Flatland deposits of the San Francisco Bay Region, California—their geology and engineering properties, and their importance to comprehensive planning

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A series of closely related earth-science studies that define the nature and severity of earthquake hazards associated with geologic conditions

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FOREWORD

This report is a product of the San Francisco Bay Region Environment and Resources Planning Study, an experimental program designed to facilitate the use of earth-science information in regional planning and decisionmaking. The study is jointly supported by the U.S. Geological Survey, Department of the Interior, and the Office of Policy Development and Research, Department of Housing and Urban Development. The Association of Bay Area Governments participates in the study and provides a liaison and communication link with other regional planning agencies and with county and local governments.

Although the study focuses on the nine-county, 7,400-square-mile (19,000-square-kilometers) San Francisco Bay region, it bears on an issue that is of national concern. This issue—how best to accommodate orderly development and growth while conserving our natural resource base, insuring public health and safety, and minimizing degradation of our natural and man-made environment—is difficult and complex. The complexity, however, can be greatly reduced if we understand the natural characteristics of the land, the processes that shape it, its resource potential, and its natural hazards. These subjects are chiefly within the domain of the earth sciences: geology, geophysics, hydrology, and the soil sciences. Appropriate earth-science information, if available, can be rationally applied in guiding growth and development, but the existence of the information does not assure its effective use in the day-to-day decisions that shape development. Planners, elected officials, and the public rarely have the training or experience needed to recognize the significance of basic earth-science information, and many of the conventional methods of communicating earth-science information are ill suited to their needs.

It is hoped that the study will aid the planning and decisionmaking community by (1) identifying important problems that are rooted in the earth sciences and related to growth and development in the bay region; (2) providing the earth-science information that is needed to solve these problems; (3) interpreting and publishing findings in forms understandable to and usable by nonscientists; (4) establishing new avenues of communication between scientists and users, and (5) exploring alternate ways of applying earth-science information in planning and decisionmaking.

Since the study was started in 1970, it has produced more than 100 reports and maps. These cover a wide range of topics: reduction of flood and earthquake hazards, unstable slopes, engineering characteristics of hillside and lowland areas, mineral and water resources management, disposal of solid and liquid waste, erosion and sedimentation problems, bay-water circulation patterns, and others. The methods used in the study and the results it has produced have elicited broad interest, and a wide range of applications, from planners, government officials, industry, universities, and the general public.

This report on flatland deposits and their land-use significance examines the low-lying areas of the San Francisco Bay region where urban centers are numerous and the population is dense. These areas of low relief are also likely to be favored sites for future growth, for they are easily reached by existing roads and railroads, and their relatively level surface is adapted to a variety of intensive uses of the land. But the lowlands are not uniform. They include valley floors and terraces, plains, low alluvial slopes, marshlands, and marine terraces. These landforms result from a number of different geologic processes, they are underlain by deposits with different physical and chemical properties, and they respond differently to the impact of use.

This report evaluates the different flatland deposits, both in terms of their natural properties and in terms of the geologic processes that they record. It also discusses how earth-science knowledge of the deposits and the processes that formed them may be incorporated into planning for better use of the land. These two closely related topics are addressed in separate sections of the report. The first section identifies the different kinds of deposits that underlie flatlands of the bay region, describes their properties and the processes that formed them, and demonstrates how this knowledge can be used to predict the consequences of changing land use. The second section of the report shows how planners and decisionmakers working within the conventional framework of comprehensive planning can use interpreted earth-science information to assess alternative uses of land.

Robert D. Brown Jr.

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DEFINITION OF TERMS

For the convenience of readers unfamiliar with some of the geologic terms used in this report, the following glossary has been prepared. We hope it will save a number of trips to the dictionary and make the text easier to understand.

Alluviation. The process of building up of sediments by a stream at places where stream velocity is decreased. The coarsest particles are the first to settle and the finest muds the last.

Anticyclone. An atmospheric high-pressure system in which the wind blows spirally outward in a clockwise direction in the Northern Hemisphere.

Aquiclude. A relatively imprevious rock layer that forms the upper or lower boundary of an aquifer but does not transmit enough water to supply wells or springs.

Aquifer. A permeable layer of rock that contains enough ground water to yield significant quantities of water to wells and springs.

Berm. A low bench or narrow terrace on the back shore of a beach formed of material thrown up by storm waves.

Colluvium. Any loose mass of soil or rock fragments that moves downslope largely by the force of gravity. Usually it is thicker at the base of the slope.

Diatom. A microscopic single-celled plant that secretes siliceous cell walls in a great variety of forms.

Eolian. Deposits laid down by the wind, landforms eroded by the wind, or structures such as ripple marks made by the wind.

Facies. A rock unit distinguished from others by appearance or composition as a result of environment of deposition.

Geomorphic. Pertaining to the form of the surface features of the earth. Specifically, geomorphology is the analysis of landforms and their mode of origin.

Holocene. The most recent epoch of geologic time, extending from 10,000 years ago to the present time.

Indurated. Rock or soil compacted by pressure, cementation, and heat.

Interfluvial. The land lying between streams.

Isohyet. A line connecting points of equal precipitation.

Isoseismal line. A line connecting points on the Earth's surface at which earthquake intensity is the same.

Lithified. The consolidation of a loose sediment into a solid rock.

Lithostatic load. The vertical load at a point in the Earth's crust equal to the load that would be exerted by a column of the overlying rock or soil.

Littoral drift. Material (such as sand, gravel, and shell fragments) that is moved along the coast by an ocean current.

Plate tectonics. An Earth model in which a small number (10–25) of large, broad, thick plates of the Earth's surface believed to "float" on an underlayer and move more or less independently, grinding against each other like ice floes in a river. The plates are propelled from the rear by sea-floor spreading. The continents form part of the plates and move with them like blocks of wood in an ice floe.

Pleistocene. An epoch of geologic time extending from 10,000 years ago to 1.8 million years ago; it includes the last Ice Age.

Pliocene. The epoch of geologic time before the Pleistocene. Its age covers the span of 1.8 to 7 million years ago.

Pore pressures. The pressure exerted by the fluid that fills the pore spaces between the particles in a rock layer.

P wave. A type of earthquake wave that moves by alternating compression and expansion of material in the direction of movement. The P stands for primary because it is the fastest of the earthquake waves and so arrives before the secondary or S wave.

Quaternary. A period of geologic time thought to cover the past 1.8 million years. It consists of two epochs—the Pleistocene and Holocene.

Radiometric age. An age determined by measuring the disintegration rate of radioactive elements. The age may be calculated by measuring a short-life element like carbon-14, or a long-life element plus its decay product such as potassium-40/argon-40.

Sea-floor spreading. A theory that the oceanic crust is forming by upwelling and cooling of lava along the mid-oceanic ridges and is moving away from the ridges at the rate of 1–10 centimeters per year. This movement is thought to provide the source of power for the movement of large "plates" of the Earth's crust. (See "plate tectonics.")

Seismic impedance (acoustic impedance). The product of seismic S-wave velocity and bulk density.

Seismic velocity. The rate of propagation of an elastic wave. The velocity depends upon the type of wave and the elastic properties and density of the Earth material through which it travels.

Shear wave, S wave. A type of earthquake wave that moves by a shearing of material, so that there is movement perpendicular to the direction of propagation. S stands for secondary because it travels slower than the P or primary body waves.

Soil horizon. A layer of soil distinguished from adjacent layers by such characteristics as structure, color, texture, or chemical composition. Soil horizons are generally designated by capital letters, for example, A horizon or B horizon.

Soil profile. A vertical section of a soil that shows all its layers and the material from which it was derived.

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Subduction. The process of one crustal block moving beneath another—by folding, faulting, or both.

Tectonics. A study of the origin, relations, and evolution of structural features of the Earth's crust, such as folding and faulting of the rocks.

Tsunami. A sea wave produced by any large-scale, short-duration disturbance of the ocean floor, principally by a shallow submarine earthquake. Tsunamis are characterized by great speed and may cause considerable damage along an exposed coast thousand of miles from the source.

FLATLAND DEPOSITS OF THE SAN FRANCISCO BAY REGION, CALIFORNIA—THEIR GEOLOGY AND ENGINEERING PROPERTIES, AND THEIR IMPORTANCE TO COMPREHENSIVE PLANNING

By E. J. HELLEY and K. R. LAJOIE

ABSTRACT

Geologic maps of the deposits underlying the flatlands (slope less than 15 percent) of the San Francisco Bay region provide urban and regional planners and decisionmakers with earth-science information regarding geologic hazards and resources. The flatlands are particularly suitable for development because the low relief permits simple, relatively low cost construction, but parts of the flatlands possess unusual geologic characteristics that must be taken into account if development and the use of resources are to be effectively managed.

To examine the flatland characteristics systematically, 13 geologic units are mapped in the area surrounding San Francisco Bay, in the outlying valleys, and in the coastal zone. The geologic units are studied and mapped by unconventional methods. These include the use of 19th-century maps and coastal charts, and pre-1940 aerial photography; studies of environments of deposition, soil, and stratigraphy; and age determinations from radiometric methods, paleontology, and archaeology. Among the geologic units that can be recognized and mapped are the estuarine (bay) muds and marsh deposits; and alluvial-fan, channel, flood-basin, levee, dune, and beach deposits. The 13 geologic units shown on the map that accompanies the report range in age from oldest Pleistocene (1.8 million years) to deposits that are still forming today.

The engineering properties of these units are determined by analyzing unpublished reports by private consultants, the geologic and engineering literature, bore-hole logs for highway and bridge construction, and U.S. Geological Survey field studies. The engineering properties are shown to be systematically related to the age of the geologic units. These properties include bulk density, moisture content, penetration resistance, seismic wave velocities, and liquefaction potential. The depositional processes and age of each unit give a basis for predicting potential geologic hazards as well as natural resources. Most potential hazards are related to water or to earthquakes. Water-related hazards include flooding, rapid channel changes, salt-water intrusion, subsidence, ground settlement, and shrinking and swelling. Seismic hazards include ground-motion amplification and liquefaction with possible ground failure. The young estuarine muds and flood-basin deposits are most susceptible to seismic hazards.

Natural resources are also evaluated for each unit. The agricultural potential of the soils is probably most important because this vital resource is generally lost forever after urbanization. The flatlands are also a source for sand and gravel, clay, peat, shells, and salts.

The hazards and resource potential are identified for each unit so that regional planners will have sound information on which to base their decisions regarding land use.

How this information can be evaluated and applied is shown in a hypothetical land-capability study. Each geologic unit is rated for relative capability for agriculture, urban residential development, ground-water recharge, and sand and gravel extraction. The study shows that bay mud has low capability for all uses considered, that relatively few units have high capability for agriculture or ground-water recharge, and that most units have high or moderate capability for urban residential development. The ratings bring into focus potential land-use conflicts that require resolution through evaluating economic, political, social, and other environmental information. Land-capability studies can assure that natural factors are given full consideration in the planning process and direct attention to areas and problems needing further investigation before land-development decisions are made.

Three examples of planning response to particular flatland potential problems are (1) the policies and permit procedures of the San Francisco Bay Conservation and Development Commission under which development proposals for construction on fill over bay mud are reviewed by a board including earth-science and engineering professionals, (2) policies and project-review criteria of the Association of Bay Area Governments emphasizing the regional importance of prime agricultural land, and (3) the geologic and soils report requirements of Santa Clara County, which are related to mapped risk zones in the baylands. These examples show how geologic studies can be effectively used in land-use planning to foster safe, economical, and environmentally sound land-use decisions.

INTRODUCTION

By William E. Spangle, Martha L. Blair, Edward J. Helley and Kenneth R. Lajoie

PROBLEMS AND PURPOSES

The San Francisco Bay region consists of the nine counties surrounding San Francisco Bay (fig. 1)—the largest estuary on the California coast. The area is characterized by diversity in topography, natural resources, and climate. It is richly endowed with outstanding scenic and recreational resources; a mild climate; large open-space areas; large areas of flat, easily developed land; fertile soils; good water supplies; extensive inland waterways; and fine harbors. These favorable natural features have attracted a large population which has produced a vigorous and diversified social and economic system. The area is one of the most attractive urban-suburban complexes in the United States.

FIGURE 1.—The nine counties in the San Francisco Bay Region.

The region, however, is not without its environmental problems. Many natural constraints to land use in the bay region were ignored or were not recognized in the period of rapid population growth since World War II. As a result, valuable and irreplaceable natural resources such as prime agricultural land were destroyed, houses and public facilities were built on landslides and active faults, overdraft of ground-water aquifers caused severe subsidence in some areas, and development took place on active flood plains. Recognition in the late 1960's that many of these problems relate to geologic factors led to the formation of the San Francisco Bay Region Study jointly funded by the U.S. Geological Survey and the Department of Housing and Urban Development. This study was designed to provide some of the basic geologic data needed to develop guidelines for the use of the land and natural resources of the San Francisco Bay region.

Most of the residential, agricultural, industrial, and commercial development in the bay region is in the nearly flat lowland areas surrounding the bay and extending into the outlying mountainous areas as narrow valleys (fig. 2). In effect, these flat low-

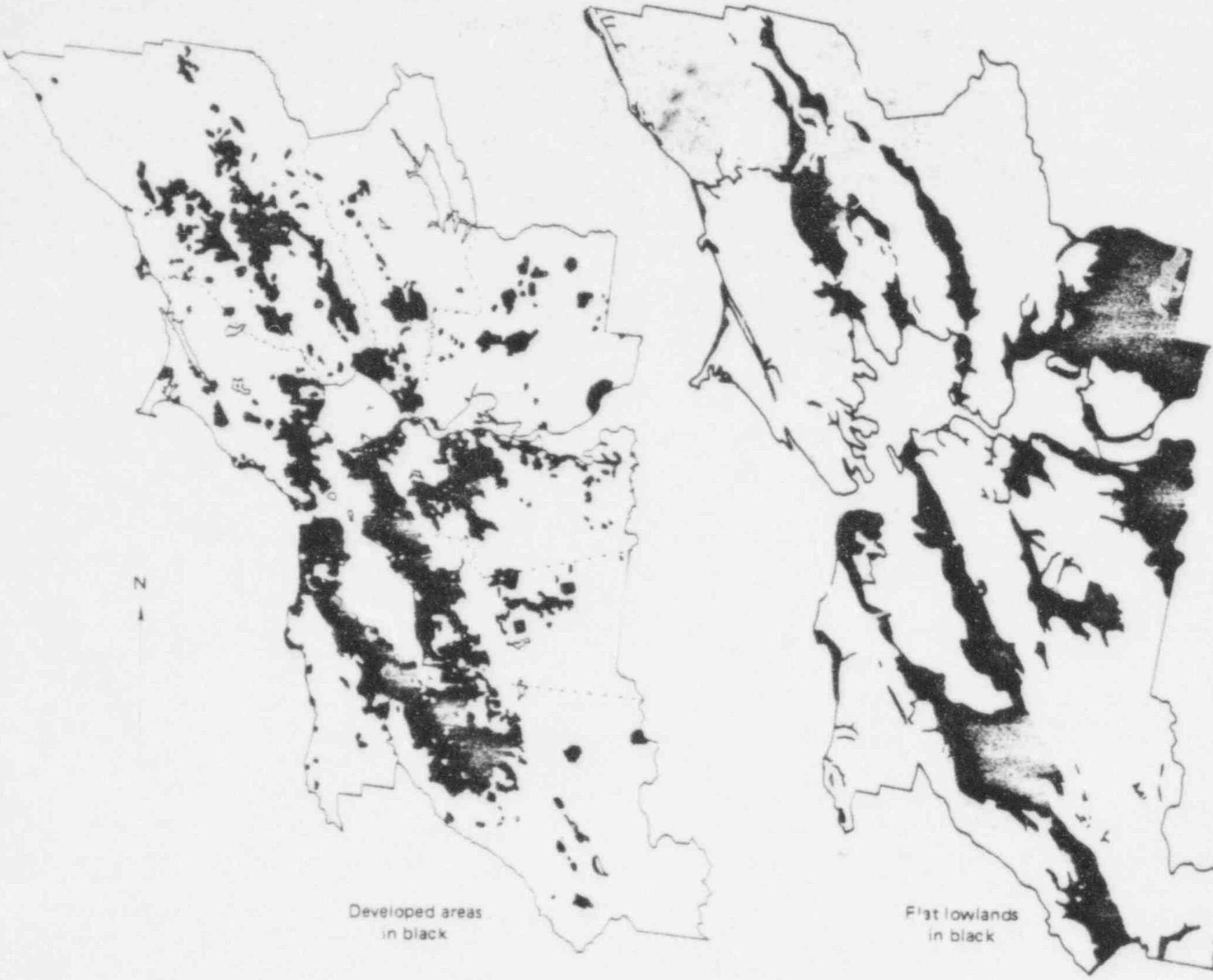

FIGURE 2.—The developed areas and flat lowland areas in the San Francisco Bay region. Developed areas consist of low-, medium-, and high-density residential, commercial, industrial, military, and transportation facilities as of 1965. Data from Association of Bay Area Governments, 1966.

lands are themselves an important natural resource of the bay region. Most future urban development can be expected to occur in these flatlands. The purpose of this report is twofold: (1) to identify the geologic units and processes of these lowland areas, placing particular emphasis on the opportunities and constraints associated with the deposits that underlie these areas, and (2) to show h[illegible] information concerning the natural characteristics of flatland areas can be used in regional planning to influence future land-use decisions.

PLANNING AND DECISIONMAKING

The information needed in regional planning and the extent to which it can affect decisions depend on the nature of the planning and decisionmaking process, the powers and objectives of the agencies involved in planning, and the natural features and processes of the planning area. These aspects of the San Francisco Bay region provide the basis for the interpretation and application of geologic information in regional planning.

Planning is the process of devising and carrying out a course of action to reach an identified objective. As an organized governmental activity, planning seeks to improve the decisions of public bodies and administrators. Comprehensive planning treats the long-term development of an area considering all major determinants of growth and change—economic, political, social, and physical.

A land-use plan is a key component of a comprehensive plan providing a link between more general goals and policies and the pattern of land develop-

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ment. A land-use plan includes objectives, policies, and proposals for the type, pattern, and intensity of land use. A functional plan describes needed facilities and operations for a specific function of government such as transportation, water development, flood control, or emergency response; it is more specific than a comprehensive plan and usually has a shorter range. Any plan, when adopted by the governing body of an agency, is official public policy. This report is primarily concerned with land-use planning and decisionmaking carried out by regional agencies.

The process of developing comprehensive, land-use, and functional plans generally consists of six steps: identifying problems and defining goals and objectives, collecting and interpreting data, formulating plans, evaluating impacts, reviewing and adopting plans, and implementing plans. These steps, shown in figure 3, are interrelated. Plan formulation often indicates the need for additional information, additional information may alter the concept of the objectives and problems, and plan implementation may reveal the need for more additional information or modification of the plan.

The steps in the planning process consitute a systematic approach to informed decisionmaking applicable to most governmental activities. The product of the process is a logical and internally consistent plan or set of plans and programs to guide public and private decisions. The planning process is ongoing, producing refinements, revisions, and new plans and implementing programs as additional information is obtained, new issues and problems raised, or changes in public attitudes recognized. Public participation is essential throughout the planning process. Success in implementing a plan depends on widespread public support, which can be gained only if all major segments of the public participate in the planning process.

Decisions occur throughout the process, ranging from the decision to engage in a planning effort to the final approval of a plan and adoption of implementing regulations, programs, and procedures. Elected public officials have final responsibility for most key policy decisions, although persons in nonelective positions actually make many important day-to-day decisions.

The process shown is generally applicable regardless of jurisdictional level, subject area, or size of planning area. However, the actual content of the plans varies widely depending on the responsibility, authority, and financial position of the planning agency; the diversity of the planning area; scope of the planning effort; and availability of data. For example, regional councils of governments (COGs) are likely to emphasize developing procedures and criteria for use in reviewing major projects and plans. This is beacause the COGs' primary power derives from federally mandated review processes. Local agencies are more likely to emphasize objectives, policies, and criteria to provide a basis for land-use and development regulation—traditionally a local responsibility.

AGENCIES FOR REGIONAL LAND-USE PLANNING

In the San Francisco Bay region, planning and decisionmaking authority at the regional level is

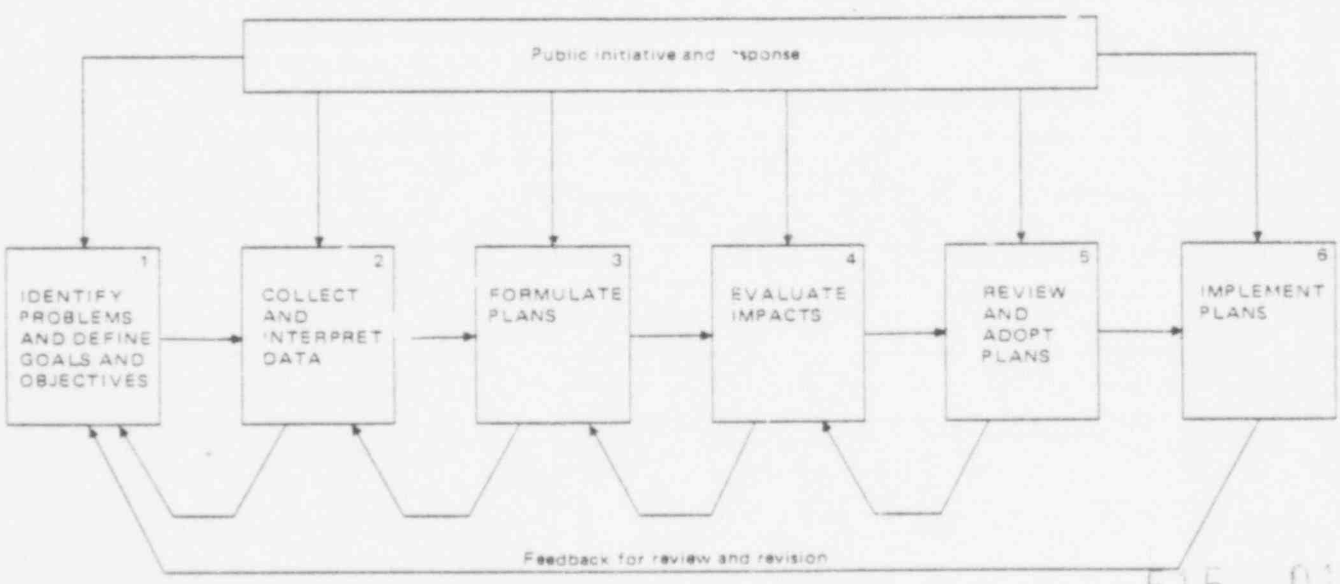

FIGURE 3.—The land-use planning process.

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diffused among more than 20 agencies with different but sometimes overlaping responsibilities and jurisdictional boundaries. The agencies with duties or powers affecting land use fall into the following five basic categories:

- Comprehensive planning agencies.
- Functional planning agencies.
- Agencies with permit authority.
- Regulatory agencies.
- Single-purpose planning and operating districts.

COMPREHENSIVE PLANNING AGENCIES

The Association of Bay Area Governments (ABAG) is responsible for areawide comprehensive planning. Established in 1961 to develop plans and policies pertinent to regionwide problems, ABAG is a voluntary association of local governments. Present voting membership includes 7 counties and 85 cities out of a potential voting membership of 9 counties and 92 cities. However, all 9 counties are included within the ABAG planning area.

ABAG's adopted regional plan consists of the *Regional Plan 1970-1990* (1970), the *Regional Airport Systems Study Final Plan* (1972), *Regional Open Space Plan, Phase II* (1972), *Regional Ocean Coastline Plan* (1973), plus goals and policies adopted from time to time by the General Assembly or Executive Committee (Memorandum to staff from Revan A. F. Tranter, Executive Director, ABAG, November 11, 1974). An important aspect of ABAG's planning activity is developing procedures, standards, and criteria for identifying and reviewing regionally significant projects and plans. Geologic information is needed by ABAG to carry out all of its planning functions.

ABAG's primary power to implement its plans and policies derives from its designation by the Federal government as the areawide clearinghouse agency for the San Francisco Bay region. In this capacity, ABAG reviews local requests for Federal funds available from about 150 Federal programs, including among others local applications for Community Development Block Grants and Comprehensive Planning Assistance Grants authorized by the Housing and Community Development Act of 1974. As a clearinghouse agency, ABAG also reviews proposed Federal projects and federally required Environmental Impact Statements. ABAG's review is advisory. However, because the funding agency must explain in writing a decision to override a negative finding by ABAG and because many projects are usually competing for limited funds, ABAG's recommendations are usually heeded. ABAG may also review state-required Environmental Impact Reports and any project it deems to be regionally significant. In addition, ABAG can directly participate in planning programs with other public agencies through joint memoranda of agreement. As a voluntary association with advisory functions, ABAG's powers of plan implementation ultimately depend on its ability, through well-conceived plans, development and dissemination of information, and the art of persuasion, to influence the decisions of other public agencies—regional, Federal, State, and local.

FUNCTIONAL PLANNING AGENCIES

The Metropolitan Transportation Commission (MTC) and Bay Area Comprehensive Health Planning Council (BACHPC) have specific mandates to engage in areawide functional planning with respect to transportation, health facilities, and waste-water treatment, respectively. The planning and project-review responsibilities, and other duties these agencies may be authorized to perform, are normally coordinated with ABAG activities. Each agency reviews local plans and projects for conformance with its functional plan.

MTC was established to coordinate the development of regional transportation facilities. It is charged with preparing and adopting a Regional Transportation Plan including proposals for major highways, mass transit, transbay bridges, airports, and harbors. It must also develop a transportation improvement program and a financial program for carrying out the program. The adopted Regional Transportation Plan is to be the bay area component of a statewide transportation plan required by Assembly Bill 69 (1972) Metropolitan Transportation Commission, 1975.

MTC has stronger project review powers than the other functional agencies. MTC's approval is required for certain projects, including transbay bridges, public multi-county transit systems on exclusive rights of way, construction of State highways, and all applications from local governments or districts for State or Federal funds for any kind of transportation facility. In addition to reviewing projects, MTC administers, for the bay area, the public transit funds acquired from State and local sales taxes on gasoline. MTC needs geologic information in planning the location of transportation facilities and reviewing transportation proposals.

BACHPC is a voluntary federation of nine county health-planning councils. It is recognized by State

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and Federal authorities as the agency to undertake and coordinate comprehensive health planning. The agency was organized to prepare a regional health plan to evaluate proposals for construction of new health facilities. BACHPC's primary power is the review of requests for Federal and State funds. The comments are advisory, but since requests for funds usually exceed funds available, the BACHPC review comments can be determining. BACHPC needs to consider geology, particularly seismic hazards, in locating and designing medical facilities.

AGENCIES WITH PERMIT AUTHORITY

The San Francisco Bay Conservation and Development Commission (BCDC) and the California Coastal Zone Conservation Commission (CCZCC) are the major agencies having permit authority. BCDC was created by the State Legislature to prepare a comprehensive plan for San Francisco Bay and its shores and to control development within its area of jurisdiction. The plan was adopted by the State Legislature, and BCDC became a permanent agency charged with carrying out the plan. The adopted plan has legal status and guides the review of projects. BCDC shares authority over land-use decisions with the cities and counties, which retain normal land-use and building-permit controls. However, with certain minor exceptions, a permit from BCDC is required for all projects within its area of jurisdiction. Thus, in effect, it holds veto power over any project proposal in conflict with the San Francisco Bay Plan. Geologic information was extensively used by BCDC in preparing its plan and is almost always needed for project review.

In 1972, California voters adopted, by initiative, legislation to create the California Coastal Zone Conservation Commission and subordinate regional commissions.

The CCZCC, working with six regional commissions, is charged with preparing a plan for the future of the California coastal zone. While the plan was being prepared, the commissions controlled all development, through a permit process, to insure consistency with the objectives of the established legislation and the emerging plan policies. The plan was presented to the Governor and legislature in December 1975 for adoption and implementation. In 1976, the California Coastal Act was enacted, establishing the policies and governmental mechanism for ensuring wise use of the State's coastal areas. Coastal areas of the bay region are represented by two commissions: Central (San Mateo County) and North Central (San Francisco, Marin, and Sonoma Counties). CCZCC used geologic information in preparing the coastal plan and, if maintained as a permanent organization, will continue to need geologic data.

REGULATORY AGENCIES

Regional agencies with a primary purpose of establishing, enforcing, and administrating regulations are the Bay Area Air Pollution Control District (BAAPCD) and the San Francisco Bay Regional Water Quality Control Board (RWQCB). The BAAPCD is responsible for establishing and carrying out a program to reduce air contaminants from both stationary and moving sources, and the RWQCB is responsible for formulating and adopting a water-quality control plan. However, the major influence of each agency on land-use decisions derives from its authority to set and enforce standards. For example, the RWQCB has issued moratoriums on sewer hook-ups in certain localities to prevent deterioration of water quality. In addition, any project that may have an effect on water quality must receive a permit from the board before it can be undertaken. Similarly, the BAAPCD, with jurisdiction over the nine counties, except for parts of Solano and Sonoma Counties, is required to consider the effects of land-use decisions on air quality. The BAAPCD has little potential need for geologic information, but the RWQCB can use such information to help determine the effect of proposed projects on water quality.

SINGLE-PURPOSE PLANNING OPERATING DISTRICTS

A number of agencies typically are given taxing powers and the responsibility to plan, develop, construct, operate, and maintain particular facilities or services. Bay Area Rapid Transit District, East Bay Regional Park District, Golden Gate Bridge Highway and Transportation District, and East Bay Municipal Utility District are examples of such agencies. These agencies use geologic information primarily in locating and designing regional facilities.

INTERGOVERNMENTAL RELATIONS

The diffusion of planning responsibility and regulatory powers among so many regional agencies works against development of a coordinated, comprehensive approach to the solution of regional land-use and environmental problems. This diffusion is compounded by the authority and responsibility lodged with governmental agencies at the other jurisdictional levels. The operations of regional agencies affect and are affected by the planning and decisionmaking of government agencies at Federal, State, and local levels.

Federal and State agencies often preempt or limit regional decisionmaking by imposing requirements for funds, criteria for programs, shared responsibility for specific functions such as transportation, and regulations concerning, for example, environmental quality or the content of local plans.

Regional and, to an increasing extent, local governmental agencies are highly dependent on Federal and State funds to carry out their responsibilities. This means that plans and programs developed at the regional and local level are often framed with an eye not only to locally expressed objectives and concerns but also to Federal and State program-funding requirements. Thus, individual governmental decisions become part of the network of decisions made by other agencies at different jurisdictional levels over a period of time.

Land-use decisions are made within this context of complex inter-governmental relations. The effective use of geologic information in planning by the various regional agencies often depends on complementary decisions of other regional, Federal, State and local agencies. All the regional agencies described above engage in, or have some impact on, land-use planning and decisionmaking. Many make use of geologic information in developing plans, establishing criteria, reviewing projects, locating and designing facilities, or enforcing regulations. The information on the geologic characteristics, problems, and potentials of flatland areas presented in this report can assist these regional agencies to plan and act with greater awareness of the physical environment.

REGIONAL SETTING

GEOGRAPHIC SETTING

The San Francisco Bay region lies between lat 36° and 39° N. and extends across the lowest and narrowest segment of the Coast Ranges in central California and into the west edge of the Great Valley of California (fig. 4). This region covers an area of 7,461 square miles (19,320 km²) consisting of northwest trending mountain ranges, broad basins, and narrow valleys generally paralleling major geologic structures and the coastline of central California.

About 65 percent (4,920 mi², 12,740 km²) consists of rounded hills and rugged mountain uplands with many ridge crests rising above 1,000 feet (300 m) and a few peaks rising above 4,000 feet (1200 m) (fig. 5). Almost 11 percent (784 mi², 2,030 km²) consists of the open water and tidal marshlands of the bay itself that lie at or close to sea level. The remaining 24 percent (1,757 mi², 4,550 km²) consists of the relatively flat lowland areas (generally less than 200 feet (60 m) above sea level) that constitute the broad alluvial plain surrounding the bay, the broad to narrow valley bottoms extending from the bay plain into the surrounding hills, and the narrow elevated marine terraces cut into the mountains along the Pacific Coast.

CLIMATE

The San Francisco Bay region has a mediterranean climate with mild wet winters and warm dry summers (fig. 6). This type of climate is common on western continental coasts between lat 30° and 50° N. where coastal ocean currents moderate the effects of seasonal changes in temperature.

The climate along the coast is marked by moderate and even temperatures, heavy persistent summer fog, and winds from the west-northwest. In contrast, inland areas have a wider range of temperature and have less wind. Temperatures are influenced by elevation and local topography. Higher summer temperatures and lower winter temperatures occur in low areas isolated by mountainous terrain. This kind of climate is also true of areas far distant from the bay and its temperature-moderating waters. Precipi-

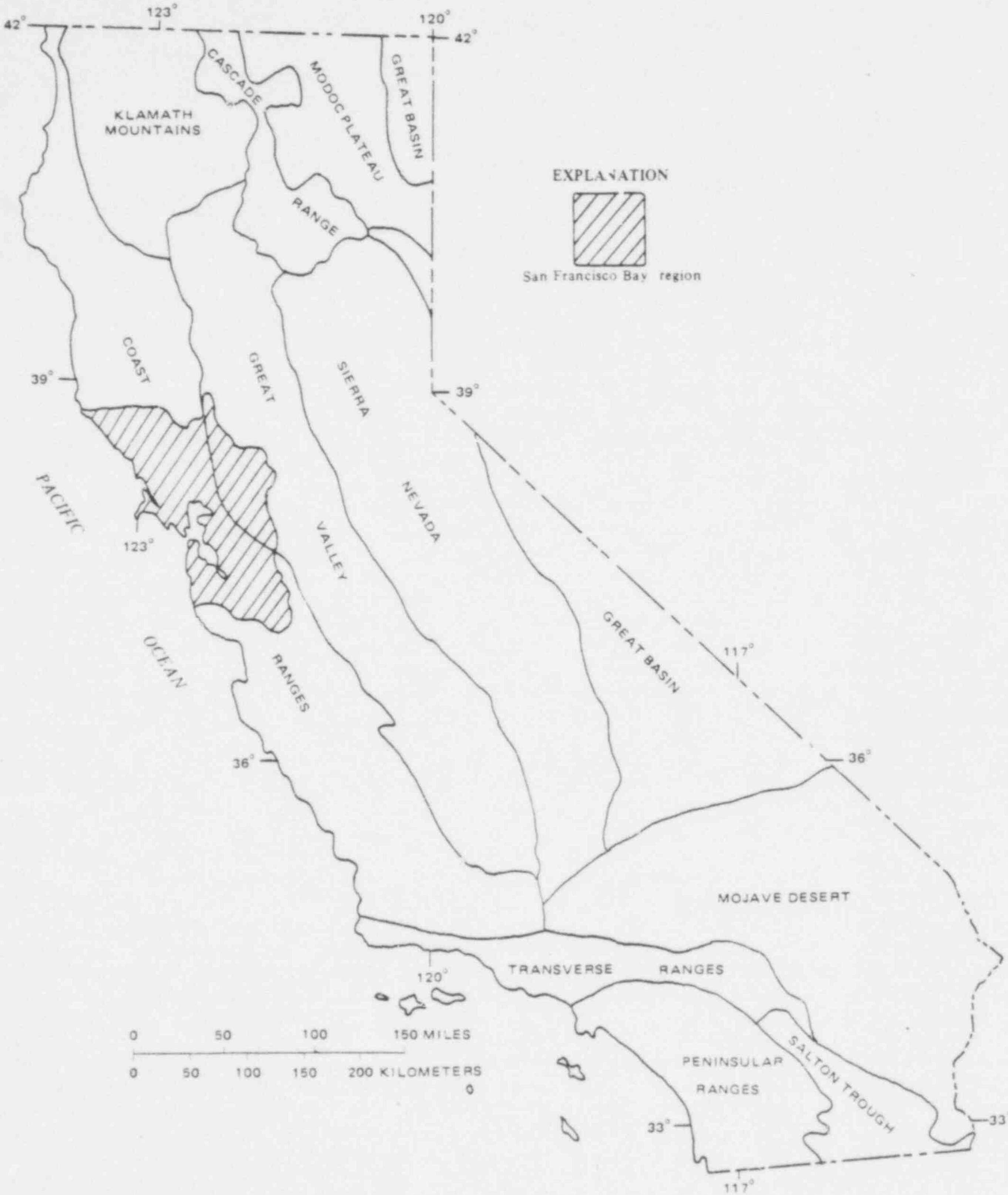

FIGURE 4.—Physiographic provinces of California and location of San Francisco Bay region (California Division of Mines and Geology, 1966, p. 17).

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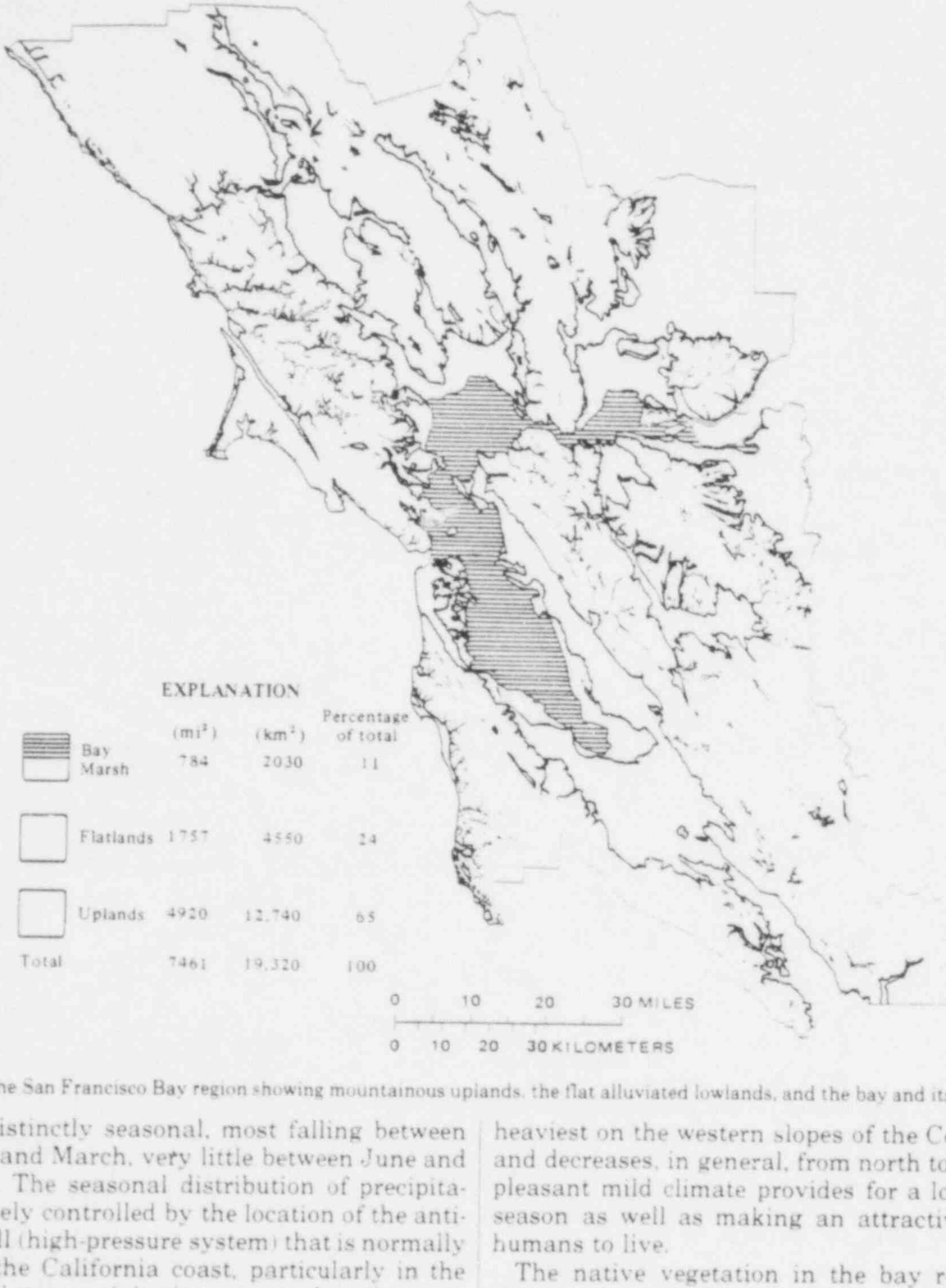

FIGURE 5.—The San Francisco Bay region showing mountainous uplands, the flat alluviated lowlands, and the bay and its tidal marshes.

tation is distinctly seasonal, most falling between November and March, very little between June and September. The seasonal distribution of precipitation is largely controlled by the location of the anticyclonic cell (high-pressure system) that is normally found off the California coast, particularly in the summer. Winter precipitation occurs when this anticyclone is absent or far south of its normal position, which blocks storm systems from the Gulf of Alaska. Almost all precipitation is in the form of rain and what little snow falls usually soon melts.

Average annual precipitation ranges from 10-20 inches (25-50 cm) in the dry interior valleys to 40-60 inches (100-150 cm) and locally to 80 inches (200 cm) in the high coastal mountains (fig. 7). Precipitation is heaviest on the western slopes of the Coast Ranges and decreases, in general, from north to south. This pleasant mild climate provides for a long growing season as well as making an attractive place for humans to live.

The native vegetation in the bay region north through Sonoma County and south through Santa Clara County is dominated by plants adapted to mild climatic conditions including a summer drought. The bay area is actually a meeting ground for many plant species from the north Pacific Coast that reach their southern limit in the bay region and other plants from southern California that reach their northern limit here. The native plants evolved here in their own ecological niches, which we refer to as biotic

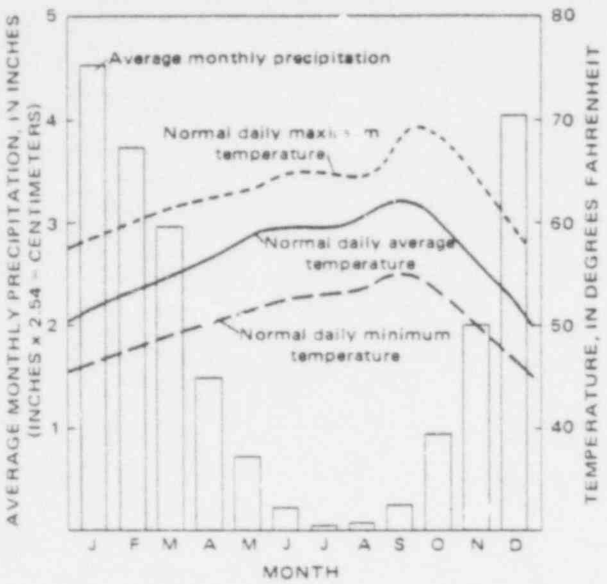

FIGURE 6.—Annual temperature and precipitation variations in San Francisco.

communities. These plant communities are bay and salt marsh, freshwater marsh, the open coast, chaparral, grasslands, broad-leaved forest, and coniferous forest. The flatland deposits underlie almost all but the last two communities. However, the broad-leaved and coniferous forests do cover stream terrace deposits in the outer valleys. The native plant communities are summarized below from Metcalf (1959) and Smith (1968).

Community	*Characteristic vegetation*
Bay and salt marsh	Salt grass (*Distichilis spicata*)
	Cordgrass (*Spartina foliosa*)
	Pickle-weed (*Salicornia, spp.*)
	Marsh rosemary (*Limonium commune*)
	Marsh Grindelia (*Grindelia cuneifolia*)
	Sea bite (*Suaeda californica*)
Freshwater marsh	Common tule (*Scirpus acutus, S. robustus,* and *S. communis*)
	California bulrush (*Scirpus californicus*)
	Cat-tail (*Typha latifolia*)
	Sedge (*Carex senta*)
Open coast	Surf grass (*Phyllospadix torreyi* and *P. scouleri*)
	Tree lupine (*Lupinus arboreus*)
	Sea rocket (*Cakile edentula*)
	Blue grass (*Poa douglasi*)
	Sand verbena (*Abronia sp.*)
	Beach grass (*Ammonphila arendria*)
Chaparral	Chamise (*Adenostoma fasciculatum*)
	Scrub oak (*Quercus dumosa*)
	Buckbrush (*Ceanothus cuneatus*)
	Coffee berry (*Rhamnus californica*)
	Leather oak (*Quercus durata*)
	Interior live oak (*Quercus wislizeni*)
	Coast live oak (*Quercus agrifolia*)
	Manzanita (*Arctostaphylos canescens*)
	Wild lilac (*Ceanothus sp.*)
Grasslands	Blue bunch grass (*Festuca idahoensis*)
	California oat grass (*Danthonia californica*)
	Foothill sedge (*Carex tumulicola*)
	Soft chess (*Bromus hordeaceus*)
	Red brome (*Bromus rubens*)
	Wild oats (*Avena fatua*)
	Coyote bush (*Baccharis pilularis*)
	Coast live oak (*Quercus agrifolia*)
	California buckeye (*Aesculus californica*)
	California laurel (*Umbellularia californica*)

Before discussing the broadleaf and coniferous communities, it is worth noting that the native trees of the bay area can be divided into three groups primarily on the basis of their leaf characteristics. These are the conifers, broadleaf evergreens, and broadleaf deciduous trees. Conifers are cone-bearing evergreen trees distinguished by their simple needle-like or scalelike leaves. Broadleaf evergreens are those trees that keep all or most of their leaves, usually leathery, throughout the year. Broadleaf deciduous trees are those that lose their leaves in winter. Their leaves are usually thinner and less leathery than the broadleaf evergreen (Williams and Monroe, 1967).

Community	*Characteristic vegetation*
Broadleaf forest	Sycamore (*Platanus racemosa*)
Riparian woodlands	Willow (*Salix sp.*)
	Bigleaf Maple (*Acer macrophyllum*)

Community	*Characteristic vegetation*
Riparian woodlands—Continued	Oregon ash (*Fraximus latifolia*)
	California buckeye (*Aesculus californica*)
	California laurel (*Umbellularia californ.ca*)
Ripirian woodlands—Continued	Creek dogwood (*Cornus californica*)
	Poison oak (*Rhus diversiloba*)
	Hoary nettle (*Urtica holosericar*)

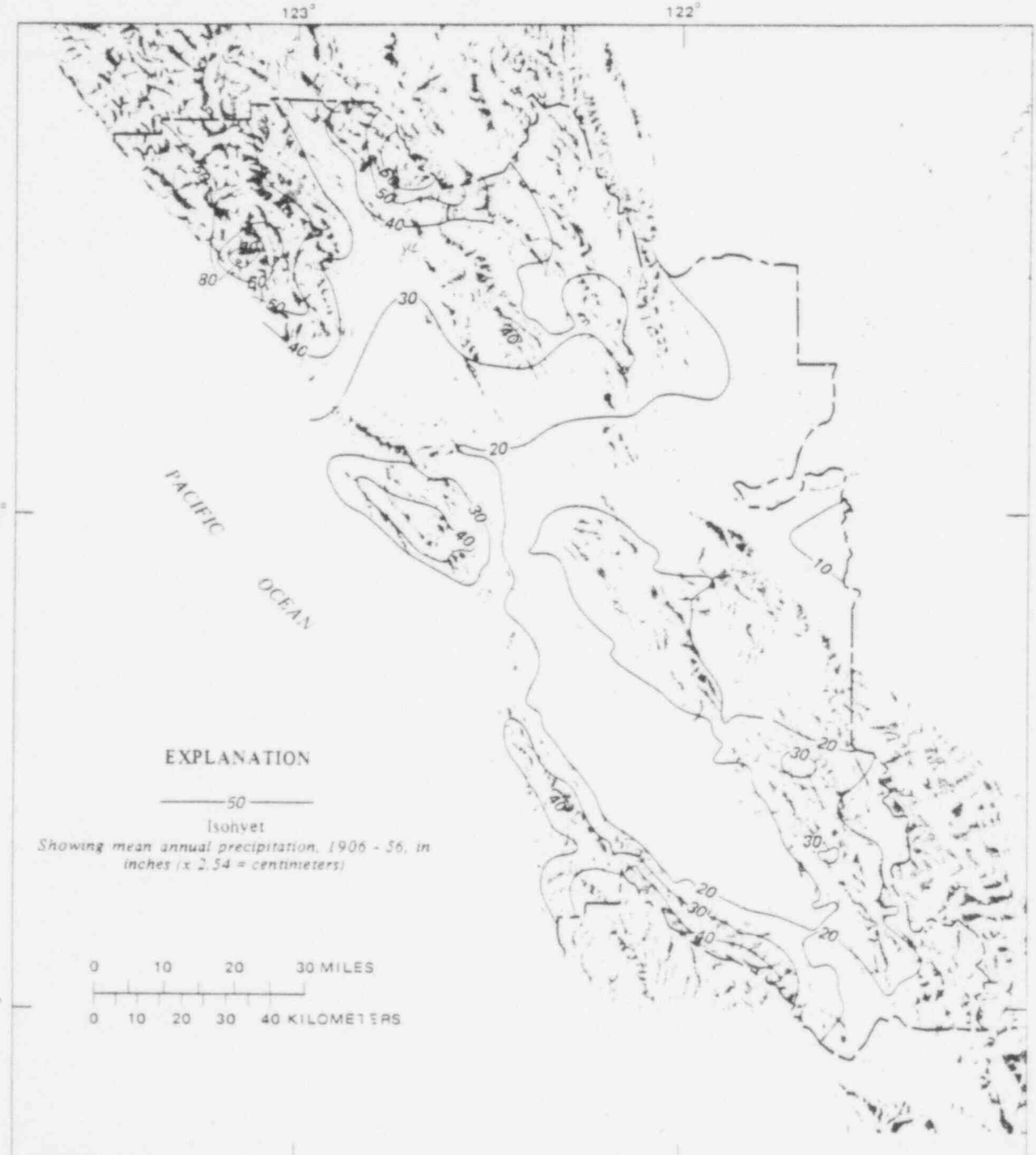

FIGURE 7.—Precipitation distribution in San Francisco Bay region. After Rantz (1971).

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Community	Characteristic vegetation
Oak woodlands	Live cak (*Quercus agrifolia*)
	California buckeye (*Aesculus californica*)
	California laurel (*Umbellularia californica*)
	Black oak (*Quercus kelloggi*)
	Blue oak (*Quercus douglasi*)
	Oregon oak (*Quercus garryana*)
	Interior live oak (*Quercus wislizeni*)
	Madrone (*Arbutus menziesii*)
	Poison oak (*Rhus diversiloba*)
	Manzanita (*Arctostaphylos* sp.)
	Coyote bush (*Baccharis pilularis*)
	Chamise (*Adenostoma fasciculatum*)
	Lupines (*Lupinus* sp.)
Coniferous forest	Coast redwood (*Sequoia sempervirens*)
	Douglas fir (*Pseudotsuga menziesii*)
	Monterey cypress (*Cupressus macrocarpa*)
	Monterey pine (*Pinus radiata*)
	Knobcone pine (*Pinus attenuata*)
	Bishop pine (*Pinus muricata*)
	Wax myrtle (*Myrica californica*)
	Redwood sorrel (*Oxalis oregona*)
	Ponderosa pine (*Pinus ponderosa*)
	Thimble berry (*Rubus parviflora*)
	California sword fern (*Polystichum munitum*)
	Firs (*Abies* sp.)
	Spruce (*Picea* sp.)
	Western yew (*Taxus brevifolia*)
	Incense cedar (*Libocedrus decurrens*)

The mild climatic conditions result in relatively moderate rock-weathering and erosional conditions which give a characteristic rounded aspect to much of the upland landscape. Weathered rock material is not removed rapidly from the hilly uplands, so bedrock outcrops are few and decomposed rock debris mantles most hillslopes. Soil creep caused largely by seasonal shrinking and swelling of expansive clays in the mantle of weathered rock debris is a dominant erosional process that tends to form smooth, rounded hills. Landsliding, induced in large measure by heavy winter rains, is another dominant erosional process and commonly forms steep, irregular slopes on exposed hillsides and in deep narrow canyons. The weathered rock debris that accumulates in gulley and canyon bottoms is eroded and transported to the alluvial lowlands mainly by winter floods. In the recent geologic past, when climatic conditions were cooler and moister, the rates and relative importance of various weathering and erosional processes were probably slightly different from those of today.

The moderate and stable climatic conditions result in more than 300 agricultural growing days per year over much of the area, but the summer drought prevents summer crop cultivation without irrigation. Local ground-water supplies are usually insufficient for intensive irrigation, so water impoundments and imports are necessary for summer cultivation.

The total agricultural, domestic, and industrial demands for water are far greater than local supplies. Consequently, water imports, primarily from the Sierra Nevada, are necessary for immediate use and recharge of ground-water aquifers in much of the region.

DRAINAGE

The Sacramento and San Joaquin Rivers, which drain most of the Great Valley of interior California (about 27 percent of the state), coalesce in a broad marshy delta east of the bay region and empty into the Pacific Ocean through Suisun Bay, San Pablo Bay, and the Golden Gate (fig. 8). Almost all the fresh water entering the estuary is derived from this interior drainage area, which is about 50 times larger than the local drainage area emptying directly into the San Francisco Bay estuary (McCulloch and others, 1970).

The San Francisco Bay region itself is drained by a network of ephemeral streams and small rivers (fig. 9). Only the broad valleys in the central 50 percent of the region drain directly into the bay. About 25 percent of the region drains northward and westward into the Pacific Ocean, 20 percent drains eastward into the Great Valley, then into the bay through the delta, and the remaining 5 percent drains southward into Monterey Bay.

The streams that drain these basins transport weathered rock debris from the upland areas to the lowlands where it is deposited to form flat alluvial plains and estuarine mudflats. The two large rivers draining the Great Valley bring debris into the bay region from as far away as the Sierra Nevada and Klamath Mountains (fig. 3). Most of the coarse gravel and sand carried by these rivers is deposited in the Great Valley. (Gilbert, 1917) Much of the fine-grained silt and clay carried in suspension is transported into San Pablo Bay, into San Francisco Bay, and even directly into the Pacific Ocean through the Golden Gate. Estuarine currents produced by tidal action distribute this debris throughout the bay and into southern San Francisco Bay where it settles to the bottom during slack water periods and forms the fine-grained, water-saturated deposit called "bay mud."

FIGURE 8.—Area of interior California that drains through San Francisco Bay.

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Most of the debris forming the sedimentary deposits, particularly the alluvial deposits, is derived locally, however, and is transported only short distances from the upland to immediately adjacent lowlands. These sediments generally consist of broken rock debris (gravel, sand, silt, and clay) eroded, transported, and deposited by streams to form alluvial fans on broad lowlands and stream terraces in narrow valleys. The mineralogic and lithologic composition of these sediments is variable and is governed by the composition of the rocks exposed in source areas, weathering and depositional processes, and post-depositional alteration. Much of the alluvial material in the narrow valleys and on the upper part of alluvial fans is merely in temporary residence, however, and will be eventually reworked, broken down, and transported to lower elevations where it will become a permanent part of the thick sedimentary deposits filling the slowly subsiding basins.

GEOLOGY AND ENGINEERING PROPERTIES OF THE FLATLAND DEPOSITS

By Edward J. Helley and Kenneth R. Lajoie

GEOLOGIC HISTORY

The known geologic history of the San Francisco Bay region is only about one-fortieth as long as the

Figure 9.—Major drainage divides and basins, San Francisco Bay region.

earth as a whole. The oldest known rocks on earth are about 3.8 billion years old, whereas the oldest exposed in the bay region are only 100 million years old. In turn, the oldest deposits considered in detail in this report are only about one-half million years old, and the geologic history we consider in detail is less than one two-hundreth that of the bay region as a whole. The youngest deposits are still forming today. Therefore, the geologic materials exposed at the surface in the flat lowland region, though formed of debris eroded from much older rocks in the surrounding uplands, are extremely young in geologic terms and most of the geologic processes that formed them are still active today and are of concern in land-use planning.

Figure 10 gives a perspective of geologic time from the origin of the earth to the present. Figure 11 shows the types of rocks that occur in the bay region together with their geologic age.

The following paragraphs are a brief summary of the history and character of the older bedrock formations of the bay region from which the deposits that concern us were derived. The history we infer for the oldest of these deposits depends largely on modern concepts of sea-floor spreading and plate tectonics. For a more complete review of plate tectonics, see Oxburgh, 1974.

Between 100 and 65 million years ago, during the closing phases of the Mesozoic Era, great quantities of basaltic lava flows, red siliceous ooze, and muddy sand and mud accumulated in irregularly interbedded layers on an ocean floor west of what is now California. During this same time, an equally large quantity of mud, sand, and gravel accumulated in regular beds on the floor of a deep trench along what was then the margin of the North American Continent and is now the site of the Great Valley and eastern Coast Ranges. The ocean-floor sequence was lithified to hard sandstone, chert, and greenstone (metamorphosed basalt), partly crushed, and thoroughly mixed as the sea-floor on which it rested was dragged beneath the edge of the continent by subduction. This sequence is now known as the Franciscan Formation. The regularly bedded sequence on top of the surface of underthrusting was not so intensely disturbed, although it too was lithified to relatively hard sandstone, shale, and conglomerate. These rocks are now known as the Great Valley sequence. At the time of underthrusting, masses of gabbro and rock that later formed serpentine, originally parts of the Earth's mantle and lower crust, were incorporated into the Franciscan Formation and along the base of the Great Valley sequence. East of the San Andreas fault these rocks now make up most of the high mountains and uplands and underlie all other deposits at depth.

Granitic rocks, which solidified from molten magma about 90 million years ago in the area now occupied by southern California, were subsequently moved northwestward along the San Andreas fault to a position opposite San Francisco Bay. They now underlie at depth all land areas and the continental shelf west of the fault and are exposed at the surface on Montara Mountain, on the Point Reyes peninsula, the Farallon Islands, and Bodega Head.

During most of the Cenozoic Era (the last 65 million years), the crustal blocks that are now the San Francisco Bay region appear to have been divided into smaller sinking areas, that formed basins and embayments, interspersed with areas of uplift that formed highland areas. Sand, clay, and gravel eroded from the highlands or brought in from the east were deposited beneath the sea or on alluvial plains above sea level in the subsided basins and were interbedded with accumulations of diatom ooze and locally of volcanic rocks. The positions of basins and uplifts shifted from time to time, and areas that had been basins of accumulation were uplifted and vice versa. During periods of crustal movement, the sedimentary accumulations were lithified into sandstone, shale, conglomerate, and chert and were tilted, folded, and faulted. In general, they did not become as hard as the Mesozoic rocks, the younger rocks are less deformed and less lithified than the older rocks.

When a former basin of accumulation was uplifted to form a highland, its Cenozoic cover was eroded (in part, at least) to fill nearby newly formed basins, and the Mesozoic basement was re-exposed. Remnants of the Cenozoic rocks are found today mainly beneath the floors of existing basins, but they also make up two important highlands of the bay region, the Santa Cruz Mountains west of the San Andreas fault, and the Berkeley Hills-Mt. Diablo area.

Volcanic rocks are found in the Santa Cruz Mountains and Berkeley Hills and make up several mountain ranges north of San Pablo Bay in Sonoma, Napa, and Solano Counties.

The alternation of highland and basin is still going on, for the Berkeley Hills was a lowland as recently as 6 million years ago, and is now a major highland, and the San Francisco Bay valley, which was probably a highland at that time, is apparently now slowly subsiding.

The geography of the bay region was significantly different 2-3 million years ago from what it is today; for example, Mt. Diablo and the Carquinez Straits did not exist (Sarna-Wojcicki, 1971). The bay as we know it did not exist, and the interior of California probably did not drain to the Pacific Ocean through this region until about 1 million years ago. Geologic evidence throughout coastal California indicates that the terrane west of the San Andreas fault has been moving northwestward relative to the terrane east of the fault at a rate of about 1-2 inches (2.5-5.0 cm) per year for the past several million years as a result of displacement along the fault. Therefore, the Point Reyes peninsula probably lay south of the present Golden Gate within the past several million years and actually may have blocked it within the past 1-3 million years. Throughout this time the ancestral bay basin was subsiding and filling with sediments that today are highly folded and faulted (Hall, 1966). These partly indurated sediments are now exposed only in discontinuous outcrops around the margins of the lowland basins (fig. 11). During this time the bay, when it existed, was connected with the ocean through passages far different from the present Golden Gate.

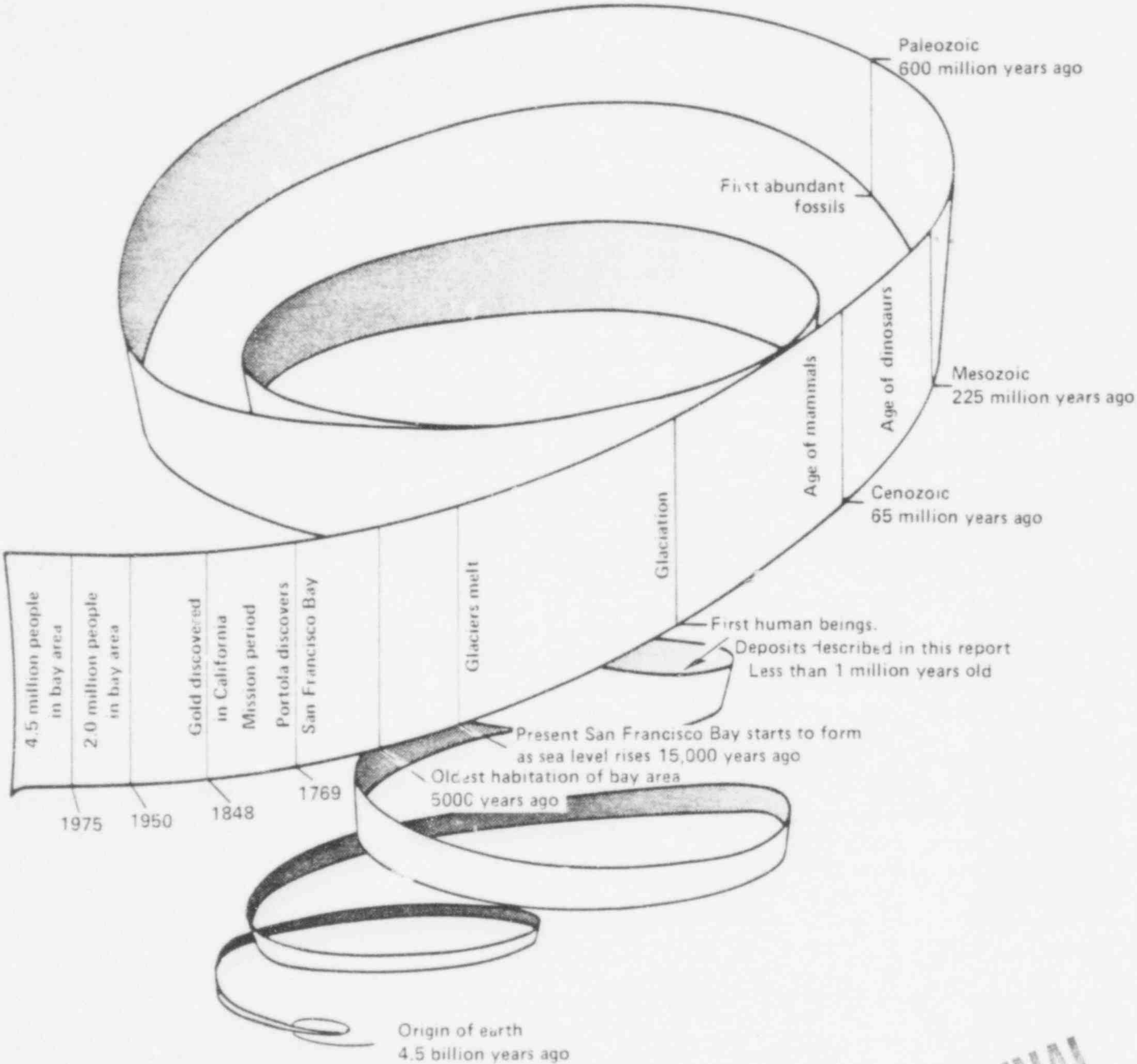

FIGURE 10.—Geologic time in perspective.

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In addition to tectonic effects, major changes in sea level caused by worldwide climatic fluctuations over the past million years or so have left their geologic imprint on the bay region. When the climate was colder than it is today, sea level was lower because large volumes of ocean water were stored on the continents in glaciers. During these periods there was no bay and the ocean shoreline was located as far west as the Farallon Islands. When the climate was relatively warm, as it is today, sea level was close to its present position because the glaciers partially melted and the water they contained returned to the

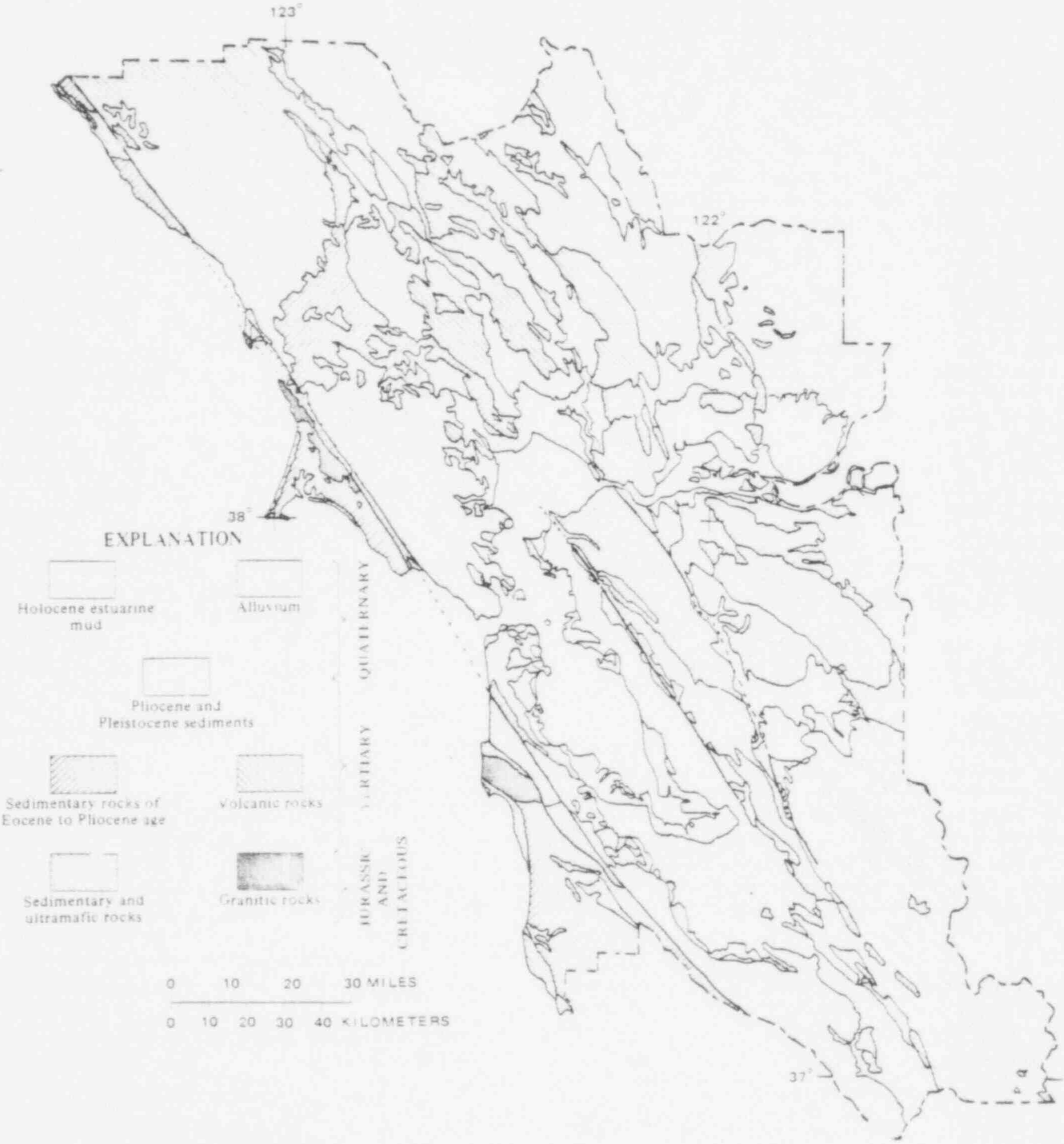

FIGURE 11.—Generalized geologic map of San Francisco Bay region. Modified from Schlocker, 1971.

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oceans. During warm periods, the bay basin was partially flooded, as it is today, and the ocean shoreline was located approximately in its present position. During each of these major sea-level highstands, estuarine sediments were deposited in the bay and wave erosion cut a nearly flat marine terrace into the coastal mountains. A vertical succession of as many as six of these terraces capped by a thin veneer of marine sediments occurs along the coast indicating general uplift of the coastal mountains 400-600 feet (120-180 m) during the past ½-1 million years. The youngest marine terrace, which is the lowest and usually the best preserved, probably formed during the last major highstand of sea level between 120,000 and 70,000 years ago. Uplift and deformation of these marine terraces by faulting and folding clearly record the tecton ctivity that has affected the coastal region in the fairly recent geologic past. The deformation was quite irregular—s e areas were uplifted and others depressed.

During the last Pleistocene glacial advances between about 70,000 and 10,000 years ago, sea level stood as much as 300-400 feet (90-120 m) below its present elevation (fig. 12). The streams presently draining into the bay were merely tributaries of a large river flowing through the bay region from the Great Valley and across the broad coastal plain between the narrow canyon that is now the Golden Gate and the Farallon Islands. Camels, bison, mammoths, sloths, and horses roamed the broad inland valleys whose nearly flat floors, now partly occupied by the bay, were covered by fresh-water marshes and open coniferous woodlands consisting mainly of Douglas-fir (*Pseudostuga menziesii*) and incense-cedar (*Libocedrus decurrens*), two species tolerant of cooler climates.

Because the coastline lay so much farther west, it is reasonable to believe that Sequoia were not abundant, for today they are found only within 30 miles (49 km) of the coastal fog belt. Perhaps the lack of oak is indicative of a wetter climate, at least one without a summer drought.

About 15,000 years ago, sea level began to rise as glaciers in the northern latitudes began to melt. Subsequent changes in sea level in the San Francisco Bay area are recorded by tidal-marsh deposits located at the base of Holocene estuarine sediments. These marsh sediments accumulated near sea level when it was lower than today, so their radiocarbon ages closely approximate the ages of sea levels in the past. The local record of Holocene sea-level changes indicates that the rising sea entered the Golden Gate 10,000-11,000 years ago. The newly formed bay then spread across land areas as rapidly as 100 feet (30 m) per year; it reached the vicinity of the Dumbarton Bridge about 8,000 years ago. Subsequent shoreline changes have been more gradual because of a decrease in the rate of sea-level rise since about 5,000-6,000 years ago. The ocean reached its present level at about this time and so should have San Francisco Bay (fig. 12). However, the active tectonic nature of the bay region strongly suggests that the bay waters are still expanding, especially in the southern part of the bay. As sea level rose throughout this interval, the base levels of the streams in the bay region were raised slightly, the younger alluvial sediments were deposited on the flood plains around the growing bay, and the younger bay mud was deposited beneath the rising water. All these younger deposits exposed on the alluvial apron around the bay plain and the extensive valleys of the region are less than 5,000 years old. These deposits are also found buried beneath the transgressive bay muds, and here they are older but still less than 9,300 years old.

In most areas along the coast, the post-Pleistocene rise in sea level inundated the lower parts of the deeply incised valleys of the large coastal streams and caused them partially to fill with sediment. The lower course of the Russian River is a fine example.

The bedrock of the Russian River valley lies at least 125 feet (38 m) below sea level near the river mouth and at least 80 feet (24 m) below sea level near Guerneville, about 12 miles (19 km) upstream (Higgins, 1952).

The modern depositional processes operating on the lowlands are mainly the result of the region's mediterranean climate and active tectonic setting. The interaction between easily eroded bedrock and the heavy winter rains causes large seasonal fluctuations in the sediment loads carried by streams from the uplands down to the bay. During times of high surface-water runoff, sediments are supplied from slopewash, landslides, and gullying, then carried by shifting alluvial channels to the marshlands and bay. Some material is deposited on the alluvial plain, especially when streams overtop their banks and spread their sediment-laden waters over the low plains and basins. The finest grained sediment reaches the bay and is moved by tidal currents and waves. It may be deposited as fine estuarine mud or be eroded and transported out of the bay through the Golden Gate. The modern depositional and erosional processes operating along the bay are summarized in figure 13.

Along the coast, the depositional and erosional processes are controlled less by the climate than by wind and wave action. Sediment is supplied to the coastline by streams and rivers but much is also derived by erosion of sea cliffs. Littoral drift moves the sediment along the coast where some is lost to deeper water, some is blown off the beaches to form dunes, and the rest remains as beach material. Just as with the sediments on the alluvial plain surrounding San Francisco Bay, the finer grained sediments like clay and silt are carried farther from their source. When sediment ceases to be supplied to the coast, the supply of sand for beach material decreases, but the

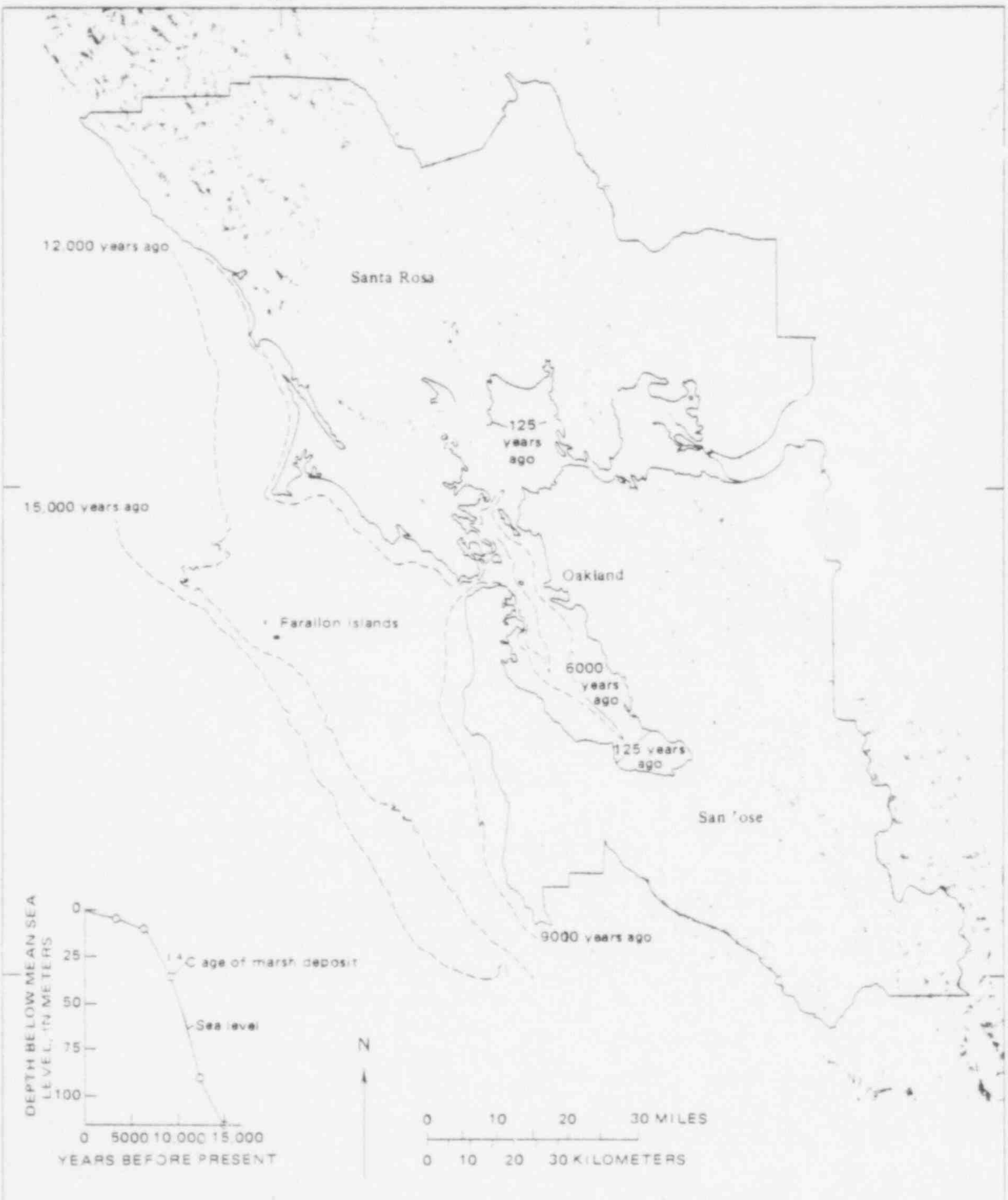

FIGURE 12.—Shorelines of San Francisco Bay and Pacific Ocean during Holocene transgression.

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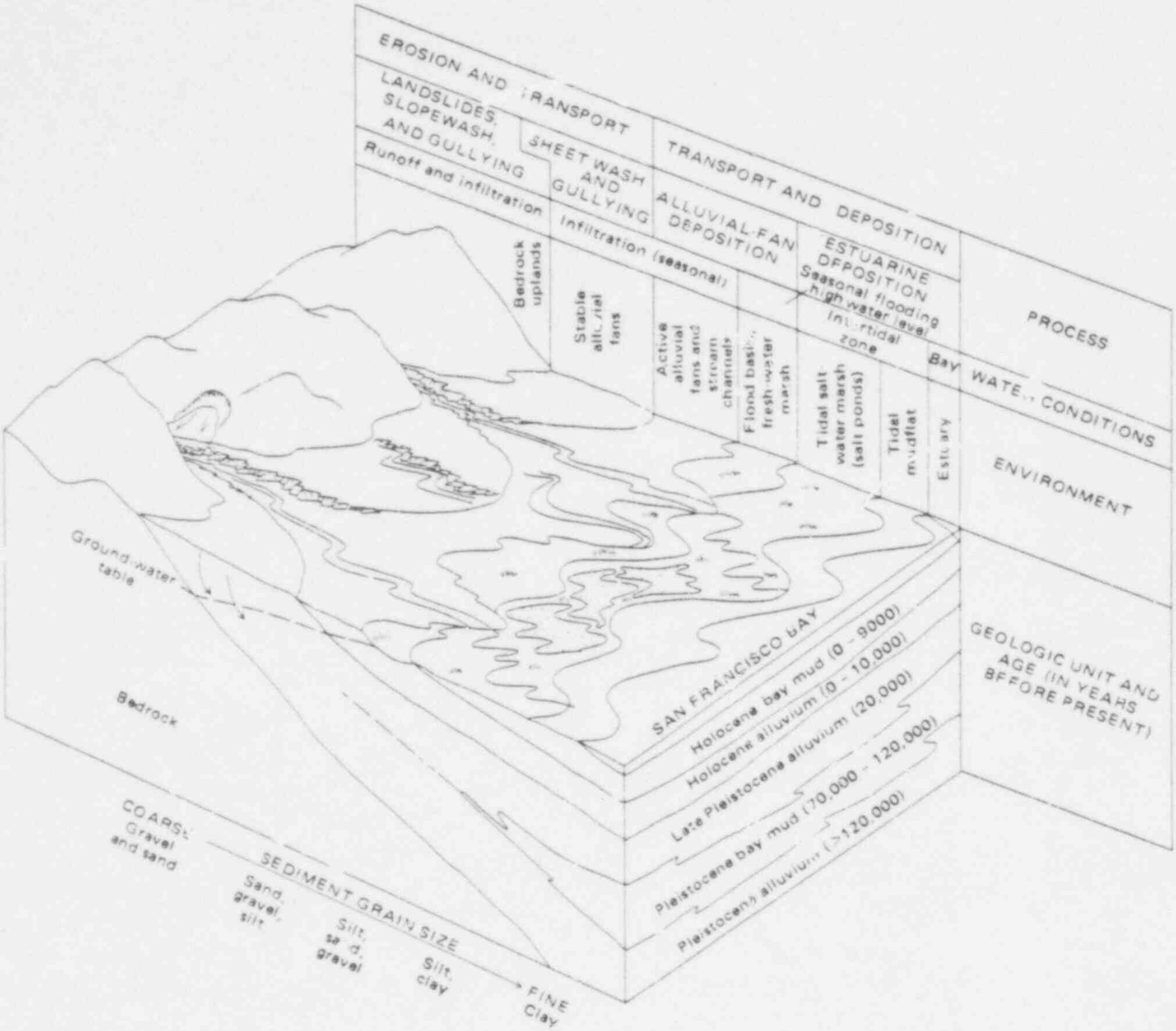

FIGURE 13.—Diagram of modern depositional and erosional processes along the bay plains.

littoral drift and wind erosion continue, and the beaches can disappear. During winter months most beaches are smallest, and bedrock may be exposed where strong wave action during storms has removed the sand. The reverse is true during summer months when most beaches are largest. A summary of coastal processes is shown in figure 14.

GEOLOGIC MAP OF FLATLAND AREAS

The map units that appear on plates 1, 2, and 3 are described according to geologic age from oldest to youngest. Most of the information used for establishing an absolute chronology and for correlating sedimentary deposits in the bay region was obtained from published and unpublished geologic, archeologic, and engineering reports. These diverse and readily available sources provided the data for constructing an initial working model and determined where subsequent dating information was needed. Many of the samples dated specifically for this study were obtained from the numerous drill cores collected as much as 25 years ago for engineering foundation studies of various proposed or existing trans-bay bridges. Extensive use of radiocarbon dating was made when appropriate sample material was already available or was discovered during the course of fieldwork.

In addition to each map unit listed by age the following geologic characteristics are discussed: physical description and lithology, thickness, age, distribution and stratigraphy, origin of deposit, and

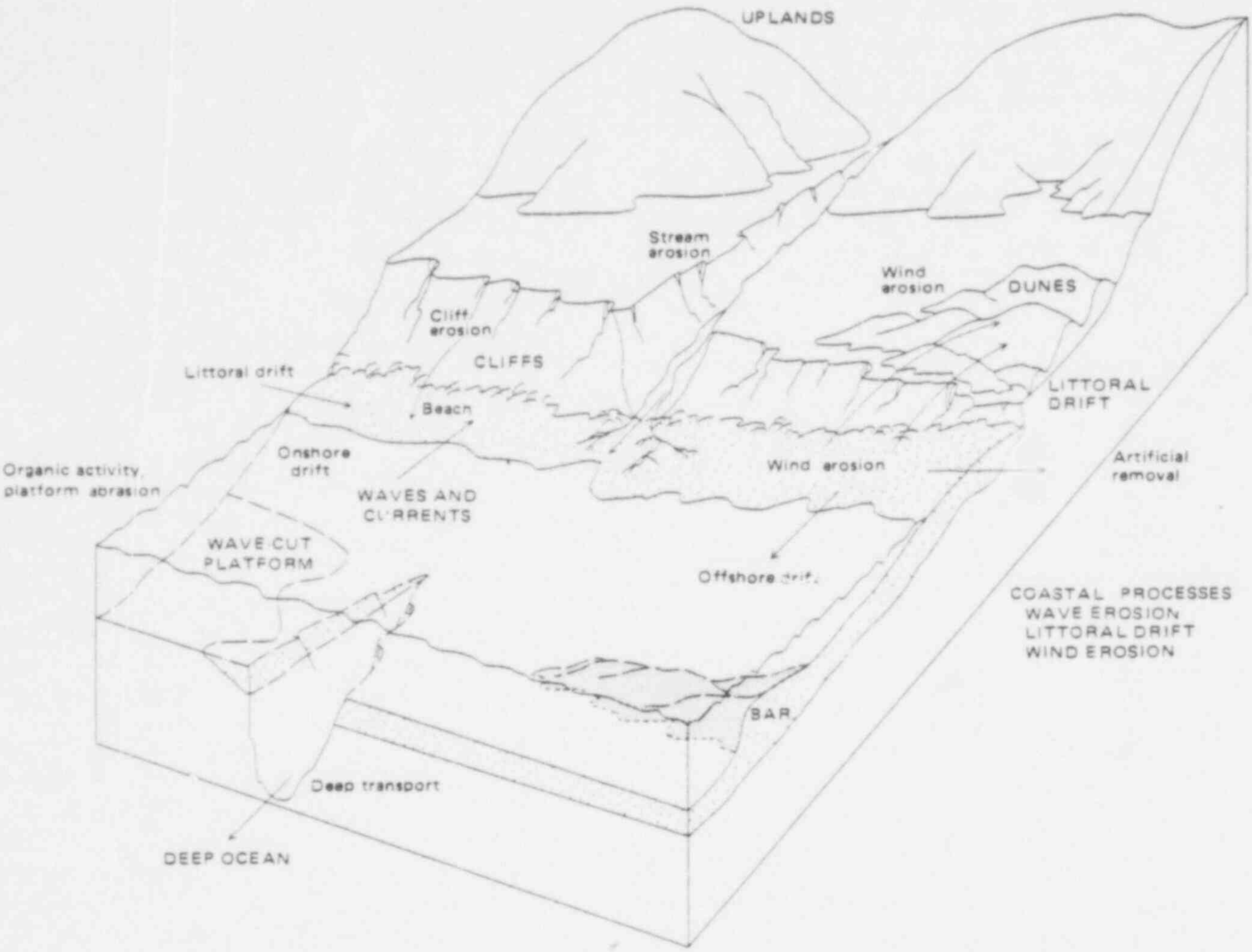

FIGURE 14.—Summary of coastal processes.

topographic form and relation to modern drainage. Since the amount of information known about each characteristic varies widely, some units can be described in much greater detail than others. The data are tabulated here for convenience.

HOLOCENE DEPOSITS (LESS THAN 10,000 YEARS OLD)

Estuarine deposits, Bay mud (Qhbm)

Physical description and lithology

Unconsolidated, water-saturated, dark, plastic clay and silty clay rich in organic material. Locally contains lenses and stringers of well-sorted silt and sand as well as beds of peat.

Locally contains fresh- and brackish-water gastropod and pelecypod shells and beds of peat.

See Pestrong (1972) for more detailed information on composition and physical properties of bay mud.

Thickness much as 120 feet (37 m) beneath the bay. Thins to less than 1 foot (0.3 m) around the margins of the bay. Probably less than 10 feet (3 m) thick in small coastal lagoons and estuaries.

Age

Presently forming. Oldest dated deposits in bay basin, 9,600 years old (Atwater and others, 1976).

Locally contain Holocene molluscan fossils. Upper part contains molluscan species introduced by man in past 100 years.

Distribution and stratigraphy

Underlies the waters of San Francisco Bay and small coastal lagoons and estuaries. Found generally below 8 feet (2.5 m) above mean sea level. Interfingers with Holocene alluvial deposits along the margins of the bay and in the lowest parts of broad valleys along the Pacific Coast and also overlies undifferentiated young alluvial deposits and older alluvium. Forms flat marshlands with low levees adjacent to tidal sloughs and gently sloping mudflats exposed only during low tides. Much of the area of exposure shown is used as salt-water evaporating ponds and much is covered by a thin veneer of artificial fill. See Nichols and Wright (1971) for more detailed information on distribution of young bay mud.

Origin of deposit

Between mean sea level and high tide line (+8 ft, 2.5 m). Deposited primarily in brackish- to salt-water marshes along the margins of the bay and in coastal lagoons. Below mean sea level deposited on tidally exposed mudflats and beneath the shallow waters of the bay.

Beach and dune sand deposits (Qhs)

Physical description and lithology

Loose well-sorted fine- to medium-grained sand. Includes some small deposits stabilized by vegetation. Mineral composition is variable and generally reflects local bedrock lithologies.

Locally may contain lenses of gravel or clay rich in organic material. Some dune deposits contain aboriginal artifacts and kitchen middens.

Thickness

The thickness of beach sand varies seasonally. Heavy surf strips sand from beaches and deposits it in shallow water offshore during the winter. Milder surf pushes the sand back onto the beaches during the summer. Dune sand thickness varies constantly but may locally exceed 25 feet (8 m).

Age

Presently forming. Large dune fields on Franklin Point, Año Nuevo Point, Point Reyes, Toms Point, and Bodega Head. Probably initially formed about 5,000 years ago when sea level attained its present elevation.

Distribution and statigraphy

Beach sand is found intermittently along the Pacific Coast close to sea level. The largest, most permanent deposits occur in sheltered coves and embankments such as Half Moon Bay, Bodega Bay, and Point Reyes peninsula. Dune sand occurs locally above beaches but is most extensive on headlands, such as Bodega Head, Point Reyes, Franklin Point, and Año Nuevo Point. Beach sand overlies bedrock except where it overlies marine terrace deposits. Dune sand generally overlies marine terrace deposits.

Origin of deposit

Beach sand is generally derived locally by wave abrasion of sea cliffs and by stream erosion in adjacent hills. Wave action winnows silt and clay from rock debris supplied to the beaches and leaves a residuum of clean, well-sorted sand. Dune sand is derived from beaches by the wind.

Human activity, such as damming streams and stabilizing sea cliffs and beaches, may have locally disrupted sand supply.

Topographic form and relation to modern drainage

Beach sand forms seasonally and changes configuration from broad, flat, gently sloping beaches to steep beaches with high berms. Dune sand forms low mounds in small deposits but forms parabolic dunes (U-shaped in the direction of the wind) and longitudinal dunes (linear ridges oriented parallel to the wind direction) in the large deposits at Point Reyes, Bodega Head, Franklin Point, and Año Nuevo Point.

Fine-grained alluvium (Qhaf)

Physical description and lithology

Unconsolidated, plastic, moderately to poorly sorted silt and clay rich in organic material. Seasonally saturated. Irregularly bedded.

Locally contains fresh-water gastropod and pelecypod shells, aboriginal artifacts, and skeletal remains.

Thickness

Generally less than 10 feet (3 m) thick.

Age

Presently forming where basins are not artificially drained or filled. Oldest deposits, along bay plain, are probably 5,000 to 7,000 years old.

Locally contains Holocene molluscan fossils.

Distribution and stratigraphy

Found in poorly drained, nearly horizontal basins between active and abandoned stream levees at the outer margins of alluvial fans adjacent to San Francisco Bay and in the lower parts of broad coastal valleys. Interfingers with and grades into coarser grained stream deposits toward higher elevations and with finer grained salt-water marsh deposits toward lower elevations. Overlies older alluvial fan and stream terrace deposits on the bay margin and bedrock along the coast.

Origin of deposit

Deposited from standing floodwaters that periodically inundate low interfluvial basin areas and locally form seasonal fresh-water marshes.

Presently being formed but depositional processes severely disrupted by modern cultural activity.

Topographic form and relation to modern drainage

Forms flat floodbasins between stream levees at or near sea level.

Presently being deposited by modern streams but recent cultural activity has disrupted formative processes.

Potential resources and uses

Agricultural soils developed on these deposits provide good to fair farming if well drained.

Potential geologic hazards and problems

Shrink-swell problems; periodic flooding; poorly drained, seasonal standing water due to high water table; potentially liquefiable where local shallow sand beds exist and are saturated.

Poor to fair foundation conditions because of the shrinking and swelling and poor drainage.

Low shear strength, high seasonal water content, and potentially liquefiable layers near the surface suggest strong ground-motion amplification during earthquakes and the possibility of ground failure.

Fine-grained salt-affected alluvium (Qhafs)

Physical description and lithology

Unconsolidated, plastic, moderately to poorly sorted, silt and clay rich in organic material. Seasonally saturated. Irregularly bedded; carbonate nodules and mottled weathering profile common.

Contains fresh-water gastropod and pelecypod shells; locally contains aboriginal artifacts and skeletal remains.

Thickness

Generally less than 10 feet (3 m).

Age

Presently forming where basins are not artificially drained or filled. Oldest deposits along bay margin, probably 5,000 to 7,000 years old.

Distribution and stratigraphy

Exposed along margins of south San Francisco Bay from latitudes of San Mateo and Hayward southward only. Interfingers with and grades into coarser grained stream deposits toward higher elevations and with finer grained salt-water marsh deposits toward lower elevations.

Origin of deposit

Similar to fine-grained alluvium.

Topographic form and relation to modern drainage

Similar to fine-grained alluvium.

Medium-grained alluvium (Qham)

Physical description and lithology

Unconsolidated, moderately sorted, moderately permeable fine sand, silt, and clayey silt with occasional thin beds of coarse sand. Well bedded.

Contains minor amounts of organic matter including fresh-water gastropod and pelecypod shells; locally contains aboriginal artifacts and skeletal remains.

Thickness

Thickness ranges from 0 to about 12 feet (4 m). Generally thickest in levees along streams and where deposits interfinger with and grade into coarse-grained younger alluvial fan deposits.

Distribution and stratigraphy

In some narrow canyons as valley fills and stream terraces. Interfingers with and grades into coarse-grained deposits along streams in broad valleys and on flood plains in broad valleys and on the outer edges of large alluvial fans on the broad alluvial plain marginal to San Francisco Bay. Interfingers with and grades into finer grai d

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basin deposits in the lower parts of broad coastal valleys and in the interfluvial basins adjacent to San Francisco Bay. Overlies bedrock in narrow valleys; overlies older alluvial fan deposits on the alluvial plain marginal to the bay and older alluvial fan deposits and marine terrace deposits on the lower marine terraces along the Pacific Coast.

Origin of deposit

Origin similar to younger alluvial fan deposits but deposited farther from source, therefore finer grained than coarse-grained alluvium. Local bedrock characteristics may control grain size in narrow canyons.

Age

Presently being formed but depositional processes disrupted severely by recent human activity.

Topographic form and relation to modern drainage

Forms flat flood plains in some narrow valleys. Forms active levees and flood plains in broad valleys and at the outer margins of large alluvial plain marginal to San Francisco Bay.

Presently being deposited by modern streams, but recent cultural activity has disrupted formative processes.

Coarse-grained alluvium (Qhac)

Physical description and lithology

Unconsolidated, moderately sorted, permeable sand and silt with coarse sand and gravel becoming abundant toward fan heads and in narrow canyons. Well bedded.

Locally contains aboriginal artifacts and skeletal remains.

Thickness

Thickness ranges from less than 10 feet (3 m) to as much as 50 feet (15 m). Thickest deposits in valley bottoms and at the heads of alluvial fans.

Age

Presently forming. Oldest deposits probably 5,000 to 7,000 years old

Distribution and stratigraphy

On active stream terraces and as valley fills in narrow canyons where it interfingers with and grades into colluvium along the walls and at the heads of the canyons. Found along streams in the lower parts of broad valleys and at the heads of alluvial fans where streams flow from narrow bedrock canyons onto alluvial plains marginal to the bay or onto low marine terraces along the Pacific Coast. Interfingers with and grades into medium-grained alluvium on flood plains, in broad valleys, and at the outer edges of alluvial fans. Overlies bedrock at fan heads and in valleys; overlies late Pleistocene alluvial fan deposits and the Colma Formation on the alluvial plain marginal to the bay; overlies late Pleistocene alluvium and marine terrace deposits on the lower marine terraces along the Pacific Coast.

Origin of deposit

Fragmented and transported material derived from bedrock uplands and older unconsolidated sediments deposited by flowing water on active stream levees and flood plains primarily during floods. When streams overflow their banks during floods, the coarsest debris is deposited close to stream channel to form natural levees. The factors that initiated the cycle of deposition represented by the younger sedimentary deposits are probably related to the climatic and base-level changes associated with the drastic rise in sea level between 15,000 and 5,000 years ago.

Depositional processes disrupted severely by recent human activity.

Topographic form and relation to modern drainage

Forms flat flood plains and terraces in narrow valleys. Forms well-drained levees and flat flood plains in broad valleys. Forms well-drained small alluvial fans where small streams flow from narrow bedrock valleys onto marine terraces. Forms well-drained stream levees and flat flood plains near the heads of large alluvial fans on the alluvial plain marginal to San Francisco Bay.

PLEISTOCENE DEPOSITS (1.8 MILLION–10,000 YEARS OLD)

Early Pleistocene alluvium (Qpea)

Physical description and lithology

Moderately consolidated, deeply weathered, poorly sorted, irregularly interbedded clay, silt, sand, and gravel.

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Lithology is variable and dependent on local source rocks; for example, deposits in the north bay generally indicate the Sonoma Volcanics as a source.

Thickness

Maximum thickness unknown but at least 150 feet (46 m) thick and probably reaches a maximum thickness of 500 feet (150 m) under south San Francisco Bay.

Age

About 70,000 years and older. Maximum age unknown but probably between 70,000 and 1.8 million years old.

Distribution and stratigraphy

Exposed primarily along the highest parts of narrow valleys outside the immediate San Francisco Bay valley, such as along Dry Creek north of Healdsburg, the Santa Rosa Plain south of the Russian River, and west of Napa in Redwood Valley. These deposits generally represent the highly dissected remnants of alluvial terrace deposits. The rivers and streams that laid them down were probably similar to those that deposited the late Pleistocene alluvium. The early Pleistocene deposits generally overlie bedrock; some deeply dissected channels within them are filled with younger deposits.

Origin of deposit

Deposited from flowing water on stream terraces and alluvial fans. Similar in origin to late Pleistocene alluvium. Greater age is indicated by the deeper dissection and erosion of the soil profiles. As with the late Pleistocene alluvial deposits, these earlier ones may have been laid down during a lower stand of sea level.

Topographic form and relation to modern drainage

Forms very old highly dissected alluvial terrace deposits. Farther removed from the streams that deposited them and related, in fact, only by being in the same valley.

The fluvial regime that deposited these sediments was probably similar to the one that deposited the late Pleistocene alluvium.

Marine and Continental deposits (Qpmc)

Physical description and lithology

In the northwest and central parts of the exposed area, the Colma consists of pale-colored, loose or friable, well-sorted, fine- to medium-grained sand with subordinate gravel, sandy silt, and clay. In the southeast part of area, it consists mostly of sand and silty clay. See Bonilla (1965) for more complete description.

Thickness

Maximum thickness about 200 feet (60 m) (Bonilla, 1965).

Age

Exact age unknown but may be one-half to one million years old.

Distribution and stratigraphy

Occurs in a narrow zone between Burlingame on the southeast, through Colma Valley to Daly City on the northwest. Overlies bedrock. Locally overlain by younger deposits. Probably correlates with oldest marine terrace deposits in the southern part of San Mateo County.

Origin of deposit

Deposited in shallow marine and continental environment. The Colma was probably deposited at or near present sea level and has been subsequently uplifted and tilted to the east by tectonic forces. The site of Colma Valley was a shallow marine passageway connecting the ocean with an ancestral bay during the time the Colma Formation was deposited. The ancient site of Colma Valley was probably very much like the Golden Gate is today.

Topographic form and relation to modern drainage

Forms southeasterly tilted floor of Colma Valley. Modern streams dissecting original flat surface have formed low rolling hills.

Late Pleistocene and Holocene alluvial deposits partially fill the lower part of small valleys eroded into the Colma Formation.

Undifferentiated bedrock

No mapping was attempted for the older consolidated rock units such as the Franciscan assemblage or Great Valley sequence.

MARINE TERRACE DEPOSITS (QPMT)

Physical description and lithology

Weakly consolidated, slightly weathered sand and gravel. Usually consists of an undifferentiated lower part of shallow-water marine sediments and an upper part of alluvium and colluvium. Lower part commonly consists of conglomeratic sand or fine- to medium-grained micaceous sand overlain by horizontally bedded and cross-bedded medium- to coarse-grained sand. Upper part generally consists of poorly sorted, irregularly bedded sand and gravelly sand.

Lower part of deposits on youngest terrace contains shallow-water molluscan shells and occasional marine mammal skeletal remains.

Thickness

As much as 70 feet (20 m) thick in the Half Moon Bay area but generally less than 30 feet (10 m) thick.

Age

Deposits on the lowest and most extensive marine terrace are probably 70,000 to 120,000 years old. The deposits on the highest terraces may be one-half to one million years old and may correlate with the Colma Formation in the northern part of San Mateo County.

Lower part of younger (lowest) terrace deposits contain late Pleistocene marine molluscan fauna.

Distribution and stratigraphy

Occurs on flat, gently sloping, wave-eroded platforms along Pacific Coast between sea level and 500 feet above sea level. Overlies bedrock. Locally overlain by alluvial deposits and by sand dunes. Some of the deposits on the highest terraces in the southern part of the coast may correlate with the Colma Formation in the northern part of San Mateo County.

Origin of deposit

Lower marine part deposited in shallow, nearshore marine environment. Upper continental part deposited as alluvium and (or) colluvium by streams and (or) mudflows. Marine terraces and their deposits formed during periodic high stands of sea level. All terraces were probably formed at or near present sea level but have been subsequently uplifted, tilted, and folded by tectonic forces.

Topographic form and relation to modern drainage

Forms flat, gently tilted and warped terraces along the Pacific Coast. Lateral continuity of terraces has been destroyed by faulting, folding, wave erosion (cliff retreat) and steam dissection. Terraces have generally elevated above sea level and are not part of the modern terrace erosion cycle, which was initiated about 5,000 years ago when sea level reached its present elevation.

Late Pleistocene alluvium (Qpa)

Physical description and lithology

Weakly consolidated, slightly weathered, poorly sorted, irregular interbedded clay, silt, sand, and gravel. Grades progressively from coarse-grained stream deposits on abandoned terraces in bedrock canyons and at the heads of old alluvial fans into fine-grained alluvial fan and fresh-water marsh deposits near the present shore of the bay.

Contains local accumulations of fresh-water gastropods and pelecypods and continental vertebrate fauna including camel, bison, horse, sloth, and mammoth.

Thickness

Maximum thickness unknown, but at least 150 feet (46 m) thick. Maximum thickness of entire sedimentary pile beneath south San Francisco Bay is probably between 1,000 and 2,000 feet (300–600 m).

Age

About 10,000 years old and older. Maximum age unknown but probably between 35,000 and 70,000 years old.

Locally contain late Pleistocene (Rancholabrean) vertebrate and invertebrate fossil faunas.

Distribution and stratigraphy

Exposed primarily along the highest part of the broad alluvial plain marginal to the bay. Along the northern bay margin and along the Pacific Coast occurs on abandoned flood plains deeply incised by channels that are partly filled by younger alluvial deposits. Along the southern bay margin overlapped by younger deposits. Inter-

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fingers with and grades into older basin deposits near and under the bay. Overlies bedrock and marine terrace deposits along the Pacific Coast. Overlies bed. ck, the Colma Formation, and deformed older sedimentary deposits (bedrock) on alluvial plain marginal to the bay.

Origin of deposit

Deposited from flowing water in stream channels, on stream terraces, and on alluvial fans. Similar in origin to younger alluvial fan deposits; greater age is indicated by slight consolidation and better soil profile development than on younger deposits. The upper part of this unit in the bay basin was deposited by streams graded to lower stands of sea level; the bay did not exist during period of deposition.

Topographic form and relation to modern drainage

Forms old, slightly dissected alluvial fans with subdued levees and stream channels. Forms dissected, abandoned flood plains in bedrock canyons and on coastal marine terraces. Incised by modern streams in canyons and at the heads of old alluvial fans.

The fluvial regime that deposited these sediments was very similar to the recent one that deposited the younger alluvial deposits.

Beach(?) and dune sand deposits (Merritt Sand) (Qps)

Physical description and lithology

Loose, well-sorted, fine- to medium-grained sand with subordinate silt.

Thickness

Maximum thickness near Oakland of about 50 feet (15 m).

Age

Overlies peaty mud older than 40,000 years (radiocarbon-dated), therefore oldest deposits at least 40,000 years old but may include younger deposits.

Distribution and stratigraphy

Exposed at northeast end of south San Francisco Bay near southwest Oakland, in Alameda, and on Bay Farm Island. Recognized in borehole logs to extend under San Francisco Bay southwestward the latitude of the San Mateo-Hayward Bridge. Also extends westward intermittently across the bay and may correlate in part with dune deposits in San Francisco.

Origin of deposit

Probably derived chiefly by wind eroding and transporting stream sediments during lower stands of sea level that occurred more than 40,000 years ago but probably less than 100,000 years ago. May have been modified by beach or shoreline processes as sea level rose.

Topographic form and relation to modern drainage

The distribution and shape suggest that the present form is little modified and is probably primary. The large prong-like dunes are oriented parallel to the ancient northwest wind direction.

GEOLOGIC MAPPING TECHNIQUES

One of the main purposes of the current geologic study of the San Francisco Bay region has been to differentiate the alluvial and estuarine deposits underlying the gently sloping (less than 15 percent) sedimentary plain between the bay and the surrounding hills. Specificially, attempts were made to relate deposits to the processes that were responsible for their origin. Shortcuts and innovative mapping techniques have been used because approximately 7,500 square miles (19,425 km²) was mapped in only 3 years. The alluvial units are defined by various geologic criteria such as depositional environment, geomorphic expression, soil-profile development, age, induration, compaction, and texture. The distribution of the units is determined primarily from topographic maps, published soil series maps, and aerial photographs. Figures 15, 16, 17, and 18 illustrate the evolution of such a geologic map for a small area near Palo Alto. The late Quaternary deposits of the entire region are mapped on plates 1, 2, and 3. This mapping differs from a soil series map in that it considers greater thicknesses than the upper few feet and is largely based on the process by which the deposit was laid down. For example, floodbasin deposits are shown separately from alluvial fans.

On the basis of relative soil-profile development, the 18 alluvial soil series described in the Soil Conservation Service (1968) report on the region (fig. 16) fall into two distinct groups that reflect some basic differences in the deposits on which they are developed. The soil units with strongly developed weathering profiles constitute one group, and those with weakly

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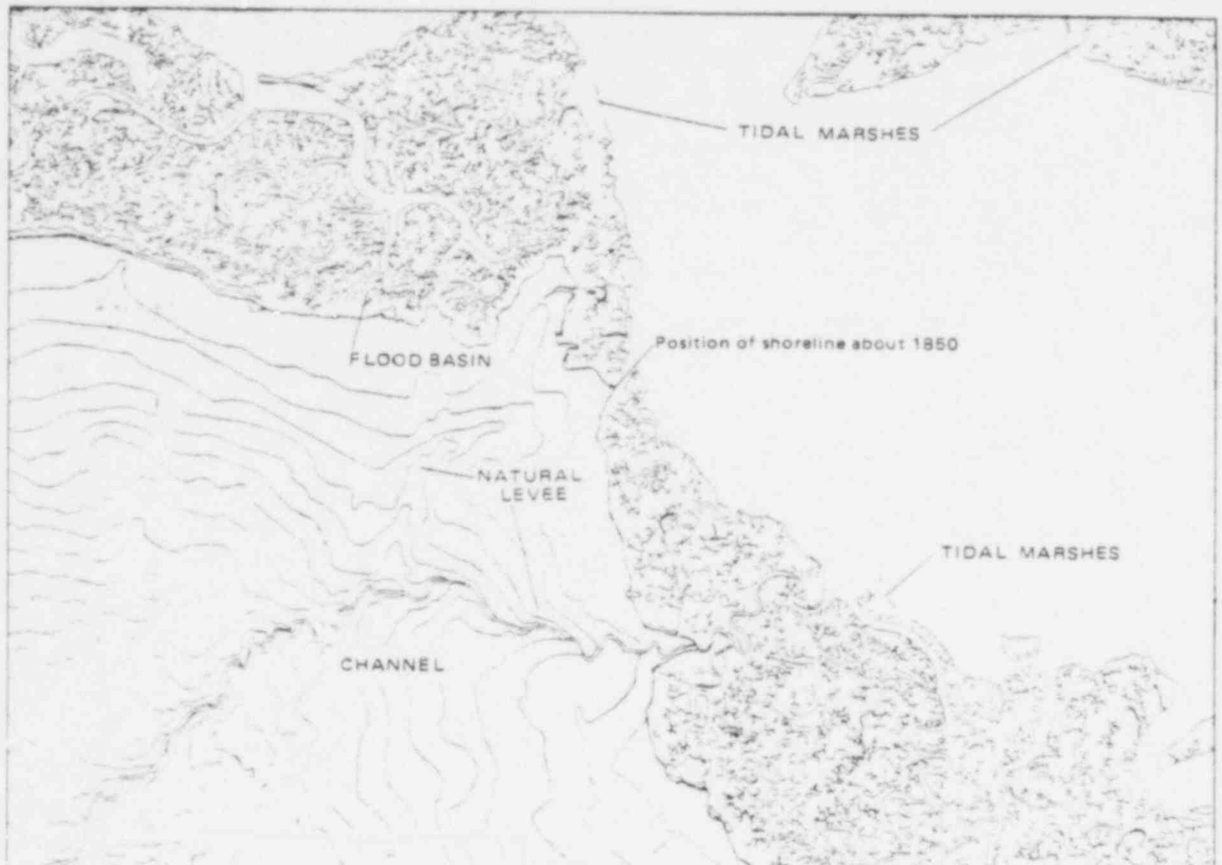

FIGURE 15.—Alluvial deposits related to geologic processes in the Palo Alto area. The enhanced contour lines (derived from USGS 7.5-minute Mountain View and Palo Alto quadrangles) reveal the fluvial geomorphic features, alluvial fans, natural stream levees, and floodbasins on the broad alluvial plain between the bay marshlands and the irregular bedrock uplands. Distribution of former tidal marshland from Nichols and Wright (1971).

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to moderately developed weathering profiles constitute the other. Soil profiles are developed by physical and chemical weathering processes at the surface of the Earth; therefore, well-developed soil profiles generally indicate that the materials on which they are formed have been exposed to either intense weathering conditions or moderate weathering conditions for a considerable length of time. The alluvial deposits on which the strongly developed weathering profiles occur were inferred to be significantly older than the deposits on which the weakly to moderately developed profiles occur because the weathering conditons in the bay region are relatively uniform. These two groups of deposits, therefore, simply indicate younger and older alluvial deposits. (fig. 17).

The younger deposits make up the alluvial fans being formed under the existing regime. The streams forming these young fans are graded to present sea level. These younger deposits and the bay mud into which they grade are informally referred to as Holocene deposits (fig. 18). The older alluvial deposits, now partly covered by the Holocene deposits, make up alluvial fans formed by these same streams when they were graded to lower stands of sea level during the late Pleistocene (prior to about 10,000 years ago). These older deposits are informally referred to as late Pleistocene alluvium (fig. 18).

The Holocene alluvium is differentiated further into depositional units called facies (fig. 18) on the basis of textural characteristics (that is, gravel, sand, silt, and clay) obtained primarily from published soil reports and unpublished engineering foundation reports, and the depositional environment (such as stream levees and floodbasins) determined from geomorphic expression as shown on topographic maps and aerial photographs. These facies grade from coarse-grained gravel and sand deposits, which form prominent stream levees at the highest part of the alluvial fans, into medium-grained sand and silt deposits, which form broad flood plains and subdued levees along the lower margins of the alluvial fans. These stream deposits grade into and interfinger with fine-grained silt and clay deposits, which form the flat floor of floodbasins between stream levees on the outer margins of the alluvial fans directly adjacent to the bay marshlands. These fine-grained basin deposits and some of the medium-grained levee deposits interfinger with and grade into the bay mud—the carbonaceous silty clay that was deposited in the marshes and on the mudflats of San Francisco Bay during Holocene time (roughly the past 10,000 years).

This gradation from coarse-grained to fine-grained sediment in the Holocene alluvium is a natural consequence of very recent stream erosion, transportation, and deposition. The coarsest rock debris eroded from the bedrock uplands is deposited near the base of the hills where the rapidly flowing streams enter the broad, gently sloping alluvial plain. Only the finer grained debris is carried by the ever-slackening water to the lower parts of the alluvial fans and eventually into the bay itself where it is deposited as bay mud. The landward extent of the saturated, plastic bay mud underlying the former marshes and tidal mudflats of San Francisco Bay (fig. 15) was established from early (ca. 1850) U.S. Coast and Geodetic Survey hydrographic charts (Nichols and Wright, 1971) rather than from direct field observation, because human activity over the past 50 years has obscured its original distribution.

Long exposure to erosion and weathering processes has altered the original geomorphic expression and physical character of the late Pleistocene alluvial deposits, thus they have not been separated into depositional facies similar to those of the Holocene alluvial deposits in this study.

In the areas of the bay region where detailed soils data are not available, the alluvial deposits have been differentiated by using only the geomorphic and genetic criteria derived from aerial photographs and extrapolated from areas where detailed soils data provide the main and most reliable means of recognition. Fossils, archeological remains, and radiometric ages corroborate the relative ages and correlations based on these limited data. The upper part of the late Pleistocene alluvial deposits contains a Rancholabrean fossil vertebrate fauna consisting mainly of extinct species (for example, camel, horse, bison, mammoth, and ground sloth), whereas the Holocene alluvial deposits contain a fossil fauna completely modern in aspect (for example, deer and elk).

The upper part of the late Pleistocene alluvium contains fossil wood and fresh-water molluscan shells that yield radiocarbon dates of about 22,000 years ago. Holocene alluvial deposits contain fossil wood, shells, and archeological remains that yield radiocarbon dates of about 5,000 years or less. Peat and shell deposits in the bay mud yield radiocarbon dates that range from about 9,600 years at the base of the unit in the lowest parts of the basin to modern age at the top of the unit. These ages from the bay mud date the latest marine transgression into the basin—a transgression that agrees very well with the post-Pleistocene rise in sea level established from worldwide data (Milliman and Emery, 1968). In general, the partial flooding of the basin resulting from this rise in sea level raised the base level of the local

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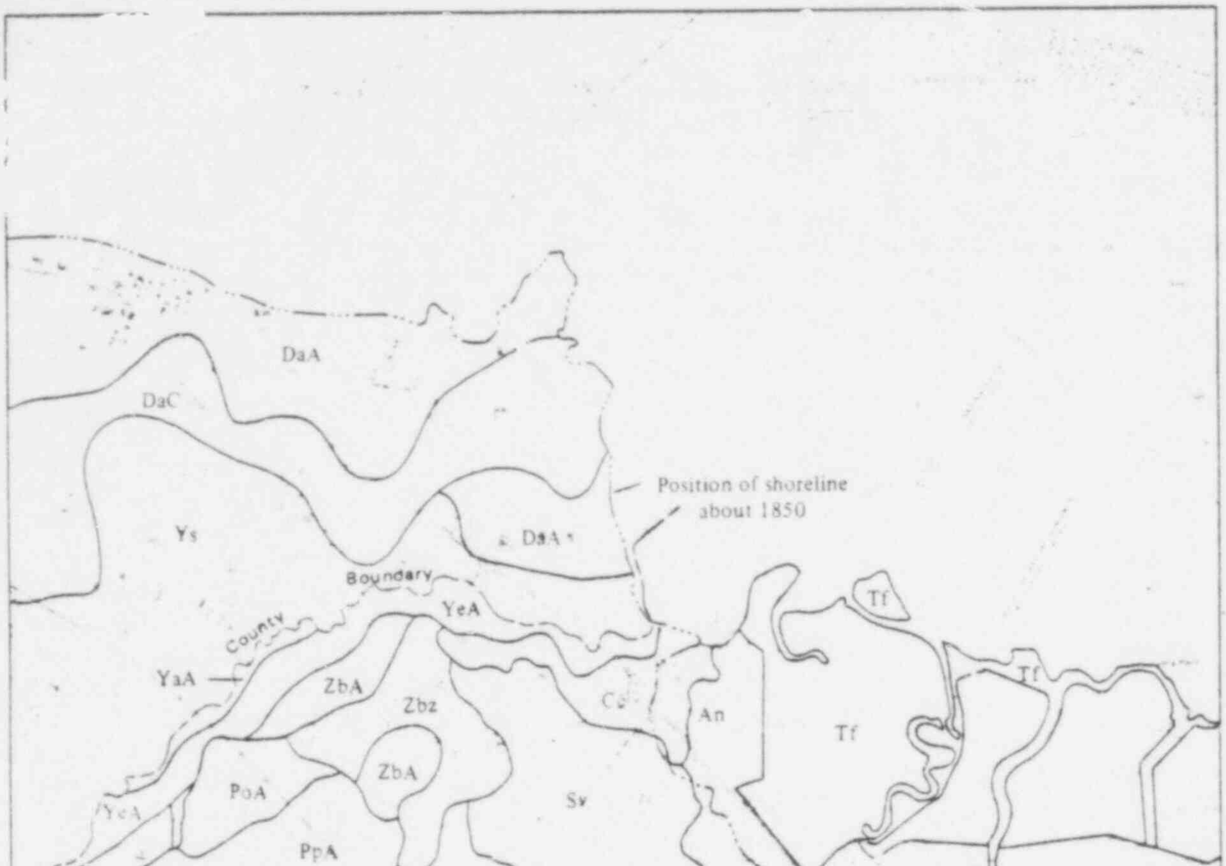

FIGURE 16.—Soil units in Palo Alto area. Soil units are defined primarily on the basis of profile development, texture, and slope. Soil profile development is controlled by many factors including time, climate, parent material, slope, and biological activity. In this area where weathering conditions and parent material are relatively uniform, the time factor is clearly expressed by relative soil-profile development, which can therefore be used as a means of differentiating alluvial deposits on the basis of relative age. The symbols shown on the map refer to the names of local soil series.

EXPLANATION

Soil Series in the Palo Alto area*

Alluvial soil series with weakly to moderately developed weathering profiles:

An	Alviso clay
Ba	Bayshore clay
Ca	Campbell silty clay loam
Cc	Campbell silty clay loam, clay substrate
Ch	Clear Lake clay, drained
CrA	Cropley clay; 0- to 2-percent slopes
CrC	Cropley clay; 2- to 9-percent slopes
Csa	Cropley clay loam; 0- to 2-percent slopes
GbB	Garretson gravelly loam; 0- to 5-percent slopes
Pf	Pacheco loams, clay substrate
Sv	Sunnyvale silty clay, drained
YaA	Yolo loam; 0- to 2-percent slopes
YeA	Yolo silty clay loam; 0- to 2-percent slopes
Ys	Yolo loam; no slope given, taken from older survey
ZbA	Zamora silty clay loam; 1- to 3-percent slopes
ZbC	Zamora clay loam; 2- to 9-percent slopes
Zbz	Zamora clay loam; 0- to 2-percent slopes

Alluvial soil series with strongly developed weathering profiles:

PbA	Pleasanton loam; 0- to 2-percent slopes
PoC	Pleasanton clay loam; 0- to 2-percent slopes
PpA	Pleasanton gravelly loam; 0- to 2-percent slopes
PpC	Pleasanton gravelly clay loam; 2- to 9-percent slopes
RaC	Rincon clay loam; 0- to 2-percent slopes
RaC2	Rincon clay loam; 2- to 9-percent slopes
SdA	San Ysidro loam; 0- to 2-percent slopes
SdB	San Ysidro loam; 2- to 9-percent slopes
SdB2	San Ysidro loam; 2- to 9-percent slopes, eroded

Upland soil series (nonalluvial soils):

AvD	Azule silty clay laom; 2- to 9-percent slopes
AvD2	Azule silty clay loam; 9- to 15-percent slopes
AvE	Azule silty clay loam; 15- to 30-percent slopes
DaA	Diablo clay; 0- to 2-percent slopes
DaC	Diablo clay; 2- to 9-percent slopes
DaE	Diablo clay; 15- to 30-percent slopes
GcE	Gaviota loam; 15- to 30-percent slopes
GoD	Gilroy clay loam; 5- to 15-percent slopes
GoE	Gilroy clay loam; 15- to 30-percent slopes
GmE	Gaviota-Los Gatos complex; 15- to 30-percent slopes
LgE	Los Gatos clay loam
LoE	Los Osos clay loam; 15- to 30-percent slopes
Lkg3	Los Gatos and Maymen complex; 50- to 75-percent slopes
LtD	Los Trancos stony clay; 15- to 30-percent slopes
PrC	Positas-Saratoga loam; 2- to 9-percent slopes
ShE	Soper gravelly loam
SgC	Saratoga-Positas loam; 2- to 9-percent slopes

Miscellaneous map symbols:

KfB	Kitchen middens, archeological site
PkG	Gravel pits
Tf	Tidal mudflats

*From U.S. Soil Conservation Service (1968).

FIGURE 16.—Continued.

streams and began the present depositional cycle represented by the Holocene alluvial deposits. The fact that the Holocene alluvial deposits around the margins of the bay are graded to the present sea level is used as one means of identifying these deposits and adds credence to the relative ages and correlations based on other criteria. The stratigraphic relations of the various alluvial facies are shown in figure 19 for the plain bordering San Francisco Bay.

PHYSICAL PROPERTIES OF GEOLOGIC UNITS

Physical properties of the various geologic units such as texture, thickness, bulk density, induration, and seismic velocity are needed to assess their potential for becoming geologic hazards. These properties were compiled or interpreted from readily available sources (fig. 20) and were augmented by direct measurement where no data existed or where verification of existing data was needed. This information also was used to differentiate units where soil series were ambiguous or had not been mapped.

Very few data are available on the total thickness of the unconsolidated and semiconsolidated deposits filling the bay basin. A few deep drill holes and several seismic profiles (Hazelwood, 1974) indicate that these sediments are probably more than 1,970 feet (600 m) thick in the San Jose Area and decrease irregularly to 200-300 feet (60-90 m) to the north near San Francisco.

The thickness of the younger units is fairly well known from numerous shallow bore holes described in engineering reports (fig. 20) and from shallow seismic surveys where bore-hole data are lacking. The Holocene alluvium (fig. 18) generally ranges in thickness from about 50 feet (15 m) near the heads of alluvial fans to about 10 feet (3 m) near the margins of the bay. The Holocene bay mud ranges in thickness from 0 to as much as 120 feet (36 m).

The thickness of the late Pleistocene alluvium (fig. 18) is not precisely known because its base is not distinctly defined in the thick sedimentary section beneath the bay and the surrounding alluvial plain. Where the base of the late Pleistocene alluvium can be seen on stream terraces in narrow valleys, these sediments are about 10 feet (3 m) thick. They are probably as much as 130 feet (40 m) thick beneath the bay where they overlie an old estuarine mud identified by marine fossils brought up in a drill sample. Still older Pleistocene alluvial deposits probably underlie these deeply buried estuarine muds, but their total thickness is not known. In the southern bay area, these deposits may grade downward into the Pliocene and early Pleistocene alluvial deposits or may lie unconformably on them.

Published soils maps and unpublished engineering reports from highway departments and engineering consultants are the main source of data on the physical properties of the various geologic units. Each unit generally has a distinctive range of values for properties such as grain size, sorting, bulk density, compaction, induration, and moisture content. This relation is true partly because some of the units, in particular the three facies of Holocene alluvium, are defined and delineated by using physical properties

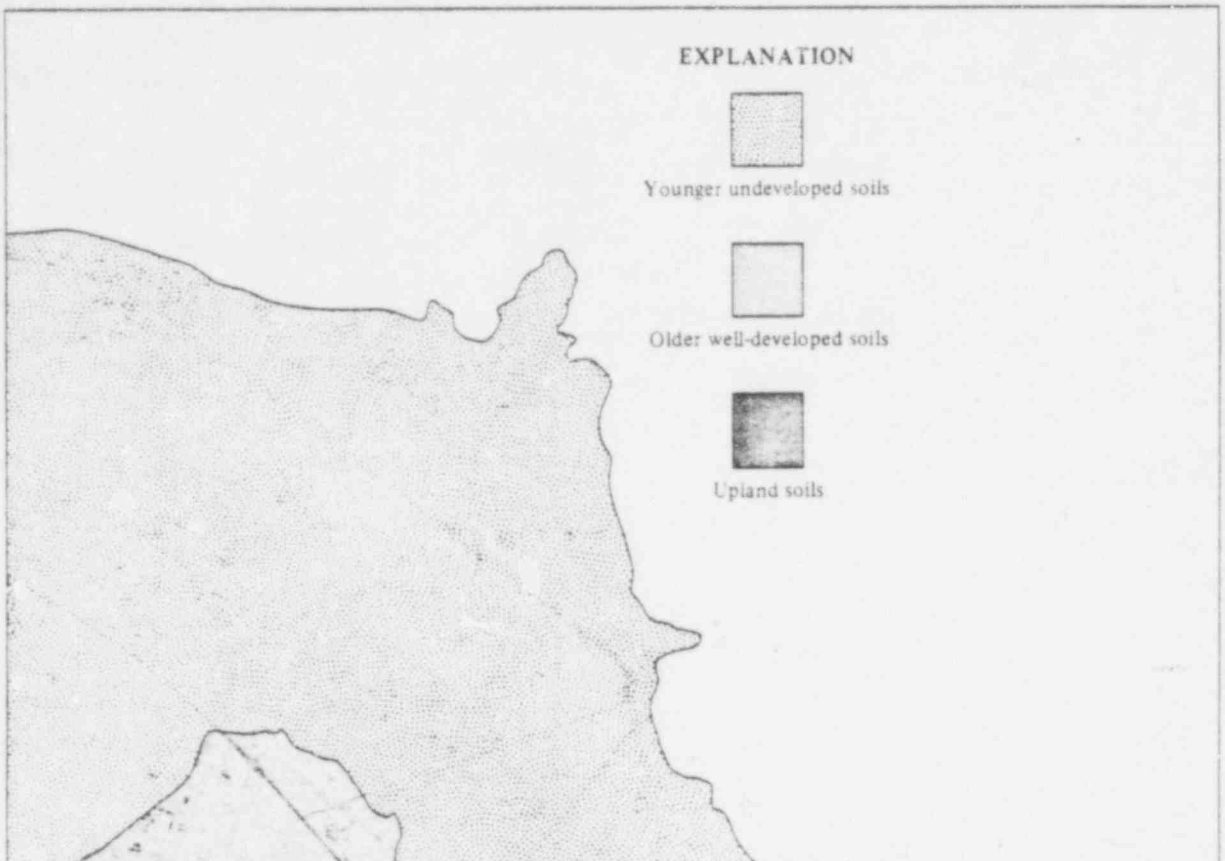

FIGURE 17.—Distribution of younger and older alluvial deposits in the Palo Alto area as determined primarily from relative soil-profile development of soil series as mapped by Soil Conservation Service (fig.15). Alluvial deposits on which weak to moderate weathering profiles are developed were initially inferred to be younger than alluvial deposits on which strong weathering profiles are developed. Radiocarbon and fossil data have confirmed this relative age classification. The younger alluvial deposits contain modern vertebrate and invertebrate fossils and organic remains that yield radiocarbon ages of about 5,000 years ago and younger. The older alluvial deposits locally contain extinct late Pleistocene vertebrate fossils such as camel, sloth, bison, and mastodon, and organic remains that yield radiocarbon ages of about 20,000 years.

such as grain size and induration.

The primary physical properties such as grain size and sorting are controlled by the depositional environment, whereas the secondary properties such as induration, compaction, and bulk density generally increase with age of the geologic units. This variation of the secondary physical properties with age is indicated by the increasing penetration resistance from the Holocene deposits to the various bedrock units. The very low penetration resistance of the bay mud is attributable to its extremely high water content, fine grain size, and loose packing, which reflect its youthful age. Older, deeply buried estuarine muds would have higher penetration resistances due to loss of water during compaction. Penetrometer resistance can be used to estimate relative densities which, with data on grain size, sorting, and moisture content, can be used to evaluate liquefaction potential in shallow, unconsolidated deposits. Liquefaction of unconsolidated materials may or may not cause ground failure; the conditions that determine whether or not ground failure is likely to occur are given in table 1.

Figures 21-24 illustrate the range of some physical properties of the geologic map units. These properties were compiled and interpreted from readily available sources, such as bridge and highway data and private engineering reports, and were augmented by direct measurement where no data existed or where verification of existing data was needed. Numerical values were excluded because statistical validity could not be determined for so vast an area. These diagrams, then, are to be interpreted only as a general guide to the physical properties and should not be substituted for on-site investigation.

SEISMIC PROPERTIES

The relation between seismic behavior and specific physical properties is still not well known. Seismic properties of the various units are described in terms of their response to seismically induced energy rather than in terms of any inherent physical characteristic. Experience has shown, however, that low-density, water-saturated, soft sediments tend to amplify some components of seismic energy. Consequently, more shaking will occur in areas underlain by these sediments. Because of the amplification of bedrock motion, great damage may be expected (depending on the nature of the structure) where these soft sediments are thickest. Areas with different shaking characteristics can be determined from studying good geologic maps. Distinctions can commonly be made on the basis of firmness and geologic age (Borcherdt, Joyner, Warrick and Gibbs, 1975). Figure 25 shows the change in P (compressional) and S (shear) wave velocities as a function of depth (also age) at Ravenswood Point, San Mateo County.

TABLE 1.—*Factors and conditions controlling liquefaction-induced ground failure*

Factor affecting liquefied material	Condition conducive to ground failure	Condition not conducive to ground failure
Lateral confinement	Not confined Along stream banks Near cliff faces	Confined laterally Depression such as a floodbasin Flat plain
Slope	Gentle to steep slopes Alluvial fans to hillslopes	Horizontal to gentle slopes Flat alluvial surfaces Flat floors of floodbasins
Loading	Nonuniform loading Differential thickness of overlying material	Uniform loading Uniform thickness of overlying material

The stratigraphic relations and seismic velocities (P-wave and S-wave) of the various deposits are shown in a block diagram for part of south San Francisco Bay (fig. 26). This area was chosen because reliable information on depth to bedrock as well as reliable velocity data were available.

POTENTIAL PROBLEMS IN FLATLAND REGIONS

The geologic units shown on the regional flatlands map (pl. 1) have characteristics that constrain or favor particular uses of the land. Some potential problems and opportunities can be quite accurately identified from the map. Others can be only broadly inferred; definition requires additional, more specific information.

WATER-RELATED PROBLEMS

The flatland deposits are traversed by the many streams that formed them. These water courses, big and small, can flood, overtopping their banks and inundating lowlands. High ground-water conditions usually exist during the winter rainy season and can cause problems in low-lying basins and marshes fringing the bay that are underlain by units such as bay mud, fine-grained alluvium, and fine-grained salt-affected alluvium.

During the summer drought, ground water supplies are usually heavily used for irrigation. Overdraft of the ground water has led to both land subsidence and salt water encroachment. A general summary of the water-related processes is shown in figure 27. The diagram shows the kinds of problems that may be associated with the different flatland deposits from the foot of the bedrock uplands down to the tidal mudflats. Surface water obviously plays a significant role in distributing the sedimentary materials, which in turn can control the ground water characteristics.

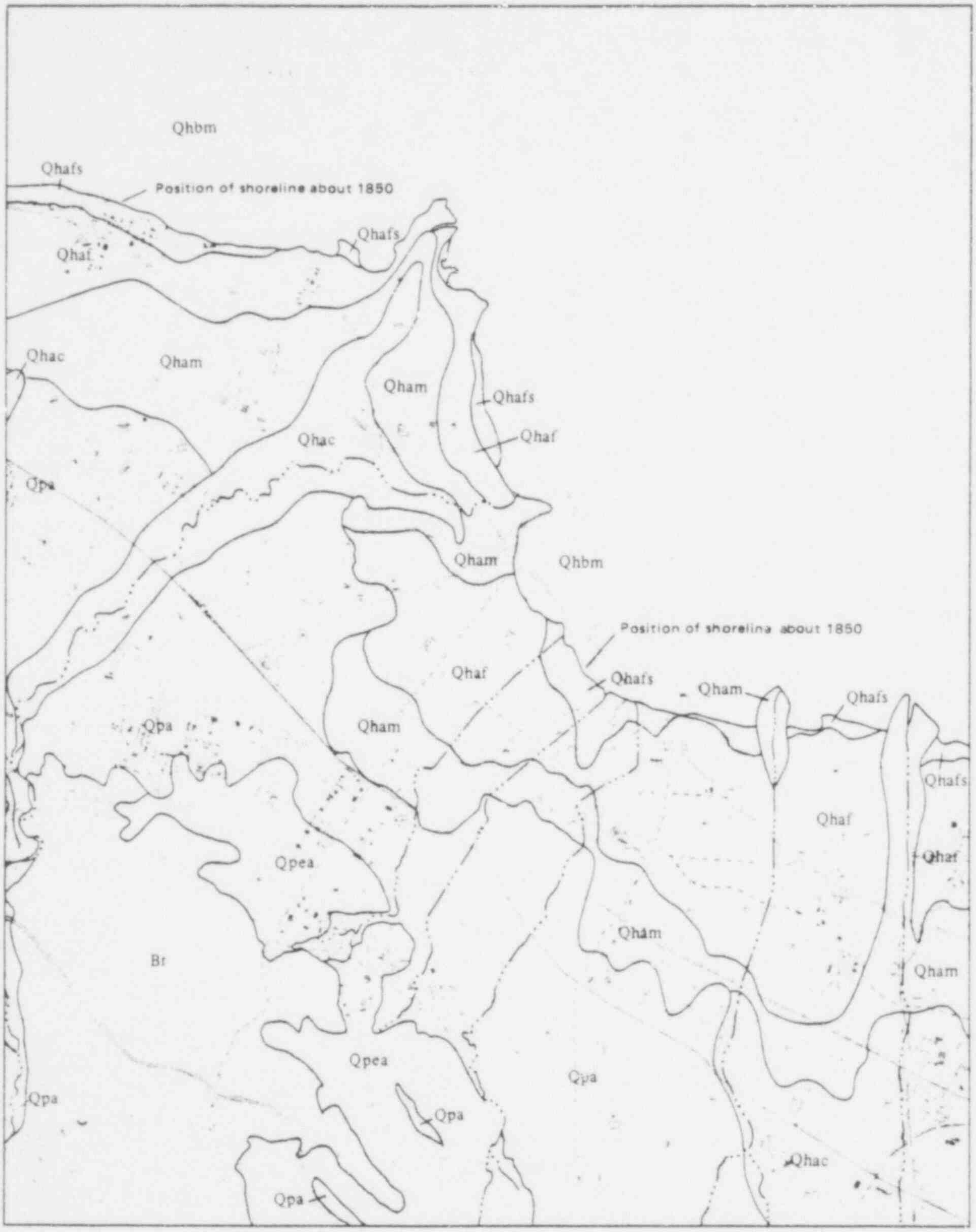

FIGURE 18.—Rock units in the Palo Alto area.

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FIGURE 18 EXPLANATION
ROCK UNITS IN THE PALO ALTO AREA

Description of Map Units

Holocene deposits (less than 10,000 years old):

Estuarine deposits (0-9,000 years old):

Qhbm Bay mud. Water-saturated estuarine mud, predominantly clay and silty clay underlying marshlands and tidal mudflats of San Francisco Bay. Contains a few lenses of well-sorted fine sand and silt and a few shelly and peaty layers. Interfingers with and grades into fine-grained and medium-grained alluvium; generally overlies early Holocene alluvium or late Pleistocene alluvium 0–120 ft (0–40 m) thick.

Alluvial deposits (0-5,000 years old):

Qhaf Fine-grained alluvium. Plastic, poorly sorted carbonaceous clay and silty clay in poorly drained interfluvial basins marginal to bay marshlands. Locally contains thin beds of well-sorted silt, sand, and fine gravel; contains modern vertebrate fossils and fresh-water gastropod and pelecypod shells. Interfingers with and grades into bay mud and medium-grained alluvium; overlies late Pleistocene alluvium. Generally less than 15 feet (5 m) thick.

Qhafs Salt affected fine-grained alluvium; same as Qhaf but containing high concentration of salt.

Qham Medium-grained alluvium. Loose, moderately drained, moderately sorted sand forming alluvial plains and stream levees. Locally contains beds of well-sorted clay, silt, and gravel; contains modern vertebrate fossils and fresh-water gastropod and pelecypod shells. Intermediate in character and lateral extent between fine-grained and coarse-grained alluvium with which it interfingers; generally overlies late Pleistocene alluvium. Generally less than 21 feet (7 m) thick.

Qhac Coarse-grained alluvium. Loose well-drained, moderately sorted, permeable sand and gravel forming stream levees and flood plains on higher parts of alluvial fans; gravel becomes dominant toward fan heads. Locally contains beds of well-sorted silt, sand, and gravel; contains modern vertebrate fossils and fresh-water pelecypod and gastropod shells. Thickness ranges from as much as 50 feet (15 m) at fan heads to 20 feet (6 m) where these deposits interfinger with and grade into medium-grained alluvium; overlies late Pleistocene alluvium and bedrock.

Pleistocene deposits (10,000–3,000,000 years old):

Qpa Late Pleistocene alluvium (10,000–70,000? years old). Weathered, slightly consolidated and indurated alluvial fan deposits consisting primarily of gravel and sand with some silt. Less permeable than Holocene alluvium. Locally contains fresh-water pelecypod and gastropod shells and extinct late Pleistocene vertebrate fossils. Overlain by Holocene deposits on lower parts of alluvial plain; incised by channels that are partly filled with Holocene alluvium on higher parts of alluvial plain. Maximum thickness unknown but at least 150 feet (45 m) near margins of present bay where these deposits overlie deeply buried Pleistocene estuarine deposits.

Bedrock:

Qpea Early Pleistocene and Pliocene alluvium. Tectonically deformed alluvial-fan deposits with local minor amounts of shallow-water marine deposits. Weakly to moderately indurated gravel, sand, and silt with subordinate amounts of lacustrine silt and clay; local thin tuff beds; contains late Pliocene and early Pleistocene vertebrate fossils. Underlies late Pleistocene alluvium; overlies or in fault contact with Franciscan Formation. Consists of the Santa Clara Formation in southwest bay area.

Br Undifferentiated Tertiary bedrock. Well-indurated sandstone, shale, and volcanic rocks. In map area underlies or is in fault contact with Pliocene and early Pleistocene alluvium.

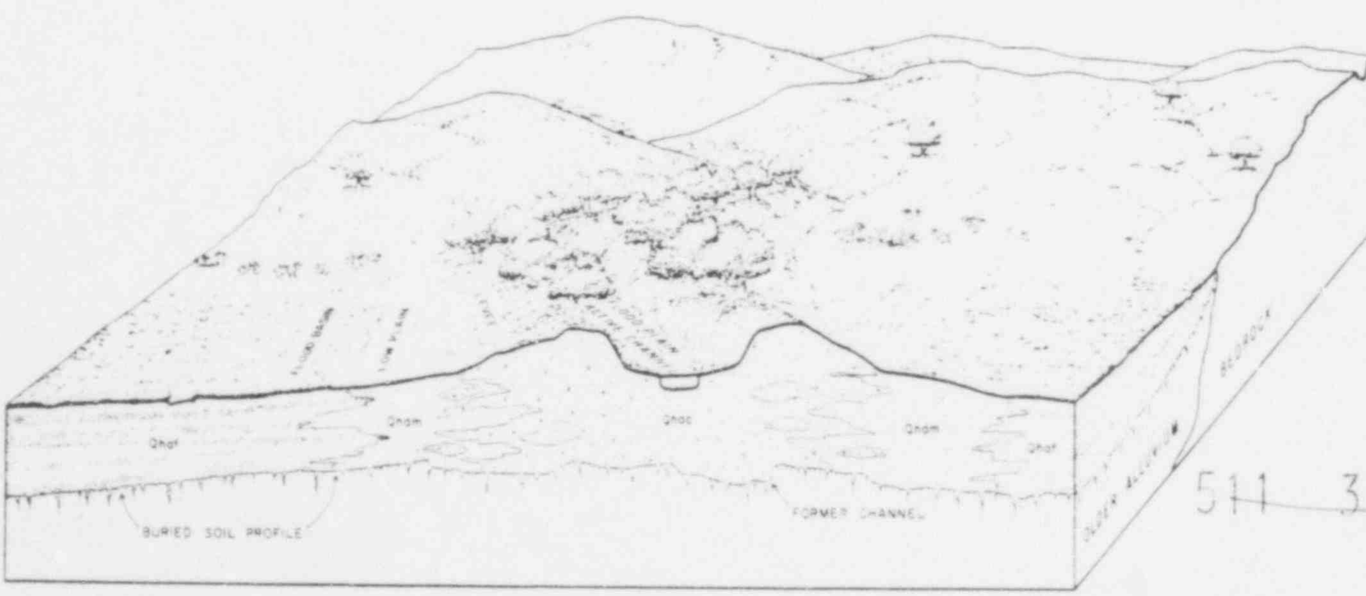

FIGURE 19.—Facies relations in younger alluvial deposits.

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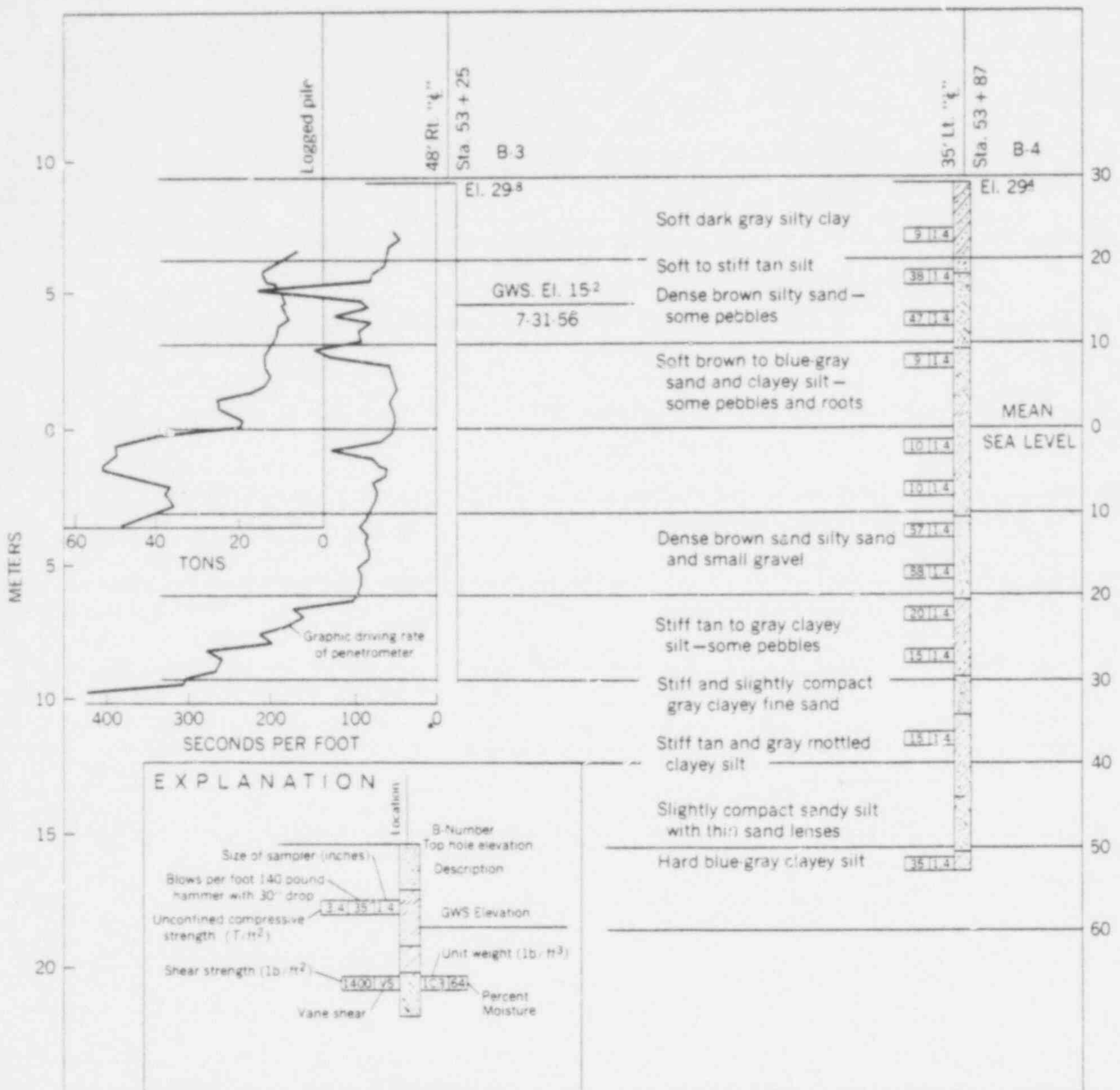

FIGURE 20.—An unpublished highway engineering boring log from which thickness and physical properties of alluvial deposits were partly derived. The sudden decrease in the driving rate of the penetrometer at 20 feet (6.3m) is interpreted to be the stratigraphic contact between the Holocene alluvium and the underlying late Pleistocene alluvium.

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FIGURE 21.—Ranges of relative natural moisture content of the geologic map units shown on plates 1–3. Moisture content is the amount of moisture in a given mass of natural material expressed as weight of water divided by weight of oven-dried material, usually multiplied by 100 to give a percentage. Usually moisture content decreases with geologic age; however, units that extend below sea level, such as beach and dune sand deposits (Qhs), Pleistocene beach? and dune sand deposits (Qps), and marine terrace deposits (Qpmt) may be saturated. ▶

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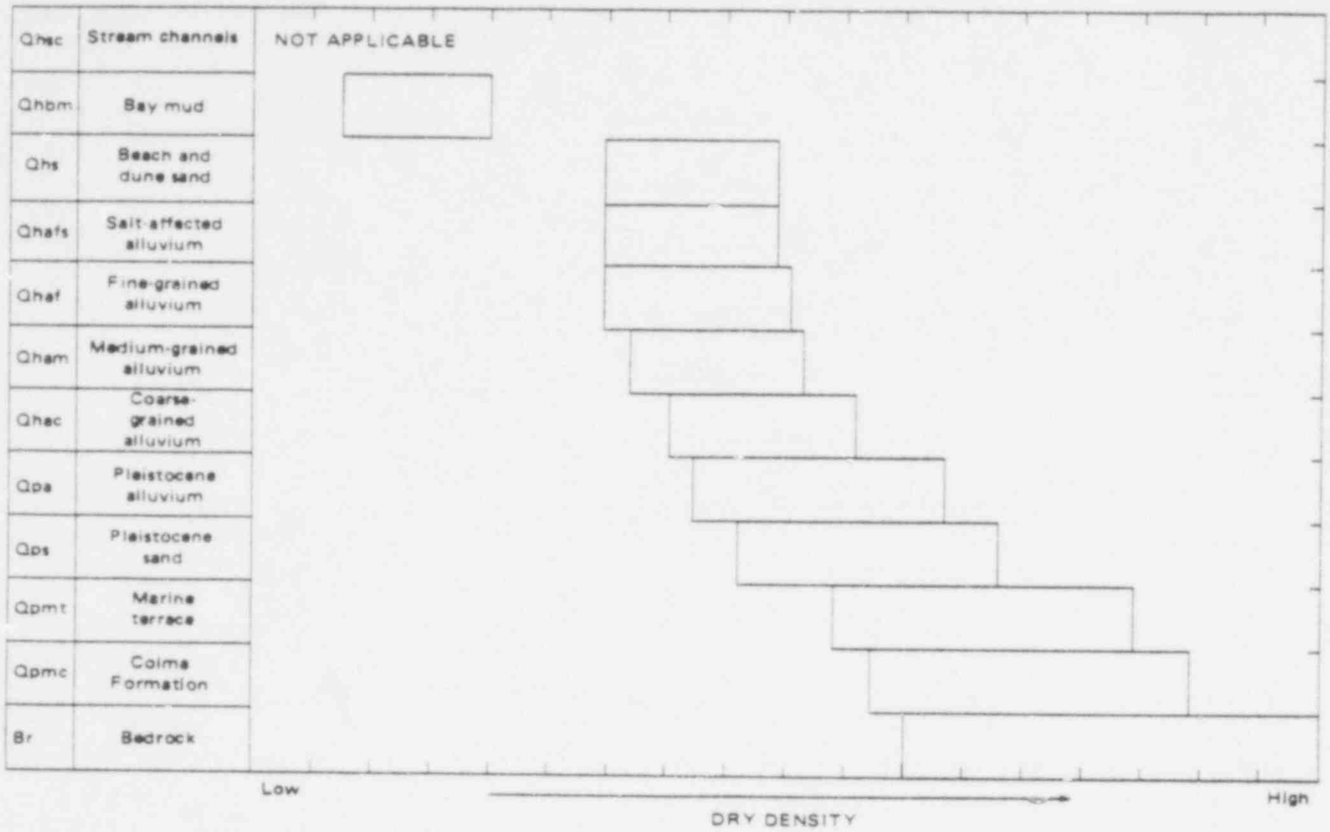
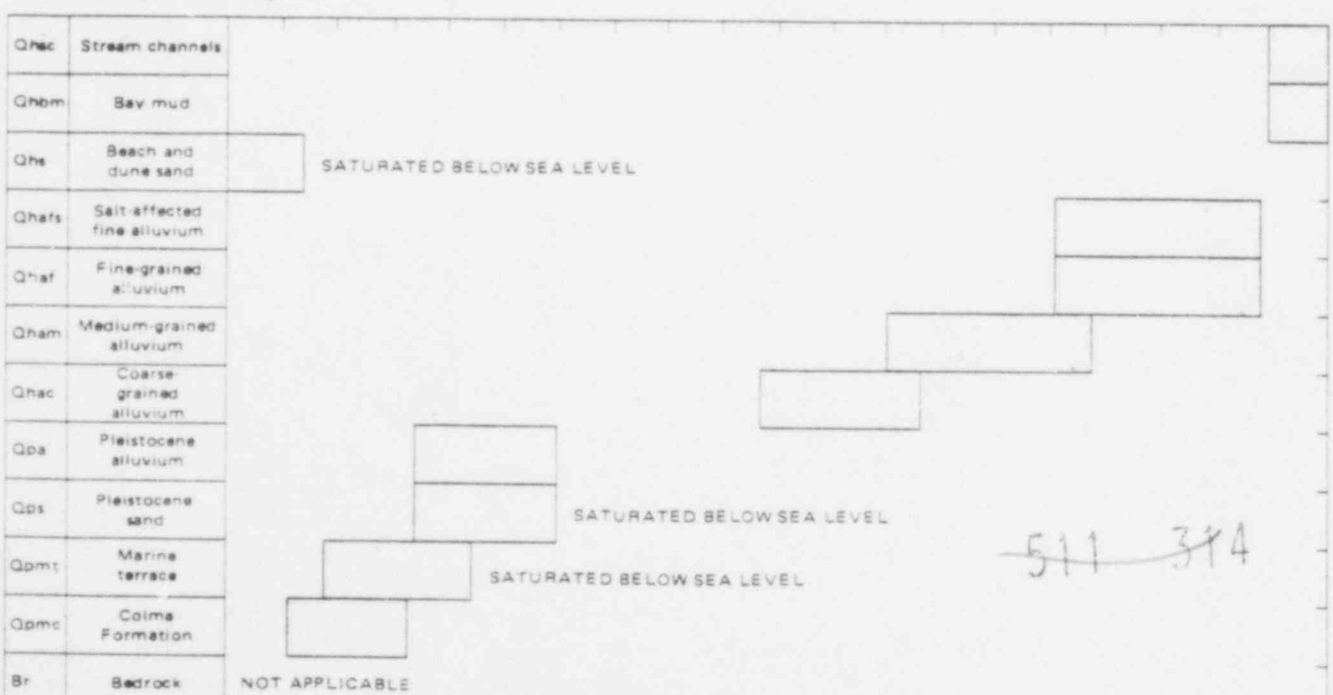


FIGURE 21.—Ranges of relative dry densities of the geologic map units (pls. 1–3). Dry density is a measure of the mass of earth materials relative to an equal volume of water. For planning purposes geologic units that have higher densities are generally better foundation materials and behave with lower ground-motion amplification during earthquakes. It should be noted the dry densities increase with geologic age of the map unit.



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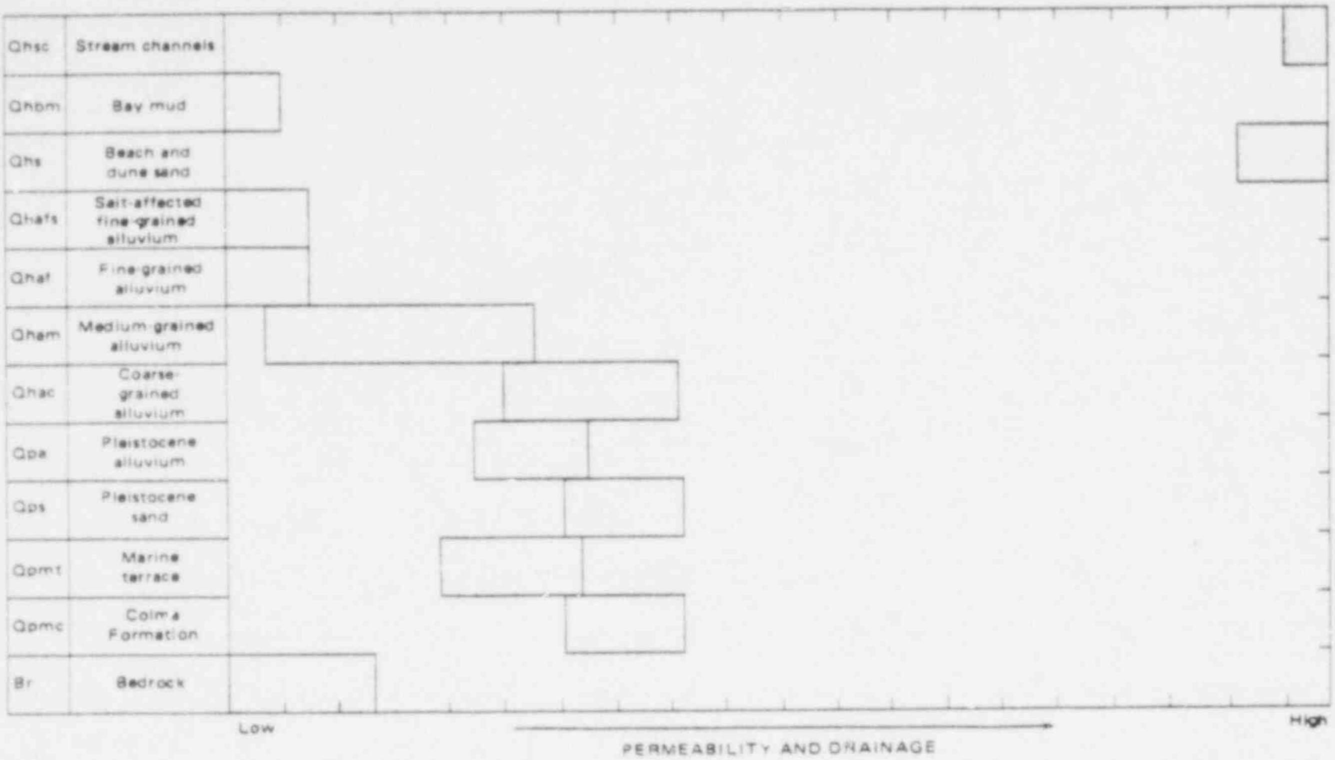
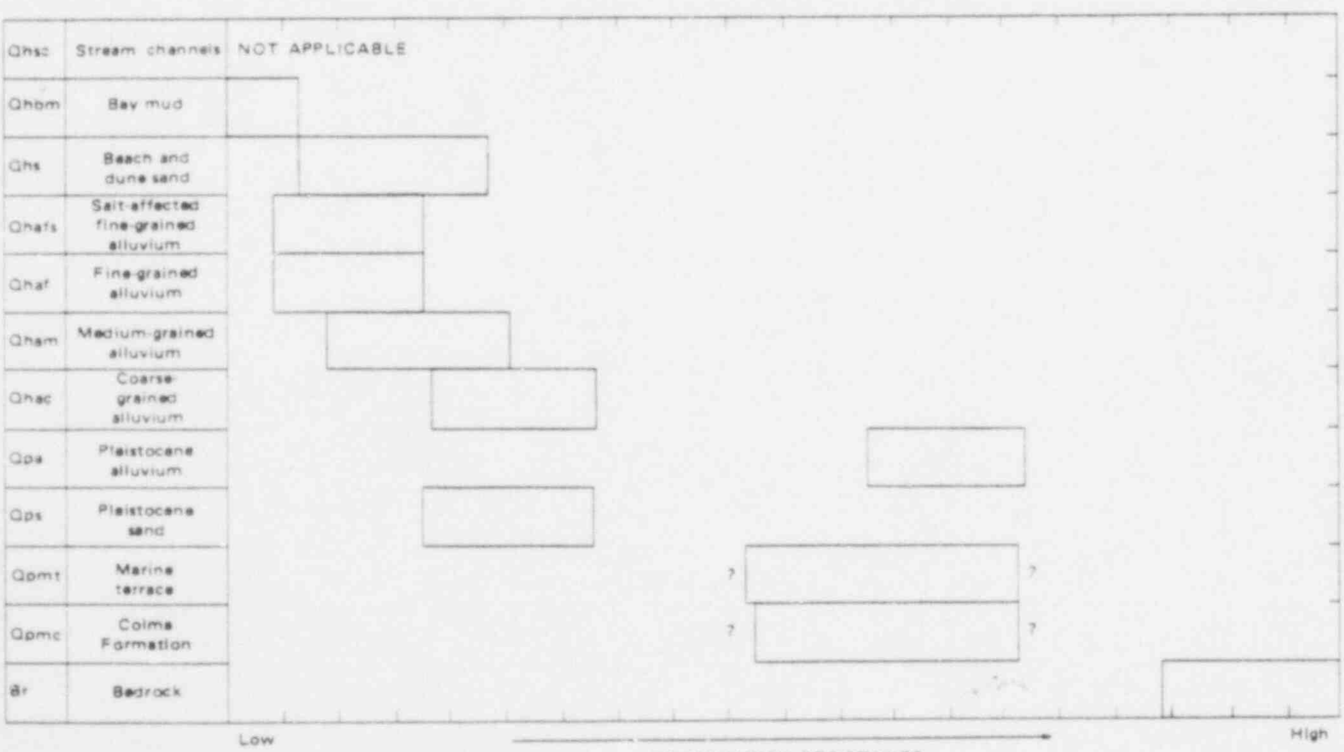


FIGURE 23.—Ranges of relative permeability of the geologic map units. Here permeability refers to the property or capacity of a geologic unit to transmit a fluid; it is a function of the porosity and compaction of the geologic units. In general, fine-grained units such as Qhbm (bay mud) and Qhaf (fine-grained alluvium) have low permeabilities and are poor transmitters of fluids. Such units will be poorly drained and pose problems of standing water especially during the rainy season.



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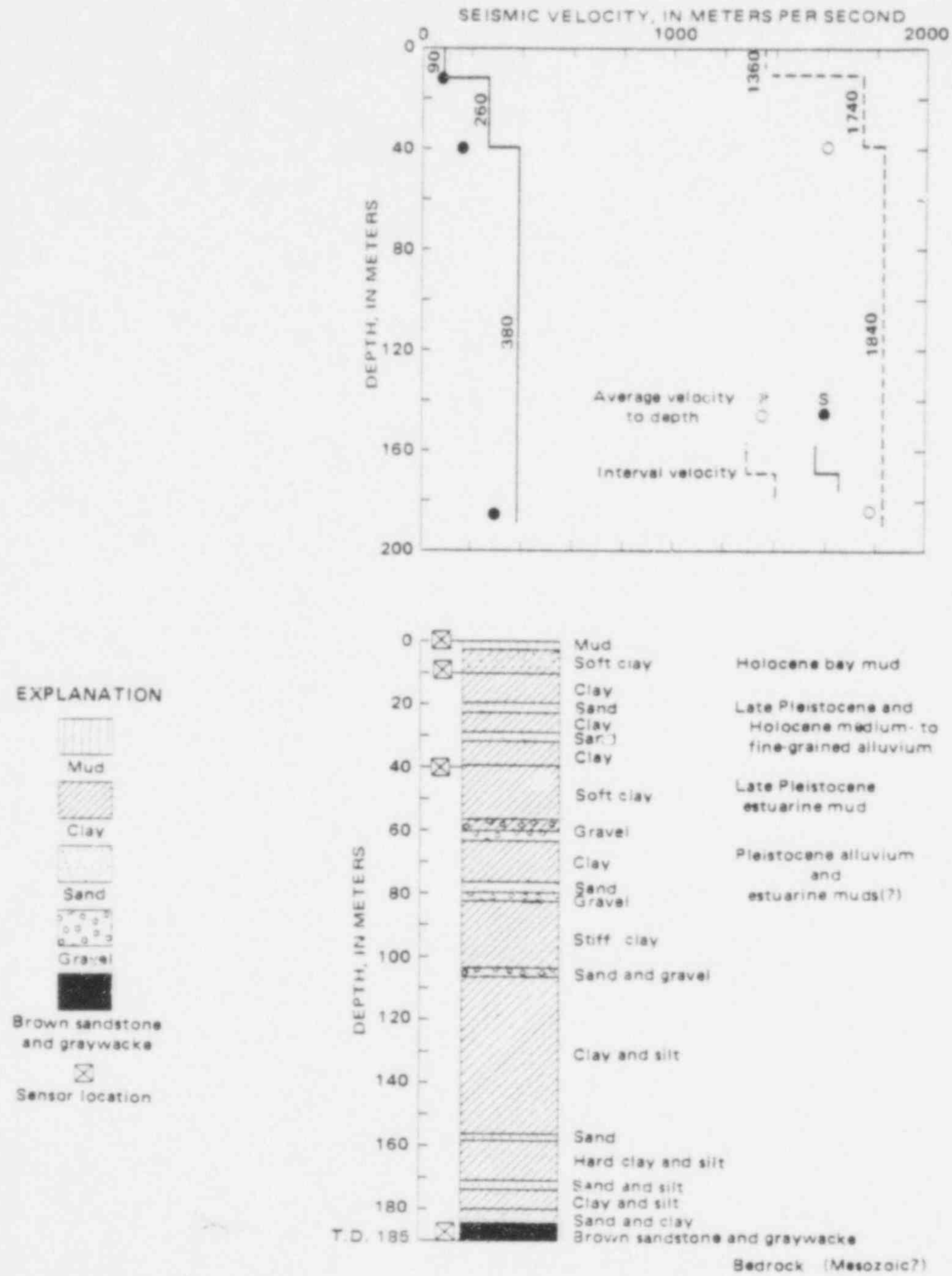

FIGURE 25.—The seismic properties of the rock units at Ravenswood Point, San Mateo County (Warrick, 1974). The schematic vertical section shows the sediments related to depth; the graph shows the change in P-wave and S-wave velocities in relation to depth and age.

◄ FIGURE 24.—Ranges of the relative penetration resistance of the geologic map units. Penetration resistance is measured in the field by the "standard penetration test" that determines the number of blows required by a standard weight (140 lbs, 63 kg), when dropped from a standard height (30 in, 0.76 m), to drive a standard sampling spoon a standard penetration (12 in, 0.3 m). Units with low penetration resistance generally make poor foundation materials. Note that penetration resistance tends to increase with geologic age.

FLOODING

Because the Holocene alluvial sediments were deposited primarily by floods along streams of the present drainage system, there should be a significant correlation between their distribution and the

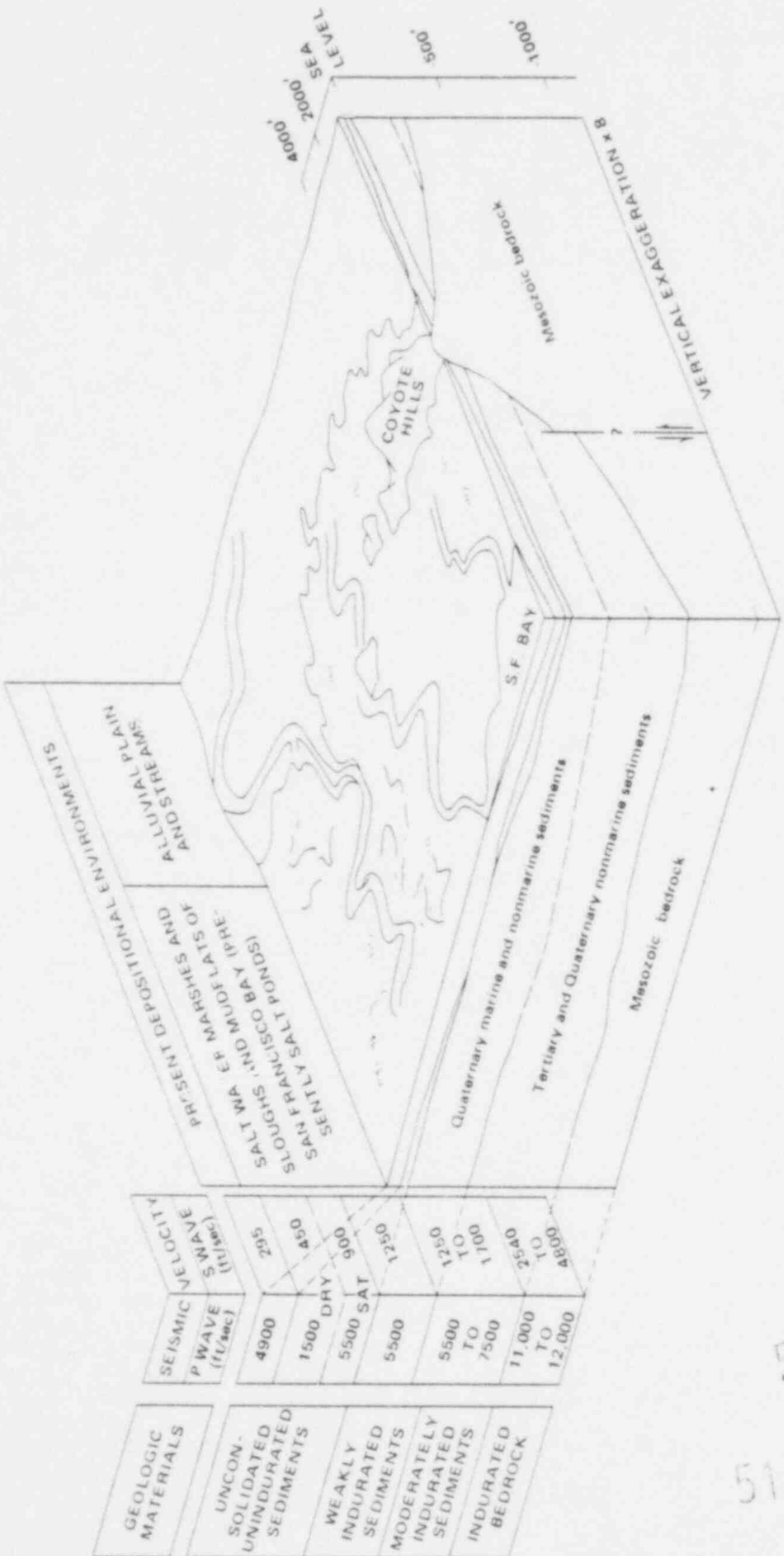

FIGURE 26.—Stratigraphic relations and seismic velocities.

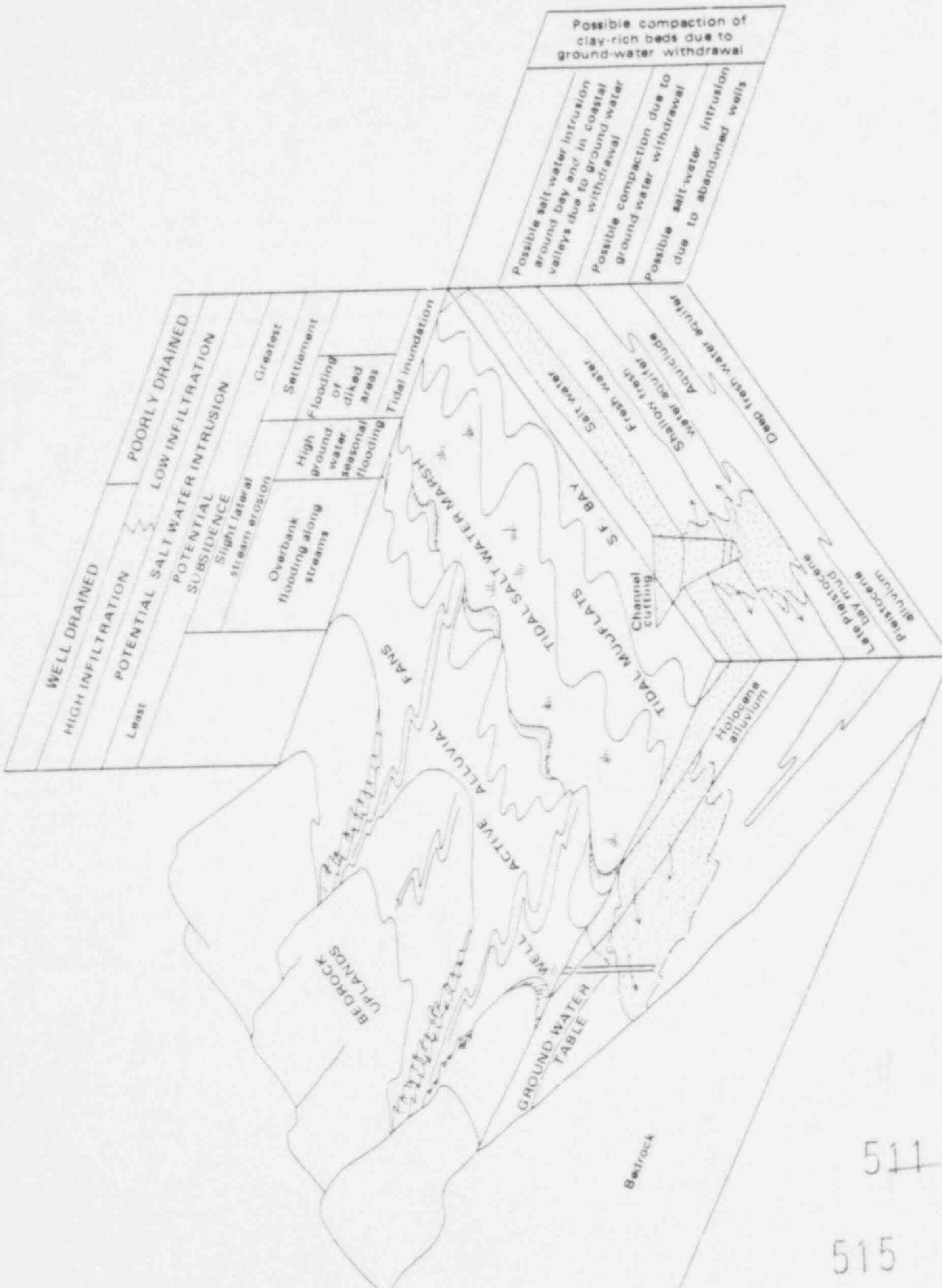

FIGURE 27.—Potential water problems on the alluvial plain bordering San Francisco Bay.

areas inundated by historic floods. A comparison of maps showing the distribution of Holocene deposits (fig. 18) and flood-prone areas derived from historical flood data and hydrographic data (fig. 28) indicates that this correlation is strongest on modern flood plains underlain by the coarse- and medium-grained Holocene deposits and the low floodbasins underlain by fine-grained deposits at the outer edges of the Holocene alluvial fans. Without modern flood-control measures the correlation would probably have been greater in the alluviated areas. As expected, the tidal marshes underlain by Holocene estuarine deposits are flood prone.

The map of flood-prone areas provides a more accurate delineation of areas currently subject to flooding than the flatland deposits map. However, in areas where direct information pertaining to flooding is not available, an approximate delineation of flood-prone areas can be made if the distribution of young alluvial deposits is known. In addition to geologic maps of unconsolidated deposits, such as the flatland deposits map, soils maps showing alluvial materials may be used to locate flood-prone areas.

FIGURE 28.—Flood-prone areas in the San Francisco Bay basin based on distribution of Holocene sediment. The sediments at the ground surface within the shaded areas were deposited predominantly by floodwaters over the past 5,000–7,000 years. After Limerines, Lee, and Lugo (1973).

STREAM CHANNEL CHANGES

Natural lateral stream migration is a slow process generally caused by streambank erosion and occurs most commonly on flat valley floors where streams rework their own levee and flood-plain deposits (principally the coarse- and medium-grained Holocene deposits). However, the channels of most streams have been severely modified by artificial channels and revetments, and lateral migration caused by streambank erosion has been greatly reduced.

Under natural conditions, sudden changes in stream courses may occur on gently sloping alluvial fans and flat valley floors when floodwaters cut through natural levees or when stream channels are filled with flood-borne debris and the stream is diverted. The numerous abandoned natural stream channel and levee systems branching from each other and radiating from the heads of large Holocene alluvial fans indicate that stream course changes were common over the past 5,000 years or so (fig. 17). Many streams, particularly those in the developed areas, have been artificially diverted into buried culverts or fairly straight lined ditches for flood control. Along many other streams natural levees have been built up and streambanks revetted. These and other flood-control practices have virtually eliminated the possibility of sudden stream course changes.

SALT-WATER INTRUSION

Salt-water intrusion or encroachment is the movement of salt water into a ground-water aquifer normally containing fresh water. Encroachment in the bay region is possible only along coastal regions where fresh-water aquifers lie below sea level and are in hydraulic continuity with sea water. Salt-water intrusion is natural in some coastal areas and bay margin where precipitation is low and aquifer recharge from upland areas is insufficient to prevent the sea water from percolating into the aquifer. Salt-water intrusion can also be caused artificially by overdraft of ground-water aquifers that are in hydraulic continuity with ocean water. Figure 29 illustrates four ways fresh-water aquifers may be intruded by salt water.

In the coastal area of central California, precipitation and ground-water recharge are generally sufficient to prevent salt-water intrusion. In the San Francisco Bay region where most ground-water aquifers are unconsolidated sedimentary deposits, salt-water intrusion is possible in alluviated lowlands surrounding the bay and in lower parts of narrow alluviated coastal valleys (fig. 30). In all these areas, aquifers consisting of medium- to coarse-grained alluvium are in hydraulic continuity with salt water but under natural conditions have a sufficient head of fresh water to prevent intrusion.

Salt-water intrusion has affected the shallow aquifers (less than 100 feet (30 m) deep in the southern San Francisco Bay region. Several factors contributing to this condition include decline of pressure in the deep confined aquifers, lowering of the water table in the shallow aquifers, and subsidence, which has lowered stream channels and allowed tidal inflow to penetrate farther upstream and contaminate ground water from the surface (Page and Wire, 1969). Water from shallow wells in the northern Santa Clara Valley commonly contains 100 parts per million chloride but may contain as much as 700 parts per million (Page and Wire, 1969). The chloride content of water from these areas has not changed since it was first recorded in the late 1930's (Tolman and Poland, 1940). Restoring ground-water levels, sealing abandoned wells, and restricting deep dredging in the bay which might expose fresh-water aquifers can eventu-

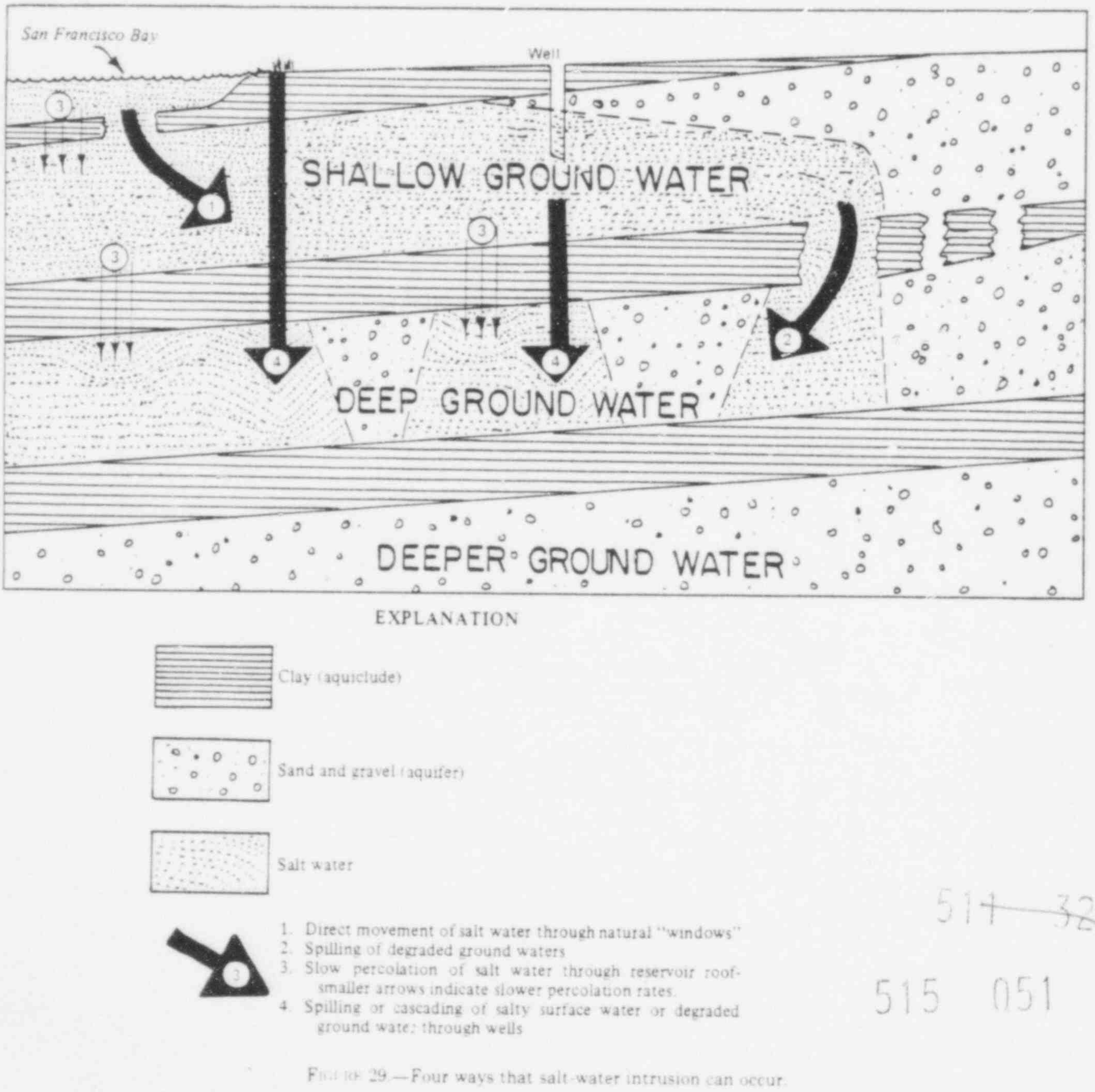

FIGURE 29.—Four ways that salt-water intrusion can occur.

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ally eliminate this problem (Page and Wire, 1969). Man-induced causes of salt-water intrusion in the bay region are (1) overdraft of fresh-water aquifers in hydraulic continuity with ocean water, (2) subsidence of coastal regions owing to withdrawal of liquids or gas, which allows tidal ocean water to

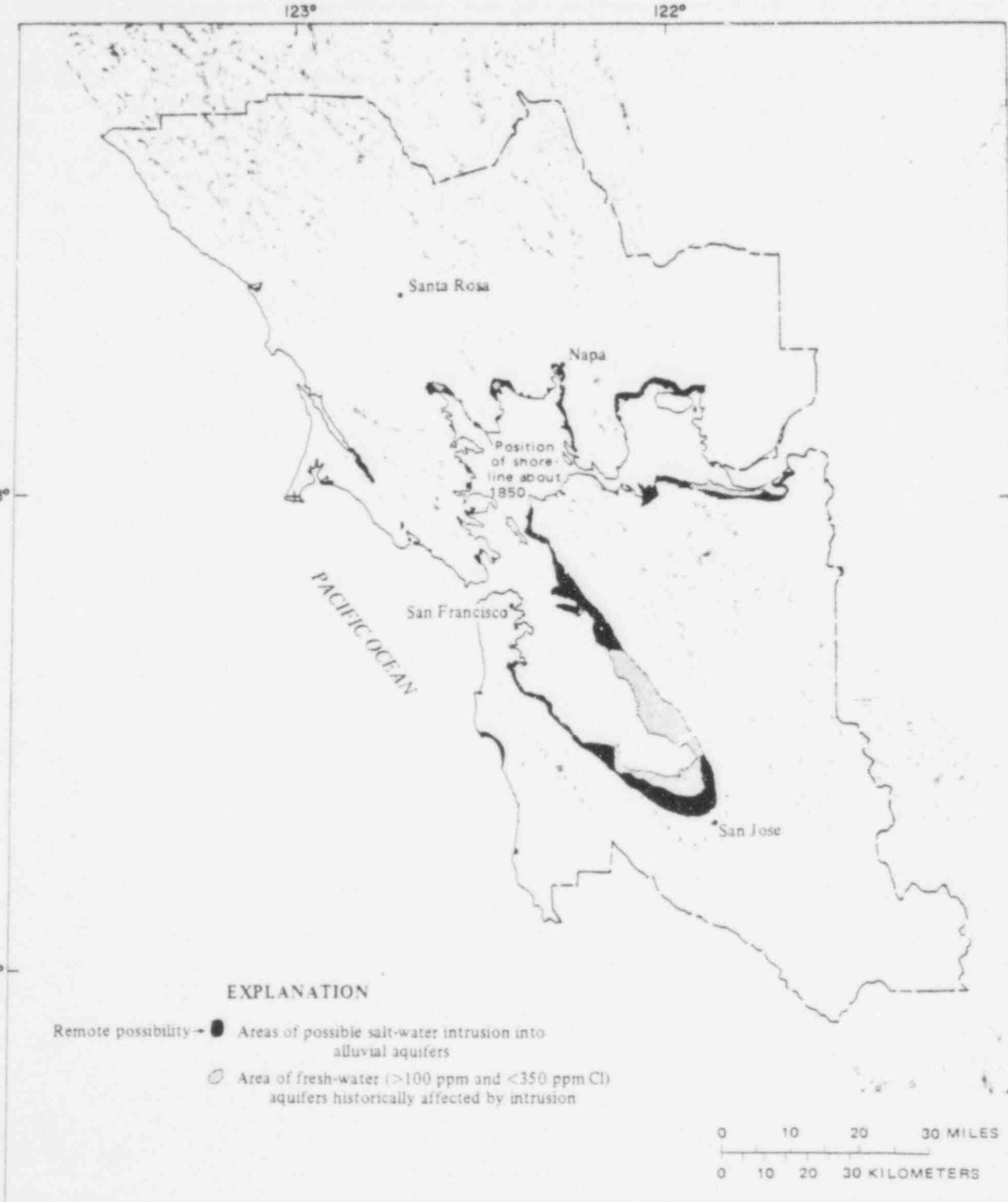

FIGURE 30.—Areas of salt-water intrusion.

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penetrate farther up coastal streams, (3) depletion of discharge of coastal rivers, which allows tidal ocean water to penetrate farther upstream, and (4) penetrating aquicludes beneath estuaries by dredging or drilling, which allows salt water to enter underlying fresh-water aquifers.

SUBSIDENCE

Subsidence is the gradual settling or sinking of an area with little or no horizontal motion. Subsidence is common in flatland areas and creates land-use problems especially in coastal regions if land subsides below sea level.

Subsidence is caused by natural processes such as oxidation, solution, thawing, drying, wetting, compaction of subsurface materials, tectonic downwarping, or by a combination of these factors. The rate of natural subsidence is not known but is so low that it has not significantly affected man's activities in the bay region over the past 200 years.

Subsidence may also be caused by man's activities, such as removal of subsurface solids, liquids, or gases, or by wetting certain types of dry clay-rich sediments resulting in collapse of intergranular supporting structures. Subsidence caused by these processes may be relatively rapid and have significant impact on man's activities. This rapid subsidence is generally not hazardous to human life except where conditions are created that may trigger the failure of a dam or levee. However, subsidence has caused millions of dollars worth of property damage and necessitated expensive protective measures throughout the country.

Within the bay region subsidence primarily is restricted to the flatlands (fig. 31) and is mainly caused by three different processes: (1) collapse of clay-rich beds at depth in the center of the bay region owing to excessive ground water withdrawal, (2) oxidation of peat-rich beds near the surface in the delta region after lowering of the ground water table, and (3) withdrawal of natural gas from Tertiary rocks at depth in the Rio Vista area. Subsidence due to the first two processes is directly related to the character and distribution of flatland deposits.

Subsidence caused by ground-water withdrawal is a major problem in several parts of the bay region. Subsidence in Santa Clara Valley has been described by Poland (1971). The land adjacent to the bay subsided 2-8 feet (0.6-2.4 m) between 1912 and 1967 because of overdraft of water from confined aquifers (more than 100 ft (30 m) deep) (figs. 32 and 33). Dikes and levees have been constructed to prevent flooding of about 30 square miles (78 km²) of salt evaporation ponds and 17 square miles (44 km²) of area landward of these ponds. The public cost, as of 1971, of levee construction due to subsidence was about $9 million, and general cost of repair to water wells damaged or destroyed by compaction was at least $4 million.

The primary cause of the rapid subsidence in the Santa Clara Valley area was the compaction of fine-grained, clayey sediments in the central part of the valley where the ground-water table was lowered drastically by pumping. These fine-grained materials such as clay, silt, and sandy clay, which are compressible and which restrict the movement of ground water, constitute a major part of the valley fill and are most abundant in the central part of the basin. The valley fill around the margins of the basin is incompressible coarser grained material such as sand and gravel which allows ground water infiltration. To a depth of 500 feet (153 m) the deposits at Campbell are about 75 percent gravel, whereas the deposits between Agnew and Alviso to 500 ft are 80 percent clay. The subsidence potential due to compaction of fine-grained sediments is therefore much greater in the central part of the basin than around its margins (fig. 32).

Subsidence in the Santa Clara Valley was virtually halted by 1971 because the water table was raised by an extensive ground water recharge project. Water was imported and stored in percolation ponds located in the permeable deposits (primarily late Pleistocene alluvium) around the southern margins of the basin. Poland (1971) predicts that if ground water management can raise and maintain artesian head at least 20 feet (7 m) above 1971 levels, man-induced subsidence will be stopped permanently in the Santa Clara Valley.

In general the potential for subsidence caused by ground-water withdrawal in flatland regions is greatest in areas underlain by thick sequences of fine-grained sediment and least in areas underlain by a thin veneer of sediment or by coarse-grained deposits. On the basis of this generalization, the potential for subsidence in the bay region is highest in the low central part of the bay basin where bay mud and fine-grained Holocene alluvium are underlain by a thick sequence of similar deposits, and lowest at the high basin perimeter where coarse-grained sediments at the surface are underlain by thick sequences of similar deposits. Such a generalization can serve only as a very rough approximation of possible problem areas, which need to be investigated in more detail. Many other factors, particularly man's activities, influence the occurrence and rate of subsidence. It should be emphasized that compaction of fine-grained deposits makes subsidence irreversible, hence it is extremely important to avoid an overdraft of the ground water in the first place.

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Subsidence primarily caused by oxidation and compaction of artificially drained peat deposits as much as 40 feet (12 m) thick, which underlie about 450 square miles (1,165 km²) of the Sacramento-San Joaquin delta, affects a small area in the eastern part of the San Francisco Bay region (Weir, 1950). Peat is

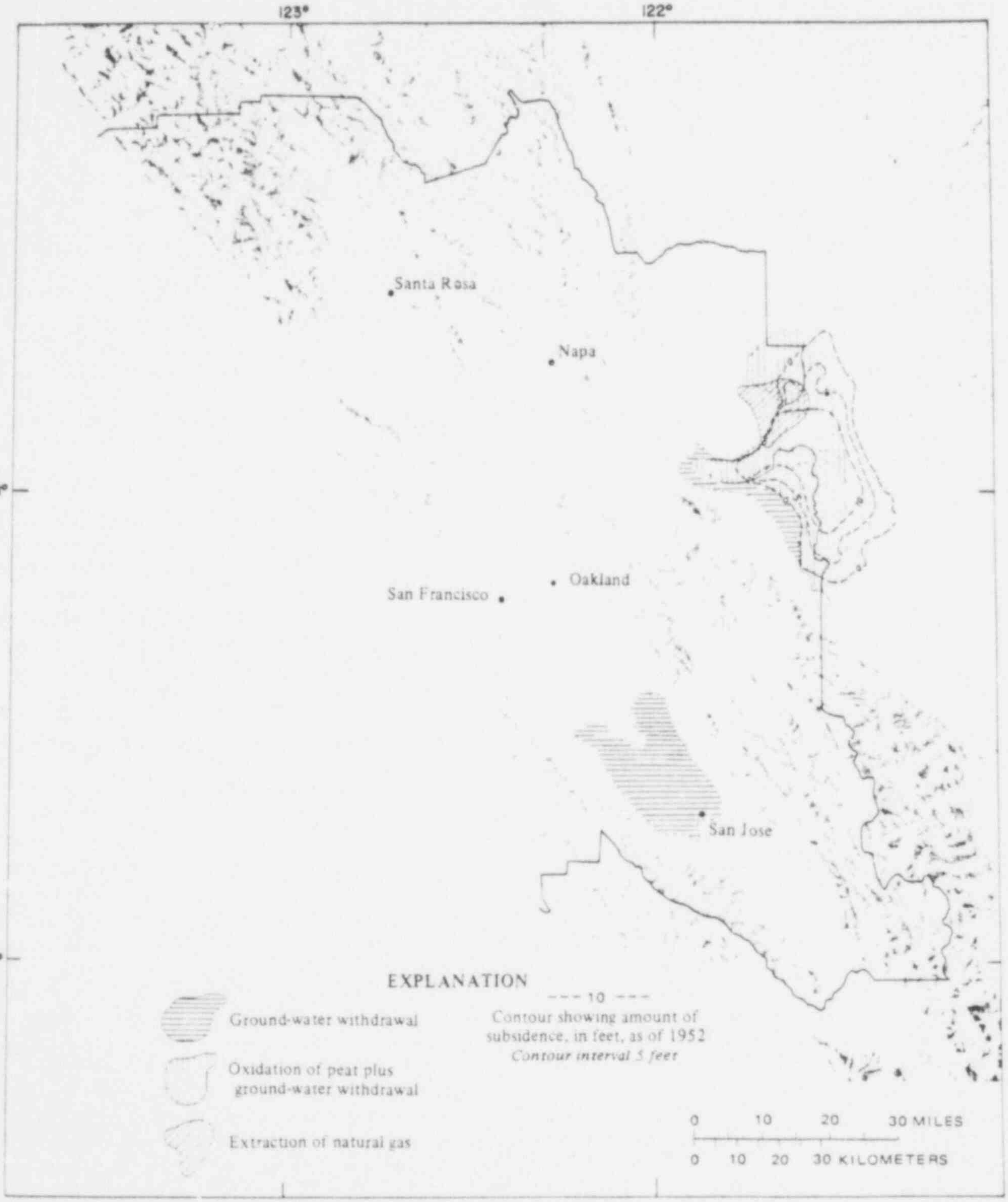

FIGURE 31.—Areas affected by subsidence.

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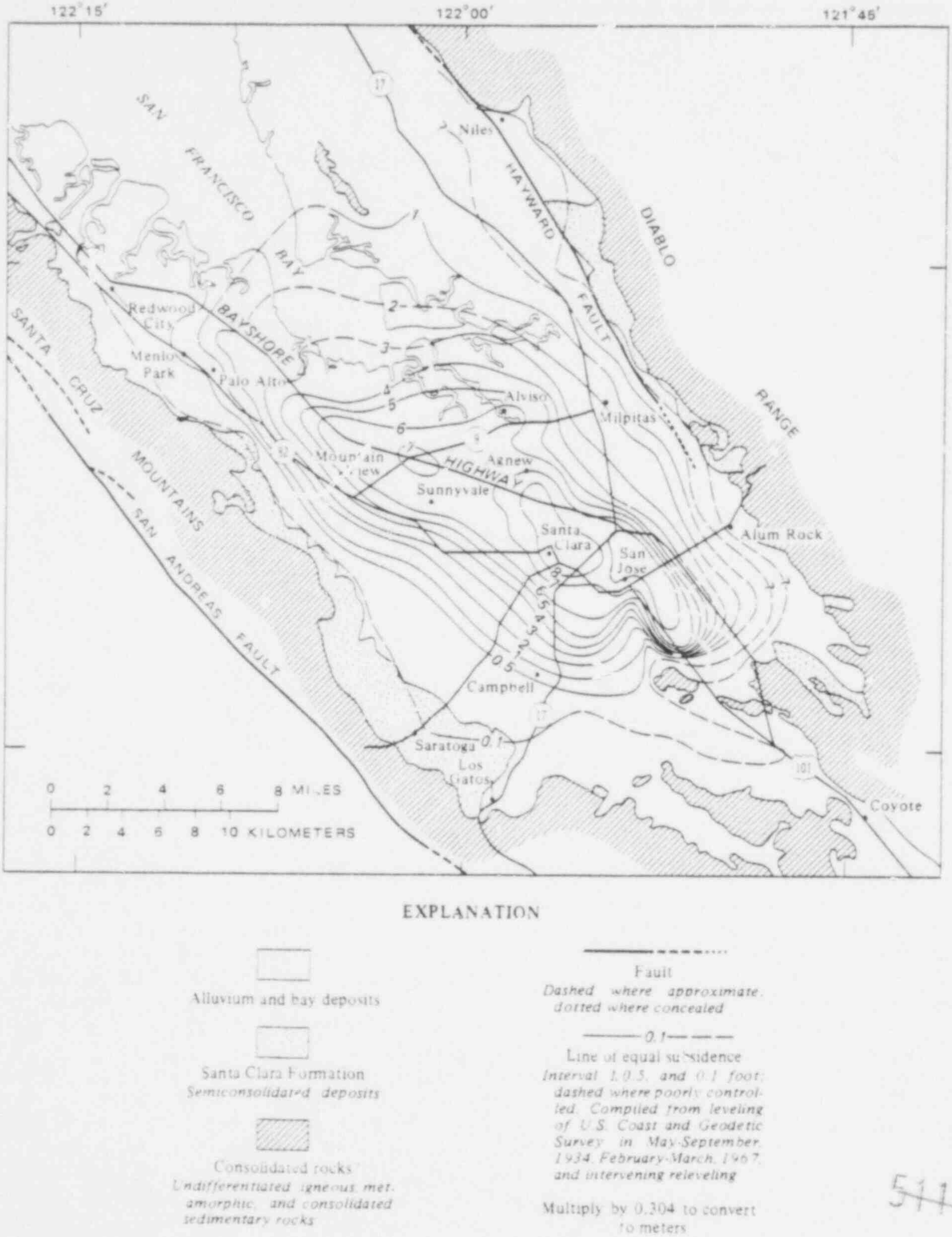

FIGURE 32.—Land subsidence from 1934 to 1967, Santa Clara Valley, California (Poland, 1969).

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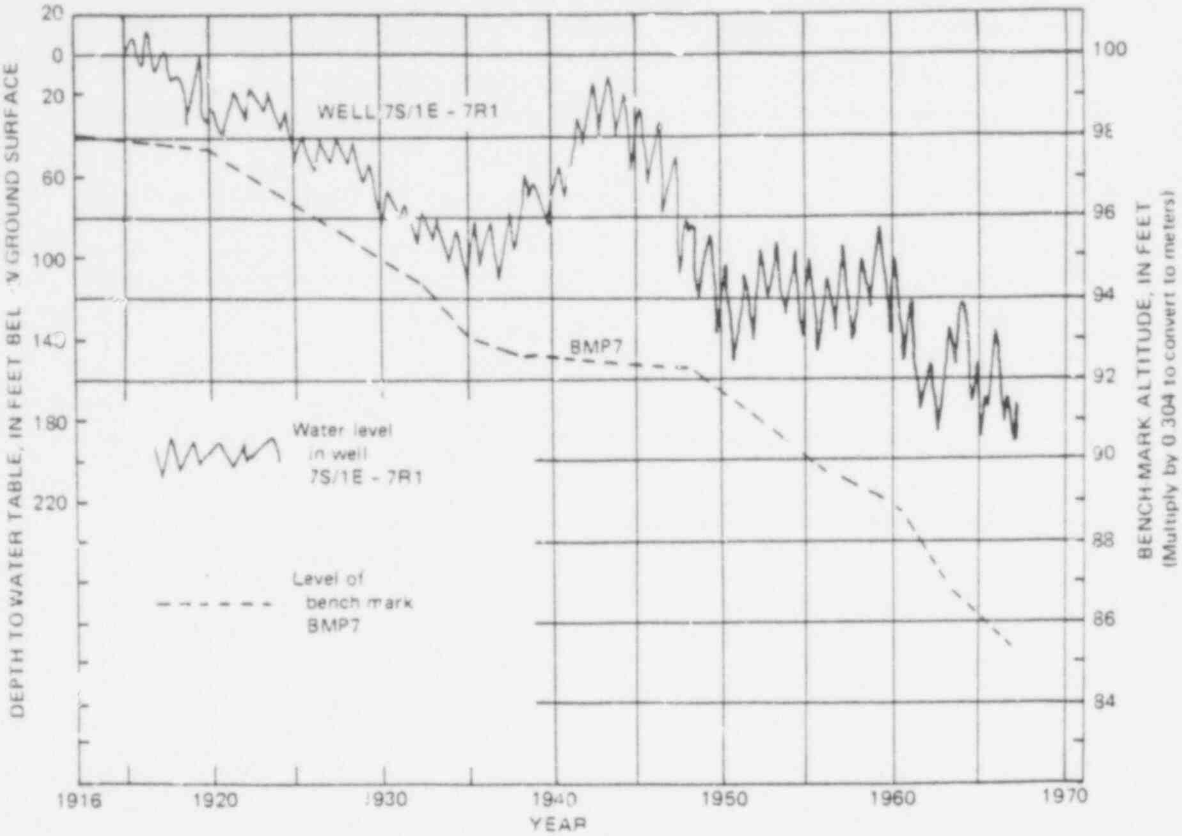

FIGURE 33.—Change in altitude at bench mark BMP7 in San Jose and change in water-table level in nearby well (from Poland, 1971). Note the close correspondence with time between the drop in water level and bench mark BMP7. Note that the scales for water level and bench mark level are different. The water table dropped almost 200 ft (60m) between 1925 and 1967, which resulted in a 13 ft (4 m) subsidence of the bench mark.

an unconsolidated deposit of partially carbonized marsh or bog plant remains with a high water content. Peat generally accumulates under acidic conditions in quiet water where there is little bacterial activity. Subsidence in areas underlain by peat-rich sediments is caused by drainage, which results in shrinkage from drying, oxidation, and wind erosion (Weir, 1950). Compaction by farm machinery and burning also contributes to subsidence in these drained, peat-rich sediments.

The total subsidence pattern in the delta area is complicated because subsidence due to ground water withdrawal is occurring throughout much of the delta region and subsidence due to natural-gas extraction from bedrock units is occurring around Rio Vista (fig. 31). The proportion of subsidence due to each process is not presently known. The subsidence due to gas extraction is not related to the flatland deposits but contributes to a serious local problem.

The main problem created by subsidence in the delta region is flooding where low flatland areas have sunk below sea level. Several parts of the delta have flooded in recent years, and the flood potential becomes greater as subsidence continues.

Three tracts of land adjacent to Contra Costa County—Bacon Island, Mildred Island, and Roberts Island—which were originally at or slightly above sea level were between 10 and 11 feet (3.0-3.4 m) below sea level (fig. 34). Between 1922 and 1946 these three islands subsided at rates between 0.2-0.3 feet (0.06 m-0.09 m) per year. The most recent data on the subsidence in the delta were published in 1948. Unfortunately no later data are available. An extensive network of dikes is needed to protect the islands from flooding. Dike failure during high tides and periods of heavy runoff has resulted in flooding of extensive areas. In 1952 the levees on Franks Tract in eastern Contra Costa County failed and the island was flooded. This island was not drained after the flood and is now a state recreation area used for sport fishing. In the winter of 1968-69 a section of levee on Sherman Island failed and the island was flooded (Poland, 1969). This island was inundated by floodwaters again in the winter of 1970-71. The potential for flooding is even higher during earthquakes when levee failure may be extensive.

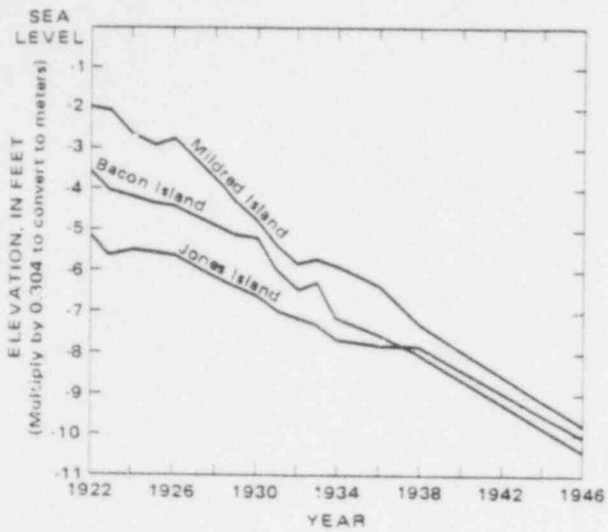

FIGURE 34.—Progressive subsidence of Mildred, Bacon, and Jones Islands in the Sacramento-San Joaquin delta primarily due to peat oxidation between 1922 and 1946 (from Weir, 1950).

Levee-maintenance problems will increase in the delta region as continued drainage for cultivation lowers the land surface farther (Poland, 1969). Total subsidence will be greatest in those areas where the proportion of peat to mineral detritus in the sediment is highest. In some areas where peat constituted only a small part of the accumulated sediment and has been completely oxidized, subsidence may have ceased or is at least greatly reduced. Where peat has been completely depleted, the residual mineral silt and sand are still rich in organic nutrients and make excellent agricultural soil.

SETTLEMENT

Settlement is the gradual downward movement of an engineered structure due to compaction of the unconsolidated material below the foundation. Settlement is most extreme over mud and loose fine-grained sediments (clay and silt) having a high water content. If the load of an engineered structure is relatively small or is emplaced gradually, the water in the voids between the silt and clay grains can escape slowly until the grains are in sufficiently close contact to carry the load and resist further compaction. In this case the settlement of an engineered structure would be relatively slow and would eventually cease. If the load is relatively large or applied suddenly, the high pore water pressures produced in the underlying mud will reduce the shear strength of the mud, which may result in failure. Under these conditions the mud may flow laterally out from under the load and produce bulges or mud waves around the sinking structure. It is likely that both these processes work simultaneously but at different rates under real but variable conditions. In any case the rate of settlement is usually most rapid immediately after loading and gradually decreases with time. The total amount of settlement that may occur is dependent on the physical properties of the sediment, its thickness, laterally confining conditions, and the size and distribution of the load (fig. 35).

The deposit that most frequently is associated with settlement problems in the San Francisco Bay region is the fine-grained Holocene estuarine mud. The extremely low shear strength of this loose, water-saturated material, which is a major cause of settlement, is reflected in its low shear-wave velocities, around 300 ft/sec (90 m/sec) (figs. 25 and 26). Lee and Praszker (1969) review the causes of settlement and discuss several case histories in the bay region.

Settlement problems are usually associated with structures placed on artificial fills overlying thick deposits (>10ft, 3 m) of bay mud. Structures placed on piles founded on secure materials beneath bay mud may also have problems if the surrounding region settles and leaves the structure stranded above grade. This problem is particularly serious at the Alameda Naval Air Station where ramps have been built to maintain access to several buildings (case history 3, Edgar Becker, in Lee and Praszker, 1969).

If a structure on artificial fill settles uniformly, the major problems created are poor drainage and failure of rigid subsurface utility connections. If one part of a structure settles more or at a different rate than another part—differential settlement—mechanical components such as doors and elevators may no longer work, but more importantly the structure itself may be seriously weakened. Structures weakened by differential settlement may not perform well, particularly during earthquakes. Structural weakening due to differential settlement prior to and during earthquakes may be the main cause of the greater observed damage to buildings on artificially filled land over unconsolidated mud (Steinbrugge, 1969). Modern engineering practices can minimize the effects of settlement, but the costs of mitigating measures are high, and there is still the greater likelihood that an average modern building on bay fill will have greater preearthquake stresses within it then will a similar building on structurally firm ground (Steinbrugge, 1969).

Some of the most severe settlement problems in the bay region exist in the low basin areas of San Francisco, the Embarcadero waterfront, (Lee and Praszker, 1969) (fig. 36), and the Mission basin (Steinbrugge, 1969) (fig. 37). In these areas structures were

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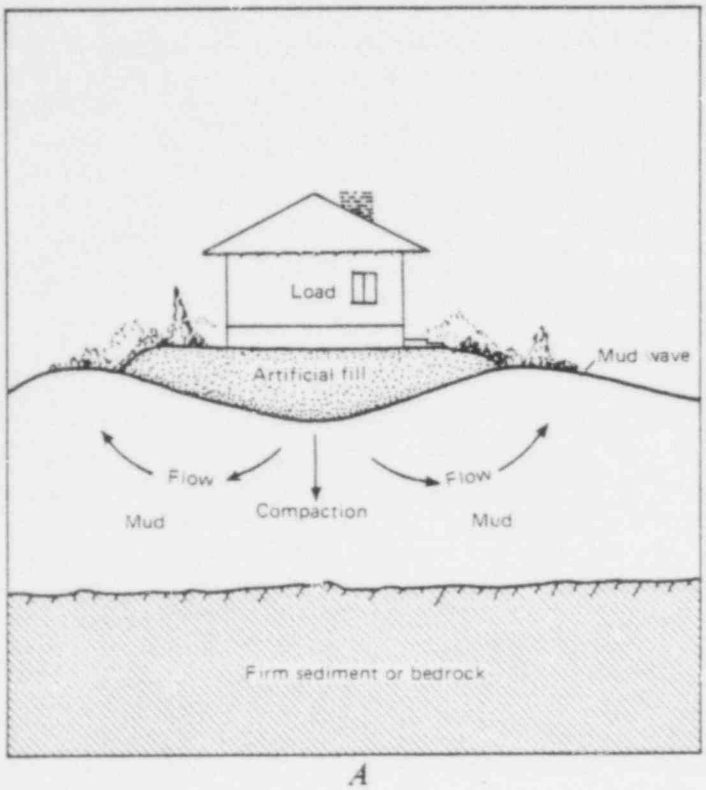

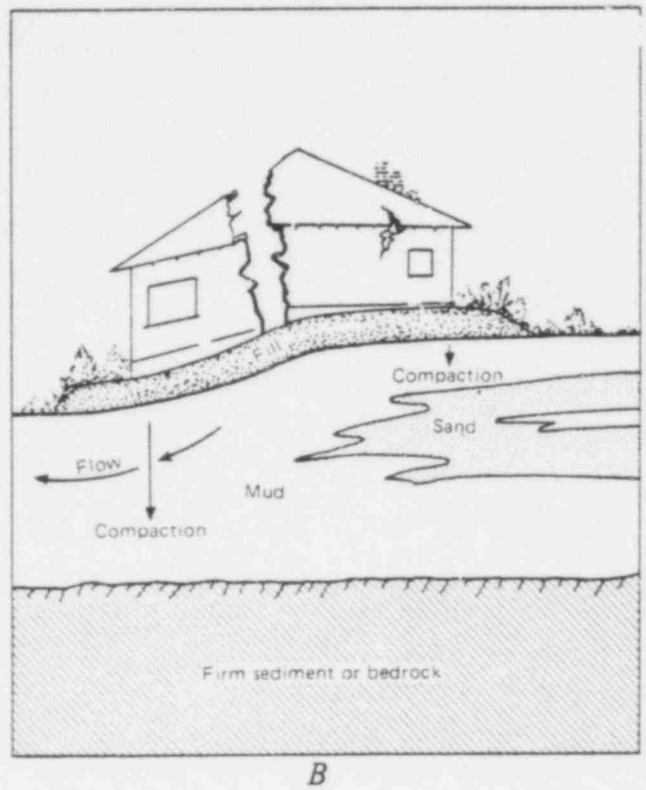

FIGURE 35.—Diagrammatic cross sections showing examples of settlement. A, Settlement of an engineered structure placed on artificial fill overlying mud that has low shear strength. B, causes and effects of differential settlement. The lateral variability in the underlying mud results in differential settlement, which may damage the engineered structure.

built on randomly placed fill, consisting principally of rubbish, overlying Holocene bay mud.

Settlement problems also occur on more recently placed fills overlying the bay mud at the toll plaza of the San Francisco-Oakland Bay Bridge, Treasure Island, and the Alameda Naval Air Station (Lee and Praszker, 1969). The phenomenon of differential settlement is clearly observed and felt along freeway segments constructed on engineered fills overlying bay mud, such as the Candlestick Causeway in South San Francisco, where the flexible asphalt road surface is deformed into a series of low-amplitude waves. Small offsets in runways caused by minor differential settlement are a continuous maintenance problem at airports built on fill overlying bay mud.

Differential settlement has also created problems in some residential communities built on artificial fills overlying bay mud. A recently constructed apartment complex in Larkspur along Corte Madera Creek was severely damaged by settlement and had to be abandoned (Brewer, 1973). Several homes in Foster City, which is built on artificial fill overlying bay mud along the bay shore of San Mateo County, are beginning to show signs of structural damage caused by differential settlement.

SHRINK-SWELL

Shrink-swell is a cyclic change in volume that occurs in fine-grained sediments because of expansion and contraction of clay caused by wetting and drying (fig. 38).

The potential for shrink-swell problems in the bay region is highest in areas underlain by the Holocene bay mud and the fine-grained Holocene basin deposits, which contain high quantities of expansive clay derived from the uplands by erosion. The Pleistocene alluvial deposits may contain large quantities of expansive clay at the surface. (This clay was formed in place by weathering.) The coarse- and medium-grained Holocene alluvial deposits contain less detrital expansive clay and are not intensely weathered, therefore, they have moderate or low shrink-swell problems.

Because of the relatively minor economic losses resulting from shrink-swell conditions on alluvial deposits, this problem is usually ignored in determining land uses; however, large economic losses have occurred on such soils formed on bedrock (Meehan and others, 1975). Shrink-swell problems can usually be overcome with proper foundation engineering. The main effect, therefore, is on the cost of construc-

FIGURE 36.—Settlement of the land surface on the San Francisco waterfront. From Lee and Praszker (1969).

tion in areas underlain by clay-rich deposits with shrink-swell potential.

SEISMIC HAZARDS

SEISMIC RESPONSE

Seismic response is the total reaction of a particular area to earthquake shaking. Therefore, seismic response includes the type and intensity of ground shaking, permanent changes of elevation (uplift and subsidence), temporary changes of condition such as liquefaction, and ground failure, lurching, lateral spreading, and landsliding (fig. 39). The level of ground shaking at a particular site depends on distance from the epicentral region and local geologic conditions. In regions underlain by bedrock, ground shaking will be greatest at the epicenter and decrease with distance away from the epicenter. In regions underlain by thick sequences of unconsolidated sedimentary deposits, certain frequencies of ground shaking may be amplified above bedrock levels ow-

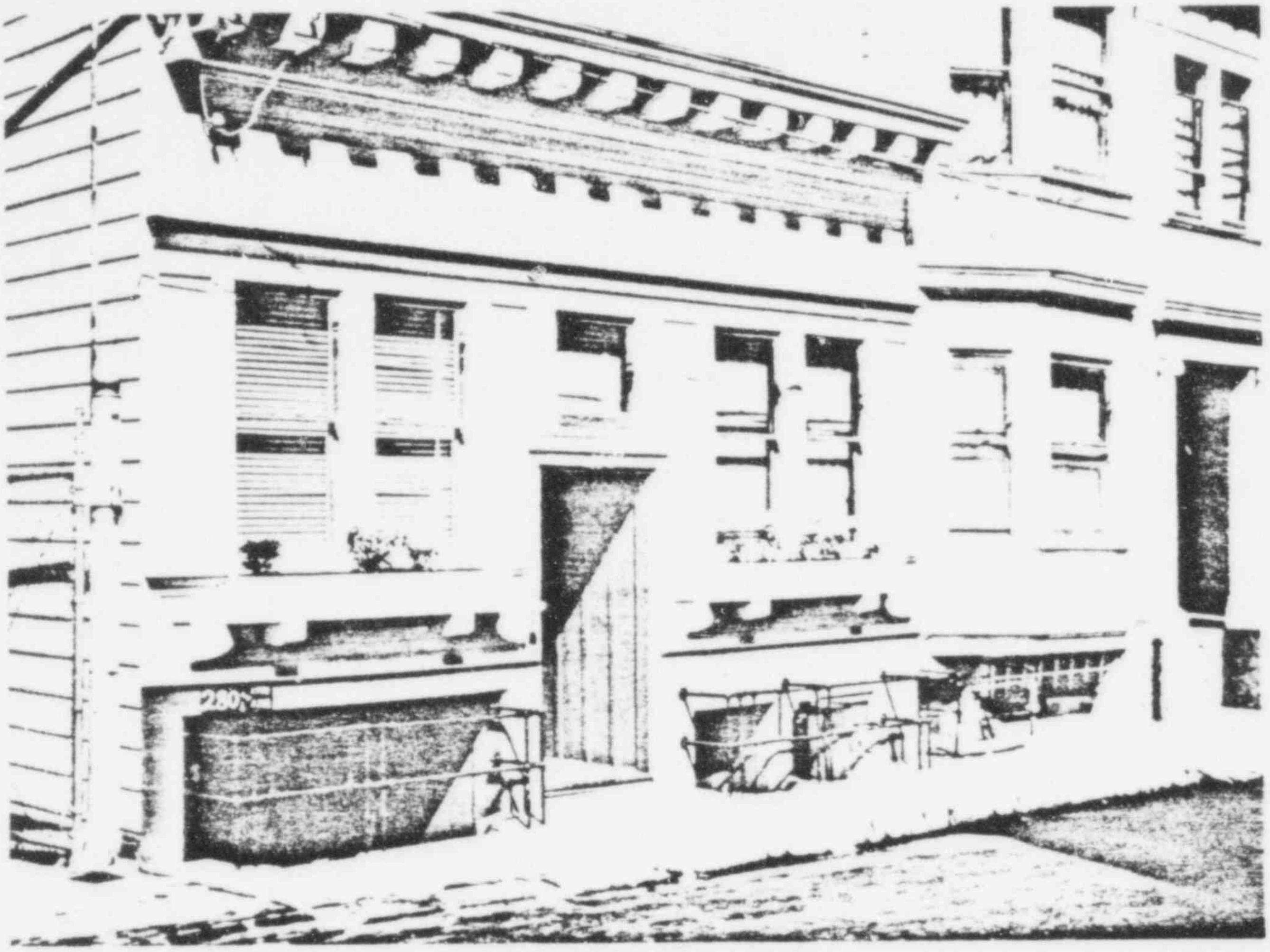

FIGURE 37.—Subsidence of San Francisco buildings built on filled ground that was formerly swamp. Street and sidewalk have been raised by additional fill; the top of the garage door on the left side of the house is now only about 2 feet (0.6m) above the sidewalk (California Division of Mines and Geology, 1966, p. 452).

ing to resonance and impedance contrasts. The block diagram (fig. 39) summarizes potential seismic hazards from the bedrock uplands downslope across the alluvial plain and across the tidelands into the bay itself. In this example, seismic energy originates at the San Andreas fault zone and is attenuated in the bedrock with distance from the fault. Seismic amplifications at the land surface on different materials—alluvium and bay mud, for example—may differ from the bedrock amplification in response to conditions described in the following section.

SEISMIC AMPLIFICATION

Medvedev (1965) showed that seismic impedance (defined as the product of S-wave velocity and bulk density, $V_s \times \rho$) can be used roughly to predict relative ground response. The potential for seismic amplification increases as the impedance contrast between adjacent layers increase if other parameters such as stratigraphic thickness are constant. Because thickness is important, downhole measurements are necessary to help predict amplification. Amplification of seismic waves from nuclear test blasts was measured at three surface sites (fig. 40), and amplification of horizontal ground motion generated by the San Fernando earthquake of February 1971 was measured at a downhole site at Ravenswood Point, San Mateo County (fig. 41). The trend of the amount of amplification recorded at the three different surface sites is quite similar to the trend of the amplification measured at different levels at the downhole site.

Density, S-wave velocity, and therefore impedance of geologic units increase with age (fig. 42).

The Holocene bay mud has the lowest impedance owing to both its low density and its low S-wave

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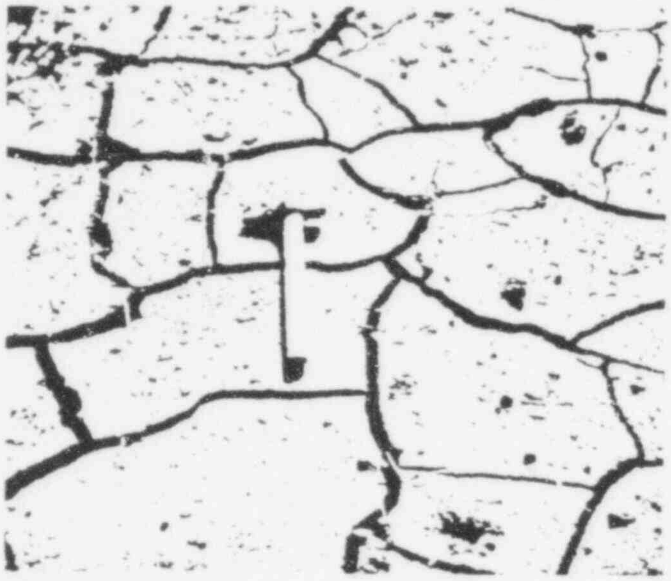

FIGURE 38.—Surface cracks formed in clay-rich sediments due to shrinkage during desiccation. When these sediments are again wetted, the expansive clay (mostly montmorillonite) will absorb water and expand, thus causing a change in volume that will close these cracks and elevate the surface slightly. Movement caused by this cyclic change in volume may be damaging to improperly designed structures. Young unweathered coarse-grained deposits generally have low clay content and therefore have low shrink-swell potential. Older, deeply weathered coarse-grained deposits may contain high concentrations of clay in the B-horizon of soils developed on them, and therefore, may have a moderate to high shrink-swell potential.

velocity. The three facies of the loose Holocene alluvium (pl. 1, 2, and 3) have very similar physical properties and therefore are combined into one geologic unit; this unit has only slightly lower impedance values then the weakly consolidated late Pleistocene alluvium. The variability of physical properties within and between the bedrock units is reflected in their relatively wide range of moderate to high impedance values.

The schematic cross section in figure 42 shows the generalized stratigraphic relations in the southwestern bay region with the high impedance contrasts between units represented by slightly heavier contact lines. Considering only the impedance contrasts, amplification of bedrock motion would be expected to be low to moderate where bay mud overlies late Pleistocene alluvium or where Holocene alluvium overlies Pliocene and early Pleistocene alluvium. The impedance data suggest that the highest levels of amplification would occur where thick deposits of bay mud directly overlie Franciscan bedrock.

Because seismic amplification is dependent frequently on and therefore controlled by other factors such as stratigraphic thickness, predicted amplification potential using only impedance data is not very precise. These crude predictions are consistent, however, with comparative low-strain ground motion measurements which show that the highest amplification occur on bay mud sites. It is probably significant that four of the generalized geologic units with distinct low-strain amplifications roughly correspond to the four groups of geologic units with similar impedance values (groups separated by heavy lines in figure 42).

Combining the geologic units into groups with similar impedance values provides a useful means of evaluating earthquake intensity data and low-strain-level response data. For example, if deposits with similar impedance values behave differently in an earthquake, other variables such as stratigraphic thickness might be investigated. Borcherdt, Gibbs, and Lajoie (1975), using intensity data from the 1906 San Francisco earthquake, amplification spectra from nuclear explosions, and seismic properties of the geologic map units, produced a map showing estimated relative intensities of ground shaking that would be produced in the south San Francisco Bay region by a large earthquake on either the San Andreas or the Hayward fault (fig. 43).

Although we cannot now predict when, where, and how great the next earthquake will be, we can for planning purposes anticipate where the effects of ground shaking will be severe. That this can be done may be seen in the comparison between local geology and earthquake damage for the February 1974 earthquake in Dunedin, New Zealand (figs. 44 and 45). Areas experiencing greatest damage are commonly underlain by loose unconsolidated sediments, Holocene estuarine mud, and Pleistocene and Holocene alluvium.

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LIQUEFACTION POTENTIAL

Liquefaction is defined as the transformation of a loose, water-saturated granular material such as sand from a solid state to a liquefied state as a consequence of increased pore-water pressure (Youd and others, 1973). In the solid state, the sand grains are touching each other and the weight of any overlying material is supported by these intergranular contacts. In a liquefied state, the sand grains lose contact, usually only momentarily, and the weight of any overlying material is transferred to the water, which is incompressible, filling the spaces between sand grains. In this state the sand can flow like a fluid but will do so only if it is not confined. This description of liquefaction defines liquefaction as a transformation process rather than the actual flow of liquefied material (or ground failure) that might

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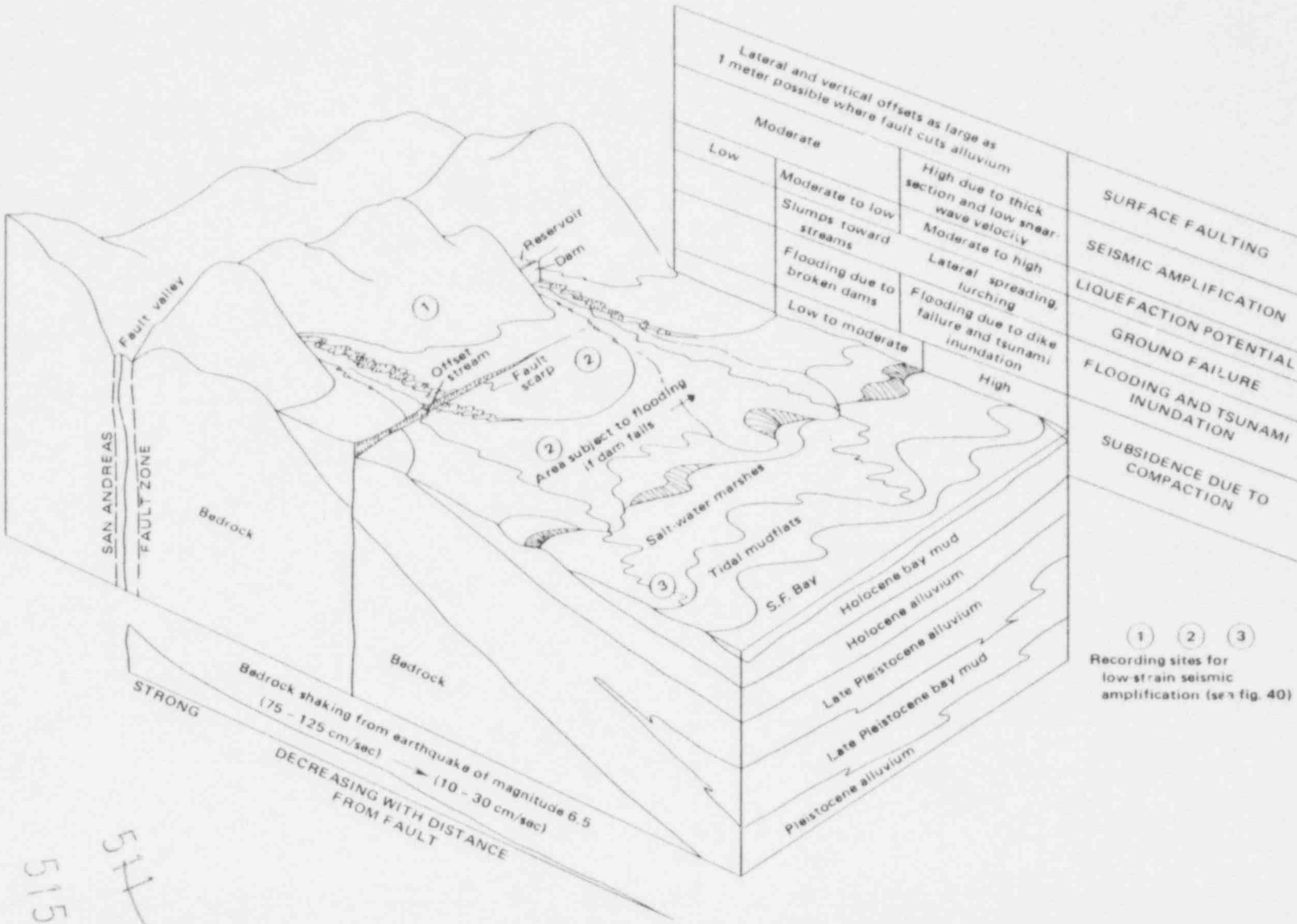

FIGURE 39.—Potential seismic hazards on the alluvial plain and near the bay.

result from this flow. Therefore, a potential for liquefaction does not necessarily imply a similar potential for ground failure.

A major cause of liquefaction is ground shaking during earthquakes. Seismic shaking raises the pore-water pressure repeatedly so that the sand grains are momentarily forced apart. The geologic materials most likely to liquefy during an earthquake are loose water-saturated well-sorted (i.e., little or no clay-size material present) silt and sand lying within about 100 feet below the ground surface (Youd and others, 1975). At greater depths the pressure from the weight of the overlying materials is generally too high to be overcome by the seismically induced increased fluid pressures, and liquefaction rarely occurs.

If a bed of silt or sand liquefies during an earthquake and can flow toward a free face such as a cliff or down a gentle slope, ground failure may occur.

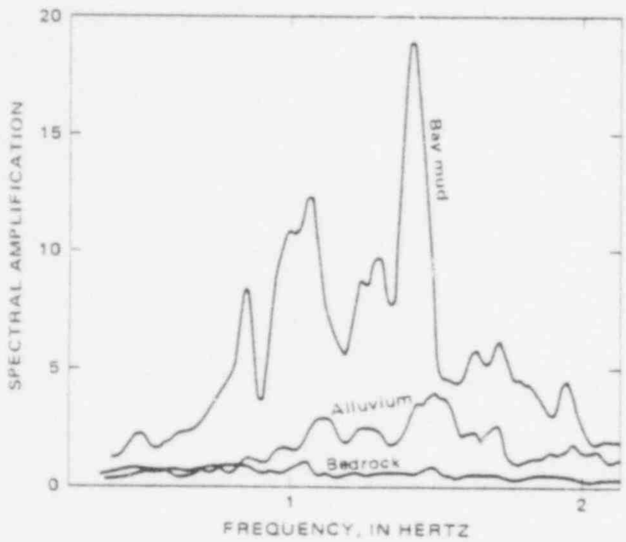

FIGURE 40.—Seismic amplification (Gibbs and Borcherdt, 1974). This diagram illustrates the effect of local geology on ground motion. Seismic waves generated in Nevada by underground nuclear test blasts were recorded at three different sites in the southern San Francisco Bay region. Site 1 was on bedrock, site 2 was on a thick sequence of alluvial deposits, and site 3 was on bay mud. The bedrock signal was slightly amplified where it traveled upward through a thick sequence of alluvium. This same bedrock signal was amplified even more where it traveled upward through a thick sequence of alluvium and then through a layer of bay mud. Note that the seismic waves with frequencies between 1 and 1.5 hertz were amplified the most. The seismic waves recorded at these three sites were so small that they could not be felt. For seismic waves that are large enough to be felt, the amplification ratios most likely would be smaller than those illustrated here, but the general relation of bay mud amplifying more than alluvium would be maintained.

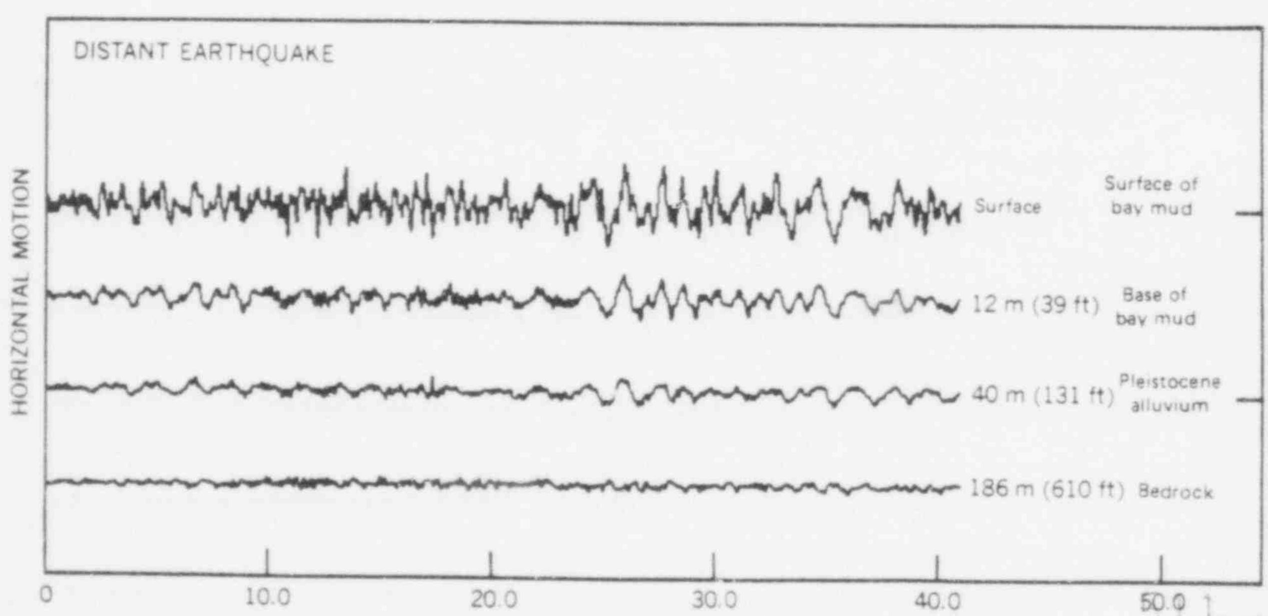

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FIGURE 41.—Horizontal ground motions at Ravenswood site recorded on downhole seismometers from a distant earthquake (Borcherdt, Joyner, Warrick, and Gibbs, 1975). The horizontal motions of the bedrock were amplified significantly as they traveled upward through the 571 feet (174 m) of weakly to moderately consolidated alluvium and 39 feet (12 m) of unconsolidated estuarine mud. Note that the trend in amplification at this one site is similar to the trend observed on three different sites (fig. 40).

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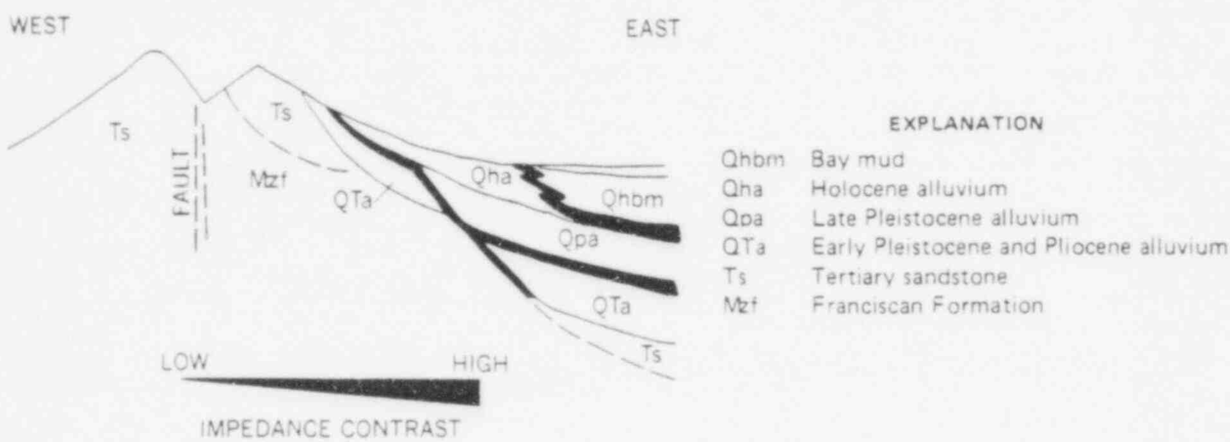
Severe and extensive ground failure occurred during the 1906 San Francisco earthquake in the Monterey Bay region where large areas along the Pajaro and Salinas Rivers shifted laterally due to liquefaction and the flow of sand and silt beds underlying the river banks (Youd, 1975). At several localities in this area, liquefied sand flowed upward through cracks to the ground surface and formed small volcanolike craters. Also during the 1906 earthquake, ground failure was extensive in Colma Valley in south San Francisco where liquefied alluvium caused lateral shifting of several tens of feet down the gentle slope along the axis of the valley (Youd, 1975).

Liquefaction-induced ground failure can also occur on level ground if the liquefied material is unevenly loaded. In this case the liquefied sand may flow out from under the area bearing the heaviest load. Tall apartment buildings in Niigata Japan, toppled over during an earthquake in 1964 because sand beds beneath them liquefied and could not support the uneven load of the buildings.

Areas that are potentially liquefiable can be mapped if the physical properties of the sediments are known or can be reasonably inferred. Beds of loose water-saturated well-sorted silt and sand have the highest liquefaction potential, and beds of dry, poorly sorted, well-indurated sediment have the lowest liquefaction potential (fig. 46). A map of liquefaction potential for moderate to large earthquakes in the southern San Francisco Bay region (Youd and others, 1975) was produced using standard penetrometer data to assess relative density of the geologic units mapped by the present authors and by Webster (1973). The saturated clay-free coarse silt and sand with relative densities less than 65 percent (poorly consolidated) are considered to have high liquefaction potential even in a moderate earthquake (M4–6.5). Water-saturated clay-free sediments



Unit	Thickness (m)	Relative bulk density, ρ (g/cm³)	Penetration resistance[1] (blows/ft)	P-wave velocity, V_p (m/sec)	S-wave velocity, V_s (m/sec)	Impedance, $V_s\rho$
Qhbm	0–36	1.3–1.7	0	*1400* [2]	90–130 [3]	117–153
Qha	0–15	1.9	20–80	300–600 [4]	*200–300*	380–*570*
Qpa	10–45	2.1	100	1500–2100	200–400 [5]	420–*630*
QTa	0–250?	2.0	100-refusal	2500	*1200*	*2400*
Ts	0–*300*	2.4	Refusal	1500–3300	500–*1400*	*1200–3360*
Mzf	......	2.7	Refusal	2800–4000	*1400–2000*	*3780–5400*

[1] Test used 140-lb hammer droppec 30 in.
[2] Figures in italics are estimated values
[3] From Warrick (1974)
[4] Above water table. Below water table V_p = 1500–1700
[5] R. E. Warrick (oral commun., 1974)

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FIGURE 42.—Schematic cross section of southwestern San Francisco Bay and description of certain physical properties of the generalized geologic units (Lajoie and Helley, 1975, fig. 31).

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with relative densities greater than 90 percent (highly consolidated) are considered to have low liquefaction potential, even in a major earthquake. Saturated clay-free sediments with relative densities between 65 and 90 percent have moderate liquefaction potential that depends on intensity and duration of ground

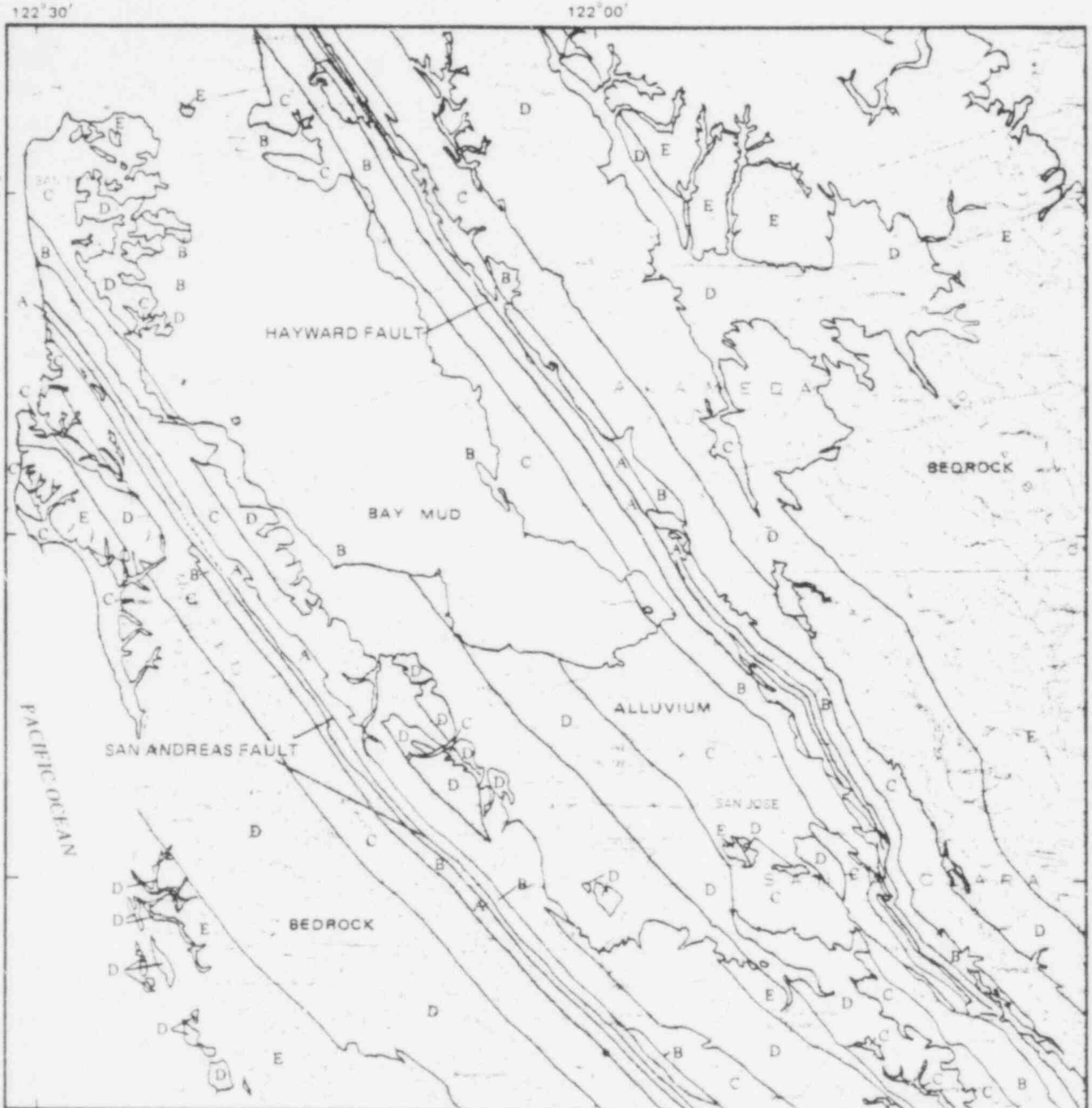

FIGURE 43.—Estimated relative intensities of ground shaking in the south San Francisco Bay region from large earthquakes on the San Andreas and Hayward faults (Borcherdt, Gibbs, and Lajoie, 1975). 1906 San Francisco earthquake scale of Wood (1908): (A) Very violent, (B) Violent, (C) Very strong, (D) Strong, (E) Weak. Note that areas of violent intensity (B) lie immediately adjacent to the faults in the regions underlain by bedrock but lie at successively greater distances from the faults in areas underlain by alluvium and bay mud. This broadening of the higher intensity zones is due to seismic amplification of the bedrock waves by the unconsolidated sedimentary deposits.

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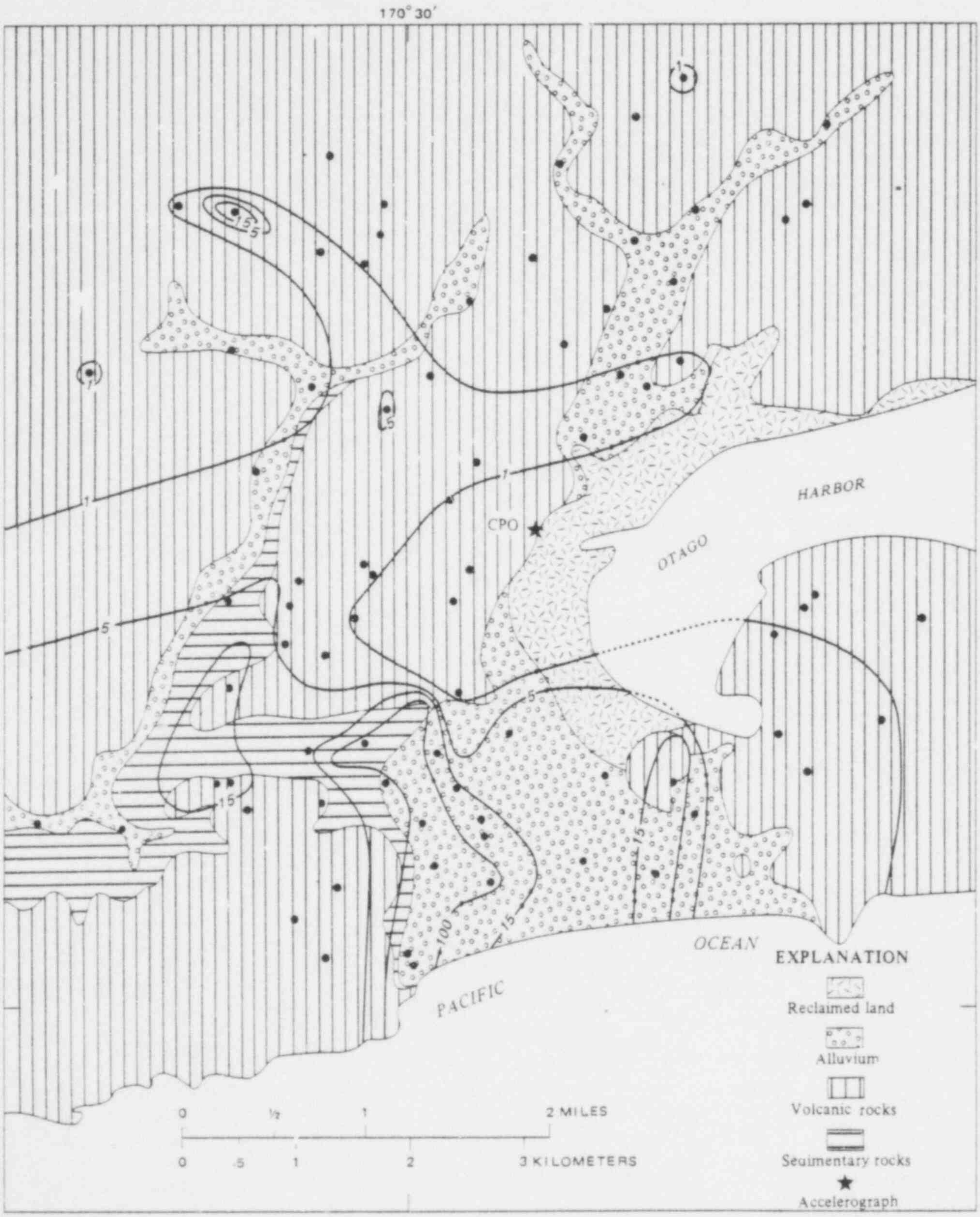

FIGURE 44.—Simplified geologic map of the Dunedin area (modified from Bishop 1974) with isoseismal contours based on the number of fallen items in grocery stores (heavy dots). Contours at 1, 5, 15, and 100 items.

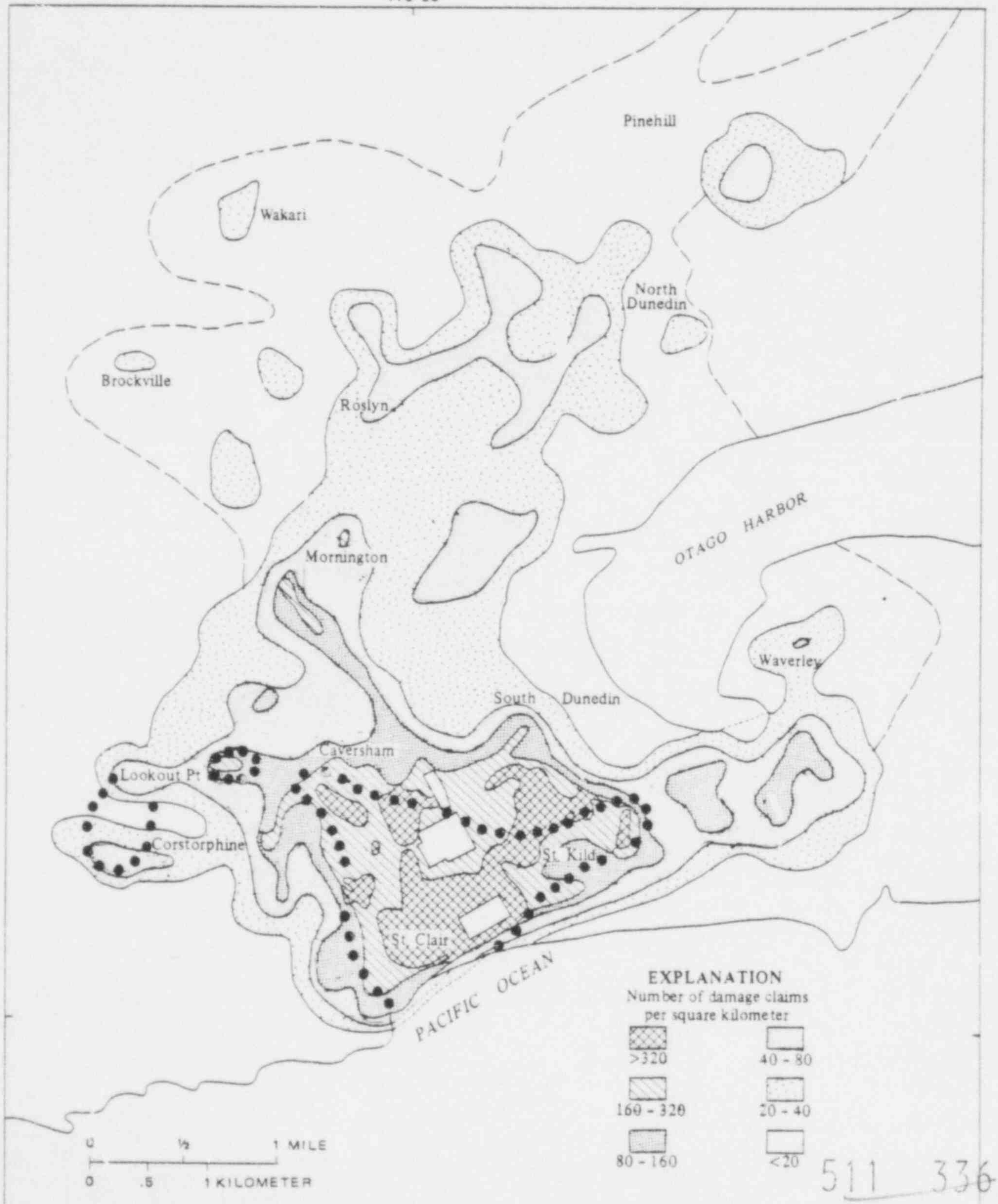

FIGURE 45—Density of damage claims resulting from the Dunedin earthquake. Contours at 20, 40, 80, 160, and 320 claims per square kilometer. Dashed line indicates limits of built-up area where it extends beyond the lowest contour. Heavy dotted line indicates inner zone of more intense chimney damage. Unshaded rectangular areas are large playing fields.

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shaking and textural properties of the sediments. In general, granular sediments in the young alluvial and estuarine deposits exhibit more of the properties conducive to liquefaction than the older alluvial deposits (fig. 46). Table 2 summarizes the standard penetration data used to determine the liquefaction potential of the various alluvial deposits in the southern bay region (Youd and others, 1975). Because the alluvial deposits over the entire bay region were distinguished by using the same criteria, conclusions

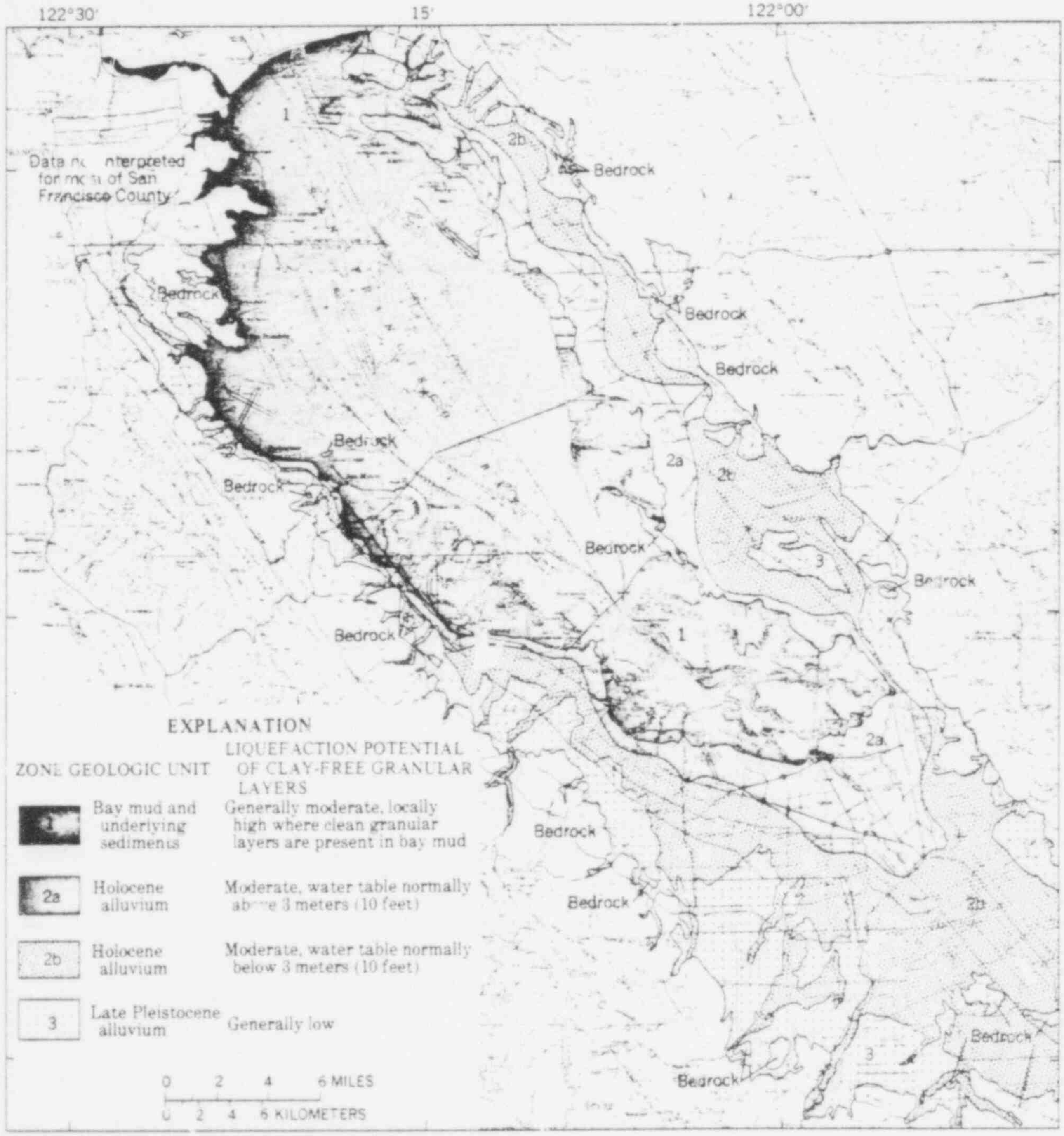

FIGURE 46.—Preliminary map showing liquefaction potential for the southern San Francisco Bay region. The map shows generalized liquefaction potential of granular layers in each map zone but does not delineate locations of these layers. Hence, the map is useful for designating zones where special consideration should be given to the possibility of liquefaction, but it is not valid for assessing the liquefacation potential of a given site. From Youd, Nichols, Helley and Lajoie, 1975, fig. 50.

TABLE 2.—*Summary of liquefaction potential analysis using standard penetration data*

[Two probable local earthquakes are considered: (a) a moderate earthquake (M=6.5) and (b) a large earthquake (M=8.0). Sediments likely to liquefy during a moderate earthquake are classified as having high liquefaction potential, those unlikely to liquefy during a large earthquake are classified as having low liquefaction potential, and those intermediate between these two categories are classified as having marginal liquefaction potential. D_r = relative density]

Zone	Sedimentary unit	Standard penetration test data (percent indicating): D_r < 65 percent (high liquefaction potential)	65 percent < D_r < 90 percent (marginal liquefaction potential)	D_r > 90 percent (low liquefaction potential)	Number of tests
1	Older (Pleistocene) alluvial deposits	11	29	60	357
2	Younger (Holocene) alluvial deposits	22	33	45	708
3	Deposits underlying young bay sediments	33	28	39	155
4	Deposits within young bay sediments	71	21	8	54

drawn from these data in the southern bay region can be extrapolated to other areas as a first approximation of liquefaction potential. However, because of local variability, these data cannot be used to determine the liquefaction potential of a particular site even in the southern bay area where engineering data were analyzed. A qualitative list of factors and conditions controlling liquefaction are given in table 3. This summary provides a list of properties that must be investigated on any site to evaluate the potential for liquefaction.

RESOURCES AND POTENTIALS

WATER RESOURCES

Infiltration is the movement of surface water into the ground through cracks in rocks or through the interconnected spaces between the constituent grains of sedimentary deposits. The rate of infiltration into a sedimentary deposit is controlled by its permeability and the depth to the ground water table. The higher the permeability, the higher the possible infiltration rate. Permeability is determined by numerous factors (table 4) including grain size, grain shape, and sorting that combine to control the size and continuity of the spaces between grains. Well-sorted, coarse-grained sediments, such as alluvial gravel and dune sands, generally have large interconnected spaces between the particles of rock and therefore would be expected to have relatively high permeabilities and infiltration rates compared to fine grained sediments.

The geologic units of flatland materials can be roughly ranked in terms of permeability and, hence, infiltration rate on the basis of grain size. The infiltration rate would be expected to be high in stream channel deposits and sand; moderate in coarse-grained Holocene alluvium and Pleistocene deposits

TABLE 3.—*Factors and conditions controlling liquefaction*

Factor	Condition conducive to liquefaction	Conditions not conducive to liquefaction
Grain size of sediment	Coarse silt and fine sand	Clay, coarse sand, gravel
Sorting (Variability in grain size)	Well sorted Uniform grain size Clay free (less than 3 percent)	Poorly sorted Nonuniform grain size High clay content (more than 3 percent)
Cementation[1]	Uncemented Loose	Cemented Hard
Consolidation (Compaction)	Unconsolidated Noncompacted Loose Low shear strength	Semiconsolidated to consolidated Moderately to high compacted High shear strength
Relative density[2]	Low relative density Less than 65 percent for small earthquakes	High relative density More than 90 percent for largest earthquake
Standard penetration[3]	Low	High
Geologic age[4]	Generally young Holocene Late Pleistocene	Generally older Pleistocene and older
Water saturation	Saturated Pore spaces filled High ground-water table Bay deposits, flood basins, lower parts of alluvial fans	Partly unsaturated to dry Pore spaces not filled Low ground-water table Higher parts of alluvial fans
Pore-water pressure	High Greater than lithostatic load	Low Less than lithostatic load
Depth	Within 100 feet (30 m) of surface Low lithostatic load	Greater than 100 feet (30 m) depth Less than lithostatic load
Seismic activity	High seismic activity High probability of moderate to great earthquakes	Low seismic activity Low probability of moderate to large earthquakes

[1] Particles may be cemented together by calcite, silica, iron oxides, or other materials.
[2] Relative density primarily reflects the degree of compaction in a sediment. 100 percent relative density means a sediment is at its maximum compaction, all the pore space is filled; 0 percent relative density means a sediment is at its minimum compaction, it is in its loosest condition and pore space is at a maximum.
[3] Standard penetration generally reflects degree of induration, which is a combination of compaction and cementation. Low standard penetration values indicate a sediment that is not compacted and is not cemented.
[4] In a general way, the age of a deposit is reflected in certain physical properties such as induration. Older alluvial deposits are generally more highly indurated than younger deposits.

and low in the fine-grained Holocene deposits. Figure 47 shows expected infiltration rates based on the distribution of the various sedimentary deposits.

Depth to ground water table is another important factor controlling infiltration rates. If the water table is close to the ground surface, the infiltration rate will be low. Within the bay region, high water tables and therefore low infiltration rates are found most commonly in the tidal mudflats underlain by bay mud

TABLE 4.—*Factors affecting porosity and permeability of sedimentary deposits*

Factor	Porosity	Permeability
Grain size:		
Fine grained	Smaller pore space	Lower
Coarse grained	Larger pore space	Higher
Sorting:		
Well sorted	Increased pore space	Higher
Poorly sorted	Decreased pore space	Lower
Compaction:		
Uncompacted	Pore space at maximum	Increases
Compacted	Pore spaced reduced	Decreases
Cementation:		
Not cemented	Pore space open	Increases
Cemented	Pore space reduced	Decreases
Depth of burial:		
Shallow	Low pressure, pores open	High
Deep	High pressure, pores closed	Low, but Transmissibility may be high
Geologic age:		
Young	At maximum	At maximum
Old	Decreasing	Reduced

and the low floodbasins at the outer margins of alluvial fans, which are underlain by fine-grained alluvial deposits. Low water tables occur along the higher well-drained parts of the alluviated areas underlain by coarse-grained alluvial deposits.

Information concerning infiltration rates is important in land-use planning for several reasons:

1. Areas with low infiltration rates are likely to present drainage problems that can affect both rural and urban use of the land.
2. Areas with very high infiltration rates are potential sites for aquifer recharge areas. Urbanization of such areas inhibits the replacement of ground water supplies lost through natural seepage or withdrawal by man.
3. The quality of ground water is affected by land uses within and near areas of high infiltration potential. For example, the location of solid-waste disposal sites in such areas may cause ground water contamination.

Areas favorable for ground water recharge can be precisely delineated by means of resistivity investigations (fig. 48). By comparing maps that show favorable recharge areas with other maps that show areas known to have high infiltration rates, unfavorable or undesirable recharge areas can be eliminated. It can also serve as the basis for determining where resistivity investigations should be undertaken. A modern soil survey also evaluates soil units in terms of permeability and, if available, can be used to delineate areas with recharge potential and with probable drainage problems.

SOIL

Soil, the natural medium for growth of land plants, is one of the primary elements in the life support system of all terrestrial life and is therefore one of the most valuable natural resources. The highest quality agricultural soils are fine- to medium-grained, well-drained sediments that are high in nutrients, easily worked, and have moderate water-holding capacity. In the San Francisco Bay region, these conditions are found most frequently on the Holocene alluvial deposits on flat valley bottoms and on the gently sloping fans marginal to the bay. These deposits have been built up primarily by floods over the past 5,000–7,000 years. Because these deposits are very youthful, they have not been deeply weathered nor significantly indurated. The soil profiles developed on these deposits lack well-developed clayey B horizons and are therefore permeable and easily tilled. Also, the lack of deep weathering means that the mineral nutrients have not been leached. Along levees and flood plains that are frequently flooded, fresh material brought in from the upland areas periodically replenishes the supply of mineral nutrients.

The most widespread ranking of land for agricultural uses is done by the U.S. Soil Conservation Service (1970); it has developed a standard format for expressing land capability for agriculture. Information developed by USGS for this report uses Soil Conservation Service soil survey data wherever available. In those areas where modern soil surveys have not been done, agricultural capability is inferred from the usual characteristics of the soil associated with each mapped geologic unit.

Figure 49 contains a brief description of the SCS capability classes and shows a typical topographic distribution of the eight classes. Generally speaking, class I, II, and III soils, those most suitable for agriculture, occur in flatland areas. Utilizing the Soil Conservation Service ranking system, the geologic units with the highest potential for agricultural use (class I, II, and III soils) are Holocene fine-, medium-, and coarse-grained alluvium, Pleistocene alluvial fans, and Quaternary marine terraces.

The flatlands map (pl. 1) provides a generalized overview of areas that may have agricultural potential. However, in areas where modern soil surveys have been completed, the soil surveys more accurately identify agricultural potential.

The distribution of water and soil resources in the flatlands bordering the bay is shown in figure 50. The

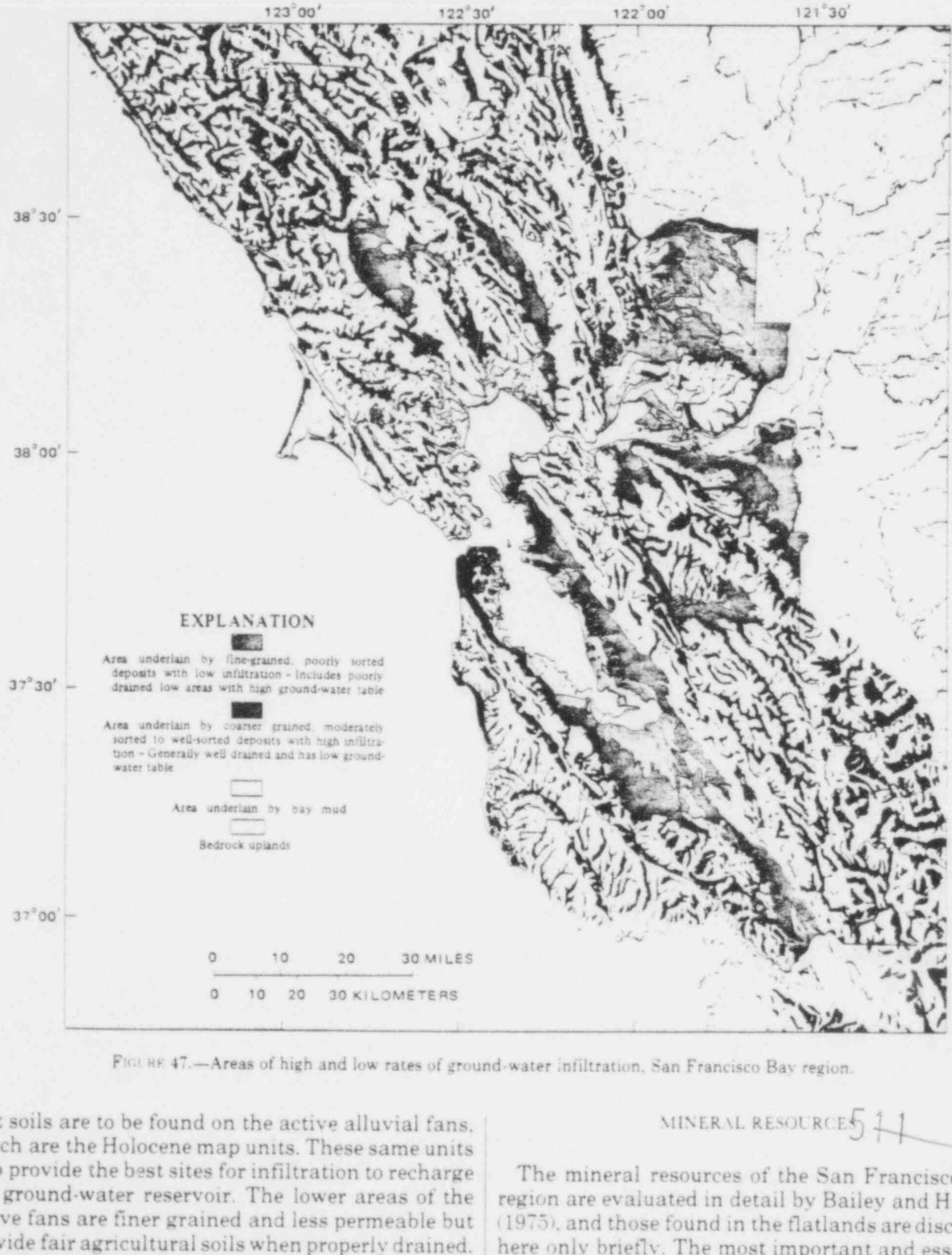

FIGURE 47.—Areas of high and low rates of ground-water infiltration, San Francisco Bay region.

best soils are to be found on the active alluvial fans, which are the Holocene map units. These same units also provide the best sites for infiltration to recharge the ground-water reservoir. The lower areas of the active fans are finer grained and less permeable but provide fair agricultural soils when properly drained. The flatlands immediately adjacent to the bay are useful as flood basins and also provide areas in which to evaporate salt from the bay water.

MINERAL RESOURCES

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The mineral resources of the San Francisco Bay region are evaluated in detail by Bailey and Harden (1975), and those found in the flatlands are discussed here only briefly. The most important and essential mineral resources in the flatlands are sand and gravel. All other mineral resources—clay, salines, shell, and peat—are of lesser economic importance.

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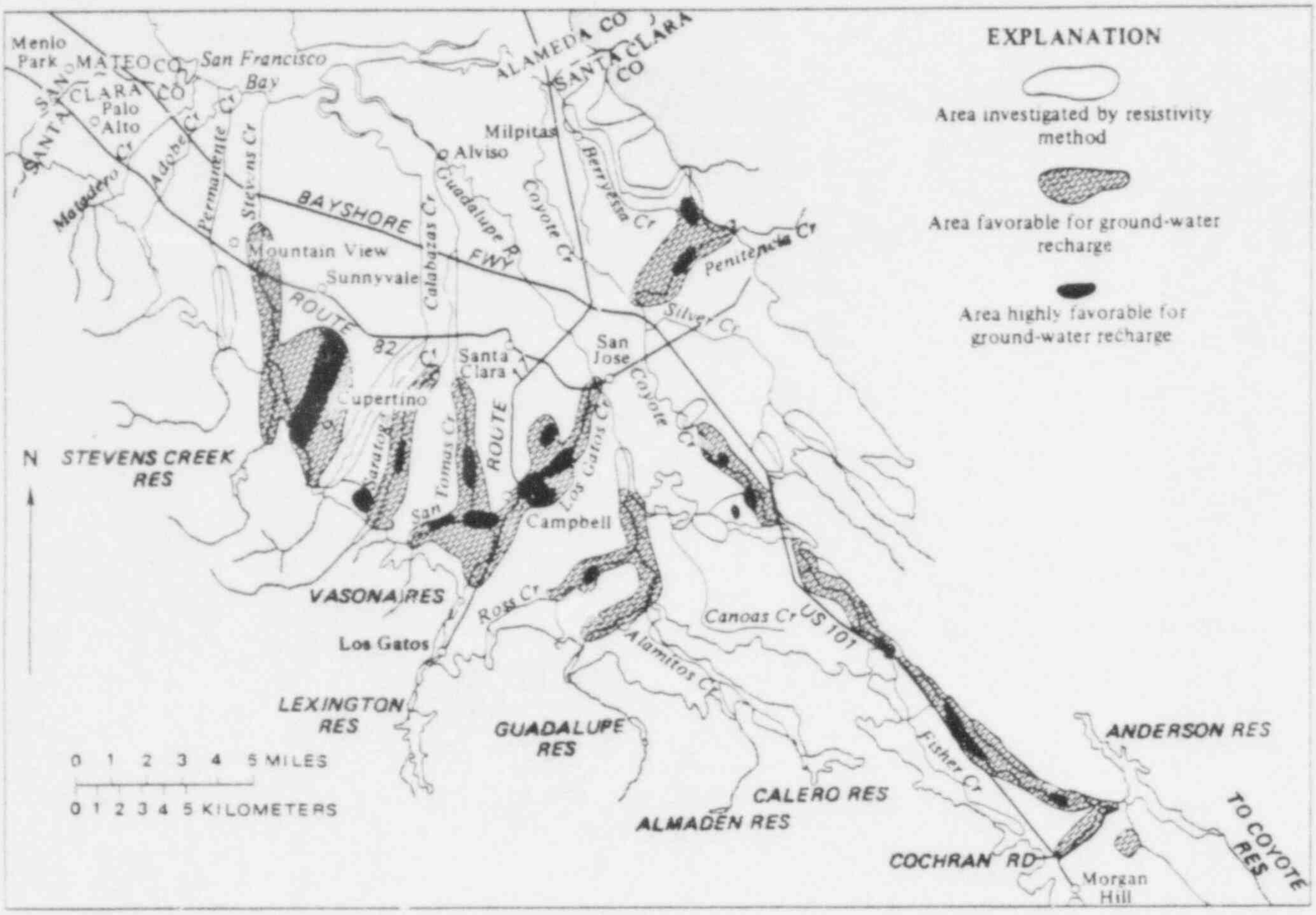

FIGURE 48.—Areas favorable for ground water recharge in southern Santa Clara County. After Page and Wire (1969).

SAND AND GRAVEL

Though sand and gravel—basic construction materials—are widespread in the flatlands, they are not unlimited resources. Indeed, minable sand and gravel resources are small in terms of projected needs (Burnett and Barneyback, 1975). About half the sand and gravel used in the bay area is for aggregate in concrete and the rest for bituminous pavement, road base, and fill (Burnett and Barneyback, 1975).

Deposits of sand and gravel occur in all bay area counties, but much of this material is unusable because it is of poor quality. Minable deposits occur in half the bay counties in both modern and ancient stream-channel, flood-plain, and alluvial-fan deposits (fig. 51). Small quantities of sand have been mined from the beach and dune deposits along the coast. Much of the originally available sand and gravel is not presently minable because of urbanization.

Much of the sand and gravel in the alluvial lowlands cannot be used for concrete because of certain undesirable physical or chemical properties. The most stringent quality requirements apply to sand and gravel used for concrete aggregate. This material should consist of durable minerals, such as quartz and feldspar, and should contain minimal amounts of unstable minerals (dark minerals or clay, for example) and reactive minerals (opal, zeolites, and glass). Unweathered hard tough dense well-rounded rock granules are the most desirable for concrete aggregate. This type of material is commonly found in the stream beds and on the alluvial fans of streams draining terrain underlain by old volcanic rocks and highly indurated sedimentary rocks.

The particle size distribution is also important in concrete aggregate, particularly in the sand fraction (Price, 1966; in Burnett and Barneyback, 1975). In general, the largest grain size of aggregate consistent with practical limitations is desirable. The grain-size distribution of an aggregate is controlled by processing, but the primary ratio of various sizes is important in determining the feasibility of exploiting a particular sand and gravel deposit. Therefore, depos-

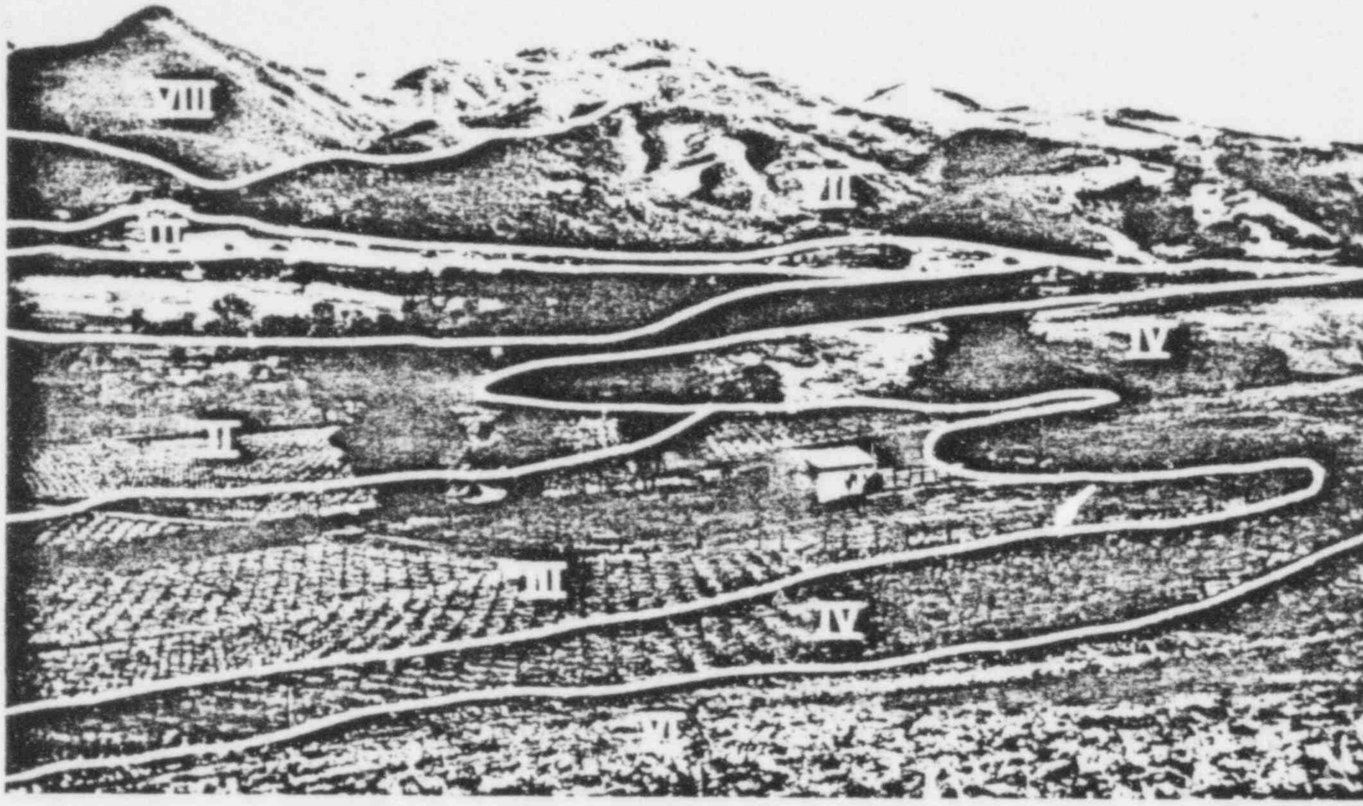

FIGURE 49.—Soil capability classes. From class I to class VIII, the choices in use become fewer and the risks become greater. From U.S. Department of Agriculture (1970).

its of relatively well sorted (low silt and clay content) sand and gravel consisting of tough, resistant particles are the most valuable for concrete aggregate. Deposits with these characteristics are abundant in outlying areas of the bay region (fig. 51), but many are a considerable distance from market centers, and many of those that are close are being eliminated as an exploitable resource by urbanization.

The deposits along the southern margin of Livermore Valley in Alameda County have supplied a major part of the sand and gravel used in the bay region. This high-quality material, which has been excavated to depths of 125 feet (38 m), consists of Holocene and, most likely, late Pleistocene alluvial fan deposits of Arroyo Mocho and Arroyo del Valle, which drain a large mountainous area underlain by Franciscan rocks.

The extraction of sand and gravel in large quantities can have very deleterious environmental effects. Large open pits frequently remain after the gravel and sand have been removed. The material removed is lost for ground-water storage, but in some areas such as Los Gatos, the resultant open pits are used as percolation ponds for ground-water recharge. At Livermore, open pits left after sand and gravel were extracted have been converted to recreation lakes.

CLAY

In the early days of California, most brick and sewer-pipe clay used was of alluvial origin and was found in valley-fill and flood-plain deposits of rivers and streams (Turner, 1951). Local red burning clay for bricks and terra cotta has been produced from the Holocene and late Pleistocene deposits of Livermore Valley and the Niles area of Alameda County. Clays have been mined extensively from deposits of similar age in the area north of San Jose in Santa Clara County.

The clay resources in the alluviated flatlands have never been systematically mapped or evaluated. Most clay deposits of commercial value probably lie in the floodbasins of the central lower parts of the alluviated lowlands where the streams carry and deposit predominantly fine-grained silt and clay. Clay may also accumulate in quiet water filling cut-

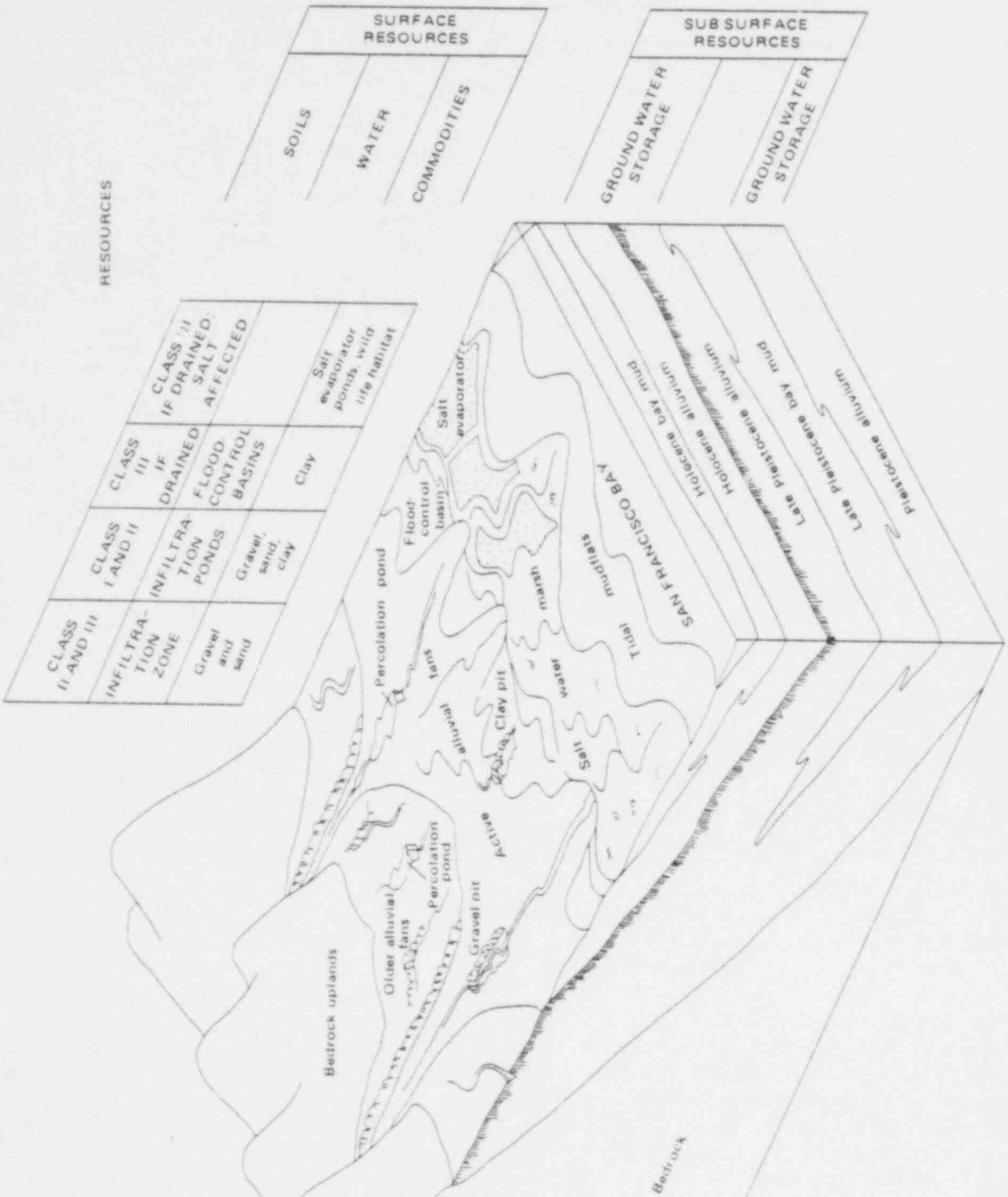

FIGURE 50.—Distribution of water and soil resources in the flatland deposits.

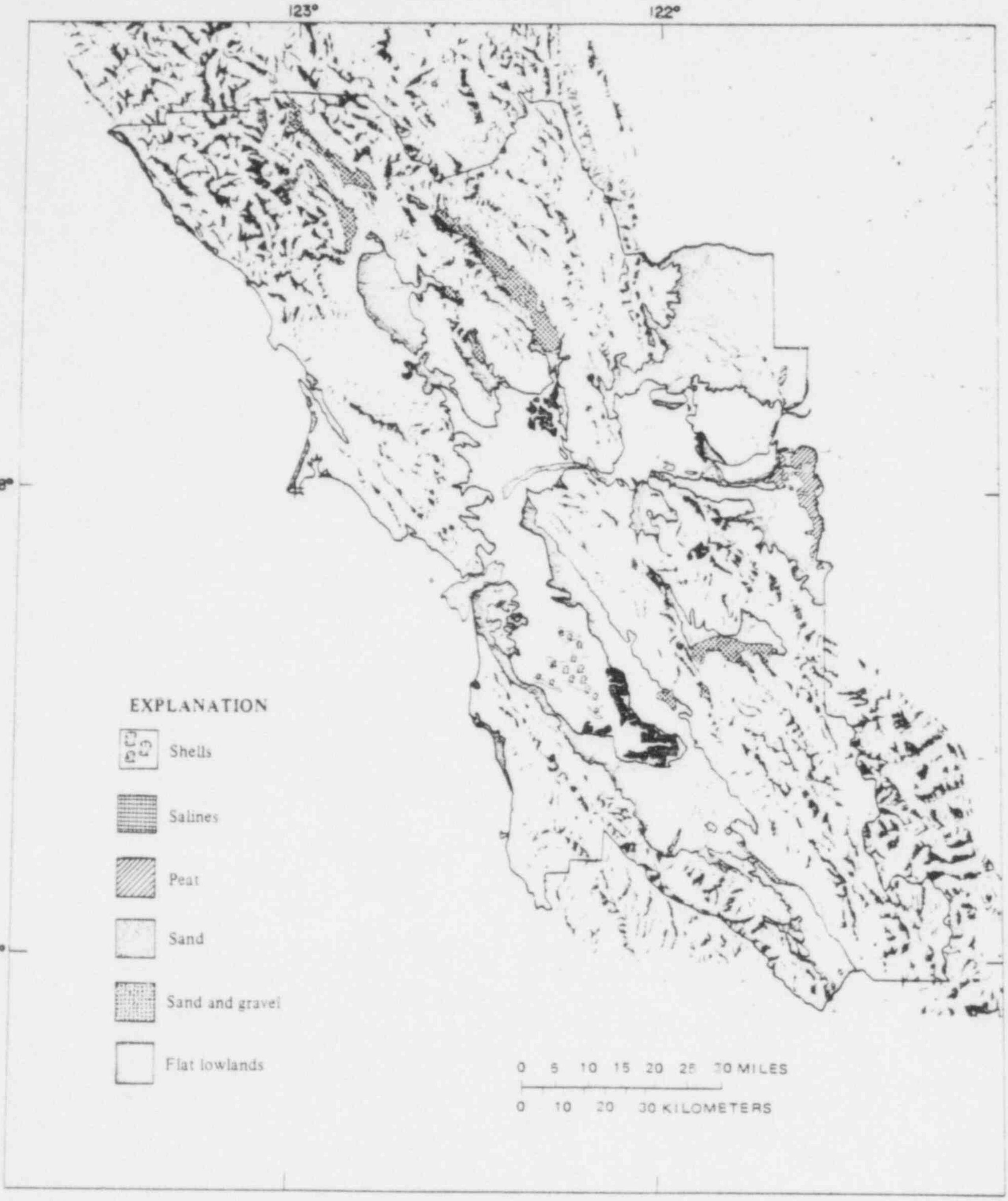

FIGURE 51.—Resources in flatland areas of bay region.

off meander loops and other natural depressions in the higher parts of alluviated areas, but these deposits are smaller than those in floodbasins.

SALINES

Salines in the bay area are derived entirely from sea water (Ver Planck, 1951). The earliest European settlers in the area gathered naturally precipitated salt from tidal lagoons along the margins of the bay. When these natural deposits were depleted around 1860, artificial evaporating ponds were constructed and continually expanded until most of the salt marsh areas in the south bay and some in northern San Pablo Bay were converted to salt production by 1970 (fig. 51).

The main natural factors that make salt production by solar evaporation a profitable business are the broad expanse of low-lying salt marshes adjacent to the bay and the cloudless summer weather. The marshes are at or close to sea level, which minimizes pumping, and the fine-grained Holocene bay mud provides a natural water-tight bottom that reduces leakage (Ver Planck, 1951).

Former salt ponds are presently being converted to urban lands such as Foster City and Redwood Shores. However, the preservation of salt ponds for salt production, which is an important economic product of the bay region, and open space, such as the Federal wildlife preserve, will probably prevent the rapid conversion to other uses at least in the near future (Goldman, 1969).

SHELL

Deposits of oyster shell, primarily *Ostrea lurida*, occur as thin discontinuous lenses on the surface of and within the upper 20-30 feet (7-9 m) of Holocene bay mud in the southern part of the bay. Roughly 30 million tons of these shells have been dredged from San Francisco Bay since 1924 (Hart, 1975; Goldman, 1969). Most of this material was used in the manufacture of cement but some was used as a source of calcium in poultry and livestock feed. The dredging of oyster shells and mud from the bay for cement manufacture ceased in 1970 due to environmental and economic reasons, but small amounts used for poultry and livestock feed and soil conditioning are still recovered by a single operator (Hart, 1975).

The distribution and character of shell deposits within the bay are not well known so the reserves of this locally important commodity cannot be definitely determined, but Welday (*in* Hart, 1975, p. 64-74) estimates that of 60 million tons (54.4 million tonnes) of available shell, about 40 million tons (36.3 million tonnes) usuable. Most of tne shell extracted to date lies at or near the bottom of the bay and is therefore very young. The living populations of *Ostrea lurida* have been almost completely destroyed by pollution of bay waters and dredging of the oyster beds so the commodity is not being replenished. Consequently, when the present oyster beds are depleted, older and more deeply buried shell beds may be exploited.

PEAT

Peat reserves in the bay region are described by Stinson (1975). Peat, which is used exclusively as a soil conditioner, occurs in the eastern parts of Contra Costa and Solano Counties in fairly pure beds greater than 30 feet (10 m) thick in some places and in three small areas near Gilroy in southern Santa Clara County (fig. 50). At present peat is recovered only from Franks Tract, a subsided and flooded island in eastern Contra Costa County where it is mined by a floating clamshell dredge in 6-8 feet (2-3 m) of fresh water.

The extraction of peat from permanently flooded areas does not conflict with other high-priority land uses. Peat extraction from diked and drained lands in the delta region would conflict with the agricultural uses of these areas. Peat is obtainable from other parts of the Sacramento-San Joaquin delta outside the bay region and therefore is not a particularly valuable resource in the bay region. Also, various substitutes for peat are available for agricultural and horticultural uses.

IMPORTANCE OF FLATLAND GEOLOGY TO COMPREHENSIVE PLANNING

By William Spangle and Martha L. Blair

Knowing the characteristics of flatland deposits is obviously important in land-use planning. Many costly and hazardous situations can be avoided or mitigated if good geologic information is available before land-use and development decisions are made. In the past, planners have relied on soil maps to identify the problems and resources of flat alluvial areas. Soil maps show deposits at the surface to a depth of rarely more than a few feet. Geologic mapping considers deposits at greater depth and is largely based on the processes forming the deposits. The delineation, description, and interpretation of flatland deposits are a new approach to geologic mapping and interpretation, designed explicitly for application to land-use planning. In the past, geologic maps rarely differentiated the various alluvial deposits common to lowland areas. These differences, as described in the entitled sections "Potential Problems in Flatlands Regions" and "Resources and Potentials," have important planning implications.

Because the information presented here is new, actual examples of successful application to land-use planning do not exist. Thus, to describe the potential planning application of data on flatland deposits, two approaches are used. First, a hypothetical example of the use of flatlands information in land-capability studies is presented to illustrate how the interpretations of the preceding two sections can be integrated and related directly to land-use planning and decisionmaking. Second, actual planning responses to selected flatland issues are described to show how land-capability considerations and information describing flatland characteristics can be incorporated into a planning and decisionmaking process. In both approaches, the objective is to describe a planning framework for the effective use of data on flatland deposits.

A basic planning and decision making framework is outlined in the section "Introduction." Geologic and other earth-science information is important in each step of the planning process shown in figure 3. The outline below provides a general framework indicating how planners, working with earth scientists, can effectively introduce geologic considerations throughout the process.

1. Identify problems and define goals and objectives.
   a. Obtain readily available geologic information for preliminary identification of natural hazards and resources.
   b. Review the data in relation to current land-use plans and policies, projected growth trends, and anticipated changes.
   c. Develop a tentative set of objectives and priorities, giving special consideration to hazards and resources.
2. Collect and interpret data.
   a. Evaluate adequacy of available geologic data and develop a program for compiling new data.
   b. Arrange with earth scientists to prepare basic and interpretive maps and texts. Map information should relate in scale and detail to other basic planning information.
   c. Estimate the probable future demand for land, considering projections of population growth and distribution, economic activity, social and cultural needs, and transportation requirements.
   d. Prepare land-capability maps showing the natural capability of each land unit to accommodate each potential use.
3. Formulate plans.
   a. On the basis of land-capability maps, appropriate projections, and economic, social, and political analyses, consider feasible alternative arrangements of land uses.
   b. Prepare alternative land-use policies and plans, incorporating as much detail as necessary to guide future decisions.
4. Evaluate impacts.
   a. Evaluate alternative land-use policies and plans for environmental, economic, and social impacts.
   b. Evaluate exposure to risk from natural hazards associated with alternative land-use policies and plans.
5. Review and adopt a plan.
   a. Present plan alternatives for review and selection by the appropriate legislative body.
   b. Schedule and hold public hearings.
   c. Adopt plan with such modifications as may be needed to respond to information provided and opinions expressed at public hearings.
6. Implement the plan.
   a. Prepare and seek adoption of land-use regulations and any land-acquisition and capital-improvement programs needed to carry out the plan.
   b. Establish guidelines and a procedure for conducting the geologic investigations needed to evaluate development proposals.
   c. Develop the procedures and capability for reviewing soils and geology reports, environmental impact assessments, and project proposals.
   d. Arrange for modification of previous steps as new or more detailed information becomes available.

DESCRIPTION OF LAND-CAPABILITY STUDIES

Land-capability studies are an important element of the land-use planning and decisionmaking framework outlined above. In any area, the existing natural features and processes present a range of constraints and opportunities for different uses of land. It is well known that the natural characteristics of different parcels of land vary as well as the physical requirements for different uses of the land. For example, farmers seek fertile soils; manufacturers in heavy industry want level sites with good foundation conditions; golf course developers look for rolling terrain with adequate surface and subsurface soil conditions.

Land-capability studies systematically record and

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formalize judgments concerning the physical features of the land with regard to particular categories of land uses. Such studies evaluate, for a specified land use, the relative physical merits of the lands in a study area. The natural features and processes considered usually include topography, hydrology, geology, soils, vegetation, and climate.

Methods of evaluating land capability differ. A study may be largely descriptive, pulling together in narrative form information concerning the natural features and processes relevant to a particular land use. Or a study may involve a fairly sophisticated effort to quantify, weigh, and aggregate the earth science information relevant to specific uses for all lands within a planning area. In any case, judgment is needed and the studies should be carried out by planners with the assistance of experienced earth scientists. Land capability analysis involves four basic steps:

1. Defining the focus of the study and the land use or uses to be considered,
2. Determining the natural characteristics affecting capability for the use or uses selected,
3. Gathering, analyzing, and presenting information describing the natural characteristics, and
4. Evaluating relative capability of land units to support the selected use or uses.

Judgments concerning the importance of each factor as well as the range of conditions within each factor can be expressed numerically. The main advantage of a quantified analysis is not greater precision of results, but greater ease in combining many judgments into an overall rating of land capability.

Land capability studies vary in focus as well as method. A study may focus on identifying constraints for particular uses; another on factors favorable for particular uses; and another on both constraining and favorable factors using positive and negative ratings. A common variation is a risk analysis, which rates land within a study area in terms of relative risk from selected natural hazards. A study may be very detailed, dividing an area into small units which are evaluated for a specific use such as a sanitary landfill; or it may be general, dividing a study area into large units which are evaluated for a broad use category such as urban development.

Judgments about relative costs involved to overcome natural conditions adverse to particular uses commonly affect values assigned in a land-capability study. The Association of Bay Area Governments in a land-capability study recently completed as part of the San Francisco Bay Region Study (Laird and others, 1979) expressed land capability directly in terms of the dollar costs associated with hazard-mitigation measures, potential property damage from natural hazards, and loss of natural resources. The method was tested in a pilot land-capability analysis of part of the Santa Clara Valley.

The pilot study focuses on geologic and hydrologic hazards and resources and makes excellent use of many San Francisco Bay region reports. Natural factors considered in evaluating land capability include earthquakes, flooding, bearing materials problems (potential for shrink and swell, settlement, liquefaction, and subsidence), slope stability, erosion and sedimentation, septic-tank limitations, and natural resources. Lands in the study area were evaluated for a range of uses: agricultural or rural, semi-rural residential, single-family residential, multi-family residential, regional commercial, downtown commercial, industrial manufacturing, and freeway.

The total expected cost associated with each natural constraint and resource for each land use was calculated. Cost information for all natural resources and problems for each 24.9-acre grid cell was aggregated for each land use. The resulting number indicates for each cell the expected dollar cost per acre of developing that cell with that land use. The range of total costs was divided into six capability levels and a land-capability map for each use was printed by computer.

Analyses of land capability provide only part of the information needed for land-use decision. Economic, social, political, and aesthetic considerations are also important. The physical capability of a parcel of land to support an intensive use may be poor, but other factors, such as location and accessibility, land cost, absence of alternative lands, or overriding public need may well indicate that the parcel should be intensively developed.

A study that systematically evaluates economic, social, and political factors, in addition to physical capability factors, is called a "land-suitability study." A land-capability study is often undertaken as part of a broader land-suitability study. On occasion, capability is, or should be, the determining factor. Areas with very low capability for sustaining a particular use can sometimes be eliminated from further consideration on that basis alone, allowing the planner to focus attention on more realistic options.

Land-capability studies are becoming increasingly important to land-use planning at all governmental levels. They assure that physical characteristics of the land will be given systematic consideration in the development of land-use plans and policies. The earth-science information requirements for such studies vary with the total land area and the specific use to be studied. At the regional level, for example, fairly generalized data may be appropriate for an analysis of land capability for regional open space. On the other hand, a study undertaken, at any governmental level, to locate specific sites with good capability for sanitary landfill will require detailed information.

IMPORTANCE OF FLATLAND DEPOSITS IN REGIONAL STUDIES

Regional land-use planning is primarily concerned with those issues that are independent of local political boundaries and thus require a coordinated response. Moreover, many areawide problems, such as water and air pollution, are directly linked to the use of land. An appropriate focus of a regional land-use plan is to identify areas where urban growth can occur with minimum environmental damage, loss of resources, private and public cost, and risk to persons and property.

Federal regulations governing eligibility for funds under the Comprehensive Planning Assistance Program (U.S. Congress, 1974) require that all agencies applying for grants must have an adopted land-use element by August 22, 1977. For areawide agencies this element must include the following:

(1) Long and short term policies, and where appropriate administrative procedures and legislative proposals, with regard to where growth should and should not take place:

(2) The type, intensity and timing of growth;

(3) Studies, criteria, standards and implementing procedures necessary for effectively guiding and controlling major decisions as to where growth shall and shall not take place; and

(4) Policies, procedures, and mechanisms necessary for coordinating local, areawide, and State land use policies with functional planning and capital investment strategies, when available, and improvements in governmental structures, systems and procedures that will facilitate the achievement of land use objectives. (U.S. Department of Housing and Urban Development, 1975, p. 36862)

The regulations also require that federally funded planning activities be conducted in accord with the National Environmental Policy Act of 1969, Public Law 91-190, (U.S. Congress, 1969) through the inclusion of environmental planning in the comprehensive planning process. Specifically, each agency shall:

(1) Identify salient elements of the natural and the man-made environments, their interrelationships, and major problems and/or opportunities they present for community development;

(2) Assess those environmental factors which will:

(i) Minimize or prevent undue damage, unwise use, or unwarranted pre-empting of natural resources and opportunities;

(ii) Recognize and make prudent allowance for major latent environmental dangers or risks (e.g., floods, mud slides, earthquakes, air and water pollution); and

(iii) Foster the human benefits obtainable from use of the natural environment by wise use of the opportunities available (e.g., use of natural drainage systems for park and recreational areas); (U.S. Department of Housing and Urban Development, 1975, p. 36860)

Regional or areawide planning agencies are also being funded by the Environmental Protection Agency (EPA) under Section 208 of the Federal Water Pollution Control Act of 1972 (U.S. Congress, 1972) to carry out waste-water management planning. Each plan must contain a land-use element. EPA and HUD have signed an interagency agreement to assure that land use plans prepared under one program meet the requirements of the other.

Because of Federal support for areawide land-use planning emphasizing environmental concerns, land-capability studies are needed and are likely to be applied with increasing effectiveness. Evaluating land capability is important in developing policies with regard to "where growth should and should not take place" (U.S. Department of Housing and Urban Development, 1975). Such evaluation helps identify (1) areas where land preparation, building, and maintenance costs are likely to be higher than average; (2) areas where structures are subject to damage from natural processes and occupants may be subject to injury or loss of life; and (3) areas where certain uses of the land may alter or interfere with natural features or processes.

In the San Francisco Bay region, evaluation of capability of flatland areas to accommodate urban uses is particularly important, because most urban growth is expected to occur in these areas (Association of Bay Area Governments, 1970, p. 6). Urban growth is a process of converting land from rural or other relatively nonintensive uses to urban use. Thus evaluating capability of lands for agriculture and other open-space uses is also essential in order to identify areas of conflicting capability and possible trade-offs. As stated in ABAG's adopted regional plan:

It is on the Bay plain area that circles the Bay, and the larger valleys of Santa Clara, Napa, Sonoma, Petaluma, Livermore, and Ygnacio that the greatest amount of urban development has occurred. These valley lands, separated only by intervening ridges, are being steadily converted from agricultural to urban use to serve the needs of a growing urban population. Due to the difficulties of building on steeper slopes, those valley lands that remain unurbanized are prime targets for future urban development. The region will have to choose either to retain the prime agricultural lands and unique natural settings that these lands provide, or to allow them to be transformed by urbanization. (Association of Bay Area Governments, 1970, p. 4).

Regional evaluation of land capability must also include hillside lands. Options for location of needed housing or facilities are limited by existing development. In some areas, it may be necessary to choose between hillsides and unstable flatlands for needed development. Information on relative capability of all available lands within a planning area is necessary for rational land-use decisions.

Capability studies are especially helpful in evaluating lands for uses in which natural characteristics are critical. For instance, urban uses can be physically accommodated on most land, at some development cost, but only land with specific natural characteristics can accommodate agricultural uses. Sand and gravel extraction, fish and wildlife habitats, sanitary landfills, and ground-water recharge areas are other examples of land uses with specific physical requirements. Early identification, at the regional level, of areas capable of sustaining such uses can avert unnecessary loss of resource potential. Recent emphasis by State and areawide agencies on identifying and protecting areas of critical environmental concern recognizes the relation between land use and natural characteristics of the land.

APPLYING INFORMATION ON FLATLAND DEPOSITS

The maps of flatland deposits and the interpretation derived from these maps provide a basis for ranking the flatland areas in terms of capability for some uses. An example of the use of the flatlands information in regional land-capability analysis is outlined in the following sections. The example indicates how the information can be used to identify potentials and problems that need further analysis. For direct use in plan formulation, the capability evaluation should cover the entire planning area (not just flatlands) and incorporate information from other sources. The example serves two purposes:

1. It indicates possible implications of the interpretations contained in the preceding two sections for regional land-use planning.
2. It illustrates a method that is useful in regional land-capability analysis.

The example is presented according to the four basic steps of land-capability studies already listed.

DEFINING THE FOCUS OF THE STUDY

The example uses the characteristics of flatland deposits to identify areas with potential land-use conflicts based on capability for urban residential development, agriculture, ground-water recharge, and sand and gravel extraction.

DETERMINING THE NATURAL CHARACTERISTICS AFFECTING LAND CAPABILITY

In the next step, those flatland characteristics affecting the capability of land to support each use are selected. Capability for agriculture is based on soil characteristics of each geologic unit as interpreted on p. 62. Capability for ground-water recharge is based on permeability of the flatland materials (as shown in fig. 47) and capability for sand and gravel extraction is derived from figure 51 and the discussion on p. 64. Capability for urban residential use is affected by several flatland characteristics: flood potential, permeability, shrink-swell potential, settlement potential, possibility of liquefaction-induced ground failure, and seismic-wave amplification. Table 5 lists (1) the characteristics affecting land capability for urban residential development derived from the map of flatlands deposits, (2) the nature of the impact, and (3) the general relation of the characteristic to the map of flatland deposits.

Other characteristics that affect land capability for urban residential uses include soil-bearing capacity, erosion potential, scenic qualities, vegetation, slope stability, and faulting. These characteristics are not considered in this example because they cannot be directly derived from the map of flatland deposits.

TABLE 5.—*Characteristics of flatland deposits affecting capability for urban residential development*

Characteristics	Nature of impact	Relation to flatland deposits
Flooding	Potential loss of life; damage to structures, personal property; erosion; cost of flood insurance; increase in flood extent or depth	Flood potential confined to Holocene alluvium and bay mud.
Permeability	Ponding; excavation problems; cost of engineered solutions such as pumping, channeling, waterproofing	Problems severe in bay mud and fine-grained alluvium.
Shrink-swell	Extra cost of foundation engineering; damages from shifting and cracking of improperly engineered foundations	Problems most likely in bay mud and fine-grained alluvium.
Settlement	Damage to structures, especially if differential settlement occurs; extra cost of special foundation engineering	Potential exists only in bay mud and delta area peats.
Liquefaction-induced ground failure	Destruction or damage to structures during earthquakes	High potential in water-saturated sand within bay mud.
Seismic wave amplification	Damage and potential destruction of structures; loss of life from seismically induced ground shaking	Potential in all flatland materials depending on thickness underlying material; most significant in bay mud.

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GATHERING, ANALYZING AND PRESENTING THE INFORMATION

The objective of the next step is to rate the relative capability of selected land units for the uses being considered. Several tasks are usually involved. First the land units to be rated are defined. These may be census tracts, political units, grid cells, or virtually any configuration that can be mapped and that is generally consistent in size with the scale of the data and the purpose of the study. In the example, the land units evaluated are the geologic units on the map of flatlands deposits (pls. 1, 2, and 3).

A scoring system is then devised to express the degree each natural factor affects the land capability. In the example, a simple scoring system is used: 3, indicates high capability; 2, moderate capability; 1, low capability; and 0, no capability for the use. More complex scoring systems can be used to define high, moderate, and low categories more precisely. For example, categories of flooding might be: Areas subject to flooding on the average of once every 1-10 years, once every 10-100 years, once every 100-500 years, or areas not subject to flooding. Regardless of how precisely the categories are described, the assignment of a numerical score is a judgment based on knowledge of the factor.

A weight is also assigned to each natural factor representing the importance relative to the other factors as a determinant of capability. The judgments made in assigning the rating and weights are crucial to the conclusions and should always be explicitly stated. In the example, a simple weighting scale of 1 to 5 was chosen.

The score is multiplied by the weight to get a weighted capability rating. The ratings for all natural factors for each unit are totalled to produce an aggregated weighted rating. The aggregated weighted ratings permit a comparison of relative capability of each unit for each use. Tables 6 and 7 summarize these operations. The scores shown in table 6 are based on the following judgments:

(1) High permeability and low potential for flooding, shrink-swell, settlement, liquefaction, and seismic wave amplification are favorable for urban residential development.

(2) High potential for flooding is a severe constraint for urban residential development and, accordingly, is given a score of zero.

The judgments made in assigning weight are less evident. They include the following considerations:

(1) Flooding affects capability for urban residential development more than the other five factors. This judgment is based on the high cost, both monetary and environmental, of providing flood protection; the relatively small area involved; the importance of flood-prone areas for other uses; and the high social and economic loss caused by floods in residential areas.

(2) Shrink-swell is judged the least important of the factors because the potential for damage can be readily and fairly inexpensively identified and mitigated with appropriate site investigation and foundation engineering.

(3) Seismic-wave amplification can cause severe damage to residential structures but, because of the infrequency of major earthquakes, uncertainties in delineating areas of high potential, and ability to design residential structures to withstand ground shaking, this factor is judged slightly less important than flooding.

(4) Settlement and liquefaction are considered moderately important. Damage to residences caused by settlement can usually be averted with appropriate site investigations and properly engineered fills. Ground failure from liquefaction can cause severe damage to residential structures, but it occurs infrequently and only in parts of the areas with high or moderate liquefaction potential.

(5) Permeability is important primarily if septic-tank systems are to be used in a residential development. Problems resulting from low

TABLE 6.—*Capability weighting and scoring system for urban residential development*

Factor	Degree of potential	Score	Weight	Weighted capability
Flooding	High	0		0
	Moderate	1	5	5
	Low	3		15
Permeability	High	3		6
	Moderate	2	2	4
	Low	1		2
Shrink-swell	High	1		1
	Moderate	2	1	2
	Low	3		3
Settlement	High	1		3
	Moderate	2	3	6
	Low	3		9
Liquefaction	High	1		3
	Moderate	2	3	6
	Low	3		9
Seismic-wave amplification	High	1		4
	Moderate	2	4	8
	Low	3		12

permeability can generally be overcome by installing adequate drainage and sewer systems.

EVALUATING RELATIVE CAPABILITY OF LAND UNITS

The capability ratings in table 7 indicate that Holocene deposits generally have lower capability for urban development than do Pleistocene deposits, and among the Holocene deposits, bay mud appears to be in a category by itself with very low capability. The numbers employed in the analysis provide only a means of aggregating the impact of various physical characteristics of each unit on urban development. The results thus need to be expressed in generalized terms. Possible aggregated ratings range from 13 to 54. Dividing the range into three nearly equal ranges representing high, moderate, and low capability gives the following results:

- 13-26 low capability: bay mud (Qhbm)
- 27-40 moderate capability: fine-grained alluvium, fine-grained-salt affected alluvium, medium-grained alluvium, and beach and dune sand deposits
- 41-54 high capability: coarse-grained alluvium, late Pleistocene alluvium, early Pleistocene alluvium, Pleistocene sand, Quaternary marine terrace deposits, and Colma Formation

These ratings can then be mapped as shown in figure 52 to show the general distribution of areas with high, moderate, and low capability for residential uses based on the factors considered in the example. This map and ratings can then be compared with those for the other uses being considered to identify areas of potential conflicts.

Developing a capability rating of the land units for agriculture, ground-water recharge, and sand and gravel extraction is, in this case, very simple. The ratings expressed in terms of high, moderate, and low capability are derived directly from the section, on "Resources and Potentials." These are summarized, along with the ratings for urban residential development, in table 8.

USE OF LAND-CAPABILITY STUDIES

At this point it is appropriate to see what has been learned from this preliminary exercise as a start in directing subsequent more complete and detailed investigations. The following observations can be made:

(1) Bay mud has low capability for all the uses considered. Special attention should be given to identifying positive attributes for other uses. Fish and wildlife habitats, oyster shell deposits, salt production, and water-related recreational activities should be identified and evaluated.

(2) High capability for all uses exists in areas underlain by coarse-grained alluvium and moderate or high in areas underlain by medium-grained alluvium and late Pleistocene alluvium. The need to determine appropriate land uses for these areas is obvious. Since relatively few areas have high potential for agriculture and ground-water recharge, these uses should be given priority consideration in land-use determina-

TABLE 7.—*Capability rating of geologic units for urban residential development*

[Qhsc, which is shown on the map, is not rated because it occurs only in active stream channels and is not suitable for urban development.]

Capability rating	Low	Moderate				High					
	Geologic units										
Characteristic	Qhbm	Qhaf	Qhafs	Qham	Qhs	Qhac	Qpa	Qpea	Qps	Qpmt	Qpmc
Flooding	0	0	0	0	[1]5	5	5	[illegible]	15	15	15
Permeability	2	2	2	4	6	6	6	6	6	6	6
Shrink-swell	1	1	1	2	3	3	2	3	3	2	3
Settlement	3	9	9	9	9	9	9	9	9	9	9
Liquefaction[2]	3	6	6	6	3	9	9	9	6	9	9
Seismic wave amplification	4	12	12	12	12	12	12	12	12	12	12
Aggregated weighted capability	13	30	30	33	38	44	53	54	51	53	54

[1]Qhs, where it occurs as beach sand, is subject to daily tidal flooding; where it occurs as dunes, it may not be flooded at all.
[2]Liquefaction potential exists only where well-sorted granular material at shallow depth is saturated with water and is confined within impermeable layers.

CAUTION: Taking these numbers literally may be hazardous to your planning area!

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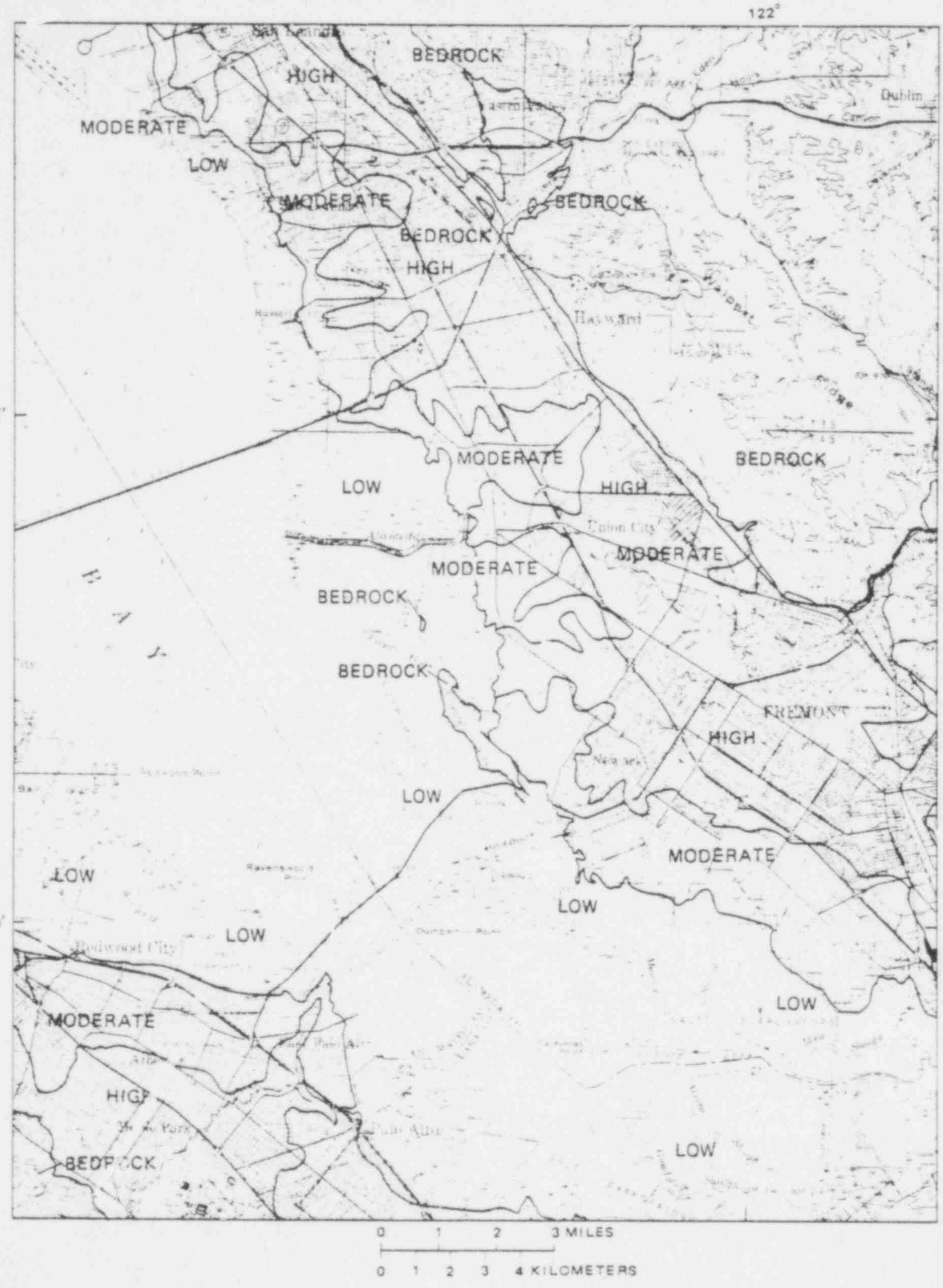

FIGURE 52.—Part of bay region showing areas with high, moderate, and low capability for urban residential development.

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TABLE 8.—*Capability rating of geologic units for selected uses*

Land units	Land uses			
	Agriculture[1]	Ground-water recharge[2]	Sand and gravel extraction[3]	Urban residential development
Qhbm	Low	Low	Low	Low
Qhaf	Moderate	Low	Low	Moderate
Qhafs	Low	Low	Low	Moderate
Qham	High	Moderate	High	Moderate
Qhac	High	High	High	High
Qhs	Low	High	Moderate	Moderate
Qpa	Moderate	Moderate	High	High
Qpea	Low	Moderate	Low	High
Qps	Low	Moderate	Low	High
Qpmt	Moderate	Moderate	Low	High
Qpmc	Low	Moderate	Low	High
Qhsc	Low	High	High	Not applicable

[1] Rating from section on "Soil."
[2] Rating from figure 47 and section on "Water Resources."
[3] Rating from figure 51 and section on "Sand and Gravel."

tions. Suitability factors are likely to be important in these areas.

(3) Many of the units have high capability for urban development. Natural characteristics are less constraining for this use than for the other uses considered. The ratings indicate where constraints to urban development may occur and where potential for urban growth conflicts with potential for priority uses.

Capability ratings are only part of the information needed to formulate land-use plans. Final decisions must rest upon other environmental, social, economic, and cultural information. Combining all relevant information can be accomplished through a suitability study, as noted earlier. The method is the same as for a capability study, but the information requirements are broader. For most urban uses, capability analysis is appropriately carried out as an integral part of a broader suitability study. Even for uses where natural characteristics may be paramount, such as agriculture, sanitary landfills, or other open-space uses, the final decision on land use usually depends, at least in part, on suitability factors. Accessibility, distance from markets, and ecological constraints, for example, may be critical. A capability study is, however, valuable in defining options and limitations early in the planning process and can be effective in narrowing the scope of a subsequent suitability analysis. For example, identifying lands with high capability for agricultural uses early in the planning process focuses the analysis of suitability factors on those lands with high capability. Sequential analysis can save the time and expense of acquiring needless data concerning agricultural suitability for lands clearly incapable of supporting such uses.

In evaluating land for urban uses, suitability factors can be usefully incorporated into the original analysis. This is because most land can physically accommodate most uses. The question is, usually, at what cost and risk. The answer to these questions involves suitability factors.

The ratings based on characteristics of flatland deposits can focus further investigation by identifying problems and potential to be considered throughout the planning process. Table 9 sets forth, by way of example, the planning implications of the capability ratings for urban residential development.

Basically, as noted earlier, a capability rating for urban uses provides an overview of potential public and private costs; risks to property and persons; and, combined with capability information for priority uses, some possible adverse impacts.

PLANNING RESPONSE TO FLATLAND ISSUES

PLANNING FOR THE BAYLANDS

The capability ratings for urban residential development provide a generalized view of differences in the ease and cost of construction and risks of building on different flatland deposits. Characteristics of flatland deposits rarely cause land to be totally incapable of supporting residential uses. They may, however, strongly affect the cost of land preparation, construction, and maintenance. Shrink-swell and settlement problems, poor permeability, and inadequate drainage can generally be overcome using well-established engineering techniques, but these techniques can be expensive, and they do not always avert continuing maintenance problems.

In the San Francisco Bay region, such problems are particularly severe on bay mud, as shown in the capability example and described in the section "Potential Problems in Flatlands Regions." Most land areas underlain by bay mud are subject to tidal action and must be (or have been) diked and filled prior to development. In many places, the demand for flat, buildable land, adjacent to existing urban areas has been strong enough to make diking and filling worth the cost. Commercial, industrial, and residential developments as well as major public facilities including two international airports and a naval air station have been built on fill over bay mud. It is possible to develop the land-fill on top of the bay mud, but the cost will be high.

Foster City is a privately developed new town started in 1963 on a diked and filled island in San Francisco Bay just south of the San Francisco International Airport (also built on filled land). Buildings require foundations of reinforced concrete with continuous footings or piles. In the mid-1960's founda-

TABLE 9.—*Regional planning implications of capability rating for urban residential development*

Steps in Planning Process	Informational Requirements	Land Use Evaluation	Developmental Factors
Data collection and interpretation	Other natural data and economic, social, political, esthetic, and other relevant information should be collected.	Additional detailed information concerning characteristics of flatland deposits, particularly potential for agriculture, should be collected.	Information detailing potential for open space or other nonintensive uses of such areas should be collected.
Plan formulation	Areas can be considered for urban development by process of elimination.	Evaluation of other natural and economic, social, political, esthetic factors is needed to make initial judgments concerning land use. Agricultural uses should be considered.	Areas can be considered for open space by process of elimination; presence of wildlife habitats, sensitive ecological systems, potential for water-related recreation may be important. Urban development should be recommended only if great public benefit can be shown.
Project review A-95 review (Assoc. of Bay Area Governments or permit process (Bay Conservation and Development Commission)	Unless other factors indicate problems, additional information concerning flatland deposits may not be needed.	Site investigations of soil and geology may be needed in reviewing projects.	Site investigations of soil and geologic conditions needed. Developer must provide evidence that site can be safely developed.
Environmental Impact Statement and Environmental Impact Report	Environmental problems not related to nature of flatland deposits likely to be more important.	Environmental assessment should consider constraints posed by flatland deposits.	Detailed environmental assessment of flatland constraints should be provided and considered.

tion construction alone cost an average of \$1.00-\$1.50 per square foot of floor space more than it would have on firmer ground; the cost would be higher today (Ronald Campbell, oral commun., July 20, 1975). An additional cost of approximately \$100 per house was required to provide utility service in the mid-1960's; the additional cost today (1975) is about \$300 (Lee Ham, oral commun., July 25, 1975).

Land-preparation costs are also high. The land must be diked, drained, and filled to be usable. At Redwood Shores, a major community development on bay fill just south of Foster City, it costs an average of \$8,000 per acre to dewater, demulch, and recondition the already-diked land prior to filling. The filling operation costs about \$6,000 per acre per foot of fill to place, spread, and compact (Gene Mascarelli, oral commun., July 25, 1975).

Costs such as these can be readily justified by a land developer, because of the high market value of the prepared land. In Redwood Shores, filled residential land commands a price between \$73,000 and \$93,000 per acre. The costs of land preparation and construction are assumed by the private sector of the economy. But public costs may also be high, particularly for maintenance of roads, storm and sewer pipelines, and other public improvements. Thus construction on bay mud involves a public as well as private economic commitment. This fiscal impact is an appropriate concern of land-use planning.

As discussed in the section on "Potential Problems in Flatlands Regions," risks from flooding, liquefaction, and seismic wave amplification are also high on lands underlain by bay mud. The ecological-environmental impact from filling the bay for urban developments is also great. Yet in spite of these constraints, urban development on bay mud has taken and continues to take place. The San Francisco Bay Conservation and Development Commission Plan states:

> As the Bay Area's population increases, pressure to fill the Bay for many purposes will increase. New flat land will be sought for many urban uses because most, if not all, of the flat land in communities bordering the Bay is already in use—for residences, businesses, industries, airports, roadways, etc. Past diking and filling of tidelands and marshlands has already reduced the size of the Bay from about 680 square miles in area to little more than 400. Although some of this diked land remains, at least temporarily, as salt ponds or managed wetlands, it has nevertheless been removed from the tides of the Bay. (San Francisco Bay Conservation and Development Commission, 1969, p. 2).

The reduction in size of the bay by diking and

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filling (fig. 53) became a major public issue during the 1960's, because of the environmental, ecological, and climatological impacts of continued bay filling as well as growing concern over the safety of structures on bay fill—particularly during an earthquake.

Public efforts to stop indiscriminate filling of the bay led to State adoption of the McAteer-Petrie Act of 1965, creating the BCDC, (Bay Conservation and Development Commission). BCDC was authorized to prepare a comprehensive plan for the conservation of the bay and development of its shorelands and to recommend appropriate procedures and institutions

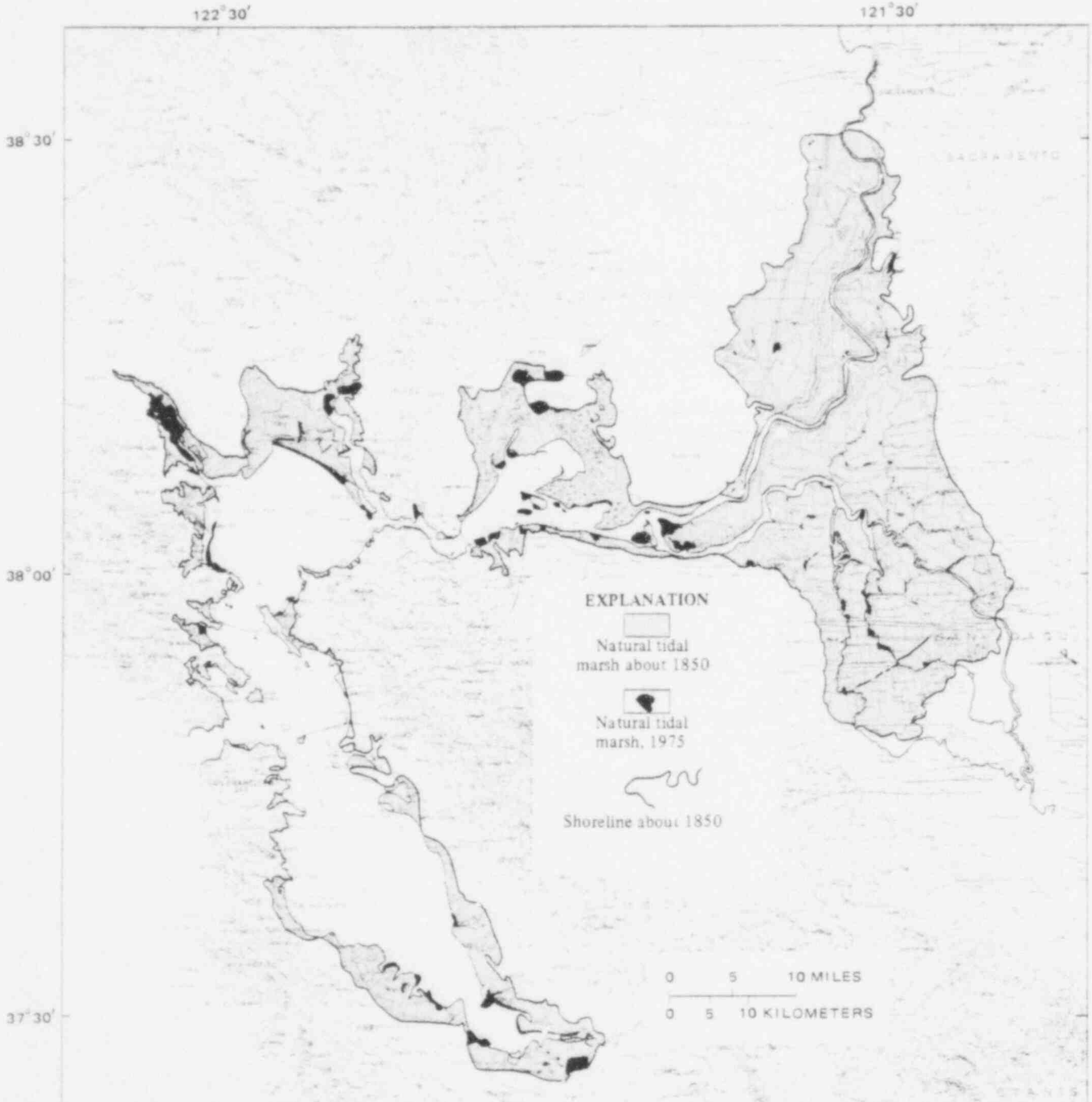

FIGURE 53.—Reduction in area of natural tidal marsh around San Francisco Bay between 1850 and 1975. Location of 1850 shoreline from Nichols and Wright (1971).

to carry out the plan. The San Francisco Bay Plan was completed in 1969 and adopted by the State Legislature (San Francisco Bay Conservation and Development Commission, 1969). BCDC became a permanent organization with responsibility to revise and implement the plan. The findings, policies, and regulatory procedures that are set forth in the San Francisco Bay Plan demonstrate how earth-science information was used to address problems of regional concern.

Although no formal capability analysis was undertaken in preparing the San Francisco Bay Plan, specific information concerning known natural constraints and opportunities for various land uses was sought and applied in the planning process. Twenty-three separate technical reports on the physical, ecological, social, and economic aspects of the bay and its use were published during the planning period, including several related to the nature of flatland deposits. The plan addresses the issues of the environmental impact of bay fill and the safety of fills (San Francisco Bay Conservation and Development Commission, 1969, p. 1).

Major undesirable effects of fill were recognized (San Francisco Bay Conservation and Development Commission, 1969, p. 1-2) as: (1) loss or degradation of an important fish and wildlife habitat, (2) decrease in the ability of the bay to assimilate pollutants, (3) reduction of the moderating effect of the bay upon local climate and an increase in the danger of air pollution, and (4) diminished scenic beauty of the bay.

Despite these harmful impacts, some bay filling may be desirable or necessary if the benefits outweigh the disadvantages. A permit is required from BCDC for any filling or dredging of the bay and lands subject to tidal action. Permits may be issued for fills if one of the following four conditions is met:

(1) The filling is in accord with the Bay Plan policies as to the Bay-related purposes for which filling may be needed (i.e., ports, water-related industry, and water-related recreation) and is shown on the Bay Plan maps as likely to be needed; or (2) The filling is in accord with Bay Plan policies as to purposes for which some fill may be needed if there is no other alternative (i.e., airports, roads, and utility routes); or (3) The filling is in accord with the Bay Plan policies as to minor fills for improving shoreline appearance or public access; or (4) The filling would provide on privately-owned property for new public access to the Bay and for improvement of shoreline appearance—in addition to what would be provided by the other Bay Plan policies—and the filling would be for Bay-oriented commercial recreation and Bay-oriented public assembly purposes. (San Francisco Bay Conservation and Development Commission, 1969, p. 36).

The question of safety of the fill must also be addressed before BCDC can issue a permit for filling. The following section, adapted from San Francisco Bay Conservation and Development Commission (1969, p. 15, 17), lists the findings and policies of the BCDC plan relevant to safety of fills.

Finding.—Virtually all fills in San Francisco Bay are placed on top of bay mud, which presents many engineering problems. The construction of a sound fill depends in part on the stability of the base upon which it is placed. Safety of a fill also depends on the manner in which the filling is done and the materials used for the fill. Construction of a fill or building that will be safe enough for the intended use requires (1) recognition and investigation of all potential hazards—including (a) settling of a fill or a building over a long period of time, and (b) ground failure caused by the manner of constructing the fill or by shaking during a major earthquake—and (2) construction of the fill or building in a manner specifically designed to minimize these hazards. While the construction of buildings on fills overlying bay deposits involves a greater number of potential hazards than construction on rock or on dense hard soil deposits, adequate design measures can be taken to reduce the hazards to acceptable levels.

Policy.—The bay agency should appoint a Fill Review Board consisting of geologists, civil engineers specializing in soils engineering, structural engineers, and architects competent to and adequately empowered to (a) establish and revise safety criteria for bay fills and structure thereon, (b) review all except minor projects for the adequacy of their specific safety provisions and make recommendations concerning these provisions, (c) prescribe an inspection system to assure placement of fill according to approved designs, and (d) gather and make available performance data developed from specific projects. These activities would complement the functions of local building departments and local planning departments, none of which is presently staffed to provide soils inspections.

Even if the bay plan indicates that a fill may be permissible, no fill or building should be constructed if hazards cannot be overcome adequately for the intended use in accordance with the criteria prescribed by the Fill Review Board.

To provide vitally needed information on the effects of earthquakes on all kinds of soils, installation of strong-motion seismographs should be required on all future major land fills. In addition, the Bay agency should encourage installation of strong-motion seismographs in other developments on problem soils, and in other areas recommended by the U.S. Geological Survey, for purposes of data comparison and evaluation.

Finding.—Flood damage to fills and shore-line

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areas can result from a combination of heavy rainfall, high tides, and winds blowing onshore. To prevent such damage, buildings near the shoreline should be above the highest expected flood mark (9 feet above sea level is generally set as the safe mark except in the southern part of the south bay, where the higher tides require almost a foot more elevation) or should be protected by dikes of an adequate height.

Policy.—To prevent damage from flooding, buildings on fill or near the shoreline should have adequate flood protection as determined by competent engineers. As a general rule, buildings near the shoreline should be at least 9 feet above mean sea level (standard USGS datum) or should be protected by dikes of an equivalent height and by any necessary pumping facilities. In the south half of the south bay, this height should be at least 10 feet. Exceptions to the general height rule may be made for development specifically designed to tolerate periodic flooding.

Finding.—Excessive pumping from underground fresh-water reservoirs has caused extensive subsidence of the ground surface in the San Jose area and as far north as Dumbarton Bridge (Poland, 1971, shows subsidence from 1934 to 1967). Indications are that if heavy ground-water pumping is continued indefinitely in the south Bay area, land in the Alviso area (which has already subsided about 7 ft since 1912) could subside up to 7 ft more; if this occurs, extensive dikes may be needed to prevent inundation of low-lying areas by the high tides.

Policy.—To minimize the potential hazard to bayside development from subsidence due to ground-water withdrawal, all proposed developments at the lower end of the south bay should be sufficiently high above mean sea level or sufficiently protected by dikes to allow for the effects of additional subsidence, utilizing the latest information available from the U.S. Geological Survey.

A permit from BCDC is also required for development of the bay shoreline—the area extending inland from the bay a maximum of 1,000 feet (305 m). The control over shoreline development is considered necessary to reduce pressures for bay filling and provide public access to the bay. Water-related uses such as ports, recreation, and wildlife preserves are given priority.

The BCDC plan and permit procedures provide a framework for the continuing use of geologic information in land-use planning and decisionmaking. The kind of information summarized in this report can be used directly by BCDC in revising its plan and in a State-sponsored study of Suisun Marsh. BCDC uses information on flatland deposits in its permit process to evaluate the safety of proposed fills. This general information of geologic characteristics is used to help determine what site-specific information should be required from the applicant.

The Fill Review Board, as presently constituted, has the expertise to review and evaluate soils and geologic reports provided by an applicant. This activity is a critical factor in the agency's effective use of geologic information. Significant improvement in the seismic engineering of fills and design of structures has resulted from the board's insistence on a thorough evaluation of geologic hazards at a project site (San Francisco Bay Conservation and Development Commission, 1974, p. 8).

The availability of geologic information presented in a form understandable to nongeologists is considered very important to BCDC. Such information expands the understanding of both decisionmakers and project applicants and can improve the quality of project proposals and commission decisions.

THE URBAN-AGRICULTURAL CONFLICT

The generally high capability of many flatland areas for both agricultural and urban uses is a major land-use planning concern. In California, the process of urban growth is, for the most part, the process of converting land from agricultural to urban uses. Nearly 4.5 million acres of the State's most productive farmland have been converted to nonagricultural uses since 1947 (Dean, 1975, p. 18). The California OPR (Office of Planning and Research) (California Office of Planning and Research, 1974) states that over the last two decades, 15,000–20,000 acres of highly productive land per year have been converted to nonagricultural uses. Although OPR reports that from 1960–72 California had a net gain of 56,000 acres of agricultural land per year, reversing the trend of the 1950's, the gain is in irrigated land, which commonly requires intensive use of energy and chemical fertilizers to produce high yields.

Planning future land uses to meet the land requirements of both agricultural and urban uses must be based on the best information available concerning land capability for both categories of use. As described in the section on "Land Capability Studies," information on flatland deposits is important in evaluating agricultural and urban land capability. The map of flatland deposits (pl. 1, 2, and 3) provides a generalized view of agricultural capability (see section on "Soil"). Information such as this can be used in combination with Soil Conservation Service soil ratings, if available, to identify lands meriting further investigation for agricultural potential.

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Planning for the use of agricultural land requires a broad, even a global, perspective of future productive capacity and food needs. Within a national and state policy framework, regional planning can be particularly important in reconciling urban and agricultural demands for land. The Association of Bay Area Governments (1970) recommends a "city-centered" pattern of development accommodating new growth through in-filling and extension of existing urban areas and development of new communities. A major justification for this growth pattern is to preserve resources, particularly agricultural lands.

The need to preserve agricultural lands is more explicity expressed in ABAG's Open Space Plan, Phase II (Association of Bay Area Governments, 1972). This plan includes lands with agricultural capability in the category, "open space for managed resource production" (Association of Bay Area Governments, 1972). ABAG's draft report, Areas of Critical Environmental Concern (Association of Bay Area Governments, 1975), spells out more specifically the "regional interest" in agricultural lands. The report sets forth the following policies concerning agricultural lands:

> (1) Preserve agricultural lands which serve the following functions:
> (a) Production of a unique or specialty crop, a high percentage of which is grown in the region (e.g., wine grapes, brussels sprouts);
> (b) Production of crops and commodities which, in order to realize their productive value, must be produced in locations proximate to urban areas (e.g., dairy products, cut flowers).
> (2) Protect all agricultural lands through the support of public service policies which prevent the premature conversion of such lands to urban uses. (Association of Bay Area Governments, 1975, p. 11).

Specific criteria, based on evidence of the capability of land for various agricultural uses, were developed by ABAG to identify "critical areas." Lands meeting these criteria are regionally significant areas of critical environmental concern. Local plans and projects are to be reviewed by ABAG for consistency with the policies and criteria. ABAG also expects local projects and plans to be reviewed for consistency with policies and criteria regarding areas of critical environmental concern as part of required environmental impact statements or reports. As stated by ABAG:

> An Environmental Impact Statement or Report, if it is to be considered adequate by ABAG, should follow a two-step process:
> 1. It should assess first of all whether a proposed plan or project falls within the purview of the Critical Area policies;
> 2. It should make a finding as to whether such activity is consistent with the policies and criteria contained in this document. (Association of Bay Area Governments, 1975, 83 p.)

In addition to project review, ABAG recommends preserving agricultural lands through local installment purchase and saleback or zoning (Association of Bay Area Governments, 1972). Installment purchase and saleback has not been used to any extent, but local zoning has been effectively used. For example, most of the productive agricultural land of the Napa Valley has been zoned "Agricultural Preserve" (AP) since 1968 (Napa County, 1968). Minimum lot size for new parcels within the 25,000-acre "preserve" is 20 acres. This zoning, permitting extensive agriculture and processing in addition to grazing and cultivation, clearly establishes agriculture as the primary use of the valley.

The AP zone was challenged in the courts by the Napa Valley United Farmers but was upheld by the Superior Court of the County of Napa, in a decision on February 17, 1971, as a proper exercise of police powers which benefited, not only the public at large, but also those whose land was regulated (Overview Corp., 1973, p. 20).

PLANNING FOR HAZARDOUS AREAS

Information on flatlands deposits can help identify areas posing risk from natural hazards. The degree of risk depends on the severity, pervasiveness, and frequency of hazardous events together with the land-use intensity, building type, and occupancy of the hazardous areas. Decisions regarding risk involve balancing the public and private benefits from reducing risk against the costs. The threshold point beyond which no further public action is considered necessary or worthwhile to reduce risk is often referred to as the "acceptable level of risk". The California Council on Intergovernmental Relations defines risk levels as follows:

> *Acceptable Risk:* The level of risk below which no specific action by local government is deemed necessary, other than making the risk known.
> *Unacceptable Risk:* Level of risk above which specific action by government is deemed necessary to protect life and property.
> *Avoidable Risk:* Risk not necessary to take because the individual or public goals can be achieved at the same or less total 'cost' by other means without taking the risk. (California Council of Intergovernmental Relations, 1973, p. IV-26).

Individual judgments concerning acceptable, unacceptable, and avoidable risks are highly subjective judgments at the community level and are made through the political process. These judgments can be improved if information relating the possible losses from the hazards to the cost of reducing them is provided and widely disseminated.

The Urban Geology Master Plan (California Division of Mines and Geology, 1973) attempts to place risk from natural hazards in perspective by project-ing losses from major hazards from 1970-2000 assuming the present level of risk mitigation. The study estimates both the costs of hazard mitigation and the benefits that could be achieved if all feasible methods of hazard mitigation were employed. This provides the framework for assigning a benefit/cost ratio for risk reduction efforts. Table 10 summarizes the results for hazards present in many flatland areas.

The benefit/cost approach can help a public agency assign priorities for the use of funds for risk reduction. A thorough understanding of the nature of the hazard is necessary to evaluate risk and risk reduction measures.

SEISMIC HAZARDS—A SPECIAL PROBLEM

A major cause of structural damage from earthquakes is ground shaking. The severity of damage from ground shaking depends on both the nature and design of the structure and on the geologic materials that underlie it. A structure resting on bedrock may be relatively little damaged by ground motion, while another of similar design and construction but located on thick, water-saturated unconsolidated deposits may be heavily damaged.

In seismically active areas, the need to plan urban facilities to minimize risk is extremely important. In recent years, new information on the causes and nature of earthquakes and their effects has led to efforts to mitigate those effects where possible. In California, a seismic safety element is now a required part of the general plan for all cities and counties. Development along active faults is controlled under provisions of the Alquist-Priolo Special Studies Zones Act (California State Legislature Public Resources Code, Sec. 2621, 2625, 1972 as amended 1975), and plans for disaster preparedness are now being developed for all seismically active areas of the State. Consequently, many planning agencies need information of the effects of earthquakes, and if this information is available, its use is assured. Seismic risk maps are one means of predicting earthquake effects in a form useful to land-use planners. Such risk maps divide a planning area into zones according to the relative degree of potential damage to structures and are commonly related to an earthquake of stated magnitude (called the "design earthquake").

Knowledge of the properties and thickness of flatland deposits is critical in evaluating the potential risk from ground shaking, whether this risk results from seismic wave amplification or from liquefaction potential. The planner, working closely with a seismic specialist, can then relate land uses, building, and occupancy types to the risk zones. Guidance in this task is provided by the California Joint Committee for Seismic Safety (January 1974). Table 11 describes acceptable risk in terms of the kinds of structures and their occupancy.

At the regional level seismic risk studies are useful in formulating regional growth policies. Careful study of high-risk areas will indicate the cost of hazard mitigation and may reveal areas that are well suited for low-intensity recreational and open-space uses.

Many areas underlain by unstable bay muds, for example are marshes that provide important wildlife habitats. Areas with open-space potential together with risk to urban uses can be important elements of regional open-space plans and preservation efforts.

SANTA CLARA COUNTY BAYLANDS STUDY

Santa Clara County prepared a subarea plan for the baylands within its jurisdiction which takes into account the hazards—seismic and nonseismic—associated with flatland deposits. Consultants' studies of geologic and structural engineering problems were used to identify the natural hazards of the planning area and to describe their implications for specific land uses. The resulting report divided the planning area into risk zones (the basis of potential for settlement and ground failure, under both seismic and nonseismic conditions. Table 12 lists the risk zones and the nature of the hazard in each. Figure 54 is a map of the risk zones. Table 13 relates land and building uses to the risk zones.

TABLE 10.—*Projected losses due to geologic problems in California, 1970-2000*

[Adapted from California Division of Mines and Geology, 1973, p. 4]

Geologic problem	Projected losses 1970-2000	Possible loss reduction	Cost of loss reduction	Benefit/cost ratio
Earthquake shaking	$21 billion	$10.5 billion	$2 billion	5
Loss of mineral resources	17 billion	15 billion	90 million	167
Flooding	6.5 billion	3.4 billion	2.7 billion	1.3
Erosion	600 million	400 million	250 million	1.5
Expansive soils	150 million	149 million	7.5 million	20
Subsidence	26 million	13 million	9 million	1.5

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TABLE 11.—*A scale of acceptable risks*

Level of acceptable risk	Kinds of structures	Extra project cost probably required to reduce risk to an acceptable level
Extremely low[1]	Structures whose continued functioning is critical, or whose failure might be catastrophic: nuclear reactors, large dams, power intertie systems, plants manufacturing or storing explosives or toxic materials.	No set percentage (whatever is required for maximum attainable safety).
Slightly higher than under level 1[1]	Structures whose use is critically needed after a disaster: important utility centers; hospitals; fire, police, and emergency communication facilities; fire stations; and critical transportation elements such as bridges and overpasses; also smaller dams.	5-25 percent of project cost[2].
Lowest possible risk to occupants of the structure[3]	Structures of high occupancy, or whose use after a disaster would be particularly convenient: schools, churches, theaters, large hotels, and high-rise buildings housing large numbers of people, other places normally attracting large concentrations of people, civic buildings such as fire stations, secondary utility structures, extremely large commercial enterprises, most roads, alternative or noncritical bridges and overpasses.	5-15 percent of project cost[4].
An "ordinary" level of risk to occupants of the structure[3,5]	The vast majority of structures: most commercial and industrial buildings small hotels and apartment buildings, and and single family residences.	1-2 percent of project cost, in most cases (2-10 percent of project cost in a minority of cases)[4]

[1] Failure of a single structure may affect substantial populations.

[2] These additional percentages are based on the assumption that base cost is the total cost of the building or other facility when ready for occupancy. In addition, it is assumed that the structure would have been designed and built in accordance with current California practice. Moreover, the estimated additional cost presumes that the structures in this acceptable-risk category are to embody sufficient safety to remain functional after an earthquake.

[3] Failure of a single structure would affect primarily only the occupants.

[4] These additional percentages are based on the assumption that the base cost is the total cost of the building or facility when ready for occupancy. In addition, it is assumed that the structure would have been designed and built in accordance with current California practice. Moreover, the estimated additional cost presumes that structures in this acceptable-risk category are to be sufficiently safe to give reasonable assurance of preventing injury or loss of life during an earthquake, but otherwise not necessarily to remain functional.

[5] "Ordinary risk": Resist minor earthquakes without damage; resist moderate earthquakes without structural damage, but with some non-structural damage; resist major earthquakes of the intensity or severity of the strongest experienced in California, without collapse, but with some structural as well as nonstructural damage. In most structures, it is expected that structural damage, even in a major earthquake, could be limited to repairable damage (Danehy, 1969).

TABLE 12.—*Risk zones for settlement and ground failure*

[Established by subsurface conditions in the baylands of Santa Clara County. Adapted from Woodward-Clyde and Assoc. and McClure and Messinger (1970), p. 10.]

Risk zone	Surface effect	Subsurface cause
A	Little risk of settlement or ground failure	-------
B_{DL}	Significant settlement	Liquefaction of confined granular layer in alluvium (seismic loading).
C_S	Moderate to substantial settlement and(or) differential settlement	Consolidated of bay mud or soft clay (static unloading).
D_D	Substantial settlement and(or) differential settlement	Consolidation of uncontrolled dump fill or sanitary land fill (static loading).
D_{SL}	Failure of ground surface	Liquefaction of granular surface layer (seismic loading).
D_{LS}	Failure of ground surface	Lateral spreading toward free face (seismic loading).

The plan adopts these uses with the stipulation that any developer in the baylands provide data from test boring and sample testing in depth to demonstrate that a proposed development site is not in a higher risk zone than shown. Establishing an Advisory Review Board was recommended to advise public agencies on the adequacy of engineering investigations, design, and construction methods in the baylands.

On the basis of the plan, the county adopted an ordinance requiring a soils report for all major subdivisions unless specifically exempted. Geologic reports and site investigations are required for all subdivisions on or adjacent to potentially hazardous areas as depicted on official county hazard maps. The map of risk zones for land-use planning (fig. 54) is one of the official hazard maps. Geologic reports are normally required for development in risk zones C and D and may be required in risk zones A and B.

A key feature of the successful integration of geologic considerations into plan development and administration in the Santa Clara County Baylands program is the use of the appropriate expertise at each stage of the planning process. In the baylands study, an engineering geologist gathered available geologic data, and together with a structural engineer, divided the study area into zones on the basis of the expected surface effects of geologic conditions. They then worked cooperatively to determine the range of land uses and building types that could be accommodated in each zone with reasonable safety on the basis of:

(1) The possible types of geologic risks such as settlement, liquefaction, lateral spreading, ground shaking, tsunamis and fault rup-

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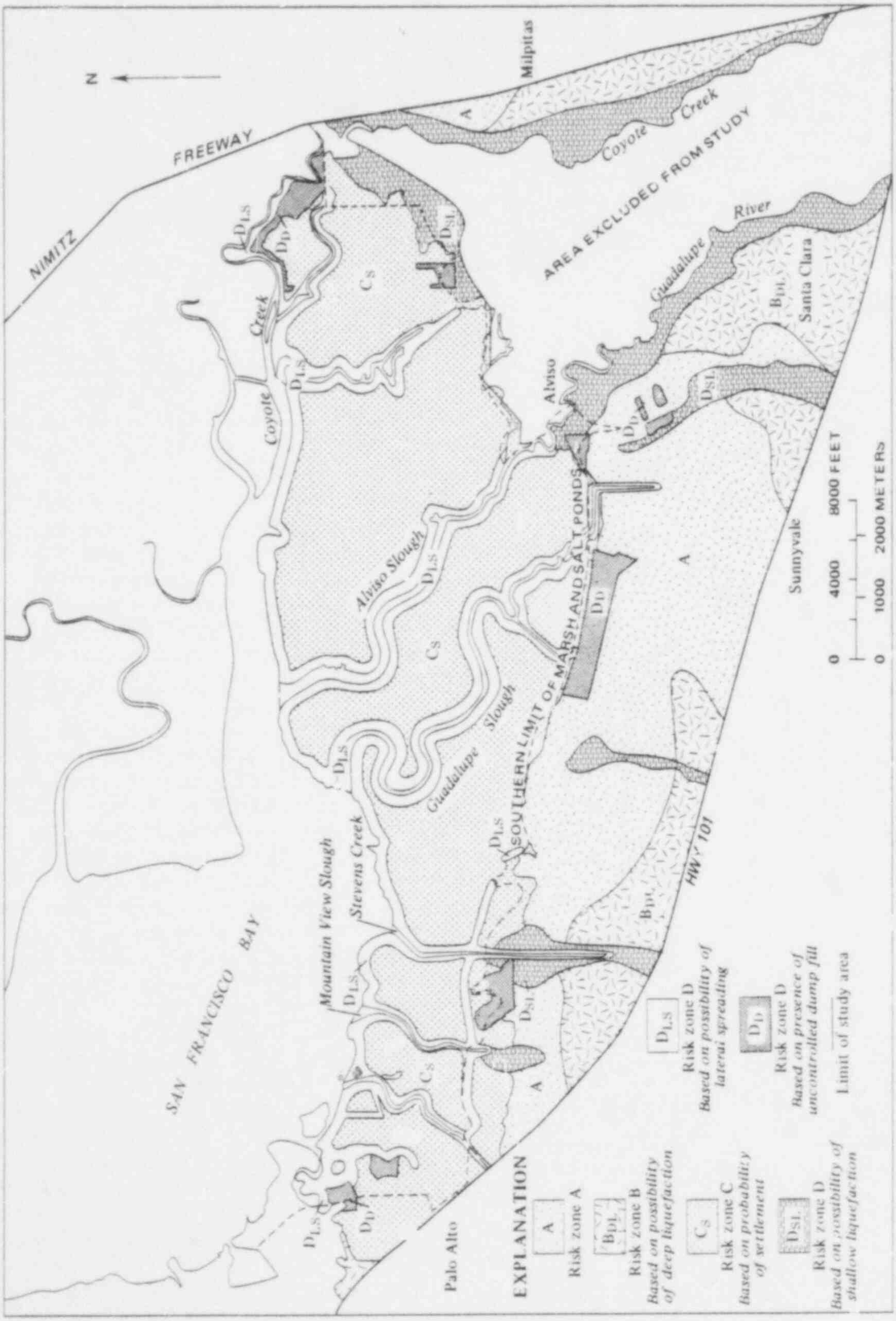

FIGURE 54.—Risk zones for land-use planning, Santa Clara County baylands. From Woodward-Clyde and Associates and McClure and Messinger (1970, part II, fig. 4).

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TABLE 13.—*Land and building uses for various risk zones*

(Adapted from Santa Clara County Planning Policy Committee, 1972, p. 22)

Land and building uses	Risk zones (see fig. 54)			
Group A buildings:	A	B	C	D
Hospital and nursing homes	X	--	--	--
Auditoriums and theaters	X	--	--	--
Schools	X	--	--	--
Transportation and airports	X	--	--	--
Public and private offices	X	--	--	--
Major Utility	X	--	--	--
Other building uses	X	--	--	--
Group B buildings:				
Residential-multiple units	X	X	--	--
Residential, 1 and 2 family	X	X	--	--
Small Commercial	X	X	--	--
Small public	X	X	--	--
Small schools, one story	X	X	--	--
Utilities	X	X	--	--
Group C buildings:				
"Industrial park" commercial	X	X	X	--
Light and heavy industry	X	X	X	--
Small public, if mandatory	X	X	X	--
Airport maintenance	X	X	X	--
Group D buildings:				
Water-oriented industry	X	X	X	--
Wharves and docks	X	X	X	--
Warehouses	X	X	X	--
Group D open space:				
Agriculture, marinas, public and private open spaces, marshlands and saltponds, and small appurtenant buildings	X	X	X	X

ture; (2) The ability to identify land areas where these types of geologic risks are possible; (3) The ability to assign either qualitative or quantitive limits on the possible effects of these risks; (4) The types of land and building uses and their socio-economic importance; (5) The behavior of buildings and other improvements under static and seismic conditions; (6) The ability of "normal" practices of investigation, design, construction, inspection, and enforcement to develop recommendations and procedures to provide adequate levels of protection; (7) The ability to develop and implement special investigation, design, construction, inspection, and enforcement procedures where normal procedures are considered inadequate. (Santa Clara County Planning Policy Committee, 1972, p. 27).

Using the interpretations and recommendations of the engineering geologist and structural engineer, plus other relevant information, the planner developed land-use policies and recommendations and defined procedures for obtaining more detailed geologic investigations, if needed, at the time of an application for a zoning change, land division, grading permit or building permit. After adoption of the policies and procedures, a geologist was added to the County staff to assist planners and engineers in administering the policies and review procedures.

The relation between planning phase and the use of geologic expertise in the Santa Clara County Baylands study provides a model applicable to other planning areas with known or suspected geologic hazards. However, the sequence as described assumes the availability of basic geologic data. The process of incorporating geologic considerations into land-use planning starts with basic geologic maps or more specialized maps such as the map of flatland deposits and continues through successive refinements of the basic geologic data and interpretations to relate geologic conditions to particular land uses and structural types.

SUMMARY

Geologic information about flatland areas is of particular importance in land-use planning because most urban development occurs in relatively flat terrain. Geologic studies can help identify potential problems such as flooding, stream-channel changes, salt-water intrusion, subsidence, settlement, shrink and swell, and various earthquake-induced hazards. In addition, geologic studies can locate many natural resources including ground-water recharge and storage areas, agricultural soils, and deposits of sand, salt, gravel, and clay. A planning jurisdiction can then direct future growth to reduce risk from natural hazards, avoid excessive development costs, and preserve essential resources.

The maps of flatland deposits included with this report (pls. 1, 2, and 3) illustrate an innovative approach to geologic mapping. Unconsolidated alluvial deposits occurring in areas with slopes of less than 15 percent are differentiated largely on the basis of composition and age. These characteristics are important in determining the engineering properties of the deposits, particularly the potential for seismic wave amplification and liquefaction. With the aid of existing soils data, topographic maps, aerial photographs, and limited fieldwork, geologists completed the mapping of flatland deposits of the entire 7,281 square mile (19,316 km^2) San Francisco Bay region in only three years.

The maps were prepared specifically for use in land-use planning. Each map unit is described in terms of its geologic characteristics, engineering properties, resource potential, and any special problems related to the safety and cost of land development.

In the past, planners have used modern soils series maps prepared primarily by the U.S. Soil Conservation Service to identify the problems and resources discussed here. Where available, these maps are an excellent source of information, particularly to evaluate land capability for agriculture, erosion potential, and tendencies of the soil to corrode or expand. However, the approach used here adds a new dimension to the usual soils data by considering greater depth of deposits and the processes by which they formed. This added dimension is especially important in geologically active areas such as the west coast, but it can also be useful elsewhere in the country. The geologic approach to mapping flatland surficial deposits is essential in seismically active areas in order to evaluate ground shaking and the possibility of ground failure. In addition, geologic information is needed to assess potential for groundwater storage and recharge, and problems of settlement and subsidence. These are major concerns throughout the country.

Since formative processes are emphasized, geologic description of alluvial deposits explicitly includes geologic-hydrologic relations. These relations are important in understanding the direction and nature of long-term changes in the natural environment that can affect the use of land.

The map of flatland deposits, at a scale of 1:125,000, provides a regional overview of flatland characteristics. Areawide information at this scale provides an excellent framework for developing a data-collection program at the regional and local levels. It allows a planning agency to focus on those areas with identified problems or resource potential, and those areas where land uses are most likely to change. The public and private benefits of specific identification of resource and hazard areas before land development occurs are substantial because it is almost always easier and less expensive to address site problems before development than to try to correct them afterward.

As discussed in the sections on planning approaches to flatland problems and resources, geologic information is important throughout the planning process. Information on flatland geology, along with data on hillside geology and other earth-science and environmental information, is needed to:

1. Evaluate the relative physical capability of land to accommodate proposed uses;
2. Develop land-use policies and plans at the regional and local levels responsive to the physical problems and potentials of the land;
3. Define appropriate soils and geologic investigations needed for project design and review;
4. Establish procedures to review soils and geologic reports, environmental impact assessments, and other information submitted for project review;
5. Prepare and administer land-use and development regulations implementing adopted policies and plans.

A qualified earth scientist, on or available to, the planning staff to assist in interpreting and applying geologic data is essential. Wisely used, geologic information can lead to safer, less costly, and more environmentally sensitive use of our valuable, but limited, land resources.

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