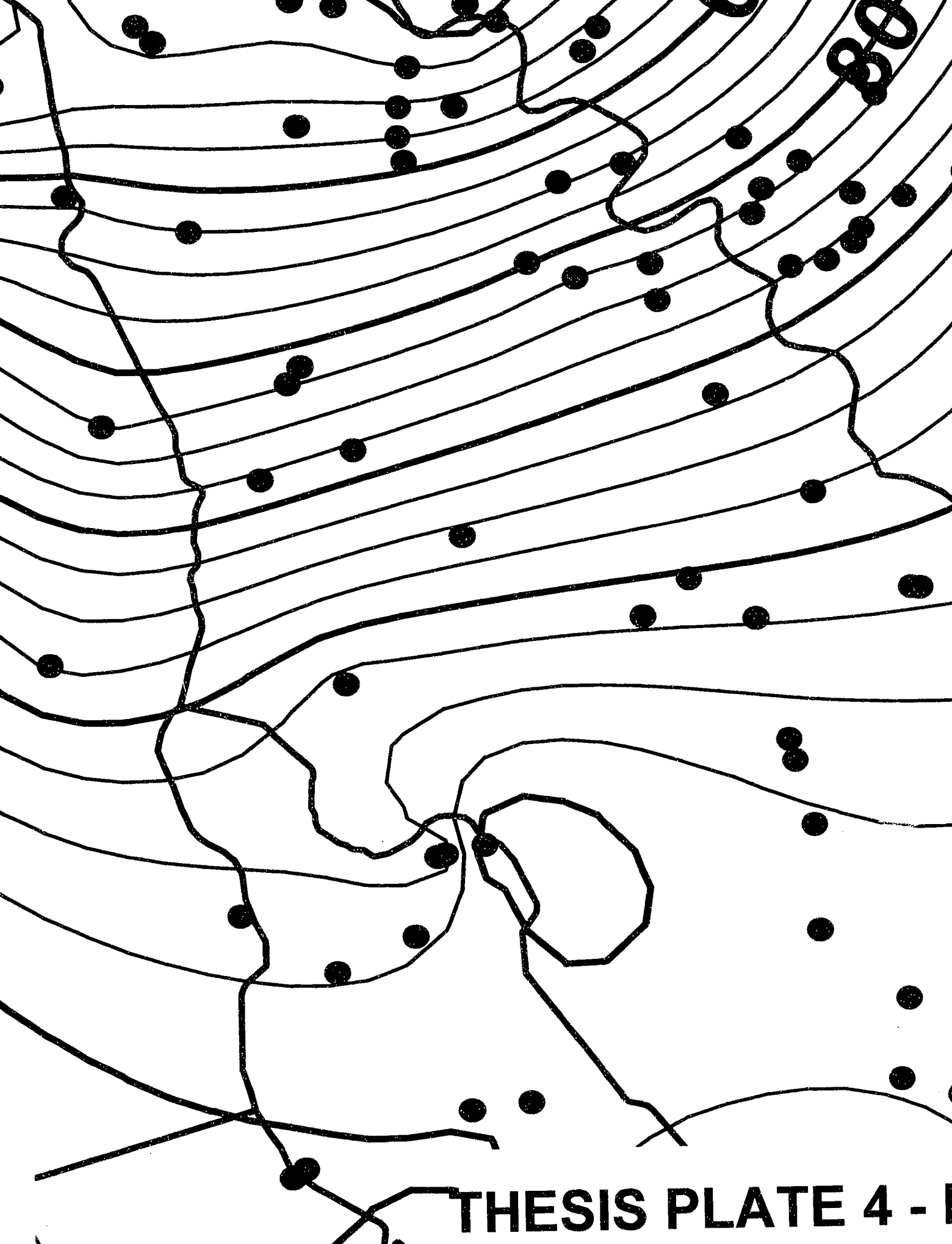
THESIS PLATE 4 -

**Pleistocene surface elevation map**
(interpreted) in feet (modified after

# SCALE IN KILOMETERS

| 0 | 1 | 2 |
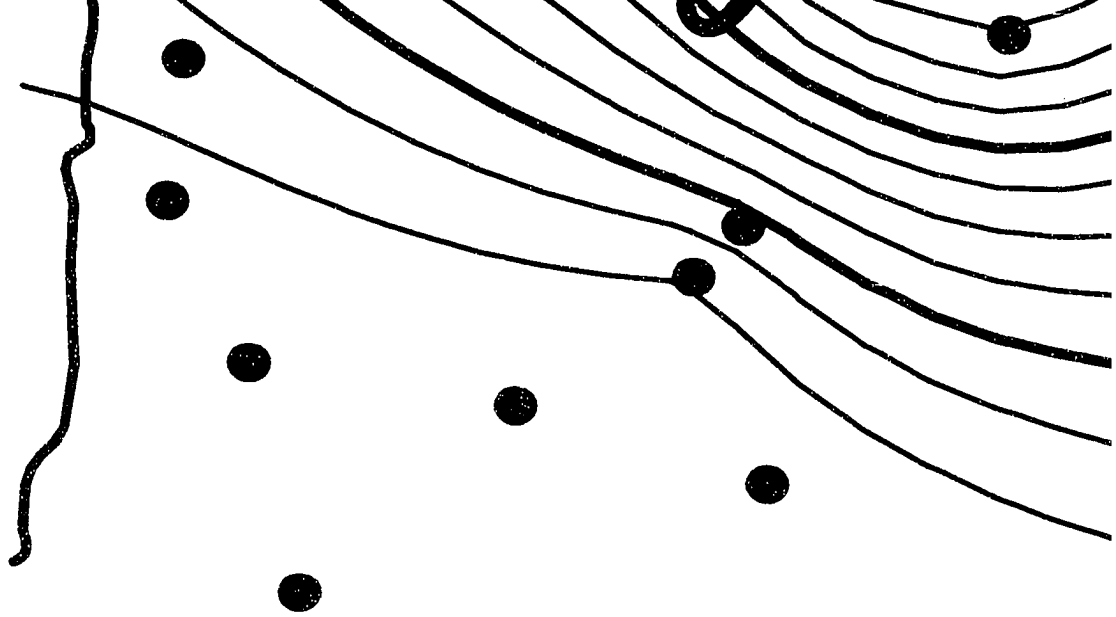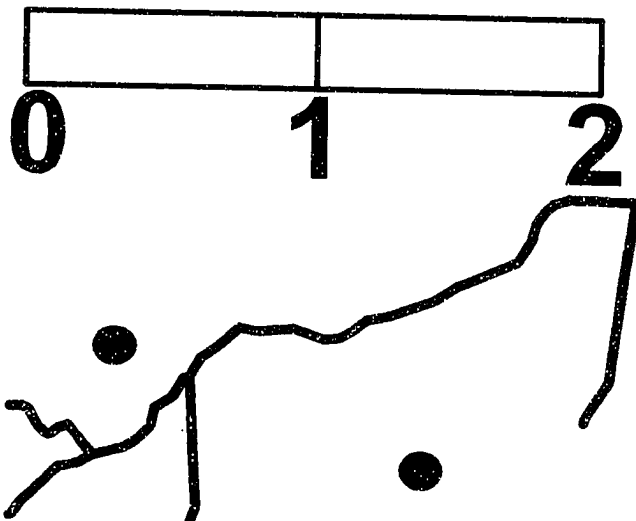
• GEOTECHNICAL BORIN

— PLEISTOCENE SURFAC
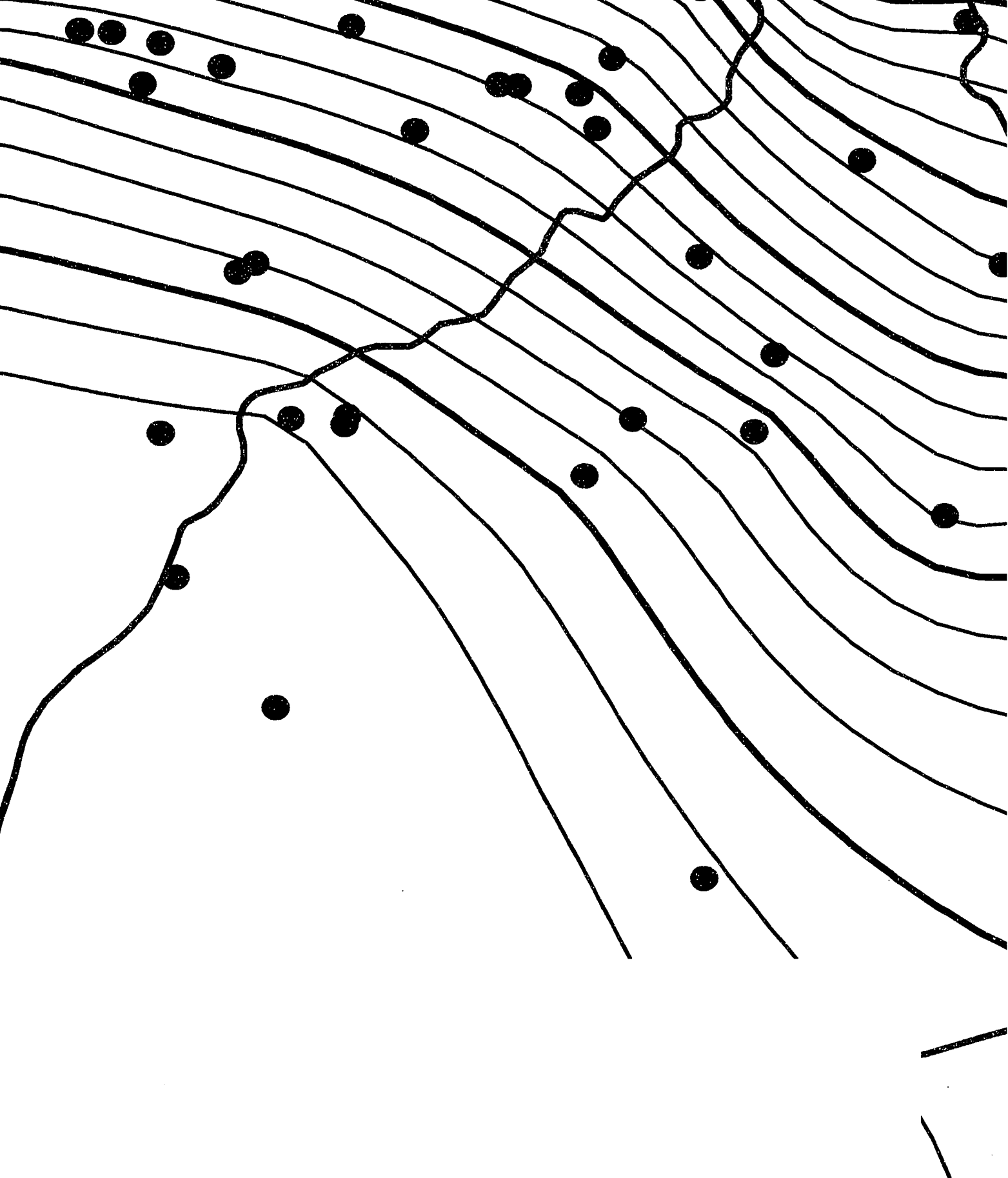
ELEVATION CONTOURS
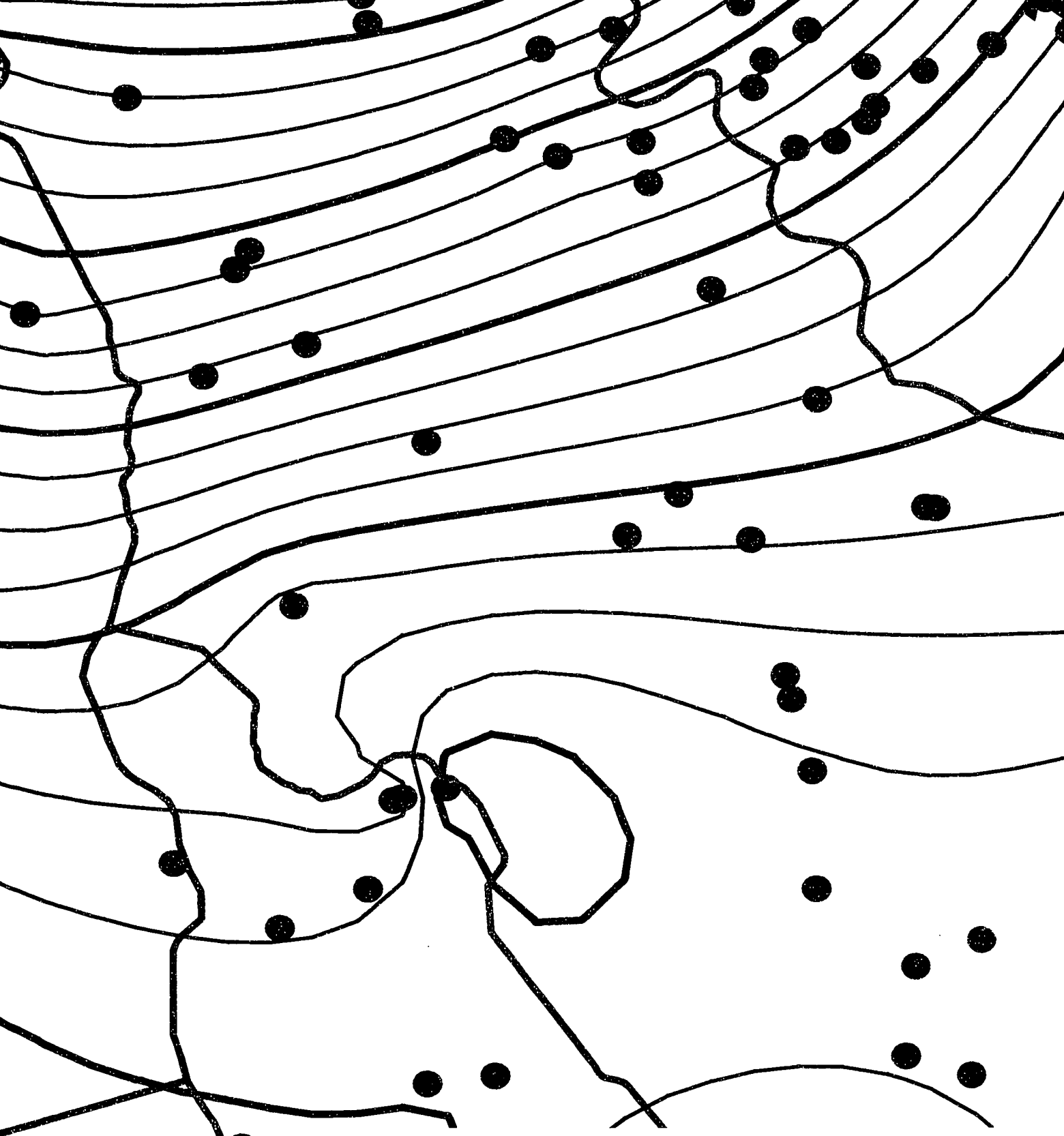
THESIS PLATE 4 - Pleis
(in
Cl
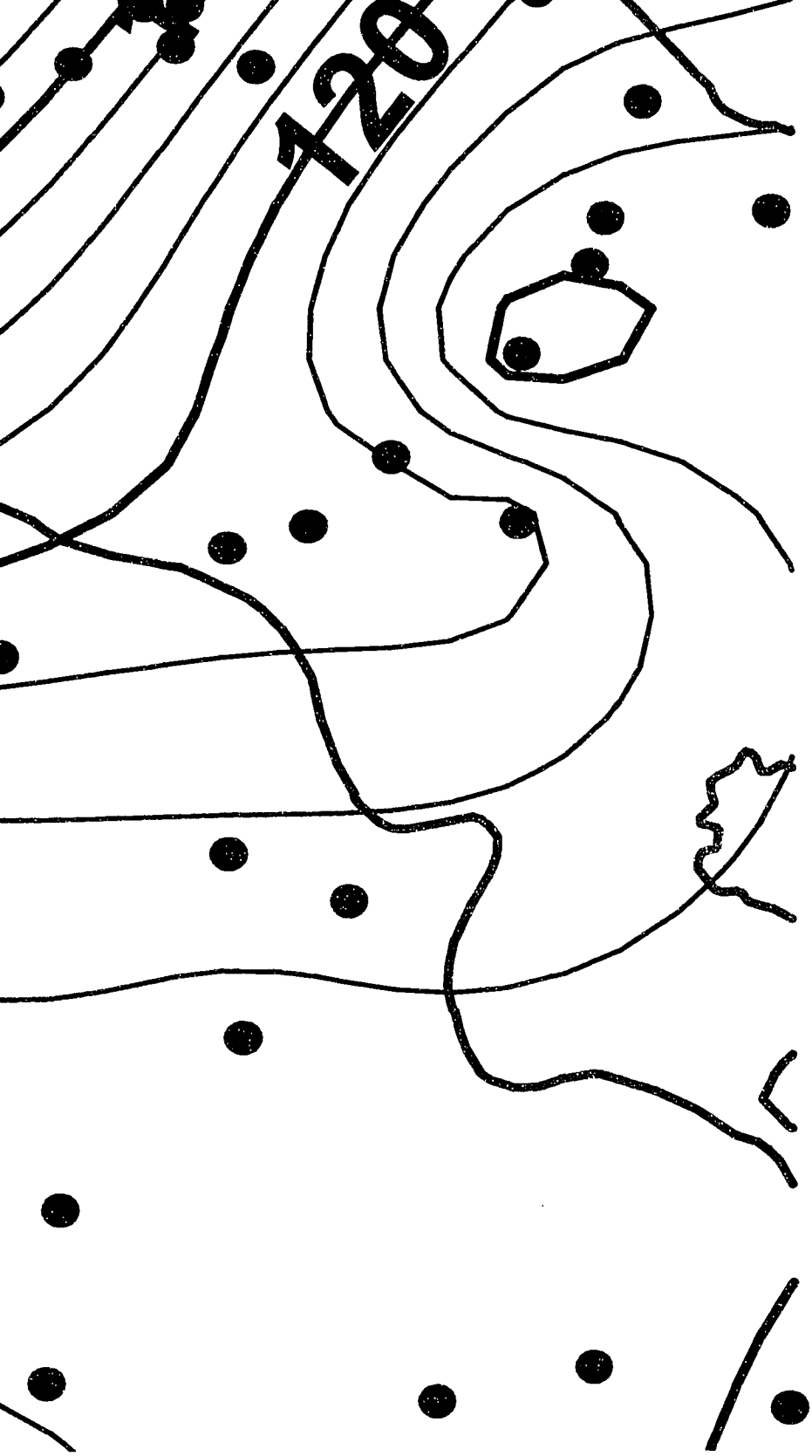
**Pleistocene surface elevation map (interpreted) in feet (modified after Clahan et al., 2002)**

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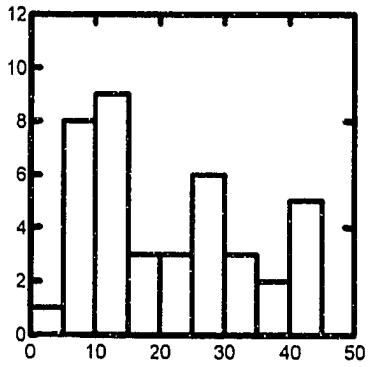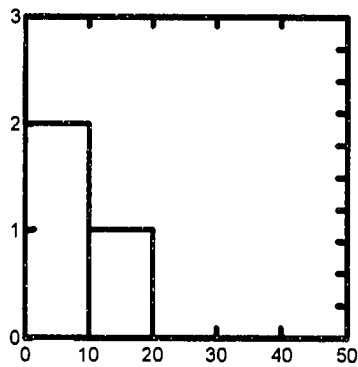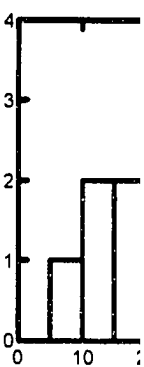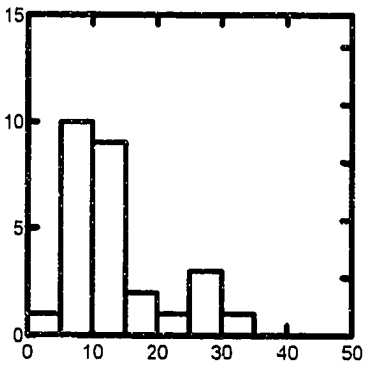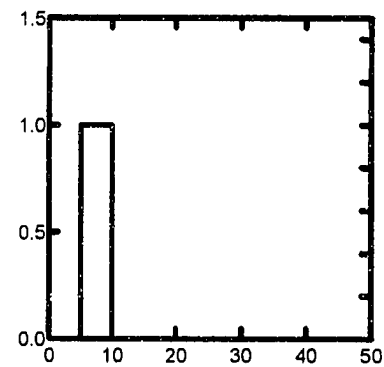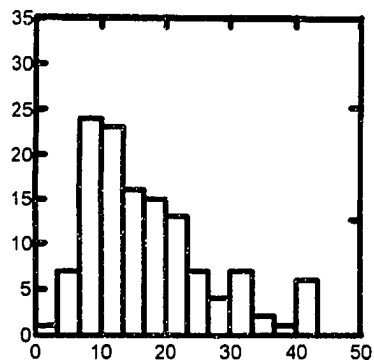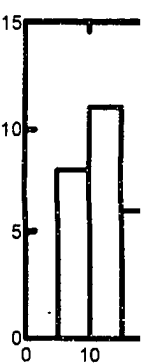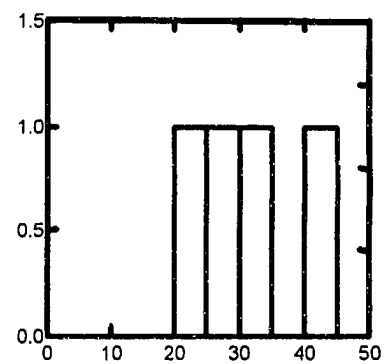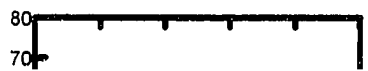
# Qhc
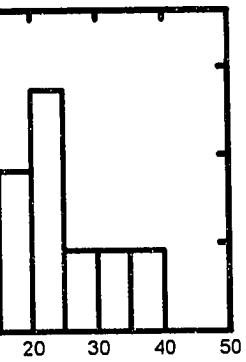
# Qhfy
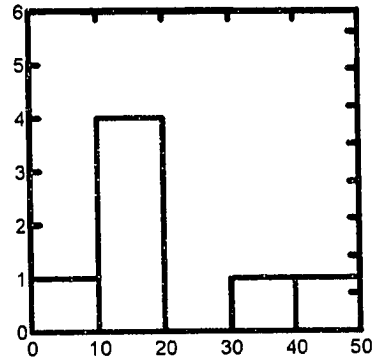
# Qhly
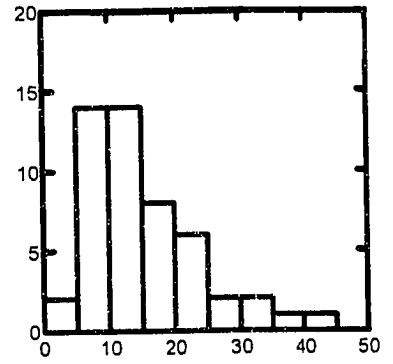
# Qhfe
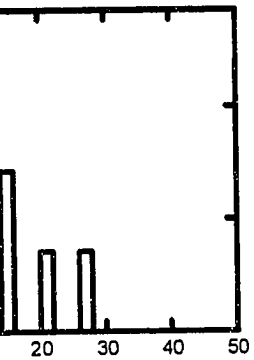
# Qhf
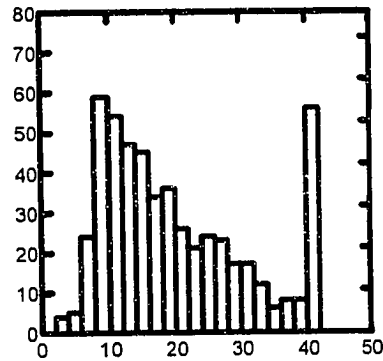
# Qhff

# Qf

# Ql

# Qt
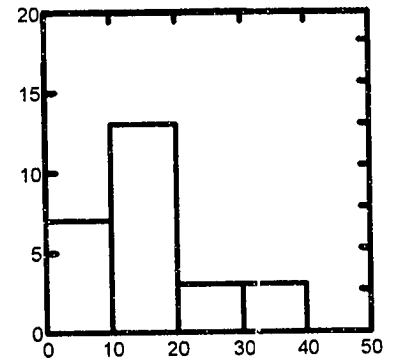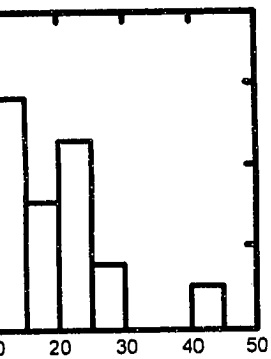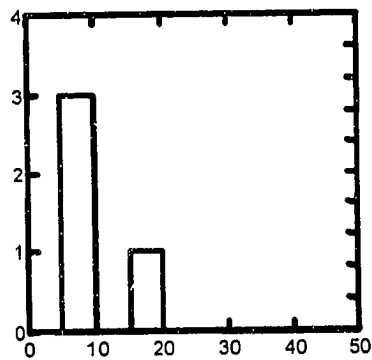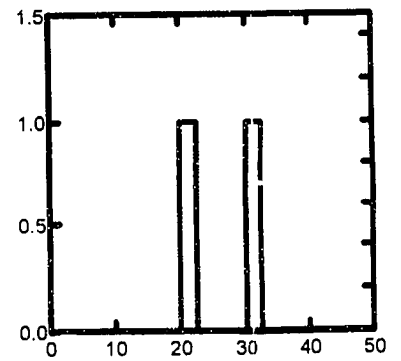
# Legend

Qhly
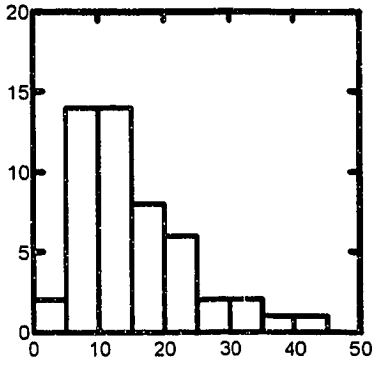


Qhff



Qt
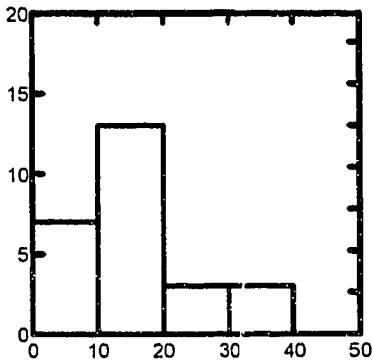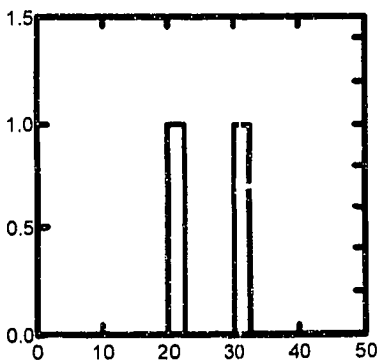


THESIS PLATE 5 -

Histograms showing
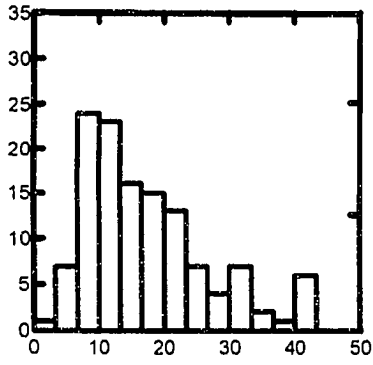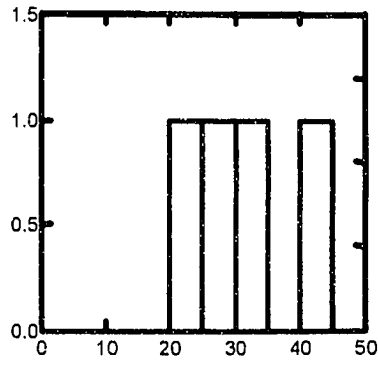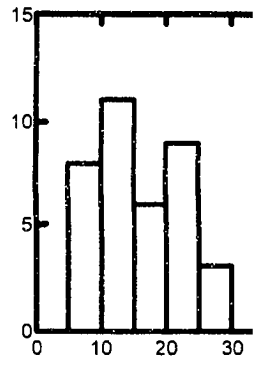
Qhl
Qht
Qf
Qpf
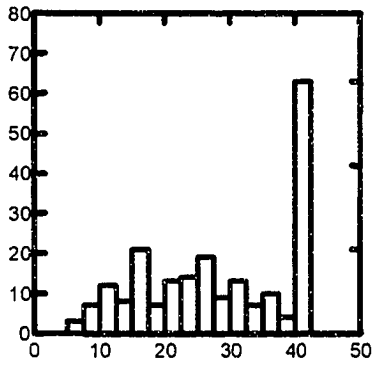
Count

## Qf

## Ql

## Qt



# Legend

$(N_1)_{60,cs}$

## Qt
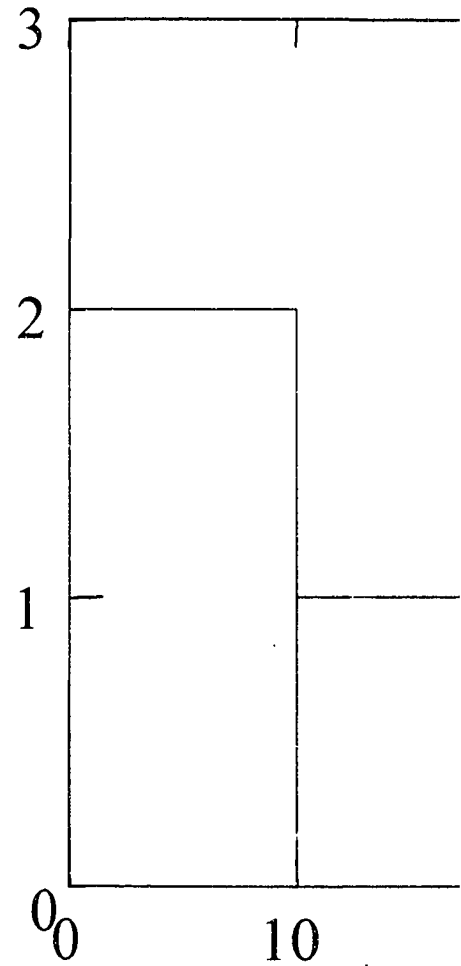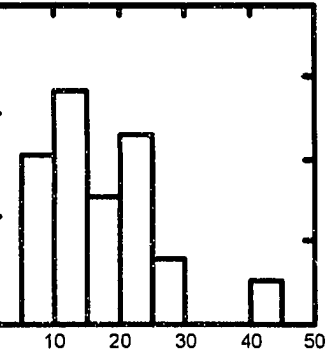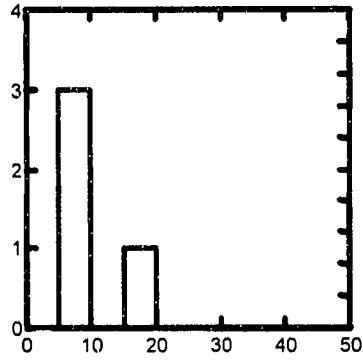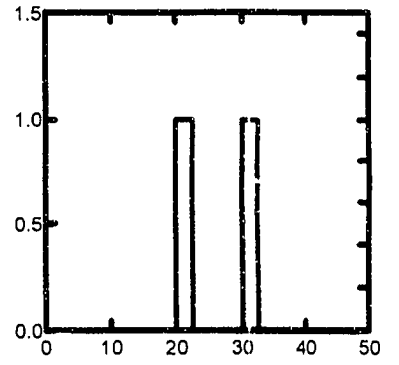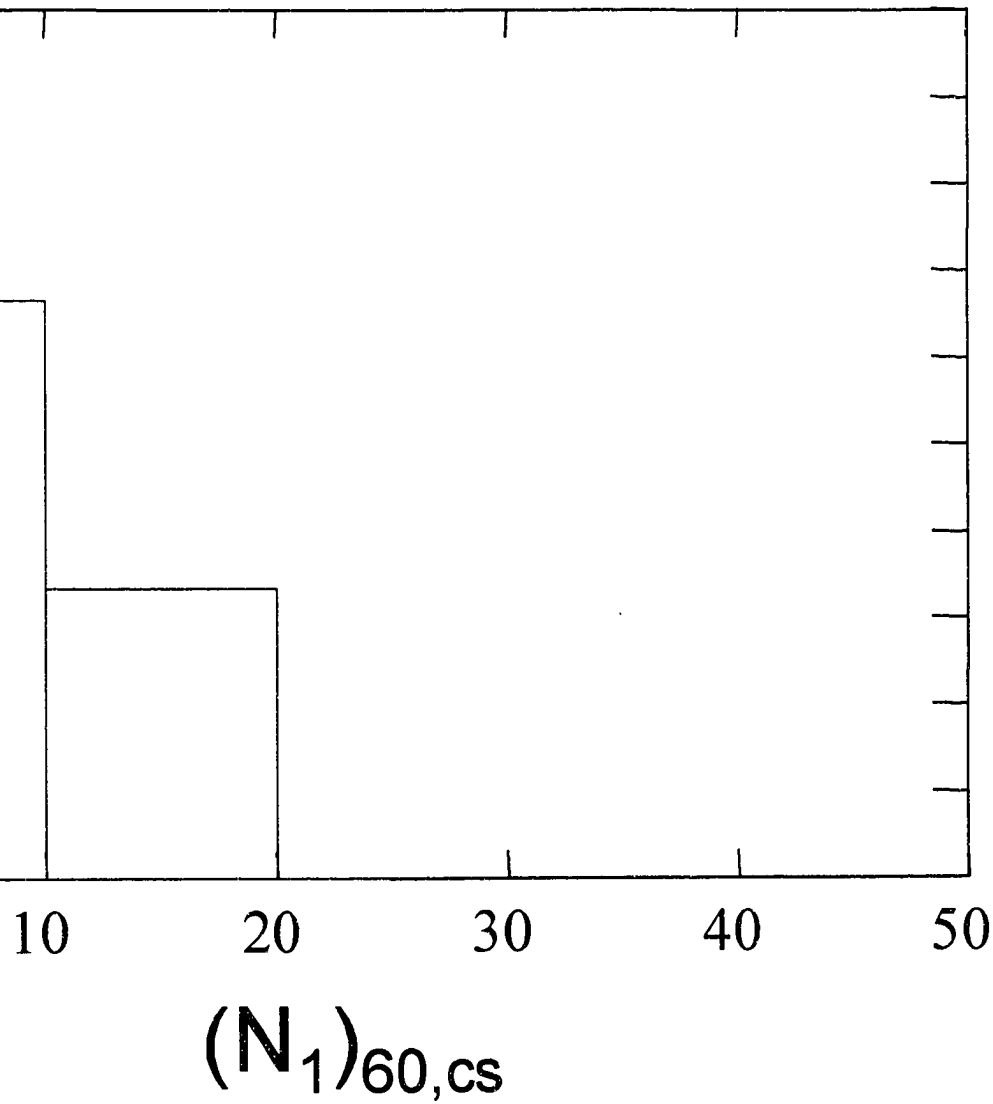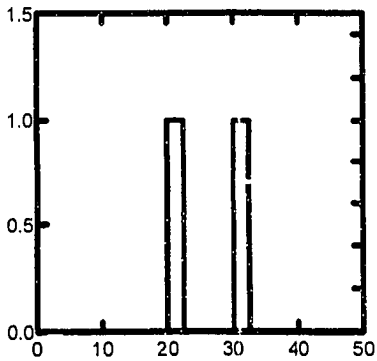


THESIS PLATE 5 -

Histograms showing fines corrected penetration resistance for every layer in the project database of geotechnical boring logs. (Knudsen et al. 2004)

# NOTE TO USERS

Oversize maps and charts are microfilmed in sections in the following manner:

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UMI®

**NC**

40
32

30    4525

30        25

40

55

39.

36.5

30 78.5

25

30

26.5

15

30

20 60

29.5
41.5

15

44

35

52.

20

25

21.5

25
41.5

25

4525

91

14

40

52

20.5

25

REA

20.5
25
40
30
20.5
80
46.5
25
80
101.5
25
51.5
15
61.5
40
200 105
40 40 20 50
15
15.5
80 20 20
21.5
29.5
20
39.5
41
40
1625
90
60
141.5
19.5
101.5
40
5 5
1620
20
40
36.5 20
20
66
41.5
35
25
21.5
101
125
20 25
25
46
86
50.3
50
70
69.5
51.5
50
20.5
85
36
20.5
35
26
50.5
76 20
41.5
20
24.5
51

16.25

36.5

SAN JOSE

20

20.5

30.5

23.5

35

146

66.5 70.5

30

36.5

41

40
40.5

130

30

25

26.5 76.5

51.5

30

30 21.5
40

56 65

46

30

66.5

21.5    41.5    15

56.5

35

50.5    33.5  20

28.5    60.5

45
15

51.5    30    31.5
35   15

20    23

40    40 27   25.5
20   51.5   40

15    20

40.5

93

15    41.5

45

50.5    14

30

40

20

45.5

31.5

40

0
43

30

19

76.5

81.5

96

29.5

75

15.5
40
61.5
40

30.5
26.5

80.5

30 30
64
20

85

25
91.5  20
40
31.5
15
40

15

30
20

21

30

35
20

31.5

30

30

31.5

21.5

40

46.5

41.5

35

31
30

41

44.5

40

25

40

40

30

15.5

40

19

76.5

81.5

75

70

29.5

15.5
40
61.5
40

30 30
64
20

15

30

20

10

21

35

20

20

40

41.5

25      20

35

44.5

40

15.5

37° 15'

122° 00'

Milpitas base map prepared by the U. S. Geological Survey, 1961, photorevised 1980.
Calaveras Reservoir base map prepared by the U. S. Geological Survey, 1961, photorevised 19:
San Jose East base map prepared by the U. S. Geological Survey, 1961, photorevised 1980.
San Jose West base map prepared by the U. S. Geological Survey, 1961, photorevised 1980.

**REFERENCE:**
Quaternary geologic maps of the Milpitas, Calaveras Reservoir, San Jose East and San Jose W
Quadrangles modified after Witter et al., (2006)

| Milpitas | Calaveras Reservoir |
|----------|---------------------|
| San Jose West | San Jose East |

# THESIS PLATE 6 - Volumetric Strain Summed for Each Boring and (

# Volumetric Strain

28

80.5  15

25

40

30

64.5

30

41.5

20

31
36.5

35

19

36.5

14

101.5

22.5

38

20

40

d 1980.
0.
30.

se West

### Scale

0    1    2    3    4

**Kilometers**

N

W — E

S

Geologic Map Units Grouped by Median Volumetric Strain, Anne Rosins

Map labels (boring total depths):
41, 44.5, 40, 25, 40, 30, 40, 15.5, 80, 22, 41.5, 25, 40, 40, 80, 41.5, 35

5

## Volumetric strain summed for boring

- 4% to 10%
- 3% to 4%
- 2% to 3%
- 1% to 2%
- 0% to 1%

36  Boring total depth

## Geologic Map Units Gr
## Median Volumetric Stra

- [ ] HIGH: afbm, Qhfe
- [ ] MODERATE-HIGH: a
- [ ] MODERATE: ac, Qhly
- [ ] LOW: Qf
- [ ] VERY LOW:Qhc, Qhf
- [ ] BEDROCK
- [ ] WATER
- [ ] Quaternary units in th
  boring data collected
  Qt, Qa, Qpb, Qpa, Q

ki, 2007
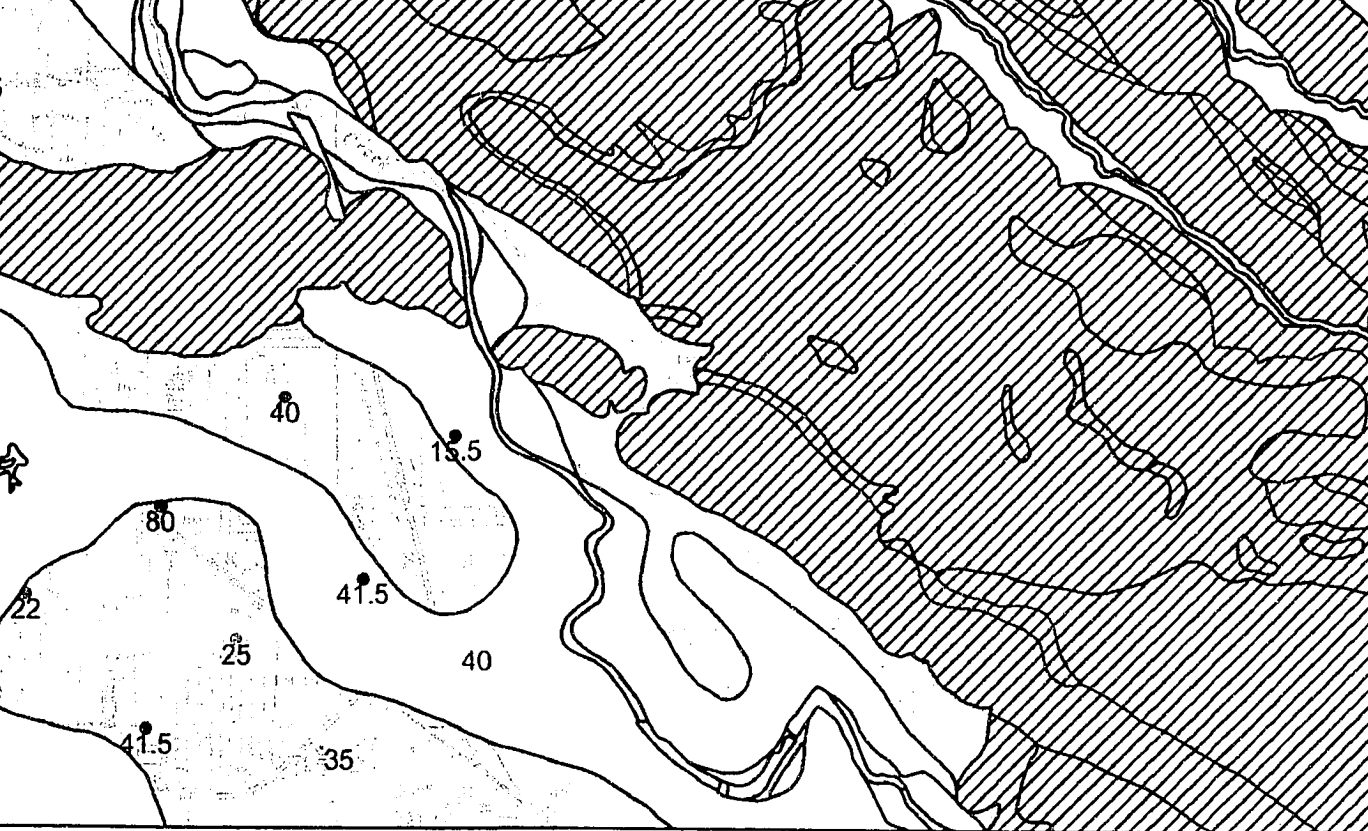
37° 15'

121° 45'

## Volumetric strain summed for boring

- 4% to 10%
- 3% to 4%
- 2% to 3%
- 1% to 2%
- 0% to 1%

36 Boring total depth

## Geologic Map Units Grouped by Median Volumetric Strain

HIGH: afbm, Qhfe

MODERATE-HIGH: alf, Qhfy, Qhty

MODERATE: ac, Qhly, Qhff, Qhl, Qht

LOW: Qf

VERY LOW:Qhc, Qhf, Qfp

BEDROCK

WATER

Quaternary units in the study area for which no boring data collected: gq, Qhbm, Qhb, Qha, Ql, Qt, Qa, Qpb, Qpa, Qof, Qoa

# NOTE TO USERS

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This reproduction is the best copy available.

N

122° 00'
37° 30'

30    4525

32

30        25        40

# NOT EVALUATED - OUTSID

55

39.5

36.5

30 78.5

30

25

30

26.5

15

20 60

39.5
41.5

15

52.5

44

20

100

35

25
21.5

25
41.5

25

4525

14

20.5 20

40

EA

121° 45'

37° 30'

41.5
14
20.5 20
40
25 30
80 46.5
101.5 25
80 51.5
40 15
25 15
20 15.5
80 25 20
21.5 29.5 20 1625
39.5 40
16.25
141.5 36.5
101.5
19.5 40
51.5
1625
20
40 20 25
36.5 20
35 25
1.5 20 25
101 12.5 20 25
46 60
146
70 69.5 50.3
51.5 55
20.5 85 54
35 36
76 26.5 76.5
20.5 50.5 20
41.5 76

San Jose

Alum Park

Alum Rock

34.5

20.5

20

3.5

35

30

66.5 70.5

36.5

0

60.8

50

41

30

25

51.5

20

30

36.5

41

25

51.5

25

40

19

6.5

81.5

75

70

15.5
61 40
40

29.5

30 30
64
20
20

15

30
20

10

20

21

35
20

20

25 20

41.5

35

44.5

40

37° 15'

122° 00'   Milpitas base map prepared by the U. S. Geological Survey, 1961, photorevised 1980.
Calaveras Reservoir base map prepared by the U. S. Geological Survey, 1961, photorevised 1980.
San Jose East base map prepared by the U. S. Geological Survey, 1961, photorevised 1980.
San Jose West base map prepared by the U. S. Geological Survey, 1961, photorevised 1980.

**REFERENCE:**
Quaternary geologic maps of the Milpitas, Calaveras Reservoir, San Jose East and San Jose West
Quadrangles modified after Witter et al., (2006)

| Milpitas | Calaveras Reservoir |
|----------|---------------------|
| San Jose West | San Jose East |

# THESIS PLATE 7 - Shear Strain Summed for Each Boring and Geolog

# Shear Strain

**Scale**

0       1       2       3       4

**Kilometers**

c Map Units Grouped by Median Shear Strain, Anne Rosinski, 2007

Map labels (shear strain values and depths): 40, 25, 40, 30, 40, 15.5, 80, 41.5, 22, 25, 40, 40, 30, 41.5, 35, 5

## Shear strain summed for boring

- 40% to 50%
- 30% to 40%
- 20% to 30%
- 10% to 20%
- 0% to 10%

36  Boring total depth

## Geologic Map Units Grouped Median Shear Strain

HIGH: afbm

MODERATE-HIGH: Qhfe

MODERATE: alf, ac, Qhfy, Qhly, Qhty, Qhl

LOW: Qhff, Qht

VERY LOW: Qhc, Qhf, Qf, Qpf

Bedrock

Water

Quaternary units in the study area for which no boring data collected: gq, Qhbm, Qhb, Qha, Ql, Qt, Qa, Qpb, Qpa, Qof, Qoa.

40

15.5

80

22

41.5

25

40

41.5

35

37° 15'

121° 45'

## Shear strain summed for boring

- 40% to 50%
- 30% to 40%
- 20% to 30%
- 10% to 20%
- 0% to 10%

36 Boring total depth

## Geologic Map Units Grouped by Median Shear Strain

HIGH: afbm

MODERATE-HIGH: Qhfe

MODERATE: alf, ac, Qhfy, Qhly, Qhty, Qhl

LOW: Qhff, Qht

VERY LOW: Qhc, Qhf, Qf, Qpf

Bedrock

Water

Quaternary units in the study area for which no boring data collected: gq, Qhbm, Qhb, Qha, Ql, Qt, Qa, Qpb, Qpa, Qof, Qoa.