EQL Report No. 17-A

SEDIMENT MANAGEMENT FOR SOUTHERN CALIFORNIA MOUNTAINS, COASTAL PLAINS AND SHORELINE

PART A
REGIONAL GEOLOGICAL HISTORY

by

EDWARD W. FALL

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Environmental Quality Laboratory
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PREFACE

In southern California the natural environmental system involves the continual relocation of sedimentary materials. Particles are eroded from inland areas where there is sufficient relief and precipitation. Then, with reductions in hydraulic gradient along the stream course and at the shoreline, the velocity of surface runoff is reduced and there is deposition. Generally, coarse sand, gravel and larger particles are deposited near the base of the eroding surfaces (mountains and hills) and the finer sediments are deposited on floodplains, in bays or lagoons, and at the shoreline as delta deposits. Very fine silt and clay particles, which make up a significant part of the eroded material, are carried offshore where they eventually deposit in deeper areas. Sand deposited at the shoreline is gradually moved along the coast by waves and currents, and provides nourishment for local beaches. However, eventually much of this littoral material is also lost to offshore areas.

Human developments in the coastal region have substantially altered the natural sedimentary processes, through changes in land use, the harvesting of natural resources (logging, grazing, and sand and gravel mining); the construction and operation of water conservation facilities and flood control structures; and coastal developments.

In almost all cases these developments have grown out of recognized needs and have well served their primary purpose. At the time possible deleterious effects on the local or regional sediment balance were generally unforeseen or were felt to be of secondary importance.

In 1975 a large-scale study of inland and coastal sedimentation processes in southern California was initiated by the Environmental Quality Laboratory at the California Institute of Technology and the Center for Coastal Studies at Scripps Institution of Oceanography.

This volume is one of a series of reports from this study. Using existing data bases, this series attempts to define quantitatively inland and coastal sedimentation processes and identify the effects man has had on these processes. To resolve some issues related to long-term sediment management, additional research and data will be needed.

In the series there are four Caltech reports that provide supporting studies for the summary report (EQL Report No. 17). These reports include:

EQL Report 17-A -- Regional Geological History

EQL Report 17-B -- Inland Sediment Movements by Natural Processes

EQL Report 17-C -- Coastal Sediment Delivery by Major Rivers in Southern California

EQL Report 17-D -- Special Inland Studies

Additional supporting reports on coastal studies (shoreline sedimentation processes, control structures, dredging, etc.) are being published by the Center for Coastal Studies at Scripps Institution of Oceanography, La Jolla, California.

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REGIONAL GEOLOGIC HISTORY

A1 Introduction

The study area of the regional sedimentation project involves a stretch of coastal southern California extending from Point Conception south and east to the mouth of the Tijuana River and inland to the crest of the divide separating interior from coastal drainages (see Plate A-1). The area is characterized by youthful geomorphic terrain where tectonic disturbances continue to rejuvenate existing landforms. Like much of the rest of the western United States, faulting, folding, and warping in southern California have largely dictated the size, shape, and trend of its physiographic features. Although erosion and deposition have certainly acted to reduce relief between high and low points, their primary function has been to add details onto tectonically determined surfaces.

To understand the natural sediment budget for this area, it is necessary to understand the geology of the region and to recognize the geologic processes that influence sediment erosion, transport, and deposition. For example, since eroded sediment grain sizes depend in part on textural and compositional properties of parent rock materials, prediction of eroded grain sizes requires knowledge of the surface geology. This report will summarize regional geology and geological composition and the large scale forces that have shaped it.

Even causal examination of a raised relief map of southern California reveals that this area is readily divisible into different physiographic provinces, each having distinctly different morphological characteristics. Since the landforms in these provinces largely reflect the underlying geological conditions, it is no surprise to find that the geology of each is distinctive as well. As shown in Fig. A1-1, two of these geomorphic provinces are part of larger geomorphic units. The Transverse Ranges province is the central and

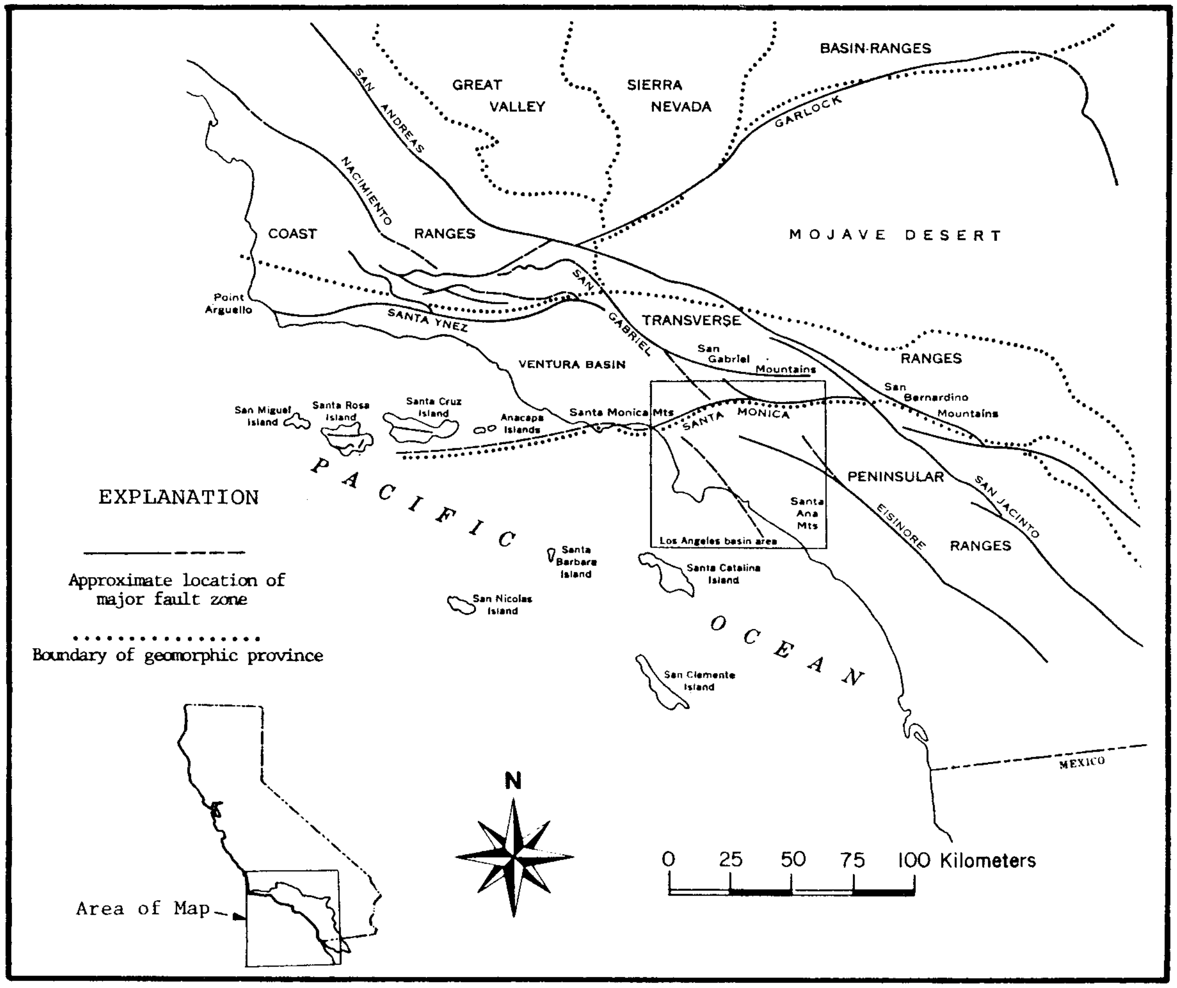

Fig. A1-1 A map of southern California showing the boundaries of the geomorphic provinces.

western portion of a narrow belt of mountain ranges extending from Point Arguello east into the desert regions of southeastern California, and the Peninsular Ranges province is the northern part of a wider band of mountain ranges stretching from Los Angeles southeast to the tip of Baja California. Both provinces have westward extensions that are submerged offshore beneath the Pacific Ocean.

The Peninsular Ranges province consists of parallel chains of mountains and intervening valleys that trend northwest. Its trend is characteristic of most of the coastal California ranges, and reflects dominant underlying geological structure. However, immediately north of Los Angeles, the east-west trending Transverse Ranges cut across this northwest structural grain and abruptly truncate the Peninsular Ranges province along a zone of steeply dipping reverse faults (see Plate A-2). The precipitous south facing escarpment of the San Gabriel Mountains provides a most impressive example of the faulting along this boundary.

Since the two provinces are distinctive from one another, it is best to describe their geology separately. Subtle differences in the structural and depositional character of the Los Angeles basin also make it desirable to treat it independently of the Peninsular Ranges with which it is normally included. These simplifications may prevent confusion in a region of complex geological history. Age dates given in the text are in all cases approximate, and meant for general reference only. They are based on the geologic time scale given in Section A7.

A2 Transverse Ranges

A2.1 Present Setting

The Transverse Ranges province comprises a band of semi-parallel mountain ranges and valleys that stretches almost 540 km from Point Arguello east into the Colorado Desert. The province is characterized by rugged relief of thousands of meters, and contains the highest peaks in southern California. The province reaches a maximum width of about 90 km between Tejon Pass and Santa Monica Bay, but it averages less than 55 km across, and narrows to a minimum of 27 km at Cajon Pass. With the exception of the offshore area, the western three quarters of this province lies within the northern part of the study area.

The morphologic features of the Transverse Ranges reflect underlying geologic structures and trend east-west, counter to the northwest grain of adjoining regions. The mountain ranges in the western part of the province are uplifted fold belts of Cenozoic (65 million years to present) sedimentary rock, and they adjoin intervening elongate valleys along high angle reverse faults or thrust faults (see Fig. A2-1). The eastern mountain ranges, in contrast, are huge blocks of ancient crystalline rocks that have been extensively sheared and fragmented through a long and complicated history of deformation. They too have been uplifted, but along a more complex system of reverse faults that tie in with the San Andreas fault zone. The folds, reverse faults, and thrust faults are expressions of compressional tectonics, and indicate north-south crustal shortening in the Transverse Ranges within the recent past, possibly in response to development of the broad bend in the San Andreas fault that appears just north of the province.

In addition to having an unusual structural trend, the Transverse Ranges possess a heterogeneous assemblage of rock types and contain some of the oldest rocks in southern California. The basement material contains mixed igneous and metamorphic rocks, some of which approach two billion years in age. These rocks outcrop extensively throughout the

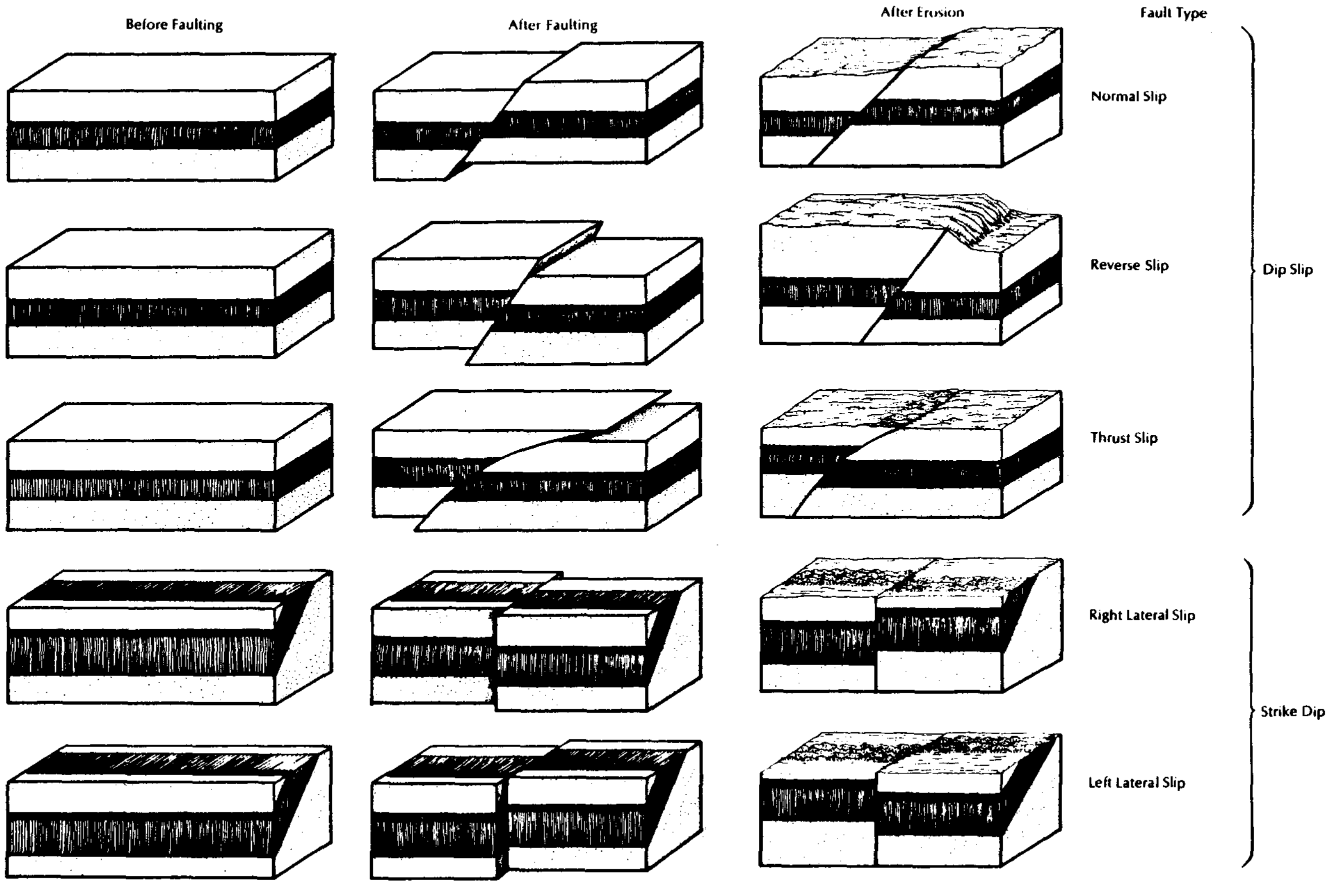

Fig. A2-1 Fault types (from Putnam, 1971) eastern ranges, but are largely buried west of the San Gabriel fault by younger marine and nonmarine sedimentary rocks, many of which were deposited as thick sequences in local basins.

Sedimentary depositional basins occupied different parts of what is now the Transverse Ranges province at various times over the last 65 million years during its Cenozoic history. The oldest of the basins was centered over the area where the Santa Ynez, Topatopa, San Rafael, Piru, and Pine mountains are today (Fig. A2-2). This basin received up to 10,000 m of fine-grained clastic marine sediments from Paleocene through Eocene time (60 to 45 million years ago). Younger basins formed in early Miocene time (24 to 27 million years ago) or later near Ventura, near the Soledad region, and near Ridge Basin. The last two of these were constricted continental depressions where sedimentation was largely fluviatile (alluvial stream formed) or lacustrine (lake formed). The Ventura depositional basin which lay farther west underwent marine deposition. All three basins received from bordering upland areas, large volumes of debris and accumulated thick deposits which became sedimentary rock upon lithification.

North-south compression within the last few million years has caused buckling of the sediments in the western Transverse Ranges and crushing of the basement rocks in the eastern Transverse Ranges. This compression has also caused a general uplift of the entire area along a system of steep reverse and thrust faults. Ongoing tectonic activity, especially faulting, in this area is evident from offsets of recent alluvium and more dramatically from the historic San Fernando earthquake of 1971.

A2.2 Geological Evolution

The geological history of the Transverse Ranges, and the rest of California as well, may be divided into two periods, conveniently separated by a major unconformity* of Late Cretaceous age (between 65

*An unconformity is an erosional surface separating younger rock strata from older rocks.

subaerial

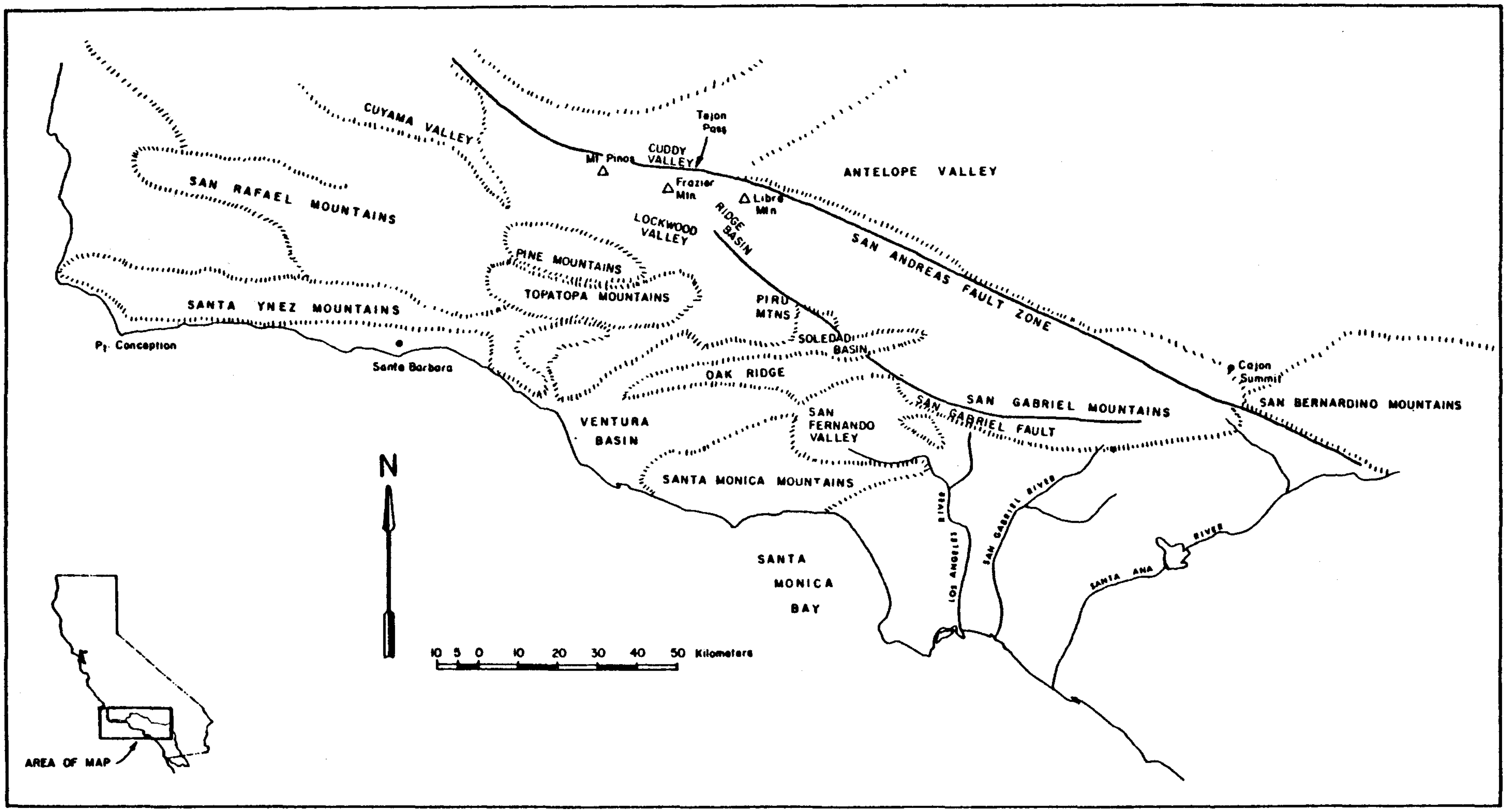

Fig. A2-2 Map of the western Transverse Range province showing the major topographic features.

and 90 million years ago). In California, the rocks younger than this unconformity are mostly clastic marine and nonmarine sediments and volcanics, none more than 70 million years old. They rest on crystalline basement rocks of igneous and/or metamorphic origin that are generally older than 90 million years. The unconformity therefore represents as much as 20 million years of missing record, and it is probably the result of a tremendous tectonic upheaval and subsequent erosion during this time that affected large portions of western North America.

The pre-Late Cretaceous basement rocks in coastal California consist of two contrasting types, the eastern basement rocks and the western basement rocks, whose relationships to one another are not entirely understood. Where the two outcrop side-by-side, they are always separated by a major tectonic contact, as along the Newport-Inglewood fault in the Los Angeles basin and outside the study area along the Nacimiento fault in the Coast Ranges (see Fig. A3-1). The two basement rock types were tectonically juxtaposed more than 70 million years ago along these and other faults, which are believed to be remnants of what was then a single extensive fracture zone. Unfortunately, in the Transverse Ranges, thick accumulations of Cenozoic sediments blanket much of the western half of the province, concealing those areas through which this zone has been interpreted to lie.

Representatives of both basement types are found in the Transverse Ranges, but only outcrops of the eastern type are found within the study area. The eastern basement occupies large areas in the north-central and eastern ranges, but like the fracture zone, it is covered west of the San Gabriel fault by Cenozoic sediments. Where it can be observed in the San Gabriel Mountains and east it consists of several wedges of shattered crystalline rock caught between major faults of the San Andreas system. The rocks that outcrop in the San Gabriel, San Bernardino, Libre, Frazier, and Mt. Piños mountain areas (Fig. A2-2), are greatly deformed and strongly metamorphosed, and include abundant intrusions of igneous material. The entire terrain is heavily fractured and sheared, giving it a rugged appearance.

The eastern basement complex in the San Gabriel Mountains contains Precambrian layered quartzofeldspathic gneisses and amphibolites nearly 2,000 million years old. These rocks are the most ancient in southern California, and they have suffered a long history of deformation and intrusion, beginning with the invasion of coarse-grained porphyritic granite between one and two billion years ago. Parts of both of these terranes underwent further high-grade metamorphism during the same period, altering some of the rocks to granulites (rocks containing a large percentage of minerals formed under extreme pressure and high temperature -- near the melting point). Subsequently a compositionally layered anorthosite-syenite complex (rocks of unusual composition ranging from almost pure calcic feldspar to mixtures of calcic and potassic feldspar, dark ferromagnesium minerals, and minor amounts of quartz) intruded the existing rock about one billion years ago. Further intrusion of granodiorite, minzonite, and granite (all light colored igneous rocks composed mainly of quartz, mica, and feldspar) followed much later during the Mesozoic era beginning nearly 225 million years ago and continuing sporadically until approximately 65 million years ago. Together, all of these rocks constitute a unique basement terrane of limited extend that has been useful in reconstructing fault offsets in southern California.

Basement rocks with lithologies and histories similar to those in the San Gabriel Mountains outcrop in the Frazier Mountain-Mt. Piños area. The suggested correlation of the two terranes has been cited as evidence for some 60 km of aggregate right-lateral strike-slip displacement along the San Gabriel fault zone in this area. The only other similar terrane known to exist in southern California lies outside the study area, in the Orocopie-Chocolate Mountains area northwest of the Salton Sea. Identification of these rocks as part of the San Gabriel type basement has been used to argue for nearly 290 km of right lateral displacement along the San Andreas fault in southern California.

The second or western type of basement rock outcrops immediately north of the study area in the northern Santa Ynez and San Rafael mountains and probably underlies much of the western Transverse Ranges. Rocks of this basement terrane belong to the Franciscan formation, a group of mildly to moderately metamorphosed shales, cherts, graywackes, conglomerates, and volcanic flows of Late Jurassic to early Late Cretaceous age (140 to 90 million years old) that locally contain tectonically emplaced serpentinite massifs. The entire group of rocks is believed to be altered fragments of oceanic crust, lacking the granitic plutonic rocks characteristic of continental basement rocks. It is currently thought that these pieces of oceanic crust accreted at a continental plate margin by interaction between continental and oceanic lithospheric plates. Evidence suggests that these rocks formed as oceanic crustal material where they were carried to a subducting plate margin with the North American continent (one plate overriding another) during the Cretaceous age (70 to 120 million years ago). Within this period the rocks were mixed losing most of their original stratigraphic order. The diastrophic emplacement of these massifs further deformed these rocks and caused profuse faulting and folding. Interaction between the north American continent and oceanic crust has been concentrated along faults of the San Andreas system for the past 30 million years (Atwater, 1970) which continues to deform these rocks. In addition to being much younger than rocks of the eastern basement, western basement rocks have undergone less metamorphism and mechanical deformation.

Following the creation of the basement terranes and their subsequent juxtaposition, is the 20 or so million years for which there is no geologic record. The causes of this unconformity elude geologists, but it is possible that the crustal forces responsible for intrusion of the great batholiths in the Sierra Nevada, Transverse Ranges, and

Peninsular Ranges earlier in Mesozoic time (90+ million years ago) led to a diastrophism and erosion which created this unconformity.

Thick sections of latest Cretaceous (65 million years ago), Tertiary (65 to 2 million years ago), and Quaternary (2 million years ago to present) sediments and minor volcanics cover the basement rocks almost entirely in the western Transverse Ranges, but only partially in the eastern ranges. From Late Cretaceous through early Eocene time (70 to 50 millions years ago) the western and parts of the eastern ranges were submerged and received thick accumulations of clastic sediments deposited largely in shallow marine and marginal marine environments. These rocks outcrop extensively in the Santa Ynez, Topatopa, Pine, and Piru mountain areas northeast of Ventura, sporadically in the Santa Monica Mountains, and in the western Libre Mountains. The eastern exposures consist of roughly 3,000 m of siltstone, sandstone, and conglomerates that were formed from marine deposits near the shoreline. The sections thicken and become finer to the west, indicating increasing water depth in that direction during deposition. Source areas, as determined from current indications and provenance analysis (locating source areas by the mineralogy of the clastic fragments deposited), lay to the north and east.

The amount of tectonic activity during the period from Late Cretaceous to Eocene is uncertain since most of the faults in the Transverse Ranges appear to be of Miocene age (23 million years) or younger. However, the entire area was exposed possibly through uplift in late Eocene time (40+ million years ago) since sediments of this age through early Miocene age (40 to 25 million years old) are largely nonmarine.

From the late Eocene through early Miocene time (40 to 25 million years ago) conglomerates, coarse sandstones, and mud flows were deposited under subaerial conditions mainly by fluvial processes in streams and on alluvial fans. Rocks formed in this way outcrop sporadically throughout the province. In the western ranges, they belong to the Sespe formation of Oligocene age (38 to 25 million years) and were formed from deposits on coalescing alluvial fans that sloped westward toward the sea. In the eastern ranges, the rocks are of earliest Miocene age or younger (25 to 20 million years old) and they belong to the Vasquez formation, as can be seen in Vasquez Rocks County Park.

The Vasquez formation accumulated as conglomerate and lacustrine deposits in an enclosed interior basin. The source of these sediments lay mainly to the south and east amidst a terrain both lithologically and morphologically similar to rocks in the San Gabriel Mountains, which occupy this location today. The fact that the Vasquez formation is nearly 3,700 m thick in places suggests that perhaps as much as 1 km or more of material was removed from the roof of the mountains at that time. Since then, the San Gabriel Mountains have supplied sediment continuously to the surrounding Vasquez (or Soledad), Los Angeles, and Ventura basins though probably at variable rates. This means that as early as late Oligocene time (30 million years ago) the San Gabriel Mountains commenced their uplift.

Rocks of similar age and composition to the Vasquez formation crop out in the Cuddy and Lockwood valleys north of Frazier Mountain. They, like the rocks in Vasquez basin, came from southern and eastern sources lithologically akin to basement rocks exposed on Frazier Mountain today. These rocks and their correlatives in the Vasquez basin are believed to be offset by subsequent movements on the San Gabriel fault, as are the basement terranes on Frazier Mountain and the San Gabriel Mountains.

Besides marking the onset of uplift in the San Gabriel and Frazier Mountain areas, the period from latest Oligocene through early Miocene time (30 to 20 million years ago) also saw the inception of movement along most of southern California's major faults as well as the formation of several structural depressions of which the Vasquez, Ventura, and Los Angeles depositional basins are the primary examples. The causes of these abrupt developments have recently been attributed to changes in crustal plate movements relative to one another, but the details of this argument are beyond the scope of this report.

Unlike the Vasquez basin, the Ventura and Los Angeles basins evolved largely under marine conditions. Although sediments had been accumulating in the Ventura sedimentary basin as in the rest of the western Transverse Ranges for much of early Tertiary time, it wasn't until the early Miocene period (23 million years ago) that a downwarped structural trough began to take form. From that time on, deposition occurred at accelerated rates, adding more than 10,700 m of marine shale, siltstone, fine-grained sandstone, and minor amounts of conglomerate to the 7,600 m of early Tertiary sediments already there. The eastern parts of this basin have since filled but continue to receive deposits of fluvial sediments, while the western half of the basin is submerged in the Santa Barbara Channel.

The Vasquez basin continued to accumulate sediment from Miocene through lower Pleistocene time (23 to 2 million years ago) although the center of deposition shifted from the Soledad region north and west to areas north of Castaic and Pyramid reservoirs. The San Gabriel fault, which was active throughout this period, maintained an uplifted land mass southwest of the low basin to the north, causing the depression to remain enclosed. Cessation of movement on the fault in early Pleistocene time (2 to 3 million years ago) brought an end to interior continental deposition when the Santa Clara River apparently breached the escarpment produced by the fault.

The western Transverse Ranges area sank beneath the sea following Oligocene time (25 or so million years ago) but formed relatively shallow marine banks or shelves compared to the contemporary Ventura of Los Angeles marine depositional basins. These basins continued to accumulate shallow water marine siltstone, sandstone, and conglomerates through Pliocene time (3 million years ago). Renewed uplift of the entire Transverse Ranges by compressional faulting and folding caused emergence of this area in Plio-Pleistocene time (2 to 3 million years ago).

A3 Los Angeles Basin

A3.1 Present Setting

The Los Angeles Basin is a broad alluviated coastal plain enclosed by mountains and hills on three sides (see Fig. A3-1). Its present physiographic limits include an area bounded on the north by the Santa Monica and San Gabriel mountains, to the east by the San Jose and Puente Hills, and on the southeast by the Santa Ana Mountains and San Joaquin Hills. The basin is elongated in a northwesterly direction, stretching 90 km between the San Joaquin Hills and Santa Monica Mountains, and laterally nearly 63 km between the San Gabriel Mountains and the sea.

In several places, disconnected semi-parallel chains of low hills penetrate the otherwise smooth surface of the basin, and rise to a few hundred meters above the alluvium. Familiar examples include the Palos Verdes Hills, the Puente-Repetto-Elysian chain, and the chain that includes Beverly Hills, Baldwin Hills, Dominguez Hills, Signal Hill, and Newport Mesa. All are superficial expressions of extensive, deep-seated tectonic discontinuities in the underlying crust whose northwest trend defined the structural grain of both the Los Angeles basin and the Peninsular Ranges farther to the south.

Besides being a physiographic lowland, the Los Angeles area is part of a depositional basin which, until recently in geologic time (within the last few hundred thousand years), was submerged beneath the Pacific Ocean, much like the nearby Santa Monica Basin today. The Los Angeles basin is centered over a structural depression within which sediments have accumulated almost continuously for the past 20 million years. Before this time, the basin did not exist as a physiographic entity, even though the area had been receiving sediment sporadically since latest Cretaceous time (70 million years ago).

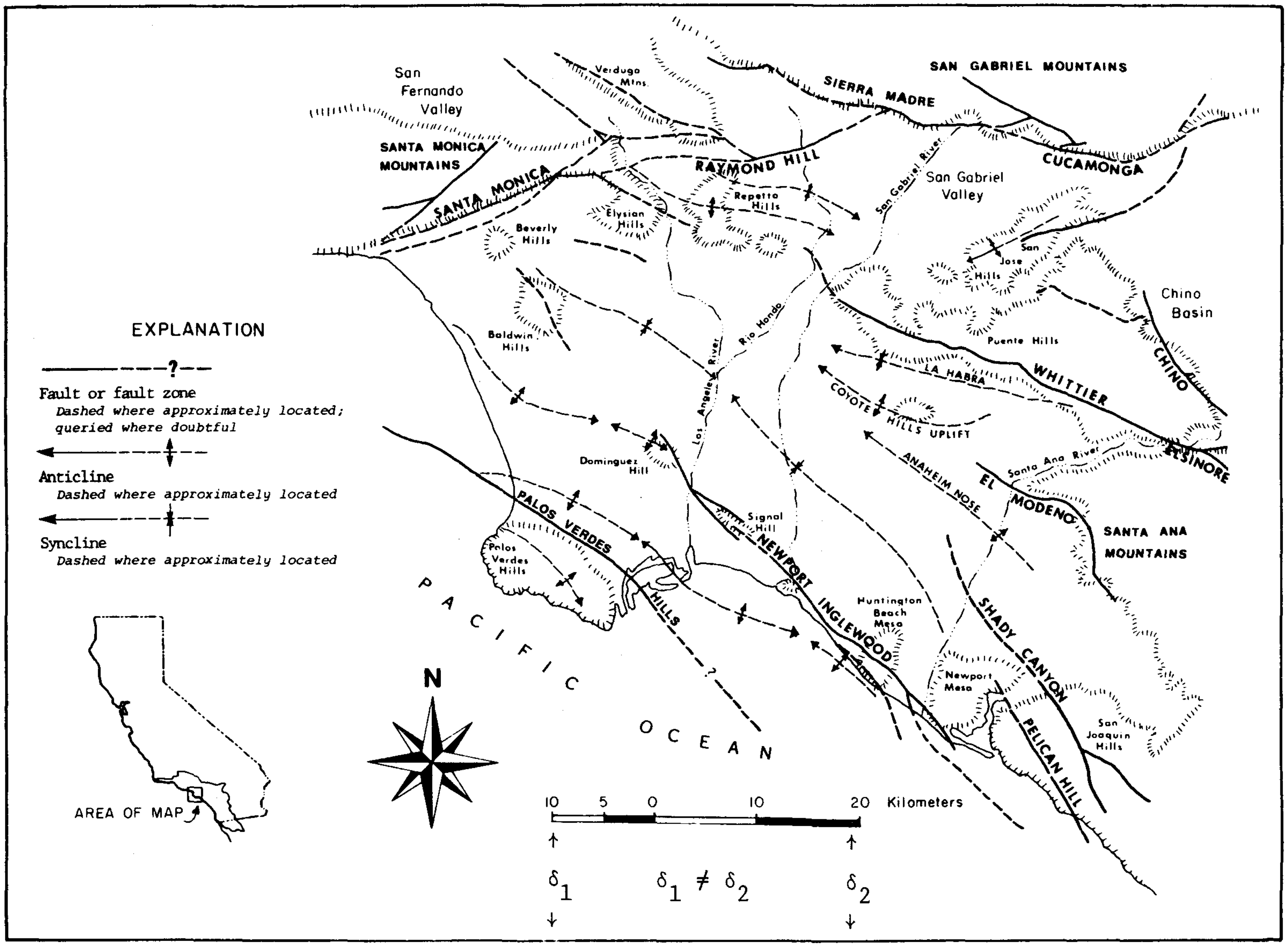

Figure A3-1 Los Angeles Basin, after Yerkes, 1965.

As indicated in the previous section, 20 million years ago large-scale changes in the interaction of continental and oceanic crustal plates caused widespread deformation throughout western North America. In response, several structural depressions developed. Among these, the Los Angeles depositional basin was the largest. Similar basins formed during the same time in the areas where Ventura and Santa Monica are today.

Inundation by the sea and deposition of marine sediments accompanied subsidence in the Los Angeles basin. At its maximum extent, the basin stretched inland to the eastern edge of what are now the San Jose and Puente hills and included parts of what has since become the northern Santa Ana Mountains, the eastern Santa Monica Mountains, and the San Fernando Valley. The basin may have at one time joined the Ventura basin to the northwest, and perhaps also the Chino basin further east in the San Bernardino-Redlands area.

Uplift of the southern California area within the last few hundred thousand years has caused the basin to emerge and marine deposition to cease. However, fluvial sedimentation, in large part the work of the Los Angeles, San Gabriel, and Santa Ana rivers, has continued to fill the basin. These rivers originate in the mountains surrounding the basin and have been the primary agents in blanketing the basin floor with alluvium. The result of this long history of marine and terrestrial deposition (over 70 million years) has been the accumulation of over 9,450 m of sediment in the deepest part of the basin.

A3.2 Geologic Evolution

Most of the rocks in the Los Angeles basin are concealed beneath a cover of recent stream-laid sand and gravel. The map showing the surficial geology of the basin (Plate A-3) illustrates that exposures are generally limited to the few scattered hills within the basin and surrounding areas. In spite of this, a great deal is known about the sub-surface geology, primarily through the study of drill core and geophysical data made available from oil explorations.

The rocks of the basin comprise three distinct groups: basement rocks, pre-basin sediments, and basin sediments. Basement rocks are the oldest (90+ million years old), and they lie beneath the great unconformity of Late Cretaceous age. They consist of two contrasting types, referred to as the eastern basement complex and the western basement complex, that are juxtaposed along the Newport-Inglewood and Santa Monica fault zones (Fig. A3-1).

The eastern basement complex is part of the extensive terrain of intrusive rocks known as the southern California batholith, which extends from Los Angeles south into the Peninsular Ranges. The southern California batholith is a complex of intrusive igneous plutons which invaded an older group of mildly to moderately metamorphosed marine sediments and volcanics in early Late Cretaceous time (90+ million years ago). It outcrops in scattered exposures in the mountains north of the Santa Monica fault zone and in the Santa Ana Mountains. In addition, many wells east of the Newport-Inglewood fault zone penetrate eastern basement at depth. It is composed of coarse-grained igneous rocks, chiefly light-colored granitic rocks rich in quartz and feldspar, which invaded an older terrane of meta-sediments and meta-volcanics (mildly metamorphosed deposits with primary sedimentary and igneous textures still visible) more than 90 million years ago. The metamorphosed complex consists of as much as 6,000 m of slate, argillite, and minor quartzite, limestone, and conglomerate overlain by an equal thickness of meta-volcanic flows, breccias, and tuffs. The rocks range in age from Triassic (225 million years old) through Hurassic (136 million years old).

The western complex is confined to the southwestern part of the basin, south of the Santa Monica fault and west of the Newport-Inglewood fault zone. It is composed of a single rock type known as the Catalina schist, a fine-grained metamorphic rock with a foliated texture and well developed schistosity (planar fabric imparted by the preferred orientation of platy minerals that is brought about when the rock is subject to direct stress during metamorphism). Relic textures and rocks associated with the schist exposed on Santa Catalina Island (40 km offshore) indicate that it was derived from metamorphosed graywacke, shale, chert, and meta-volcanic rocks containing serpentine massifs. The only other outcrops besides those on Santa Catalina Island are found on the northeast flank of the Palos Verdes Hills, but the schist is also known to be present in the sub-surface west of the Newport-Inglewood fault zone.

Catalina schist is unlike any rocks found in the eastern complex. The only rocks in the study area with similar composition and texture lie within the basement complex of the eastern Transverse Ranges north of the basin in the upper Santa Clara River drainage and are known as the Pelona schist. Rocks of the Franciscan formation, which lie outside the study area in the central and northern Coast Ranges also resemble it. However, definite correlation between Catalina schist and either of these two has not been clearly demonstrated.

Neither the age of the Catalina schist nor its stratigraphic relationship to rocks of the eastern basement complex have been successfully resolved. The oldest rocks that are deposited on the schist are of middle Miocene age (20 million years old); the oldest sediments that contain detritus derived from the schist are no older than middle Miocene age; and the only igneous rocks known to intrude it are probably of late Miocene age (12 million years old). Certainly, then, the schist existed prior to middle Miocene time, but because it is found only in tectonic contact with rocks older than this and it yields no fossils, further refinement of its age is not possible and its relationship to eastern basement rocks is indeterminate. However, based on its similarity to rocks of the Franciscan formation (the western basement in the Transverse Ranges), the Catalina schist has tentatively been assigned a Late Jurassic to early Late Cretaceous age (140 to 90 million years old).

Following the events that led to the creation of the Catalina schist and the basement rocks of the eastern complex, the southern

California area, including what is now Los Angeles, experienced a period of tectonic activity. During this episode large portions of the region were uplifted and subjected to erosion, producing the major gap in the geologic record during Late Cretaceous time (70 to 90 million years ago). Evidence of this event is preserved not only in the Los Angeles basin, but also in other parts of the study area as well.

Superjacent rocks comprising the pre-basin sediments, ranging from latest Cretaceous through Early Miocene age (70 to 22 million years old) rest directly upon the erosional surface of the eastern basement complex where they reach a maximum thickness of about 5,000 m. Late Cretaceous clastic marine sediments account for nearly 1,800 m, and Paleocene to early Miocene shallow marine and nonmarine clastic deposits constitute the remainder. These rocks were deposited primarily as marine cobble conglomerate and coarse-grained sandstone with lesser amounts of fine-grained material upon what was then a broad coastal submarine shelf. The inland extent of marine inundation probably did not exceed by much the presently known eastern limits of pre-basin deposits. The presence of thick interbedded sections of nonmarine fluviatile conglomerate and coarse-grained sandstone, however, indicates that the sea retreated and advanced episodically, exposing the land to periods of sub-areal deposition. The clastic debris in both marine and nonmarine rocks came from eastern and northeastern sources of mixed igneous and metamorphic terrain like that of the eastern basement complex. Presumably, eastern basement was emergent in these areas at that time.

At present, the pre-basin sediments outcrop in limited exposures along the northern margins of the Santa Ana Mountains and San Joaquin Hills, and within the southeastern Santa Monica Mountains. They are also known to overlie eastern basement in the sub-surface east of the Newport-Inglewood fault zone. However, they disappear west of the fault, and are not found above rocks of the western basement complex. Whether their absence here is due to erosion or nondeposition is unclear. But the presence of 4,300 m of pre-basin sediments in the San Joaquin Hills just east of the fault zone suggests that the deposits once extended west across the present fault trace. Large vertical or horizontal movements on the Newport-Inglewood fault juxtaposed the two contrasting basement types and, in the process, either elevated the southwestern block such that pre-basin sediments were stripped off the Catalina schist, or shifted it and any overlying sediments laterally to regions now far removed from the basin.

Following deposition of the pre-basin sediments, widespread tectonic uplift caused many parts of the basin to emerge. This produced an almost basin-wide erosion surface at the beginning of Middle Miocene time (16 million years ago). However, subsequent inundation by the sea once again formed a shallow marine embayment over the central parts of the basin and deposition resumed, producing a large scale unconformity.

The marine embayment that existed during Middle Miocene time received debris from exposed areas that lay east, northeast, north, and west of the basin. The first three of these areas contributed coarse debris derived from eastern basement sources. This material formed thick accumulations of poorly sorted sandstone and cobble-conglomerate around the eastern and northeastern rim of the basin; these grade into and interfinger with thin-bedded shallow marine siltstone and shales to the southwest that were deposited in the central parts of the embayment. The highland area bounding the embayment to the west yielded large amounts of Catalina schist to the basin. The sediments formed the thick beds of schist breccia that now outcrop in the San Joaquin and Palos Verdes hills.

During the latter part of Middle Miocene time, accelerated deformation and subsidence led to renewed activity along the Newport-Inglewood fault zone and the inception of movements along the

Whittier-Elsinor, Santa Monica, and Sierra Madre-Cucamonga fault zones, (Fig. A3-1). As a consequence of the increased tectonism, several volcanic fields sprang up and immense volumes of basalt began to spread over the basin. Volcanic centers developed in the eastern Santa Monica Mountains, in the northern Santa Ana Mountains, and in the San Jose Hills, and continued to be active through the close of the Middle Miocene (15 million years ago).

Extensive exposures of Middle Miocene rocks can be found today in the eastern Santa Monica Mountains, northern Santa Ana Mountains, San Joaquin Hills, and Palos Verdes Hills (Plate A-3). Limited outcrops occur in the San Jose Hills and along the southern rim of the San Gabriel Mountains near Glendora. The largest outcrops occur in the San Joaquin Hills where the exposed section is 2,100 m thick, in the northern Santa Ana Mountains where it is 760 m thick, and in the eastern Santa Monica Mountains where exposed rocks reach a thickness of 300 m.

At the close of Middle Miocene time, a short-lived period of uplifting forced the sea to recede slightly, leaving parts of the basin exposed. This is the reason for local unconformities found at the base of the Upper Miocene-Pliocene section (14 to 2 million years ago).

The physiographic Los Angeles basin owes much of its present morphology and structure to the increased tectonic activity that began in Late Miocene time (12 million years ago) and continued through Early Pleistocene time (2 million years ago). During this period subsidence and seismicity accelerated, and immense amounts of sediments were accumulated in the downwarping depression. By the end of Late Miocene time the sedimentary basin had reached its maximum size, stretching inland to San Bernardino, northward into the San Fernando Valley and southeast to the San Joaquin Hills.

The central portions of the basin continued to subside rapidly, being downdropped along the Newport-Inglewood and Whittier-Elsinor fault zones, while surrounding areas subsided less. From Late Miocene through earlier Pleistocene time (12 to 2 million years ago), nearly 5,500 m of marine siltstones, sandstones, and shales were deposited in the deepest parts of the basin. During this time, the Santa Monica and San Gabriel mountains began to form extensive raised land masses to the north of the basin, thereby increasing its influx of sediment. Palos Verdes also rose slightly but remained as a shallow marine shelf or shoal.

During Pleistocene time (2 million years ago to 11,000 years ago) the rapid deposition that had dumped nearly 9,100 m of sediment into the depositional trough finally caught up with subsidence, forcing the sea to begin a westward retreat. Much of the area, however, would have remained submerged had it not been for the mid-Pleistocene Pasadenian orogeny (beginning between one and two million years ago) which caused uplift of the region as a whole. Evidence of this orogeny is seen in the numerous marine terraces on the Palos Verdes Hills, which were uplifted faster than the surrounding terrain along the Palos Verdes fault zone, and in the chains of anticlinal hills formed from renewed compression along the Newport-Inglewood and Whittier-Elsinor fault zones, and in scarps in recent alluvium along the frontal faults of the San Gabriel and Santa Monica mountains. The orogeny is still with us; many of the hills are rising at small, but perceptible, rates as seismic activity continues.

A4 Peninsular Ranges

A4.1 Present Setting

The Peninsular Ranges province is a rugged mountainous area that spans a distance of nearly 1,600 km between southern California and the tip of Baja California. Although somewhat wider than the Transverse Ranges, the province is still quite narrow, averaging about 100 km in width and never exceeding 250 km across. Only the western half of the northern section, though, lies within the bounds of the study area (see Fig. A1-1).

As is characteristic of much of coastal California, the Peninsular Ranges trend northwest and consist of parallel chains of mountains separated from one another by elongate fault-bounded valleys. Cumulative vertical displacement along these faults has produced topographic relief of hundreds of meters between adjoining mountains and valleys, accentuating the structural grain of the province. They effectively slice the region into several rigid basement blocks, each of which has retained much of its internal coherence, unlike the blocks of crystalline rock in the eastern Transverse Ranges. The presence of fresh scarps in the alluvial fills that mantle the valley floors attest to the continuing activity along some of these fault zones.

In addition to being structurally less complex than the Transverse Ranges, the Peninsular Ranges show comparatively less variety in rock types as well. Basement rocks occupy vast areas and outcrop over some 70 percent of the province (see Plate A-3). They are genetically related to rocks of the eastern basement complex in the Los Angeles basin, consisting of mildly metamorphosed sediments and volcanics intruded by granitic rocks of the southern California batholith. Like the basement rocks in Los Angeles basin, they are neither as old nor as deformed as those in the eastern Transverse Ranges. The oldest are Paleozoic metamorphic rocks that were deposited as sediments in an ancient sea more than 320 million years ago. In spite of subsequent metamorphism, which probably occurred in association with intrusion of the batholith, these rocks have retained much of their original sedimentary textures.

Younger sediments, deposited during the past 70 million years, have concealed the basement rocks along the narrow but lengthy stretch of coastline that presently constitutes the westernmost flank of the ranges. Most of these comprise thick sections of the clastic marine rocks interrupted by local accumulations of nonmarine sandstones and conglomerates. The oldest sediments, largely Cretaceous and Eocene in age, rest directly but unconformably on the basement complex, and they are in turn overlapped to the west by younger rocks. Pleistocene marine terraces, present at many places along the coast, have recorded the periodic tectonic uplift of the southern California area in recent times.

A4.2 Geological Evolution

As elsewhere in the study area, basement rocks in the Peninsular Ranges are separated from overlying sediments by a Late Cretaceous (70 million years old) unconformity. The basement terrain in this province is probably the most uniform of any in the study area, and it outcrops over much of the region, forming the backbone of the ranges. It consists largely of granitic crystalline rocks but shows some variety including gabbro, tonalite, granodiorite, quartz monzonite, and granite. Collectively these rocks constitute the southern California batholith (Fig. A4-1).

Remnants of the older country rock into which the plutons were intruded occur as outliers surrounding the batholith and as roof pendants within it. They have an aggregate thickness of over 15,000 m, although sections this thick are not found in continuous outcrop. Medium

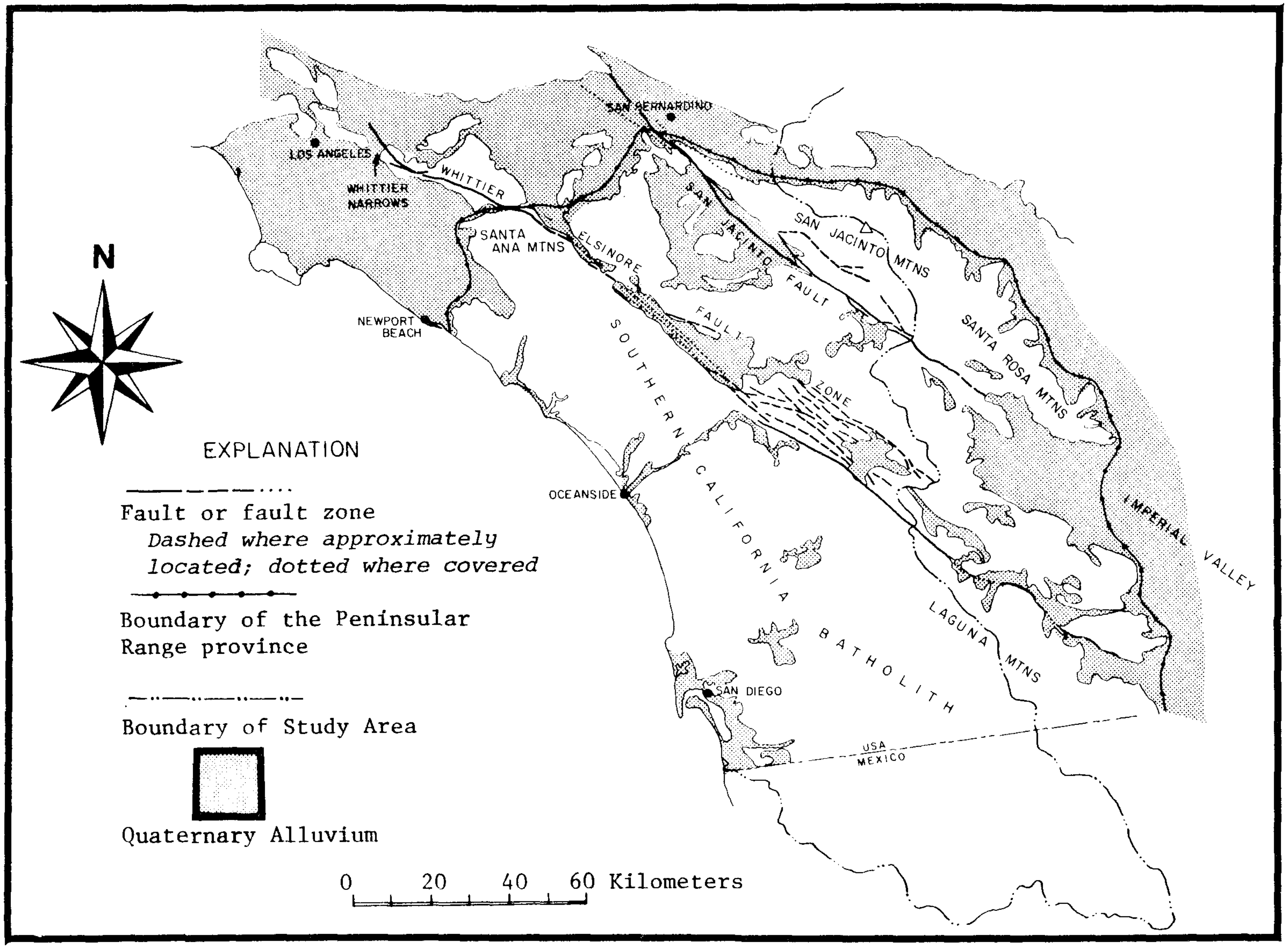

Figure A4-1 Peninsular Range Province

and high grade metamorphic rocks, primarily quartzite, marble, phyllite, schists, and a few gneisses, of Mississippian age (330 million years old) comprise the lower 6,000 m. These rocks outcrop mostly in the eastern Peninsular Ranges, in the San Jacinto and Santa Rosa mountains (Fig. A4-1). Younger rocks of the Bedford Canyon and Santiago Peak volcanic formations presumably overlie the Mississippian rocks but the contact with the older section is obscure. The younger rocks are found in limited exposures in the western half of the province where they consist of mildly metamorphosed sediments and volcanics. The Bedford Canyon formation, of Triassic age (200 million years old), is the older of the two and consists of roughly 6,000 m of mildly metamorphosed argillite, slate, quartzite, and minor limestone and conglomerate. As much as 30,000 m of metamorphosed volcanic flows, tuffs, and breccias of Late Jurassic age (150 million years old) constitutes the Santiago Peak volcanic formation, which overlies the Bedford Canyon formation unconformably.

Because the basement complex in the Peninsular Ranges lies within a less intensely deformed region than the eastern Transverse Ranges, it has not suffered the strong shearing and crushing typical of those rocks. The entire province has responded as a rigid body, much like the Sierra Nevada, in being uplifted along a steep eastern escarpment and tilted toward the west. Compositional and age similarities between rocks of the southern California batholith and the Sierra Nevada batholith suggest that their morphologic resemblance to one another is more than coincidental. In fact, it is believed that the two were emplaced as a continuous structure before Cenozoic (past 65 million years) faulting broke them apart and offset them. Even their histories of uplift are alike, beginning at the time of igneous invasion in the Cretaceous period (90+ million years ago) and continuing until the present. Just as uplift and subsequent erosion of the Sierra Nevada eventually unroofed the granitic intrusions beneath, so too was the southern California batholith exposed after overlying country rock had been stripped away. The continual uplift throughout Cenozoic time kept the central portion of the Peninsular Ranges emergent, thereby creating a sediment source for marine deposits of that era.

Late Cretaceous (70+ million years old), Tertiary (65 to 2 million years old), and Quaternary (2 million years old to present) sediments lie above the Cretaceous unconformity in a thin veneer on top of the western flank of the southern California batholith. Most are shallow marine clastic deposits of conglomerate, sandstone, and siltstone derived from eastern sources in the Peninsular Ranges. The presence of some interbedded sections of nonmarine rocks, however, suggests that sea level oscillated during their formation. Generally, however, the sediments become younger toward the west, suggesting that the sea has retreated slowly throughout Cenozoic time as the provincial block has continued to rise.

The northwest trending Whittier-Elsinor and San Jacinto faults have sliced the tilted basement into several rigid blocks. Activity on these faults probably began sometime in the early Miocene epoch (25 million years ago), although it may have commenced earlier. The San Jacinto fault is known to have a cumulative right lateral offset of 25 km and vertical displacements of hundreds of meters. These faults have affected sedimentation in the interior valleys by restricting deposition to the valleys closed by the faults. Most of the sediments are coarse-grained nonmarine sandstones and conglomerates with minor playa and fresh-water lake deposits interbedded which range from Late Miocene to Recent age (12 million years old to present). Where the fault valleys enter the lowland area of San Bernardino, though, the nonmarine rocks interfinger with shallow marine sediments deposited in that region when the Los Angeles basin was at its high-water mark in Late Miocene through Early Pliocene time (12 to 10 million years ago).

The Late Pleistocene Pasadenian orogeny (one to two million years ago), which produced a new era of deformation in each of the other provinces of the study area, also affected the Peninsular Ranges. Most notably, it increased rates of uplift such that coastal areas emerged, forcing a westward retreat of the sea. Pleistocene marine terraces only a few hundred thousand years old, and at present hundreds of meters above sea level, attest to both the recency and rapidity of this uplift. They are carved in stair-like steps, indicating that the tectonic activity producing the uplift occurred episodically. A second effect of the orogeny has been increased seismicity along existing faults. The San Jacinto fault has had several moderate earthquakes in historic times, while the Whittier-Elsinor continues to show signs of creep in the Whittier Hills.

A5 Recent Deformation in the Study Area

The three preceeding sections have treated the geologic history for each province in the study area through mid-Pleistocene time, which is the period primarily responsible for the geological features. However, it is important also to note Late Pleistocene and Recent developments (last 100,000 years) in an attempt to complete the geologic picture, and also to identify ongoing tectonic deformations that continue to shape southern California.

There is abundant evidence that the Pleistocene or Pasadenean orogeny, which began as early as two million years ago, is still active in southern California. Late Pleistocene and Recent marine terraces several tens to hundreds of meters above sea level are visible along the coast in all three provinces from Point Conception to Mexico. In the Palos Verdes Hills, for example, a total of thirteen such terraces are preserved, the highest of which rises to an elevation of 400 m. They were cut by wave action as the hills were uplifted along the Palos Verdes fault, beginning 500,000 to 1,000,000 years ago. The youngest terrace, only 30,000 years old, forms a seacliff that drops 45 m to the beach below it. In a similar fashion, inland fluvial terraces formed by streams during stable periods have been left by recent uplift as integral parts of canyon walls high above present drainage levels. The San Gabriel Mountains where the uplift rate is estimated to be between one and three meters per thousand years contain excellent examples of sub-areal terrace remnants lifted hundreds of meters above the valley floors.

Besides general uplift, the Pleistocene orogeny brought renewed activity to many of southern California's major fault zones. Increased seismicity renewed uplift of the Transverse Ranges relative to the Los Angeles basin along existing mountain-front fault zones. The numerous fault scarps in recently deposited alluvium and the historic earthquakes on the Santa Monica and Santa Susanna-Sierra Madre faults (see Plate A-2) attest to accelerated activity in the region. In the Los Angeles basin, active faults have relieved accumulated stresses by upwarp of pressure ridges rather than by abrupt surface rupture, although both the Newport-Inglewood and San Jacinto faults have experienced historical earthquakes. Examples of pressure ridges, which manifest themselves as protruding anticlinal folds in existing fault zones, and because of their youth they have created ideal conditions for stream antecedence.

Somewhere along their respective courses, the Los Angeles, San Gabriel, and Santa Ana rivers, which traverse the floor of the Los Angeles basin, each cross pressure ridges formed by the Newport-Inglewood and Whittier-Elsinor fault zones. One would logically expect the rivers to flow around the hills, following the path of least resistance, but they have instead cut through the hills, keeping on a more or less straight path to the sea. The reason for this is simply that the rivers were there first, i.e., they antecede the hills. Uplift of the hills, however, must also have been slow enough to allow the rivers to maintain their courses by downcutting; otherwise they would have been deflected. The fact that the rivers are young themselves attests to the recency of this uplift and activity on associated faults. Seismic tremors continue to be recorded along the Newport-Inglewood fault and it is thought that some of the ridges are still missing.

The above geomorphic phenomena are transient features that can only be found in areas where ongoing tectonic activities continually rejuvenate and sustain them. In coastal southern California, tectonic movements have been able to reform the land surface faster than erosion can significantly alter its configuration for much of the geological past and present.

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A7 GEOLOGICAL TIME TABLE

	RELATIVE GEOLOGIC TIME				TIME in millions of years before present	TIME OF APPEARANCE OF DIFFERENT FORMS OF LIFE
	Era	Period		Epoch		
Age of Mammals	Cenozoic	Quaternary		Holocene	0.011*	Historic record in California, 200 years Post-glacial period
				Pleistocene	1.5-2	Ice age, evolution of man.
		Tertiary	Neogene	Pliocene	5-7	Age of mammoths.
				Miocene	23-26	Spread of anthropoid apes.
			Paleogene	Oligocene	37-38	Origin of more modern families of mammals, grazing animals
				Eocene	53-54	Origin of many modern families of mammals, giant mammals.
				Paleocene	65	Origin of most orders of mammals, early horses.
Age of Reptiles	Mesozoic	Cretaceous			136	Appearance of flowering plants; extinction of dinosaurs at end; appearance of a few modern orders and families of mammals.
		Jurassic			190-195	Appearance of some modern genera of conifers; origin of mammals and birds; height of dinosaur evolution.
		Triassic			225	Dominance of mammal-like reptiles.
Age of Invertebrates	Paleozoic	Permian			280	Appearance of modern insect orders.
		Carboniferous Systems	Pennsylvanian		320	Dominance of amphibians and of primitive tropical forests which formed coal; earliest reptiles.
			Mississippian		345	Earliest amphibians
		Devonian			395	Earliest seed plants; rise of bony fishes.
		Silurian			430-440	Earliest land plants.
		Ordovician			500	Earliest known vertebrates.
		Cambrian			570	Appearance of most phyla of invertebrates.
	Precambrian					Origin of life; algae, worm burrows.
					4,500	Estimated age of earth.

Modified from U.S. Geological Survey, Geologic Names Committee, 1972.

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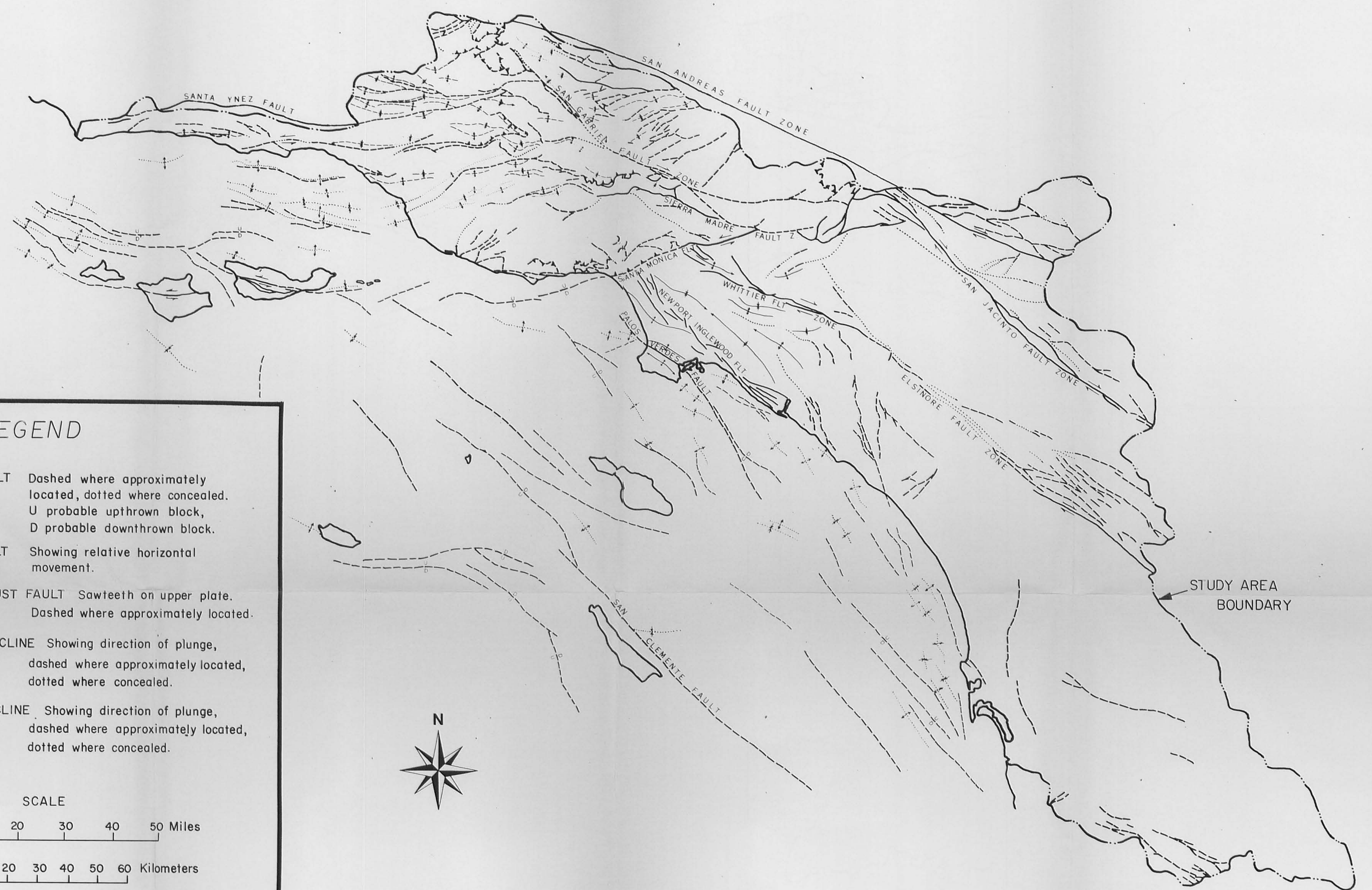
1 km X 1 km GRID SPACING
VERTICAL EXAGGERATION: approx. 10 X

PLATE A-1
SEDIMENT MANAGEMENT STUDY AREA

Prepared By Lloyd Townley
1978

Based on Topographic Data Supplied by the USGS



LEGEND

U/D FAULT Dashed where approximately located, dotted where concealed. U probable upthrown block, D probable downthrown block.

FAULT Showing relative horizontal movement.

THRUST FAULT Sawteeth on upper plate. Dashed where approximately located.

ANTICLINE Showing direction of plunge, dashed where approximately located, dotted where concealed.

SYNCLINE Showing direction of plunge, dashed where approximately located, dotted where concealed.

SCALE

0 10 20 30 40 50 Miles

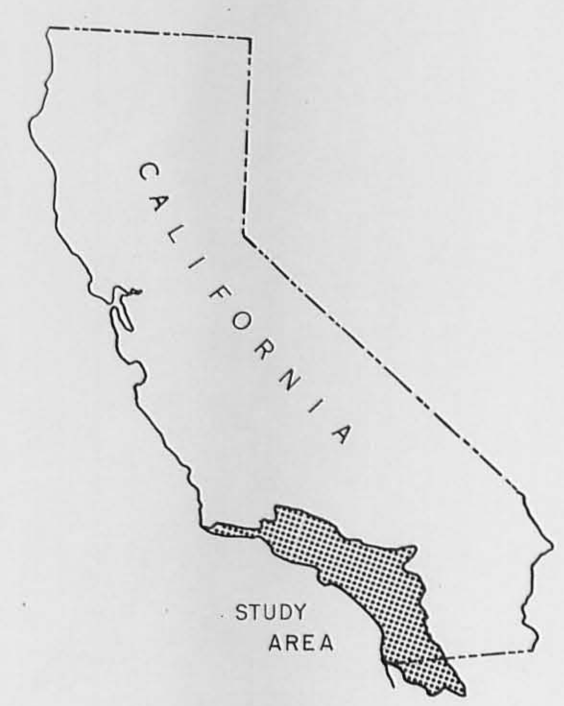
0 10 20 30 40 50 60 Kilometers

PLATE A-2
STRUCTURAL GEOLOGY

COMPILED BY EDWARD FALL*

1978

*(From Jennings, 1977, "Geologic Map of California.")



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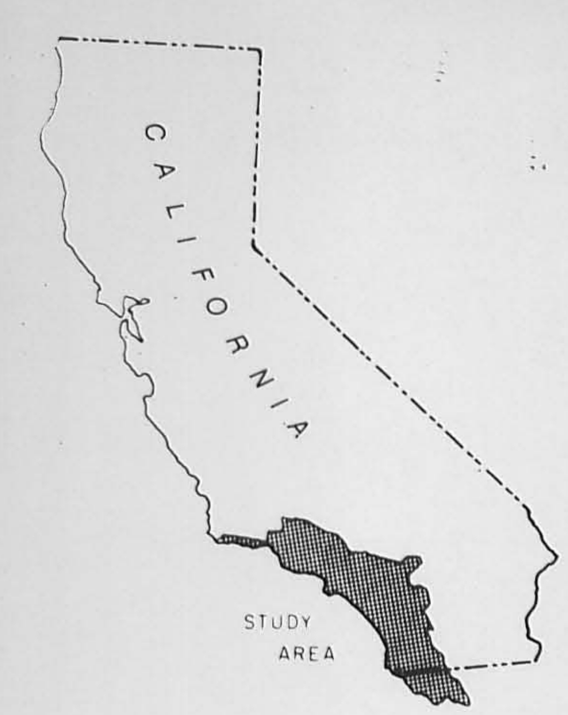
LEGEND

- Quaternary Cover
- Neogene Marine
- Neogene Continental
- Paleogene Marine
- Paleogene Continental
- Basement Complex

SCALE

0 10 20 30 40 50 Miles

0 10 20 30 40 50 60 Kilometers



INDEX MAP

PLATE A-3
SURFICIAL GEOLOGY

COMPILED BY EDWARD FALL*

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*(From Jennings, 1977, "Geologic Map of California.")

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