1990

Engineering geology, and seismic and landslide hazards of the Scotts Valley Area, Santa Cruz County, California

Jeffrey L. Bachhuber
San Jose State University

Order Number 1340494

Engineering geology, and seismic and landslide hazards of the Scotts Valley area, Santa Cruz County, California

Bachhuber, Jeffrey L., M.S.

San Jose State University, 1990

U·M·I
300 N. Zeeb Rd.
Ann Arbor, MI 48106

ENGINEERING GEOLOGY,.AND SEISMIC AND LANDSLIDE HAZARDS OF THE SCOTTS VALLEY AREA, SANTA CRUZ COUNTY, CALIFORNIA

A Thesis

Presented to

The Faculty of the Department of Geology

San Jose State University

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

By

Jeffrey L. Bachhuber

May, 1990

APPROVED FOR THE DEPARTMENT OF GEOLOGY

John W. Williams

Deborah R. Harden

Roberta K. Smith-Evernden

APPROVED FOR THE UNIVERSITY

Serena W. Stanford

ABSTRACT

ENGINEERING GEOLOGY, AND SEISMIC AND LANDSLIDE HAZARDS OF THE SCOTTS VALLEY AREA, SANTA CRUZ COUNTY, CALIFORNIA

by Jeffrey L. Bachhuber

This study focused on collection and analysis of geologic and seismic data for determination of the potential hazards resulting from earthquakes and landslides in Scotts Valley, Santa Cruz County, California. A series of maps were developed at a scale of 1:12,000 depicting engineering geology, landslide occurrence, landslide potential, and liquefaction potential.

Seismic records suggest that an earthquake equalling or exceeding 7.0 Richter Magnitude has a recurrence interval of 100 years. The greatest seismic hazard is believed to be maximum earthquakes on either the San Andreas fault (8.5 RM) or Zayante fault (7.4 RM). The late Holocene alluvial deposits exhibit a high to moderate liquefaction potential.

Landslides are one of the primary geologic processes in the study area and pose a significant geologic hazard. The landslide susceptibility map divides the area into areas of high, moderate, and low landslide potential.

Dedicated to Shelly, Hans and my Father and Mother

ACKNOWLEDGEMENTS

The completion of this thesis project was made possible by the help of many people. I am grateful for the effort expended by the members of my thesis committee: professors John Williams and Deborah Harden, and Roberta Smith-Evernden of Smith-Evernden and Associates. I especially appreciated the enthusiasm of John Williams, and the time Roberta Smith-Evernden spent with me in the field.

Bob Hana, City of Scotts Valley Chief Planner, and Glennon Culwell, acting City Mayor, allowed me access to reports on file at City offices. I hope the results of this project will prove to be a valuable asset to them.

John Woodruff, geologist consultant at PG&E, contributed large amounts of his time to assist me with field work, report preparation, and very critical reviews of early drafts of the paper. I just wish he would return my rock hammer.

Many other friends and professional associates aided me. These include John Halliday (thanks for the very long term loan of your stereo viewer), Mitch Wolfe, and Dave Rogers of Rogers/Pacific. Rogers/Pacific helped to finance the reproduction costs for the thesis project. Ray Skinner, Tom Sparrow, Joe Rafferty, Vickie Odello, Rob Wilson, David Keith Todd, and George Reid all contributed useful data to the project.

Special thanks and love are extended to the members of my family who exhibited great patience and perseverance throughout the completion of the project. My wife Shelly and son Hans were always there when I needed them, which was quite often. My father and mother provided inspiration and financial support to the completion of my graduate studies.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

Figures | Page

Tables

Plates

INTRODUCTION

General

This study area encompasses approximately 5 square miles centered around the City of Scotts Valley, Santa Cruz County, California (fig. 1). This includes most of the City of Scotts Valley, along with a portion of the surrounding unincorporated areas within the City's sphere of influence. The study area boundaries are shown on plates 1 to 4. In general, the west boundary follows the San Augustin Rancho line to the west of the City limits, and lies along the ridge crests which border Scotts Valley to the east, south, and north.

The City of Scotts Valley has a population of approximately 8,000 residents, and has experienced significant growth in residential, commercial, and light industrial development since the early 1970's. The Scotts Valley General Plan (adopted in 1986) projects a target population of approximately 14,000 residents by the year 2005.

Physiography

Scotts Valley is located in the central portion of the Santa Cruz Mountains, approximately 6 miles northeast of the Pacific Ocean. The region has a Mediterranean climate with a mean annual temperature of 55 degrees Fahrenheit. Annual average precipitation is 38-40 inches, with occasional high intensity storms (Rantz, 1971). Most of the rainfall occurs in the months of November through March.

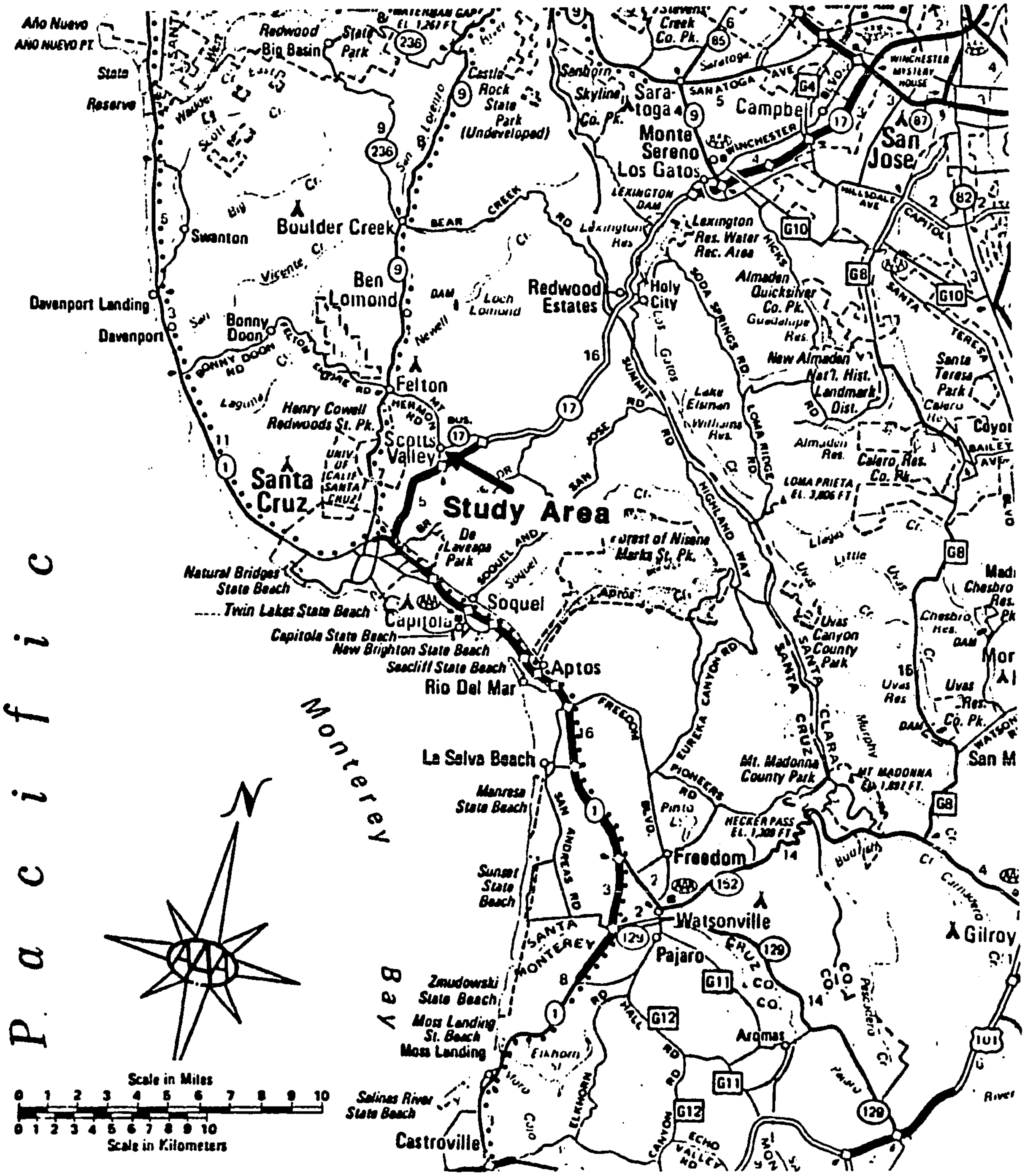


Figure 1. Location Map

The study area encompasses portions of the Carbonera Creek, Bean Creek, and Granite Creek drainage basins. The maximum topographic relief is approximately 720 feet. The highest point (1080 feet) occurs along the top of a ridge in the northeast corner of the area, and the lowest point (360 feet) occurs along Bean Creek in the southwest portion of the study area.

Scotts Valley is an "L" shaped mountain basin resulting from the incision of the Carbonera Creek drainage system. The valley is enclosed by a series of sub-parallel ridges which rise an average of 350 feet above the valley floor. The gently sloping valley floor has an area of approximately 900 acres, or 33% of the study area. The Bean Creek valley in the western portion of the study area is the location of the confluence of two major tributaries: Ruins Creek and Lockhart Gulch. The remainder of the area is occupied by moderate to steep ridges and narrow, inter-ridge valleys.

A wide variety of vegetation is established in and around Scotts Valley. Evergreen conifer forests composed of intermixed coast redwood and Douglas fir trees are located along canyon bottoms and side slopes. Broadleaf forests dominated by madrone, California laurel, and live oak trees occupy much of the area, particularly on south and southeast facing slopes. Ponderosa pine-chapparal-community vegetation is established in areas underlain by Santa Margarita Sandstone and on well insolated slopes. Riparian corridors consisting of sycamore and willow trees extend along perennial water courses.

PURPOSE AND SCOPE OF STUDY

Purpose

The purpose of this thesis project has been to identify and evaluate potential geologic hazards within the City of Scotts Valley and surrounding unincorporated areas. During the course of the study, three principal geologic hazards were identified: earthquakes, landslides, and floods. A series of detailed maps suitable for planning purposes which outline the areas of potential inundation from 100 and 500 year flood events within Scotts Valley have been prepared by the Federal Emergency Management Agency (FEMA, 1983). Because the areas of potential flood inundation have been defined by the FEMA maps, this investigation focused on identification of potential seismic (earthquake) and landslide hazards. Areas within the study area which are subject to seismically-induced ground failure and landslides are delineated on a series of maps prepared by the author which are of similar detail as the flood inundation maps. These maps will be made available to the Scotts Valley Planning Department to facilitate future planning and assist in identification of critical areas which need additional studies. It should be noted that the maps are intended to be used as a general planning tool only; they are not intended to substitute for site specific investigations.

Scope Of Study

Background Research

The initial phase of the investigation consisted of a background review of existing reports, maps, and information which have been compiled by the United States Geological Survey (USGS), California Division of Mines and Geology (CDMG), local universities, and private consulting firms.

Geotechnical soil reports and well logs on file at the City of Scotts Valley, California Department of Transportation (Caltrans) Geological Office, and David Keith Todd Consulting Engineers, Inc. of Berkeley, were reviewed to assist in the characterization of the subsurface geology. Information contained on geotechnical boring logs from these reports was used for evaluation of the engineering properties and liquefaction potential of the alluvial deposits. Aerial stereographic photographs from the USGS, University of California at Santa Cruz, and United States Soil Conservation Service were analyzed.

Field Investigation

Field mapping was conducted on an intermittent basis from August 1985 to May 1989, and for two weeks immediately following the October 17, 1989 Loma Prieta earthquake. Approximately 65 days were spent field mapping. Every major ridge, drainage course, and road in the study area were traversed. Data collected in the field were plotted on USGS 7.5 minute topographic quadrangle maps which were enlarged to 1:12,000 scale. Locations were determined in the field by taking bearings with a Brunton pocket transit and measuring by pacing from reference points. Identification and location of geologic features were aided by referencing aerial photographs. The following sets of aerial photographs were reviewed:

1) USGS JSC 8 6-8 and JSC 9 6-8 (1/8/82)- Scale 1:12,000;
2) WAC Corporation (Oregon) 13\141-144 and 13\115-117 (4/12/85)- Scale 1:31,680;
3) Soil Conservation Service (1963)- Scale 1:20,000.

Geologic units were correlated to established formal stratigraphic formations (where applicable) which are described in geologic maps and reports published by the USGS. Because the intent of this investigation was to identify potential geologic hazards, emphasis was placed on mapping the surficial geology and landslides. It should be noted that potential inaccuracies inherent in the base map and obstruction of visibility in portions of the study area from dense vegetation may reduce the accuracy of the location of mapped features to approximately 100 feet. An attempt was made to identify all pertinent geologic features in the area; however, some geologic features may not have been identified due to localized areas of difficult access, modification of features by human activity and/or geomorphic processes, dense vegetation, or thick soil cover.

PREVIOUS STUDIES

The first comprehensive geologic study of the central Santa Cruz Mountains was conducted by Branner and others, and was published as the Santa Cruz Folio geologic map (1909). Studies of parts of the Santa Cruz Mountains since the 1950's by students and faculty from the University of California system and Stanford University have been presented in numerous publications and graduate thesis. Many published reports and maps which include both original work and compilations of previous studies have been prepared by geologists working at the USGS. These include geology maps of the Laurel and Felton 15 minute quadrangles by Dibblee and others (1978), and Clark (1981), respectively. Recent compilations of the geology of Santa Cruz County have been prepared by Brabb (1986 and 1989) at a scale of 1:62,500.

The distribution of faults and potential seismic hazards in Santa Cruz County have been shown on a series of maps prepared by Hall and others (1974). This work was complemented by mapping of Quaternary deposits and liquefaction potential in Santa Cruz County by Dupre (1975). These two publications were used for evaluation of seismic hazards for the Santa Cruz County Seismic Safety Element (1975) and the Scotts Valley General Plan (1986). Cooper-Clark and Associates were contracted by Santa Cruz County to develop a preliminary landslide inventory map of the County area in 1975. This map has been used by both Santa Cruz County and the City of Scotts Valley for planning purposes.

A comprehensive series of investigations have been performed by the USGS on the landsliding and flood damage which occurred throughout the San Francisco Bay Area as a result of high intensity rainfall which fell over the area in 1982 (Ellen and Wiezcoreck, editors, 1988). An on-going study to characterize and evaluate the hydrogeology and ground water resources in the Scotts Valley area is being conducted for the Scotts Valley Water District by David Keith Todd Consulting Engineers, Inc.

REGIONAL GEOLOGY AND GEOLOGIC HISTORY

Basement Complex

The study area and surrounding region are located on a portion of the Pacific crustal plate known as the Salinian block (fig. 2). The Salinian block is bounded on the north and east by the San Andreas fault, and to the south and west by the Sur-Nacimiento fault. The Salinian block is differentiated from the adjacent structural blocks by a distinctive geology consisting of thick sequences of Tertiary marine sedimentary rocks which were deposited on basement rocks composed of upper Cretaceous plutons, and Paleozoic/Mesozoic(?) metasedimentary host rocks (protoliths). The Tertiary sediments and basement complex contrast with the tectonically mixed volcanic, sedimentary, and high-grade metamorphic rocks of the Franciscan Complex in the adjacent structural blocks.

The crystalline and metamorphic (Sur Series) rocks comprising the basement of the Salinian block have been transported northward from their point of origin (Hill and Dibblee, 1953; Hsu, 1971). These basement rocks were accreted onto the west coast of North America during the later stages of the northward transport. Numerous origins have been hypothesized for the Salinian basement rocks, including: an extension of the southern Sierra Nevada range (Hill and Dibblee, 1953); a micro-continent or peninsula which extended from the coast of North America (Hsu, 1971); and the south Pacific region (Nur and Ben-Avraham, 1971). Paleomagnetic data from rocks of late Cretaceous age in the

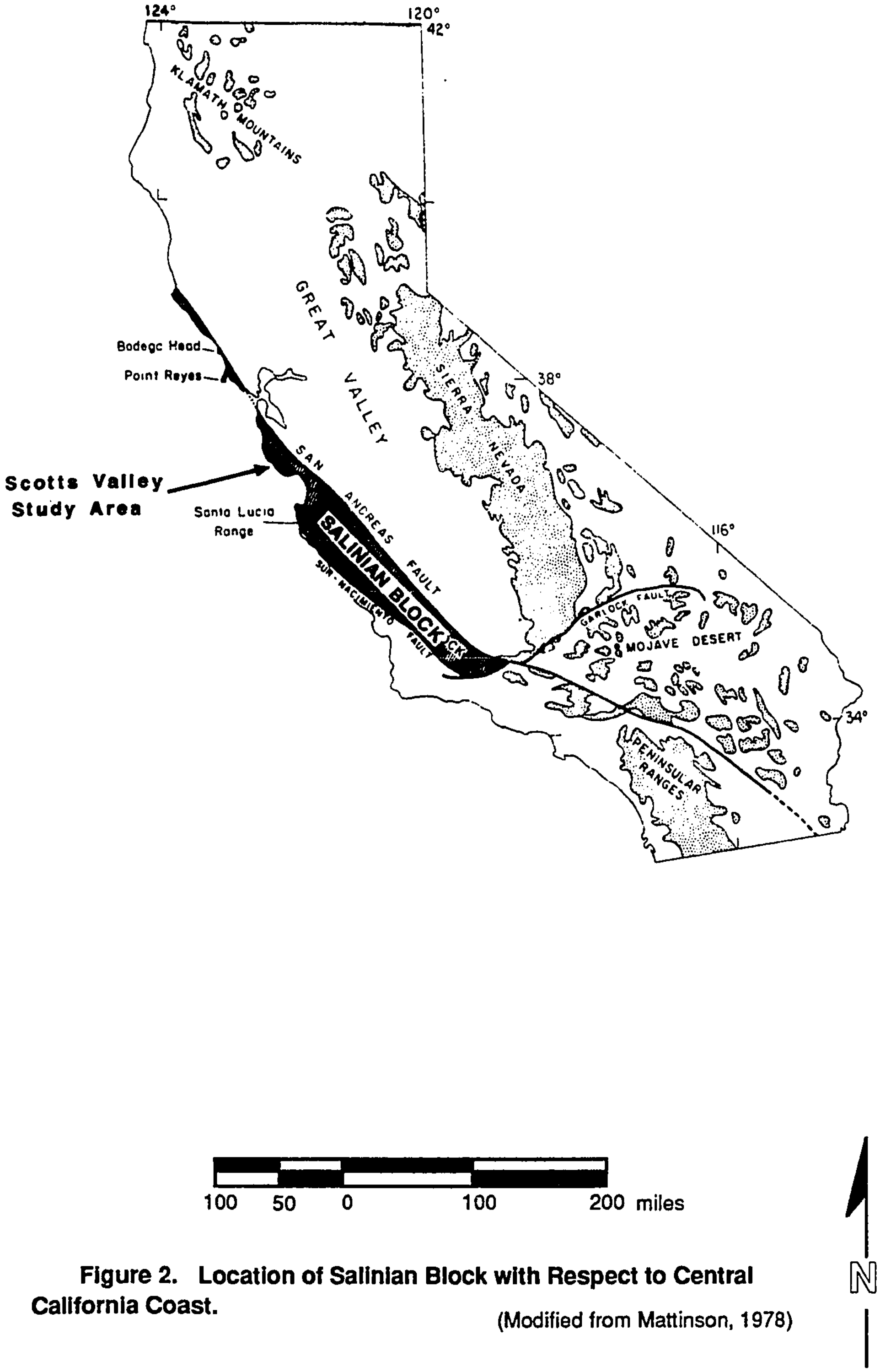


Figure 2. Location of Salinian Block with Respect to Central California Coast.

(Modified from Mattinson, 1978)

Salinian block indicate that the metasedimentary protoliths were deposited at a latitude of 21 degrees north, plus or minus 7 degrees (Williams and others, 1982). This suggests that the Salinian block has been transported a distance of over 1500 miles (2500 km) since the host rocks were initially deposited.

The mechanism(s) responsible for movement of the Salinian block are related to interactions between the Farrallon, Pacific, and North American crustal plates. Transport of the Salinian block from the late Cretaceous through the early Tertiary is theorized to have been accomplished by either oblique subduction of the Pacific crustal plate (Dickinson and others , 1987) or transform faulting along a pre-San Andreas Fault (Garfunkel, 1973). Northward migration of the triple junction between the three crustal plates is believed to have caused cessation of subduction along the central California coast during the Oligocene Epoch (Atwater, 1970). Movement between the Pacific and North American plates was shifted to the east and accommodated primarily by transform faulting after cessation of subduction. This transform faulting resulted in formation of the San Andreas Fault System in the late Tertiary Period. Translocation of the Salinian block along the San Andreas fault since the late Tertiary has been on the order of 190 miles (300 km), as evidenced by offset of middle Miocene volcanic rocks across the fault (Hill and Dibblee, 1953).

Tertiary Sedimentation On The Salinian Block

A thick sequence of sediments was deposited on the Salinian block as it was translocated to its present position. The sediments were deposited primarily within tectonically controlled marine basins, in a paleoenvironment similar to the "borderland" which presently exists off the Southern California coast. Periods of deposition were interrupted by episodes of uplift and erosion of previously deposited sediments, forming major unconformities. Most of the sediments are arkosic in composition, and consist primarily of eroded material from the crystalline basement rocks and older sedimentary rocks exposed during uplift cycles.

Four major cycles of Tertiary sedimentation are recorded in the central Santa Cruz Mountains (Clark, 1981). The sedimentary rocks in the Scotts Valley area record the two most recent sedimentary cycles which occurred in the middle Miocene, and late Miocene to early Pliocene. The geologic formations representing these sedimentation cycles are the middle Miocene Lompico Sandstone-Monterey Shale sequence, and the upper Miocene to Pliocene Santa Margarita Sandstone-Santa Cruz Mudstone-Purisima Formation sequence.

Quaternary Uplift And Erosion

Marine sedimentation ended during the Pliocene Epoch as the region began to undergo rapid tectonic uplift which is still actively occurring today (Clark, 1981; Page, 1982). Late Pliocene uplift of the Santa Cruz

Mountains is estimated to have been on the order of thousands of feet, and was accompanied by large scale faulting and deformation. The amount of uplift which occurred during the Quaternary Period is recorded in a series of elevated marine terraces eroded into the seaward slope of Ben Lomond Mountain, approximately 9 miles southwest of Scotts Valley. The highest (and presumably oldest) marine terrace is located approximately 760-780 feet above sea level, and is estimated to be between 700,000 to 1,200,000 years old (Bradley and Griggs, 1976; Lajoie and others, 1972). These data suggest that regional uplift since the mid Pleistocene has been approximately 770 feet.

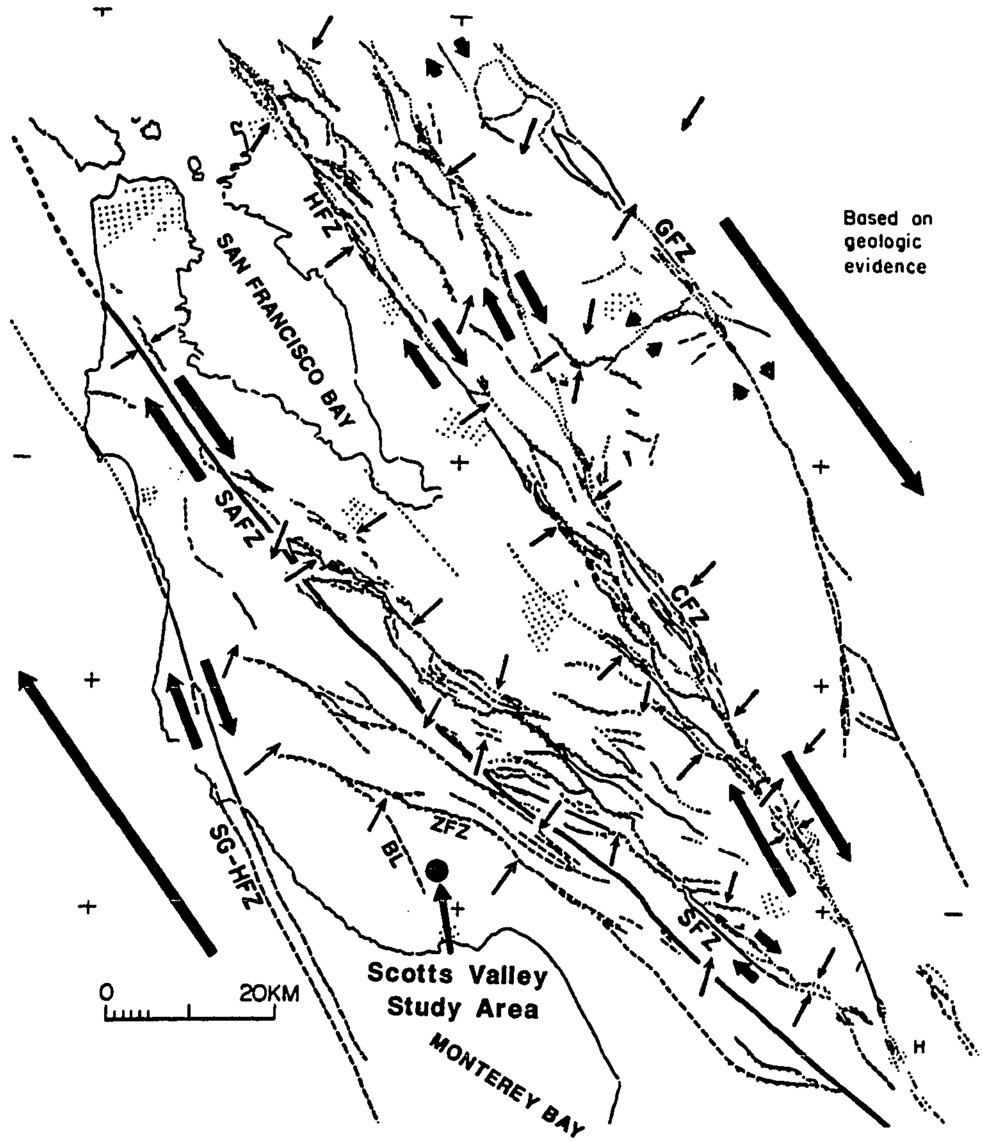
During the Quaternary Period, sedimentation within the central Santa Cruz Mountains was limited to stream deposition of alluvium within narrow mountain valleys, and sedimentation along the coastal margin. Geologic processes from the Pleistocene to the present have been dominated by rapid erosion of the subaerially exposed rocks as the region experienced uplift along the major faults bounding the Salinian block.

STRUCTURAL GEOLOGY

Structural deformation within the central Santa Cruz Mountains has been controlled by northwest transform movement between the Pacific and North American crustal plates, which has been estimated to be presently occurring at a rate of 2.2 inches (5.6 cm) per year (NEPEC, 1989). This movement has been accommodated primarily by slip along the faults within the San Andreas system since the late Tertiary Period. Page (1982) analyzed the relationship between slip on the regional faults and the orientations of major thrust faults and folds. Based on this analyses, he prepared a map showing the relative directions of Quaternary tectonic movement in the San Francisco Bay region (fig. 3). The map indicates that relative tectonic movement in the Scotts Valley area is predominantly to the northeast. This movement has resulted in crustal shortening in a northeast direction, causing major folds and thrust faults to be oriented in a northwest direction.

The central Santa Cruz Mountains segment of the Salinian block has been divided into four structural sub-blocks named the Pilarcitos, La Honda, Pigeon Point, and Ben Lomond tectonic blocks (Nilsen, 1979). These blocks are separated by northwest trending faults and are differentiated by characteristic structural features which reflect the deformation history of the individual blocks.

The study area occupies the part of the Ben Lomond block between the Zayante and Ben Lomond faults (fig. 4). In contrast to strong folding of the Tertiary sedimentary rocks on the La Honda tectonic block



BL = Ben Lomond fault
CFZ = Calaveras fault zone
GFZ = Green Valley fault zone
HFZ = Hayward fault zone
SAFZ = San Andreas fault zone
ZFZ = Zayante fault zone
SFZ = Sargent fault zone
SG-HFZ = San Gregorio-Hosgri fault zone

N

Figure 3. Quaternary Relative Plate Movements in the San Francisco Bay Region.

(Modified from Page, 1987)

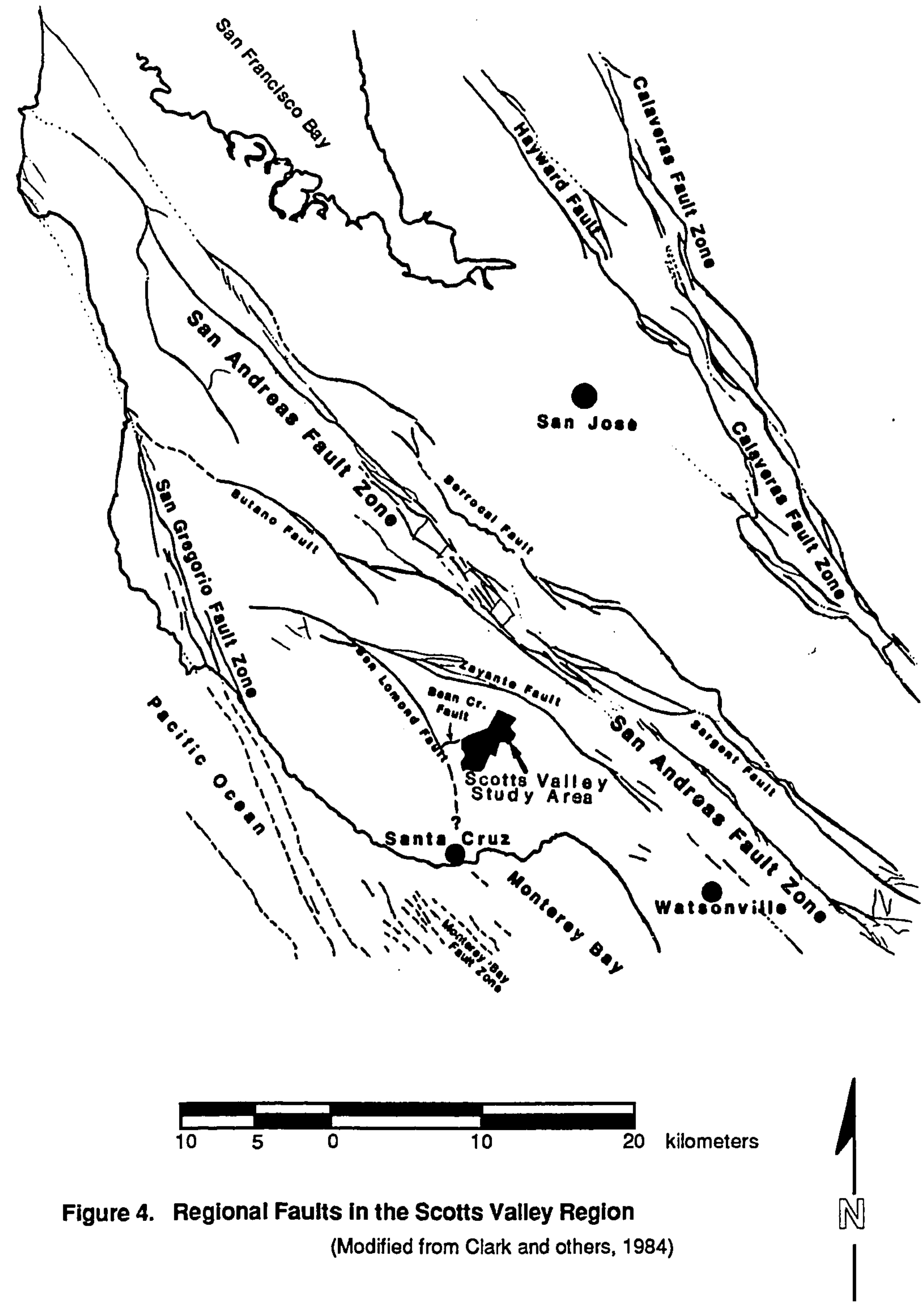


Figure 4. Regional Faults in the Scotts Valley Region

(Modified from Clark and others, 1984)

on the northeast side of the Zayante fault, sedimentary rocks in the Scotts Valley area have only been slightly deformed into broad, open folds. Deformation from regional tectonics in the Ben Lomond block has been largely accommodated by movement along the regional fault zones. It has been suggested by Clark (1981) that differences in the degree of deformation between the Tertiary sedimentary rocks to either side of the Zayante fault may have been caused by variations of the thicknesses of the Tertiary sediments. The rigidity of the shallow basement rocks in the Ben Lomond block could have limited the amount of deformation transmitted into the relatively thin sequence of the overlying sedimentary rocks.

Faults Within The Ben Lomond Block

Zayante Fault

The Zayante fault forms the northeastern boundary of the Ben Lomond block. The fault extends from near the town of Boulder Creek, southeast to the vicinity of Watsonville, where the trace of the fault is buried under Quaternary sediments (figure 4). Gravity studies performed along the projected trace of the Zayante fault southeast of Watsonville suggest that the fault continues to the northern margin of the Gabilan Range, and connects with the Vergeles fault (Coppersmith, 1979; Clark, 1981).

The Zayante fault is steeply west-dipping to vertical, and displays predominantly right lateral strike slip movement (Clark, 1981). In the Lompico area, north of Scotts Valley, the fault has displaced rocks of the Zayante Sandstone and Butano Formations approximately 0.75 miles (1.2 km) and exhibits a significant vertical component of movement (Clark, 1981). Clark has postulated that movement along the Zayante fault began in the Oligocene, and that this movement influenced deposition of the San Lorenzo Formation and Zayante Sandstone by uplifting the crystalline basement rocks to a point of emergence above sea level. Lineaments and possible Quaternary fault scarps located along the trace of the Zayante fault near Watsonville suggest that segments of the fault may have experienced movement as recent as the Holocene (Hall and Dupre, 1974; Coppersmith, 1979). Studies by Coppersmith (1979) indicate that the Zayante fault has undergone an average rate of strain of 0.006 inches (0.016 cm) per year from the Oligocene through the Holocene.

Ben Lomond Fault

The Ben Lomond fault is a vertical to steeply eastward-dipping fault which divides the central portion of the Ben Lomond structural block. The fault extends along the San Lorenzo river valley from the Zayante fault northwest of the town of Boulder Creek, to an undetermined point south of the town of Felton (fig. 4). Recent studies by Phillips (1981) and Stanley and McCaffrey (1983) have provided evidence suggesting that the Ben Lomond fault may extend southward through the City of Santa Cruz, possibly into Monterey Bay.

Tertiary sedimentary rock units along the fault trace have been vertically offset, with the east side of the fault down relative to the west side. Significant horizontal displacement along the fault has not been demonstrated, and appears to have been minor. Upper middle Miocene rocks of the Monterey Formation have been juxtaposed with lower middle Miocene rocks of the Lompico Sandstone along the trace of the Ben Lomond fault, suggesting that dip separation along the fault has been less than 600 feet (Clark, 1981). Gravity studies performed along the southern and central portion of the fault in the Felton area suggest that the crystalline basement rock has been vertically offset along the Ben Lomond fault on the order of 600 to 1050 feet (Clark and Rietman, 1973; Stanley and McCaffrey, 1983).

A 1.5 inch (3 cm) offset within a Pleistocene marine terrace along a possible southward extension of the Ben Lomond fault has been interpreted as possible evidence that the fault has been active as recently as 85,000 years ago. However, no definitive offset of Holocene deposits have been identified along the trace of the fault, nor has the fault exhibited active seismicity (Stanley and McCaffrey, 1983).

Bean Creek Fault

The Bean Creek fault is an east-west trending structural feature which was mapped by Clark (1981) for a distance of approximately 1.5 miles (2.4 km) along the lower portion of Bean Creek, from a juncture at the Ben Lomond fault west of the community of Mt. Hermon, to a point just west of the study area boundary (fig. 4). The Bean Creek fault displaces middle Miocene Monterey Formation rocks along the bottom and sides of Bean Creek. Because the Monterey Formation exposed on both sides of the fault yield foraminifer fossils of the same age, the amount of separation appears to be relatively minor (Clark, 1981). The Santa Margarita Sandstone which overlies the Monterey Formation to the east of the Bean Creek fault has not been visibly offset. This suggests that significant movements have not occurred along the Bean Creek fault since deposition of the Santa Margarita Sandstone in the middle to late Miocene.

Faults And Fractures In The Study Area

A conjugate fault and fracture system has been previously identified in the Scotts Valley area by Phillips (1981) during his study of the Santa Margarita Sandstone. Mapping by the author has confirmed the existence of the conjugate fault and fracture system. The fractures are best developed in beds within the Purisima Formation, but are also apparent to a lesser degree in the other rock units exposed in the study area. The dominant fault-fracture pattern trends northwest-southeast, approximately parallel to the orientation of the Ben Lomond fault (Phillips, 1981). A secondary fault-fracture pattern is oriented in a northeast-southwest direction, approximately 90 degrees to the dominant pattern.

A steeply dipping normal fault zone is well exposed in an abandoned quarry west of Scotts Valley Drive, in the central portion of the study area (plate 1). The fault zone displaces Santa Margarita Sandstone, Santa Cruz Mudstone, and Purisima Formation rocks, with a dip separation exceeding 40 feet. The rock units have been displaced with the west side down relative to the east side. The fault zone is up to 40 feet wide and is composed of three major splays which are separated by sheared Santa Cruz Mudstone. The sheared rocks within the fault zone are stained a dark brown color and exhibit sulfur coatings on the fracture surfaces. The strike of the fault varies across the quarry exposure, ranging from N42E to N23E. The dip direction of the fault is consistently to the northwest, but dip inclinations vary from 52 to 58 degrees.

The direction of fault displacement suggests that it formed in response to local extension in a northwest-southeast direction, approximately perpendicular to the direction of regional tectonic compression. The author attempted to determine the continuity of the fault to the northeast and southwest of the quarry exposure; however, the fault zone rapidly thins towards the south end of the quarry and is obscured by landslide deposits. The fault zone is not traceable past the quarry exposure to the north and no evidence of significant displacement could be found within bedrock exposures along the projected strike of the fault to the north or south. Aerial photographs covering portions of the study along the projected trend of the fault did not show any definitive lineaments or geomorphic features suggestive of the presence of the fault.

Folds In The Study Area

The Scotts Valley syncline projects into the central portion of the study area and is one of the major folds within the Ben Lomond structural block. This fold extends from near the town of Boulder Creek to the Scotts Valley area, and then dies out just east of Scotts Valley (Clark, 1981). The Scotts Valley syncline trends northwest-southeast, approximately 25 degrees west of the trend of the San Andreas fault, and nearly perpendicular to the trend of the quarry fault zone described in the preceding section. The orientation of the Scotts Valley syncline is indicative of regional compression in a northeast-southwest direction.

The middle Miocene sedimentary rocks in the Scotts Valley area have been more strongly folded along the Scotts Valley syncline than the upper Miocene and Pliocene sedimentary rocks, suggesting that the folding was initiated during the middle Miocene (Clark, 1981). Gentle folding of the Purisima Formation rocks indicates that folding along the Scotts Valley syncline continued into the Pliocene. Folding of the sedimentary rocks during the Miocene and early Pliocene appears to have influenced deposition of the sediments, because the thickest section of the Santa Margarita Sandstone coincides with the axis of the Scotts Valley syncline (Clark, 1981; Phillips, 1981).

GEOMORPHOLOGY

Regional Geomorphology

The Scotts Valley region is located in the central portion of the Santa Cruz Mountains, which are part of the Coast Ranges geomorphic province. The Coast Ranges are characterized by geologically youthful, deeply incised stream valleys which are bounded by steep ridge systems. The present landscape has been developed primarily during the Quaternary Period and is still being actively shaped by modern processes dominated by rapid erosion. Quaternary deposition has been confined to limited fluvial deposition along the narrow stream valley bottoms and flood plains, and marine deposition along the Pacific Ocean coastal margin.

Regional uplift has steepened the gradients of the drainage systems, causing deep incision of the streams. Mass movement on the ridge slopes between drainage systems is largely responsible for the present slope morphology.

Geomorphology Of The Study Area

Weathering and Soil Formation

Bedrock in the study area decomposes into unconsolidated deposits of rock fragments and soil by a combination of mechanical, chemical, and biological degradation. The high annual rainfall and moderate temperature promote rapid rates of chemical and biologic alteration of rock fragments separated from the main body of bedrock. Some geologic rock units in the study area are broken down primarily by mechanical weathering, such as the friable Santa Margarita Sandstone, and closely fractured beds within the Santa Cruz Mudstone.

The high rainfall and dense vegetative cover cause deep weathering of the bedrock. In some locations, susceptible bedrock units are weathered to depths exceeding 30 feet. Field observations suggest that weathering occurs to the greatest depth on north-facing, heavily vegetated slopes and along low order drainage courses which retain soil moisture and contribute large amounts of organic detritus to aid chemical weathering. The mantle of rock debris and soil is transported progressively downslope by soil creep, water erosion, and landsliding, to temporarily collect in drainages and topographic hollows. The accumulated material is periodically removed by stream erosion or landsliding, and ultimately it is carried out of the study area by the major drainage systems.

Stream Morphology and Processes

Parts of the valleys of Carbonera Creek, Bean Creek, and Granite Creek are located in the study area (pl. 1). These creek valleys are separated by sub-parallel, northwest-trending drainage divides. Carbonera Creek and Bean Creek are incised from 300 to 450 feet below the average elevation of the adjacent ridges. The base level of Bean Creek is approximately 100 feet below the level of Carbonera Creek.

The lower portions of the Carbonera Creek and Bean Creek drainages have formed broad, alluviated valleys, of which Scotts Valley is the largest in the study area. The width of the alluviated floor of Scotts Valley ranges from 1800 feet in the central portion of the study area to 2700 feet in the south-central portion of the study area. The greatest width of the alluviated floor of the Bean Creek Valley is 1000 feet. The stream channels within the alluviated portions of Carbonera Creek and Bean Creek exhibit well developed meanders and have average stream gradients of 0.007 (7 ft/1000 ft). The active channels are bounded by flood plains which slope gently upward to elevated older flood plains, alluvial terraces, or colluvial fans at the bases of the adjoining ridges.

The upper reaches of the major streams and associated tributaries have formed steep, "V" shaped valleys which have been eroded into the bedrock. These portions of the drainages have steep gradients which average over 0.02 to 0.03 (20 to 30 ft/1000 ft). Resistant bedrock exposed in the sides and bottoms of these low order drainages inhibits lateral migration, limiting the width of the valley bottoms to tens of feet. Pools and riffles characterize the channels of these steep reaches. Headward advance of the low order drainages is accomplished by formation of gullies and rills which migrate uphill and coalesce to form new drainages. Overloading of the low order streams by large influxes of sediment from landslides during intense storm events cause localized changes in the channel morphology. The changes may persist for several storm events before the landslide debris can be removed by stream erosion (Blodgett and Poeschel, 1988). Sediment deposition within the alluviated stream valleys during overbank flooding can locally exceed 5 feet on the flood plains. Floodplain deposition within the Bean Creek Valley in the southern portion of the study area during flooding in 1982 exceeded 3 feet (see Blodgett and Poeschel, 1988).

Residential and commercial development has caused significant changes in drainage morphology and processes. Extensive asphalt and concrete paving has reduced the amount of precipitation infiltration and increased the amount of storm and irrigation runoff which enters the creeks through storm drains. This has caused a significant increase in discharge volume and rate. Containment of the natural drainage channels within culverts and armored channels has prevented sections of the channels from migrating laterally, thereby inhibiting natural modification of the stream channels.

Slope Morphology and Processes

Hill and ridge slopes occupy more than 60 percent of the study area. Ridge slopes in the area average 22 to 25 degrees, but locally exceed 40 degrees where slopes have been oversteepened by landsliding, stream undercutting, or human-made excavations for roadways. The steeper portions of the ridges are subject to high rates of soil creep and landsliding, and are undergoing geologically rapid modification.

Oversteepened slopes are located along the upper reaches of Carbonera Creek and on the ridge which borders the east margin of Bean Creek.

Prominent breaks in slope on the flanks of ridges have been formed by differential erosion between rock units. Bedrock units which exhibit a relatively higher resistance to erosion include calcium carbonate cemented beds in the Santa Margarita Sandstone, porcellanite beds within the Santa Cruz Mudstone, and cemented sandstone beds within the Purisima Formation. Differential erosion between the resistant sandstone beds and erodible siltstone beds in the Purisima Formation has formed a series of buttes and rounded hills in the north part of Scotts Valley.

Many of the major ridges in the vicinity of Scotts Valley have rounded tops above an elevation of approximately 1000 feet. They also exhibit minor relief and roughly accordant summits. These rounded summits may represent older, elevated erosional surfaces which were preserved between the major drainage systems.

Development on the slopes surrounding Scotts Valley has caused modification of the slope morphology and erosion processes. Grading associated with road building and building pad construction has locally changed the configurations of slopes and low order drainage systems. Concentration of runoff water on slopes from roadways and residential development has accelerated the rates of erosion in localized areas and contributed to landsliding. Deforestation from clear-cut logging in the late 1800's probably caused increased erosion until vegetative cover was re-established, effecting localized changes in the slope morphology.

GEOLOGIC UNIT DESCRIPTIONS

Geologic units in the Scotts Valley study area include Cretaceous crystalline basement rocks, middle Miocene through Pliocene marine sedimentary rocks, and Quaternary alluvium and colluvium. The distribution of the geologic units is shown on the "AEREAL AND ENGINEERING GEOLOGY MAP" (pl. 1). The basement and marine sedimentary rocks have been previously described in detail (Brabb, 1970; Ross and Brabb, 1973; Clark, 1981). Brief summaries of the lithologies of these geologic units, as they occur in the study area, are presented in this report. Detailed mapping and differentiation of the Quaternary deposits in the Scotts Valley area has not been previously presented in published form and were one of the main emphases of the project. A description of the differentiated Quaternary deposits is also presented herein.

The geotechnical characteristics of each geologic unit in the study area were estimated from test data on boring logs included in private consultant reports on file at the City of Scotts Valley and by outcrop characteristics observed by the author.

Crystalline Basement Rock (Kgr)

Crystalline basement rocks are exposed in the southeast corner of the study area, where erosion has removed the overlying sedimentary rocks. The crystalline rocks consist primarily of light colored, compact, medium-grained, granite, quartz monzonite, granodiorite, and quartz diorite. Plutonic rocks of the Salinian basement have been dated between 70 to 90 million years old by potassium-argon dating methods (Curtis and others, 1958). The basement rocks in the Scotts Valley region exhibit close to moderately spaced orthogonal jointing. Typically, the upper 5 to 15 feet of the rock is weathered and more closely fractured.

Geotechnical Characteristics

The basement rocks are generally quite hard and relatively stable in steep cut slopes with minimal sloughing or ravelling. Granitic rock makes a good subbase material for pavements when crushed. The weathered upper portion of the basement rock can be trenched and ripped with heavy earthmoving equipment, but fresh rock may require blasting.

Lompico Sandstone (Tlo)

Lompico Sandstone Formation rocks are not exposed in the study area but have been identified in six well borings drilled in Scotts Valley at depths ranging from 172 to 564 feet. All of the wells encountering Lompico Sandstone were terminated within this formation; they therefore provide no data on the thickness of the unit.

The Lompico Sandstone Formation is of early Miocene age (Clark, 1981) and consists of well sorted, thickly bedded, arkosic sandstone with lenses and interbeds of coarse conglomerate and siltstone. The Lompico Formation is the basal member of the middle Miocene sequence of transgressive marine sedimentary rocks.

Recent hydrogeologic investigations performed for the Scotts Valley Water District indicated that the Lompico Sandstone has a potential to be developed as a significant municipal aquifer. The ground water occurring within this geologic unit appears to be confined or semi-confined by the overlying Monterey Formation.

Geotechnical Characteristics

Insufficient data exist on the Lompico Formation underlying the study area to develop general geotechnical characteristics of this unit. Because the Lompico Formation is deeply buried by younger geologic units and does not crop out in the study area, it is improbable that Lompico Formation rocks would be encountered during construction activities in the Scotts Valley area.

Monterey Formation (Tm)

Monterey Formation rocks are exposed in the study area in only one small outcrop in the bed of Carbonera Creek, but have been encountered in many wells drilled in Scotts Valley. In the wells, the Monterey Formation has been encountered at widely varying depths (28 to 312 feet deep), even in closely spaced wells. This suggests that the top of the unit was extensively eroded prior to deposition of the overlying geologic units. Based on the well logs which penetrate through the Monterey Formation, the unit ranges from 10 to 140 feet thick; it rests both conformably on top of the Lompico Sandstone Formation and nonconformably on the granitic basement rock.

The Monterey Formation is of middle Miocene age (Brabb, 1970; Clark, 1981). In the study area, it consists of medium bedded, olive-gray, organic mudstone and sandy siltstone. The Monterey Formation was deposited in a deepening marine basin and represents the upper member of the middle Miocene transgressive marine sequence. The Monterey Formation forms a relatively continuous regional aquitard.

Geotechnical Characteristics

The Monterey Formation rocks exposed along Carbonera Creek exhibit a slight to medium fissility and are moderately indurated. The rocks are generally closely to moderately fractured.

Santa Margarita Sandstone Formation (Tsm)

The Santa Margarita Sandstone crops out extensively in the study area and has been encountered in most of the water wells drilled in Scotts Valley (22 of 24 reported wells). Excellent exposures exist within sand and gravel quarries in and around the City of Scotts Valley. The Santa Margarita Sandstone thins markedly from the west side of the study area, where it locally exceeds 300 feet in thickness, to the east side of the study area, where it is locally less than 50 feet thick. In the southwest part of Scotts Valley, the Santa Margarita Sandstone nonconformably overlies the crystalline basement rocks. In some locations, the unit thins dramatically near the contact with the basement, suggesting that the crystalline rocks formed isolated knobs and ridges which projected above sea level during deposition of the

Santa Margarita Formation. In the rest of the study area, the Santa Margarita Sandstone rests unconformably on top of the Monterey Formation. Subsurface information from water wells indicates that the contact between the Santa Margarita Sandstone and Monterey Formation is an uneven erosional surface. Deep channels in the Monterey Formation are filled with coarse gravel deposits of the lower portion of the Santa Margarita Formation. These form excellent auqifers.

The upper Miocene Santa Margarita Sandstone is the lower unit of a conformable sequence of transgressive marine sedimentary rocks which were deposited between middle Miocene and middle to late Pliocene time. Studies performed on the Santa Margarita Sandstone in the Central Santa Cruz Mountains by Phillips (1981) suggest that it was deposited in a high energy, shallow marine environment. The Santa Margarita Sandstone is composed of medium-grained, well-sorted, friable, arkosic sandstone with pebble and cobble-bearing lenses. The sandstone contains fossiliferous beds which are moderately well cemented with calcium carbonate derived from dissolution of the fossils. The fossil assemblage contained within the Santa Margarita is dominated by shallow-marine echinoids, mollusks, sharks teeth, and vertebrate bones. The sandstone is generally massive to thickly bedded, and contains large planar and trough crossbedding. Fresh exposures of Santa Margarita Sandstone are yellow-gray in color, and turn light gray to white when weathered. In some exposures, the sandstone develops a thin, gray crust which is slightly harder and more resistant to erosion than sandstone which has not developed the surficial crust.

The Santa Margarita Sandstone is the primary municipal and domestic aquifer for the Scotts Valley area, and has been extensively developed. The ground water in the Santa Margarita Sandstone is primarily unconfined, but may be semi-confined by overlying sedimentary units in localized areas. Sand and gravel from the Santa Margarita Sandstone is a major mineral resource, and is locally quarried for construction aggregate and glass manufacturing.

Geotechnical Characteristics

Fresh Santa Margarita Sandstone is relatively dense, but the individual sand grains and gravel clasts are poorly cemented. As a result, the sandstone readily disintegrates into deposits of loose sand and gravel by weathering, animal burrowing, or grading activity. The sandstone also exhibits a high gullying potential from concentrated surface water flow. Excavated slopes in Santa Margarita Sandstone are commonly stable at near-vertical inclinations, but gradually start to erode and gully, causing fans of loose sand and gravel to accumulate at the bases of the slopes. The contact between the Santa Margarita Sandstone and the overlying Santa Cruz Mudstone forms a zone of regional instability, as discussed in the "LANDSLIDE" section of this report. The Santa Margarita Sandstone can be easily trenched and ripped with most earthmoving equipment, and it is a good source of well-draining, non-expansive fill material.

Santa Cruz Mudstone (Tsc)

The Santa Cruz Mudstone crops out most extensively in the north-central portion of the study area. Throughout the rest of Scotts Valley, this unit occurs in thin bands or isolated knobs near or along the tops of ridges. Surface exposures and well logs indicate that the Santa Cruz Mudstone varies from 40 to 150 feet thick in this area. The mudstone rests conformably on top of the Santa Margarita Sandstone throughout most of the study area, and is overlain conformably by the Purisima Formation. The Santa Cruz Mudstone is the upper Miocene to Pliocene part of the middle Miocene to Pliocene marine transgressive sedimentary sequence exposed in the study area. It was deposited in a deepening marine basin (Clark, 1981).

In the Scotts Valley area, the Santa Cruz Mudstone consists of thin to medium-bedded, well-indurated, olive gray to yellow brown siliceous mudstone and porcellanite. The rocks are quite hard and brittle, and lack a well developed fissility. The mudstone weathers mechanically to produce angular rock chips. The outcrop geometry of the Santa Cruz Mudstone is largely controlled by a distinctive bedding plane parting and close to moderately spaced high angle fractures.

In some locations, the Santa Cruz Mudstone is fractured sufficiently to store and transmit small to moderate quantities of water. The Santa Cruz Mudstone is more resistant to erosion than the underlying Santa Margarita Sandstone, and forms a prominent break in slope.

Geotechnical Characteristics

The Santa Cruz Mudstone is well indurated, and fracturing and bedding plane parting control the strength of the rock. Exposures of the mudstone are generally resistant to erosion. Stability in cut slopes ranges from poor to moderate, depending on the degree of fracturing and weathering. Excavated slopes in highly fractured and/or weathered rock may be subject to ravelling or toppling. The Santa Cruz Mudstone can generally be trenched and ripped with power earthmoving equipment. The contact between the Santa Margarita Sandstone and overlying Santa Cruz Mudstone forms a zone of regional instability. Many of the debris flows in the study area have occurred in colluvial deposits developed over the Santa Cruz Mudstone (pl. 2).

Purisima Formation (Tp)

Rocks of the Purisima Formation crop out extensively in the north and east portions of the study area, and also discontinuously along ridgetops in the western and southern portions of Scotts Valley. The thickness of the Purisima Formation ranges from less than 100 feet to greater than 250 feet. The Purisima Formation conformably overlies the Santa Cruz Mudstone throughout the study area. The Purisima Formation represents the upper member of the Miocene to Pliocene transgressive marine sedimentary sequence. It was deposited in a marine basin which gradually shallowed as it became filled with andesitic and rhyolitic debris (Clark, 1981).

The Purisima Formation has been divided into five members, these are fully exposed in the formation type section in the vicinity of Purisima Creek in San Mateo County (described by Cummings and others, 1962). In the vicinity of Scotts Valley, the upper portion of the Purisima Formation has been eroded away, leaving only the lower and middle portions of the formation. In the study area, the Purisima Formation is composed of thick to very thick-bedded, yellow-gray, tuffaceous and diatomaceous siltstone with interbeds of light gray diatomite and brown-gray, fine to medium-grained andesitic sandstone. The siltstone and diatomite beds are generally friable to slightly indurated and they readily weather to form rounded landforms. In most exposures, the diatomite beds exhibit well developed near-vertical, orthogonal joints; one joint set trends north-south, and the other set trends northeast-southwest. The sandstone beds are generally well cemented and are relatively resistant to erosion. Jointing and fracturing is generally more widely spaced within the sandstone beds and some of the joints and fractures have been infilled or healed. Differential erosion between siltstone and sandstone beds in the Purisima Formation has formed a series of distinctive buttes in the northern portion of the study area.

Geotechnical Characteristics

The siltstone and diatomite beds within the Purisima Formation exhibit a slight degree of cementation. It is possible that saturation could result in a substantial reduction in the bearing strength of these materials. The sandstone beds generally exhibit a high bearing strength due to the high degree of cementation. Poorly indurated zones within the siltstone beds are susceptible to erosion and gullying, whereas the sandstone beds are quite resistant to erosion. Stability of the siltstone and diatomite beds in excavated slopes ranges from fair to moderate. Highly jointed diatomite beds may experience ravelling and toppling and may only be marginally stable in steep or high cut slopes. The sandstone beds generally exhibit a moderate to high stability in cut slopes. Siltstone and diatomite beds in the Purisima Formation can generally be trenched and ripped with earthmoving equipment. The cemented sandstone beds may be difficult to trench, but should be rippable with heavy earthmoving equipment. Steep slopes underlain by Purisima Formation siltstone and diatomite are prone to landsliding on a regional scale. Numerous debris flows in the study area have occurred within colluvial deposits developed over the Purisima Formation (pl. 2).

Older Alluvium (Qoa)

Deposits of older alluvium are estimated to range in age from late Pleistocene to Holocene, based on the topographic occurrence of the deposits, degree of soil profile development, and physical characteristics. These deposits have been preserved in slightly elevated stream terraces and gently sloping former floodplains along the margins of the major valleys in the study area, at elevations above the maximum flood levels of the active stream and creek drainages. The older alluvium was deposited by higher stands of the present drainage systems, and was left as terraces or elevated flood plains when the drainages cut down through the bottoms of the valleys. The older alluvial deposits have undergone varying degrees of erosion and weathering. These processes have removed a significant volume of the deposits. The remaining deposits are generally less than 25 feet thick.

The older alluvium consists of poorly consolidated sand and gravel with varying amounts of silt and clay. Parts of the elevated stream terraces exposed along Bean Creek contain a large percentage (greater than 50 percent) of subrounded to subangular, gravel-size material. Some of the sediments have been cemented with iron oxide compounds. Soil development on the alluvium ranges from immature to well developed. Although some zones within the older alluvial deposits consist of relatively permeable sand and gravel, the unit is not a significant aquifer because of the limited thickness. The older alluvium is, however, a potential source for significant ground water recharge.

Geotechnical Characteristics

Deposits of older alluvium are generally medium dense to dense. The coarser deposits have good drainage characteristics, whereas the finer material exhibits poor to moderate drainage. The better cemented and/or denser zones within the older alluvium may be stable in shallow excavated slopes of limited height (less than 6 feet), but the looser, less cemented zones generally require support. The older alluvial deposits can generally be trenched and ripped with earth moving equipment.

Younger Alluvium (Qya)

Deposits of younger alluvium are located within the active stream channels and flood plains along the axes of the perennial drainages, in the topographically lowest portions of the valleys. The younger alluvial deposits are Holocene in age and are estimated to have been deposited within the last 5,000 years. The deposits range in thickness from approximately 5 to 40 feet.

Younger alluvium consists of unconsolidated, loose to medium dense gravel and sand with interbeds and lenses of soft to firm silt and clay. Varying amounts of organic material may also be incorporated. The average particle size gradation is within the silt to medium sand range, with a large percentage of cobble and pebble-sized clasts in stream channel deposits. Because the younger alluvial deposits are located in the lowest parts of the valleys, they are locally saturated. The younger alluvium is recent and active enough that stable surfaces and mature soil profiles are not present. In the study area, the younger alluvial deposits are too thin to store significant volumes of ground water and are not considered to be a significant aquifer.

Geotechnical Characteristics

Sediments of the younger alluvium generally exhibit highly variable bearing strengths, depending on the size and composition of the sediment, amount of organic material, and degree of saturation. Lenses of potentially liquefiable sand and silt may be present. Because the younger alluvium is located within active stream systems, structures or improvements located on these deposits may be subject to flood inundation or erosion. Variation of the composition, organic content, particle size, and degree of saturation present a potential for differential settlement of structures. Excavated slopes or foundations within younger alluvium generally require support. They may experience problems associated with a high ground water table. The deposits are generally easily excavated with earth moving and hand operated equipment.

Colluvium (Qc)

Colluvial deposits mantle most of the ridge slopes throughout the study area. These deposits have accumulated within drainage channels and at the bases ridge slopes. Only those deposits of colluvium estimated to be greater than 6 feet thick have been differentiated on the "AREAL AND ENGINEERING GEOLOGY MAP" (pl. 1). The colluvial deposits are estimated to have accumulated primarily during the Holocene.

Colluvial deposits consist of heterogeneous mixtures of unconsolidated soil, rock debris, and organic debris, resulting from weathering and downslope movement of the parent material. The composition of colluvial deposits often is similar to that of the underlying rock units. Colluvium accumulates by mass wasting processes, whereby soil and weathered bedrock material is transported down slope under the primary influence of gravity. The presence of thick deposits of colluvium indicate that high rates of mass movement (i.e. landsliding, soil creep) and weathering are occurring on a slope. The resulting deposits are not size sorted, as are water deposited sediments. Colluvial deposits are periodically removed at an accelerated rate by landsliding. Upon removal, a cycle of redeposition begins on the slopes.

Geotechnical Characteristics

Colluvial deposits exhibit widely variable bearing strengths for foundations and are subject to deformation from loading. Because colluvial deposits are heterogeneous, they pose a potential for differential settlement. Active creep processes within colluvial deposits can induce high lateral loads on rigid structures. Colluvium is the least stable of the mapped geologic units in the study area and may be subject to landsliding. The contact between colluvium and the underlying rock is a particularly critical zone of landsliding potential. Colluvial deposits may retain large amounts of water, especially during and immediately after intense rainfall events. Careful control of both surface and subsurface drainage is critical to maintain the stability of improvements constructed on colluvium. Colluvial deposits are generally unstable in excavations and usually require support for steep or high slopes.

Fill (Qf)

Fill consists of human-placed soil, rock, organic debris, and manufactured materials of historic age (generally less than 50 years old in the Scotts Valley area). Fill deposits are usually of local derivation, but also may consist of material which has been imported a significant distance. Fill deposits vary widely in thickness. In the Scotts Valley area, large fill deposits are generally limited along roads and commercially developed areas. In steeply sloping areas, locally thick fill may underlie stream or swale road crossings, or the downhill sides of building pads. The engineering behavior of fill is highly variable and is dependent on the composition and grain size of the material, amount of organics, degree of saturation, and method of placement. It is highly probable that fill soils placed prior to the mid 1960's were not engineered and are therefore susceptible to differential settlement and/or downslope movement.

SEISMOLOGY

Regional Seismicity

The central Santa Cruz Mountains are located in a highly seismic region which is traversed by the active San Andreas fault system. The locations of the major faults in the region are shown on figures 4 and 5. The high seismicity is caused by continuing transform movement between the Pacific and North American crustal plates. The plate movements induce strain in the basement rocks to either side of the plate contact. The strain becomes concentrated along pre-existing zones of weakened rock within the major fault zones.

Strain accumulation along the central Santa Cruz Mountains portion of the San Andreas fault is estimated to average approximately 0.48 to 0.64 inches (12 to 16 mm) per year (Wesnousky, 1986; NEPEC, 1988). The strain accumulates until it exceeds the strength of the rock, at which time it is released as earthquake energy when the rock masses within the fault zone fail and shear past each other. Studies by Sykes and Nishenko (1984) on the San Andreas fault in the Transverse Ranges of southern California suggest that strain may accumulate to higher levels along large bends in the fault which occur in the both the Transverse Ranges and central portion of the Santa Cruz Mountains. The bends increase the frictional resistance in the fault zone, and thus a larger amount of accumulated strain is required for the fault to rupture through the bends (Sykes and Nishenko, 1984). The high strain accumulation may increase the potential for larger earthquakes along these segments of

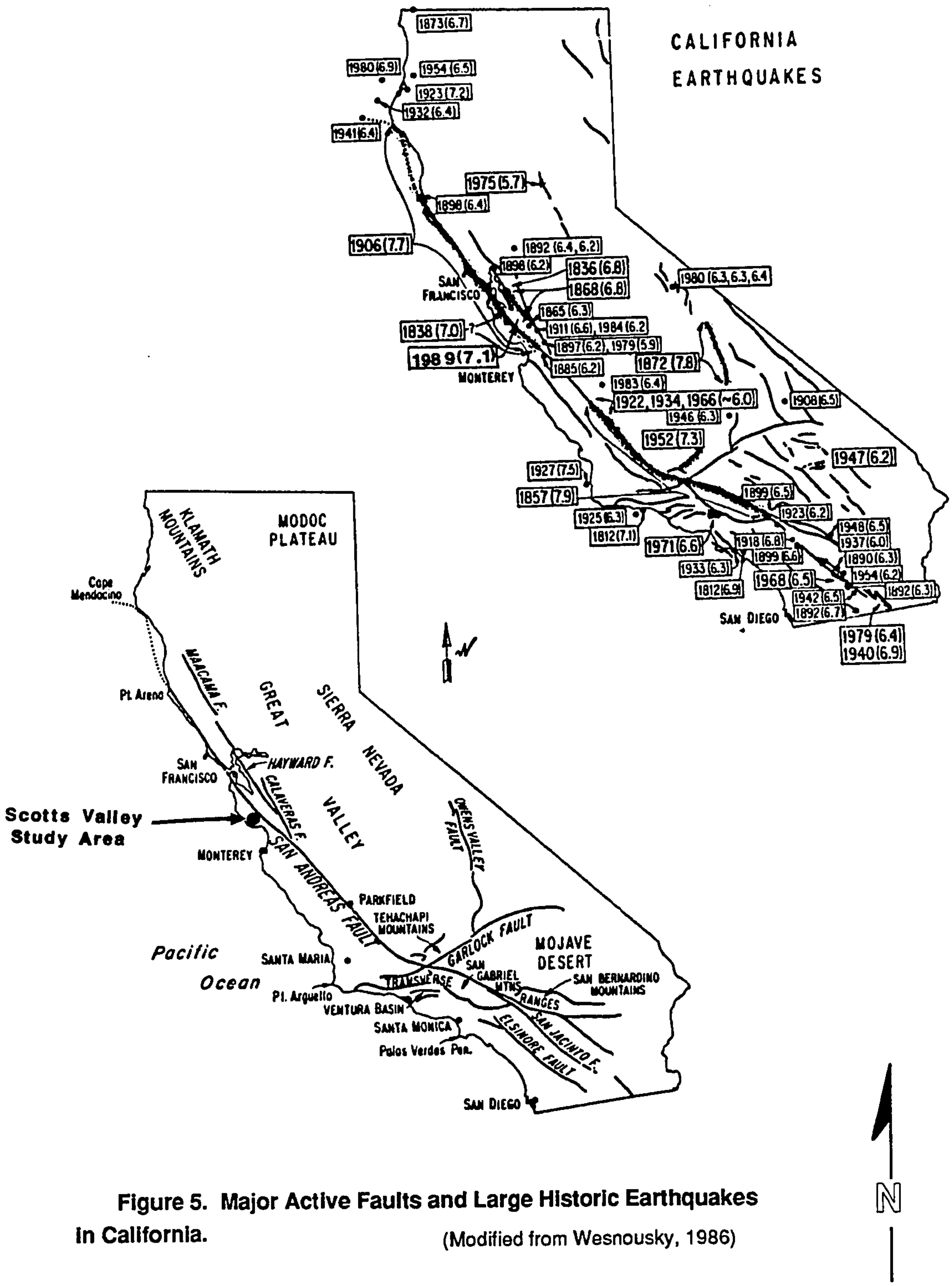


Figure 5. Major Active Faults and Large Historic Earthquakes in California. (Modified from Wesnousky, 1986)

the fault. Some segments of the major faults undergo continual small scale deformation (fault creep), thereby releasing strain before it can accumulate to a high enough level to cause a major earthquake. Evidence indicative of fault creep has been documented along segments of the San Andreas, Calaveras, Hayward, and Sargent faults in the San Francisco Bay Region (Wesson and others, 1975). Creeping portions of the faults are characterized by swarms of small earthquakes, and slow progressive earth displacements.

The locations of earthquake epicenters within a 62 mile (100 km) radius of Scotts Valley were compiled for this study from the USGS Earthquake Data Base System in Denver, Colorado in order to quantitatively evaluate the seismicity of the region. The epicenter locations for 1645 cataloged earthquake events greater than 3.0 Richter Magnitude (3.0 RM) occurring between June, 1808 and December, 1988 are shown on an earthquake epicenter location map (fig. 6). Instrumentally recorded earthquakes occurring in the region have ranged in depth from 0.60-19.0 miles, with an average depth of 4 miles. Only the larger earthquake events occurring prior to the 1930's are shown. A network of sensitive seismic recorders installed in the region in the 1930's was capable of detecting small earthquake events. Accurate historical records on earthquakes which occurred prior to that time are generally limited to the largest events which were felt over wide areas. These were thus documented in newspaper articles and other written accounts.

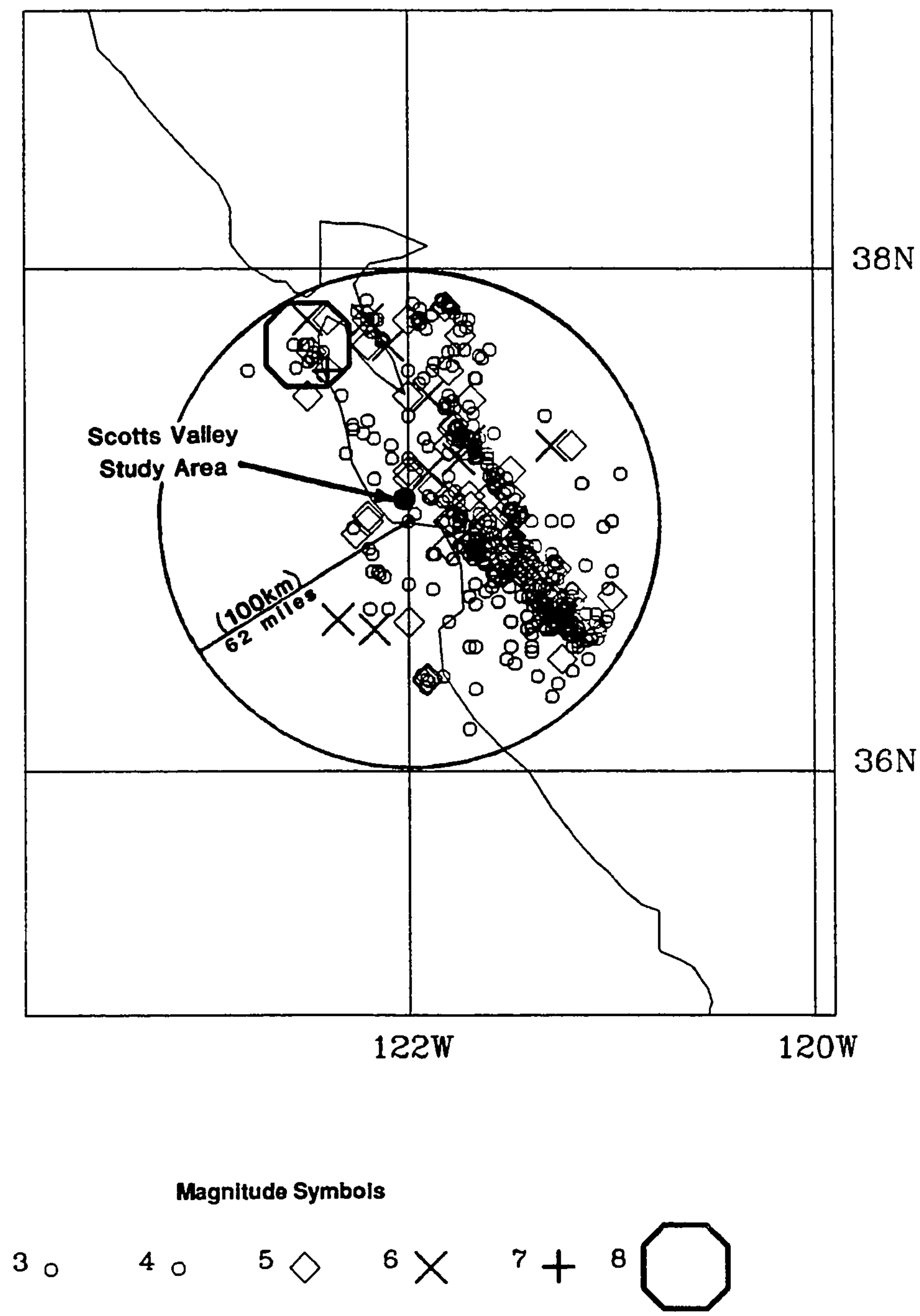


Figure 6. Epicenter map of earthquakes occurring within a 62 mile (100 km) radius of Scotts Valley from 1808 to January, 1989.

(United States Geological Survey Earthquake Data Base System)

The preliminary epicenter locations of the main shock and aftershock sequence for the October 17, 1989 Loma Prieta earthquake are plotted separately on figure 7 for clarity. This plot was prepared by the University of California at Berkeley Seismographic Stations (Bolt, 1989).

The earthquake epicenters shown on figures 6 and 7 are clustered along the traces of the San Andreas, Calaveras, Hayward, and San Gregorio faults, suggesting that each of these faults are seismically active. Large earthquakes which have caused wide-spread damage have been generated in the central California region during historic times by the San Andreas fault (1838, 1890, 1906, 1989), Hayward fault (1836, 1868), Calaveras fault (1861, 1984), and faults within Monterey Bay (1926) (fig. 5). Over 70 earthquakes equaling or exceeding 5.0 RM have been documented to have occurred within a 62 mile radius of Scotts Valley between 1808 and November 1989 (fig. 6).

1906 San Francisco Earthquake

The greatest earthquake recorded in central California during historic times was the 1906 San Francisco earthquake which was generated by the San Andreas fault and which caused severe damage extending from the Hollister area to north of San Francisco. Offsets along the surface rupture of the fault exceeded 16 feet (5 m) north of San Francisco and were on the order of 6 feet (2 m) along the central Santa Cruz Mountains section of the fault (Lawson, 1908). This earthquake event caused considerable damage throughout the Santa Cruz Mountains,

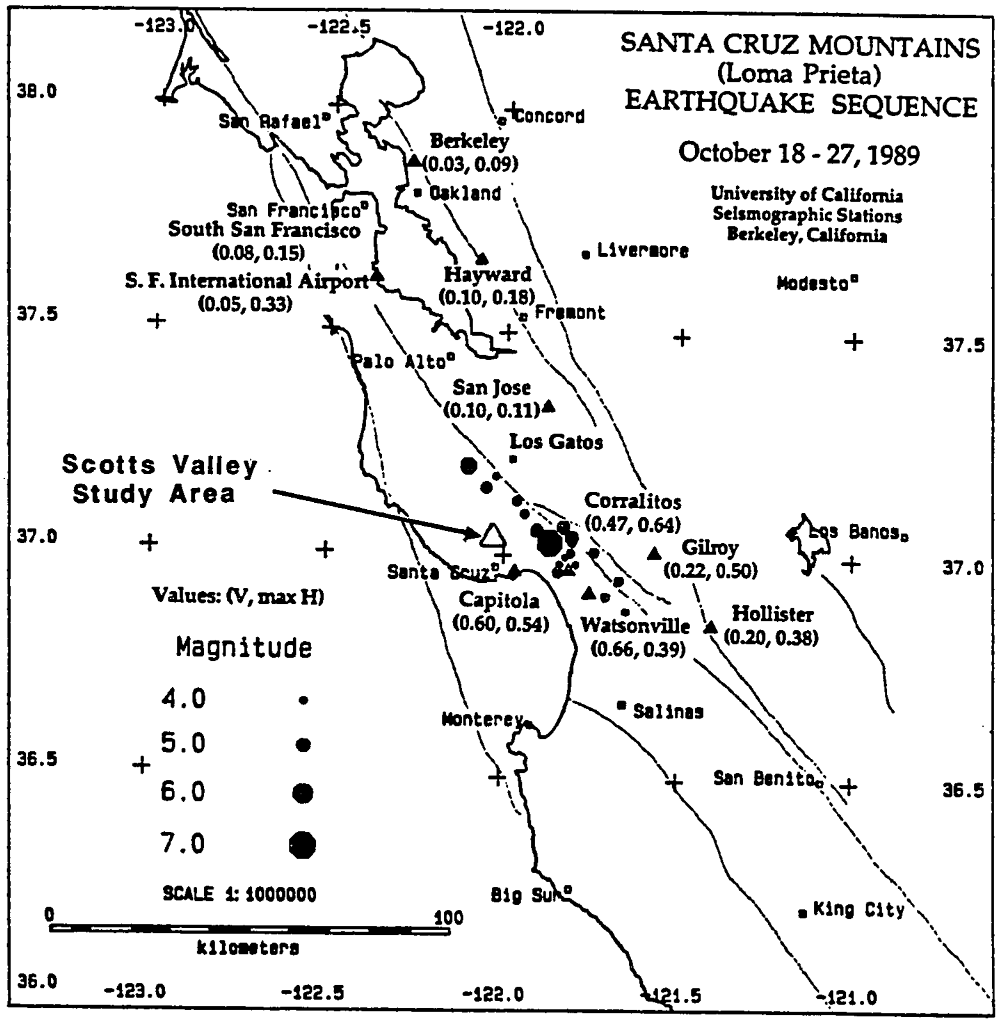


Figure 7. Location of Main Shock and Major Aftershock Sequence from 1989 Loma Prieta Earthquake.

(University of California Seismographic Stations, 1989) including extensive landsliding, localized ground cracks and failures, and stream bank failures. A compilation of seismically induced ground failures in northern California prepared by Youd and Hoose (1978) documents that landslides and ground cracks developed between Scotts Valley and the town of Felton during the 1906 earthquake. Sand boils and ground settlement were documented to have occurred along the San Lorenzo River, approximately 2 miles southwest of Scotts Valley.

1989 Loma Prieta Earthquake

The most recent earthquake to produce damaging effects in the study area was a 7.1 RM event which occurred along the Santa Cruz Mountains segment of the San Andreas fault on October 17, 1989 (1989 Loma Prieta earthquake). The epicenter of the earthquake was located northwest of the town of Corralitos, approximately 6 miles northeast of Scotts Valley (fig. 7). Seismic data indicate that the hypocenter of the earthquake was 11.5 miles deep. The USGS recorded over 4,800 aftershocks from the earthquake between October 17 and November 1, 1989, including about 25 which equaled or exceeded 4.0 RM (Bolt, 1989). The aftershock sequences suggest that a 22 mile (35 km) segment of the San Andreas fault ruptured during the earthquake, and that the rupture surface dips to the southwest approximately 70 degrees (McNutt, 1990). The fault rupture extended to within 3 to 4 miles of the earth's surface. Data from the California Strong Motion Instrumentation Program (CSMIP staff, 1989) indicate maximum recorded peak horizontal and vertical ground accelerations of 0.64g and 0.47g, respectively, near the town of Corralitos, approximately 3 miles from the earthquake epicenter.

Ground shaking effects in the epicentral region suggest that accelerations were amplified along narrow ridges and bedrock spurs (Spittler, 1989). Similar occurrences of topographic amplification of ground shaking were identified from the 1971 San Fernando earthquake in southern California (Nason, 1971; Davis and West, 1972).

Strong ground shaking from the Loma Prieta earthquake was felt throughout northern California. Significant damages were reported over 55 miles from the epicenter in the Marina District of San Francisco and along the east San Francisco Bay margin in Oakland. The areas of greatest damage outside of the epicentral area occurred in isolated "pockets" which were generally underlain by thick deposits of alluvium, especially where the alluvium underwent seismically induced liquefaction. Damages in Santa Cruz County included six fatalities and over 3,000 damaged buildings, more than 550 of which have been condemned (Mahin, 1989). Preliminary estimates of the cost of damages from the 1989 Loma Prieta earthquake exceed 6 billion dollars for the greater San Francisco Bay Area, of which 1 billion dollars damage is estimated for Santa Cruz County (Mahin, 1989). The earthquake effects in the Scotts Valley study area from the 1989 Loma Prieta earthquake are described in the following sections of this report.

Earthquake Recurrence Intervals

The recurrence intervals for earthquakes in the Scotts Valley region were estimated for this investigation by analyzing earthquake frequency statistics. The analysis was performed by plotting the number of earthquakes recorded in the USGS data base against the magnitude of earthquake events greater than 4.0 RM on a semi-log graph. This is one of the standard seismological techniques used for estimation of earthquake recurrence intervals (Mualchin, 1985). A graph showing the cumulative frequency of earthquakes over 4.0 RM within a 62 mile radius of the study area since 1808 is presented as figure 8. The data have been normalized with respect to time because data on larger earthquakes are more complete than for smaller magnitude events. The graph indicates that an earthquake exceeding 4.0 RM occurs about once a year and an earthquake equaling or exceeding 7.0 RM has a recurrence interval of approximately 100 years. The analysis suggests that the 1989 Loma Prieta earthquake was a 100 year seismic event. The recurrence intervals calculated by the author correspond well with a recurrence interval of 136 years for a 6.5 RM or greater event on the Santa Cruz Mountains segment of the San Andreas fault as predicted by the USGS. The National Earthquake Prediction Evaluation Council (NEPEC) predicted that the probability for an earthquake of 6.5 RM or greater on the Santa Cruz Mountains segment of the San Andreas fault was 30 percent for the 30 year period from 1988 to 2018. The occurrence of the 1989 Loma Prieta earthquake fits within the NEPEC prediction, and helped to validify predictive modeling of earthquakes using current analytical techniques.

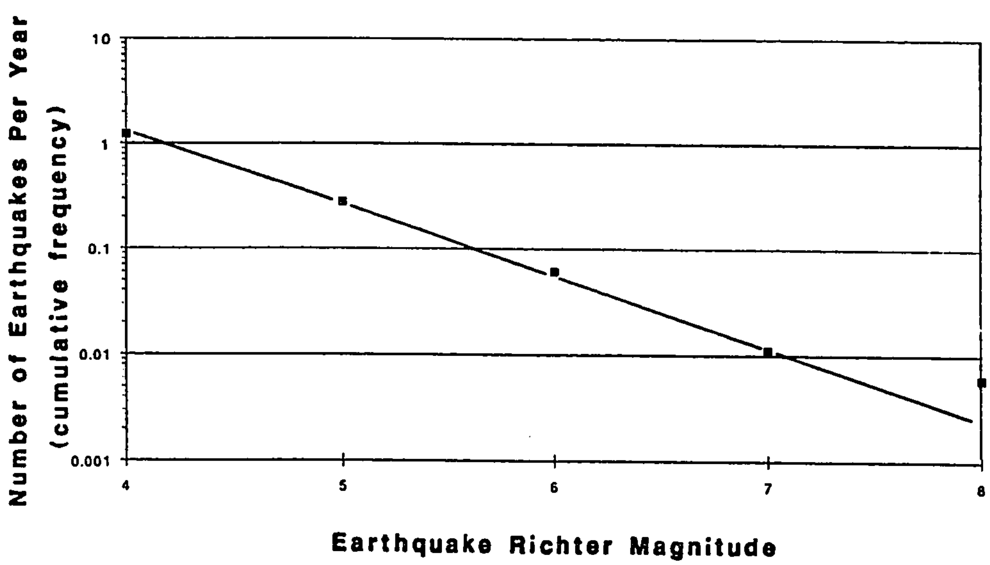


Figure 8. Cumulative Frequency of Earthquakes Greater than 3.0 RM Occuring within a 62 mile (100 km) radius of Scotts Valley from 1808 to 1988.

EARTHQUAKE HAZARDS

Earthquakes represent one of the greatest potential geologic hazards in California. The amount of damage caused by an earthquake is dependent on a number of factors including the amount of energy released by the earthquake, distance between a site and the earthquake epicenter, duration of energy release, site geology, and seismic design of structures. However, areas of incompetent or weak geologic materials may incur a higher degree of damage than areas located closer to the epicenter but which are underlain by strong geologic materials. The major hazards presented by large magnitude earthquakes include ground shaking, tectonic ground rupture along the trace of the causative or related faults, seismically-induced ground failure (lateral spreading, lurching, liquefaction), and earthquake-induced landsliding. The relative hazards from each of these effects is described in the following sections.

Evaluation of earthquake hazards in the Scotts Valley study area was accomplished by reviewing statistical data on past earthquake effects, evaluating the activity of faults in the region, evaluating the seismic response of geologic materials, and field mapping of the effects from the 1989 Loma Prieta earthquake.

Maximum Credible Earthquake

An estimate of the maximum credible earthquake (MCE) which could be generated in the Scotts Valley region is essential for evaluation of the potential future seismic hazard. A maximum credible earthquake is defined by the CDMG as the maximum earthquake which is capable of occurring within the presently known tectonic framework. One of the established empirical techniques for evaluating the potential maximum magnitude earthquake which could be generated by a fault is based on comparison between the length of historic surface rupture along the fault and the magnitude of the causative earthquake.

Analyses of faults which have not produced historic surface rupture can be made by approximating the maximum credible length of potential fault rupture, based on fault rupture length data from similar faults which have experienced historic surface rupture. Many equations relating fault rupture length to potential earthquake magnitude have been developed by various authors (e.g. Albee and Smith, 1966; Tocher, 1958; Bonilla and Buchanan, 1970). The majority of these equations are based on the assumption that half of the total fault length can rupture during any single maximum earthquake event. However, certain moderate to large historic earthquakes in California have not generated surface fault rupture (e.g., 1983 Coalinga earthquake, 1989 Loma Prieta earthquake), whereas many moderate earthquakes have generated extensive rupture (e.g., 1971 San Fernando earthquake). Additionally, it has not been scientifically quantified what fraction of a fault will rupture during a maximum magnitude earthquake event. The results from the aforementioned analyses must therefore be used with considerable judgement.

Estimates of the maximum credible earthquake which could be generated on any of the major faults within the Scotts Valley region was evaluated for this investigation by reviewing data from various published and unpublished studies on the faults and seismicity of the region (e.g., Greene and others, 1973; Hall and others, 1974). The predicted maximum earthquake for the faults were primarily derived by the empirical methods described in the preceding paragraph. The values from the various sources were averaged and compared with historic seismic events in order to obtain values for use in the Scotts Valley area. The estimated maximum earthquakes for the known active or potentially active faults are shown in table 1. The data indicate that an earthquake of 8.5 RM is possible along the San Andreas fault and that an earthquake of 7+ RM is possible along the Zayante, San Gregorio, and Monterey Bay faults. The 1989 Loma Prieta earthquake did not represent the maximum credible earthquake which could be generated by the various faults in the Scotts Valley region, but it was a major seismic event. The amount of energy which could be released by an 8.0 RM earthquake on the San Andreas fault would be approximately

Table 1. Regional Significant Faults and Anticipated Potential Earthquake Effects in the Scotts Valley Area

Fault Name	Evidence of Activity	Surface Distance From Study Area (miles)	Fault Length (miles)	Maximum Historic Earthquake (Richter Mag.)	Maximum Credible Earthquake (MCE) (Richter Mag.)	Estimated Recurrance Interval for MCE (years)	Maximum Bedrock Acceleration from MCE	Strong Shaking Duration from MCE (seconds)	Dominant Wave Period from MCE (seconds)	Expected Maximum Modified Mercalli Shaking Intensity from MCE
SAN ANDREAS FAULT (Active)	-definite historic seismicity -historic surface faulting [6] -offset Holocene deposits -young geomorphic features -measured fault creep	6.25	750	8.3 (1906) [6]	8.5 [1]	100-1000 [1],[5]	0.65g [10]	35-40 [11]	0.35 [11]	VIII-IX
SAN GREGORIO FAULT (Active)	-definite historic seismicity [2] -offset Quaternary deposits [2] -deformed Holocene Alluvium [9] -seafloor scarps along southern segment of fault [2] -young geomorphic features [9]	11.25	84 to 128 [2]	6.1?(1926)*[2]	7.4-7.9 [1],[2]	10-100(?)[5] 325-440(?)[2]	0.40g [10]	30-38 [11]	0.35 [11]	VI-VII
ZAYANTE FAULT (Potentially Active)	-possible seismicity [4] -young geomorphic features (?) -possible Holocene scarps near Watsonville [5] -possible deformation of Pleistocene fluvial deposits [5]	3	51 [5]	None	7.4 [1],[5]	100-5000(?) [5]	0.65g [10]	25-30 [11]	0.35 [11]	VIII-IX
MONTEREY BAY FAULTS (Active)	-possible historic seismicity near juncture with San Gregorio Fault [2], [4] -offset Holocene deposits on floor of Monterey Bay [2]	10-11.25	26 [2]	6.1?(1926)*[2]	6.7 (?) [2],[5]	Unknown	0.35g [10]	20-25 [11]	0.35 [11]	VI-VII
BEN LOMOND FAULT (Inactive ?)	-no conclusive historic seismicity -possible offset of Quaternary (85,000 year old) deposits [7] -no known young geomorphologic features	2.8	14+ [7]	None	5.5 (?) [5]	Unknown	0.30g [10]	10 [11]	0.35 [11]	V-VI

Fault Data Sources

[1] R. Borcherdt, 1975, Studies for Seismic Zonation of the San Francisco Bay Region
[2] H. Greene and Others, 1973, Faults and Earthquakes in the Monterey Bay Region, California
[3] R. Greensfelder, 1974, Maximum Credible Rock Acceleration from Earthquakes in California
[4] G. Griggs, 1973, Earthquake Activity between Monterey and Half Moon Bay, California
[5] T. Hall, A. Sarna-Wojcicki, and W. Dupre, 1974, Faults and Their Potential Hazards in Santa Cruz County, California
[6] A. Lawson, 1908, The California Earthquake of April 18, 1906
[7] R. McCalfrey and R. Stanley, 1983, Extent and Offset History of the Ben Lomond Fault, Santa Cruz County, California
[8] H. Seed and Others, 1975, Relationships Between Maximum Acceleration, Maximum Velocity, Distance from Source and Local Site Conditions for Moderately Strong Earthquakes
[9] G. Weber, K. LaJoie, and G. Griggs, 1979, Coastal Tectonics and Coastal Geologic Hazards in Santa Cruz and San Mateo Counties, California

Potential Earthquake Effect Sources

[10] R. Greensfelder (1974), after Schnabel and Seed (1972); rounded to the nearest 0.05g. No near-field effect considered.
[11] N. Donovan, 1974, Earthquake Hazards for Buildings
[12] R. Greensfelder (1974), after Seed and Others (1968); rounded to the nearest 0.05 seconds.

* 1926 earthquake in Monterey Bay could have been generated on either the San Gregorio or Monterey Bay Faults

60 times that of the 1989 Loma Prieta Earthquake. If such an event occurred along the portion of the San Andreas fault nearest to the study area, damages in Scotts Valley could be substantially more extensive and severe than occurred from the Loma Prieta earthquake.

Ground Shaking Hazard

Earthquake induced ground shaking is the greatest potential seismic hazard in most areas of California. This is because it is the most widespread earthquake effect and ground shaking occurs to some extent with every earthquake (Rogers and Williams, 1974). The degree of ground shaking can be quantified by scientific measurements of ground response (e.g. acceleration, velocity, displacement) or it can be evaluated in qualitative terms by the severity of effects produced by the ground shaking on natural and man-made objects (described as shaking 'intensity'). One of the more common methods to describe the severity of earthquake shaking is the Modified Mercalli Intensity Scale, described in table 2. The Modified Mercalli Intensity Scale has been used in this report for the purposes of describing potential ground shaking effects in the Scotts Valley study area.

The distribution and severity of damages in central California from the 1906 San Francisco and 1989 Loma Prieta earthquakes, and in Mexico City during the 1985 Mexico earthquake clearly demonstrated that ground shaking is strongly influenced by the underlying soil, geologic, and ground water conditions (Lawson, 1908; Seed and others, 1989).

Table 2. Modified Mercalli Intensity Scale (Abridged from Richter, 1958)

I. Detected only by sensitive instruments.

II. Felt by persons at rest, especially on upper floors of buildings; delicate suspended objects may swing.

III. Felt noticeably indoors, but not always recognized as an earthquake; standing automobiles rock slightly, vibration like a passing truck.

IV. Felt indoors by many, outdoors by few; at night some may awaken; dishes, windows, doors disturbed; hanging objects swing; motor cars rock noticeably; jolt like heavy object has impacted walls of structure.

V. Felt by most people including those located outdoors; sleepers awakened; direction of earthquake wave propagation estimated; some breakage of dishes, windows, and plaster; disturbance of tall objects; small unstable objects upset or displaced.

VI. Felt by all; many are frightened and run outdoors; walking is unsteady; glassware broken; objects fall off shelfs; furniture moved; weak plaster and chimneys crack or spall; vegetation disturbed.

VII. Difficult to stand; hanging objects swing wildly; furniture damaged; damage to unreinforced, older, or poorly constructed masonry; weak chimneys break off at roofline; some cracks in modern or well-constructed masonry; small landslides; noticed by drivers of automobiles.

VIII. Moderate to severe damage to unreinforced, older, or poorly constructed masonry; some cracks and spalling in modern, reinforced masonry; panel walls of buildings thrown out of frames; twisting and/or falling of chimneys, smokestacks, elevated tanks, walls; frames of structures shifted off foundations if not securely fastened; sand and mud ejected; drivers of automobiles disturbed.

IX. General panic; unreinforced, older, or poorly constructed masonry destroyed; modern reinforced masonry experiences moderate to severe damage; buildings shifted off foundations; ground cracks develop; underground pipes broken; large landslides.

X. Some reinforced, modern masonry and frame structures destroyed with foundations; serious damages to dams, dikes, and embankments; ground extensively cracked; railroad rails bent; large, wide-spread landslides.

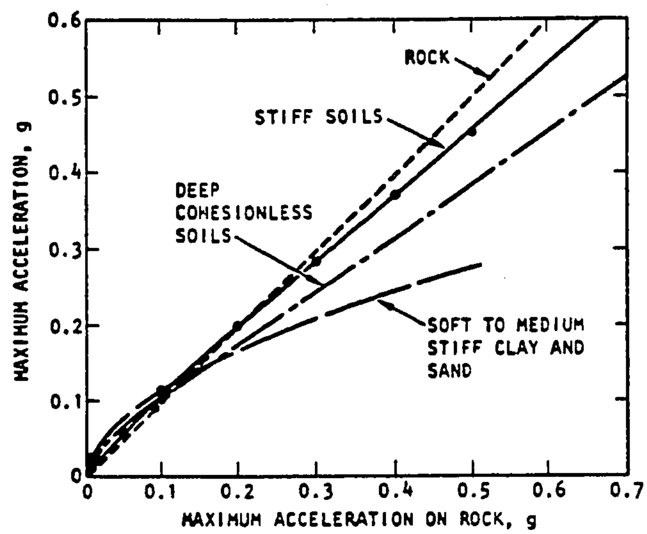
XI. Well constructed modern structures may remain standing, others are destroyed; bridges destroyed; fissures in ground; pipes severed; utilities out of service; railroad rails bent; large, extensive landslides.

XII. Damage total; waves seen on ground surface; lines of sight and level distorted; objects thrown up into air; large rock masses displaced.

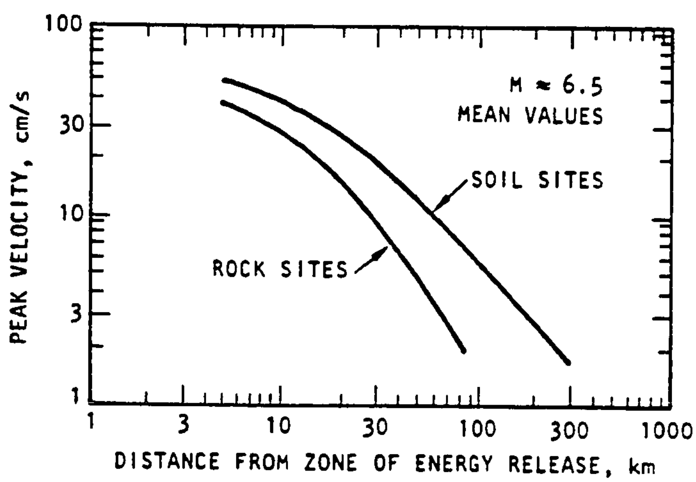
In general, damages from ground shaking and related ground failures from all three earthquake events were more severe in areas underlain by thick deposits of soft alluvial sediments or filled ground than areas underlain by competent bedrock, even when the bedrock sites were located closer to the earthquake epicenter. High ground water tables also appeared to increase the severity of ground shaking.

The influence of local geology on ground shaking effects has been analyzed and quantified by H. B. Seed and Idriss, and the results from their work are summarized in many publications (e.g. Seed and Idriss, 1971; 1982). In general, sites underlain by shallow, competent bedrock experience high accelerations, but lower particle velocities, shorter shaking duration, and lower wave amplitudes than alluvial sites (fig. 9). Sites underlain by deep, unconsolidated alluvium experience significantly increased wave amplitudes, particle velocities, and shaking durations. The greater wave amplitude and shaking duration of deep alluvial sites generally cause a greater amount of damage to structures. Thick alluvial deposits are also more susceptible to secondary ground failure from ground shaking.

A historical review of earthquake ground shaking intensity of the central California coastal region compiled by McCrory and others (1977) indicated that the Scotts Valley region has experienced Modified Mercalli (MM) shaking intensities greater than MM VI 20-25 times from the time period 1810 to 1969. Shaking intensities in the Scotts Valley area from the 1906 San Francisco Earthquake are estimated to have ranged from MM VII to MM VIII (Lawson, 1908). Based on preliminary



(Seed and Idriss, 1982)



(Sadigh et al., 1979)

Figure 9. Relationships between expected maximum acceleration of rock and soil sites, and peak velocity versus distance for soil and rock materials.

observations of damages in the Scotts Valley area, the author estimates that Modified Mercalli Intensities from the 1989 Loma Prieta Earthquake ranged from MM VI to MM VII.

The ground shaking hazard was evaluated for this investigation by: (1) conducting literature research on historic ground shaking; (2) field mapping of damages from the 1989 Loma Prieta Earthquake; (3) evaluating the regional seismicity; and (4) subjectively evaluating the local geology in the Scotts Valley area. Table 1 presents a summary of the anticipated ground shaking effects in the study area from maximum earthquakes generated on the regional active and potentially active faults.

The table shows that the greatest seismic ground shaking could occur from maximum earthquakes on the San Andreas and Zayante fault zones. The highest anticipated rock acceleration from either earthquake event is estimated to be approximately 0.65 times the force of gravity. This estimated acceleration is greater than the accelerations experienced in the Scotts Valley area from the 1989 Loma Prieta Earthquake, based on an evaluation of the extent and severity of damages noted by the author. The corresponding duration of damaging earthquake shaking would be 34 to 37 seconds for a 8.5 RM earthquake on the San Andreas fault and 24 to 30 seconds for a 7.4 RM earthquake on the Zayante fault (fig. 10). The estimated dominant wave period from both earthquakes would be on the order of 0.35 seconds. The expected Modified Modified Mercalli Intensity in the study area would be MM VIII to MM IX.

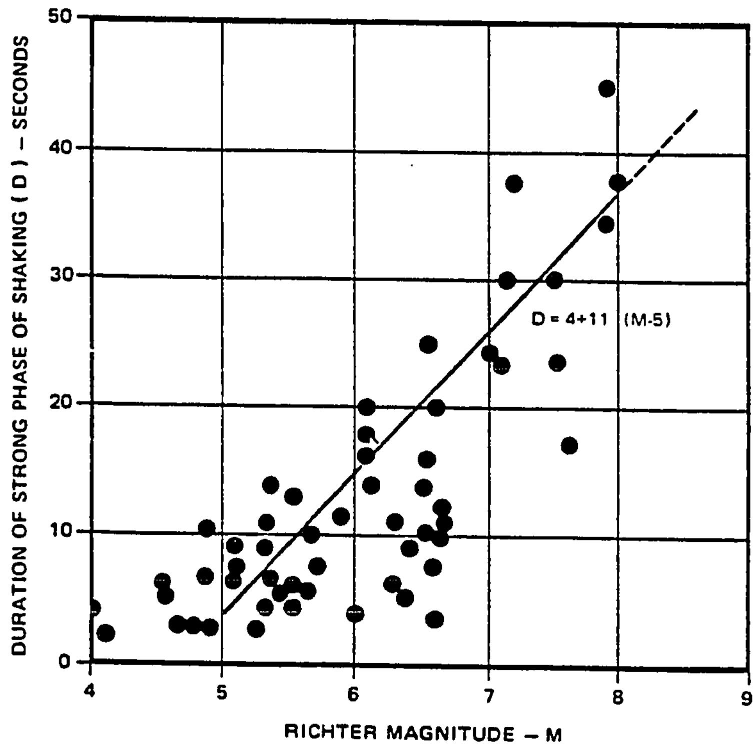


Figure 10. Relationship Between Earthquake Magnitude and Duration of Strong Shaking.

(Donovan, 1974)

The thickness of the alluvial deposits in the study area is generally less than 40 feet; therefore, it is anticipated that the alluviated areas would experience a similar magnitude of acceleration and ground shaking as bedrock areas. The alluviated areas could be subjected to a greater degree of secondary ground failure such as liquefaction.

The response of buildings to earthquake shaking is highly dependent on the design of the structure. This determines the predominant period of vibration in response to ground shaking. A critical situation can develop if the predominant period of a structure matches the predominant period of the underlying geologic materials. In this case, the structure can develop harmonic motion which greatly amplifies the movement, possibly leading to structural failure or the structures pounding against adjacent buildings which are moving out-of-phase.

1989 Loma Prieta Earthquake Ground Shaking Effects

Damages from the 1989 Loma Prieta earthquake in the study area were widespread and ranged from minor to moderate in severity. Many masonry chimneys fell or were substantially damaged, particularly those attached to older structures. Some buildings incurred structural damages, with a generally greater amount of damage occurring within older structures with inadequate anchoring between the structural framing and foundations, or with inadequate seismic shear reinforcement.

One home, located on Cadillac Drive in the central portion of the study area, experienced complete structural failure and injured an occupant.

Many windows were broken in structures throughout Scotts Valley and unsecured furnishings or objects sitting on shelves were tilted over or thrown onto the floor. The bridges which cross over Carbonera Creek on Bean Creek Road and Carbonera Way experienced minor to moderate structural damages. Analyses of damages to the Carbonera Way bridge by the author and a field assistant (John Woodruff) suggest that the structure rotated in a clockwise direction approximately 1.5 to 2 inches. The electric power supply was disrupted in the Scotts Valley area. Many businesses had to reduce or suspend operations until repairs could be made.

Overall, damages in Scotts Valley from ground shaking were substantially less than in other areas of Santa Cruz County, such as the downtown areas of Santa Cruz and Watsonville. One of the reasons for the lesser damage to structures in Scotts Valley is that a large percentage of them are of relatively recent construction (post 1960's), and thus incorporate better seismic design than older buildings located in sections of other cities. Unreinforced masonry structures and foundations, which perform poorly in earthquakes, make up a small percentage of the buildings in Scotts Valley but are relatively common in the downtown areas of Santa Cruz and Watsonville.

Seismically-induced liquefaction of alluvial deposits appears to have been partly responsible for the extensive damages in downtown Santa Cruz, but did not cause extensive damages in Scotts Valley because it occurred in localized areas which are not developed with permanent structures.

Fault Rupture Hazard

One hazard created by earthquakes is ground rupture along the trace of the causative fault. Surface rupture from historic large-magnitude earthquakes has been observed along many of the known active faults in California. Although tectonic ground rupture is usually limited to a relatively narrow zone along the trace of a fault, it can cause severe distortion or collapse of even the best engineered structures. Occurrences of historic surface rupture in California have generally occurred along faults which show evidence of prior Quaternary offsets (Wesnousky, 1986). Active fault traces which are capable of generating fault displacement can usually be identified by historic seismicity, young geomorphic features, and offset of Quaternary geologic units.

A comprehensive evaluation and mapping project of potential fault rupture hazards specific to Santa Cruz County was conducted by Hall and others (1974). Their map does not show any active or potentially active faults within the Scotts Valley study area, and shows the area to have a low potential for fault rupture.

No faults exhibiting Holocene offset or young geomorphologic features were identified in the study area during field mapping or aerial photograph analyses performed by the author. Additionally, fault displacements were not observed in the Scotts Valley study area after the 1989 Loma Prieta Earthquake. Based on available information, the potential for fault rupture is considered to be low. However, it should be noted that thick soil cover and extensive landslide deposits may obscure potentially undiscovered active fault traces. It is recommended that further investigations be performed on the fault which is exposed in the abandoned quarry to the west of Scotts Valley Drive (pl. 1) to better define its potential for surface rupture.

LIQUEFACTION

Definition

Liquefaction is the transformation of granular soil from a solid state to a liquefied state as a consequence of increased pore-water pressure induced by ground shaking. In a liquefied state, the material loses its inherent inter-granular frictional resistance and can undergo a variety of ground failures including lateral spreading, flow failure, ground oscillation, and loss of bearing capacity. Liquefaction can cause severe damages to structures, as documented vividly during the 1964 earthquake in Niigata, Japan (Seed and Idriss, 1982); the 1964 Alaska earthquake (Hanson, 1966); the 1971 San Fernando earthquake (Bennett, 1989); and the 1989 Loma Prieta Earthquake (Seed et al., 1989).

Geologic materials susceptible to liquefaction are deposits of saturated, loose, cohesionless, well-sorted silt and sand. In general, recent alluvial deposits are most susceptible to seismically induced liquefaction. With age, alluvial deposits attain an increased degree of cementation and consolidation with a corresponding increase in density.

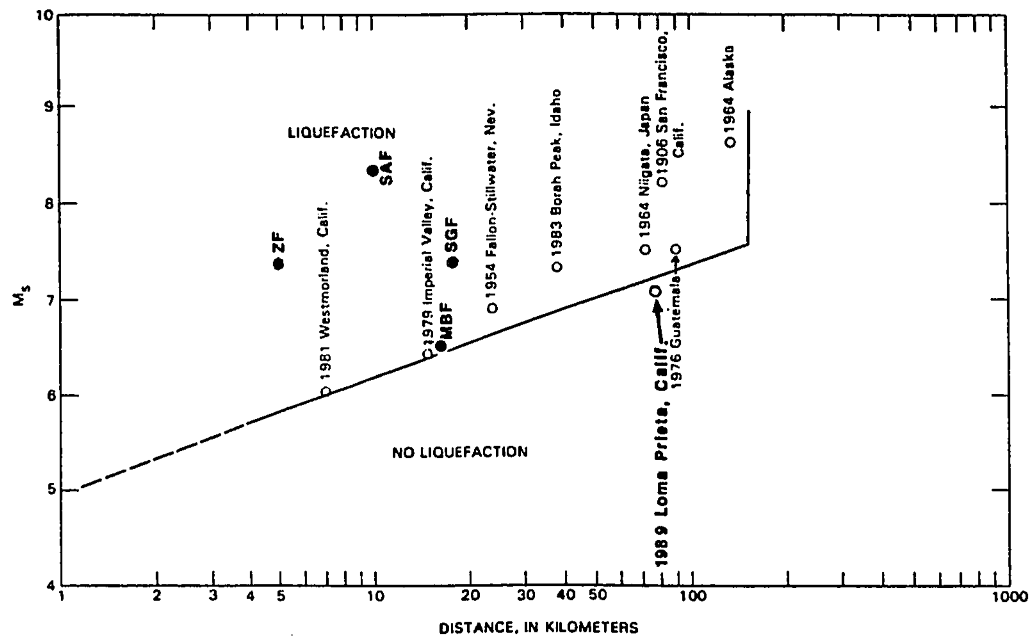
Liquefaction Opportunity

The magnitude of earthquake shaking required to produce liquefaction is inversely proportional to the distance of the site from the earthquake epicenter (Tinsley and others, 1985). The greater the magnitude of an earthquake event, the farther away significant liquefaction can occur in susceptible sediments. Liquefaction was documented to have occurred at distances of 50 to 80 miles from the epicenter of the 1964 Alaska Earthquake (Seed and Idriss, 1982) and 60 miles from the epicenter of the 1989 Loma Prieta Earthquake (Seed and others, 1989). A set of curves relating earthquake magnitude and maximum distance between the epicenter location and sites of historic liquefaction was developed by Youd and Perkins (1978)(fig. 11). The curves have been revised by the author to include data on the 1989 Loma Prieta earthquake. The liquefaction opportunity for the alluvial sediments was determined by plotting the maximum credible earthquake magnitudes determined for the active and potentially active regional faults against the closest distance between the study area and the fault traces. The resulting analysis indicated that earthquake events capable of producing liquefaction in Scotts Valley could occur from maximum credible earthquakes on all of the active and potentially active faults listed on table 1.

Liquefaction Potential

Detailed Mapping of Alluvial Deposits

The alluvial sediments which occupy the valley bottoms of the study area contain lenses and strata of potentially liquefiable silt and sand. This project included detailed geologic mapping and analysis of the alluvial sediments for the purpose of defining areas which could be subject to seismically induced liquefaction. The following



(Youd and Perkins, 1978; Youd and Wieczorek, 1982)

● Point representing plot of maximum credible earthquake magnitude versus distance between causative fault and study area for the major active and potentially active faults in the Scotts Valley region. Points located above diagonal line indicate that liquefaction could occur in susceptible sediments in the study area from a maximum credible earthquake event on the evaluated faults.

SAF = San Andreas fault
ZF = Zayante fault
MBF = Monterey Bay faults
SGF = San Gregorio fault

Figure 11. Liquefaction opportunity in Scotts Valley study area based on relation between earthquake magnitude and maximum distance at which historic liquefaction has been observed.

characteristics of the alluvial deposits were evaluated:

o depositional environment;
o geomorphic expression;
o soil-profile development;
o relative age;
o degree of induration;
o texture;
o and relative compaction.

Using these criteria, the alluvial sediments were divided into two informal geologic units: younger alluvium (Qya) and older alluvium (Qoa). The distribution of the two alluvial units within the study area is shown on plate 1 and a description of the units is included in the "GEOLOGIC UNIT DESCRIPTIONS" section of this report. The extent of the two alluvial units was mapped by a combination of stereographic analyses of aerial photographs, review of Soil Conservation Service soil maps, review of well and exploratory boring logs, and field mapping. Field mapping included observation of stream bank exposures, road cuts made in alluvial material, and shallow test holes made by the author with a hand trowel. A reconnaissance of the alluvial areas was conducted following the 1989 Loma Prieta Earthquake in order to evaluate the earthquake response of the alluvium.

Evaluation of Liquefaction Susceptibility

Studies performed in the San Francisco Bay Region by Youd and others (1975) and in southern California by Tinsley and others (1985) indicated that deposits of geologically recent alluvium (younger Holocene) are more susceptible to liquefaction than deposits of older alluvium (older Holocene to Pleistocene-aged). This has been confirmed by historic liquefaction which has most often occurred in deposits of young alluvium along active stream channels and coastal areas. The liquefaction susceptibility of alluvial deposits generally decreases inversely with the age of the sediments due to progressive consolidation and cementation. In the study area, exposures of younger alluvium are more friable and less cemented than the older alluvium.

A quantitative measure of the relative liquefaction susceptibility of the alluvium in the study area was made by evaluating Standard Penetration Test (SPT) data compiled on geotechnical boring logs in soil reports on file at the City of Scotts Valley, and the California Department of Transportation office in San Francisco. The SPT test is performed by driving a split spoon soil sampler of standardized dimensions into undisturbed soil with a 140 pound hammer dropped from a height of 30 inches. The number of hammer blows required to drive the sampler in 6-inch increments is recorded. The sum of the blow counts recorded during driving of the last two 6-inch increments are designated as the SPT blow count resistance (N). The penetration resistance of granular soils in SPT tests has been correlated to the in-situ relative density of the soils by Gibbs and Holtz (1957), and is commonly used to estimate the liquefaction potential of a soil. A sizable data base has been accumulated on the relationship between SPT blow count resistance and liquefaction potential of soils at various sites throughout the world which have experienced historic liquefaction (Seed and Idriss, 1982). The data base suggests that the SPT test provides a good approximation of the relative liquefaction susceptibility of granular soils.

The N values from SPT tests performed within the two alluvial units in the study area were plotted separately on a set of liquefaction potential curves developed by Tinsley and others (1985) for evaluation of alluvial deposits in the Los Angeles Basin. These curves allow analyses for two different earthquake magnitudes (6.5 RM and 8.0 RM) and three different ground water conditions (0, 10, and 30 feet below ground surface). Because the seismic conditions for the Scotts Valley region are similar to those for the Los Angeles Basin, the curves developed by Tinsley were determined to be applicable for evaluation of the alluvium in the study area. Figures 12 and 13 show the plots for SPT tests performed in the younger and older alluvial deposits, respectively. Only SPT tests performed in potentially liquefiable soils described as sand or silty sand were plotted. Those points plotting to the left of the M=6.5 set of curves are defined as exhibiting a high potential for liquefaction (soils potentially liquefiable during a 6.5 RM or greater event); and those plotting between the M=6.5 and M=8 sets of curves are defined as exhibiting a moderate potential for liquefaction (soils potentially liquefiable during a 8.0 RM or greater earthquake event). Points plotting to the right of the M=8 curves are considered to exhibit a low liquefaction potential. The curves representing a ground water elevation at 0 feet were selected because perched ground water zones can rapidly develop in the alluvium during

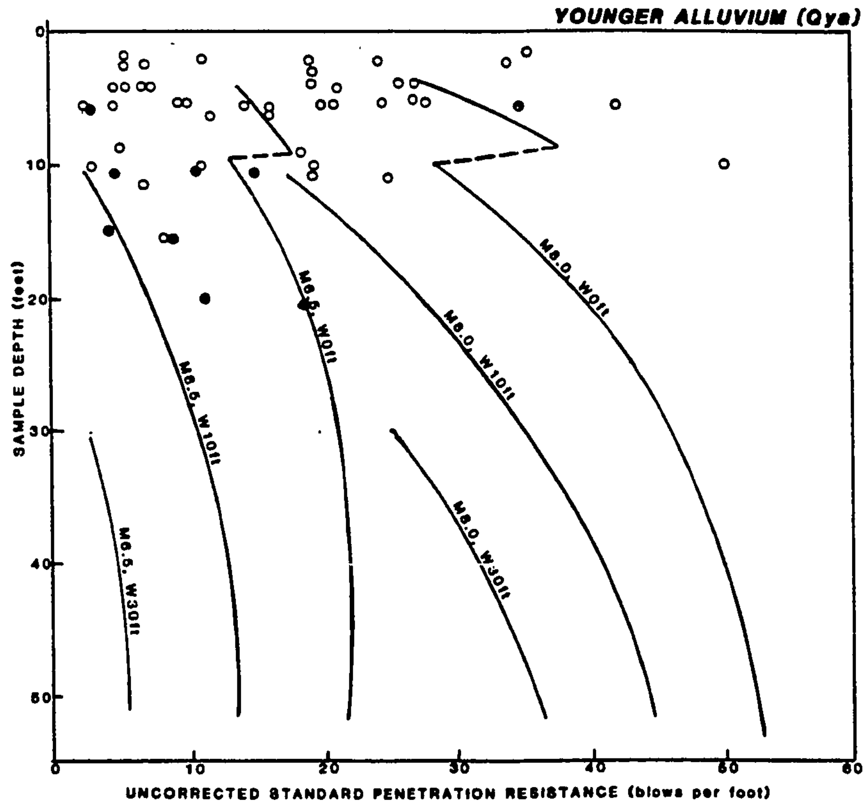


Figure 12. Liquefaction Potential Chart for Evaluation of Younger Alluvium (Qya) in Scotts Valley.

Note: Criteria used for estimating liquefaction susceptibility of alluvial deposits in Scotts Valley, using liquefaction susceptibility curves developed by Tinsley and others (1985) for evaluation of alluvium in Los Angeles Basin. Points plotting to the left of the 6.5 RM curves represent sediment with high liquefaction potential; points between 6.5 RM and 8.0 RM curves represent moderate liquefaction potential; points plotting to right of 8.0 RM curve represent low liquefaction potential. Assumptions include peak horizontal acceleration of 0.2 g and 0.5 g for 6.5 RM and 8.0 RM earthquake events, respectively; uniform dry density of 100 pcf; fine grained sand to silt sized sediment; and depth to free groundwater as indicated. Standard Penetration data obtained from soil reports on file at the City of Scotts Valley and California Department of Transportation Geologic Division office.

O = SPT sample located above water table

● = SPT sample located below water table

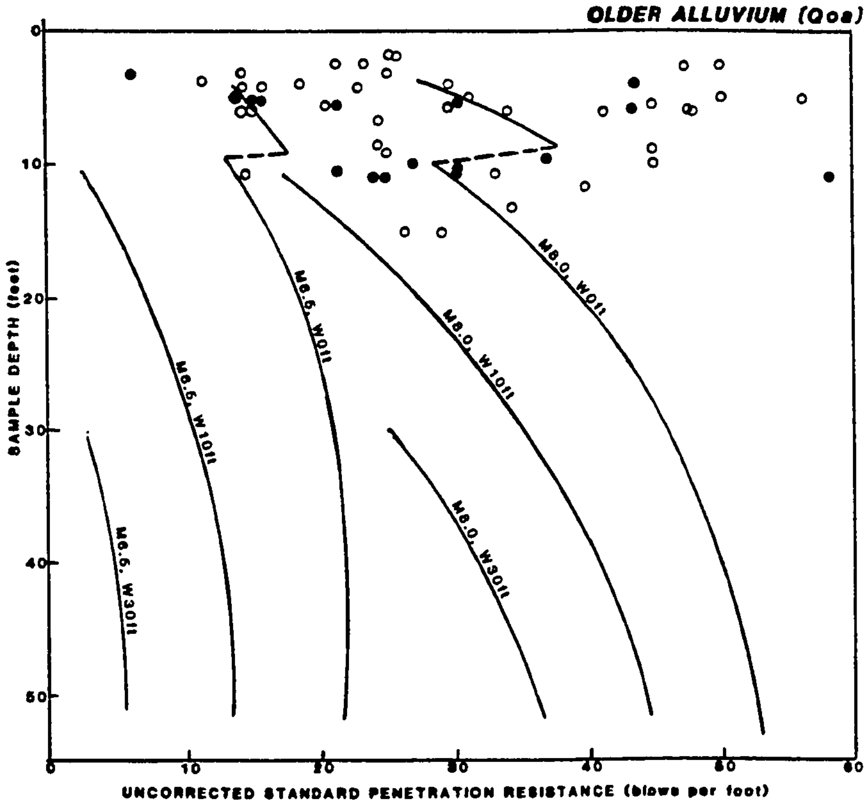


Figure 13. Liquefaction Potential Chart for Evaluation of Older Alluvium (Qoa) in Scotts Valley.

Note: Criteria used for estimating liquefaction susceptibility of alluvial deposits in Scotts Valley, using liquefaction susceptibility curves developed by Tinsley and others (1985) for evaluation of alluvium in Los Angeles Basin. Points plotting to the left of the 6.5 RM curves represent sediment with high liquefaction potential; points between 6.5 RM and 8.0 RM curves represent moderate liquefaction potential; points plotting to right of 8.0 RM curve represent low liquefaction potential. Assumptions include peak horizontal acceleration of 0.2 g and 0.5 g for 6.5 RM and 8.0 RM earthquake events, respectively; uniform dry density of 100 pcf; fine grained sand to silt sized sediment; and depth to free groundwater as indicated. Standard Penetration data obtained from soil reports on file at the City of Scotts Valley and California Department of Transportation Geologic Division office.

○ = SPT sample located above water table
● = SPT sample located below water table

heavy storms and may persist for a substantial period of time. Many of the SPT tests were performed above the ground water table, thus, the evaluation using the selected curves is considered to be conservative, as some deposits may actually never become fully saturated.

The charts show a marked difference between the liquefaction potential of the younger alluvium and the older alluvium. A large percentage of the SPT test points within the younger alluvium fall within the high and moderate liquefaction potential zones on the charts. Most of the SPT test points from the older alluvium fall within the low to moderate liquefaction potential zones on the charts (figs. 12 and 13). Of the SPT tests performed in the younger alluvium (Qya), 49% fall within the high liquefaction potential zone. Most of the SPT test points performed in the older alluvium (Qoa) fall within the moderate to low liquefaction potential zones, with only 9% plotting within the high liquefaction zone. The lesser susceptibility of the older alluvial deposits is probably due to the greater density and cementation of this unit. This is consistent with the findings of Youd and others (1975) and Tinsley (1985).

1989 Loma Prieta Earthquake Liquefaction

The author performed a field reconnaissance of parts of the study area underlain by alluvial sediments after the Loma Prieta Earthquake in order to determine if liquefaction had occurred. Extensional ground cracks, apparently caused by lateral spreading of soil over deep liquefied layers, were observed at two locations in the study area: along the downhill edge of Lockhart Gulch Road and adjacent to Carbonera Creek in the Travel Trails trailer park. The locations of these two sites are shown on plate 4. Both sites are located on areas mapped as recent alluvium.

The Lockhart Gulch Road occurrence consisted of a 6-inch wide crack which extended along the creekside edge of the road for a distance of approximately 40 feet. The crack appeared to have been formed by lateral spreading of the road fills toward the creek channel over a deep liquefied sand layer in the underlying alluvium.

The Travel Trails park site exhibited a zone of extensional ground cracks measuring approximately 350 long and 150 feet wide, adjacent to Carbonera Creek at the east side of the park. The ground cracks were oriented sub-parallel to the creek channel and ranged from 0.5 to 6 inches in width. The cracks extended continuously through both uncovered ground and asphalt surfacing. Concrete slabs in the failed zone were tilted and separated along expansion joints. The ground movements appear to have severed or damaged the water lines in the failure area. Many of the cracks exhibited vertical displacements which ranged up to 6 inches, with the creek side of the crack moved relatively downward. The estimated maximum cumulative extension across the series of cracks was 10 to 12 inches, in the direction of the creek channel. The estimated maximum cumulative vertical displacement was 10 inches. Some of the areas between the most continuous cracks appeared to have been slightly back-tilted away from the creek. Sand was observed either infilling portions of the cracks or along the edges of the cracks. It is possible that the sand issued out of the cracks during propagation of the ground failure.

Three exploratory borings were drilled in the affected area of the trailer park by a private geotechnical consulting firm to determine the subsurface conditions. Two of the borings were placed within the failure zone and one was located outside of the failure zone to the west. The two borings drilled in the area of ground cracking encountered zones of loose, saturated, well-sorted sand and silty sand at a depth of between 20 and 33 feet below the ground surface. SPT blow counts obtained in the loose sand strata suggest that these deposits exhibited a high liquefaction potential. Additionally, one of the sand zones appeared to be in a near liquefied state at the time of drilling. The loose sand zones were underlain by siltstone bedrock and overlain by sandy clay and gravelly, clayey sands which produced a substantially higher SPT blow count resistance. The boring drilled outside of the area of ground cracks encountered predominantly clayey sand and sandy clays which were noticeably denser than the sediments encountered in the other two borings. Saturated, loose sand zones exhibiting a high liquefaction potential were not encountered in the third boring.

Liquefaction Susceptibility Map

Based on results from the liquefaction potential analyses, a liquefaction susceptibility map was developed which divides the study area into three zones exhibiting different degrees of liquefaction potential (pl. 4). Areas underlain by younger alluvial deposits have been mapped as zones potentially containing sediments exhibiting a moderate to high liquefaction potential. Areas underlain by older alluvium have been mapped as zones potentially containing sediments exhibiting moderate liquefaction potential, but with an overall low potential for liquefaction. Bedrock areas have been mapped as zones of low liquefaction susceptibility.

The sites of liquefaction identified in the study area from the Loma Prieta Earthquake were located within the moderate to high liquefaction potential zone on plate 4. These occurrences provide some verification of the liquefaction susceptibility zoning. However, because the liquefaction susceptibility map was prepared from a limited SPT data base, it should only be considered an estimate of the potential response of the geologic units and should not be used as a substitute for site specific liquefaction analyses. It is recommended that future development within the areas marked as having a moderate or high liquefaction susceptibility should be preceded by comprehensive, site-specific investigations of liquefaction potential.

LANDSLIDES

Landslides are widespread throughout the Scotts Valley study area. As used in this report, the definition of a landslide is the downslope movement of soil, rock, or debris under the primary influence of gravity. The term is also extended to the resulting deposit of failed debris.

Landslides occur as a result of instability caused when the resisting strength (shear strength) holding slope materials in place is exceeded by the forces acting to drive the materials downslope (i.e. gravity). Many natural processes act to cause either a reduction in the resisting strength or an increase in the driving force. These include chemical and mechanical weathering, ground water pressures and/or seepage forces, erosional oversteepening of valley walls, adverse geologic structure, weak geologic units, and seismic shaking. In addition to these naturally occurring processes, human-induced changes brought about by grading, irrigation, or increased loading of a slope by development can also alter the equilibrium of a slope, causing landslides to occur.

Landslide Classification

The term 'landslide' includes a group of slope failure types with distinctive characteristics. Several different classification schemes have been developed to differentiate among the various types of landslides. These classification schemes generally group landslides by composition of material involved, rate of movement, degree of activity, and mechanics of movement. A modification of the Varnes classification (Varnes, 1978; pl. 2) has been used for differentiating the major types of landslides mapped in the study area.

Rotational and Translational Landslides

Rotational and translational landslides involve displacement of soil and/or bedrock along discrete failure surfaces or shear zones. The failed mass remains relatively intact during progression of the failure. Rotational slides involve rotational movement of the slide mass, whereas translational slides involve planar translation of the failed mass.

Rotational Slides. Rotational slides are characterized by a concave failure surface. The upper portion of the slide mass is typically back-tilted, while the lower portion of the slide often bulges out of the slope. Rotational slides generally occur within cohesive, homogeneous materials. The rate of failure ranges from slow, progressive movements (<5 feet/year) to moderately rapid slumping (>5 feet/day) (pl. 2). Homogeneous fill slopes and clay rich soil deposits are examples of materials which are susceptible to rotational failures.

Translational Slides. Translational slides involve movement of intact blocks of soil or rock materials along relatively planar failure surfaces. Translational slides typically develop along pre-existing planes of weakness such as bedding contacts, soil/bedrock interfaces, or continuous joints and shear zones. Translational slides can involve large volumes of material, particularly when bedding planes or continuous joints dip in the direction of the slope. Most of the large bedrock landslides in the region appear to be predominantly of the translational type which failed partially along bedding planes or between unweathered bedrock and the overlying regolith of weathered rock and soil. Translational slides are characterized by planar scarps and jumbled deposits of rock and soil debris. The rate of failure for translational slides ranges from slow movements (<5 feet/year) to rapid block glide failures (>1 foot/minute)(pl. 2).

The Love Creek landslide which occurred in January, 1982 near the town of Ben Lomond (7 miles west of Scotts Valley) is a recent example of a large translational slide. This slide involved a 1,000 foot-long slab of soil and weathered bedrock which failed rapidly along the contact between bedrock and the overlying regolith (Cotton and Cochrane, 1982).

Flow-type Landslides

Flow-type landslides include debris flows, mud flows, and debris avalanches. They consist of high density slurries of soil, debris, and water which are transported downslope in a fluid-like manner (Varnes, 1978). Mud flows are classified as flow failures which involve predominantly silt and clay sized material, whereas debris flows generally involve a mixture of weathered rock fragments and granular soil. Most of the flow failures occurring in the study area are classified as debris flows. The rate of flow failures ranges from rapid to very rapid (0.01 to >40 feet/second; Varnes, 1978). The velocity of flow failures is controlled by the density of the flow, composition of the failed material, and slope inclination. Very rapid debris flows are commonly called debris avalanches. This term has been used in this study to differentiate very rapidly moving debris flows with estimated velocities greater than 1.0 foot per second.

Flow failures form within soil and colluvial deposits of sand, silt, and rock fragments which have accumulated within unchanneled hollows and low order channels in the upper portions of drainage basins. Colluvium and soil collects in the hollows during colluviation cycles, and is removed episodically by debris flows during 'debouchment' cycles (Ellen and others, 1988). Debris flows commonly initiate as slump or slab failures of colluvial material on steep slopes exceeding about 25-27 degrees (Campbell, 1975; Ellen and others, 1988). The mobilized material degrades into water-saturated, high density slurries of soil, rock debris, and vegetation as the flow dilates and progresses downslope along drainage channels. Material is added to the failed mass by erosion of the bottom and sides of drainage channels. Mobilized material travels along drainage channels until it is deposited in low gradient reaches, at the bases of slopes, or into high flow streams where it is diluted and carried as bed and suspended load by water movement (debris torrent).

Rapidly moving debris flows can move large trees and blocks of rock as large as automobiles. The high velocity of debris flows can generate extreme impact forces which can easily destroy structures located along the paths of the flows.

Debris flows are initiated during rainstorms which produce high precipitation intensities, particularly after previous rainfall has saturated slope materials. During high intensity rainstorms, the microtopography around colluvial filled hollows directs runoff from the adjacent convex spurs and straight side slopes into the axes of the hollows (Wilson and others, 1989). As the amount of precipitation and surface runoff inflow increases above the drainage rate of the soil and underlying bedrock, a perched ground water table develops within the soil. Perched ground water tables and ground water inflow produce hydrostatic pressures and seepage forces in the colluvial deposit, reducing the frictional resistance. Complete saturation of the colluvium can also reduce the apparent cohesion in the soil which is formed by water tension between the soil grains; this further decreases the ability of the colluvial deposit to resist downslope movement.

Research on hydrologic conditions of colluvial deposits in the Marin region by students and faculty from the University of California at Berkeley, has demonstrated that the highest pore pressures occur along the axes of the hollows. These areas of high pore pressure may be partially the result of upward discharge of ground water into the hollow from the underlying bedrock (Wilson and others, 1989). A study of pore pressure response within a colluvial-filled hollow located above Glenwood Drive in Scotts Valley by Hayes (1985) indicated that peak pore water pressure lagged markedly behind the period of highest storm precipitation. Hayes postulated that the pore pressure lag could have been partially caused by ground water flow from the underlying bedrock into the colluvium. These studies suggest that upward hydraulic gradients in the colluvium from bedrock flow may act as one of the major driving forces causing initiation of debris flows at sites underlain by highly fractured and permeable bedrock (e.g. Santa Cruz Mudstone and Santa Margarita Sandstone).

Studies of the relationship between debris flows and rainfall intensity in the southern California region by Campbell (1975) suggest that rainstorms producing precipitation intensities on the order of 0.25 inches/hour following a seasonal total of approximately 10 inches may cause critical saturation of soil and colluvial deposits. Wieczorek and others (1988) performed an analysis of normalized rainfall (total storm precipitation divided by mean annual precipitation) and debris flow concentrations in the San Francisco Bay Region from data on the January, 1982 rainstorm. Their study indicated that areas with normalized rainfall above 0.30 produced moderate to dense concentrations of debris flows throughout the Bay Region.

Landslide Occurrence in Scotts Valley

Landslide Mapping Methods

Approximately 150 landslides were identified and mapped in the Scotts Valley study area by the author. The location of the landslides and related features, such as erosion gullies and debris fans, are shown on plate 2 titled "LANDSLIDES AND RELATED FEATURES MAP." The landslides were classified into three major groups: active or recently active slope failures, dormant older slope failures, and ancient inactive slope failures. Each major group was subdivided by classifying the failure as one of the following types of landslide: debris avalanche/flow, debris slide, rotational slump, or earthflow/slow debris flow.

Landslides were identified by a combination of stereographic aerial photograph analyses and field mapping. Portions of previously published landslide maps covering the study area compiled by Cooper-Clark and Associates (1975; 1:62,500) and the USGS (Wiezcoreck and others, 1988; 1:62,500) were reviewed. The landslides portrayed on these maps were checked by aerial photograph analyses and field observations. A set of aerial photographs taken for the USGS soon after the January, 1982 storm (scale 1:12,000) proved to be especially valuable for identification of slides and runout areas of debris flows which occurred during the storm. Aerial photographs were used as the primary means to identify large bedrock landslides which were not readily obvious in the field. Because of the dense vegetative cover in the area, identification of small or shallow landslide features (e.g. debris flow headscarps) by aerial photograph analyses was difficult or impossible. These features were mainly identified by field mapping. Every major ridge slope and drainage channel in the study area was traversed in an attempt to locate small landslides and shallow debris flow features. The ages of the various landslide features were estimated by the degree of modification by erosion, vegetation establishment, evidence of fresh-appearing scarps or tension cracks, disruption of human-made structures of known age, and by review of successively older aerial photographs.

Map Representation of Landslides. Larger landslide features were depicted on plate 2 to scale, but features less than approximately 50 feet in maximum dimension, or which could not be depicted accurately to scale, are shown schematically. Arrows were used to show the direction of movement of landslide deposits or the path of debris flows. Different line weights indicate the state of activity of a landslide feature: heavy, solid lines denote the most recent features; thin solid lines or broken lines indicate features of intermediate relative age; and thin broken lines separated by dots represent ancient landslide features. Question marks denote features which are suspected to have been caused by landsliding (e.g. areas of irregular, hummocky topography), but could not be positively verified. The queried features are generally of older relative age, as they commonly have been extensively modified by erosion, or are heavily vegetated.

Landslide Distribution

Plate 2 shows that landslides within the study area are concentrated on steep slopes, particularly those which have been oversteepened by rapid downcutting of streams (e.g. Bean Creek and upper Carbonera Creek). Greater than 75% of the debris flows identified in the study area by the author were initiated in the upper portions of first order drainages, on slopes exceeding 25 degrees. Steep first order drainages have also been observed as the primary site for debris flow initiation at other locations in the San Frantic Bay Area (Howard and Baldwin, 1988; Ellen et al., 1988). The single greatest concentration of landslides in the Scotts Valley study area is on the ridge slope forming the east wall of the Bean Creek Valley. This slope has been oversteepened by incision of Bean Creek and consists of a complex of landslides of varying ages. Sharp contacts between colluvial soils and the underlying Santa Margarita Sandstone bedrock are observable in many of the road cuts bounding the uphill edge of Bean Creek Road. These exposed contacts are old failure planes which were formed by past movements of the colluvium over the bedrock during previous landslide events. The road cuts have locally removed the support for these colluvial deposits. Most of the recent landslides along Bean Creek Road have formed within the colluvial soil and weathered bedrock by reactivation of the older landslide deposits.

Landslides have occurred within every bedrock formation which crops out in the study area, but occur at higher concentrations within the Santa Cruz Mudstone, at the Santa Cruz Mudstone-Santa Margarita Sandstone contact, and within the Purisima Formation (pl. 2). Slopes mantled by thick deposits of colluvium have a high incidence of slope failure. Active soil creep was also observed on most colluviated slopes. Low to moderately inclined slopes underlain exclusively by Santa Margarita Sandstone or granitic basement exhibited a low density of landslides. The relatively flat bottoms of alluviated valleys between the base of ridge slopes and active stream channels either lacked landslide features or exhibited a very low landslide density. Actively eroding reaches of alluviated stream channels exhibit moderate to high densities of stream bank failures and/or side slope landslides.

Nielsen (1984) investigated the high incidence of landslides which occurred during the January, 1982 storm along the Santa Cruz Mudstone-Santa Margarita (Tsc-Tsm) contact in the vicinity of Scotts Valley. Nielsen specifically investigated three possible causes for the high landslide density: complete saturation of the Santa Margarita Sandstone; development of a perched water table in the Santa Cruz Mudstone; and concentration of groundwater in the mudstone along pre-existing planes or weaknesses. The results of his studies suggested that complete saturation of the Santa Margarita Sandstone most likely did not occur during the storm, but perched water tables did probably develop at the bedrock contact by the contrast in permeability between the two rock units. Nielsen observed that point source ground water seepages issued out of bedrock fractures in slide scars and along the Tsc-Tsm contact at his Canham Road study site after each substantial rainstorm during the rest of the rainy season following the January, 1982 storm. The results from Nielsen's studies suggested that perched ground water tables and concentrated ground water flow along the Tsc-Tsm contact during high precipitation storm events are two of the primary causes of the high density of landslides.

The author has observed several other conditions which may also contribute to the high incidence of debris flows at the Tsc-Tsm contact. Santa Cruz Mudstone bedrock mechanically weathers into deposits of loose, non-cohesive, rock shards and fragments which are susceptible to debris flow type failures. Differential erosion between the two rock units has formed localized breaks in slope which are inclined more steeply than the ridge slopes above or below the contact. The localized steeper slopes tend to decrease the stability of the materials and increase the susceptibility to failure. In some locations, erosion of the Santa Margarita Sandstone has undermined the overlying Santa Cruz Mudstone, causing removal of support.

Most of the recent landslides mapped in the study area have occurred on slopes which have evidence of previous landslide activity. The presence of older landslide features on a slope suggests that the static equilibrium may be in a delicate balance. Past landslides may destabilize a slope by removing support for materials located above the landslide scarp area, leading to an upslope progression of failure. Statistical analyses of the relation between 1982 debris flows and slopes with evidence of previous landslide activity was performed for three locations in the western portion of Marin County by the USGS (Cannon and Langholz, 1988). Their investigation determined that the probability of debris flow occurrence was 2 to 4 times higher on slopes exhibiting previous landsliding.

January, 1982 Landslides

A relatively recent example of the potential damage presented by landsliding in California occurred in January, 1982. A major Pacific storm system stalled over the central California area and precipitated large quantities of rainfall in a short time interval. This storm initiated numerous landslides throughout the San Francisco Bay Region. Santa Cruz County was severely impacted by landslides and flooding during the storm. Damages in Santa Cruz County included twenty two deaths (Griggs, 1982) and an estimated $26,417,000 in damages to public and private property (Creasey, 1988). The Scotts Valley area was significantly impacted by storm-induced landslides, particularly along Lockhart Gulch, Bean Creek Road, and in the upper portion of the Carbonera Creek drainage basin. The Bean Creek and Carbonera Creek drainages had some of the highest densities of debris flow occurrence in Santa Cruz County (Wieczorek and others, 1988). Approximately 50 flow-type failures which are believed to have occurred during the January, 1982 storm were identified in the study area by the author. This represents an area of concentration of approximately 10 failures per square mile.

A series of debris flows in the upper Carbonera Creek drainage near Bethany Bible College, in the northernmost portion of the study area, picked up two boys who were walking along Bethany Drive. The force of the debris flow acted to throw one clear from the flow path, but carried the other into Carbonera Creek where he drowned (Wieczoreck and others, 1988). These debris flows are described in detail by Nielsen (1984). According to eyewitnesses, the main pulse of debris which crossed Bethany Drive was over 6 feet (2 m) high and carried blocks of rock half as large as automobiles (Wieczoreck and others, 1988).

Many flow-type failures occurred along Bean Creek Road during the 1982 storm, causing inundation and/or undermining of parts of the roadway. One of these failures also partially undermined the foundation of a house located uphill from the road (pl. 2).

Landslides Induced by the 1989 Loma Prieta Earthquake

Many landslides and rockfalls were initiated or reactivated in the central Santa Cruz Mountains by the 1989 Loma Prieta earthquake. In the epicentral region, large ancient landslides involving thousands of cubic yards of material were reactivated, as evidenced by large tension cracks exhibiting downslope displacements (Weber, verbal communication, 1989). In order to assess the potential risk posed by these large landslides, Santa Cruz County contracted with the Army Corps of Engineers to conduct an intensive study of these features in the Summit Road area of the County.

The author conducted a reconnaissance of the study area after the earthquake to determine if seismic shaking had caused either reactivation of existing landslides or development of new landslides. Evidence of both landslide reactivation and development of new failures was found. The "LANDSLIDE AND RELATED FEATURES MAP" was updated to include these features (pl. 2). Landslides which were reactivated generally developed new tension cracks in their upper regions, but were not fully mobilized. Many cut slope and fill failures developed along Bean Creek Road, causing blockage or undermining of parts of the road. Tension cracks exceeding 1 foot in width and exhibiting over 1.5 feet of downslope displacement were observed in the fill along the downhill side of the road. Other occurrences of landslide reactivation or initiation were spread throughout the study area, but did not exhibit the magnitude of movement or density of occurrence as along Bean Creek Road.

It is probable that more landslides would have been caused by the earthquake if the duration of strong shaking had been only slightly longer or if it had occurred when slope materials were saturated, as in the spring or after an intense rain storm. It is likely that winter rainfall will cause further movement of the landslides which were mobilized by the earthquake if mitigation methods are not employed to prevent saturation of the landslides.

LANDSLIDE HAZARDS

Landslides have a considerable potential to damage man-made structures and improvements, as well as cause injury or loss of life. The potential for landslide risk increases in California as development of landslide-prone hillsides is motivated by the scarcity of available flat land. As a result of the landslide damages from the 1982 storm, many county and municipal agencies in central California have become more aware of the need to identify landslide-prone areas and develop contingency plans to reduce the amount of damage and loss of life from future events. In order to assist these agencies, the USGS has developed a series of landslide inventory and potential maps covering the San Francisco Bay Area.

One of the major goals of this thesis has been to develop a landslide susceptibility map of sufficient detail to assist the City of Scotts Valley in delineating areas prone to landslide damages. The resulting "LANDSLIDE SUSCEPTIBILITY MAP" is included as plate 3. The study area was divided into three zones: areas of high landslide potential, areas of moderate landslide potential, and areas of low landslide potential. The following criteria were used to establish the landslide susceptibility zones: slope inclination, bedrock type, soil thickness, and distribution of existing landslides. The factors used for differentiation of each zone are described below.

Areas of High Landslide Potential

- o Slopes exceeding 25 degrees
- o First order drainage channels
- o High density of existing landslides (>5/mile)
- o Contact between the Santa Cruz Mudstone and Santa Margarita Sandstone
- o Slopes with thick colluvial deposits

Areas of Moderate Landslide Potential

- o Ridge crests surrounded by high landslide potential areas
- o Alluviated stream banks
- o Slopes between 15 degrees and 25 degrees
- o Slopes with low to moderate density of landslides (<5/mile)

Areas of Low Landslide Potential

- o Alluviated valley floors
- o Low density of existing slides
- o Uniform Santa Margarita Sandstone or granitic basement on slopes less than 20 degrees

It should be noted that the landslide susceptibility map divides the study area into broad zones for regional planning purposes and should not be construed as a substitute for site-specific investigations. Properties located in areas delineated as having a high potential of landsliding should be thoroughly investigated and analyzed specifically for slope stability prior to development.

DISCUSSION AND SUMMARY

Three main potential geologic hazards were identified in the Scotts Valley study area by this investigation: earthquakes, landslides, and floods. Other potential geologic hazards which are of primary concern in other areas of California, such as volcanism, widespread expansive soils, and coastal erosion, are either not present or not actively occurring in Scotts Valley, and therefore present a low or non-existent hazard.

This study focused on collecting and analyzing geologic data for the purpose of defining the potential seismic and landslide hazards. Analysis of the potential flood hazard was not covered in the scope of work, as it has been previously addressed by detailed flood inundation zone maps which are suitable for general planning purposes. A recent publication by the United States Geologic Survey (Ellen and Wieczorek, editors, 1988) provides a detailed description of the January, 1982 storm and related flooding.

Based on the results of this study, the primary seismic hazards in the study area are strong ground shaking and liquefaction. Strong ground shaking has occurred historically many times from regional earthquakes, most recently in October, 1989 by the Loma Prieta earthquake. Strong seismic ground shaking is likely to occur in the study area during the next century. Areas underlain by recent alluvium are susceptible to soil liquefaction and may experience localized ground failure from future strong earthquakes. The areas underlain by potentially liquefiable sediments are shown on plate 4. The potential for fault rupture in the study area is considered to be relatively low. Refer to the "SEISMIC HAZARDS" section of this report for a detailed description of the potential seismic hazards, and a description of the methods used to analyze these hazards.

Landslides present a potential geologic hazard over much of the study area, and were responsible for extensive damages in Scotts Valley during the January, 1982 storm. Fast moving debris flows probably present the greatest potential geologic hazard in the study area; this is because of their great destructive power and sudden occurrence which allows little or no warning time. Plate 3 delineates the areas most susceptible to landslide hazards. Refer to the "LANDSLIDE HAZARDS" section of this thesis for a description of the analytical procedures used for evaluation of the landslide hazard.

RECOMMENDATIONS

It is recommended that the series of geologic and hazard evaluation maps (pl. 1 to 4) which were developed by this study be used to guide regional planning in the City of Scotts Valley. The maps should prove useful for providing input to guide land use decisions and to delineate areas which warrant further geologic studies prior to development. If properly used, the information from this study can reduce or manage the risk of potential geologic hazards by allowing early identification of potential problems. The author recommends that sites located in areas of identified geologic hazards be thoroughly investigated by detailed, site-specific geologic and geotechnical investigations prior to development. These detailed studies should address the potential hazards which have been identified by this study. In order to increase and/or sustain the benefit of the maps, they should be updated periodically as new geologic information becomes available.

REFERENCES CITED

Albee, A.L., and Smith, J.L., 1966, Earthquake characteristics and fault activity in southern California, in Lung, R., and Procter, R., editors, Engineering geology in southern California: Association of Engineering Geologists, Glendale, California, p. 9-33.

Aydin, Atilla, Page, B. M., 1984, Diverse Pliocene-Quaternary tectonics in a transform environment, San Francisco Bay Region, California: Geological Society of America Bulletin, v. 95, p. 1303-13A.

Atwater, T., 1970, Implications of plate tectonics for the Cenozoic tectonic evolution of western North America: Geological Society of America Bulletin, v. 81, p. 3513-3536.

Bennett, M.J., 1989, Liquefaction analysis of the 1971 ground failure at the San Fernando Valley juvenile hall, California: Bulletin of the Association of Engineering Geologists, v. XXVI, no. 2, p. 209-226.

Blodgett, J.C., and Poeschel, K.R., 1988, Peak discharge, volume, and frequency of the January 1982 flood in the Santa Cruz Mountains and vicinity, in Ellen, S.D., and Wieczorek, G.F., editors, 1988, Landslides, floods, and marine effects of the storm of January 3-5, 1982, in the San Francisco Bay Region, California: U.S. Geological Survey Professional Paper 1434, p. 229-243.

Bolt, B.A., Lomnitz C., and McEvilly, T.V., 1968, Seismological evidence on the tectonics of central northern California and the Mendocino escarpment: Bulletin Seismological Society of America, v. 5, no.6., p. 1725-1753.

Bolt, B.A., 1989, Santa Cruz Mountains earthquake sequence of October 17, seismological considerations, in Mahin, S., Bertero, V., and Scordelis, A., editors, Preliminary report on the seismological and engineering aspects of the October 17, 1989 Santa Cruz (Loma Prieta) earthquake: Earthquake Engineering Research Center Report no. UCB/EERC-89/14, p. 1-3.

Bonilla, M.G., 1970, Surface faulting and related effects, in Wiegel, R.L., editor, Earthquake Engineering: Prentice-Hall, Inc., Englewood Cliffs, N.J., p. 47-74.

Bonilla, M.G., and Buchanan, J.M., 1970, Interim report on world wide historic surface faulting: U.S. Geological Survey Open-File Report, 32 p.

Borcherdt, R.D., editor, 1975, Studies for seismic zonation of the San Francisco Bay Region: U.S. Geological Survey Professional Paper 941-A, 102 p.

Brabb, E.E., compiler, 1986, Preliminary geologic map of Santa Cruz County, California: U.S. Geological Survey Open-File Report 86-577, map scale 1:62,500.

--------------------- 1989, Preliminary geologic map of Santa Cruz County, California: U.S. Geological Survey Miscellaneous Field Studies Map no. 1905, map scale 1:62,500.

Bradley, W.C., and Griggs, G.B., 1976, Form, genesis, and deformation of central California wave cut platforms: Geological Society of America Bulletin no. 87, p. 433-449.

Branner, J.C., Newsom, J.F., and Arnold, Ralph, 1909, Description of the Santa Cruz Quadrangle, California: U.S. Geological Survey Geology Atlas, Folio 163.

Campbell, R.H., 1975, Soil slips, debris flows, and rainstorms in the Santa Monica Mountains and vicinity, southern California: U.S. Geological Survey Professional Paper 851, 51 p.

Cannon, S.H., and Langholz, B.M., 1988, Scars and individual habitats of previous soil slips: in Ellen, S.D., and Wieczorek, G.F., Editors, 1988, Landslides, floods, and marine effects of the storm of January 3-5, 1982, in the San Francisco Bay Region, California: U.S. Geological Survey Professional Paper 1434, p. 123-125.

Clark, J.C., 1966, Tertiary Stratigraphy of the Felton-Santa Cruz Area, Santa Cruz Mountains, California: Stanford, California, Stanford University, Ph.D. Dissertation , 184 p.

----------- 1981, Stratigraphy, paleontology, and geology of the central Santa Cruz Mountains, California Coast Ranges: U.S. Geological Survey Professional Paper, 1168 p.

Clark, J.C., and Rietman, J.D., 1973, Oligocene stratigraphy, tectonics, and paleogeography southwest of the San Andreas fault, Santa Cruz Mountains and Gabilan Range, California Coast Ranges: U.S. Geological Survey Professional Paper 783, 18 p.

Cooper-Clark and Associates, 1975, Preliminary map of landslide deposits in Santa Cruz County, California, in Seismic Safety Element, an Element of the Santa Cruz County Planning Department, California: map scale 1:62,500.

Coppersmith, K., 1979, Activity assessment of the Zayante-Vergeles fault, central San Andreas system: Santa Cruz, University of California, Ph.D dissertation.

Cotton, W.R., and Cochrane, D.A., 1982, Love Creek landslide disaster, January 5, 1982: California Geology, v. 35, no. 7, p. 153-157.

Creasey, C.L., 1988, Landslide damage, a costly outcome of the storm, in Ellen, S.D., and Wieczorek, G.F., editors, 1988, Landslides, floods, and marine effects of the storm of January 3-5, 1982, in the San Francisco Bay region, California: U.S. Geological Survey Professional Paper 1434, p. 195-203.

CSMIP Staff, 1989, Second quick report on CSMIP strong-motion records from the October 17, 1989 earthquake in the Santa Cruz Mountains, California: California Division of Mines and Geology, 16 p.

Curtis, G.H., Evernden, J.F., and Lipson, J., 1958, Age determination of some granitic rocks in California by the potassium-argon method: California Division of Mines Special Report 54, 16 p.

Davis, L.L., and West, L.R., 1972, A preliminary evaluation of the effects of topography on ground motion: California Division of Mines and Geology, Bulletin 196, p. 305-311.

Dibblee, T.W. Jr., Brabb, E.E., and Clark, J.C., 1978, Preliminary geologic map of the Laurel quadrangle, Santa Cruz and Santa Clara Counties, California: U.S. Geological Survey Open-File Report 78-84, map scale 1:24,000.

Dickinson, W.R., Armin, R.A., Beckvar, N., Goodlin, T.C., Janecke, S.U., Mark, R.A., Norris, R.D., Radel, G., and Wortman, A.A., 1987, Geohistory analysis of rates of sediment accumulation and subsidence for selected California basins, in Ingersoll, R., and Ernst, W.G., editors, Development of coastal California: Prentice Hall, New Jersey, Rubey volume VI.

Donovan, N.C., 1974, Earthquake hazards for buildings: Dames and Moore Engineering Bulletin 46, p. 3-20.

Dupre', W. R., 1975, Maps showing geology and liquefaction potential of quaternary deposits in Santa Cruz County, California: U.S. Geological Survey Miscellaneous Field Studies Map MF-648, 2 sheets, map scale 1:62,500.

Dupre', W.R., and Tinsley, J.C., III, 1980, Maps showing geology and liquefaction potential of Northern Monterey and Southern Santa Cruz Counties, California : U.S. Geological Survey Miscellaneous Field Studies Map MF-1199, scale 1:62,500.

Ellen, S.D., and Wieczorek, G.F., editors, 1988, Landslides, floods, and marine effects of the storm of January 3-5, 1982, in the San Francisco Bay region, California: U.S. Geological Survey Professional Paper 1434, 310 p.

Environmental Management Consultants, 1986, City of Scotts Valley, revised general plan, 310 p.

Federal Emergency Management Agency, 1983, Flood insurance rate map, City of Scotts Valley, Santa Cruz County, map scale 1:4,800

Garfunkle, Z.,1974, Model for the late Cenozoic tectonic history of the Mojave Desert, California, and for its relation to adjacent region, Geological Society of America Bulletin, no. 85, p. 1931-1944.

Gibbs, H.J., and Holtz, W.G., 1957, Research on determining the density of sand by spoon penetration test: International Conference Soil Mechanics and Foundations Engineering, 4th, London, Proceedings v. 1, p. 35-39.

Greene, H.G., Lee, W.H., McCulloch, D.S., and Brabb, E.E., 1973, Faults and earthquakes in the Monterey Bay Region, California: U.S. Geological Survey Miscellaneous Field Studies Map MF-518, map scale 1:200,000.

Griggs, G.B., 1982, Flooding and slope failure during the January 1982 storm, Santa Cruz County, California: California Geology, v. 35, no. 7, p. 158-163.

Hall, N.T., Sarna-Wojcicki, A.M., and Dupre', W.R., 1974, Faults and their potential hazards in Santa Cruz County, California: U.S. Geological Survey Miscellaneous Field Studies Map MF-626, 13 sheets, map scale 1:62,500.

Hansen, W.R., 1966, Effects of the earthquake of March 27, 1964 at Anchorage, Alaska: U.S. Geological Survey Professional Paper 542-A, 68 p.

Hayes, J., 1985, Hydrologic behavior of a colluvium-filled bedrock hollow [abs.]: EOS (American Geophysical Union Transactions), v. 66, no. 46, p. 897.

Hill M.L., and Dibblee, T.W., 1953, San Andreas, Garlock, and Big Pine faults, California, a study of the character, history, and tectonic significance of their displacements: Geological Society of America Bulletin, v. 64, no. 4, p. 443-458.

Howard, T.R., and Baldwin, J.E., 1988, Landslides in Pacifica, California, caused by the storm, in Ellen, S.D., and Wieczorek, G.F., editors, 1988, Landslides, floods, and marine effects of the storm of January 3-5, 1982, in the San Francisco Bay Region, California: U.S. Geological Survey Professional Paper 1434, p. 63-112.

Hsu, K.J., 1971, Franciscan melanges as a model for eugeosynclinal sedimentation and underthrust tectonics: Journal Geophysical Research, v. 76, no. 5, p. 1162-1170.

Kachadoorian, R., 1971, An estimate of the damage, in the San Fernando, California earthquake of February 9, 1971: U.S. Geological Survey Professional Paper 733, p. 97-98.

Lajoie, K.R., Weber, G.E., and Tinsley, J.C., 1972, Marine terrace deformation: San Mateo and Santa Cruz Counties, in Progress report on the U.S. Geological Survey Quaternary studies in the San Francisco Bay area: Friends of the Pleistocene Guidebook, October. 6-8, 1972, p. 100-113.

Lawson, A.C., chairman, 1908, The California earthquake of April 18, 1906, Report of the State Earthquake Investigation Commission: Carnegie Institute, Washington Publication 87, 2 volumes.

Mahin, S.A., Bertero, V., and Scordelis, A., 1989, Preface, in Mahin, S., Bertero, V., and Scordelis, A., editors, Preliminary report on the seismological and engineering aspects of the October 17, 1989 Santa Cruz (Loma Prieta) earthquake: Earthquake Engineering Research Center Report no. UCB/EERC-89/14, p. 32-36.

McCrory, P.A., Greene, H.G., and Lajoie, K.R., 1977, Map showing earthquake intensity zonation and distribution of Quaternary deposits, San Mateo, Santa Cruz and Monterey Counties, California: U.S. Geological Survey Miscellaneous Field Studies Map MF-903, scale 1:250,000.

McLaughlin, R.J., 1973, Geology of the Sargent fault zone in the vicinity of Mount Madonna, Santa Clara and Santa Cruz, Counties, California: San Jose, California, San Jose State University, M.S. thesis, 108 p.

McNutt, S., 1990, Loma Prieta earthquake, October 17, 1989, Santa Cruz County, California: California Geology v. 43, no. 1, p. 3-7.

Mualchin, L., 1985, Seismological investigation for siting an LNG facility: Bulletin of the Association of Engineering Geologists, v. XXII, no. 2, p. 153-170.

Nason, R.D., 1971, Shattered earth at Wallaby Street, Sylmar, in The San Fernando, California earthquake of February 9, 1971: U.S. Geological Survey Professional Paper 733, p. 97-98.

NEPEC, 1988, Probabilities of large earthquakes occurring in California on the San Andreas fault: U.S. Geological Survey Open-File Report 88-398, 62 p.

Nur, A., and Ben-Avraham, Z., 1977, Lost Pacifica Continent: Nature, v. 270, p. 41-43.

Nilsen, T.H., 1979, Sedimentology of the Butano Sandstone, Santa Cruz Mountains, in Nilsen, T.H., and Brabb, E.E., editors, Geology of the Santa Cruz Mountains, California: Cordilleran Section, Geological Society of America, Field Trip Guidebook, 96 p.

Nielsen, H.P., 1984, Geology, rainfall, and groundwater associated with several debris flows in Santa Cruz County, California: Santa Cruz, University of California, M.S. thesis, 104 p.

Page, B.M., 1982, Modes of Quaternary tectonic movement in the San Francisco Bay Region, California, in Hart, E., Hirschfeld, S.E., and Schulz, S.S., editors, Proceedings, conference on earthquake hazards in the eastern San Francisco Bay Area: California Division of Mines and Geology Special Publication 62, p. 1-10.

Pampeyan, E.H., 1979, Preliminary map showing recency of faulting in coastal north California: U.S. Geological Survey Miscellaneous Field Studies Map MF-1070 (scale 1:250,000).

Phillips, R.L., 1981, Depositional environments of the Santa Margarita Formation in the Santa Cruz Mountains, California: Santa Cruz, University of California, Ph.D. dissertation, 358 p.

Rantz, S.E., 1971, Precipitation depth-duration-frequency relations for the San Francisco Bay region, California, with isotheyal map of the San Francisco Bay region, California showing mean annual precipitation, U.S. Geological Survey, Basic Data Contribution 25, map scale 1:500,000.

Rogers, T.H., and Williams, J.W., 1974, Potential seismic hazards in Santa Clara County, California: California Division of Mines and Geology Special Report 107, 39 p.

Roth, Richard A., 1983, Factors affecting landslide susceptibility in San Mateo County, California: Bulletin of Association of Engineering Geologists, v. XX, no.4, p. 353-372.

Seed, H.B. and Idriss, I.M., 1971, Simplified procedure for evaluating soil liquefaction potential: American Society of Civil Engineers Journal of Soil Mechanics and Foundation Division, v.97, p. 1249 - 1273.

--------------------------- 1982, Ground motions and soil liquefaction during earthquakes: Earthquake Engineering Research Institute, Berkeley, 134 p.

Seed, R.B., Boulanger, R.W., Bray, J.D., Dickenson, S.E., Kayen, J.L., Mitchell, J.K., Nicholson, P.G., Pender, M.J., Riemer, M.F., Schmertmann, G.R., and Sitar, N., 1989, The Loma Prieta earthquake of October 17, 1989 geotechnical considerations, in Mahin, S., Bertero, V., and Scordelis, A., editors, Preliminary report on the seismological and engineering aspects of the October 17, 1989 Santa Cruz (Loma Prieta) earthquake: Earthquake Engineering Research Center Report no. UCB/EERC-89/14, p. 4-14.

Stanley, R.G., and McCaffrey, R., 1983, Extent and offset history of the Ben Lomond Fault, Santa Cruz County, California, in Anderson, D., editor, Tectonics and sedimentation along faults of the San Andreas System: Society of Economic Paleontologists and Minerologists Pacific Section, Publication 30, p. 79-90.

Spittler, T.E., 1989, Landslide and ridgetop failures, Loma Prieta, Santa Cruz County, California [abs.]: SABER Society, 16th Annual Symposium, San Jose, California, San Jose State University.

Sykes L.R., and Nishenko, S.P., 1984, Probabilities of occurrence of large plate rupturing earthquakes for the San Andreas, San Jacinto, and Imperial faults, California, 1983-2003: Journal of Geophysical Research, no. 89, p. 5905-5927.

Tinsley, J.C., Youd, T.L., Perkins, D.M., and Chen, A.T.F., 1985, Evaluating liquefaction potential, in Ziony, J.I., editor, Evaluating earthquake hazards in the Los Angeles region-an earth science perspective: U.S. Geological Survey Professional Paper 1360, p. 263 -492.

Tocher, D., 1958, Earthquake energy and ground breakage: Seismological Society of America Bulletin v. 48, p. 147-153.

Varnes, D.J., 1978, Slope movement types and processes, in Schuster, R.L., and Krizeck, R.S., editors, Landslides analysis and control: U.S. Academy of Sciences, National Research Council, Transportation Research Board Special Report 176, p. 12-33.

Weber, G.E., 1989, personal communication, SABER Society meeting San Jose State University, San Jose, California.

Weber, G.E., LaJoie, K.R., Griggs, G.B., 1979, Coastal tectonics and coastal geologic hazards in Santa Cruz and San Mateo Counties, California: Geological Society of America 75th Annual Meeting Field Trip Guide.

Wesnousky, S.G., 1986, Earthquakes, Quaternary faults, and seismic hazards in California: Journal of Geophysical Research, v. 91, no. B12, p. 12,587-12,631.

Wesson, R.L., Helley, E.J., Lajoie, K.R., and Wentworth, C.M., 1975, Faults and future earthquakes, in Borcherdt, R.D., editor, Studies for seismic zonation of the San Francisco Bay region: U.S. Geological Survey Professional Paper 941-A, P. A5-A30.

Wieczorek, G.F., Mark, R.K., and Bhattacharyya, A.K., 1988, Debris flows and other landslides in San Mateo, Santa Cruz, Contra Costa, Alameda, Napa, Solano, Sonoma, Lake, and Yolo Counties, and factors influencing debris-flow distribution, in Ellen, S.D., and Wieczorek, G.F., editors, Landslides, floods, and marine effects of the storm of January 3-5, 1982, in the San Francisco Bay region, California: U.S. Geological Survey Professional Paper 1434, p. 133-161.

Wilson, C.J., Dietrich, W.E., and Narasimhan, T.N., 1989, Predicting high pore pressures and saturation overland flow in unchanneled hillslope valleys, in Comparisons in austral hydrology: the Institution of Engineers, Australia, Hydrology and Water Resources Symposium, in press.

Youd, T.L., and Hoose, S.N., 1978, Historic ground failures in northern California triggered by earthquakes: U.S. Geological Survey Professional Paper 993, 177 p.

Youd, T.L., and Perkins, D.M., 1978, Mapping liquefaction-induced ground failure potential: Proceedings of the American Society of Civil Engineers, Journal of the Geotechnical Engineering Division, v. 104, no. GT4, p. 433-446.

AREAL AND ENGINEERING GEOLC
SCOTTS VALLEY, CALIFORNI

JEFF BACHHUBER, 1989

PLATE 1

NGINEERING GEOLOGY MAP
/ALLEY, CALIFORNIA

JEFF BACHHUBER, 1989

PLATE 1

EXPLANATION

DESCRIPTION OF MAP SYMBOLS

-Geologic contact, solid where approximate, dashed where gradational or inferred

-Fault, U:relatively upthrown side D:downthrown side

-Strike and dip of inclined bedrock strata, broken where approximate

-Horizontal bedrock strata

-Strike and dip of prominant joint sets

-Spring or intermittent seep

-Axis of Scotts Valley Syncline showing direction of plunge

-Well hole location

A A' -Geologic cross section line

DESCRIPTION OF MAP UNITS

Quaternary

Qf-(Holocene) Fill, man-placed soil material, variable composition

Qc-(Holocene) Colluvium, greater than 6 feet thick, poorly sorted, intermixed soil, and

Qya-(Holocene) Younger Alluvium, unconsolidated stream-deposited sand, silt, gravel, an

Qoa-(Holocene/Pleistocene?) Older Alluvium, poorly consolidated stream terrace deposit

Tertiary

Tp-(Pliocene) Purisma Formation, thick bedded, yellow-grey, tuffaceous and diatomace

Tsc-(Upper Miocene to Pliocene) Santa Cruz Mudstone Formation, medium to thinly bedd

Tsm-(Upper Miocene) Santa Margarita Sandstone Formation, thick bedded, friable, yellov

Tm-(Middle Miocene) Monterey Shale Formation, medium bedded, olive-grey organic m

Tlo-(Middle Miocene) Lompico Sandstone Formation, thick bedded, yellow-grey arkosi radational or inferred

proximate

ion

rted, intermixed soil, and weathered rock

ited sand, silt, gravel, and clay

ed stream terrace deposits consisting of sand, silt, gravel, and minor clay

tuffaceous and diatomaceous siltstone with diatomite and andesitic sandstone beds in upper section

ion, medium to thinly bedded, laminated, yellow-brown to grey siliceous mudstone with concretions, highly fractured

hick bedded, friable, yellow to olive-grey arkosic sandstone with gravel and fossiliferous beds, cross bedded

ded, olive-grey organic mudstone and sandy siltstone

Tm-(Middle Miocene) Monterey Shale Formation, medium bedded, olive grey orga

Tlo-(Middle Miocene) Lompico Sandstone Formation, thick bedded, yellow-grey a

Cretaceous

Kgr-(Cretaceous) Crystalline Basement Rock, grey granite and granodiorite, hard

WELL LOGS (interpreted by D.K. Todd-Consultants)

depth intervals indicated in parentheses are given in feet

A-(0-20) Qal, (20-122) Tsc, (122-250) Tsm, (250-273) Tlo

B-(0-7) Qal, (7-46) Tsm, (46-60) Tm

C-(0-3) Qal, (3-90) Tsc

D-(0-3) Qal, (3-40) Tsc, (40-140) Tsm, (140-150) Tm

E-(0-3) Qal, (3-50) Tsc, (50-82) Tsm, (82-84) Tm

F-(0-25) Qal

G-(0-10) Qal, (10-28) Tsm, (28-100) Tm

H-(0-24) Qal, (24-121) Tsm

I-(0-114) Tsm, (114-240) Tm, (240-564) Tlo

J-(0-45) Qal, (45-66) Tsm

K-(0-16) Qal, (16-160) Tsm, (160-172) Tm, (172-311) Tlo

L-(0-240) Tsm

M-(0-216) Tsm

N-(0-52) Tsm, (52-80) Kgr

O-(0-12) Qal, (12-97) Tsm, (97-400) Kgr

P-(0-30) Qal, (30-120) Tsm, (120-125) Kgr?

Q-(0-4) Qal, (4-138) Tsm

ı, olive-grey organic mudstone and sandy siltstono

ed, yellow-grey arkosic sandstone, does not outcrop in study area but has been encountered in deep wells

ranodiorite, hard and massivo

ants)

et

o

O-(0-12) Qal, (12-97) Tsm, (97-400) Kgr

P-(0-30) Qal, (30-120) Tsm, (120-125) Kgr?

Q-(0-4) Qal, (4-138) Tsm

R-(0-12) Qal, (12-221) Tsm, (221-386) Tm, (386-445) Tlo

S-(0-15) Qal, (15-200) Tsm

T-(0-10) Qal, (10-287) Tsm, (287-297) Tm, (297-415) Tlo

U-(0-5) Peat, (6-130) Tsm, (130-270) Tm, (270-355) Tlo

V-(0-24) Qal, (24-312) Tsm, (312-315) Tm

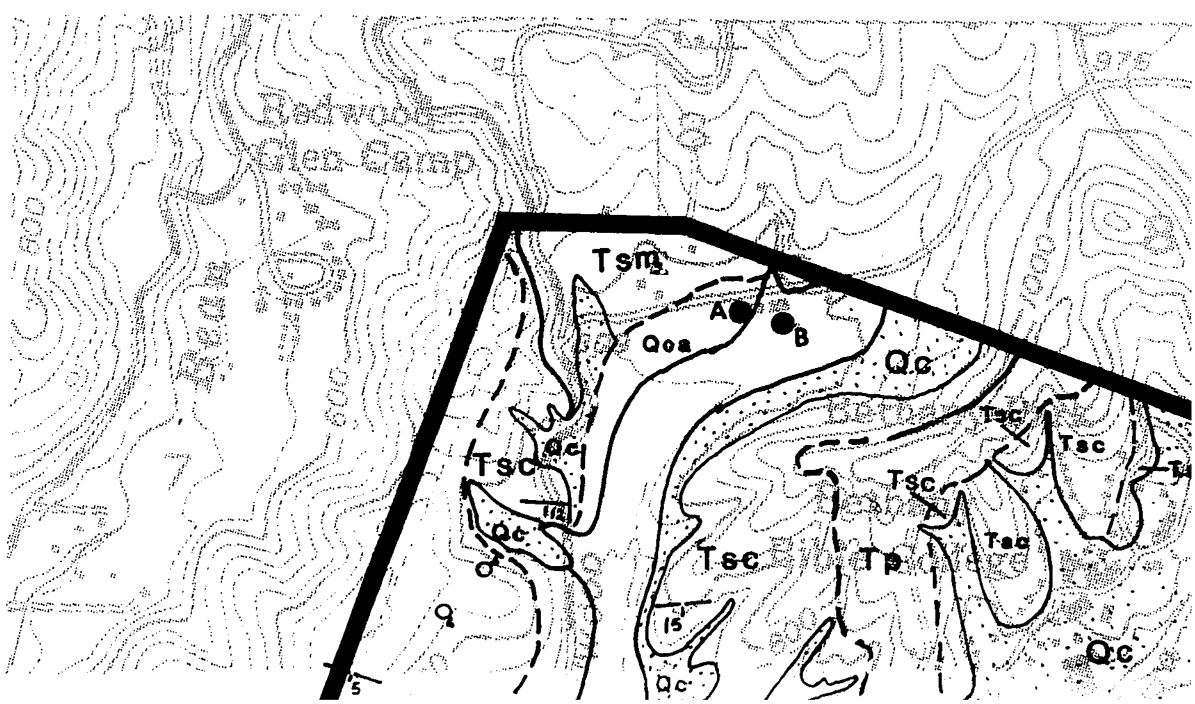
W-(0-75) Tsm

X-(0-23) Qal, (23-260) Tsm, (260-270) Tm

ENGINEERING PROPERTIES OF GEOLOGIC UNITS

Geologic Unit	Dry Unit Weight (pcf)	Moisture Content (%)	Unconfined Compressive Strength (psf)
Qc	94-114	20-30	1200-1800
Qya	97-109	18-30	1000-2000
Qoa	106-115	12-22	1500-3500
Tp	110-135+	14-20	3500-4500+
Tsc	100-130+	18-24	2800-4500+
Tsm	108-140+	6-14	2450-4500+
Kgr	130-150+	4-8	4500+

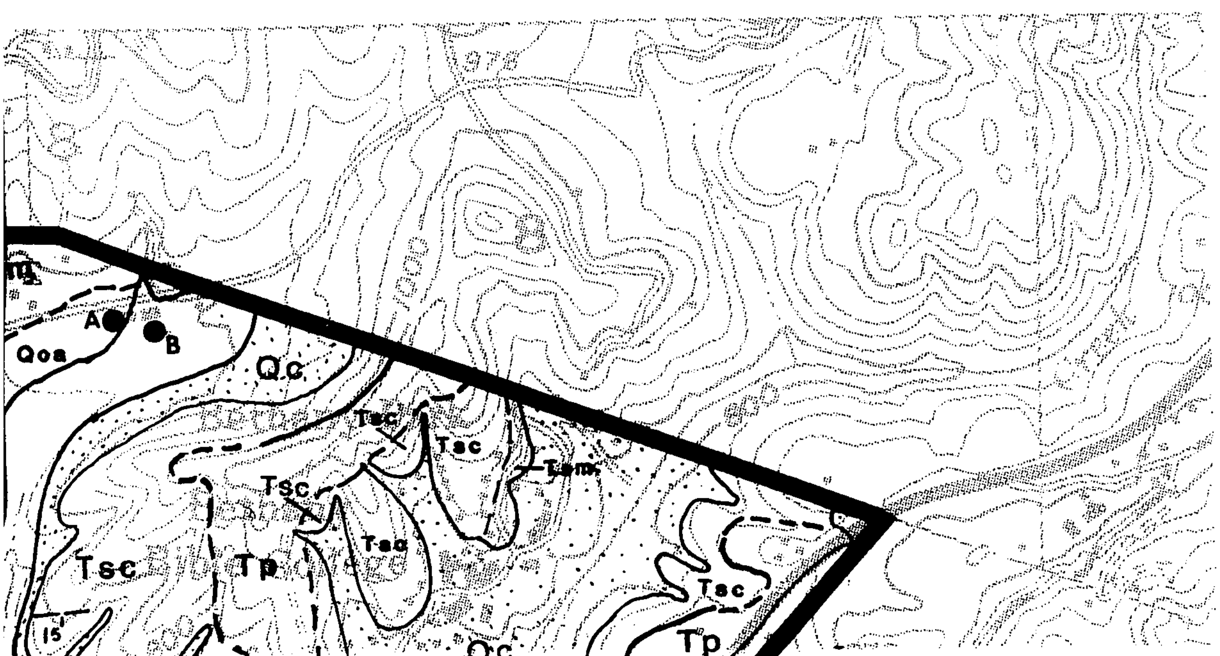
*Engineerir
included i
City of Sc
for sectic

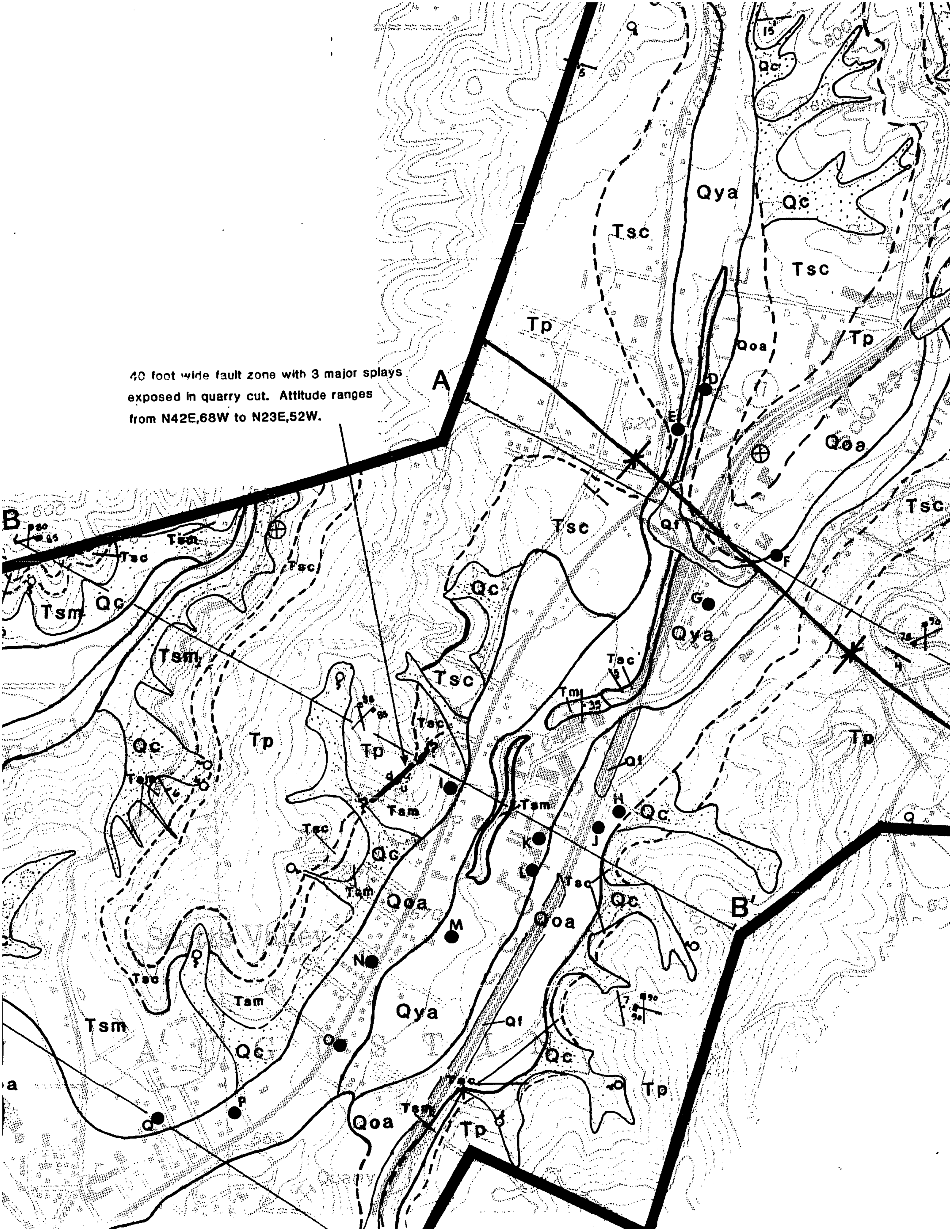


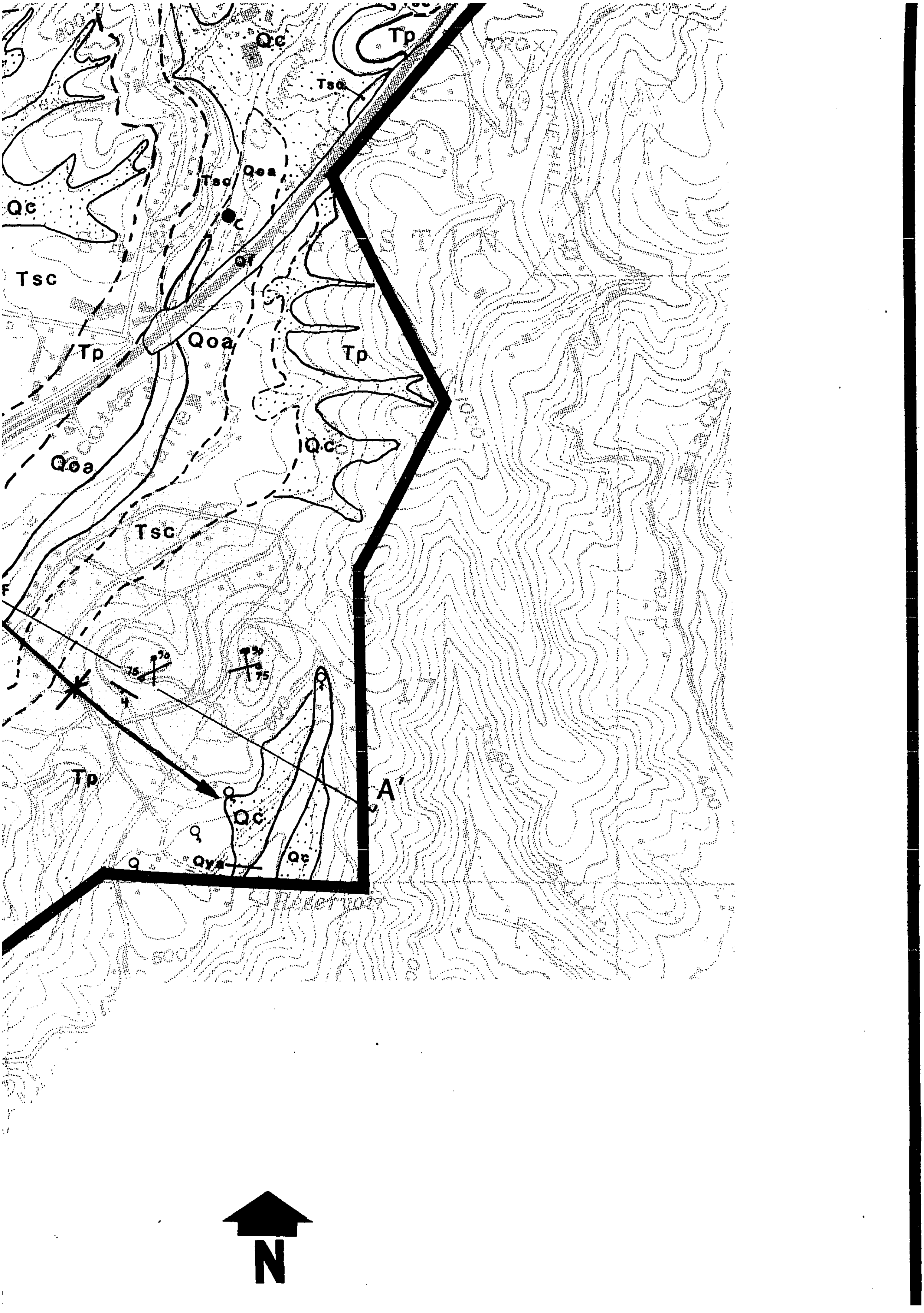
EERING PROPERTIES OF GEOLOGIC UNITS

sture tent (%)	Unconfined Compressive Strength (psf)	Internal Friction Angle (degrees)	SPT Blow Count Resistance (blows/ft.)
0-30	1200-1800	18-30	5-15
8-30	1000-2000	22-32	4-18 Avg. 12
2-22	1500-3500	25-38	18-34 Avg. 28
4-20	3500-4500+		50-100+
8-24	2800-4500+	25-38	50-100+
-14	2450-4500+		75-100+
-8	4500+		85-100+

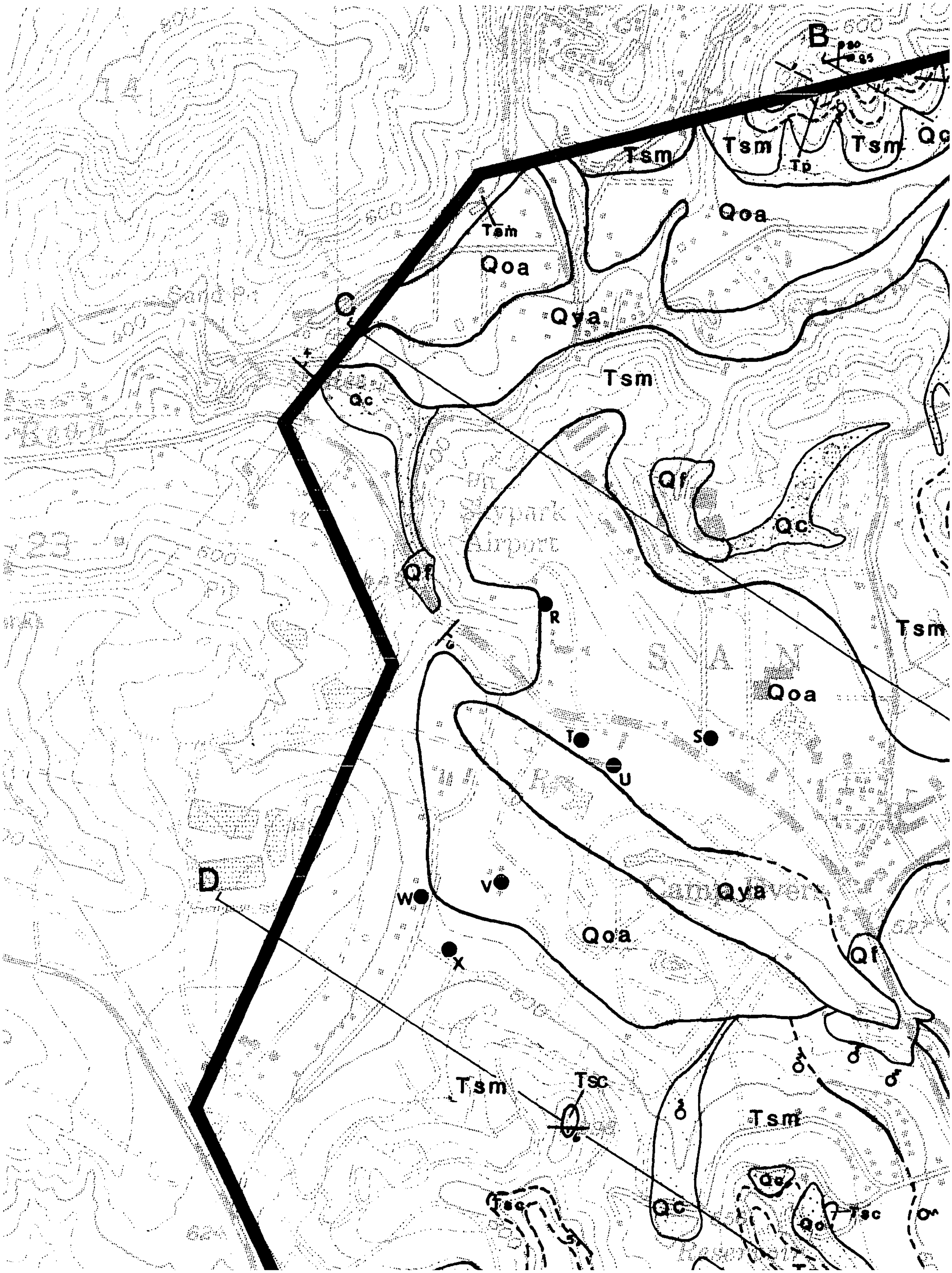
*Engineering properties obtained from test data included in consultants reports on file at the City of Scotts Valley, and from Caltrans reports for sections of Highway 17.

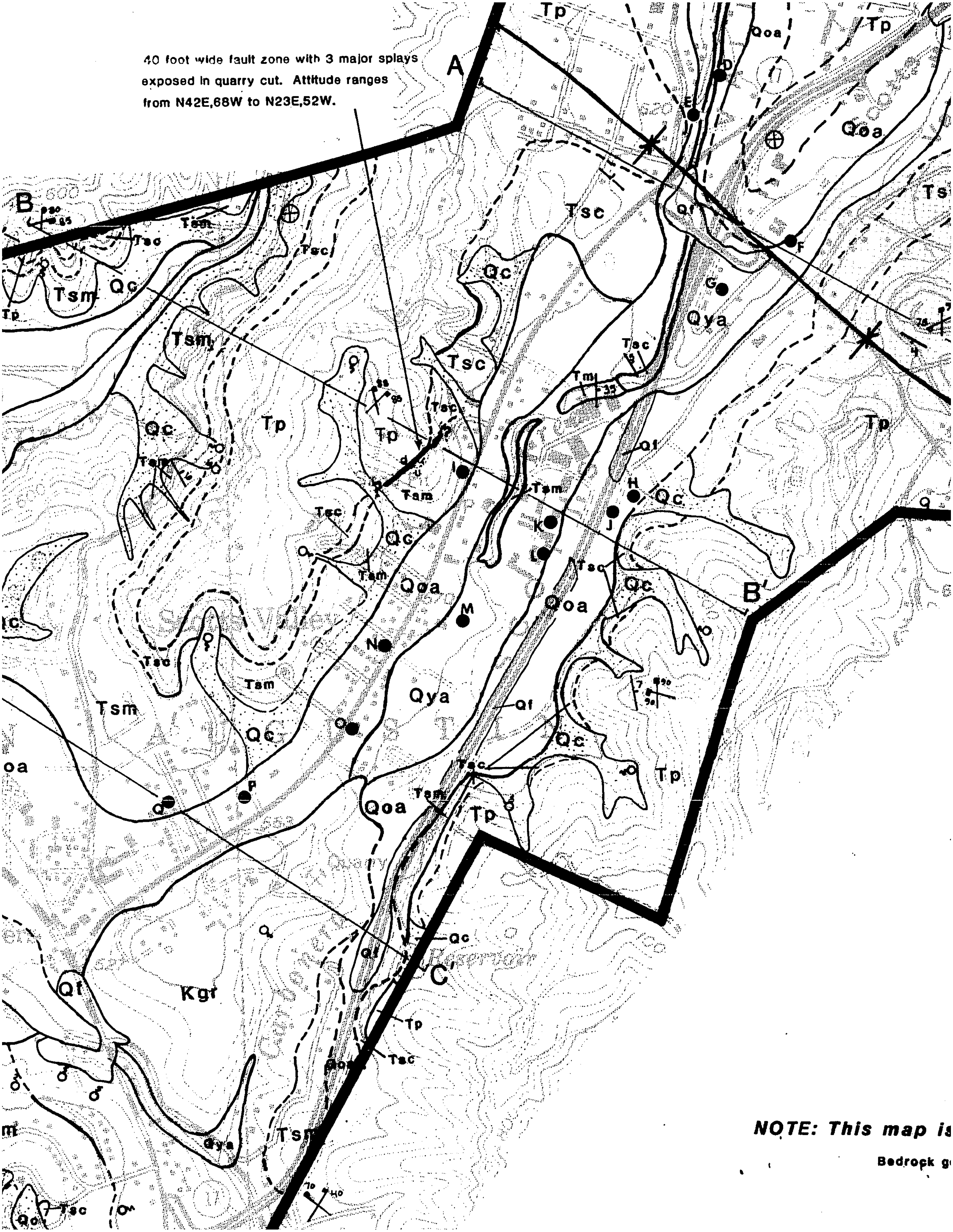



40 foot wide fault zone with 3 major splays
exposed in quarry cut. Attitude ranges
from N42E,68W to N23E,52W.
A
B
B'
Qya
Qoa
Qc
Qf
Tsc
Tp
Tsm
Tm
D
E
F
G
H
I
J
K
L
M
N
O
P
Q

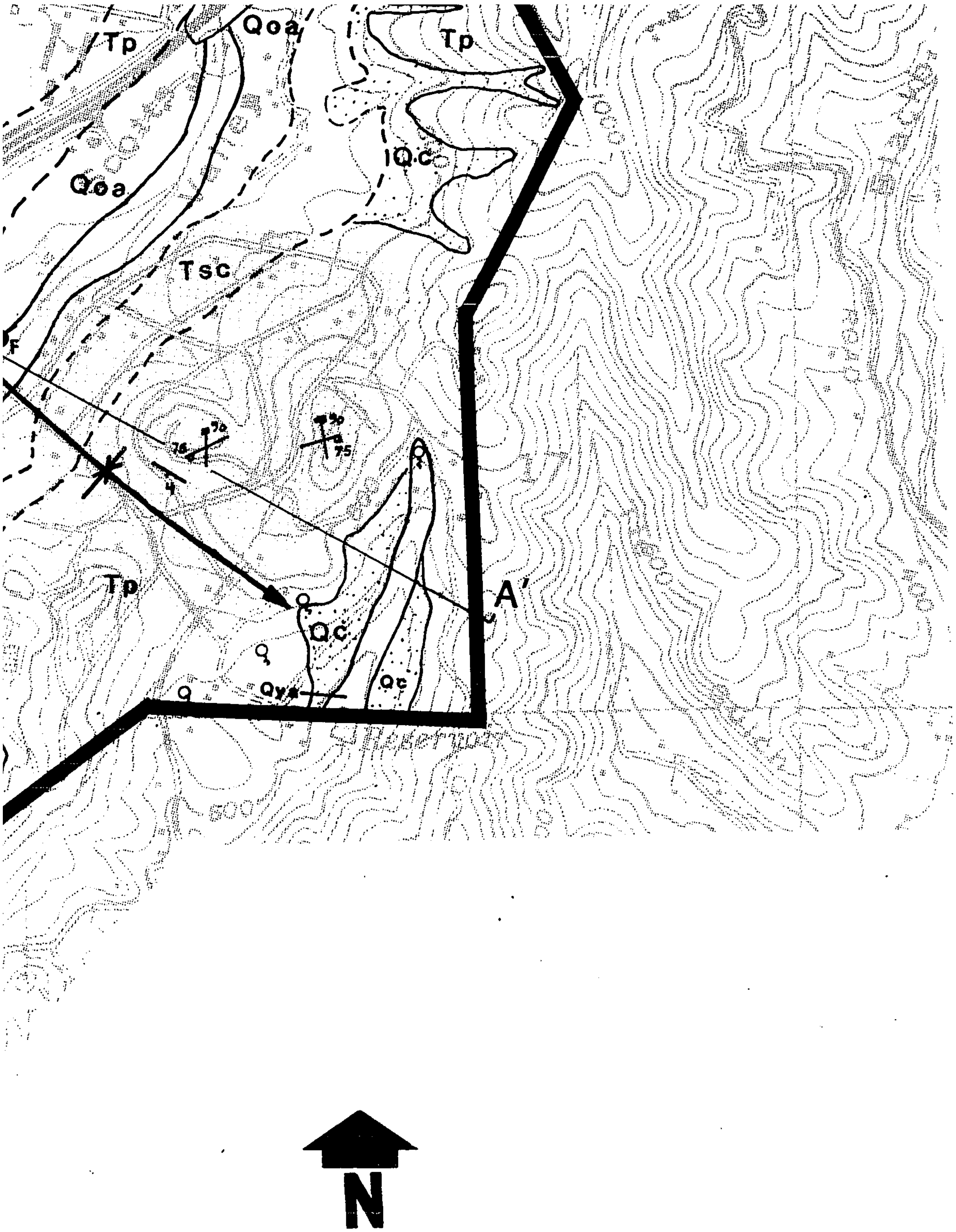


Tp
Qc
Tsc
Qoa
Tp
Qc
Tsc
Qoa
Tp
Qc
Qoa
Tsc
75
90
75
Tp
A'
Qc
Qc
Qys
N


B
C
D
Tsm
Tp
Qc
Qoa
Qya
Qf
Tsc
Skypark
Airport
R
S
T
U
V
W
X
600

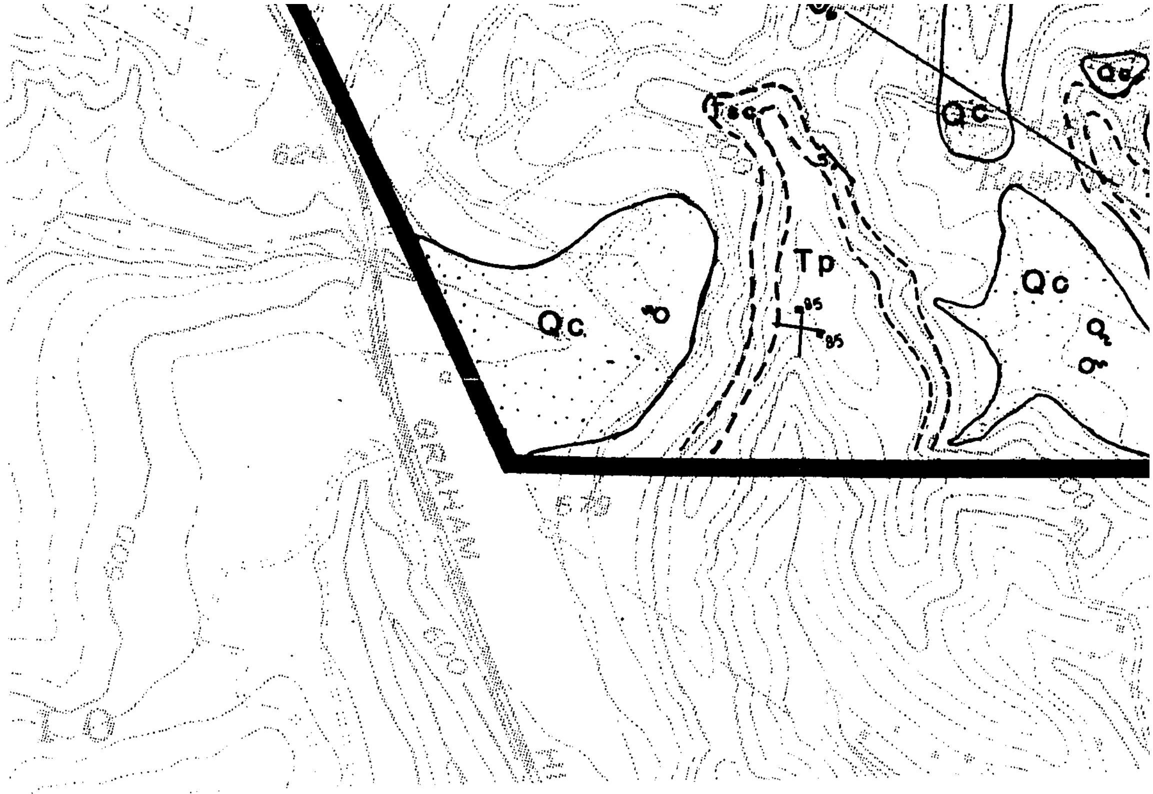


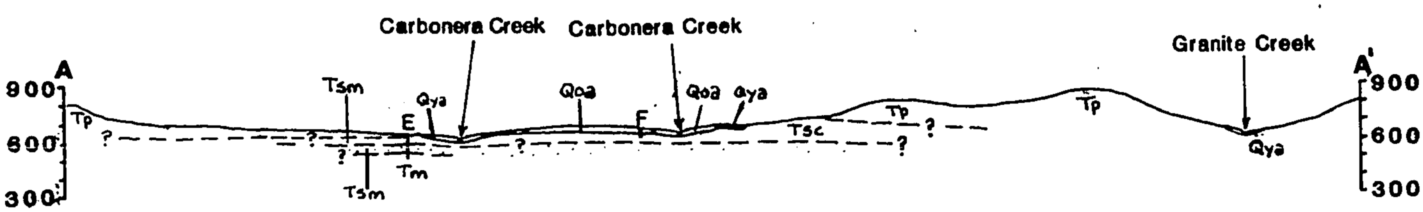
40 foot wide fault zone with 3 major splays
exposed in quarry cut. Attitude ranges
from N42E,68W to N23E,52W.
A
B
B'
C
Tp
Qoa
Tsc
Tsm
Qc
Qf
Qya
Tm
Kgr
D
E
F
G
H
I
J
K
L
M
N
P
Q
NOTE: This map is
Bedrock g

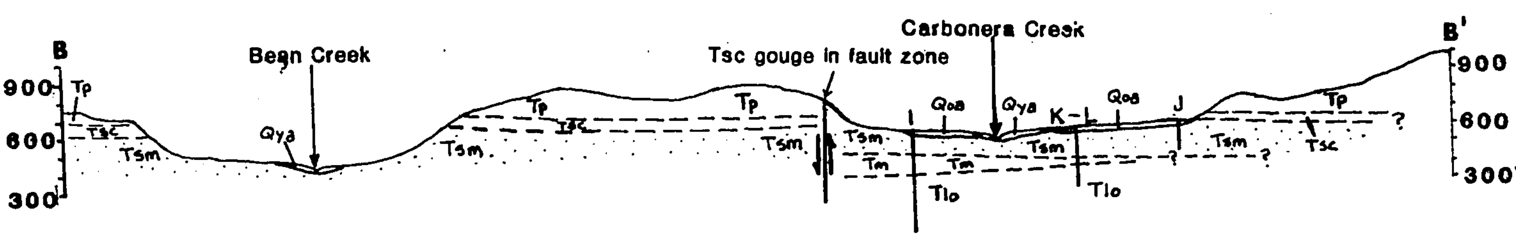


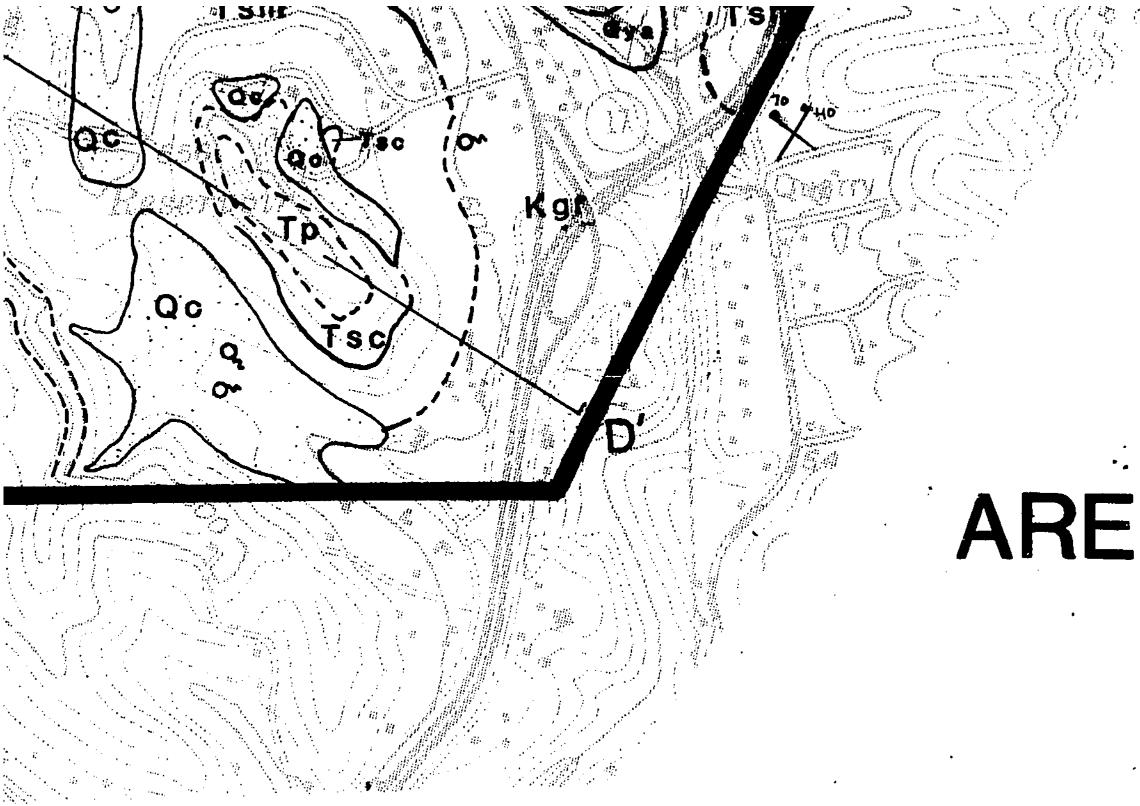
TE: This map is intended for general planning purposes only

Bedrock geology modified from Clark (1981), and Brabb (1986).


Tsc
Tp
Qc
Qc
Qc
85
85
GRAHAM
600
570


A
A'
900
600
300
Carbonera Creek
Carbonera Creek
Granite Creek
Tsm
Qya
Qoa
Qoa
Qya
Tp
E
F
Tm
Tsm
Tsc
Tp
Tp
Qya
?

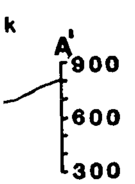

B
B'
900
600
300
Bean Creek
Tsc gouge in fault zone
Carbonera Creek
Tp
Tsc
Tsm
Qya
Tsm
Tp
Tsc
Tp
Tsm
Tsm
Tm
Tm
Tlo
Tlo
I
Qoa
Qya
K-L
Qoa
J
Tsm
Tsm
Tp
Tsc
?

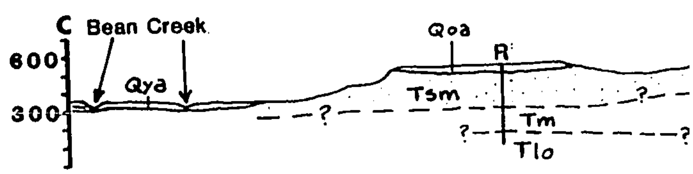


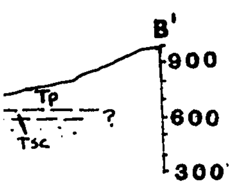
AREAL AND E

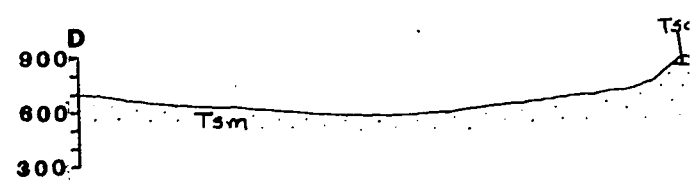
SCOTTS

CROSS SECTIONS









QTE: This map is intended for general planning purposes only

Bedrock geology modified from Clark (1981), and Brabb (1986).

Scale 1:12,000

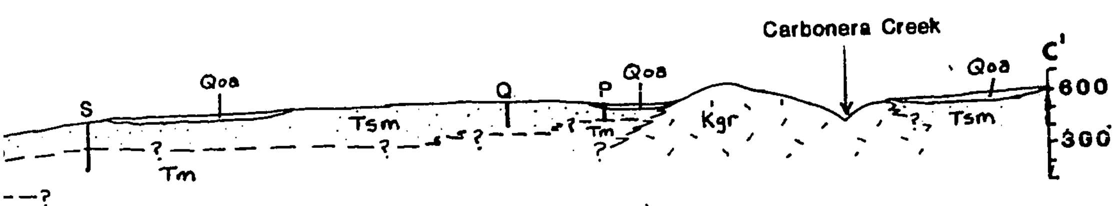
0 1000 2000 3000 FEET

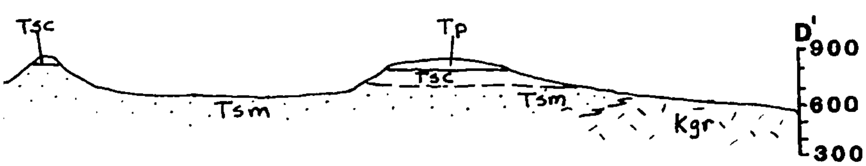
ENGINEERING GEOLOGY MAP

VALLEY, CALIFORNIA

JEFF BACHHUBER, 1989

PLATE 1



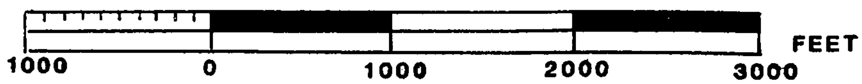


Base map enlarged from U.S. Geological Survey Laurel and Felton 7.5 minute topographic quadrangle maps

N

NOTE: This map is intended for general planning purpos

scale 1:12,000



LANDSLIDES AND RELATED FEA
SCOTTS VALLEY, CALIFORN

JEFF BACHHUBER, 1989

PLATE 2

N

intended for general planning purposes only

12,000

FEET
1000 2000 3000

) RELATED FEATURES
_LEY, CALIFORNIA

-F BACHHUBER, 1989

PLATE 2

EXPLANA

ACTIVE OR RECENTLY ACTIVE SLOPE FAILURES

debris avalanche or rapid debris flow

scarp **track** **deposit**

debris slide or rotational slump (may involve weathered bedrock)

headscarp **deposit** 89 tension crack developed from 1989 Loma Prieta Earthquake

earthflow or slower debris flow

scarp **deposit**

small debris slide or slump—less than 50 feet in dimension

DORMANT OLDER SLOPE FAILURES

debris avalanche or rapid debris flow

scarp **track**

debris slide or rotational slump (may involve weathered bedrock)

headscarp **deposit**

earthflow or slower debris flow

scarp **deposit**

50 feet in dimension

EXPLANATION

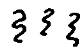
RES

:k)

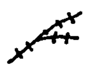
—

:k)

RELATED FEATURES


area of moderate to severe soil creep


debris fan accumulated by successions of slope failures


unstable erosion gully or drainage gully

rc road cracks from fill creep or incipient slope failure

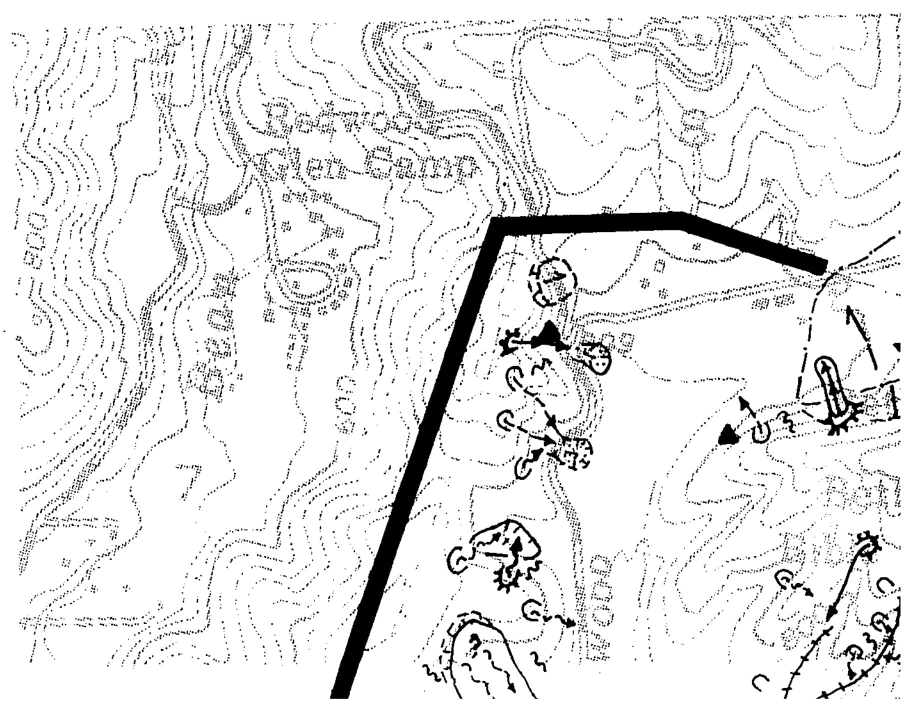

stretch of watercourse inundated by recent debris torrents

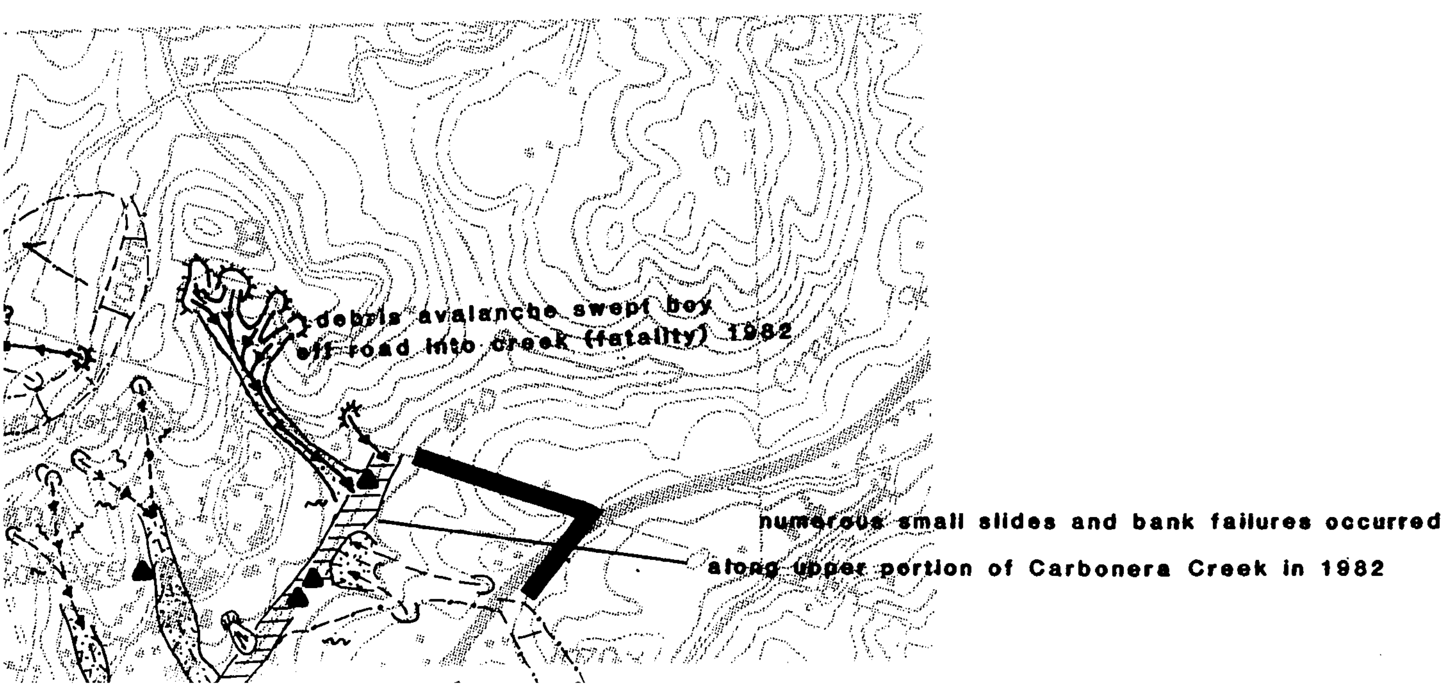
abandoned quarry with oversteepend,unstable walls ı of slope failures

slope failure

ent debris torrents

stablo walls



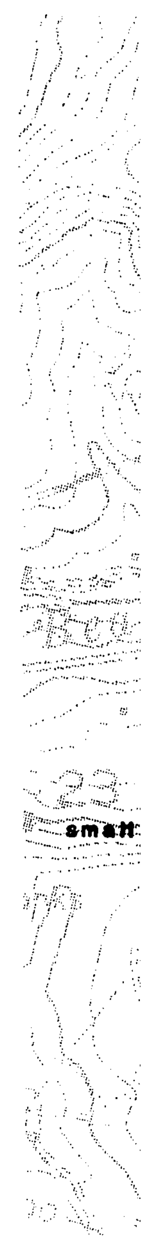

debris avalanche swept boy
off road into creek (fatality) 1982
numerous small slides and bank failures occurred
along upper portion of Carbonera Creek in 1982

⌒ scarp ⸮ deposit

△ small debris slide or slump–less than 50 feet in dimension

ANCIENT INACTIVE SLOPE FAILURES

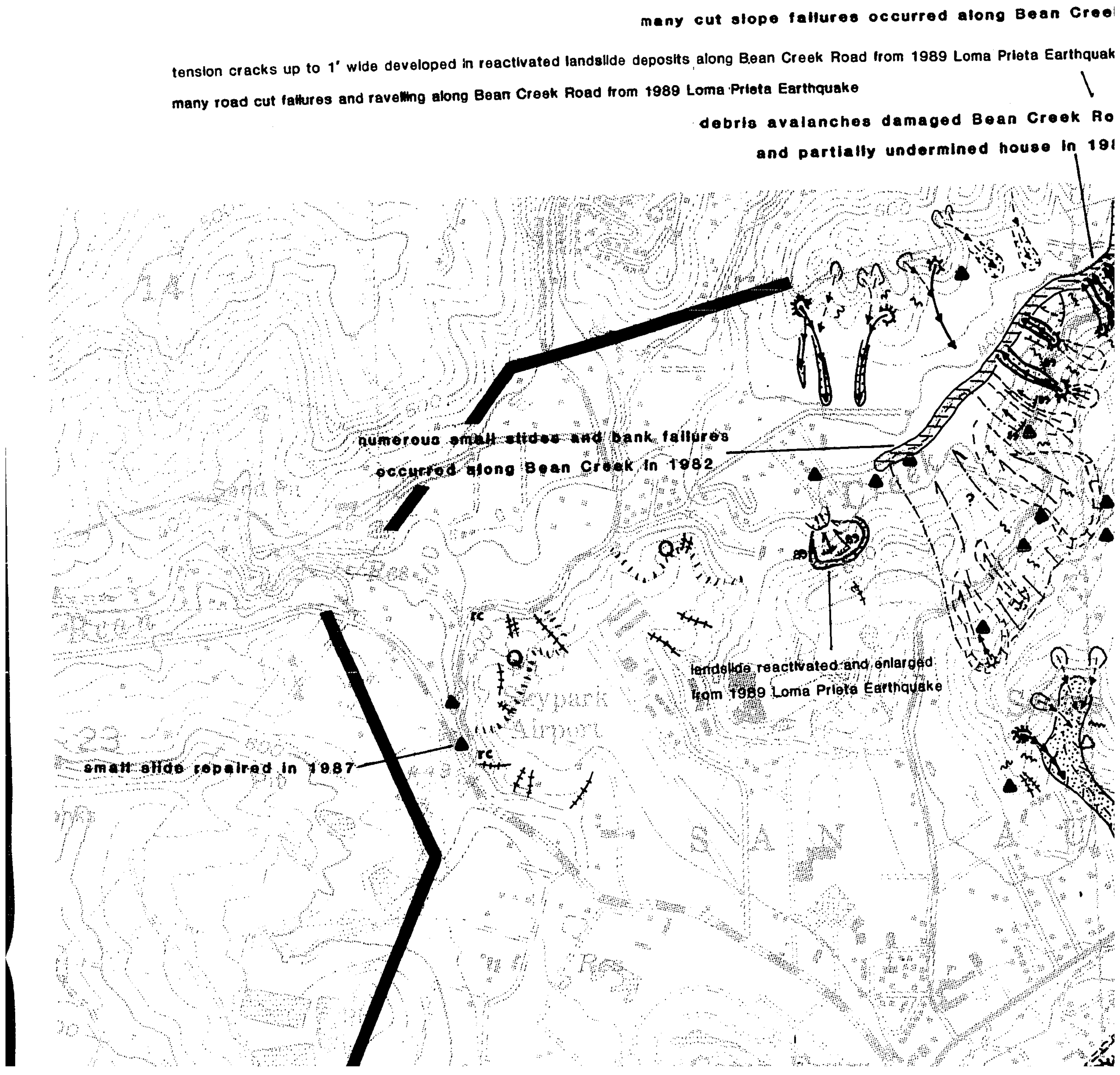

deep seated debris or bedrock slide (? denotes questionable identification)

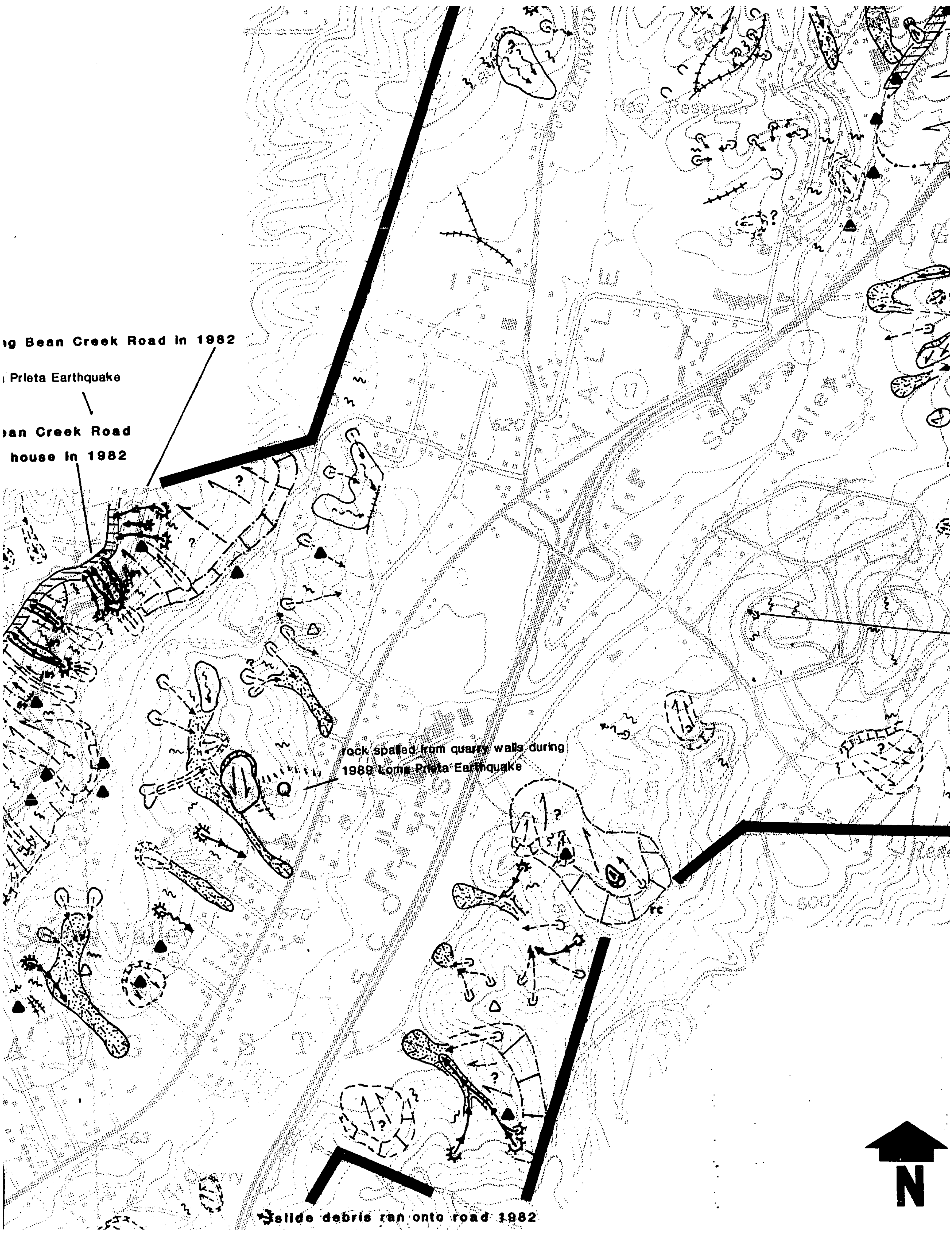


CLASSIFICATION OF LANDSLIDES

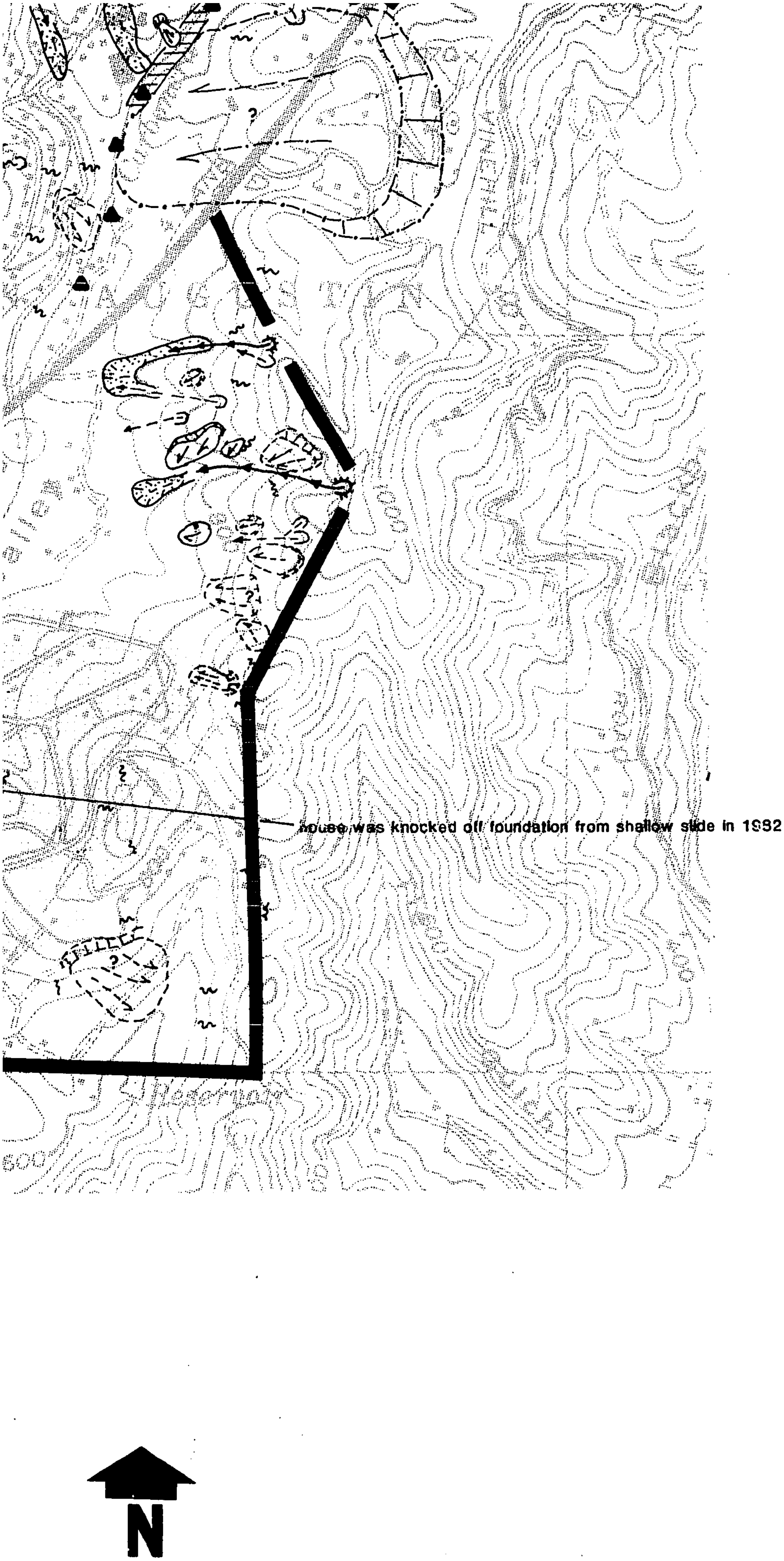
TYPE OF MOVEMENT	TYPE OF MATERIAL			
	BEDROCK		SOILS	
FALLS	ROCKFALL		SOILFALL	
SLIDES: FEW UNITS	ROTATIONAL SLUMP	PLANAR BLOCK GLIDE	PLANAR BLOCK GLIDE	ROTATIONAL BLOCK SLUMP
SLIDES: MANY UNITS		ROCKSLIDE	DEBRIS SLIDE	FAILURE BY LATERAL SPREADING

	ALL UNCONSOLIDATED			
	ROCK FRAGMENTS	SAND OR SILT	MIXED	MOSTLY PLASTIC
FLOWS: DRY	ROCK FRAGMENT FLOW	SAND RUN	LOESS FLOW	
FLOWS		RAPID EARTHFLOW	DEBRIS AVALANCHE	SLOW EARTHFLOW
FLOWS: WET		SAND OR SILT FLOW	DEBRIS FLOW	MUDFLOW


many cut slope failures occurred along Bean Cree
tension cracks up to 1' wide developed in reactivated landslide deposits along Bean Creek Road from 1989 Loma Prieta Earthquak
many road cut failures and ravelling along Bean Creek Road from 1989 Loma Prieta Earthquake
debris avalanches damaged Bean Creek Ro
and partially undermined house in 19
numerous small slides and bank failures
occurred along Bean Creek in 1982
landslide reactivated and enlarged
from 1989 Loma Prieta Earthquake
small slide repaired in 1987
rc
Q
Airport



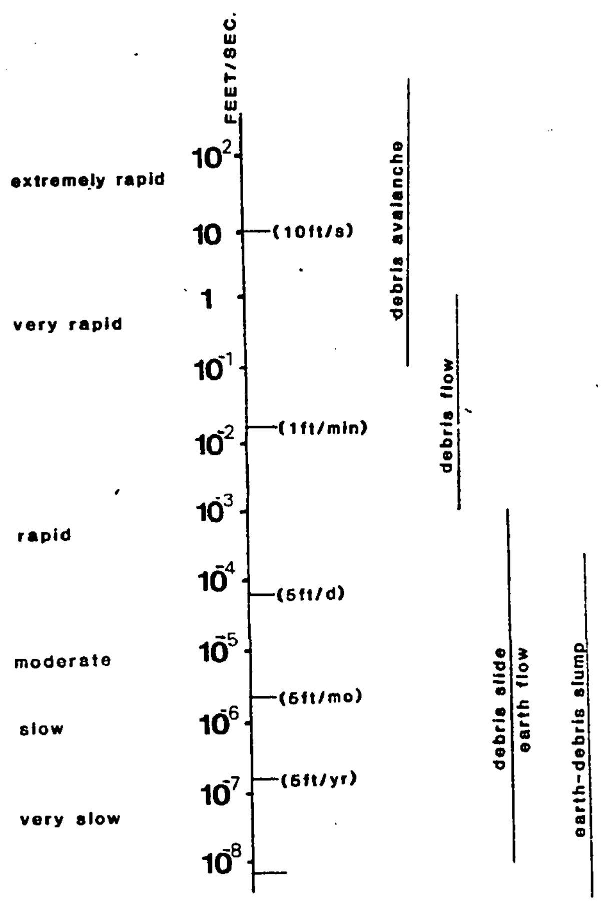
ng Bean Creek Road in 1982
Prieta Earthquake
ean Creek Road
house in 1982
rock spalled from quarry walls during
1989 Loma Prieta Earthquake
Q
rc
slide debris ran onto road 1982
N


house was knocked off foundation from shallow slide in 1982
N

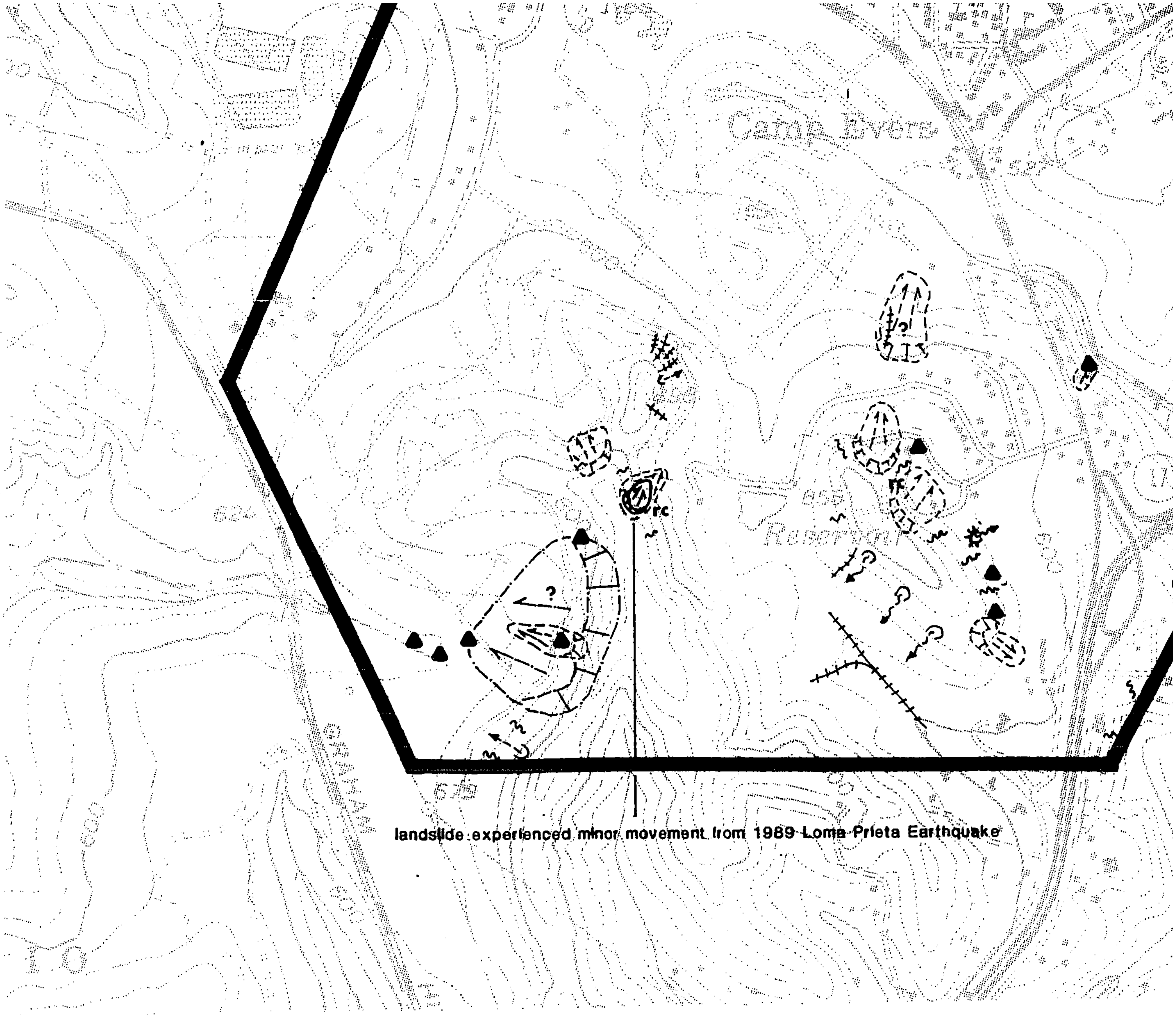
FLOWS		EARTHFLOW	AVALANCHE	EARTHFLOW
WET		SAND OR SILT FLOW	DEBRIS FLOW	MUDFLOW
COMPLEX	COMBINATIONS OF MATERIALS OR TYPE OF MOVEMENT			

(Varnes, 1978)

LANDSLIDE MOVEMENT RATES



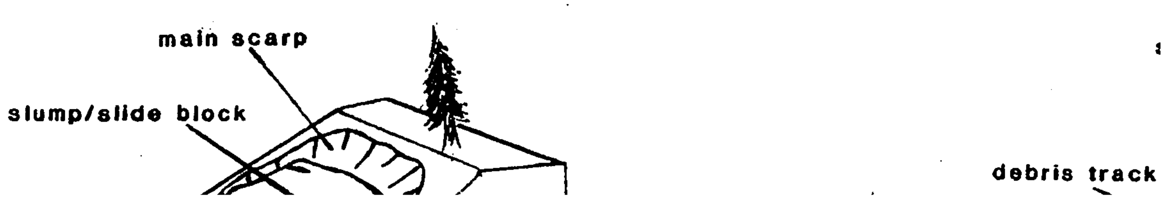
(figure modified from Varnes,1978)

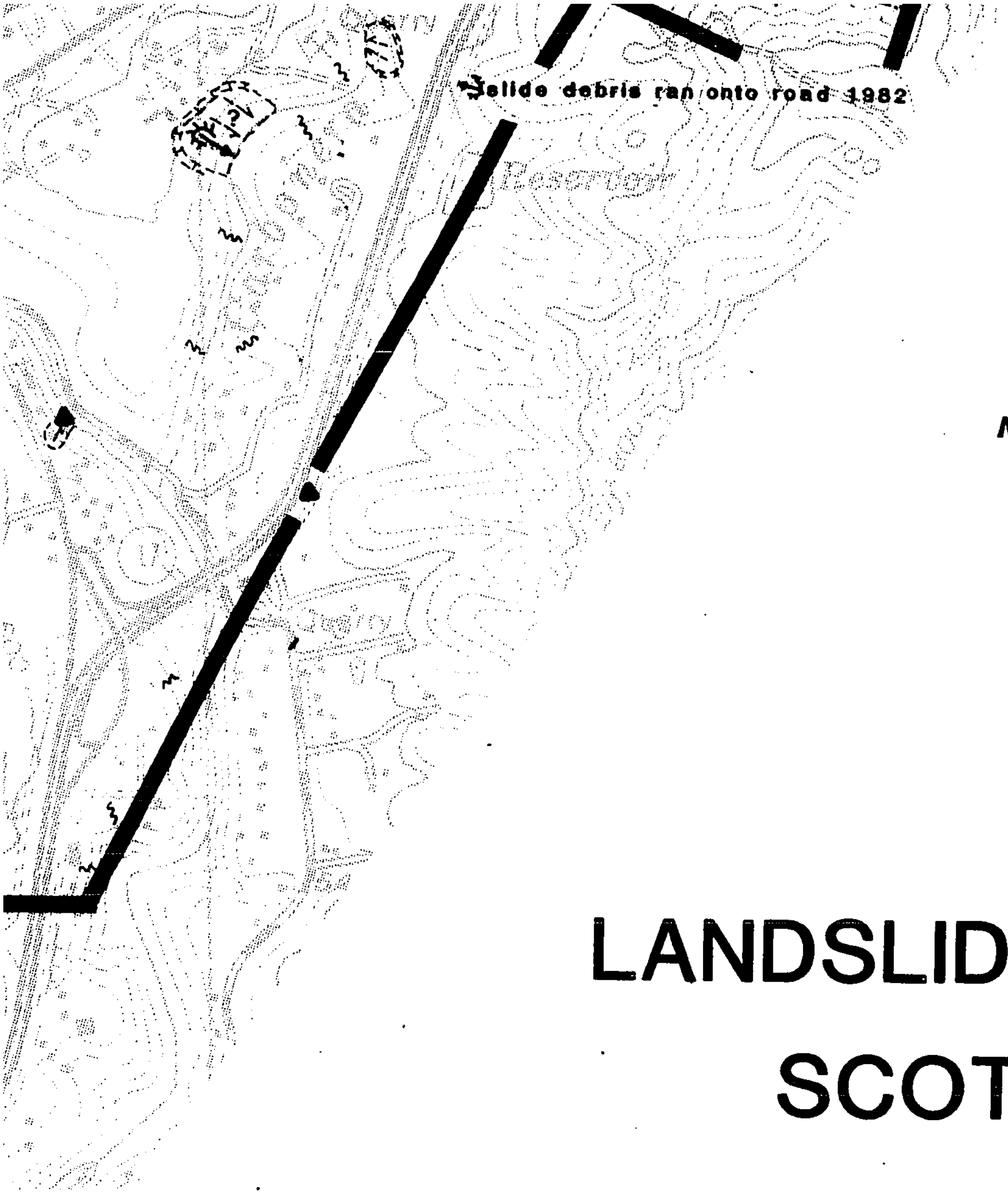


GENERAL MORPHOLOGY OF RECENTLY ACTIVE LANDSL

Cohesive slump/slide failure

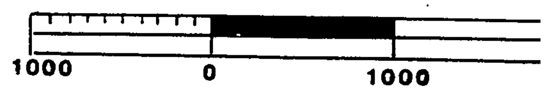
Non-co





NOTE: This map is intended f

scale 1:12,000



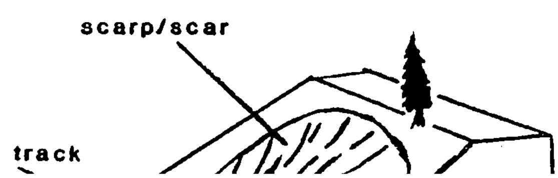
LANDSLIDES AND REL
SCOTTS VALLEY

JEFF BACHHUI

PLAT

: LANDSLIDES

Non-cohesive flow-type failure



N

; intended for general planning purposes only

:12,000

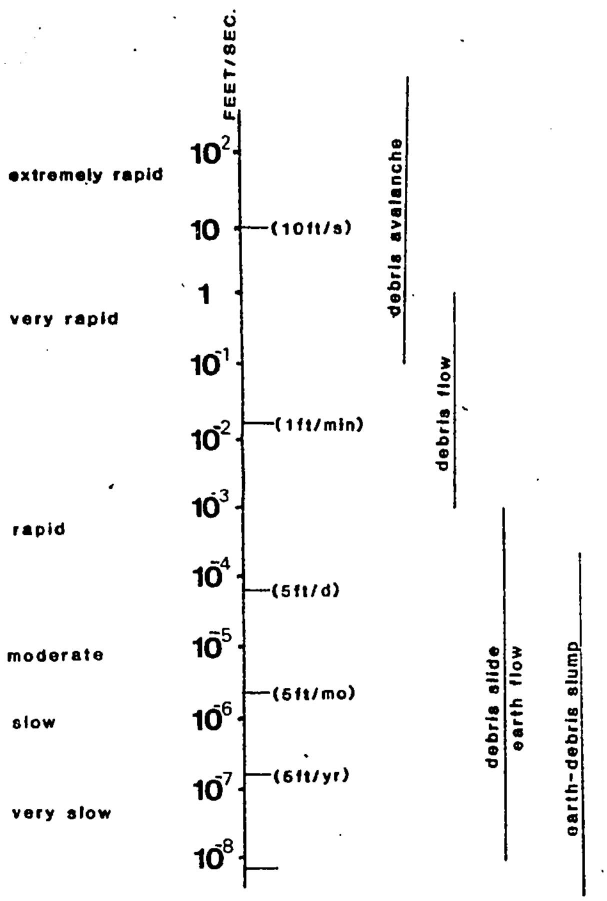
1000 2000 3000 FEET

) RELATED FEATURES
LLEY, CALIFORNIA

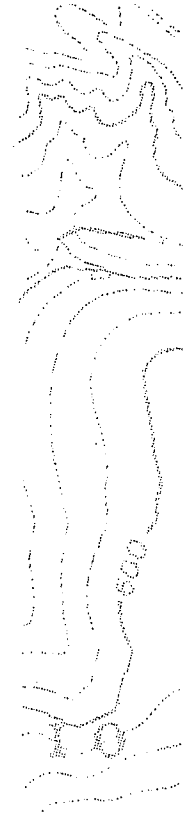
FF BACHHUBER, 1989

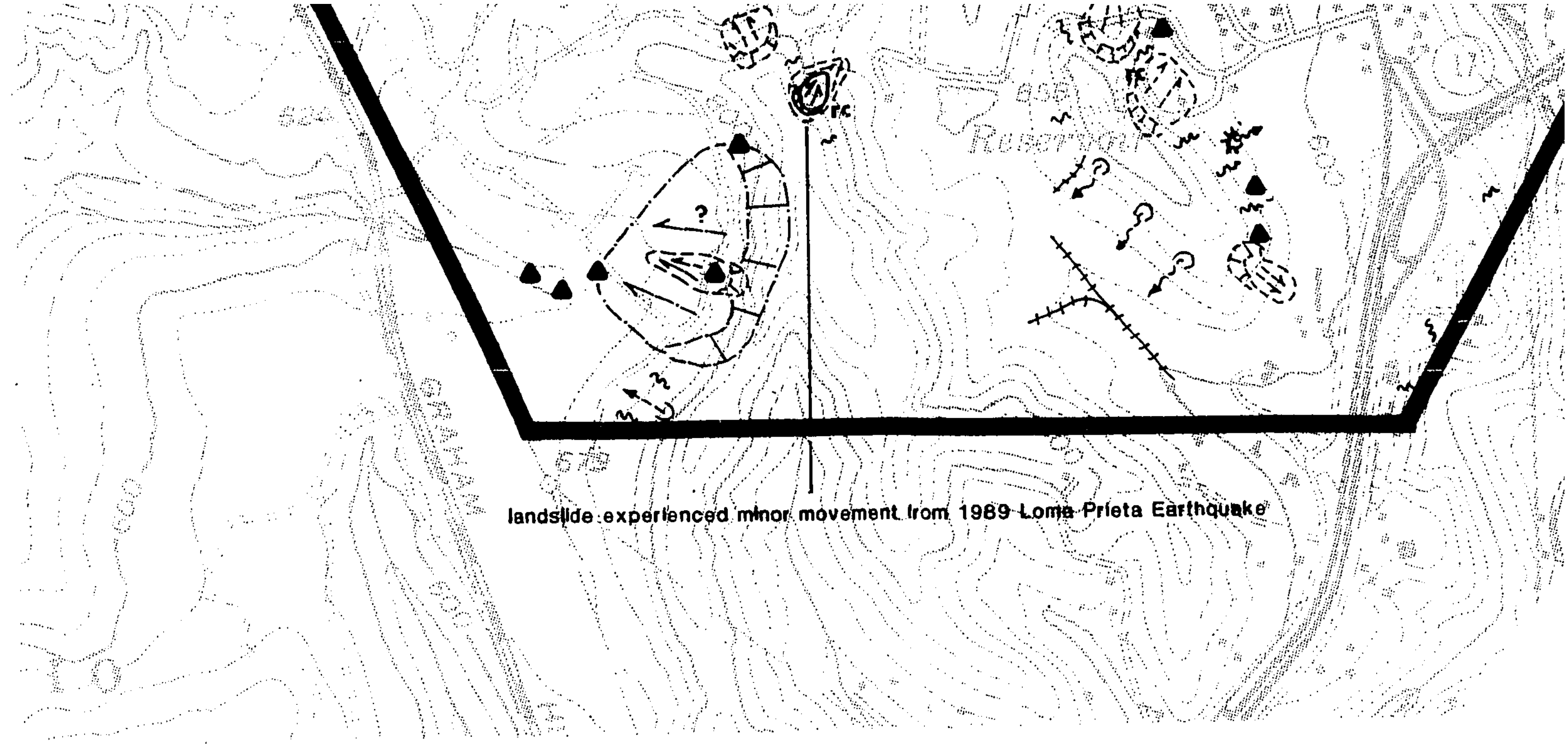
PLATE 2

LANDSLIDE MOVEMENT RATES

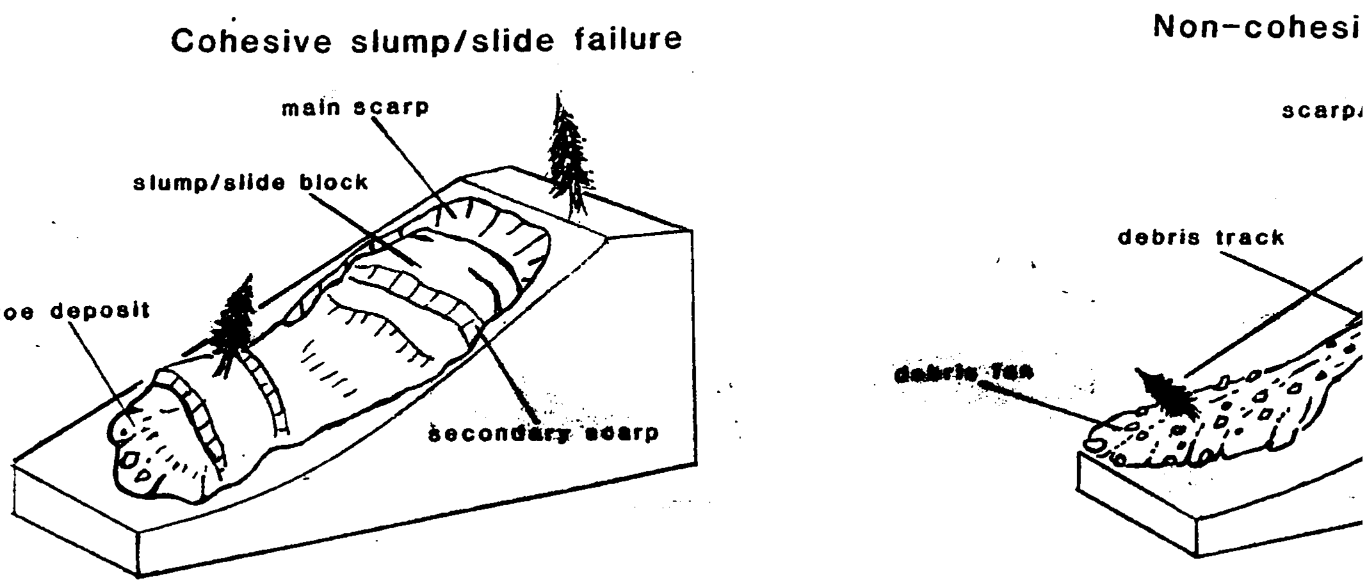


(figure modified from Varnes,1978)





GENERAL MORPHOLOGY OF RECENTLY ACTIVE LANDSLIDE



scale 1:12,000

1000 0 1000

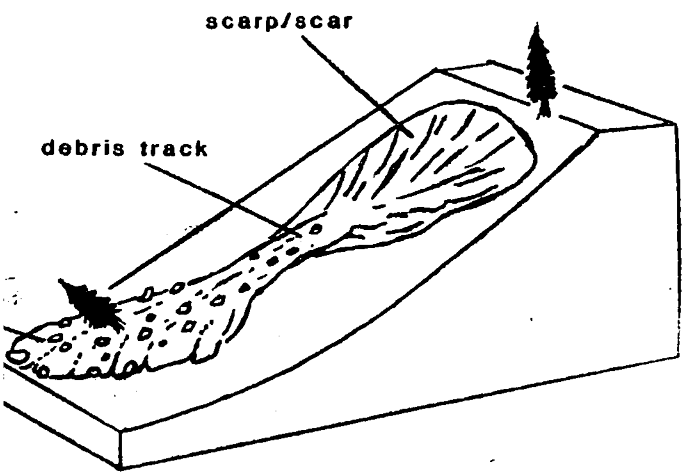
LANDSLIDES AND RE
SCOTTS VALLEY

JEFF BACHH

PLA

IVE LANDSLIDES

Non-cohesive flow-type failure



)00

000 2000 3000 FEET

RELATED FEATURES

-EY, CALIFORNIA

3ACHHUBER, 1989

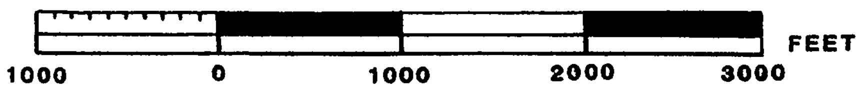
LATE 2

Base map enlarged from U.S. Geological Survey Laurel and Felton 7.5 minute topographic quadrangle maps

N

NOTE: This map is intended for general planning purposes only

scale 1:12,000



LANDSLIDE POTENTIAL MAP
SCOTTS VALLEY, CALIFORNIA

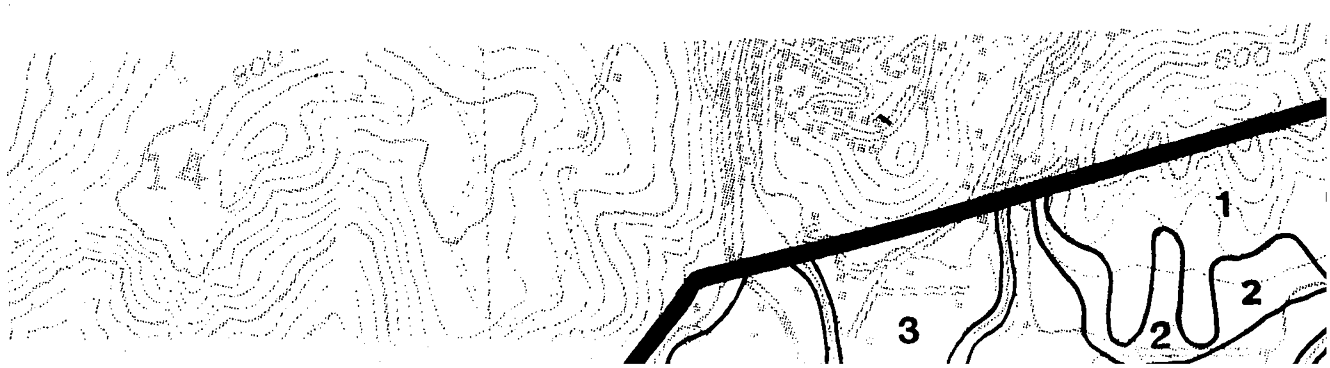
JEFF BACHHUBER, 1989

PLATE 3

Base map enlarged from U.S. Geological Survey Laurel and Felton 7.5 minute topographic q

EXPLANATION

1	Areas of high landslide and soil creep potential– drainage courses located within Zone 1 are p energy debris flows and avalanches during high precipitation storm events
2	Areas of moderate landslide and soil creep potential, and areas subject to disruption of Zone 2 also includes stream banks subject to slumping and erosion during periods of high stre
3	Areas of low landslide potential



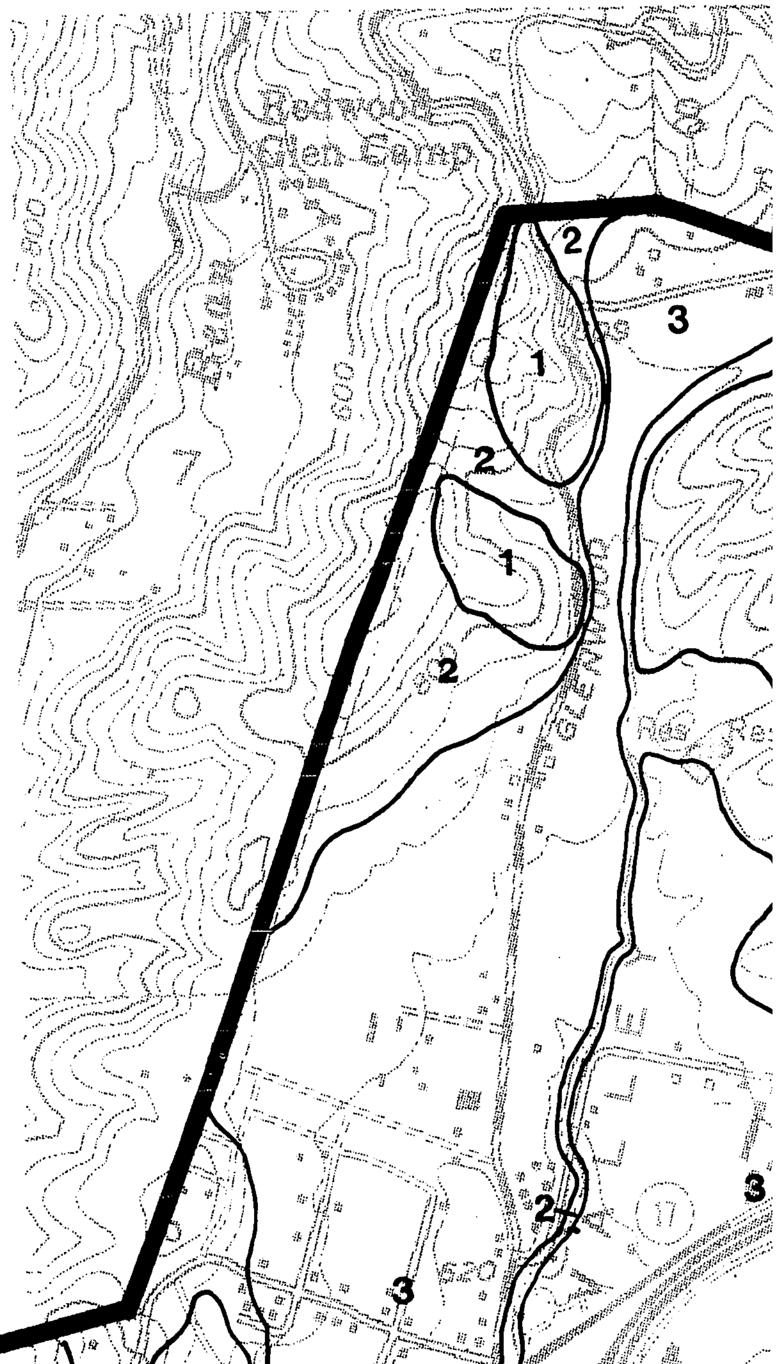
ATION

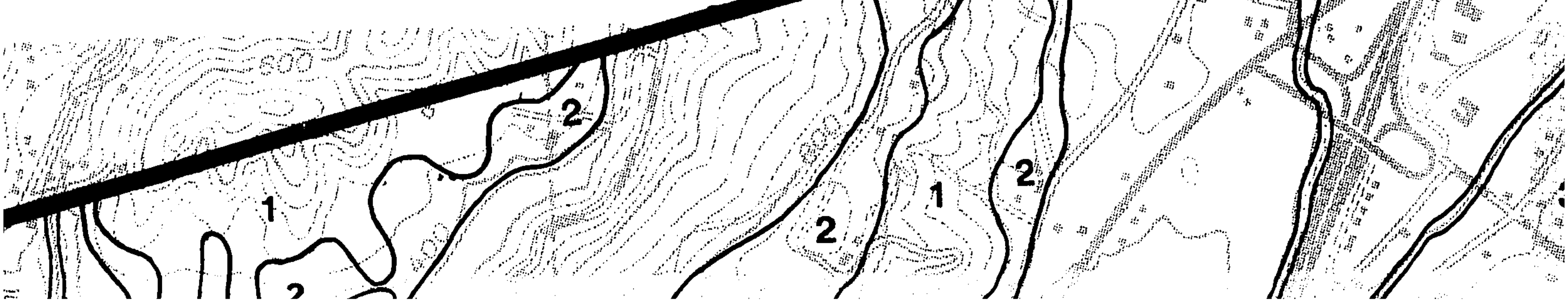
›es located within Zone 1 are potential flow paths for high

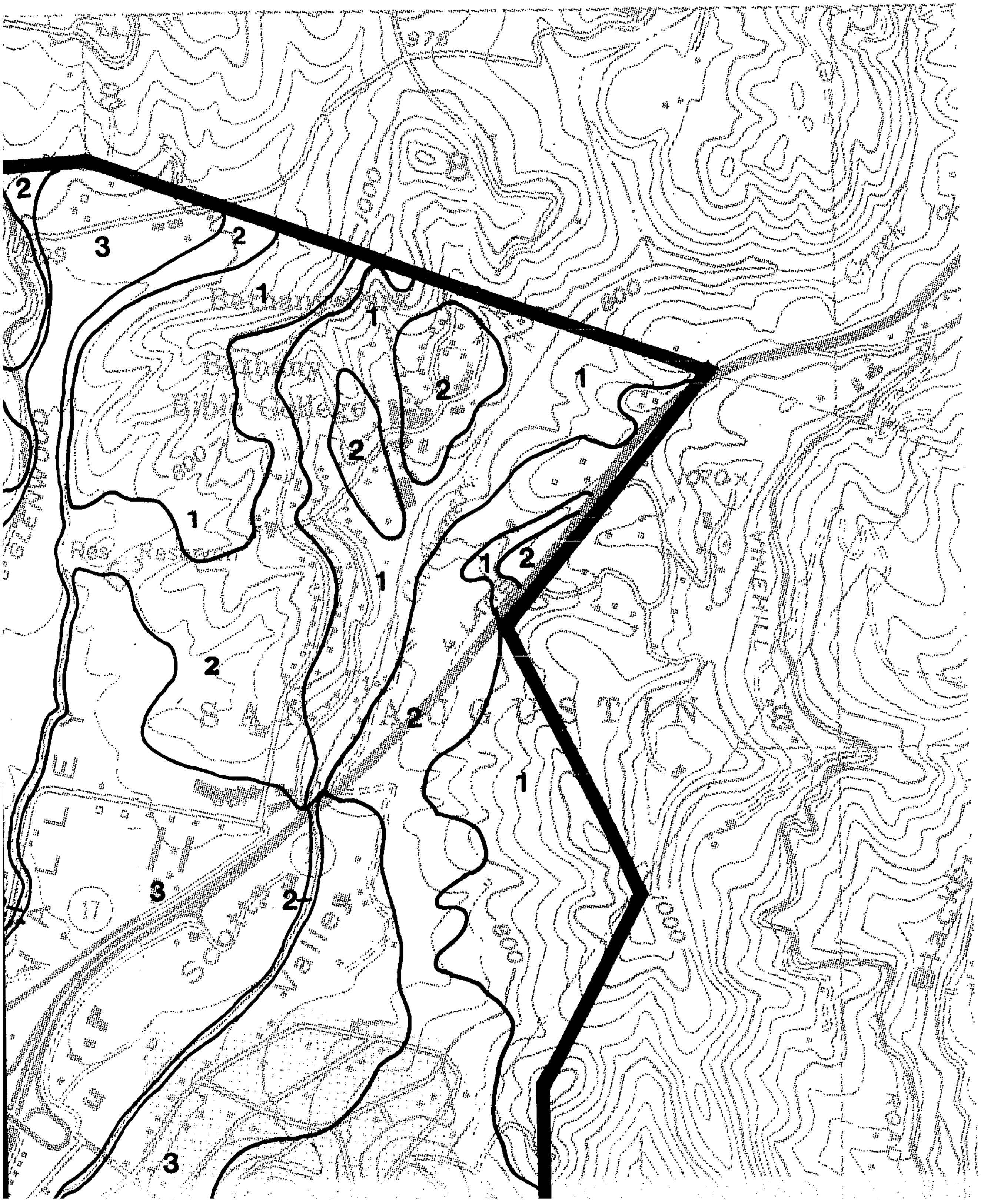
›rm events

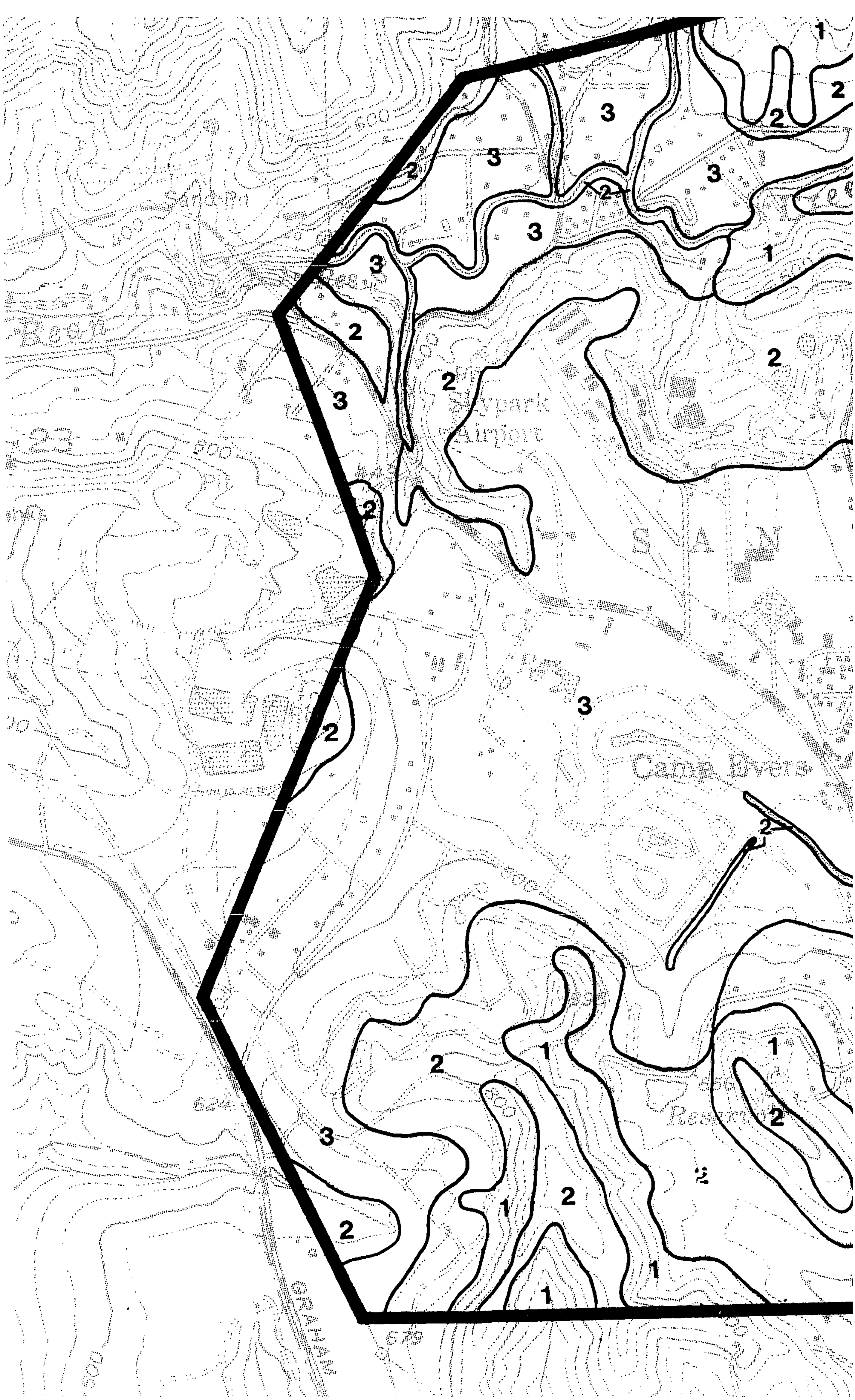
›eas subject to disruption of access by landsliding

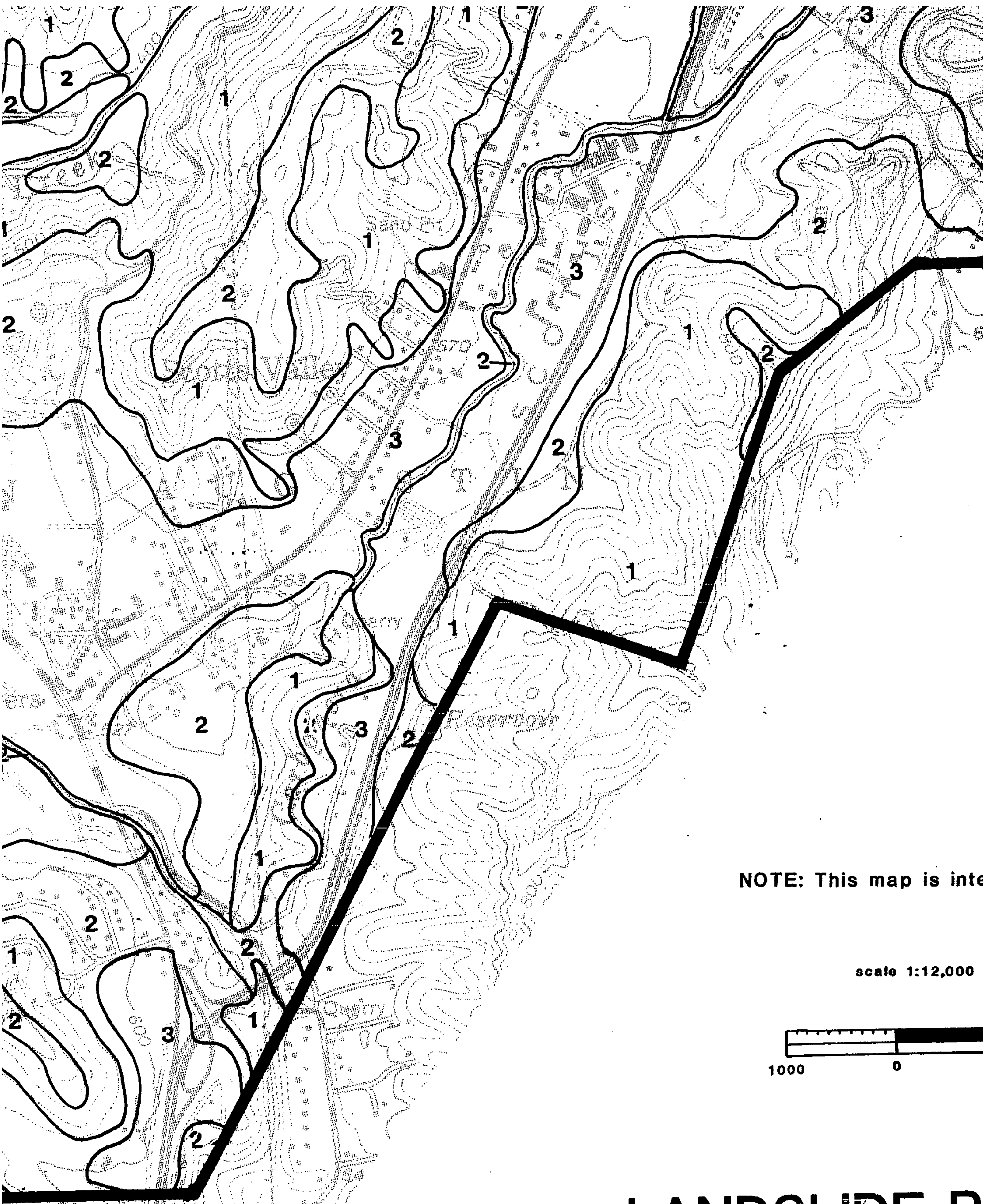
lon during periods of high stream flow







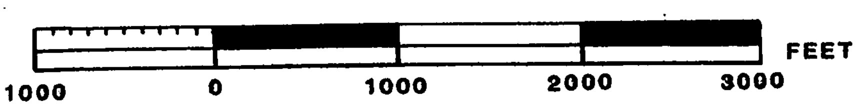

Airport
S A N
Camp Evers
GRAHAM



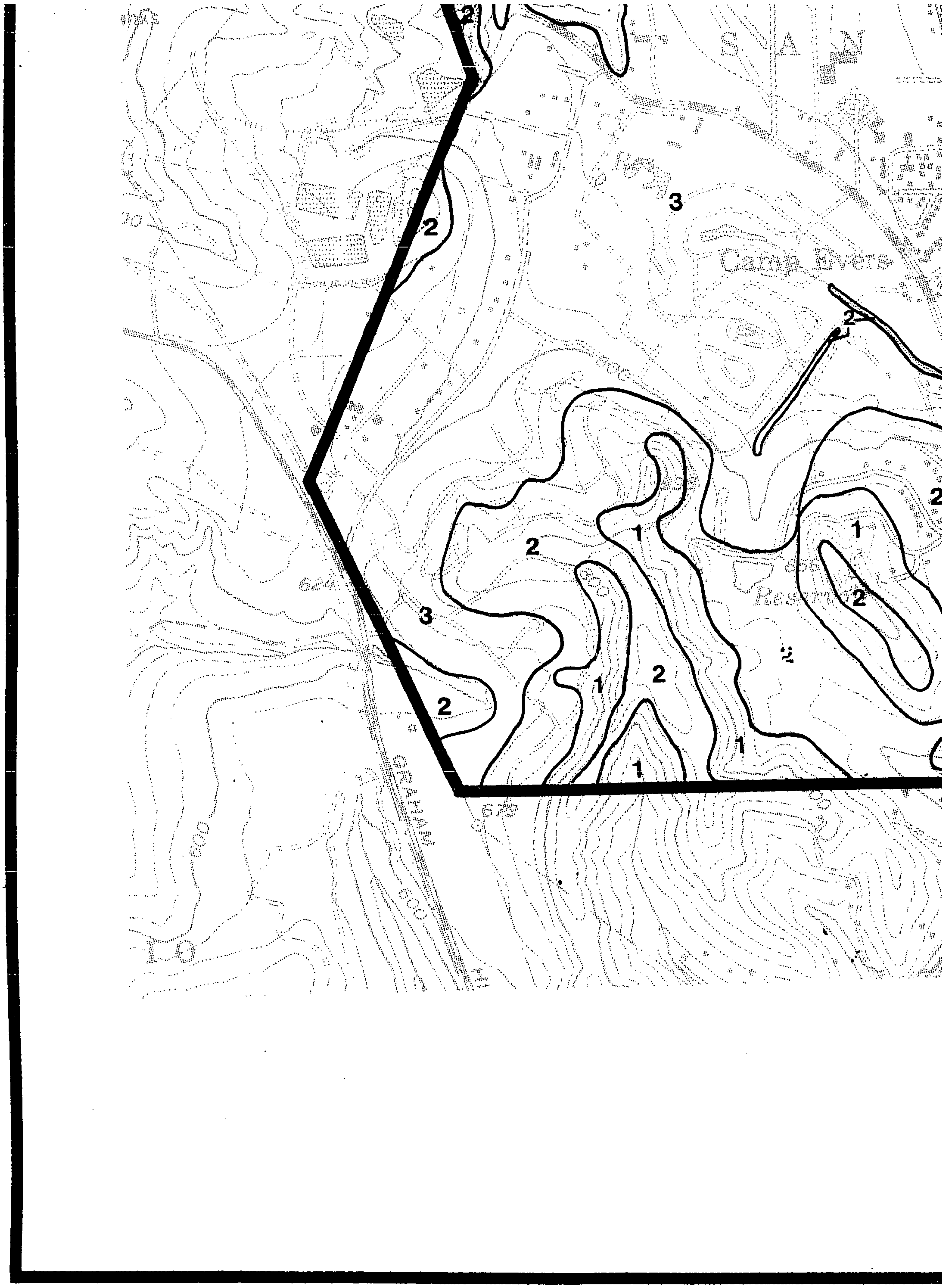
LANDSLIDE P

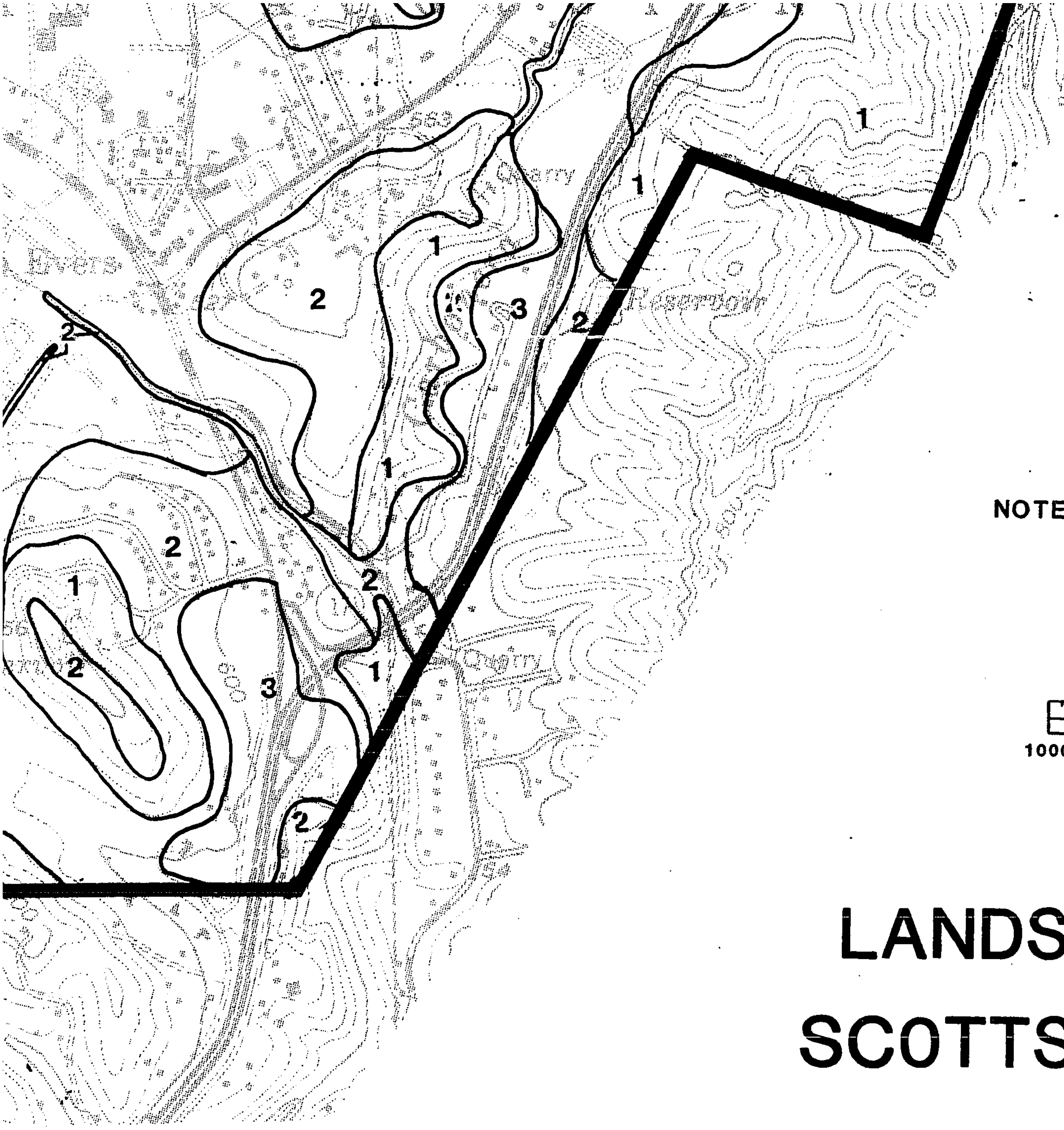
)TE: This map is intended for general planning purposes only

scale 1:12,000



)SLIDE POTENTIAL MAP


Camp Evers
GRAHAM
624
600
3
2
1



NOTE: This map i

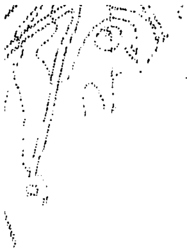
scale 1:1

1000 0

LANDSLIDE
SCOTTS VAL

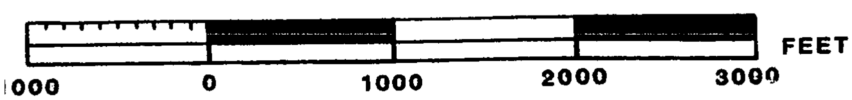
JEF

Base m



TE: This map is intended for general planning purposes only

scale 1:12,000



SLIDE POTENTIAL MAP
'S VALLEY, CALIFORNIA

JEFF BACHHUBER, 1989

PLATE 3

Base map enlarged from U.S. Geological Survey Laurel and Felton 7.5 minute topographic quadrangle

N

Note: This map is intended for general planning purpose

scale 1:12,000

1000 0 1000 2000 3000 FEET

LIQUEFACTION POTENTIAL
SCOTTS VALLEY, CALIFOR

JEFF BACHHUBER, 1989

PLATE 4

Base map enlarged from U.S. Geological Survey La

N

his map is intended for general planning purposes only

scale 1:12,000

0 1000 2000 3000 FEET

ION POTENTIAL MAP

ALLEY, CALIFORNIA

JEFF BACHHUBER, 1989

PLATE 4

Base map enlarged from U.S. Geological Survey Laurel and Felton 7.5 minute topographic quadrangle maps

EXPLANATION

A Alluvial deposits potentially containing sediments exhibiting a moderat

B Alluvial deposits potentially containing sediments exhibiting a moderat
but generally exhibiting a low liquefaction susceptibility

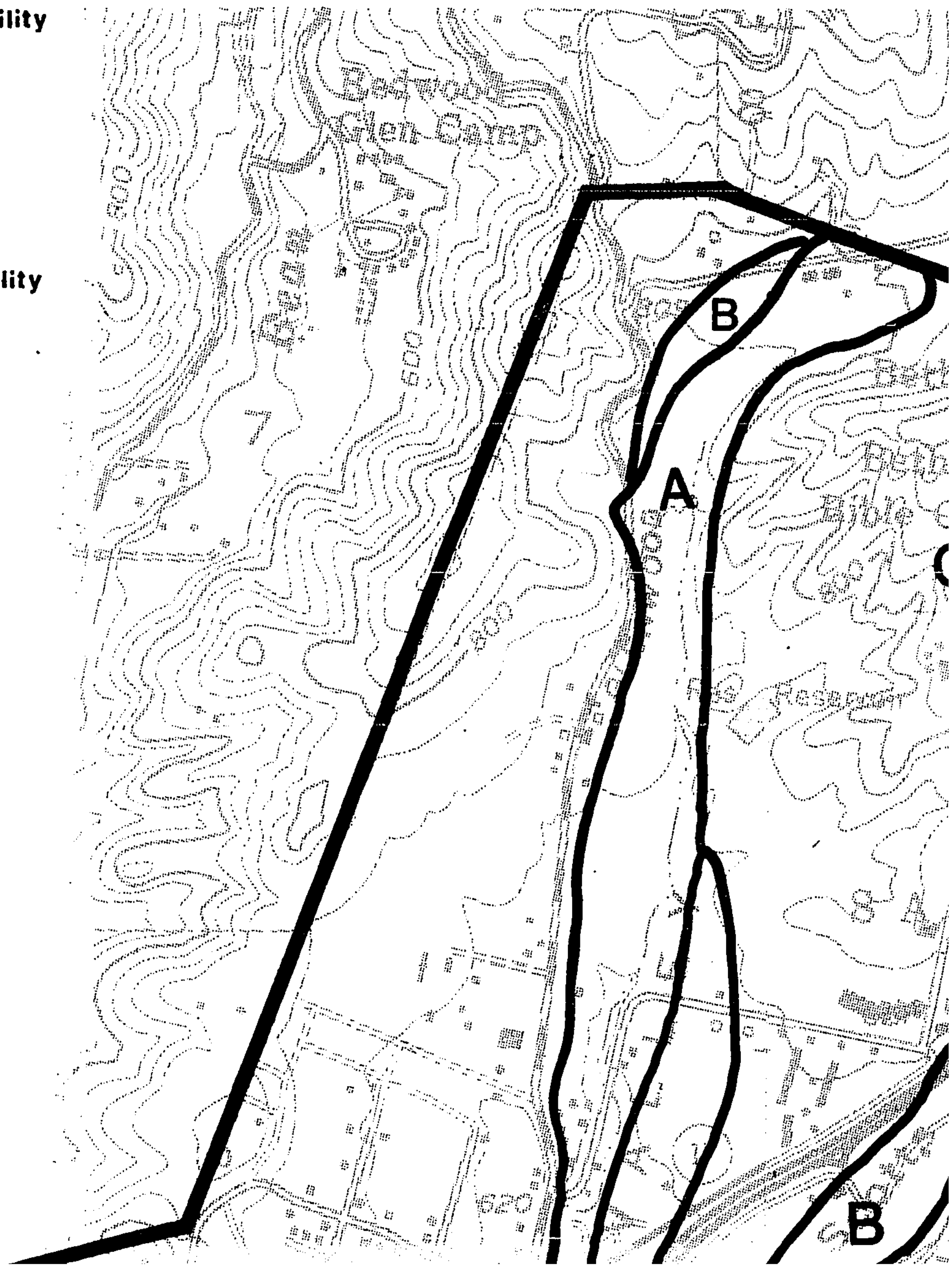
C Non-alluviated areas either not susceptible to liquefaction, or exhibitin

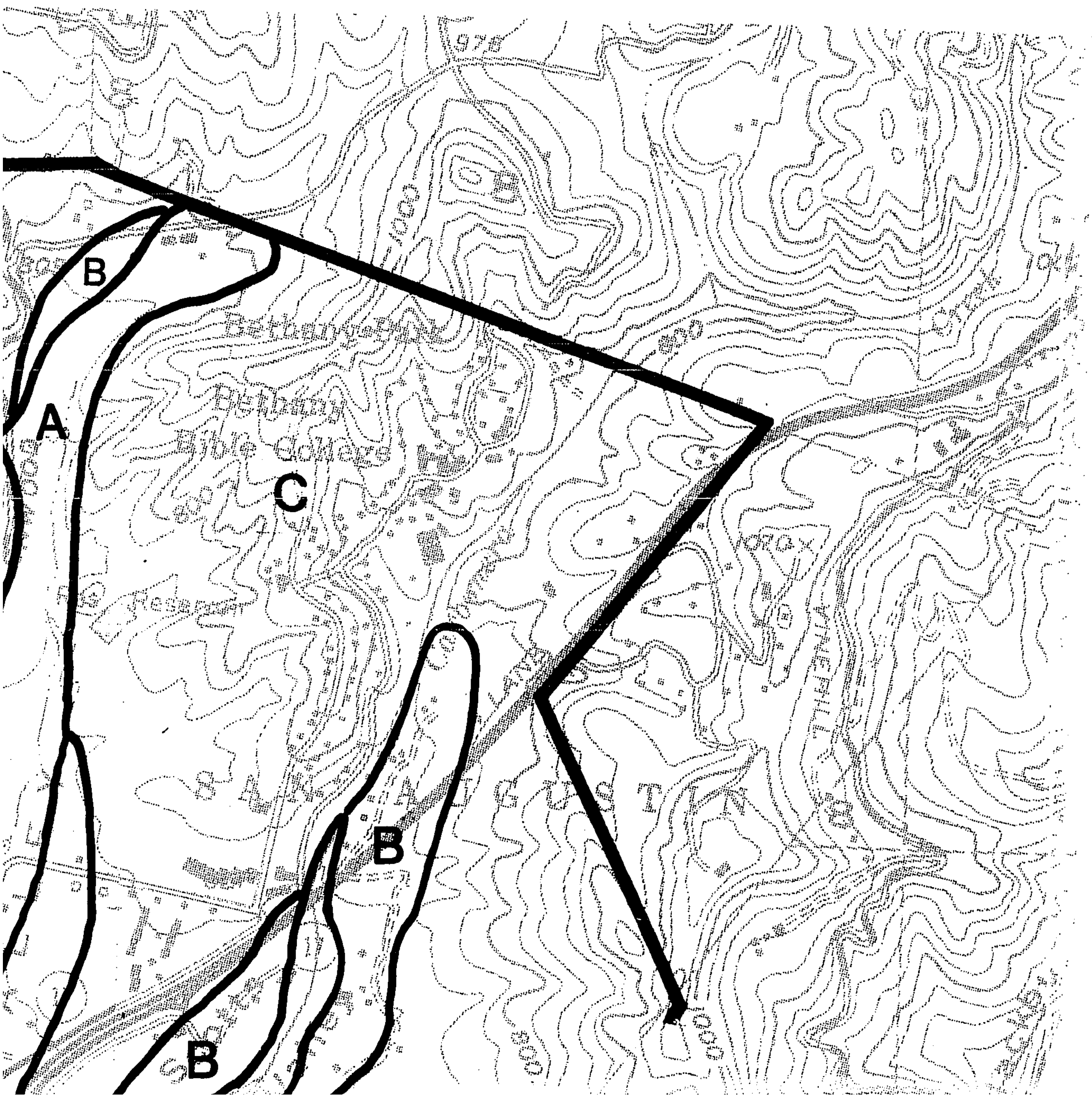
Location of tension fissure along edge of Lockhart Gulch Road
apparently caused by lateral spreading of road fills over liquefied
sand deposits caused by the 1989 Loma Prieta earthquake

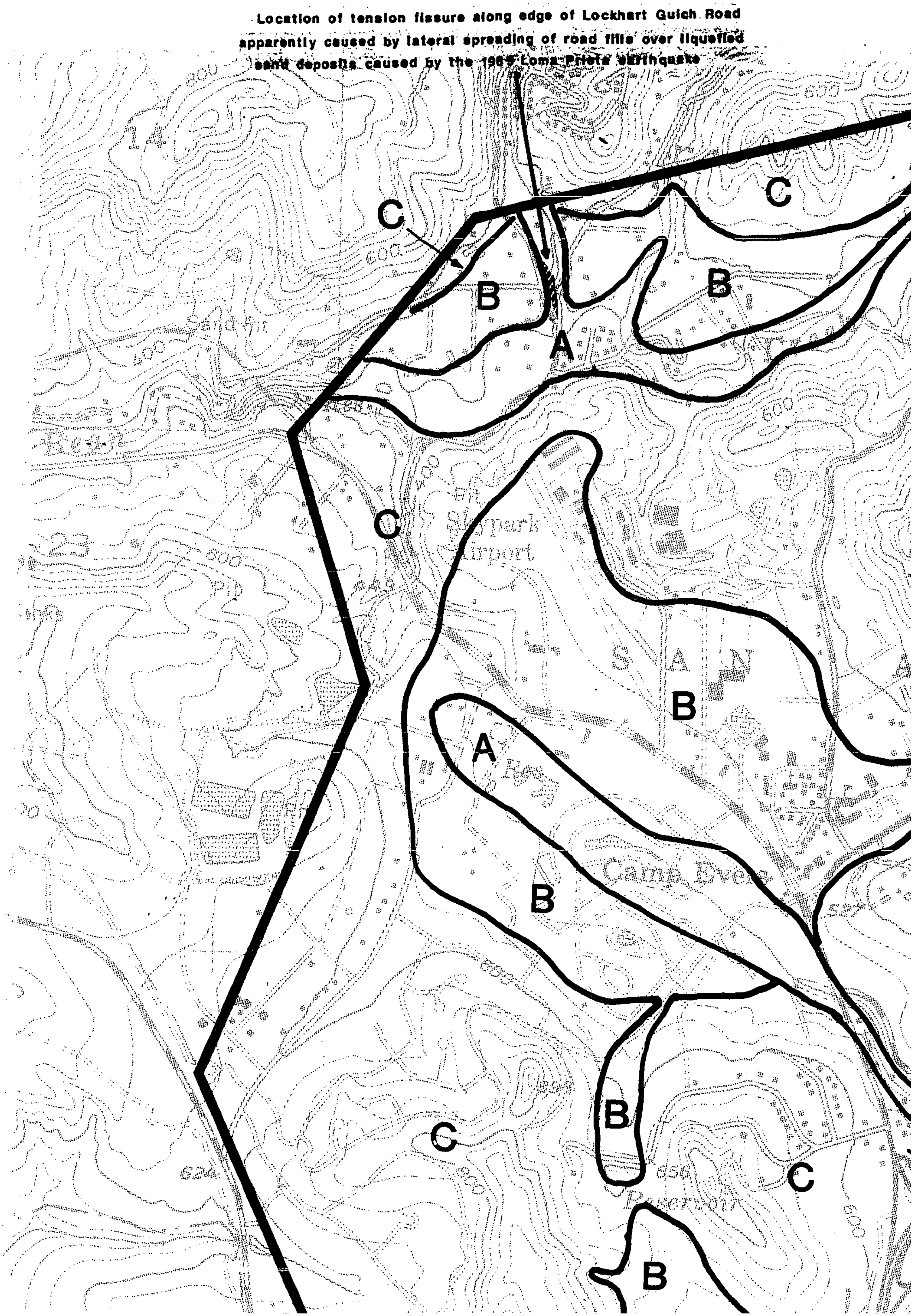
a moderate to high liquefaction susceptibility

a moderate liquefaction susceptibility,

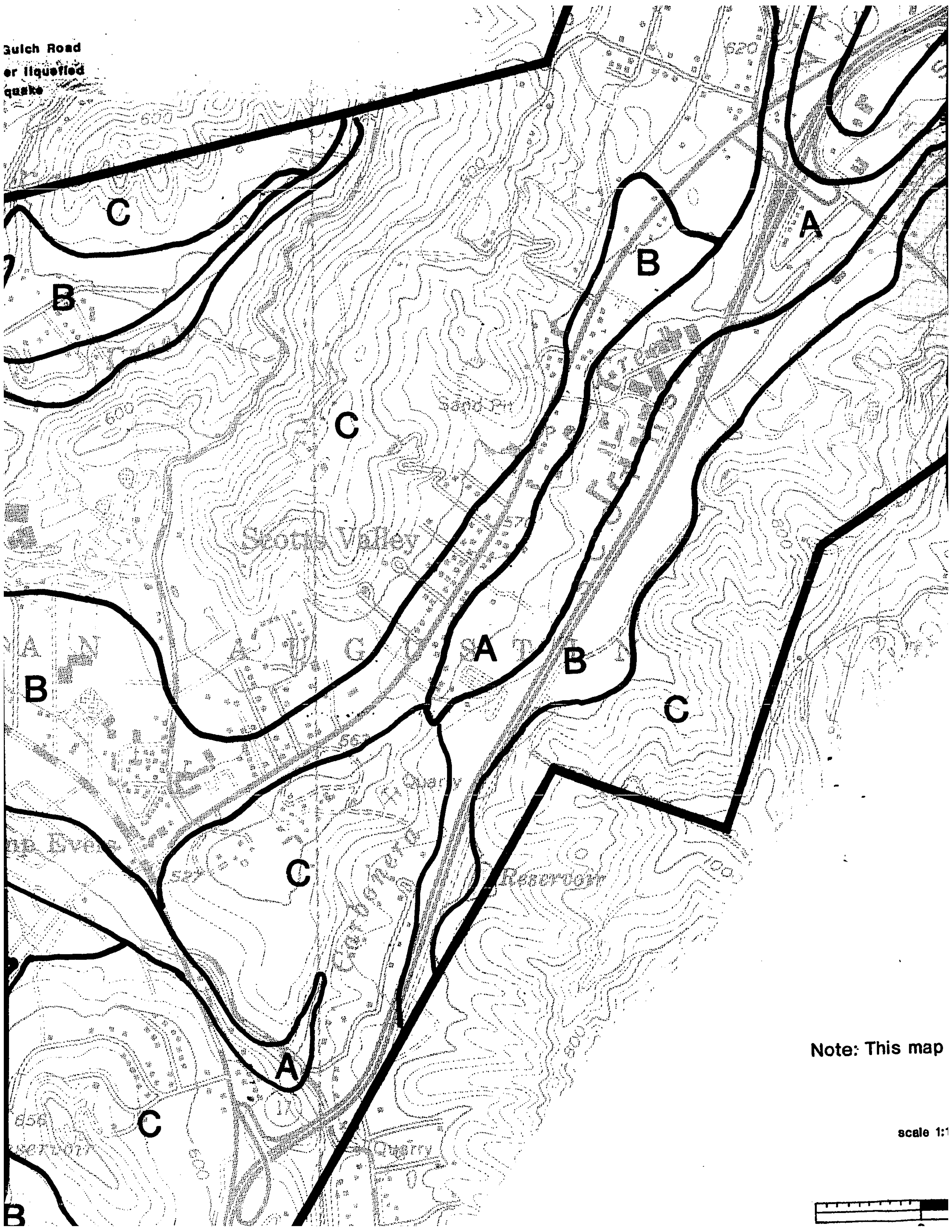
or exhibiting a low liquefaction susceptibility

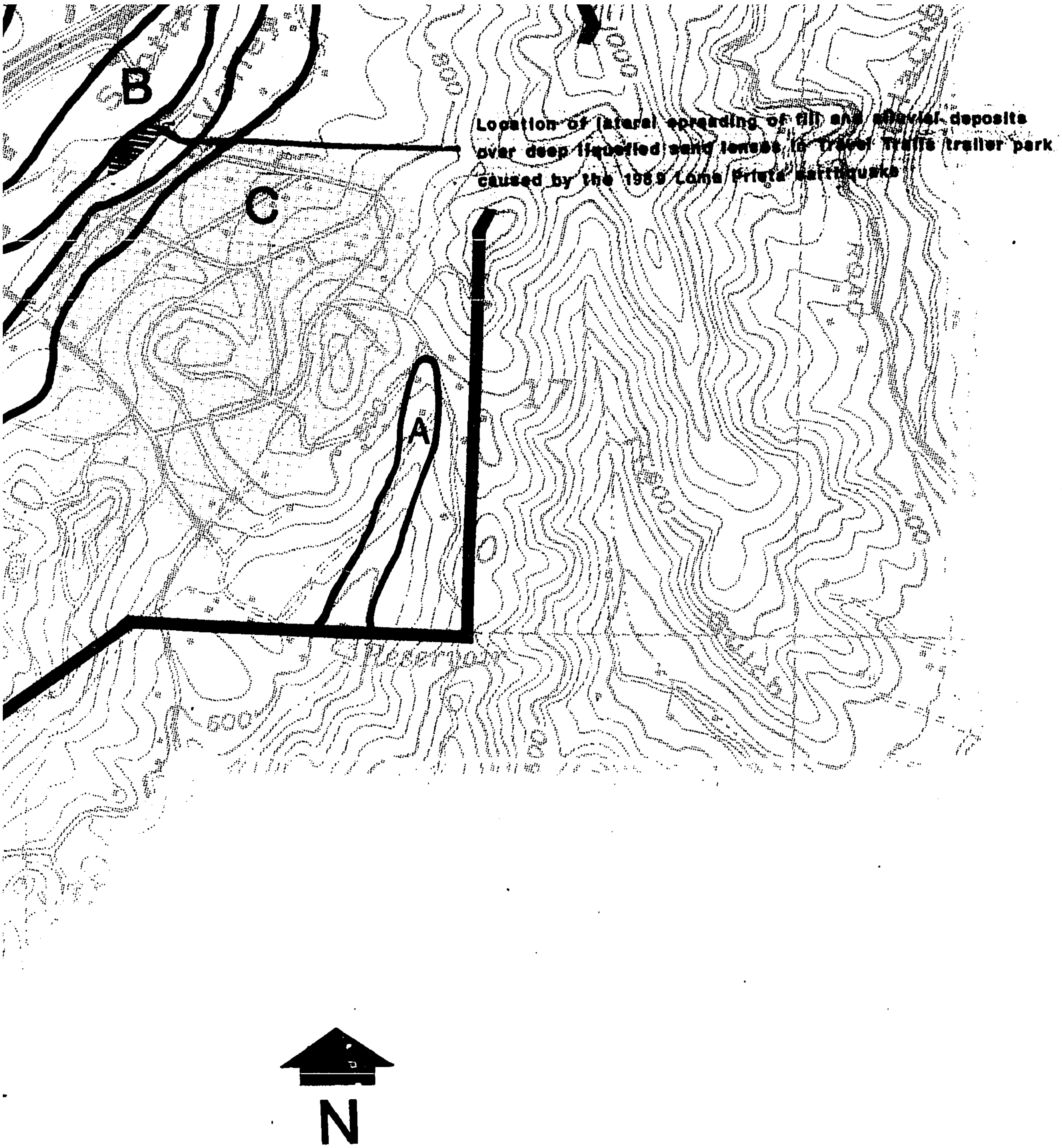



B
A
Bethany
Bible College
C
B
B



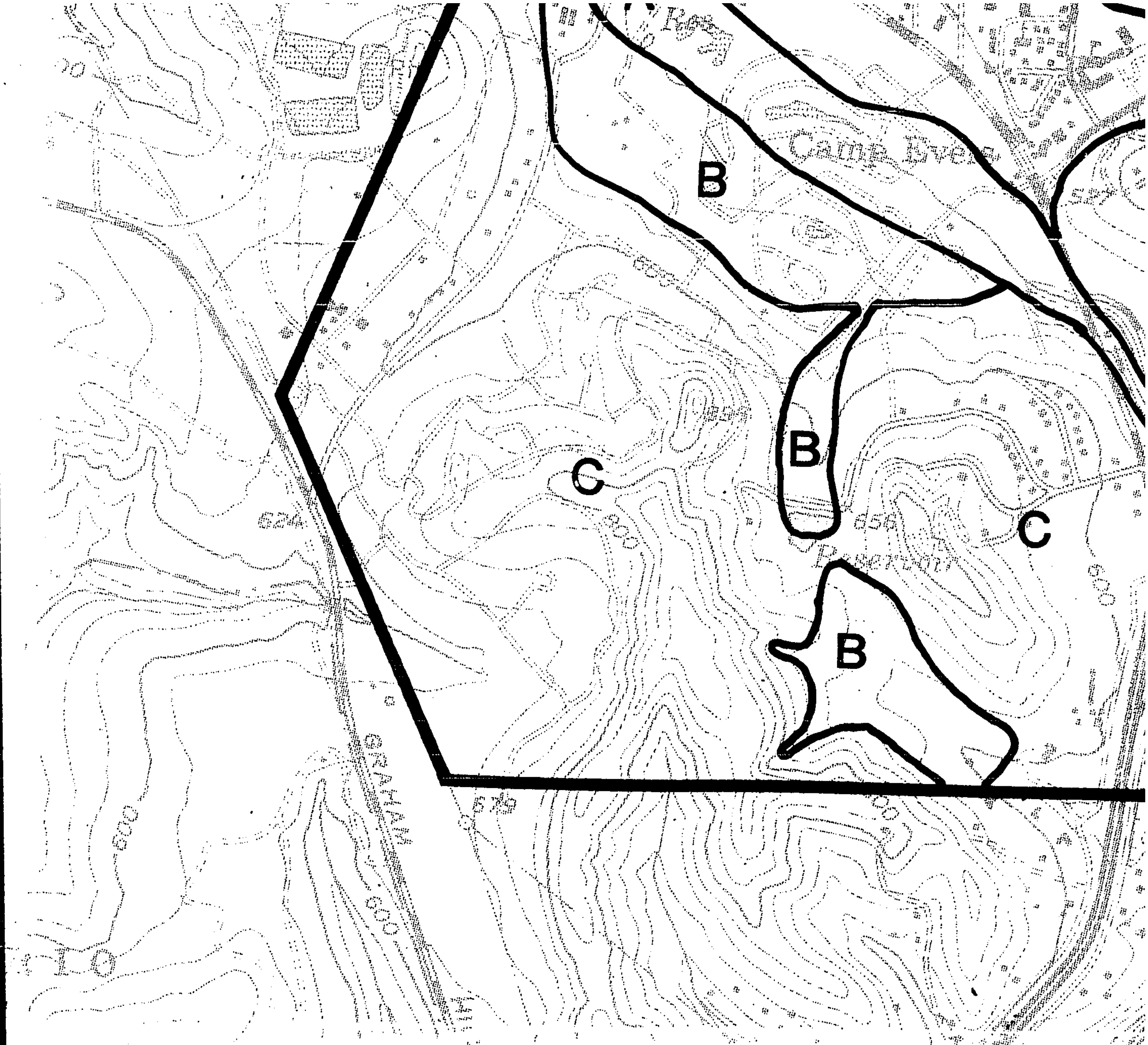
Location of tension fissure along edge of Lockhart Gulch Road
apparently caused by lateral spreading of road fills over liquefied
sand deposits caused by the 1989 Loma Prieta earthquake
C
C
B
B
A
C
A
B
A
B
B
C
C
B

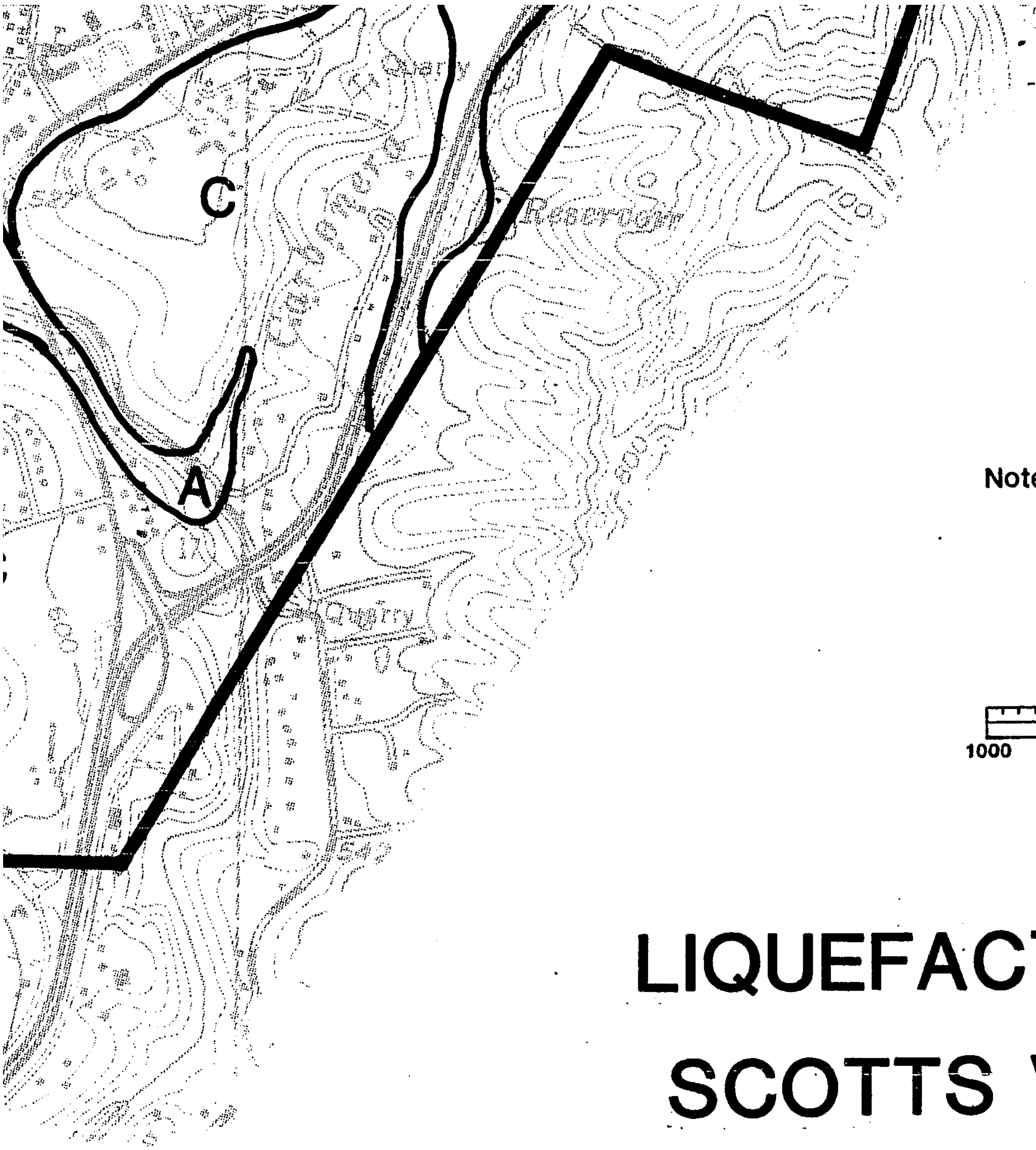

Gulch Road
er liquefied
quake
C
B
B
A
C
Scotts Valley
Sand Pit
A
B
B
C
C
A
C
B
Quarry
Reservoir
Quarry
Note: This map
scale 1:



This map is intended for general planning purposes only

scale 1:12,000


B
B
C
C
B
624
GRAHAM
600
579



Note: This map is intended for (

scale 1:12,000

1000 0 1000

LIQUEFACTION POT
SCOTTS VALLEY, (

JEFF BACHHUBE

PLAT

Base map enlarged f

N

This map is intended for general planning purposes only

scale 1:12,000

0 1000 2000 3000 FEET

TION POTENTIAL MAP
/ALLEY, CALIFORNIA

JEFF BACHHUBER, 1989

PLATE 4

Base map enlarged from U.S. Geological Survey Laurel and Felton 7.5 minute topographic quadrangle maps