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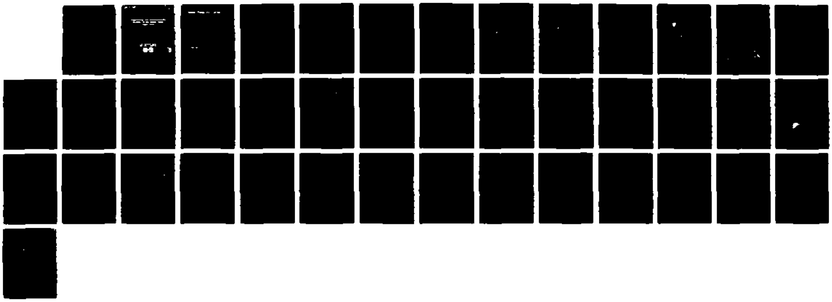

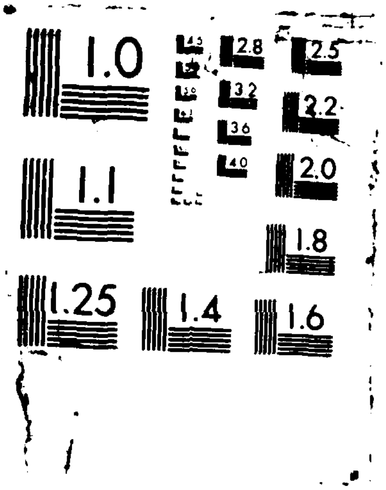
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Engineering and Environmental Geology of the Indian Wells Valley Area

by
John T. Zellmer
Research Department

NOVEMBER 1987

NAVAL WEAPONS CENTER
CHINA LAKE, CA 93555-6001

Naval Weapons Center

FOREWORD

This report describes many of the geologic and related geotechnical factors and problems that affect development within the Indian Wells Valley area. Included are discussions of active faulting and earthquakes, the potential for future volcanic activity, flooding, ground-water availability, sewage disposal, liquefaction susceptibility, and slope failure.

The report outlines work accomplished during 1982 through 1987 and was supported by Management Support Item funding.

The report has been reviewed for technical accuracy by G. R. Roquemore and R. M. Kanagawa.

Approved by
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Research Department
6 November 1987

Under authority of
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(U) The IWV area of southeastern California, is affected by several geologic and geotechnical hazards and problems. These include seismic activity, a limited ground-water resource, flooding, poor soil conditions, slope instability, liquefaction susceptibility, a locally high ground-water table, sewage and toxic waste disposal, and the potential for volcanic activity. Many of the present difficulties are directly or indirectly related to the rapid wartime building of the Naval Ordnance Test Station (now Naval Weapons Center), China Lake, during which adequate consideration was not always given to the geologic and geotechnical factors that affect the local area and region. Now that various problems and hazards have been recognized, efforts are under way to mitigate the deleterious effects of past actions and decisions and to prevent their recurrence. A major factor in these efforts is the increasing involvement of geologic and geotechnical data and expertise in decision making.

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CONTENTS

ABSTRACT

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INTRODUCTION

Indian Wells Valley (IWV) is located in southeastern California within the southwestern corner of the Great Basin and is bordered by the Sierra Nevada Range to the west and the Mojave Desert to the south. Tectonic and volcanic activity during the last 2 to 3 Ma shaped much of the present physiographic and geologic character of the region and continue to exert a combined influence. The interaction of physiography, geology, and climate of the area confront the local populace with a variety of geologic hazards and interrelated engineering and environmental geology problems. These can be grouped under the general categories of active faulting and earthquakes, potential for volcanic activity, ground water, flooding, slope instability, sewage and toxic waste disposal, and poor soil conditions. These problems and geologic hazards are not atypical of those encountered elsewhere in the desert southwest.

Many of today's engineering geology problems result from the rapid, wartime building of the Naval Ordnance Test Station, now the Naval Weapons Center (NWC) at China Lake. Prior to 1943, the population of IWV numbered about 300 and lived for the most part on small ranches and farms. The current population is about 30,000, most of whom live in the City of Ridgecrest. With the advent of NWC the population exploded, and because of wartime urgency, development occurred at furious pace and often without adequate consideration of the geologic environment and the future. As a result, many structures and facilities were constructed at convenient but geologically and geotechnically inappropriate locations. Many of these became hub areas around which later development still continues. The geologic and environmental problems are aggravated by the increasing population and its needs, both at NWC and within the surrounding communities. All of these factors have strained the environment and intensified pre-existing problems.

ACTIVE FAULTING AND EARTHQUAKES

Earthquakes and active faults are common in southern California, and IWV is no exception. The region (Figure 1) includes several major active faults including the San Andreas fault, about 150 km southwest of IWV; the Garlock fault, about 20 km to the south; the Sierra Nevada fault, which forms the west border of the valley; and the Death Valley-Furnace Creek fault zone, about 160 km to the east (Reference 1). These regional faults present varying degrees of hazard to the IWV, either because of the potential for ground shaking or because of the disruption of electrical power, natural gas, water supply, and transportation. Thus, any major earthquake in southern California could directly or indirectly deprive IWV of electricity, water, fuel, food and emergency supplies and aid, even if there is no local earthquake damage. In addition to major earthquakes along these faults, the IWV is also subject to earthquakes from several local faults, principally from the Little Lake (LLFZ) and Airport Lake (ALFZ) fault zones. These faults pass through both the NWC facilities and the City of Ridgecrest (Figure 2).

Recent geologic mapping (Reference 2) and related studies of faults in the IWV and adjacent areas have shown that both the LLFZ and ALFZ faults are actively producing earthquakes and ground deformation (References 3 through 5). The most recent period of significant seismic activity occurred during 1981-82 when five earthquake swarms with magnitudes initially reported as high as M=5.2 (Reference 6), but later downgraded to M=4.8, occurred within the NWC test ranges, about 15 km north of Ridgecrest. These earthquakes caused only minor property damage and no injuries, but they did heighten the populace's awareness of the potential for major earthquakes in the area. As a result of these earthquakes, the U.S. Geological Survey (U.S.G.S.) issued an as yet uncanceled notification that additional earthquakes with magnitudes of M=6 or greater may be expected in the foreseeable future. Consequently, many earthquake preparedness and damage prevention actions have been implemented by both individuals and government agencies from the local through Federal levels. These actions include seismic hardening of work spaces, such as installing item restraints on shelves, attaching bookcases to walls, removing or securing items that may fall and block exits; seismic hardening of communications systems; more extensive geotechnical investigations of proposed building sites; development and implementation of emergency action plans; developing closer ties between the U.S.G.S., NWC staff geologists, and NWC management; at-home storing of food and water; attaching bookcases, etc., to walls; and learning to shut off gas lines and electrical circuits. For the last several years local geologists and disaster preparedness personnel have been in demand by civic service organizations and other groups to make presentations and answer questions that deal with various aspects of the local and regional earthquake hazards.

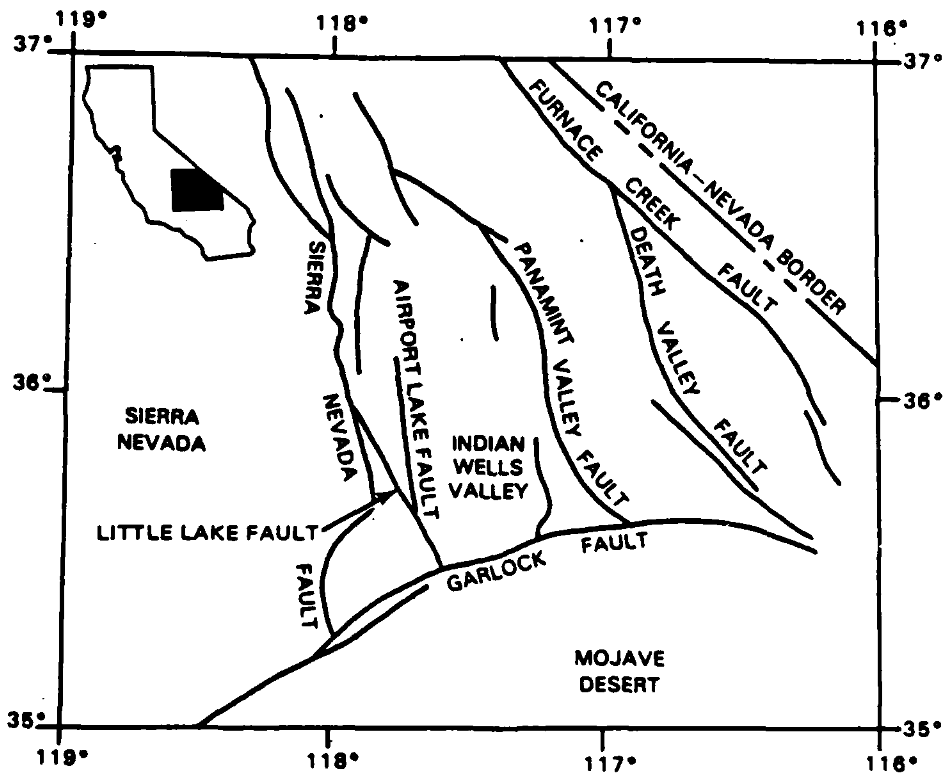

FIGURE 1. Active Faults of the Indian Wells Valley Region.

Paleoseismicity studies have shown that the LLFZ and ALFZ are probably capable of producing earthquakes in the M=6.4 to M=7.4 range with estimated recurrence intervals of 784 to 4000 years, respectively (Reference 7). Larger earthquakes, perhaps in excess of M=8.0, may be possible if interaction between the Sierra Nevada fault and LLFZ occurs. This is especially likely in that the LLFZ is an active splay of the Sierra Nevada fault that appears to be accommodating the right slip that occurs along the Sierra Nevada fault north of the faults' intersection. Earthquakes of these magnitudes should be considered as

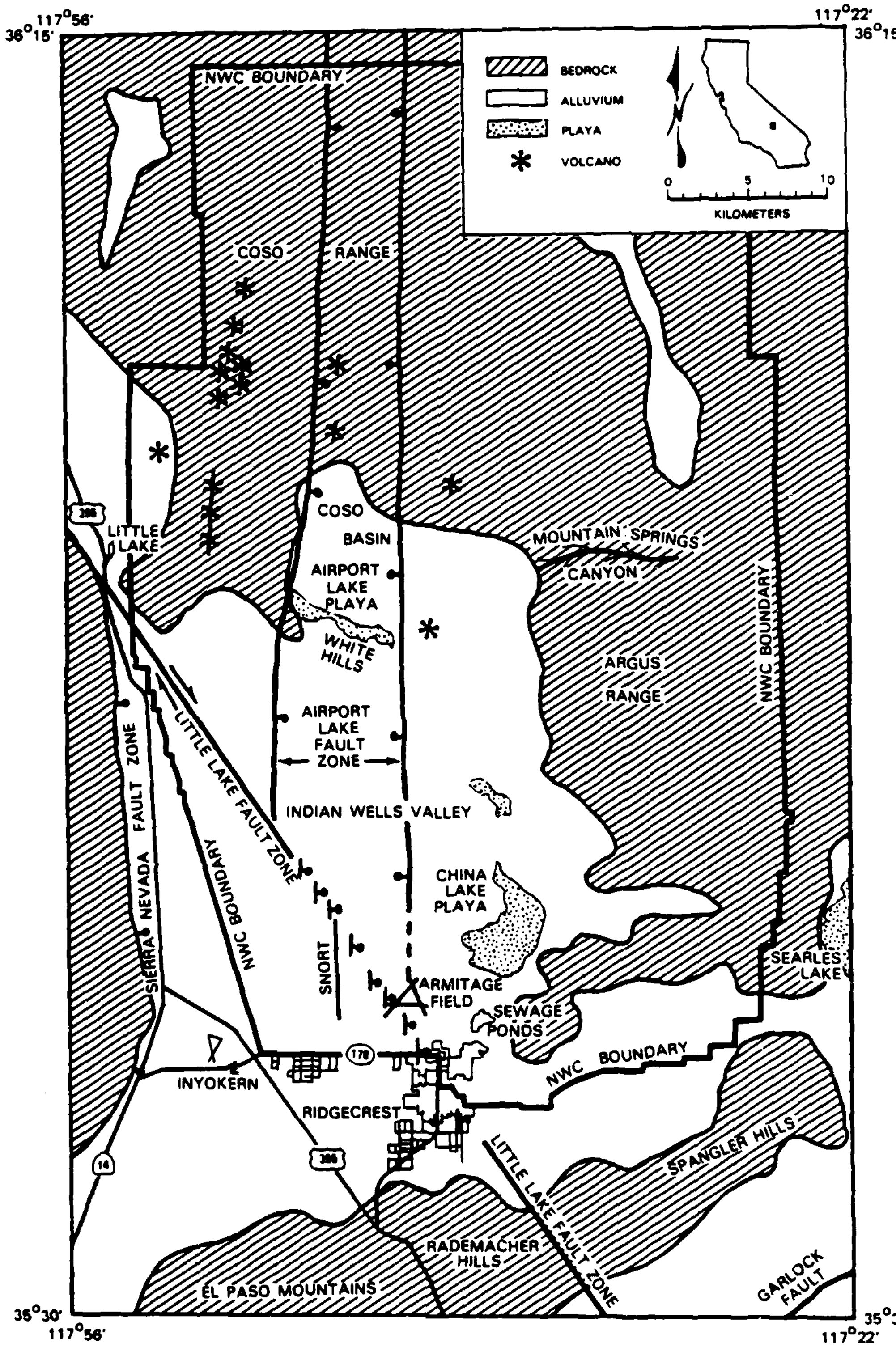

FIGURE 2. Generalized Geologic Map of the Indian Wells Valley Area.

maximum credible earthquakes. Although maximum probable earthquakes have not yet been determined, M=6 seems reasonable and is the value used in the above mentioned U.S.G.S. notification. Using only the historic record, we find that magnitude 5 could be considered as a "characteristic" earthquake (Reference 8) for the LLFZ, as three earthquakes of M=4.8 to M=5.1 have occurred along the fault since 1938. Recurrence intervals have been 23 and 21 years. The most recent, in 1982, marked the culmination of nearly 2 years of seismic swarm activity in which larger numbers of earthquakes with progressively larger principal magnitudes occurred with successive swarms.

Several seismic swarms with principal magnitudes of M=4.0 to M=4.7 have also occurred along the ALFZ. Seismic studies by Walck and Clayton suggest, however, that these swarms are related to volcanic activity (Reference 9). Zellmer, Sanders, and Roquemore agree with this conclusion, but they also point out the probability of synergism between volcanic and tectonic activity in the area (Reference 10). Sanders and others have shown that the swarm activity was probably related to magma migration within 3 km of the surface (Reference 11). Volcanic activity is addressed in greater detail in a later section.

Mapping of active faults has shown that the LLFZ and ALFZ extend beneath several important NWC facilities and through Ridgecrest (Figure 2 and Reference 2). Epicentral maps suggest that the LLFZ and ALFZ may be related to a deeper and highly active fault zone that lacks surface expression but strikes NW-SE across IWV, parallel to but slightly offset to the east from the LLFZ and terminates against the Garlock fault (Reference 4 and unpublished U.S.G.S. data). Recent work by Bent and others, however, indicates that the offset is the result of the eastward dip of the LLFZ, which places epicenters east of the mapped fault traces (Reference 12). Figure 3 shows the epicenters for the approximately 3000 earthquakes that occurred in the IWV area during 1986. The trends are nearly identical to those shown on plots of seismicity for previous years. According to Norris and others, this area was one of the most seismically active regions of California during 1986 (Reference 4).

Although the 1981-82 seismic activity occurred on the NWC test ranges, the southward continuations of the faults (Figure 4) indicate that future activity may occur within Ridgecrest. This is supported by the southward migration of epicenters during the 1981-82 earthquake swarms. About 10 km north of Ridgecrest the LLFZ and ALFZ combine to form a left-stepping, en echelon fault zone. The zone becomes indistinct in the Ridgecrest area because of its subtle surface expression and the superimposed cultural disruption that has occurred during the last half century. As a result, Roquemore and Zellmer have recommended the establishment of a seismic-hazard special studies zone (SSZ) that includes known fault traces and a buffer zone within the City of Ridgecrest (Reference 2). All new construction within this

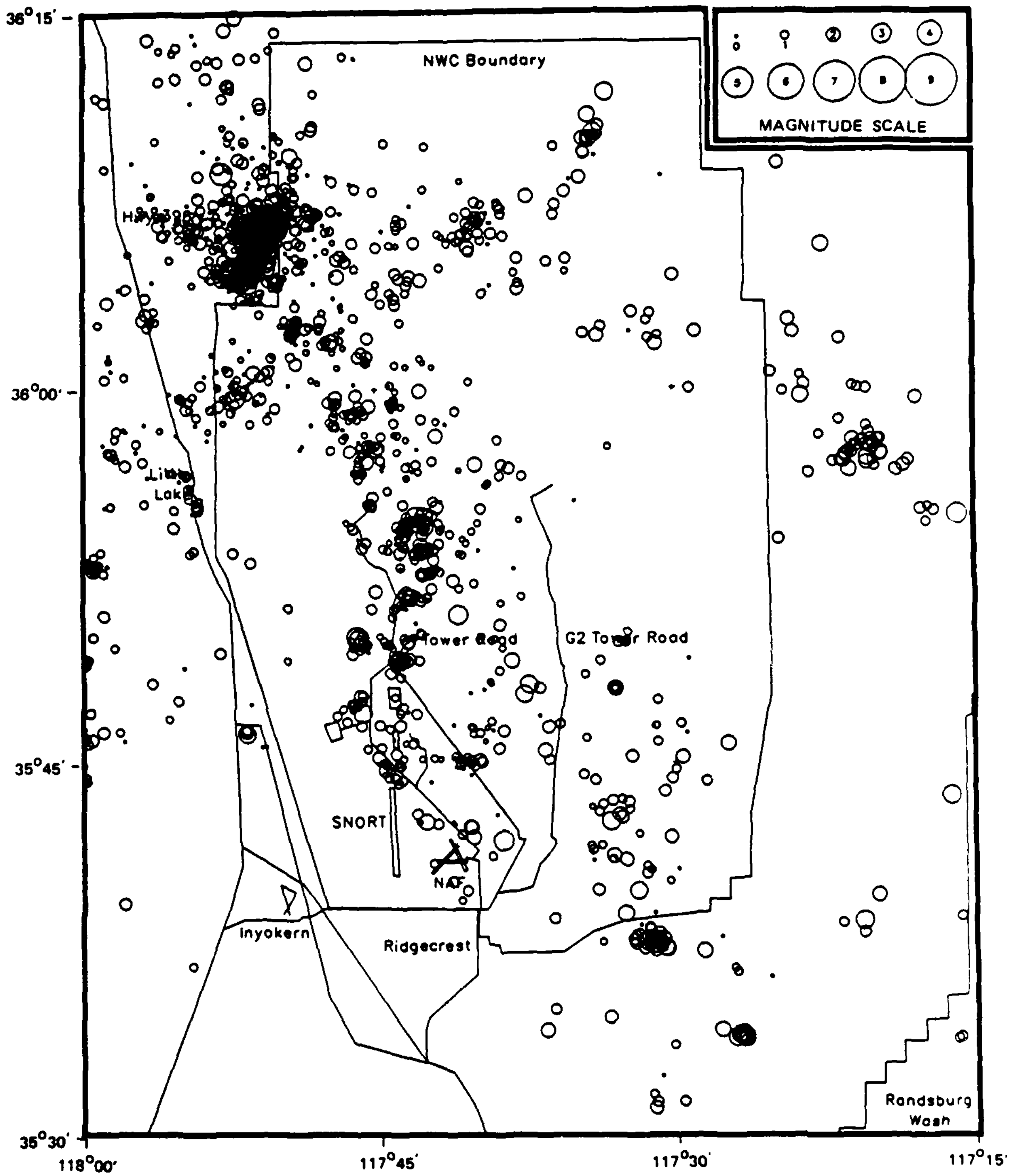

FIGURE 3. Plot of Earthquake Epicenters in the Indian Wells Valley Area During 1986. Data compiled from U.S.G.S. and California Institute of Technology earthquake catalogs.

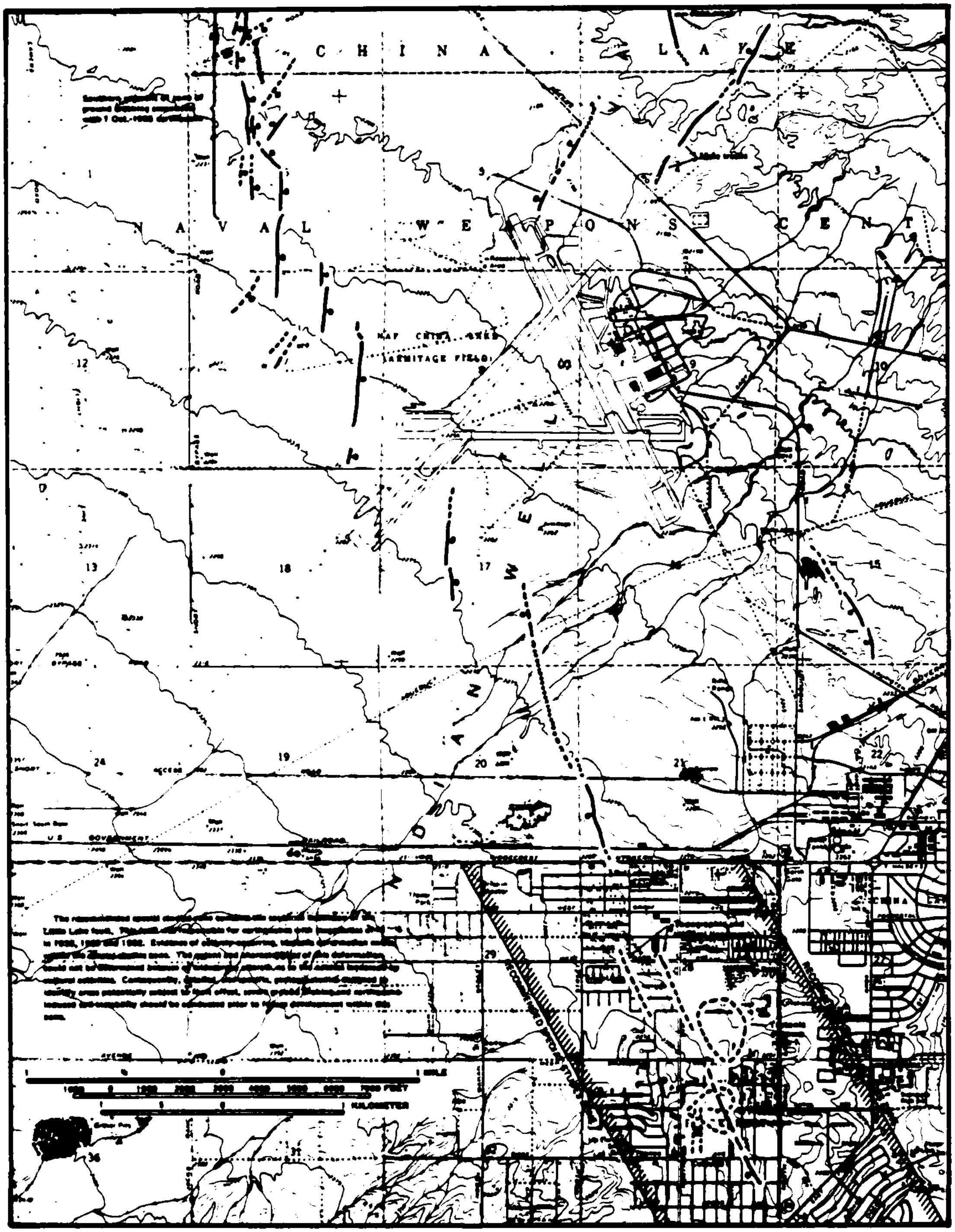

FIGURE 4. A Portion of the Ridgecrest North Quadrangle Showing Active Fault Traces and the Recommended Seismic-Hazard Special Studies Zone.

zone should be subject to prior geologic investigation of the site. The suggested zonation is an interim measure that should remain in effect until seismic-hazard zonation following the Alquist-Priolo Act guidelines can be completed by the California Division of Mines and Geology, probably in 1988 or 1989 (Reference 13). Although the seismicity is much higher than in many other portions of California, the low population density has resulted in IWV being placed low in priority for seismic zonation.

The LLFZ (Figure 2) splays southeastward from the Sierra Nevada fault near Little Lake and may accommodate some if not all of the right-slip motion of the Sierra Nevada fault in the IWV area. Near its juncture with the Sierra Nevada fault, the LLFZ is purely right slip and has a minimum slip rate of about 0.6 mm/yr as shown by an offset 440,000-year-old basalt flow (Reference 7 and 14). As the fault extends into the IWV, the motion becomes right-normal-oblique, with the east block consistently down. Here, the fault's surface expression consists dominantly of left-stepping, en echelon segments. The segments consist of highly subdued scarps ranging from less than 1 m to over 2 m in height and a few kilometers long that offset lacustrine and eolian sediments (Reference 7). These unconsolidated sediments generally range in age from Holocene to Pleistocene and consist largely of sediments deposited in the China Lake basin during the Wisconsin glaciation pluvial periods (Reference 15).

Trenching has shown that most of the scarps are probably monoclinal warps with increased fault offset with depth. In one trench the warp is intersected by a nearly vertical fault at a depth of about 4 m. Similar warps have been observed elsewhere along fault traces mapped within the study area and are interpreted to indicate fault offsets at shallow depths that have not yet propagated to the surface.

The ALFZ (Figure 2) is a well-defined zone of north-south-trending nested grabens. Fault offsets are dominantly extensional, but ramping along fault scarps argues for a minor component of right slip (Reference 7). The style of faulting and the close relationship with volcanic activity prompted Roquemore to describe the ALFZ as a rift valley or spreading center (Reference 16). The ALFZ varies in both width, from about 1 to 8 km, and vertical offset, with the maximum surface displacement of about 600 m occurring near Airport Lake. The ALFZ and LLFZ intersect over a wide zone near Armitage Field. Southward from this intersection the ALFZ is apparently offset to the east along the LLFZ and the graben character becomes less distinct. The combination of the right-normal-oblique slip of the LLFZ and the east-west extension of the ALFZ produces a segmented graben-like structure that becomes less distinct and wider than the individual fault zones. The faults that form the east border of the ALFZ surficially die out north of Ridgecrest, but seismic-refraction profiles by Zbur indicate their presence at depth (Reference 15). The LLFZ and the west border faults of the ALFZ combine into a single fault zone that extends through Ridgecrest with a left-stepping, en echelon pattern.

The seismic-hazard zone (SSZ) encompasses the projected width of the LLFZ and ALFZ and includes all mapped fault traces and other evidence of active faulting, such as surficial warps, apparent tectonic depressions, and pressure ridges that occur within the City of Ridgecrest (Reference 2). Because of the subdued character of the fault zones, the cultural disruption of the area, and the possibility that not all of the fault segments have ruptured to the surface, the exact location of all active faults within the zone probably have not been determined. An additional complication is the near-surface warping of sediments as observed in trenches along the LLFZ. Therefore, warping within the SSZ should carry the same weight and implications as clearly defined fault rupture of Holocene deposits. This opinion is informally supported by the California Division of Mines and Geology (pers. comm. 1985).

In addition to the fault mapping and related studies, an effort is being made to measure and evaluate short-term ground surface deformation that is occurring locally. The deformation was detected by comparing highly precise surveys for NWC's 6.7 km-long Supersonic Naval Ordnance Research Track (SNORT, Figure 2). The survey data indicate that the northern segment of the track, which abuts the LLFZ, bowed upward 22 mm between 1977 and 1978. Between 1978 and 1984, and probably associated with the 1982 earthquake activity, the track deformation reversed direction and bowed downward 47 mm. Between 1984 and 1986 the north end of SNORT rotated upward 49 mm. The track deformation is apparently caused by recoverable tectonic strain and therefore may be useful in predicting future earthquakes along this segment of the LLFZ. However, as pointed out by Sanders and others, magma migration may also be involved (Reference 11). The deformation and its implications are the subject of a separate paper in preparation by Zellmer and Roquemore (Reference 5).

The Sierra Nevada fault zone (SNFZ) which forms the west border of the valley does not present a surface rupture hazard to the developed portions of IWV, but nevertheless is of major importance in assessing the potential effects of seismic activity. The SNFZ is the major north-south trending range-bounding fault that forms the border between IWV and the Sierra Nevada. The fault has traditionally been considered as the western border of the Basin and Range province, but recent work suggests that regional extension is progressing into the Sierra Nevadas (References 17 through 19). Right-normal-oblique slip faulting that apparently accommodates the regional, northwest-directed shear and east-west directed extension has been documented at several locations along the fault (References 20 and 21). Reference 22 documented 4 mm/yr of right slip parallel to the fault and 1 mm/yr of extension normal to it in Owens Valley, based on geodetic surveys.

The largest earthquake known to have occurred along the SNFZ was the 1872, Lone Pine, California, event with an estimated magnitude of 8.25 (Reference 23). This event occurred along the Owens Valley fault segment of the SNFZ. Surface ruptures from this event extended to within about 70 km of Ridgecrest. In his studies of historic and paleoseismicity of the region, Wallace classifies the segment of the SNFZ that borders IWV as a seismic gap capable of producing $M \geq 7.0$ earthquakes (References 24 and 25). Recent mapping along the SNFZ in IWV (Reference 2) has revealed numerous fault traces. Although movement along these faults during the last 10,000 years has not been unequivocally demonstrated, Roquemore and Zellmer argue that the regional tectonic setting, the youthful appearance of the faults, and the designation of the zone as a seismic gap should qualify the SNFZ within IWV as an active fault capable of producing earthquakes of $M \geq 8$.

The Garlock fault zone (GFZ) strikes easterly across Southern California and passes about 25 km south of Ridgecrest. It is one of the state's longest active faults and forms the boundary between the extensional tectonics of the Basin and Range province to the north and the relatively more stable Mojave Desert province to the south. Numerous studies have shown that the GFZ is a major, active, left-slip fault; the western segment of which is slipping at an average rate of 7 mm/yr, and the eastern segment of which is temporarily locked. Astiz and Allen summarize much of what is known of the seismology and tectonics of the fault and conclude from their study that the eastern segment of the GFZ, that is, the segment between about the Garlock townsite and Death Valley, is a seismic gap capable of producing earthquakes of $M = 7.6$ and possibly as large as $M \approx 8$ (Reference 26).

The four active fault zones discussed above are capable of producing moderate to great earthquakes. Each fault passes beneath or near population centers, transportation routes, utility corridors, and U.S. Navy research and test facilities. As a consequence, studies of the SNFZ, GFZ, LLFZ, and ALFZ, especially within the NWC range areas, have been an ongoing project for several years, and have been extended into the surrounding communities and region (Reference 2). Work completed to date within IWV includes the mapping of active faults within an area of over 1400 square km^2, the publication of seven complete 7-1/2 minute quadrangles and portions of four additional quadrangles, the logging of numerous trenches, the seismic profiling of fault zones, and the establishment of a dense seismometer network and several trilateration networks, dry tilt arrays and level lines. Portions of this work have been in cooperation with the U.S.G.S. and universities. The active fault maps will be updated as necessary and data obtained from the monitoring systems is continually evaluated. Data and interpretations resulting from these studies are available to individuals, planners, and other interested parties.

VOLCANIC ACTIVITY

Volcanic activity has played a major role in the development of the northern portion of the IWV and the formation of the Coso Range (References 27 and 28). Recent data suggest that the local volcanism that has been occurring for at least the last 3 Ma has extended southward into the valley. Analysis of seismic and other data has led to the conclusion that at least two and possibly more areas of the valley are underlain by molten rock (References 9 through 11 and 29).

The seismic technique first used to locate and characterize the magmatic bodies is the same as that previously used to investigate intrusive activity at the Mammoth Lakes area, about 200 km to the north (Reference 30). The technique involves an analysis of P and S wave arrival times and waveforms. Studies have shown that P waves passing through molten rock are of smaller amplitudes and arrive later than rays not passing through the body. S waves that pass through molten rock generally arrive late, are markedly attenuated, and occasionally are absent from the waveform. These are also the characteristics of seismic waves passing through portions of the IWV. Other data, such as thermal ground-water wells that also emanate a hydrogen sulfide odor, and localized ground deformation support the conclusion of shallow magma bodies (Reference 10).

The possibility of shallow magma bodies existing beneath the IWV has stimulated a large amount of scientific interest. Consequently, a low-level research effort is being conducted by NWC in association with members of three other institutions. This research is focusing on seismic wave studies to better locate and characterize the probable magma bodies. Existing U.S.G.S. seismic stations and portable seismic event recorders are currently being used to collect data. These data are analyzed using tomographic inversion of compressional waves to obtain a three-dimensional seismic velocity structure of the region encompassing the postulated magma bodies (Reference 9). The resulting velocity structures indicate that the magma bodies are shallow sill-like forms with tops at a depth of about 3 km and bases about 5 km. More recent seismic data analyses by Sanders and others suggest that the bodies are tabular or plume shaped and appear to be fed at their bases by a narrow dike or pipe, possibly coincident with the Sierra Nevada fault (Reference 11). As yet there are no data to indicate that the bodies are increasing in volume or pose a threat of eruption within the foreseeable future. These data suggest, however, that the bodies may be within 1 km of the sedimentary fill-bedrock contact at the base of IWV.

In addition to these, another magma body is thought to exist at greater depth beneath the Coso Range. This body underlies an active geothermal field that is currently being developed for electrical power generation. Teleseismic P-wave delay studies had suggested the presence of magma at a depth greater than 5 km (Reference 31). More recent studies suggest that small magma bodies may exist in this region as shallow as 3 km, but any large magmatic body must reside below 10 km (Reference 9). Although the depth of the postulated magma beneath the Coso Range has not yet been completely resolved, geothermal exploration wells have shown encouraging results, and a 32 MW electrical power-generation plant is in operation.

The Coso Range has been the site of explosive rhyolitic eruptions and basaltic flows for at least the last 3 Ma and studies of the periodicity of eruption indicate that a new period of basaltic eruptive activity may be near (Reference 28). Portions of the Coso Range display high levels of shallow seismic activity, and seismograms occasionally show wave forms suggestive of harmonic tremor indicative of magma movement. Three-dimensional plotting of several thousand hypocenters obtained by Walter and Weaver show clustering around the feeders of the numerous young rhyolitic domes that occur in the volcanic field (Reference 32). Geodetic leveling and trilateration networks within the Coso Range have shown a slight bulging accompanied by east-west extension and north-south shortening (Reference 33). These data may indicate the initial stages of renewed volcanic activity. Remnants of a phreatomagmatic eruption have been recognized in the Coso Basin area of IWV (Figure 2). Palagonite tuffs associated with this eruption have been interpreted by Roquemore (Reference 34) to have been erupted within the last 1.75 Ma. The tuff is exposed over an area of about 13 km^2 and has a probable source area at or near Airport Lake. Because the tuff apparently erupted through saturated sediments, the characteristics of the eruption should reveal much about the potential effects of a phreatomagmatic eruption associated with the postulated magma bodies beneath IWV. These magma bodies are overlain by as much as 1900 m of saturated sediments.

Several methods are being used to monitor and better understand activity within the volcanic field. Much of this work is a cooperative effort between NWC and the U.S.G.S. Monitoring currently includes several permanent seismometer stations, portable seismic event recorders, periodic surveys of the level line and trilateration networks, continuous sampling of hydrogen gas emissions, and fumorolic gas analyses. Mapping of ejecta from a large rhyolitic eruption to better understand the characteristics of past eruptions is also being conducted (References 34 and 36). The results of this mapping have been used to develop a computer model showing the distribution, transport velocities, and thicknesses of various eruption products (References 37 through 40). Figure 5 shows the expected thickness of the pyroclastic flow and surge deposits and the velocity at which they would be transported at various locations relative to the eruption center. The model superimposes a Mt. St. Helens-size eruption on the topography of the Coso volcanic area and IWV. These data are being used to determine the hazard that may result from future volcanic activity in the IWV. The computer model can also be easily tailored to other volcanic areas and has attracted international attention, largely because of its potential use in educating government officials and the general public of the potential hazards associated with volcanic eruptions.

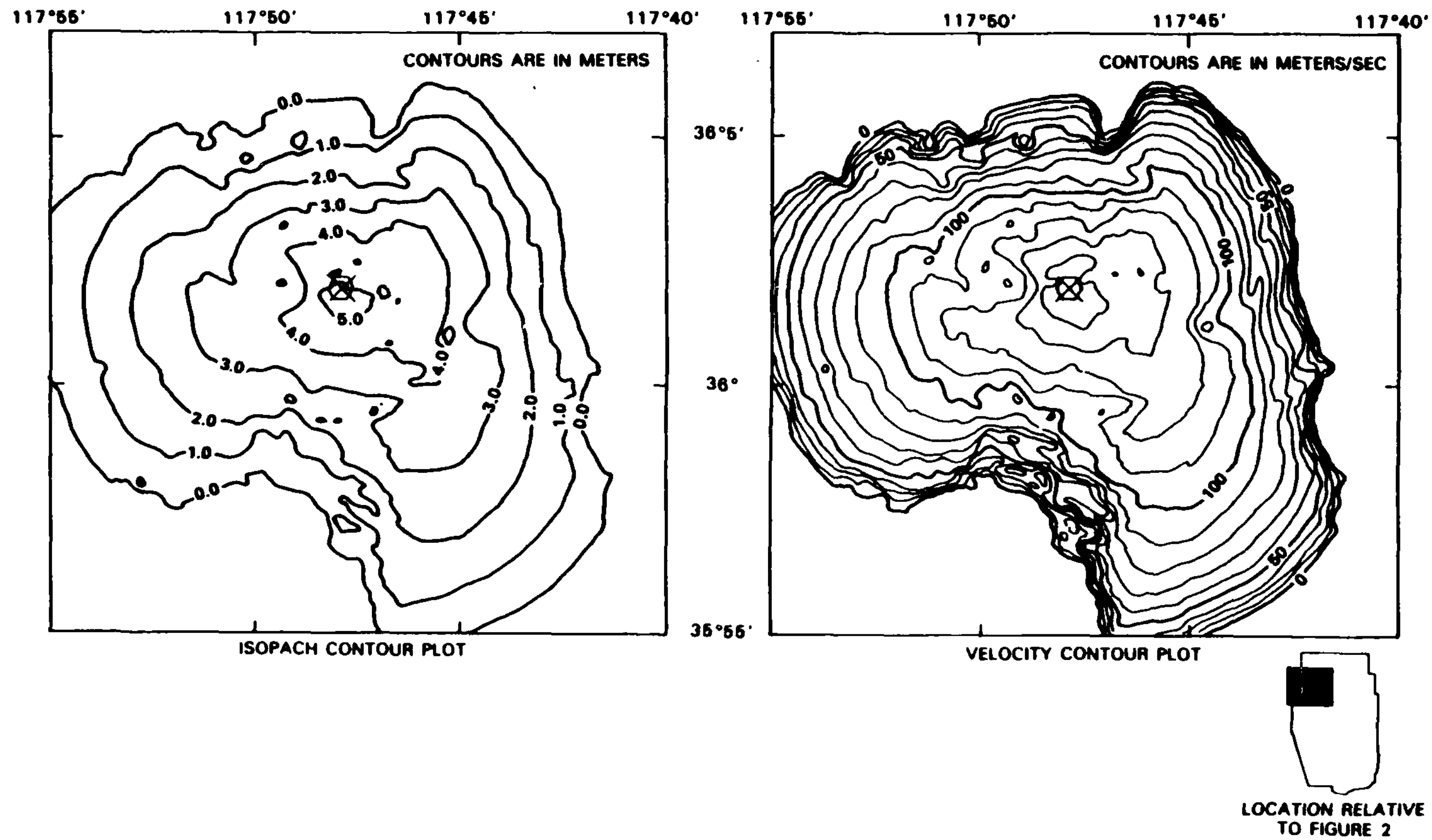

FIGURE 5. Expected Thickness and Transport Velocities of Pyroclastic Flow and Surge Deposits Resulting From a Mt. St. Helens - Sized Eruption in the Coso Volcanic Field. Adapted from Blackerby and others (in press).

FLASH FLOODING AND DEBRIS FLOWS

The IWV lies near the northern border of the Mojave Desert. The elevation of the valley floor is at about 725 m, and the surrounding mountains rise to elevations in excess of 2500 m. Annual precipitation averages 9 cm on the valley floor and about 25 cm in the surrounding mountains, most of which occurs during the winter; but late summer thunderstorms are common and often destructive. During 1983 and 1984, rainfall from thunderstorms in nearby mountain areas resulted in severe flash flooding within Ridgecrest and at NWC. Flood damage during the 1984 storm totalled $40,000,000, about 75% of which occurred to NWC facilities. Although no deaths were attributed to the 1984 flood, several persons were saved from drowning or serious injury. During the 1983 flooding, one person died when her car was swept from the highway and another narrowly avoided the same fate when her car was swept nearly 2 km downstream by a flash flood. Debris floods and debris flows that occurred at the same time and discussed here without differentiation, destroyed, damaged or buried roads and structures. Up to 2 m of sand was deposited against the outside of some NWC buildings and a meter or more of sediment was not uncommon within certain buildings, after the flood waters battered open heavy steel doors. The basement and first floor of the largest laboratory complex at NWC were flooded by 3 m of water and mud that caused nearly $30,000,000 of damage, destroyed thousands of irreplaceable documents that were in storage, and disrupted research for several months. Sheet flooding with estimated depths of 50 cm inundated many areas.

The major population areas and most of the NWC facilities are located between the China Lake playa and the southern end of the IWV (Figure 2). Much of the local drainage issuing from the Sierra Nevada, El Paso Mountains, Rademacher Hills, and Spangler Hills flows in a north to northeast direction through developed and semideveloped areas to the local base level at China Lake playa. Except where diverted by roads, residential and commercial development or artificial channels, the flood waters are generally confined to well defined arroyos. Flood water diversions and impoundments resulting from human intervention are largely responsible for the flood damage. City streets have become unplanned flood channels of sufficient magnitude to sweep automobiles downstream. Poorly designed and maintained culverts and artificial drainage channels resulted in water impoundments and unplanned diversions. The problem is continually exacerbated by vegetation removal and building construction that decreases infiltration and increases runoff and runoff velocity. Because of the large amount of development that is occurring and being planned in the Ridgecrest area, the problem is likely to increase in severity, unless mitigative steps are taken, several of which are being considered.

Within the NWC test ranges, the major flood impact has been damage to range access roads. In the wake of a large storm, much of the range area may be inaccessible due to road damage or blockage. These generally result from intense rainfall in the Argus Range or Coso Range that is funnelled through narrow, high gradient canyons. The resulting flash floods and debris flows may render major sections of the canyon roads and the main access road along the range front impassable. During 1984, several persons working in remote areas of the test ranges had to be rescued by helicopters or off-road vehicles because of road closures. In addition to the costs related to road repair, the closures may cause several days of expensive delay in the normally busy test-range schedule. Temporary repairs returned the most important range roads to service within a few days, and permanent repairs were gradually completed over a 2-year period. Included was the complete rebuilding of several kilometers of a main access road to avoid similar flood-related problems in the future.

As a result of the recent flood damage, flood mitigation has been a priority effort at NWC for the last several years. Mountain Springs Canyon Road (Figure 2) was realigned and rebuilt to decrease the potential for future flood damage and ensure year around availability. Reconstruction required 58,700 m^3 of cut and 39,900 m^3 of fill over the 10.4 km-long road. Because most of the previous damage resulted from inadequate surface drainage and erosion at ephemeral stream crossings, these areas were redesigned to accommodate runoff associated with twice the 100-year storm as estimated from available climatological data. These data, however, may not adequately reflect the effects of localized thunderstorms. The road rebuilding involved locally raising the road grade a meter or more; installing larger longitudinal drainage ditches with numerous subgrade, crossover culverts; and installing oversized culverts. But, because of uncertainties regarding the maximum rainfall, these are considered adequate only for nuisance water. To protect the road at stream crossings during major storms, the culverts are covered by a wide concrete blanket. Should the culvert become constricted or the road otherwise be overtopped by flooding, the concrete blanket was designed to prevent erosion of the road subgrade, thus allowing the road to be returned to full service in as short a time as possible and usable by four wheel drive vehicles almost immediately. Culverts were selected in favor of "Arizona Crossings" because the culverts should decrease the necessity of clearing debris from the road surface after each flood. The long-term appropriateness of this decision has yet to be verified in that some culverts have experienced clogging from run-off due to minor storms. The clogging may, however, be the result of post-construction debris that should decrease in volume as the cut slopes and drainage channels reach equilibrium and are flushed of loose sediment. Periodic cleaning, however, will probably be necessary to maintain the effectiveness of the culverts and associated drainage improvements.

As was stated earlier, most of the damage to the populated areas of NWC resulted from drainages that were inadequate to accommodate the runoff from the 1984, 60-year storm. Consequently, the important drainage channels are being improved. Depending on local conditions, this has involved cleaning, widening, deepening, increasing embankment height; building diversion embankments; installing markedly larger culverts; and installing a low, concrete diversion wall around the major laboratory complex that was substantially damaged during the 1984 flood. Many of the undersized culverts and drainage channels that resulted in flooding of the laboratory have been improved; and a new, high volume drainage channel that leads directly to the playa has been excavated. In other areas, berms now protect facilities that were previously damaged. Emergency plans have also been prepared for mobilizing men, equipment, and materials to quickly erect temporary berms, widen channels, and complete other projects whose need may develop during a flood or flood warning. The NWC weather office will also issue warnings whenever conditions conducive to heavy rainfall are anticipated so that appropriate preparatory actions can be taken. These mitigation projects, when integrated with future construction, should divert and restrict most of the flood water to adequately sized drainage channels. The water can then be safely transported away from the major work areas and instead be allowed to flood the China Lake playa, the local base level. Flash flood warnings will allow for the mobilization of men, equipment, and materials to better protect critical facilities and areas.

The City of Ridgecrest has been less effective than NWC in its efforts to reduce future flood damage, but is moving forward. Flood damage repair and mitigation are only two of the major problems facing the rapidly growing city, and the lack of action is largely related to budgetary constraints rather than lack of concern. The City is currently completing a major redevelopment plan that should address many of the flood-related problems. In concert with this action, the U.S. Army Corps of Engineers is being asked to assess the flooding problem and develop mitigation plans that will probably involve the interception and diversion of flood waters away from developed areas and areas zoned for development.

GROUND WATER

Within the next several years IWV, as has happened to many other desert communities, will begin to experience the effects of groundwater overdraft unless extensive water conservation steps are implemented or other sources of water are developed (Reference 41). Studies by the U.S.G.S. have shown that pumpage has exceeded mean long-term annual recharge since 1966 (Reference 42). Located in a desert region, IWV receives sparse rainfall, about 14 cm per year over the entire valley; and evaporation is high, about 200 cm per year on the valley floor (Reference 43). Ground-water recharge, as is typical of most desert basins, is largely limited to subsurface influx from ephemeral streams that drain the bordering mountains, which themselves lie within the Sierra Nevada rainshadow. The ground-water table over most of the IWV is generally too deep to receive recharge directly from infiltrated precipitation and surface runoff. As Blaney points out, recharge seldom occurs until precipitation exceeds about 41 cm per year; and even then, only about 5% of the total becomes ground water (Reference 44). In general, the local precipitation and runoff serve only to increase soil moisture at shallow depths. Little, if any, reaches the potable water table although recharge to local, near-surface, nonpotable aquifers does occur, especially near the China Lake playa.

The local hydrologic system is composed of two ground-water bodies (Reference 45): a shallow aquifer perched on lacustrine clays near and around the China Lake playa; and a deeper, locally confined aquifer that underlies most of the valley. The shallow aquifer is nonpotable with total dissolved solids (TDS) values locally in excess of 67,000 milligrams per liter. The deeper aquifer supplies all of the domestic and agricultural water used in IWV and adjacent Searles Valley. The quality of the water is generally quite high, with TDS values of less than 500 found in most of the major wells. Reference 46 suggests that the lower part of the aquifer contains poorer quality water and that lowering of the table, as is now occurring, would eventually result in lower quality water being produced. Some recent unpublished data support this concept. This and many other questions should be resolved upon completion of the U.S.G.S. ground-water study described in Reference 45. A three-dimensional ground-water model of IWV is currently undergoing final development by the U.S.G.S., and work is in progress to include solute transport in the model.

St. Amand reports that during 1984, ground-water usage was about 32.7×10^6 m^3 (1 acre foot equals 1233 m^3) and recharge amounted to only 8.6×10^6 m^3 (Reference 41). Increased agricultural usage since 1984 has probably increased total annual usage to about 41.9×10^6 m^3 (pers. comm. P. St. Amand, 1987). Recent unpublished data based on computer modeling argue for about 12.3×10^6 m^3 per year of recharge and 28.4×10^6 m^3 per year of usage. In spite of the differences in estimates, it is clear that usage greatly exceeds recharge. For the last several years, usage has been increasing at a rate of about 10% annually, a factor that can only exacerbate the existing problem (Reference 41). Additionally, unpublished isotopic data suggest that some of the water currently being pumped may have entered the ground-water system 8000-12000 years ago, during the Wisconsin pluvial lake periods.

The progressively declining water table levels in many areas argue for ground-water mining. Continued lowering of the water table will severely aggravate the existing water problem through contamination of the potable water aquifers by an influx of highly saline ground water that is now largely restricted to the China Lake playa. St. Amand's analysis indicates that the overdraft will eventually cause a reversal in the ground-water flow gradients that will allow migration of saline waters from the near-surface aquifer near the playa into the surrounding and underlying potable aquifer (Reference 41). Predictions based on mathematical ground-water modeling by Mallory indicate that the direction of flow could locally have reversed as early as 1984 and that a pronounced reversed gradient would be established by 2020 (Reference 47). Also, overpumping may affect the state of stress at depth and allow underlying saline waters to migrate vertically into the limited overlying potable aquifers (Reference 41). Contamination by an influx of saline water has forced the abandonment of one of the major domestic water pump fields. Most of the ground-water availability problem can be overcome by reducing the excessive demand now placed on a limited resource by conservation, reuse, and improved withdrawal schemes.

The intrusion of saline water is only one of the many contaminants that may adversely affect the local ground water. Prior to the recognition of the environmental consequences that are so well known today, disposal of toxic wastes by surface dumping, shallow burial or injection occurred at several NWC locations and possibly in the surrounding communities and undeveloped desert areas. A number of former disposal sites at NWC have been identified and are being studied or decontaminated (Reference 43, 48, and 49). These sites contain a range of toxic materials including aviation fuels, solvents, beryllium, propellants, explosives, pyrotechnics, laboratory waste, heavy metals, cyanide, industrial detergents, degreasers, and other materials. The decontamination effort has only begun and several years will be required to complete the task.

Major factors affecting the decontamination effort include identifying the sites because of the loss or lack of records; determining the toxic materials that are or may be present; determining the mobility of the contaminants and potential dispersal methods; determining the potential hazard; and designing and implementing decontamination procedures when necessary. Several studies have been undertaken to answer these questions, and as a result, decontamination of some sites has begun and others are scheduled in the near future.

Aviation fuels, solvents, and fluids present one of the largest problems in terms of disposed volume and affected area. Between 1945 and 1982, an estimated 3.8×10^6 liters of substandard aviation and jet fuel was disposed of at Armitage Field (Figure 2) in dry wells or wasted on the ground surface; and an undetermined volume of aircraft wash water, sediment laden fuel, and used engine fluids from the aircraft cleaning and maintenance areas was disposed of by allowing the fluids to flow into unlined storm run-off ditches (Reference 43). These disposal practices were discontinued during 1981 and 1982.

Subsurface investigations have found fuel floating on the water table over an estimated area of about 9000 m^2. The fuel thickness ranges from 0 to 1.3 m, and fuel vapor has been detected over a much larger area. A recovery system thought capable of removing 70 to 80% of the fuel has been installed (Reference 43). The recovery system consists of specially designed wells that will pump free fuel and fuel-contaminated ground water from the shallow aquifer and equipment to separate the fuel and water. After separation, the fuel will be temporarily stored for later reclamation. The decontaminated water will be disposed of in a ditch leading to the playa. Although the volume of fuel is large, it does not present an immediate hazard because ground water down-gradient from the site is not being used and intermingles with the nonpotable shallow aquifer system. However, should ground-water gradients reverse because of overpumping, as was discussed earlier, any remaining contaminated water could eventually reach the deeper, potable water aquifer.

Considering that an adequate supply of high-quality ground water may be difficult to provide over the long term, the idea of problems resulting from excessive ground water appears contradictory. The fact remains, however, that in localized areas a rising water table is responsible for damage to roads, buildings, and other facilities and structures at NWC. Preliminary assessments indicate that the problem is a result of artificial recharge to the unconfined aquifer, primarily by leakage from sewage ponds (Figure 2). The additional annual ground-water influx is estimated to be nearly 3.7×10^6 m^3 and is concentrated within a proportionately small area of NWC (Reference 43). More recent estimates by a consulting firm place the current volume at 5.2×10^6 m^3 and this is expected to increase to 6.0×10^6 m^3 by the year 2010.

The shallow, unconfined aquifer is composed of lacustrine, alluvial, and eolian sediments ranging from less than 1 m to 10's of meters thick and underlain by an impermeable clay horizon. Because of the influx, ground-water mounding is occurring which locally results in standing surface water. The most serious problems occur down gradient from the mounds where the rising water table has flooded basements, resulted in damaged rebar and spalled concrete, disrupted utilities, disrupted weapons testing, caused differential settlement of foundations, damaged roads, rendered areas impassable and exacerbated the liquefaction potential of the sediments. Figure 6 shows the general area affected by the rising water table.

Several problems have complicated implementing a solution to the ground-water problem. These include the coordination of several jurisdictions and attaining agreement commensurate with the responsibilities of each, agreeing on a solution or range of solutions, obtaining funding and accommodating the Mojave tui chub (Gila bicolor mojavensis), a Federally-protected fish. The sewage treatment plant and ponds were expanded and upgraded during the mid 1970's to combine the waste disposal systems of NWC and the City of Ridgecrest into a single facility (Figure 6). The facility is located on NWC at the site of the original NWC sewage ponds that is operated by the City with NWC considered as a customer. The permits under which the new ponds were constructed stipulated that they would be for evaporation only. Because they are in violation of the original operating permits and are contaminating the ground water, the State Water Quality Control Board is in the process of ordering the City to bring the ponds into compliance.

The City, in conjunction with an environmental engineering consulting firm, has determined that repairing or replacing the ponds is not economically feasible. Alternatively, it appears that exporting partially treated water to adjacent Searles Valley for industrial usage is practical from both economic and engineering considerations. Exportation of the water is attractive in that it would mitigate the infiltration and consequent ground-water flooding problem, it could generate revenue to offset construction and operating costs of the pipeline, and industrial use of the water would decrease the demand for potable ground water from IWV. The City's consultant estimates that about 3.1×10^6 m^3 of industrial use water is available for export and that this volume may double by the year 2010. Exportation of the water will require the construction of a 41 cm diameter pipe line 35 km long, pumping facilities and possibly a well point dewatering system down-gradient from the sewage ponds. If the exportation plan is approved the water table will gradually decrease to the pre-mid 1970s elevations, resulting in diminishing damage and operational handicaps for NWC.

A general lowering of the water table will however, create other problems unless provisions are made to maintain the water level within the Mojave tui chub habitat. In 1971, the California Department of Fish and Game planted a small population of the endangered fish into a pond and marsh area locally known as Lark Seep and located north and down-gradient of the sewer ponds (Figure 6). It is now known that the habitat, originally thought naturally spring fed, is actually maintained by leakage from original NWC sewage ponds built during the early 1940s and by the newer City ponds.

The chub found the Lark Seep area and its drainage channels to be an ideal habitat that allowed it to thrive while other populations rapidly disappeared, and NWC now has one of the few if not the only

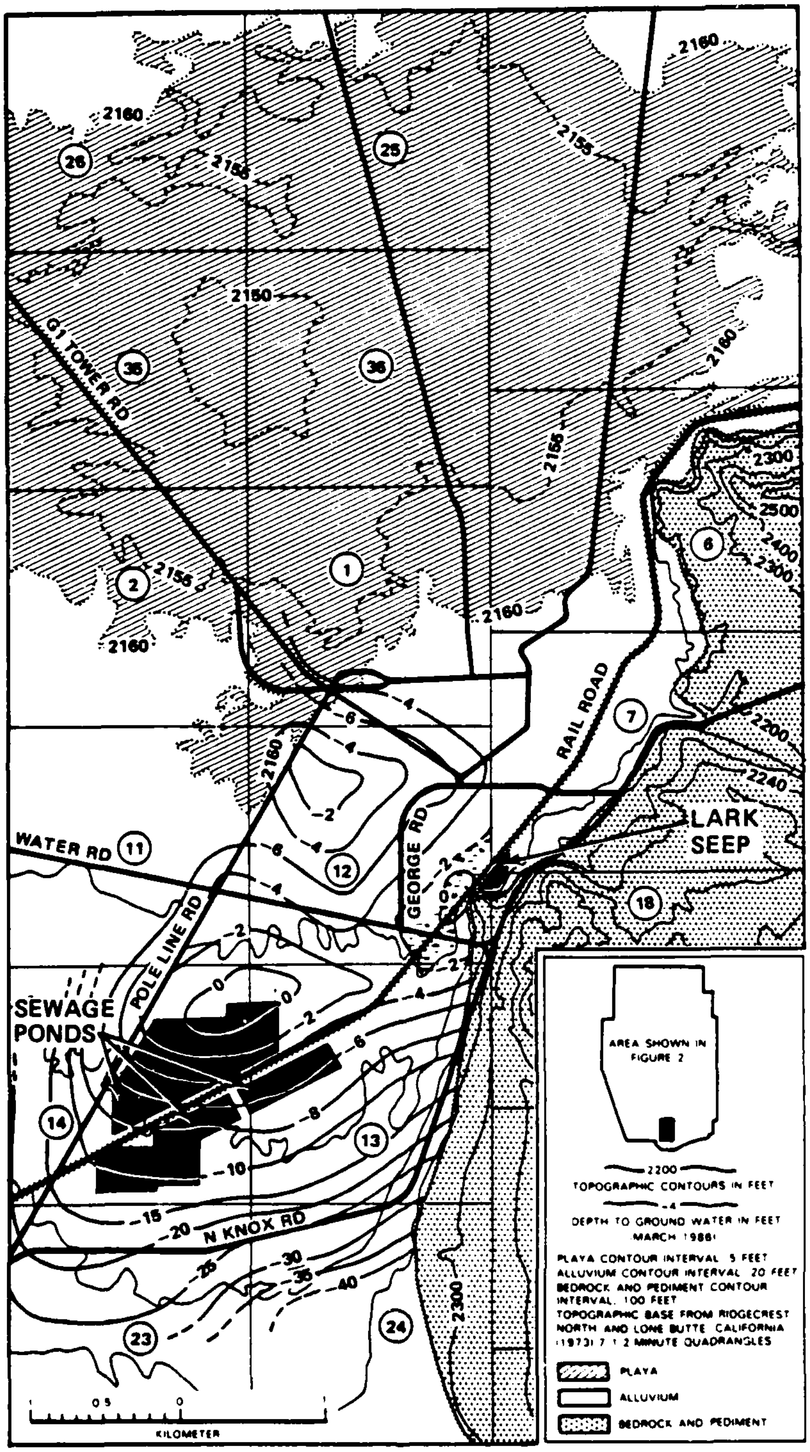

FIGURE 6. Map of a Portion of the NWC Test Range Area Showing the Location of the Sewage Ponds, Depth to Ground-Water Contours, Lark Seep, China Lake Playa and the Generalized Geology.

expanding Mojave tui chub population in existence. The original agreement between the State and NWC stipulated that NWC could terminate the experiment at its discretion and return the fish to the custody of the State. However, the chub has since become a Federally-protected, endangered species. Consequently, the U.S. Fish and Wildlife Service must now be consulted regarding any project that may affect the viability of the chub population.

As initially envisioned, the City's dewatering plan would ultimately result in the destruction of the chub habitat by exporting water that would otherwise infiltrate and artificially recharge the habitat. Several solutions have been proposed to allow dewatering and simultaneously protect the habitat. The simplest solution would be to artificially supply water to Lark Seep (Figure 6), but this would still result in an unacceptably high ground-water table down gradient. Other possible solutions include isolating Lark Seep from the ground-water system by lining the pond with clay or other material or constructing an impermeable barrier, such as slurry wall around the seep. These solutions would require the replenishment of water lost through evapotranspiration and other causes. Developing a new habitat at a different location is also possible, but is unlikely because of the initial cost, maintenance costs, fresh water requirements and the concern that the resulting wet lands and associated vegetation would attract birds and other wildlife by creating another artificial wildlife refuge. The involved agencies are working closely to develop a plan to allow dewatering to begin as soon as possible and without jeopardizing the chub population's viability.

After a dewatering plan is approved, the necessary permits granted and funding obtained, the City's consultant estimates that at least 18 months will be required to design and construct the pipeline system for exporting water to Searles Valley. Realistically, several years could pass before lowering of the water table can begin. In view of the escalating rate of damage, a delay of this magnitude is undesirable, and interim methods of locally lowering the water table in critical areas without affecting the chub habitat are being investigated. Proposed solutions include (1) the installation of a chain of shallow wells to cut off ground-water flow to critical areas; (2) the installation of well-point dewatering systems around mission-essential facilities; and (3) the installation of a grout or slurry cutoff wall at selected locations. Initially, any removed ground water would be conveyed to the China Lake playa by a system of pipes and existing drainage ditches and released at or below the 2155-foot contour (Figure 6). Storage below the 2155-foot contour is about 3.95×10^6 m^3, but the annual evaporation rate of 2 m will effectively increase the storage capacity dramatically. The water could also be pumped over the topographic divide into the adjacent basin, with much of the energy cost recovered by installing a small hydroelectric plant at the end of the pipeline. Once the City's water export system is installed, any water collected by localized dewatering systems could be added to that being exported to Searles Valley for industrial usage.

Localized dewatering would not interfere with the chub's habitat and would complement the City's plans by locally lowering the water table to elevations below that possible by simply removing the ponds from service. The main advantage of the aforementioned solutions is that dewatering could begin as soon as funds become available rather than having to wait for the chub issue to be resolved; however, the costs and technical feasibilities of these solutions may prevent their implementation.

The various solutions are being evaluated by staff engineers and geoscientists to determine cost, engineering feasibility, and suitability of each solution. A major portion of the evaluation will be based on a review of existing geologic data, well drilling and pump tests, seismic refraction profiling, possible electrical resistivity studies, and other geotechnical exploration and evaluation techniques.

LIQUEFACTION

The artificially induced high water table exacerbates problems associated with the naturally shallow water table that occupies the lower portions of the pluvial China Lake basin (Figure 2). A major effect of the high water table is the increased susceptibility of the near-surface sediments to liquefaction. Banks found that about 114 km^2 of NWC are underlain by sediments highly susceptible to liquefaction and that a much larger area extending into Ridgecrest is underlain by sediments of moderate susceptibility (Reference 50). Banks' susceptibility classification is based on sediment characteristics such as grain size, sorting and degree of consolidation, depth to the water table, and expected seismic site acceleration. Figure 7 shows the susceptibility of various areas to liquefaction as well as depth to ground-water contours.

Recent earthquakes have apparently caused liquefaction that resulted in minor structural damage to buildings. During and following the M=4.8 earthquake on 1 October 1982, minor wall cracking, door jamming, and similar problems attributed to liquefaction-induced differential foundation settlements occurred to several structures. Local expulsions of water and fine-grained sediments onto dry playa surfaces are thought to have occurred during the same earthquake sequence. As shown by Banks' map (Figure 7), most of the test range facilities are underlain by sediments with high to moderate liquefaction susceptibilities (Reference 50). Recent geotechnical and geologic investigations have verified Banks' mapping in many areas. Any local earthquakes significantly larger than the 1982 event will probably have serious consequences for NWC, especially where the water table has risen.

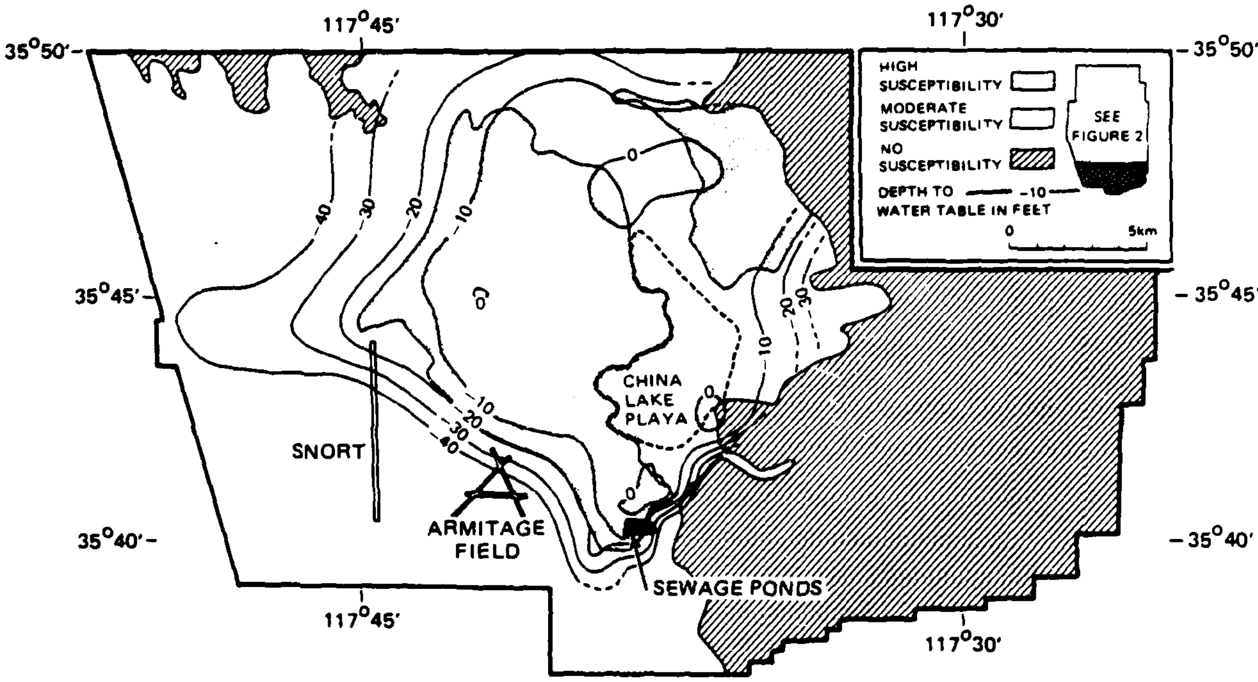

FIGURE 7. Map Showing Liquefaction Susceptibility of the Southern Portion of the NWC Test Range Area. (Modified from Reference 50.)

Ridgecrest and other populated areas of the valley would be less affected by liquefaction because of the deeper water table and tendency for coarser sediments to occur away from the playa area. There are, however, several areas that may be susceptible to liquefaction-induced slope failures, such as lateral spreading. Gentle slopes underlain by liquefaction-susceptible sediments occur within limited areas of NWC, especially north and northeast of China Lake playa (Figure 2). This unpopulated and largely undeveloped area contains southwest-dipping slopes with angles of 1 to 2 degrees. Slopes with angles as gentle as 0.3 degree have failed by lateral spreading (References 51 and 52). Slopes exceeding 0.3 degree are common throughout much of the area studied by Banks and their materials were found to be highly or moderately susceptible to liquefaction (Reference 50). Liquefaction-induced lateral spreading and associated soil failure could conceivably occur over many areas of NWC where the water table is less than 10 m deep (Figure 7), but the sparsity of development in these areas would generally limit the damage to roads and utility corridors.

Although the potential for severe liquefaction and other seismic-related hazards is now well known to NWC, many older structures were not designed to withstand seismic effects as they are currently understood. Many of the structures range in age from 20 to over 40 years, and as a consequence, foundation studies deemed necessary by today's standards and state of knowledge were not done prior to design and construction. Also, many of the structures were built during wartime conditions when speed of design and construction may have taken precedence over geotechnical considerations. Refitting to prevent or withstand differential settlement would exceed the replacement cost of many of the structures and therefore is financially impractical. Lowering of the water table, both locally and areally, appears to be the most cost effective and attractive solution to the liquefaction problem in many of the potentially affected areas.

As was discussed in the ground-water section, plans are being made to lower the water table to the pre-1970's levels by exporting partially treated sewage water that would otherwise artificially recharge the shallow aquifer system. The dewatering plan is a major step in solving the potential liquefaction problem, but by itself will not constitute the ultimate solution for the entire area. Dewatering will have the greatest effect near the sewage ponds where the maximum ground-water mounding occurs. Here, the water level may decrease sufficiently to preclude liquefaction, but in other areas the water table may remain near the natural near-surface level of the adjacent playa area. Diverting a portion of the export water into the Lark Seep area to protect the chub habitat may prevent any significant decrease in the down gradient water table unless leakage is prevented or greatly reduced. Selectively lowering the water table beneath mission-essential structures or in limited areas as an adjunct to the City's plan should prevent or minimize the liquefaction hazard beneath the selected structures but will have little if any effect on other structures in the area.

This sort of plan is reasonable in that many of the structures have exceeded their design life or otherwise have outlived their usefulness. The cost of maintenance and renovation is rapidly escalating because of the age of the structures and their inappropriateness for present needs. Rather than expend large sums of money for temporary solutions, it is probably better to accept the short-term risk of liquefaction and selectively replace inadequate structures with modern, seismic-resistant facilities designed to meet today's and the future's needs. Now that the potential for seismic activity and liquefaction has been recognized, there is a much greater awareness of the need to properly site, design, and build new structures to accommodate these and other geotechnical problems. As a result, geotechnical investigations and design input are assuming a decidedly more prominent role than in the past.

SLOPE FAILURE

Slope failure hazards in the IWV area are generally limited to rock falls and landsliding from the steep slopes and canyon walls of the surrounding mountains that would most likely be triggered by earthquakes. However, development in and adjacent to mountainous areas aggravates the limited hazard that now exists from occasional rockfalls and landslides unrelated to seismic shaking. During an airphoto reconnaissance of the region, six landslides exceeding 0.5 km^2 in area were recognized. These include three in the Coso Range granitic rocks with areas of 0.6, 1.4, and 2.1 km^2; one in Coso Range volcanic rocks of 1.9 km^2; one in the central Argus Range volcanic rocks of 6.7 km^2; and one in Sierra Nevada granitic rocks of over 10.0 km^2. Although none of these have been studied in detail, all, based on geomorphic evidence, appear to be late Pleistocene to early or mid Holocene in age. The scarcity of young landslides of any size probably results from the present arid climate that has dominated the region during much of the Holocene.

Although the arid climate and thin, poorly developed soils in many areas will diminish the number of slope failures, rock falls and rock slides are likely to occur. Well-developed jointing with orientations favorable to slope failure commonly occurs in the steep mountain areas. Because these areas are largely unpopulated, the greatest impact will be to transportation routes. Even minor failures could prevent access to many areas. At NWC the greatest hazard exists in Mountain Springs Canyon (Figure 2). Here, a main access road extends about 8 km through a 500-m-deep canyon with slopes averaging 35 degrees, but locally are considerably steeper. Well-developed orthogonal joints that yield granitic blocks of up to several cubic meters in volume intersect the canyon walls. Locally, highly sheared or weathered bedrock supports the road and toes of slopes. In other areas the road passes through colluvium and alluvial fan deposits with cut slopes of 3/4:1 to 1/2:1 (horizontal:-vertical) and heights up to about 17 m. In areas of limited stability, catchments were constructed, where space permitted, to contain falling rock; and large, potentially unstable, boulders were removed by blasting. The slope problem is aggravated by undercutting by the ephemeral stream that drains the canyon. Flash flooding of this stream seriously damaged the road in 1984. Although the road through the canyon has been rebuilt, cost factors prevented complete alleviation of the rockfall and slope stability hazard, especially as would be required by seismic considerations.

Historically, road closures due to slope failure have not been a problem in the area, but the potential for seismic shaking may alter this fortuitous circumstance. As was discussed previously, the area lies within a highly seismically active region. References 51 and

53 discuss the effects of seismic shaking on slope stability. Their data show that even moderate earthquakes can have a serious impact on slope stability, especially in mountainous terrain. In the Mammoth Lakes region of California, about 200 km north of IWV, a sequence of magnitude 6 or greater earthquakes during May 1980 triggered several thousand landslides with volumes as great as 200,000 m^3 throughout an area of about 2500 km^2 (Reference 53). Most slopes contributing to rock falls and slides were steeper than 50 degrees, but slopes steeper than 35 degrees and covering a range of lithologies generally contributed to the slope failures. Slopes steeper than 35 degrees composed of quasistable materials are common in the canyons of the Coso and Argus Ranges and along the Sierra Nevada front (Figure 2). The north-draining slopes of the El Paso Range and Rademacher Hills are generally much more stable because of their gentler slopes.

To better identify areas subject to slope failure a limited study is being planned for selected areas of IWV. The study will identify unstable and potentially unstable areas and estimate the extent of hazard that exists or that may develop as the result of seismic loading. The study will involve air-photo analysis, field mapping, a stereographic analysis of possible failure planes, static limiting-equilibrium determinations, and the effects of superimposed seismic loads from probable earthquakes along local faults. The study may be expanded to include detailed investigation of areas having the greatest hazard potential if warranted by the initial results.

An unusual, but nevertheless potentially serious slope stability problem exists along the Sierra Nevada range front. About 70 years ago, the Los Angeles Aqueduct was constructed along the range front with apparently little understanding of the local geology. The aqueduct was built within or adjacent to what is now known to be the Sierra Nevada fault zone. The zone has the potential for great earthquakes as is shown by the 1872 M=8.3 Lone Pine earthquake and is considered by Wallace to be a seismic gap (References 24 and 25). Even moderate earthquakes along this zone could cause damage to the aqueduct, if not its total failure. Damage or failure could result from direct ground rupture, shaking, or from slope failure either above or below the aqueduct. Leakage from any cause could decrease the stability of the aqueduct-supporting materials and lead to eventual failure. Although the exact cause of the damage has not been determined, the aqueduct was apparently seriously damaged north of IWV near Owens Lake by an earthquake in 1917 with a probable magnitude greater than M=5 (Reference 54). Some reports cite rupture of the aqueduct while others claim that the damage resulted from rockslides. Whatever the cause of this particular damage, it is clear that slope stability problems will probably impact the operation of the aqueduct in this region.

CONCLUSIONS

Most of the geologic hazards and geotechnical problems that affect the IWV area are related directly or indirectly to the early site selection and development that proceeded without the level of adequate consideration for the environment and the local geology that is now considered necessary. Numerous steps are now being taken to minimize the deleterious effects of the earlier actions and decisions and to prevent their repetition. As a result of experience and modern geologic and geotechnical investigations, site selection and design now incorporate a much higher level of geologic and geotechnical detail than was previously included. Reconnaissance and detailed studies of the local geology and geotechnical parameters will continue, now that their importance has been recognized. Although development will still occur in geotechnically unfavorable areas, new structures are more adequately designed to accommodate site conditions that previously may have gone unrecognized or not have been fully appreciated.

In the long term, the most serious problems to affect this area will be an adequate water supply and the effects of seismic activity. Even though the longevity of the ground-water supply is generally known to be in question, there is still a demand for increased development, highly water-consumptive agricultural usage, humid-region landscaping, and additional recreational amenities such as golf courses, swimming pools, and "water parks." Although many of these are desirable, considerations of the implications of a desert climate and the limited water supply are sometimes subordinated to economic arguments and personal wants. In the populated desert southwest, the seriousness of a limited water resource is often not fully appreciated by our modern society at large until water rates rise exponentially or until nothing happens when the spigot is opened. It appears that this problem can be solved only by education of the public and the actions of enlightened and farsighted public officials.

The mitigation of earthquake hazards must be treated similarly, that is, through public awareness and governmental action such as zoning and site investigation requirements. Moderate to great earthquakes are inevitable in this region and their effects must be addressed. Recognizing this necessity, NWC provided funds for the mapping of active faults, seismicity studies, liquefaction susceptibility studies, and for obtaining other critical geologic and geotechnical information. These data, in combination with public awareness, have resulted in major advances in seismic-hazard mitigation efforts in the private and public sectors.

Nevertheless, there is still occasional opposition to siting new structures and facilities in geologically and geotechnically more appropriate, but less convenient or otherwise less desirable locations. In many cases this reluctance results from a poor understanding of the implications of extant or potential geologic hazards or geotechnical considerations relative to the longevity and long-term maintenance costs of the structure. The general trend of increasing consultation with geologists and geotechnical engineers in early phases of site selection, design, and construction should over time negate much of the opposition.

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