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STRUCTURE, QUATERNARY HISTORY, AND GENERAL GEOLOGY OF THE CORRAL CANYON AREA, LOS ANGELES COUNTY, CALIFORNIA

by

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U. S. Geological Survey

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Frontispiece.--Northward aerial view of the Corral Canyon site, showing approximate trace of Malibu Coast fault (dotted where concealed), Corral Canyon at center, plant site at the mouth of Corral Canyon, and large landslides that flank the mouth of Corral Canyon. The grassy slopes in fore- and middleground are underlain by intensely deformed sedimentary rocks in the Malibu Coast zone, whereas bold terrain in background is underlain by relatively undeformed sedimentary and volcanic rocks. Photograph courtesy Department of Water and Power, City of Los Angeles.

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ABSTRACT

The Corral Canyon nuclear power plant site consists of about 305 acres near the mouth of Corral Canyon in the central Santa Monica Mountains; it is located on an east-trending segment of the Pacific Coast between Point Dume and Malibu Canyon, about 28 miles due west of Los Angeles.

The Santa Monica Mountains are the southwesternmost mainland part of the Transverse Ranges province, the east-trending features of which transect the otherwise relatively uniform northwesterly trend of the geomorphic and geologic features of coastal California. The south margin of the Transverse Ranges is marked by the Santa Monica fault system, which extends eastward near the 34th parallel for at least 145 miles from near Santa Cruz Island to the San Andreas fault zone. In the central Santa Monica Mountains area the Santa Monica fault system includes the Malibu Coast fault and Malibu Coast zone of deformation on the north; on the south it includes an inferred fault--the Anacapa fault--considered to follow an east-trending topographic escarpment on the sea floor about 5 miles south of the Malibu Coast fault. The low-lying terrain south of the fault system, including the Los Angeles basin and the largely submerged Continental Borderland offshore, are dominated by northwest-trending structural features.

The Malibu Coast zone is a wide, east-trending band of asymmetrically folded, sheared, and faulted bedrock that extends for more than 20 miles along the north margin of the Santa Monica fault system west of Santa Monica. Near the north margin of the Malibu Coast zone the north-dipping, east-trending Malibu Coast fault juxtaposes unlike, in part contemporaneous sedimentary rock sections; it is inferred to be the near-surface expression of a major crustal boundary between completely unrelated basement rocks. Comparison of contemporaneous structural features and stratigraphic sections (Late Cretaceous to middle Miocene sedimentary, rocks and middle Miocene volcanic and intrusive igneous rocks on the north; middle and upper Miocene sedimentary and middle Miocene volcanic rocks on the south) across the fault demonstrates that neither strike slip of less than 25 miles nor high-angle dip slip can account for this juxtaposition. Instead, the Malibu Coast fault is inferred to have been the locus of large-magnitude, north-south oriented, horizontal shortening (north, or upper, block thrust over south block). This movement occurred at or near the northern boundary of the Continental Borderland, the eastern boundary of which is inferred to be the northwest-trending known-active Newport-Inglewood zone of en echelon right lateral strike-slip faults in the western Los Angeles basin.

Local structural features and their relation to regional features, such as those in the Malibu Coast zone, form the basis for the interpretation that the Malibu Coast fault has acted chiefly as a thrust fault. Within the Malibu Coast zone, on both sides of the Malibu Coast fault, structural features in rocks that range in age from Late Cretaceous to late Miocene are remarkably uniform in orientation. The predominant trend of bedding, axial surfaces of numerous asymmetric folds, locally pervasive shear surfaces, and faults is approximately east-west and their predominant dip is northward. The axes of the folds plunge gently east or west. Evidence from faults and shears within the zone indicates that relative movement on most of these was north (upper) over south. Beyond the Malibu Coast zone to the north and south the rocks entirely lack the asymmetric folds, overturned beds, and the locally abundant shears that characterize the rocks within the zone; these rocks were therefore not subjected to the same deforming forces that existed near the Malibu Coast fault. Movement on the Malibu Coast fault and deformation in the Malibu Coast zone occurred chiefly during the interval between late Miocene and late Pleistocene time. The youngest-known faulting in the Malibu Coast zone is late Pleistocene in age. There is no known displacement of the ground surface in the Malibu Coast zone that can be attributed to Recent faulting, and deposits of known Recent age are not displaced by faults in underlying older deposits or on the projected trends of such faults.

The Corral Canyon site is in the Malibu Coast zone of deformation and is bisected by the Malibu Coast fault. The middle Miocene bedrock of the plant site (600 to 1,200 feet south of the Malibu Coast fault) consists of pervasively sheared mudstone that contains sparse to numerous, chiefly north-dipping, shear-bounded pods of sandstone less than 1 inch to more than 10 feet long. The deformation indicated by these features is inferred to have resulted from north-over-south translation within the rock mass, accompanied by extension in two dimensions parallel to the bedding and structure. The north-over-south translation produced folds of several scales in bedding and, coupled with extension of the rock mass, it disrupted and segmented most pre-existing sandstone beds.

The mudstone failed by brittle fracture on a small scale as indicated by innumerable flat to gently curved, slickensided, anastomosing shear surfaces. The sandstone also failed by brittle fracture as indicated by numerous fractures normal to bedding and long dimension of the pods, and by displacement on some of the fractures. In addition, no clear evidence of fluid or plastic deformation of the sandstone nor, on a small scale, of the mudstone, has been preserved.

Faults of several magnitudes are present in bedrock of the Corral Canyon site. The Malibu Coast fault, about 800 feet north of the reactor location, is of regional significance and large magnitude of displacement; where well exposed, its trace is marked by a zone of brecciated and sheared rock as much as 75 feet wide. Faults of lesser magnitude, such as fault A near the north boundary of the plant site, separate different formational units and are characterized by zones of sheared and brecciated rock up to several feet wide. Such faults can be traced for only hundreds to thousands of feet; they probably have displacements of hundreds of feet. Intraformational faults, such as fault F, exposed in Corral Creek and trench 3 (the reactor-location trench), are characterized by local truncation of structure and are commonly marked by thin, but recognizable zones of sheared rock or breccia. Such features can be traced tens to hundreds of feet; their displacements are probably on the order of tens of feet. Finally, innumerable shears, locally continuous or concentrated in narrow bands, pervade the mudstone of the Corral Canyon site. Minor displacement has occurred on these features, as indicated by disrupted sandstone beds and slickensides. Aggregate displacement across several feet of such sheared rock may amount to several feet. All demonstrable fault movement in the Corral Canyon site is pre-Recent (more than about 10,000 years) in age.

A 270 foot-long exploratory trench (trench 3); trending northeastward across the reactor location, was opened in late April, 1965. The trench exposed unit B mudstone and sandstone along its entire length (Unit B is the older of two formations that make up the stratigraphic section exposed south of the Malibu Coast fault; it is middle Miocene and consists of clay-rich mudstone, interbedded sandstone, locally thick sequences of extrusive igneous rocks, and local lenses of schist breccia.). The north-eastern 80 feet of the trench exposed weathered unit B mudstone and sand-stone that is within a landslide. The sole of the landslide is exposed at about station 80 feet in the trench, where on the northwest face of the trench bedrock has been moved over a deposit of sand and gravel that contains mussel shells, of probable kitchen midden origin, that are about 3,000 years old. Nearly horizontal westward movement of the landslide mass is recorded by approximately east-west trending, gently westward-plunging striations on the principal and related slip surfaces exposed in trench 3. West of trench 3 (in a temporary bulldozer cut), striations on the principal slip surface, which there curves to the northwest, have an eastward plunge, and probably indicate an upward component of movement near the toe of the landslide. The topography of the canyon wall just east of the trench is consistent with the existence of this landslide mass.

A fault (fault F) within unit B crosses the trench about 35 feet northeast of the center of the reactor location. Mudstone that contains small to large sandstone pods north of the fault is juxtaposed with mudstone that contains thin beds of sandstone and seams of montmorillonite, and minor tuff. This fault is exposed in trench 2 on the canyon wall to the east, and west of trench 3 it is exposed in the creek bank and on the west wall of Corral Canyon; its location can also be traced in six of the borings in the plant site. Displacement on the fault has probably been dip slip, on the order of at least tens of feet; all movement occurred prior to the deposition of the overlying Recent sand and gravel (floodplain deposits of Corral Canyon).

All of the bedrock exposed in trench 3 and in the plant site was tectonically deformed between late Miocene and late Pleistocene time, both by folding and faulting, and by pervasive shearing. Sandstone occurs as pods northeast of and immediately south of fault F, and as thin, disrupted, but still somewhat continuous beds south of fault F. Both north-over-south translation and two-dimensional extension probably were involved in deformation of the rock.

Four of the six test trenches excavated on the main coastal terrace east of Corral Canyon exposed disrupted surficial deposits of late Pleistocene age. This disruption is associated spatially with displacement in the underlying bedrock and coincides approximately with the projected trace of fault A. The disruption indicated by exposures in the test trenches on the main coastal terrace, as well as that of marine terrace deposits in gully C to the southeast, may be due either to faulting or possibly to movement of a now-buried landslide of undetermined extent. All of these disruptions are pre-Recent in age, for they are unconformably overlain by undisturbed surficial material that has a radiocarbon age of about 9,500 years.

Factors that should be considered during engineering design and construction in the Corral Canyon site include tectonic activity (seismicity and the probability of future faulting), landslides, floods, type and abundance of clays in the rocks, offshore geology, and marine processes.

The structural and tectonic environment in which the movement on the Malibu Coast fault and Malibu Coast zone occurred probably still exists. The Malibu Coast zone and western half of the Santa Monica fault system are located within an east-trending belt of seismicity that is higher than that of the Transverse Ranges to the north or of much of the Continental Borderland to the south by a factor of about 4; faulted upper Pleistocene terrace deposits are present at several localities in the Malibu Coast zone within, west of, and east of the Corral Canyon site; and the Malibu Coast fault is inferred to be related structurally to the tectonically active Newport-Inglewood zone of western Los Angeles basin.

The Santa Monica fault system is tectonically active at depth as indicated by its continuing minor seismicity and its inferred structural relation to the known-active Newport-Inglewood zone; however, the known record for Recent time contains no evidence of surface faulting in the Malibu Coast zone. Because surface faulting has commonly accompanied earthquakes of Richter Magnitude 6.0 or greater in Nevada and California, and because estimates of the largest earthquake ever to be expected along the Santa Monica fault system range as high as M. $7\frac{1}{4}$, the probability of future surface faulting at Corral Canyon must be based in part on the location of any future large-magnitude shocks in the Santa Monica fault system. Comparisons of degree and time of deformation in different parts of the fault system indicate that future faulting is at least as likely to occur in the Malibu Coast zone as in any other part. The available seismic record is not sufficient to establish the recurrence interval for large-magnitude faults in the system; this interval is greater than the approximately 200 years of historic time and it may exceed the approximately 10,000 years of Recent time. As this recurrence interval is large compared to 50 years, the probability that a large-magnitude shock with center near Corral Canyon will occur during the next 50 years is very low. This very low probability, coupled with the lack of evidence for surface faulting in the Malibu Coast zone during Recent time, indicates that the probability of permanent displacement of the ground surface by faulting at Corral Canyon during the next 50 years is very low (this same very low probability was described in the U. S. Geological Survey report of 1964 as negligible, which was used there in the sense of very low). This assessment implies no judgment of public risk; it is not intended as a judgment of the consequences of surface faulting in any particular utilization of the Corral Canyon site.

The Corral Canyon area is characterized by several large and numerous small landslides of both the slump and debris flow types; most of the slides involve bedrock. Bedrock in the plant site is mudstone and interbedded sandstone that contains significant amounts of montmorillonitic (swelling) clays and is readily susceptible to slope failure; cuts with slopes longer or steeper than natural slopes now standing near the plant site may fail. The low altitude of the plant site, the very gentle slope of the sea floor offshore, and the northward dip of the structural features make seaward sliding of the entire plant site improbable.

The Corral Canyon area is subject to both disastrous brush fires and short, intense rainstorms that can saturate the ground and then provide flood-stage runoff. The "50-year flood" at Corral Canyon may range as high as 1,500 cfs for normal watershed conditions and 3,000 cfs for a burned-over watershed. Corral Canyon could be dammed by landslide debris upstream from the plant site during a period of high runoff. If ponded floodwaters overflowed and quickly eroded such a dam, a major flood, perhaps on the order of 10,000 cfs, could result near the canyon mouth.

Offshore facilities will be founded on a gently sloping sea floor of low relief that is underlain by surficial deposits and folded and faulted sedimentary and volcanic rocks within the Malibu Coast zone. Such facilities may be affected by storm and seismic waves, and by littoral drifting of sediment.

INTRODUCTION

Purpose and scope

The U. S. Geological Survey was requested by the U. S. Atomic Energy Commission to make a geologic study of an area in and adjoining the mouth of Corral Canyon, Los Angeles County, California (frontispiece), which has been proposed by the Department of Water and Power of the City of Los Angeles as a site for a nuclear-fueled power plant. This report describes the regional geologic setting of the Corral Canyon site, its detailed geology, and geologic factors that should be considered during engineering design and construction of the plant. The report is based on examination of the very limited natural exposures in the area, study of test trenches in and adjacent to the plant site, and on regional perspective gained from detailed mapping in nearby parts of the central Santa Monica Mountains and elsewhere in the Los Angeles basin area.

Previous work

Published results of geologic investigations pertinent to the Corral Canyon site are few. Durrell (1954) published a planimetric map compilation of the geology of the Santa Monica Mountains at a scale of 1 inch = 2 miles, and a brief text (Durrell, 1956) that summarizes the information presented on the map. Bailey (1954) published an outline geologic map at a scale of 1 inch = 6 miles, based largely on original work, which shows the Santa Monica Mountains and their relation to the western part of the Transverse Ranges province.

Detailed geologic maps available to the public include preliminary maps at a scale of 1 inch = 1,000 feet, which have been open-filed by the U. S. Geological Survey, and which are products of a cooperative program with Los Angeles County. These maps show the coastal parts of the Malibu Beach quadrangle (Schoellhamer and Yerkes, 1961), the Point Dume quadrangle (Schoellhamer and others, 1962), and the southwest part of the Topanga quadrangle (Yerkes and others, 1964). The Corral Canyon site is within the area shown on the Malibu Beach map. The Point Dume map has a more complete description of the stratigraphic section south of the Malibu Coast fault; this section underlies the south half of the Corral Canyon site. The Topanga map and sections show parts of the folded thrust sheets that characterize much of the central part of the mountains north of the Malibu Coast fault. Several unpublished reports on the Corral Canyon site have been made available since December 1964; those of Cleveland and Troxel (1965), Hoffman and Smith (1965), Jahns (1965), and Kamb (1965) contain large-scale detailed geologic maps at scales of 1 inch to 500 feet or less, of all or parts of the site. Other recent reports concerning seismology of the Corral Canyon area include those by Benioff (1965) and Housner (1965).

The present report incorporates, as appropriate, and supersedes two previous reports by the U. S. Geological Survey (Yerkes and Wentworth, 1964; Wentworth and Yerkes, 1965); new material includes data on several new exploratory trenches and radiometric dating of soils and shells from flood-plain and coastal terrace deposits.

Methods of investigation

Field work for the present report consisted of 74 man-days in January to May, 1964, 65 man-days in November and December, 1964, and 46 man-days in March to May, 1965, a total of 185 man-days. Field data were plotted directly on stereopairs of 1,947 vertical aerial photographs (enlarged to 1 inch = 515 feet from 1 inch = about 2,000 feet). These data were transferred by inspection from the photographs to the topographic base map (1 inch = 500 feet). This base map is a photographic reduction of a map (1 inch = 100 feet) supplied by the Department of Water and Power of the City of Los Angeles and compiled from vertical aerial photography (1 inch = 500 feet) flown in 1963. The vertical faces of several test trenches were mapped in detail: trenches A, B, C, D, E, and F on the main coastal terrace east of and adjoining Corral Canyon were mapped at 1 inch = 4 feet or 1 inch = 10 feet with points measured from horizontal control fixed to the trench faces; trenches 1 and 2 on the east wall of Corral Canyon were mapped at 1 inch = 10 feet with tape and jacob staff control. The southeast face of trench 3, in the proposed reactor site, was mapped at 1 inch = about 2½ feet on a photographic mosaic, which included vertical and horizontal control supplied by the Department of Water and Power, City of Los Angeles; the entire trench was mapped at a scale of 1 inch = 20 feet. During backfilling of trench 3, two exploratory bulldozer cuts were made northwest of the trench to locate the continuation of a slip surface exposed at about 80 feet in the trench; cut one was mapped at 1 inch = 20 feet and cut two at 1 inch = 10 feet.

Laboratory investigation consisted of X-ray diffractometry to determine the mineralogy, clay composition, and clay abundance of several samples of bedrock and surficial deposits; free-swelling tests of four of the samples; examination of thin sections of samples of bedrock from test trenches and borings in and near the plant site; and carbonate analyses and determination of soil properties for samples from Soil Profile 1.

Acknowledgments

The preparation of this report was greatly facilitated by the contributions of other organizations and individuals. The Department of Water and Power, City of Los Angeles, provided the topographic base for the geologic map, as well as numerous aerial photographs. The authors are indebted to the Converse Foundation Engineers, Pasadena, California, for core samples of bedrock from test borings in and near the plant site, as well as boring logs and other pertinent data. C. R. Allen, C. F. Richter, and J. M. Nordquist of the California Institute of Technology and P. St. Amand of the U. S. Naval Ordnance Test Station at China Lake, California, permitted reproduction of part of plate 1 of their unpublished manuscript titled "Relationship between seismicity and geologic structure in the southern California region."

Many members of the U. S. Geological Survey made important contributions. J. T. McGill supplied results of detailed mapping in the coastal area between Topanga Canyon and Santa Monica and demonstrated that upper Pleistocene terrace deposits are faulted at several localities. Reuben Kachadoorian and R. H. Campbell contributed greatly to the field investigation; Campbell, B. M. Madsen, and E. W. Tooker provided X-ray determinations;

P. W. Birkeland studied soils in the site, supplied an estimate of their absolute age, and assisted in preparation of the section on soils; J. N. Rosholt supplied preliminary ages for several samples based on uranium-thorium ratios of shell material from marine terrace deposits; Meyer Rubin supplied C^{14} dates for several critical samples; R. A. Loney provided guidance during preparation and interpretation of orientation diagrams for the structural analysis; W. O. Addicott and P. B. Smith made determinations and interpretations of numerous fossil collections; Estella Leopold examined and interpreted pollen samples from soils; and L. E. Young of Water Resources Division provided estimates of flood magnitude, stage, and frequency for Corral Canyon and assisted in preparation of the section on floods.

GEOGRAPHY

Location

The Corral Canyon site (frontispiece) consists of about 305 acres on an east-trending segment of the Pacific Coast of southern California in western Los Angeles County (figs. 1 and 3). The area includes the mouth of Corral Canyon and is near the west boundary of the Malibu Beach 7½-minute topographic quadrangle. The boundaries of the Corral Canyon site are shown on the geologic map (fig. 4). Within the Corral Canyon site it is proposed (Hoffman and Smith, 1965, drawings 1, 3) that about 43 acres near the canyon mouth will be graded to about altitude 35 feet for construction and improvement; this 43-acre area is herein termed the graded site. Within the graded site it is proposed (Dept. Water and

Power, City of Los Angeles, 1964, fig. 2.7-1a) that about 7.3 acres at the mouth of the canyon will be occupied by buildings for the reactor, generator, and appurtenant facilities (but excluding the switch racks); this 7.3-acre area is herein termed the plant site (fig. 2), and its boundaries are shown on the geologic map (fig. 4) and on the outline map of the plant site (fig. 7). Within the plant site it is proposed that the reactor will occupy a circular pit 150 feet in diameter (fig. 7) with floor at altitude about 15 feet subsea (Hoffman and Smith, 1965, drawing 2); this is termed the reactor location.

The mouth of Corral Canyon is about 28 miles west of downtown Los Angeles, about 14 miles west of Santa Monica, about 12 miles south-southwest of Woodland Hills (at the south edge of the San Fernando Valley), and about 27 miles east-southeast of Oxnard, a city on the coastal plain west of the Santa Monica Mountains.

Physiography

The Corral Canyon site is on the south (Pacific Coast) margin of the east-trending Santa Monica Mountains, about midway between their east and west ends. The south flank of the Mountains rises rather steeply, from sea level at the site to more than 2,800 feet 4 miles to the north. This part of the mountains is underlain chiefly by folded and faulted Tertiary sedimentary and volcanic rocks; it is drained by south-flowing, actively eroding, intermittent streams. The resulting topography on the south flank of the mountains is youthful and rugged (frontispiece). Along the coast of the central Santa Monica Mountains

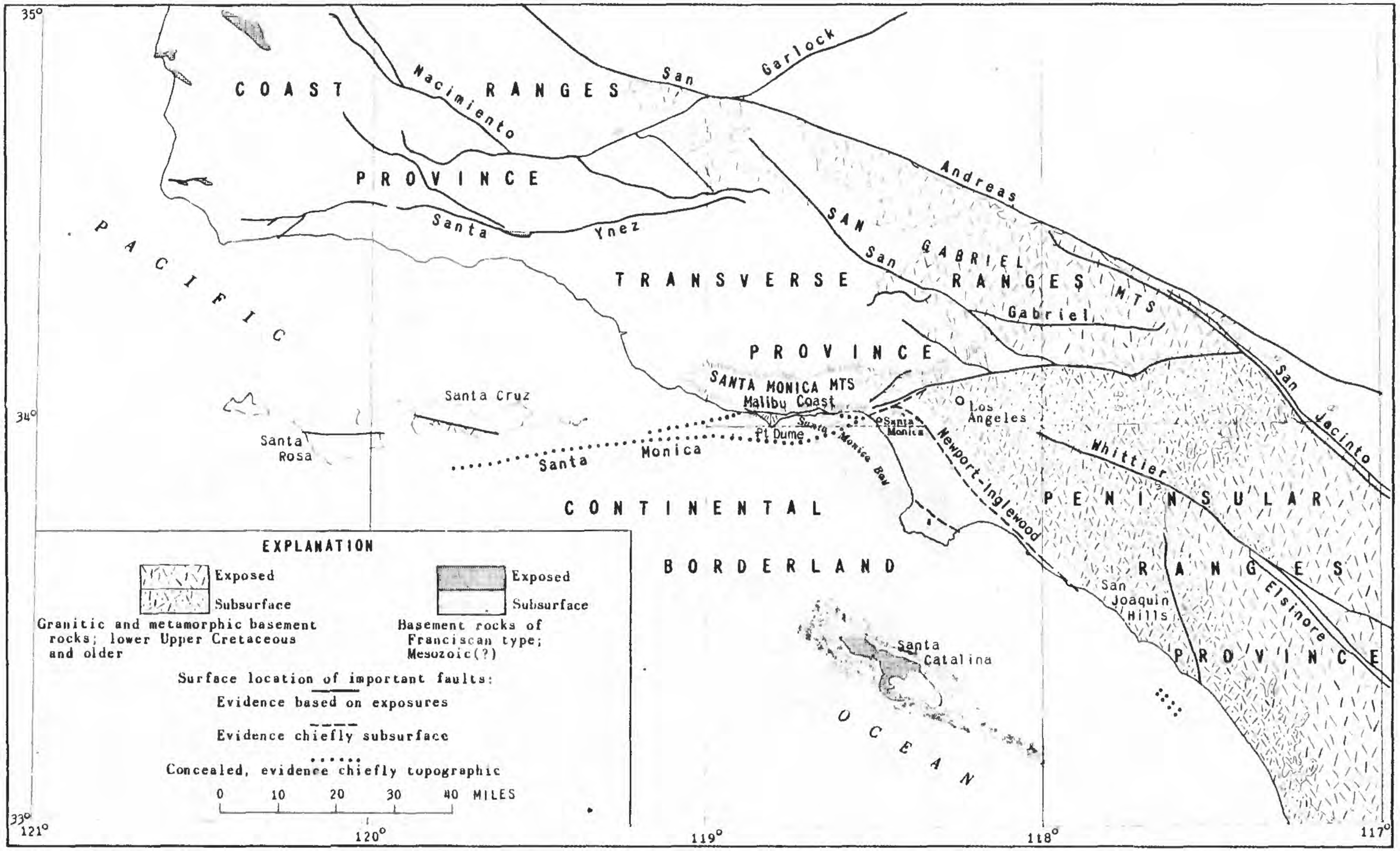

Fig. 1. Outline map of part of southern California showing geomorphic provinces, exposures of basement rocks and their distribution as known or inferred from subsurface data, and approximate location of major faults. Data from Emery (1960), Hill and others (1964), and Smith (1964).

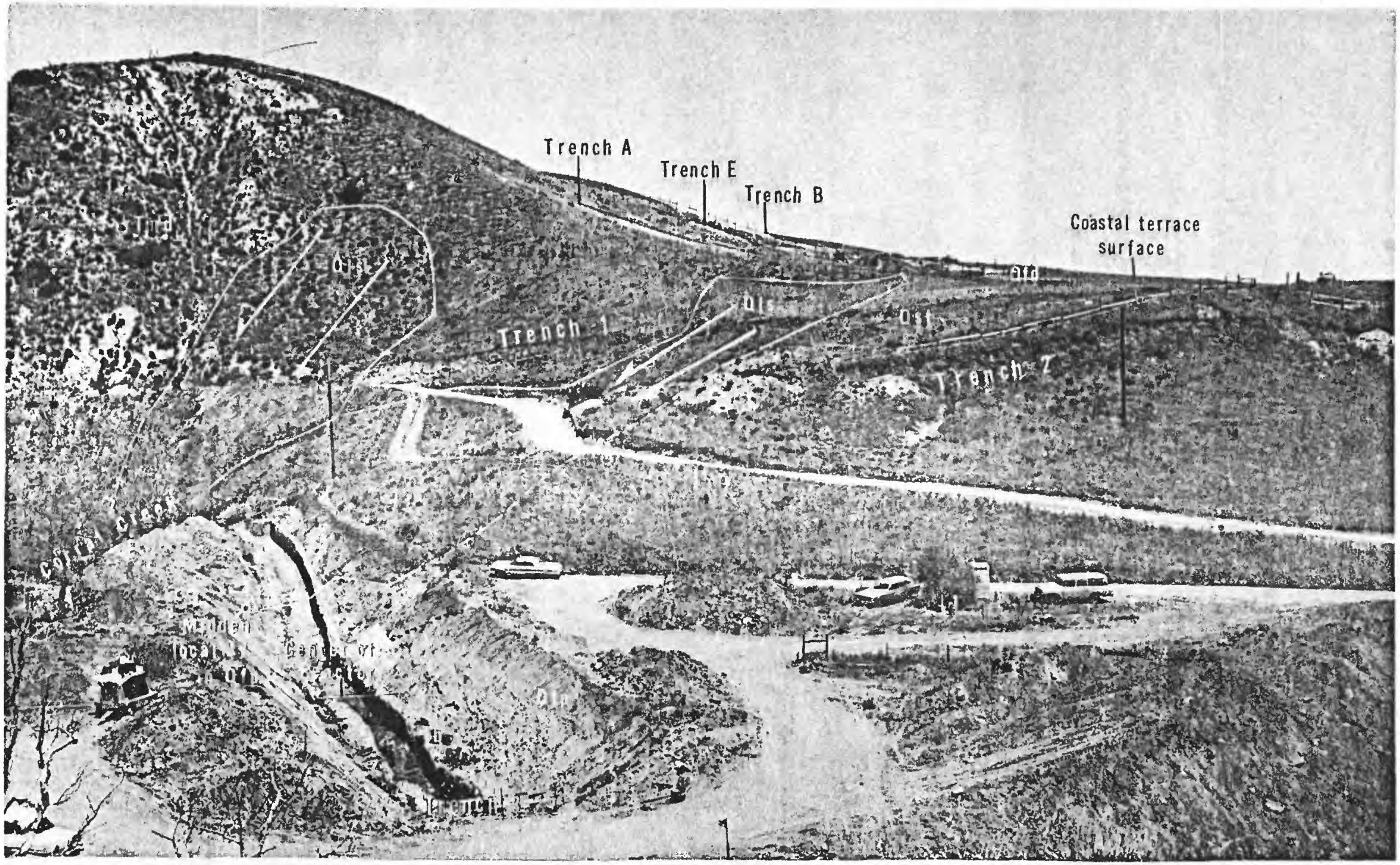

Fig. 2.--East wall of Corral Canyon and part of plant site, looking northeastward. Trench 3 (reactor location) in left foreground exposed unit B bedrock (Tb) in bottom; the overlying flood-plain deposits (Qfp), which contain shells about 3,000 years old at midden locality; and buried slip surface of landslide along which unit B overrode the flood-plain deposits. Hill at upper left is underlain by Monterey Shale (Tmd) beyond fault "A", which is buried by landslide (Qls), and which trends toward upper right beneath surficial deposits (Qfd) of coastal terrace. Test trenches 1 and 2 expose stream terrace deposits (Qst) overlying unit B bedrock south of fault "A".

the bedrock is commonly mantled by a wide band of marine and nonmarine Quaternary terrace, colluvial, and alluvial deposits, which are expressed as smooth, gently south-dipping slopes as high as 500 feet in altitude (frontispiece; figs. 4 and 5). In the Corral Canyon area an east-trending belt, about 2,000 feet wide of smooth rounded spurs and hills, rises to altitudes of 300 to 700 feet and separates the lower, terraced area along the coast from higher, deeply dissected terrain to the north. The east- and west-facing slopes in this belt of hills are oversteepened by erosion and are commonly modified by landslides.

Corral Creek, at the mouth of which the plant site is located, is a south-flowing, intermittent stream about 4 miles long and has a drainage basin of about 3.6 square miles. East of Corral Canyon three small, south-trending gullies less than a mile long are incised into the coastal terrace; these have been informally designated, from east to west, gullies A, B, and C (fig. 4).

REGIONAL GEOLOGIC SETTING

The Santa Monica Mountains form the southwesternmost mainland part of the Transverse Ranges province, which is characterized by east-trending mountains and valleys; the western part of this province, west of the San Andreas fault zone, is about 160 miles long and 50 miles wide (fig. 1). This major geomorphic-geologic province abruptly transects the otherwise relatively uniform northwest trend of geomorphic and geologic features in the Coast Ranges province to the north and in the Peninsular Ranges province and Continental Borderland[1] to the south; the Continental

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[1] The term Continental Borderland was applied by Shepherd and Emery (1941) to the offshore tract between the mainland and the continental slope of southern California; this definition implicitly includes the east-trending Channel Islands (which are underlain by basement rocks correlated with those of the Santa Monica Mountains) and Santa Barbara Channel north of latitude 34°. The term is here applied to that part of the offshore tract south of the Channel Islands, which is characterized by northwest structural trends and underlain chiefly if not entirely by Catalina Schist basement of Franciscan aspect; it thus coincides with the Southern Franciscan area of Reed (1933, fig. 6). In this sense, the term has both physiographic and geologic relevance.

Borderland is largely submerged beneath the Pacific Ocean.

The south margin of the western Transverse Ranges west of the San Andreas fault zone is marked by a series of east-trending faults near latitude 34° N., which include, from west to east, the Malibu Coast, Hollywood-Raymond Hill, and Sierra Madre-Cucamonga faults. These, plus the Benedict Canyon fault of the eastern Santa Monica Mountains and a postulated fault (Anacapa fault of Hill, 1928) that probably follows a submerged topographic scarp south of Point Dume (fig. 1), have been termed the Santa Monica fault system by Barbat (1958). The Santa Monica fault system forms the geologic boundary between the high Transverse Ranges on the north and the Peninsular Ranges and low Continental Borderland on the south.

Malibu Coast fault and Malibu Coast zone

The east-trending Malibu Coast fault is the northernmost fault in the west part of the Santa Monica fault system; it traverses the south margin of the central Santa Monica Mountains and forms the structural boundary between rocks of the mountains on the north and those of the Continental Borderland on the south. The Malibu Coast fault lies within and is a part of an east-trending zone of deformation about 1 mile wide near the north margin of the Santa Monica fault system in the central Santa Monica Mountains, the Malibu Coast zone.

North of the Malibu Coast fault the basement rocks consist of Jurassic metasedimentary rocks and lower Upper Cretaceous plutonic intrusive rocks (time scale, fig. 53), which in the eastern Santa Monica Mountains are exposed as the core of a west-plunging anticline. The stratigraphic sequence that overlies the basement rocks consists of unmetamorphosed sedimentary rocks of Late Cretaceous to late Miocene age derived chiefly from areas north of the Malibu Coast fault (the northern facies), and middle Miocene volcanic rocks (Durrell, 1954). This sequence is cut by at least three extensive folded thrust faults (Yerkes and others, 1964), which are truncated on the south and dragged downward by the Malibu Coast fault. Each of the thrust sheets commonly contains a unique part of the stratigraphic section; the uppermost of these is the Malibu Bowl thrust sheet, which consists of middle Miocene rocks and underlies the north half of the Corral Canyon site (fig. 3).

South of the Malibu Coast fault, in the Continental Borderland, the known basement rocks are Catalina Schist of probable Mesozoic age (Durrell, 1956, p. 3; Emery, 1960, p. 67; Woodford, 1960). Catalina Schist is exposed on Santa Catalina Island, in the Palos Verdes Hills (Woodring and others, 1946), is well known from many exploratory wells in the western Los Angeles basin (Schoellhamer and Woodford, 1951), is probably present at about 5,000 feet subsea in an exploratory well drilled on Point Dume (Sovereign Oil Co. well Malibu 1--see fig. 5), and contributed detritus to Miocene sedimentary rocks now exposed south of the Malibu Coast fault. The Catalina Schist includes chlorite and glaucophane schists and kindred rocks similar in lithology to rocks of the Franciscan Formation. A thin sequence of middle and upper Miocene sedimentary rocks, derived in part from areas now offshore (southern facies), and middle Miocene igneous rocks unconformably overlie the basement; this sequence is in part equivalent in age (late middle Miocene) to the youngest thrusting north of the Malibu Coast fault, which resulted in the Malibu Bowl thrust fault. In contrast to the section north of the Malibu Coast fault, lower Tertiary and Upper Cretaceous rocks are missing from this sequence.

Large horizontal displacement on the Malibu Coast fault is required by its juxtaposition of these unlike stratigraphic sections and basement rocks. Eight miles of left-lateral strike slip in mid-Miocene time has been attributed to the Santa Monica fault system by Barbat (1958, fig. 1, p. 64), based on data from the area east of Santa Monica. In the area just west of Santa Monica the basement rock surface of the north block

is 10,000 to 12,000 feet higher than that of the south block (McCulloh, 1960, p. 322). Knapp and others (1962) show more than 7,500 feet of reverse dip separation of the basement surface (north side up) across the fault system in the area just east of Santa Monica. However, in the area west of Santa Monica, neither strike slip of less than 25 miles nor steep dip slip can account for the lack of continuation of the Malibu Bowl and other north-block thrust sheets onto the south block. Instead, southern-facies rocks of the same age as thrust faults in the north block are exposed south of the Malibu Coast fault (figs. 3 and 5). In addition, the east-trending Malibu Coast zone of deformation, which includes the Malibu Coast fault, is characterized by significant evidence of north-over-south compressive deformation. This evidence consists of (1) generally north-dipping features such as bedding, axial surfaces of numerous folds, and surfaces of shears and faults, including the Malibu Coast fault over most of its length; (2) gently plunging fold axes that trend subparallel to the Malibu Coast fault; and (3) local small-scale evidence of north-over-south movement on minor north-dipping faults (see Structure and Structural analysis). It is inferred that the Malibu Coast fault and Malibu Coast zone are features produced chiefly by north-over-south thrusting, during which large-scale horizontal shortening of the crust occurred.

Newport-Inglewood zone

The Newport-Inglewood zone of *en echelon* faults and folds in the western Los Angeles basin probably overlies the buried east boundary of the Catalina Schist basement of the Continental Borderland (Woodford and others, 1954, p. 74; Barbat, 1958, fig. 2; Woodford, 1960, fig. 1); it trends northwestward to intersect or merge with the Malibu Coast zone near Santa Monica (fig. 1). Near the Newport-Inglewood zone the Catalina Schist basement is at depths of 12,000 to 14,000 feet below sea level (McCulloh, 1960), and is buried by clastic sedimentary rocks of middle Miocene to Recent age. Because of deep burial, the position of the faults in basement rocks and the distribution of basement rock types are only locally well-known from subsurface exploration for oil (Schoellhamer and Woodford, 1951).

Faults of the Newport-Inglewood zone exhibit right-lateral strike slip of 3,000 to 5,000 feet in rocks of Pliocene age (Hill, 1954; Rothwell, 1958) and subsurface oilfield facilities have been sheared in a right-lateral sense (Bravinder, 1942).

Regional fault system

The Malibu Coast and Newport-Inglewood zones are inferred to be the crustal-block boundary faults that juxtapose Catalina Schist basement of the Continental Borderland on the south and west against granitic and metamorphic basement of the Transverse and Peninsular Ranges on the north and east (fig. 1). The Newport-Inglewood zone exhibits right-lateral strike slip in the overlying sedimentary section and the Malibu Coast zone exhibits strong evidence of north-over-south thrusting. These two zones are considered to be related parts of a primary crustal fault system, on which rocks of the Continental Borderland have moved relatively northward past rocks of the Peninsular Ranges along the Newport-Inglewood zone and beneath rocks of the Santa Monica Mountains at their overriding south margin along the Malibu Coast fault.

GEOLOGY OF THE CORRAL CANYON SITE

Bedrock

The Corral Canyon site is bisected by the east-trending Malibu Coast fault (fig. 4). The bedrock of the site north of the fault consists of folded, poorly exposed, marine sedimentary rocks referred by Schoellhamer and Yerkes (1961) to the middle Miocene Upper Topanga Formation of Durrell (1954). Exposed bedrock south of the fault consists of four east-trending bands of variously folded and sheared middle Miocene marine sedimentary rocks, and small areas of middle Miocene volcanic rocks near the southern corners of the site. Rocks in these bands are Monterey Shale (Schoellhamer and Yerkes, 1961), which is largely covered by surficial deposits east of Corral Canyon, and an unnamed stratigraphic unit, unit B, which is largely covered by surficial deposits in the band along the coast. Unit B was not distinguished from the Monterey Shale in the Corral Canyon area by Schoellhamer and Yerkes (1961), but has since been mapped into the area from the Point Dume quadrangle to the west (fig. 5), where it was first recognized and mapped (Schoellhamer and others, 1962).

Natural exposures of bedrock in the Corral Canyon site are poor; good outcrops are present only in deep gullies, on landslide scarps, rarely on steep canyon walls and in the numerous artificial cuts. Bedrock in natural exposures and shallow cuts is weathered, whereas bedrock exposed in some of the deeper test trenches (for example, mudstone exposed in trenches 3 and F) is fresh, olive gray to black in color, rather than the pale-gray, pale-olive, or yellowish-brown of the weathered rock.

Bedrock north of the Malibu Coast fault

Upper Topanga Formation of Durrell.--Late middle Miocene rocks of the Upper Topanga Formation form that part of the Malibu Bowl thrust sheet which underlies the north half of the Corral Canyon site. The Upper Topanga Formation here is characterized by (1) marine sandstone sequences that contain interbeds and thicker sequences of fissile marine siltstone, (2) rhythmic bedding, and (3) the common presence of biotite. Sequences or sets of thick sandstone beds that contain subordinate thin siltstone interbeds alternate with sequences of siltstone that contain about 50 percent thin and medium-thick sandstone beds.

Sandstone, locally friable, makes up more than 50 percent of the unit. It is very light gray to pale yellowish orange or light brownish gray, ranges from silty and fine-grained sandstone to coarse-grained and pebbly sandstone, and is dominantly medium grained and moderately to poorly sorted. Sandstone beds are generally 2 to 4 feet thick, are commonly graded, and some have finely laminated tops. Sand grains are subangular to subrounded and consist of quartz, feldspar, and scarce dark-colored lithic fragments; biotite is present in all but the coarser phases, rarely makes up more than 5 percent of the rock, and is commonly concentrated in laminated rock. Sandstone in the finer grained sequences occurs in beds ½ to 24 inches thick, and is fine to medium grained, moderately to poorly sorted, and similar to the thick sandstone beds in composition and internal structure. Some beds are thick, hard, calcareous, poorly sorted, coarse grained and pebbly, and fracture across quartz grains. Gypsum and jarosite(?) fill and coat fractures and joints in some places.

The siltstones are clayey, laminated, and fissile, and have concentrations of mica, carbon flakes, and less commonly, fish scales on the lamination planes. The rock is pale yellowish brown and forms beds 1 to 24 inches thick as interbeds in the sandstone sequences. It disintegrates into plates and wedges ¼ to 5 inches in length. A characteristic of the Upper Topanga siltstones throughout the central part of the Santa Monica Mountains is the presence of scattered to abundant, hard, dolomitic grayish-orange, ellipsoidal sandy siltstone concretions 4 to 10 feet in length.

The base of the Upper Topanga Formation is gradational with the underlying middle Miocene volcanic rocks of the Middle Topanga Formation. The faulting and fairly tight folding of the rocks prevents determination of the thickness of the formation in this area; north of the Corral Canyon site its minimum stratigraphic thickness is about 3,500 feet.

Bedrock south of the Malibu Coast fault

Unit B.--Unit B consists of mudstone, sandstone, and volcanic rocks. The volcanic rocks probably underlie the sedimentary rocks for the most part, but some are interbedded with the sedimentary rock.

Unit B volcanic rocks.--Small areas of volcanic rocks are present near the southwest and southeast corners of the Corral Canyon site (fig. 4). The rocks in the southwest corner are quite resistant to erosion and form bold outcrops and steep slopes; those in the southeast corner form a small, resistant ledge in the surf zone.

The volcanic rocks near the southwest corner of the Corral Canyon site range from vitric-lithic andesitic(?) tuff breccia containing about 30 percent volcanic fragments in an altered (montmorillonitic) glass and lithic ash matrix, to dense volcanic breccia. Breccia fragments range from $\frac{1}{4}$ to greater than 18 inches in longest dimension. For the most part the rock is unstratified, except for crude orientation of some of the larger fragments; the rock is locally well-stratified west of the Corral Canyon site (fig. 5).

The volcanic rocks near the southeast corner of the Corral Canyon site consist of massive flow rock, pillowed rock, and volcanic breccia. In the pillowed rock most of the pillows have thin rinds of black glass and bands of vesicles parallel to the pillow margins; and in some cases hard, recrystallized sedimentary rock occurs in the interstices.

Contacts of the volcanic rock near the southwest corner of the Corral Canyon site are faults that have locally been quite tightly folded (fig. 4); southeast of the Corral Canyon site volcanic rocks are locally interbedded with unit B sedimentary rocks (fig. 5). The thickness of the volcanic rocks mapped in the Corral Canyon site is quite small. The maximum exposed thickness of unit B volcanic rocks is about 1,700 feet in the Point Dume quadrangle.

Unit B sedimentary rocks.--Rocks assigned to this unit form two elongate, east-trending fault slivers, parallel to and south of the Malibu Coast fault (fig. 4).

Unit B sedimentary rocks consist of whitish, friable, feldspathic sandstone; interbedded sandstone and gray and gray-green mudstone; brown, locally tuffaceous or diatomaceous mudstone, and limited amounts of claystone. Thick sandstone sequences containing subordinate mudstone alternate with thick mudstone sequences containing subordinate sandstone.

The sandstone is very light gray to yellowish gray, fine to medium grained, and moderately to poorly sorted; it contains quartz, feldspar, white mica, chlorite, and rare fragments of Catalina Schist. Beds are commonly 3 to 36 inches thick. Many beds are graded both in grain size and by an upward increase in abundance of siltstone as laminations near or at the tops of beds. One very thick bed just west of the mouth of Corral Canyon contains about 10 percent angular to subrounded fragments of yellowish-gray, fine- to coarse-grained, calcareous siltstone or sandstone, some containing pholad(?) borings. Siltstone interbeds in the sandstone sequences are $\frac{1}{2}$ to about 6 inches thick, yellowish gray to pale yellowish brown and light yellowish gray in color, and internally laminated.

Mudstone or clayey siltstone forms about 60 percent of unit B in and near the plant site. Mudstone in the mudstone-sandstone sequences (north of fault "F") is olive gray, gray, or grayish black when fresh, and weathers to pale-olive-gray or yellowish brown. It is silty to slightly sandy, and is interbedded with 1/8- to 36-inch-thick beds of fine- to coarse-grained sandstone, some of which are graded or laminated. Beds of hard dolomitic(?) siltstone or fine-grained sandstone are locally present, as well as fish scales and Foraminifera. Mudstone without significant interbedded sandstone (south of fault "F" in the reactor site--see fig. 8 and Structure of plant site for location) is olive gray to black where fresh and weathers to pale brown or "pinkish" yellowish brown. This mudstone locally contains small ellipsoidal pods of sandstone, fragments of tuff, scattered phosphatic pellets, concentrations of montmorillonite, and abundant Foraminifera. Pyrite occurs rarely in sandstone and as euhedral crystals on shear surfaces in mudstone in unweathered rock, whereas gypsum and bright yellow jarosite(?) fill and coat fractures in weathered rock. In all the test borings the fresh mudstone is dark gray, olive gray, or black.

Silty cristobalite rock (altered tuffaceous sediment?) with streaks of sheared mudstone was exposed in test trench 2 on the east wall of Corral Canyon, and similar material, probably cristobalite rock, was exposed in trench B (unit v, fig. 9). This rock carries a foraminiferal fauna somewhat more characteristic of Monterey Shale than of unit B in composition and inferred ecology. Because the rock is not exposed beyond these two trenches, because it contains mudstone similar to that of unit B, and the Monterey Shale in the area is not known to contain such rock, it is herein referred to unit B.

Unit B sedimentary strata are distinguished from locally somewhat similar Upper Topanga beds by (1) the local presence of Catalina Schist detritus in the sandstones, (2) a general lack of biotite, (3) the punky, diatomaceous nature or clay-rich, nonfissile character of some of the mudstone, and (4) the relative abundance of gypsum and jarosite(?) in fractures.

Unit B sedimentary rocks in the southern of the two main fault slices (fig. 4) are folded and intensely sheared and those in the northern fault slice are folded; all contacts of unit B in the Corral Canyon site are faults. Thickness of the unit cannot be determined.

Unit B is middle Miocene on the basis of Foraminifera. Unit B volcanic rocks east and west of the Corral Canyon site contain interbedded sedimentary rocks that bear Foraminifera assigned an early middle Miocene age (Relizian stage of Kleinpell, 1938). Unit B sedimentary rocks in the Corral Canyon site locally contain abundant Foraminifera assigned a late middle Miocene age (Luisian stage of Kleinpell). The 25 collections listed (Appendix A) are from localities in or near the palnt site; they were identified and assigned a middle Miocene age by P. B. Smith of the U. S. Geological Survey.

On the basis of comparison with dozens of other collections from Miocene rocks south of the Malibu Coast fault in this general area, these collections have been divided into two ecologic categories by Smith. Collections 2-2, 2-3, 2-4, 2-5, and 2-6 contain numerous species represented by abundant numbers and large individuals that include indicators of age and bathyal depth; in these respects the faunas resemble those from the Monterey Shale east and west of the Corral Canyon site. Collections 1 through 18, 2-1 and 2-7, however, contain relatively sparse numbers of small species. Although the collections of the second group are generally nondiagnostic as to precise age and depth, they are inferred to represent deeper waters than the first category; in this respect they resemble faunas from unit B east and west of the Corral Canyon site. Several collections similar to nos. 2-1 and 2-7 were obtained from rock samples from boring no. 11 at 90, 120, and 125 feet. Although the collections of both categories are generally contemporaneous, no mixing of the two categories could be discerned, such as might be expected if large-scale submarine sliding of soft sediments had occurred.

Monterey Shale.--White-weathering, generally resistant, dolomitic or diatomaceous, thin to medium-thick and persistently bedded Monterey Shale is widespread in the Malibu Coast zone. This deformed Monterey Shale is differentiated from the largely homoclinal sequence of Monterey Shale on Point Dume, south of the Malibu Coast zone, by the presence throughout of small and medium, east-trending folds and by numerous small faults and associated breccia (fig. 6). The deformed Monterey Shale occurs chiefly in a

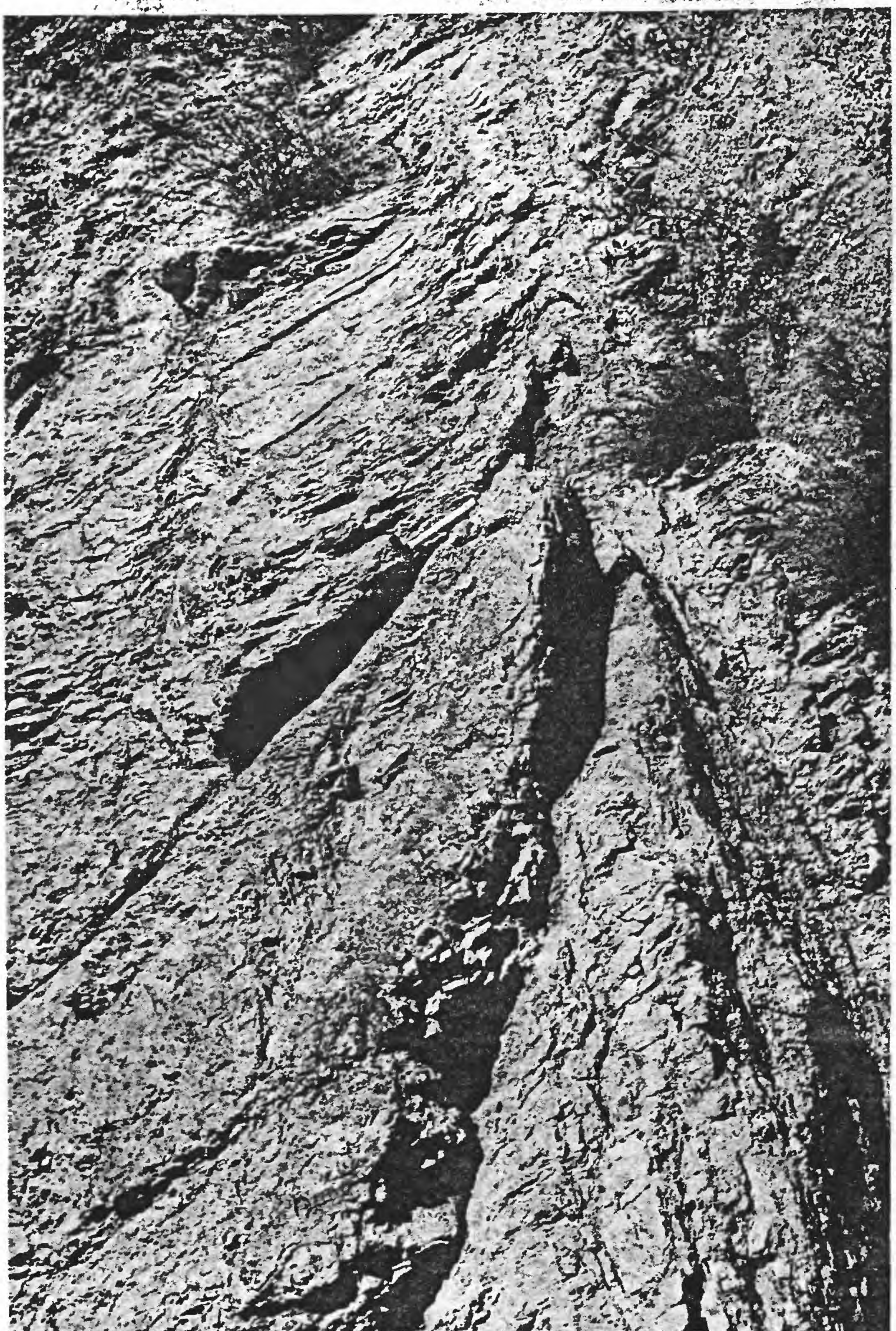


Fig. 6.--Sheared and shattered Monterey Shale on the east wall of Corral Canyon; outcrop is just north of fault "A" near north boundary of the plant site. One major shear trends across the outcrop just above its base; two other shears trend obliquely down into the first from the left. Hammer at center for scale.

resistant band immediately south of the Malibu Coast fault; a second east-trending band is present along part of the coast between Corral Canyon and Point Dume (fig. 5). The deformed Monterey Shale is chiefly middle Miocene (Luisian) in age on the basis of Foraminifera; one collection from near Malibu Canyon is late Miocene (Mohnian) in age.

Near the mouth of Corral Canyon the Monterey Shale consists chiefly of light-brownish-gray to light-olive-gray, laminated, nonfissile siltstone and silty sandstone. The siltstone beds are 1 to 2 feet thick; some beds are light colored, punky, and diatomaceous and others are darker colored, hard, calcareous, and flaggy. Gypsum and bright-yellow jarosite(?) fill and coat fractures and joints.

Sandstone is present as light-brownish-gray to pale-yellowish-gray interbeds 1 to 2 feet thick. It is very fine grained and well sorted, and has wispy, black laminations. The sandstone is extremely hard and erosion resistant due to silica(?) cement, and locally makes up as much as 20 percent of the total formation.

Contacts of the deformed Monterey Shale in the Corral Canyon site are all faults. These faults and the tight folds and shears in the rock prevent determination of the stratigraphic thickness of the unit.

Sediment sources

The sedimentary rocks now juxtaposed by the Malibu Coast fault contain sediment derived from contrasting sources. The Upper Topanga Formation, north of the fault, contains abundant biotite; in the northeast part of the Santa Monica Mountains it contains distinctive gravel that indicates derivation from older rocks now exposed to the north and east. In contrast, sandstones of unit B and Monterey Shale south of the fault contain white mica, chlorite, and rare detritus of Catalina Schist, which indicate derivation in part from basement rocks of the Continental Borderland.

Surficial deposits

Unconsolidated surficial deposits in the Corral Canyon site are present chiefly on the coastal terraces and in Corral Canyon. These deposits overlie bedrock in about 55 percent of the Corral Canyon site and about 90 percent of the plant site (fig. 4). Age of the deposits ranges from late Pleistocene to Recent.

Landslide deposits

Landslides of various sizes and ages occupy about 35 percent of the Corral Canyon site. The deposits consist chiefly of bedrock ranging from large unbroken slices to a jumble of small fragments, and range from thin soil slides to bedrock slides perhaps as much as 200 feet thick. Because they are a factor in site development, landslides are more fully discussed under "Geologic factors that should be considered during engineering design and construction."

Coastal terrace deposits

Marine coastal terrace deposits and their cover of thicker and more extensive nonmarine deposits underlie about 7 percent of the Corral Canyon site. Two recognized terrace levels are present: a high, narrow terrace at about 250 feet altitude; and a relatively broad platform with a shoreline angle (intersection of the old sea cliff with the surf-cut bedrock platform) at about 170 to 176 feet altitude.

Recognition of the high terrace at about 250 feet altitude is based on its expression as a topographic bench on the south-facing slopes adjacent to the coast, and correlation with terrace M (fig. 49) by its altitude and position in the terrace sequence. Terrace M is the Malibu terrace of Davis (1933), of which a large remnant is preserved north of Point Dume.

The most prominent terrace of the Corral Canyon site has a shoreline angle exposed in trench B at about 176 feet above sea level and on the west wall of gully A at somewhat more than 167 feet. This terrace is correlated by position in the terrace sequence and approximate altitude (see discussion under Age of structural features--Physiographic features) with terrace C (fig. 49), which lies between the Malibu and Dume terraces of Davis (1933).

In the Corral Canyon site the platform of terrace C extends seaward from an altitude at its inland edge of about 167 to 176 feet to an altitude of about 130 feet at the eroded south edge. The platform is not simple in configuration, for in gully C (fig. 14) it is displaced, upper or north side relatively up, some 15 or 20 feet along a slip surface of unknown extent. Smaller-scale disruption of the terrace platform is exposed in trenches B, C, and D (fig. 12). In addition, this platform has been greatly modified by stream erosion, as is shown by stream terrace deposits that overlie bedrock at altitude 130 feet in trench E (Unit G-3, fig. 13);

these deposits are approximately on the trend of, but some 40 feet below, the shoreline angle of the platform. The platform is also truncated by the colluvial-alluvial clay of unit CF in trench B (fig.11).

The lower part of the deposits on terrace C consists of as much as 20 feet of marine sand and gravel. These marine sediments are exposed in trenches B, C, D, and F, in intermittent exposures along the truncated seaward margin of the terrace, and in gullies A, B (fig. 48), and C (see also Hoffman and Smith, 1965, drawing 1). The gravel is locally as much as 10 feet thick and consists of pebble- to boulder-sized, well-rounded clasts derived from conglomeratic beds in Miocene and older rocks that underlie nearby parts of the mountains. As much as 12 feet of friable, well sorted, fine-grained marine sand overlies the gravel and locally lies directly upon the bedrock platform.

Nonmarine clay, sand, and sandy gravel unconformably overlie the marine deposits and locally rest on bedrock. The nonmarine gravel consists of lenses and beds as much as 4 feet thick with subrounded pebbles, cobbles, and boulders up to 16 inches in longest dimension (average 2 to 3 inches). The sand is clayey to silty, dominantly medium grained, and occurs in beds as much as 4 feet thick. Some moderately to well-sorted laminated sand is locally present near the top of the marine deposits. The clay is dark brownish gray to brownish black, unbedded, and variably sandy (equivalent to unit CF of fig. 15).

Well-sorted sand with some gravel is poorly exposed where it over-lies bedrock at altitude about 80 feet just east of the mouth of Corral Canyon; this deposit is considered by Cleveland and Troxel (1965) and Hoffman and Smith (1965) to be marine. Shells reported from this deposit by Cleveland and Troxel (1965) need not indicate marine deposition, as they were found in exposures on a slope down which shell fragments of midden origin are moving. This sand and gravel is most likely a stream terrace deposit, in view of the presence of similar sediments both to the north along the east wall of the canyon at altitudes of 70 and 90 feet (fig. 9) and eastward under the terrace surface in trenches A and E at altitudes of 137 and 130 feet, respectively (figs. 10 and 13).

The age of the marine terraces is based on radiometric dating of shells from deposition on the "100-foot" coastal terrace, in California. Shell material from marine deposits on this terrace 2 miles west of Corral Canyon (sample from locality M 1710, fig. 5) has an estimated maximum age of 130,000 years as based on uranium series disequilibrium (determined by J. N. Rosholt of the U. S. Geological Survey, written communication, 1965; see Appendix C for details). There may be little difference in the actual age of this sample and one from deposits on the lowest emergent terrace at Palos Verdes Hills (sse below). The Molluscan fauna from locality M 1710 is late Pleistocene in age and has been correlated (Addicott, 1964) with one from upper Pleistocene marine deposits on the lowest emergent marine terrace in Potrero Canyon west of Santa Monica. The latter locality (loc. 61 of Hoots, 1931) is at an altitude of about 240 feet;

it is located on the north flank of broad anticlinal fold in the terrace platform and covering deposits (detailed mapping of J. T. McGill). The Potrero Canyon fauna has in turn been correlated with those from the upper Pleistocene Palos Verdes Sand, a marine deposit on the lowest emergent, or "100-foot" terrace at Palos Verdes Hills (Woodring and others, 1946, p. 106). These marine faunas do not provide sufficient resolution to distinguish between different terrace levels; they do indicate that all the deposits are late Pleistocene in age. Shell material from the PalosVerdes Sand has been tentatively dated by the uranium series disequilibrium method at about 130,000 years by Broecker and Kaufman (unpub. ms.); the age of similar material is estimated to be a maximum of 110,000 years (sample M 2017) by J. N. Rosholt of the U. S. Geological Survey (written communication, 1965; see Appendix C for details). Shell material from marine deposits on the "100-foot" terrace at Santa Cruz, California, has been dated at about 115,000 years by the same method (Blanchard, 1963). The Palos Verdes Hills are about 27 miles southeast of Corral Canyon, and the Santa Cruz area is about 280 miles to the northwest. The fact that the lowest emergent terrace at three such distant points on the California coast have such similar ages and shoreline-angle altitudes suggests that terrace D (the lowest emergent terrace in the Corral Canyon area, shoreline angle at about 110 feet altitude) may be correlative with the lowest emergent terraces at the other two localities.

Marine deposits on the platform of terrace C at Corral Canyon have yielded one well-preserved specimen of the upper Pleistocene shallow marine gastropod Thais biserialis (from unit Sdm, trench B; see sample YCC11E, Appendix B), as well as a few fragments of marine intertidal- to sublittoral-zone invertebrates (unit Sdm, trench C; and sample CW 115 from gully B; see Appendix B). Shell material from marine deposits on terrace C near the mouth of gully B has an estimated maximum age of 280,000 years as based on uranium series disequilibrium (determined by J. N. Rosholt, U. S. Geological Survey; written communication, 1965; see Appendix C for details). Relative age differences determined by this method, where large, are probably valid; thus the gully B sample from terrace C is probably significantly older than the samples from the lowest emergent terrace at Palos Verdes Hills and from terrace D.

Terrace C, the next recognized emergent terrace above terrace D, has a shoreline angle at altitude about 170 to 176 feet in the Corral Canyon site (fig. 49). Because terrace C is considerably more dissected than terrace D and is higher, it is inferred to be older. Both terraces are late Pleistocene in age; terrace D is probably about 120,000 years old, and terrace C is probably significantly older, perhaps as much as 280,000 years old. The marine deposits of terrace C are overlain in the Corral Canyon area by colluvial-alluvial deposits with a radiocarbon age of about 9,430 years (table 3).

Terrace M has yielded no fossils; its age is inferred to be greater than that of terrace C on the basis of its higher position in the terrace sequence and its greater dissection.

Stream terrace deposits

Stream terrace deposits partially mantle the east wall of Corral Canyon near the plant site; small remnants have also been mapped on the west wall of the canyon, and well-sorted sand and gravel at the east side of the canyon mouth are mapped as stream terrace deposits (see previous section). In addition, stream terrace deposits underlie part of the coastal terrace at least 500 feet east of present Corral Creek, as indicated by exposures in trenches A and E (units G-2 and G-3, figs. 10 and 13). The deposits on the east wall of Corral Canyon overlie the bedrock surface at altitudes as high as 85 feet above sea level (fig. 9). Where it is exposed, their base is a complex bedrock surface resulting from erosion at different places and different times; it slopes as steeply as 45° into the canyon. The surface of the deposits exhibits irregular local relief, probably reflecting different positions and levels of stream meanders as it was formed. In test trenches 1 and 2 on the east wall of Corral Canyon the stream terrace deposits (unit G-3 of fig. 9) consist of loose friable sand and up to 60 percent gravel. The gravel consists of angular to generally rounded pebbles, cobbles, and boulders as much as 3 feet in maximum dimension (average about 4 inches) that locally exhibit excellent north-dipping imbrication, indicating deposition by a south-flowing current. Much of the gravel can be identified as having been derived from areas north of the Malibu Coast fault. Sand is present as crudely stratified lenses and beds as much as 2 feet thick or as matrix in the gravel. The sand is pale gray, yellowish brown, or dark brown, variably silty or clayey, medium to coarse grained and generally moderately to well sorted. The thickness of the deposits may locally attain about 20 feet. The presence of stream terrace deposits at about 138 feet altitude in trench A (fig. 10) and about 129 feet altitude in trench E (fig. 13), coupled with their absence in trench B, indicates that the Corral Creek drainage once flowed as far eastward of its present course as trench E, thence probably southward to the sea.

In trench A the stream deposits (unit G-2) consist of a basal gravel that contains subrounded pebbles of resistant rock as long as 2 inches in a matrix of reddish-brown, poorly to moderately sorted, silty to medium-grained sand and an overlying brown, fine-grained silty sand that contains scattered pebbles. In trench E the stream deposits (unit G-3) consist of stratified gravel that contains rounded to subrounded pebbles, cobbles, and boulders as much as 18 inches in maximum dimension (average, about 8 inches) in a matrix of poorly sorted, friable, medium- to coarse-grained sand. The gravel exhibits moderately developed northwest-dipping imbrication, consistent with former eastward bend in the Corral Canyon drainage.

Colluvial deposits

Colluvial or slope-wash deposits form by imperceptible downslope movement of superficial detritus; they mantle the canyon walls and the south-facing slopes between Corral Canyon and gully A and in large part obscure the inland edge of the coastal terrace.

The deposits consist of tough, coherent sandy clay or clayey sand; the color is brownish gray, olive gray, or brownish black. The sand is silty to fine grained. In the test trench exposures the deposit commonly contains scattered subrounded pebbles and cobbles at the base and about 5 percent fragments of Monterey Shale. In trench B (fig. 11) the deposit contains a stringer of pebbles, cobbles, and a few boulders of resistant sandstone and volcanic rock. The lower part of the deposit commonly contains locally abundant calcium carbonate in veins, patches, streaks, and as coating on fractures and gravel, or as a fine network of rootlike veinlets (mycelium carbonate).

The colluvial deposits are as much as 12 feet thick in trench B; similar deposits (units CF and C4) in trench E are 35 to 40 feet thick. The basal part of the colluvial deposits is probably equivalent in age to the lower part of the alluvial fan deposits at the south end of trench B (see Age of Profile 1 under Soils).

Talus deposits

A small deposit of talus, or rock waste, has accumulated beneath the steep, south slope of the Middle Topanga volcanic rocks exposed just north of the Corral Canyon site. The material consists of angular and subangular fragments of volcanic rock, ranging in size from about 1 inch to large blocks at least 6 feet across. Maximum thickness of the deposit, estimated from topography, may be 20 to 30 feet.

Alluvial fan deposits

Alluvial fan deposits locally overlie the flood plain along Corral Canyon, and also overlie coastal terrace deposits between Corral Canyon and gully A. The fan deposits on the terrace surfaces were mapped on the basis of topographic expression; they may actually be more extensive than shown on the geologic map (fig. 4). In addition, a small fan has formed on the large landslide west of the mouth of Corral Canyon.

The alluvial fans on the coastal terrace have moderately steep slopes near their heads; the slopes decrease toward the outer margins of the fans and merge so inconspicuously with the slopes of the underlying deposits that the outer margins of the fans cannot be precisely located. Some of the deposits of the westernmost fan on the terrace east of Corral Canyon were exposed by test trench B (fig. 11, unit CF south of about station 200). They consist of tough, brownish-black, silty to fine-grained sandy clay. The material contains about 5 percent angular rock fragments and numerous rounded pebbles, cobbles, and a few boulders of resistant rock in a train and randomly scattered. The lower part contains abundant calcium carbonate in patches, streaks, and as coating on rock fragments. The alluvial fan material south of 200 feet cannot be distinguished on a lithologic basis from colluvial deposits north of 200 feet. The smaller and steeper fans in Corral Canyon have local relief of as much as 5 feet, and grade from steep slopes at their heads to low slopes, which merge inconspicuously with the flood-plain surface. In Corral Canyon the alluvial fan material consists chiefly of pebbles, cobbles, and boulders in a matrix of clay, silt, and fine- to coarse-grained sand.

The maximum thickness of alluvial fan deposits is no more than about 12 feet on the terrace east of Corral Canyon; the thickness of the deposits in Corral Canyon is unknown. A sample from the basal part of the alluvial fan deposits at the south end of trench B contains organic carbon with an age of about 9,430 years, assuming no contamination by carbon derived from contemporary plant rootlets or bedrock (see Age of Profile 1 under Soils and table 5, sample CW 116B).

Flood-plain deposits

Flood-plain deposits occur along Corral Canyon, where two levels of deposits are mapped as one unit. Patches of flood-plain deposits too small to indicate at the scale of the geologic map are present in gully A. Both levels of flood-plain deposits in Corral Canyon have relatively planar surfaces that slope downstream and slightly toward the creek. The flood-plain material grades downstream into smaller fragments. It consists of pebbles, cobbles, and boulders of volcanic rock, derived from areas north of the Malibu Coast fault, in a matrix of gravel and pebbly sand; near the plant site it contains considerable coarse-grained, friable, pebbly sand in lenses as much as 8 feet thick (unit Sd-3, fig. 8).

The thickness of the deposits ranges from less than 1 foot along the upper reaches of the canyon in the Corral Canyon site to about 20 feet in trench 3 (fig. 8). Shell material (probably midden) from flood-plain deposits about 10 feet below the ground surface in the plant site (locality A in unit Sd-3, fig. 8b) has a radiocarbon age of about 3,000 years (table 5); shell material (midden) from the surface of the flood-plain deposits about 230 feet north of the north boundary of the plant site has a radiocarbon age of 1,000 ± 250 years (determined by Meyer Rubin, U. S. Geological Survey).

Stream deposits

Stream deposits were mapped in the bottom of Corral Canyon; similar deposits too small to show at the scale of the geologic map are present along the other drainage channels in the Corral Canyon site. The deposits vary substantially in character between the upper part and the mouth of Corral Canyon. At the north boundary of the Corral Canyon site the stream deposits consist of subangular to subrounded cobbles and boulders as much as 5 feet in longest dimension in a matrix of sand. This coarse, bouldery gravel grades downstream into finer grained detritus, so that near the mouth of Corral Canyon the deposit consists of subrounded to rounded rock fragments generally less than 1 foot in diameter in a matrix of medium- to fine-grained sand.

The gravel is locally derived and consists chiefly of volcanic rock with some sandstone and siltstone. Sand and silt are derived largely from the local bedrock, and the larger boulders are derived from volcanic rocks of the Middle Topanga Formation exposed north of the Corral Canyon site. The stream deposits are about 18 feet thick at the mouth of Corral Canyon (boring 21, fig. 4); they are Recent in age, on the basis of their position in contemporary stream channels.

Beach deposits

Beach deposits along the coastline south of the Corral Canyon site consist of fine- to medium-grained sand, much of which reaches the beach by littoral drifting from the west (Trask, 1955), and by sediment discharge from local drainage basins; additional sand may be derived from shoreline erosion. The thickness of the deposits is about 6 feet at the mouth of Corral Canyon (boring 22, fig. 4).

Soils

Soils developed on surficial deposits in the Corral Canyon site provide an important tool for dating those deposits; they are particularly significant because they furnish restrictions on the age of some of the landslides and young faults in the site.

Soils develop near the ground surface in parent materials of various character, chiefly under the influence of climate, organisms, and topographic relief acting through some period of time (Jenny, 1941). In the general case the resulting soil profile consists of three basic horizons: an organic-rich A horizon at the top; a lighter-colored, structured, clay-rich B horizon; and a C horizon that consists of parent material that is oxidized and(or) enriched in calcium carbonate (see Buckman and Brady, 1960, for general discussion of soils). The degree of development of these profiles in particular parent materials is time-dependent, thus allowing estimates of age to be made from the character of the soil profiles (Richmond, 1962; Morrison, 1964).

Two main soil types present in the Corral Canyon area are Chernozem Great Soil Group, developed on fine-grained alluvial-colluvial material; and soils with well-developed textural-B horizons, formed on sand and gravel, that could be classified as Prairie Planosol Great Soil Group. These soils were studied by P. W. Birkeland in March and May, 1965, with emphasis on the soil (Profile 1 and correlations) critical to dating the young faults.

Chernozem Great Soil Group

A distinctive soil profile (Profile 1, table 1) has formed on the clayey alluvial fan and colluvial material (unit CF in the test trenches, figs. 10, 11, 12, 13, and 15) that buries the older deposits and underlies much of the gently sloping coastal terrace surface east of Corral Canyon. This soil is fairly typical of the Chernozem Great Soil Group, in which a thick surface unit rich in organic matter (A horizon) overlies a unit high in carbonates (C_{ca} horizon). Profile 1 is characterized by an A horizon nearly free of calcium carbonate, a C_{1ca} horizon that contains noticeable calcium carbonate in a network of fine rootlike veinlets (mycelium calcium carbonate), and a C_{2ca} horizon in which the calcium carbonate is not only more abundant, but is also segregated from the soil into soft powdery veins that coat the surfaces of the soil structural units (peds). No B horizon is recognized in Profile 1. In some cases the soil profile extends down through the whole thickness of the deposit (as much as 12 feet) to the top of the underlying unit. However, in two exposures (test trench E and gully C, where Profile 4 is equivalent to Profile 1), the base of the lower calcium carbonate-bearing (C_{2ca}) horizon is exposed and overlies a C_3 horizon that contains no or very little calcium carbonate, and is considered to be primary parent material.

Table 1.--Soil descriptions

Profile 1: Chernozem soil with a segregated calcium carbonate (C_{2ca}) developed in clay (soil textural term; see U.S. Dept. Agriculture, 1951, for soil terminology) with minor rock fragments (unit CF). Described at station 226 feet in trench B (fig. 11). See fig. 11 for thickness, and table 2 for calcium carbonate content.

(S1)[1] A horizon: Dark-gray (10 YR 4/1[2], dry) clay, granular structure free of calcium carbonate except for slight amounts locally.

(S2) C_{1ca} horizon: Dark-grayish-brown (10 YR 4/2, dry) clay, strong prismatic structure with prism diameters generally less than 1 inch, calcium carbonate common in fine rootlike veins (mycelium calcium carbonate) that cut across the structural units.

(S3) C_{2ca} horizon: Dark-grayish-brown (10 YR 4/2, dry) clay, strong prismatic structure with prism diameters 1 inch or more. Calcium carbonate in the upper 3 feet of this horizon is distributed in rootlike veins similar to but wider (0.5 to 1 mm) than those in the C_{1ca} horizon. Deeper in this horizon the calcium carbonate occurs in relatively thick powdery veins that coat the surfaces of the structural units. Segregation of the calcium carbonate is good; the interior of the structural units is nearly free of calcium carbonate. Calcium carbonate also forms rare soft nodules and coats the few pebbles present.

Profile 2: Chernozem soil with a mycelium calcium carbonate C_{2ca} horizon, similar and equivalent to Profile 1; grades laterally within 4 feet into typical Profile 1; C_{2ca} horizons have common base. Developed in clay with about 10 percent Monterey Shale fragments (unit CF). Described at station 94 feet in trench E (fig. 13).

(S1) A horizon: (0-21 in.) the typical A horizon of Profile 1.

(S2) C_{1ca} horizon: (21-67 in.) similar to the C_{1ca} horizon of Profile 1, with mycelium calcium carbonate. At 35 inches and below the material contains more rock fragments.

1/ S1, S2, etc. are keyed to soil horizons in trenches A, B, D, and E (figs. 10, 11, 12, and 13, respectively).

2/ Soil colors from Munsell Soil Color Charts: Munsell Color Company, Inc., Baltimore, Maryland; 1954 Edition.

(S12) C_{2ca} horizon: (67-96 in.) this does not resemble the segregated calcium carbonate C_{2ca} horizon of Profile 1, but is similar to the upper part of that horizon. The calcium carbonate here is mycelial throughout, with the veins up to 1 mm across; it is more abundant (about 10 percent) than in the C_{1ca} horizon above.

C_3 horizon: (96 in. +) grayish-brown (5 YR 3/2, moist) sandy clay with about 10 percent Monterey Shale fragments.

<u>Profile 3</u>: Chernozem soil with a mycelium calcium carbonate C_{2ca} horizon, developed in clay with about 10 percent Monterey Shale fragments (unit CF), overlying clay and oxidized profiles developed in sand (unit Sd). Described at station 52 feet at trench D (fig. 12).

(S1) A horizon: (0-28 in.) very dark brown (10 YR 2/2, moist) clay, granular structure, very friable to friable, no noticeable calcium carbonate, 2 to 3 percent angular Monterey Shale fragments.

(S2) C_{1ca} horizon: (28-51 in.) same color, consistence, percent fragments, and texture as A horizon, weak subangular blocky structure, thin veins of mycelium calcium carbonate, very similar to the C_{1ca} horizon of Profile 1.

(S12) C_{2ca} horizon: (51-91 in.) dark brown (10 YR 3/3, moist) clay, moderate angular blocky (less than 2 inches) structure, firm, about 10 percent angular Monterey Shale fragments, mycelium calcium carbonate throughout with veinlets commonly 1 mm across and some up to 2 mm across (similar in percent and distribution to mycelium calcium carbonate in top of the C_{2ca} horizon of Profile 1). No segregated calcium carbonate along faces as is seen in the lower part of the C_{2ca} horizon of Profile 1.

(S13) II A_b horizon: (91-101 in.) dark-yellowish-brown (10 YR 4/4, moist sandy loam, friable, massive, 3 to 5 percent angular Monterey Shale fragments up to 2 inches, some calcium carbonate throughout (1 to 2 percent?); mycelium calcium carbonate abundant in less than 5 percent of area, but almost as abundant as in overlying horizon; sharply defined boundary.

(S14) II B_b horizon: (101-115 in.) strong brown (7.5 YR 5/6, moist) light sandy loam (less clay than above), very few reddish brown (5 YR 4/4), incipient clay films, massive friable, slight amount of calcium carbonate in places (in part mycelial); this is a color B horizon with a gradational boundary.

(S15) To the north stations at 32-48 feet (fig. 12) the color B horizon is banded in a zone as much as 2 feet thick. The two kinds of bands are yellowish red (5 YR 4/6, moist) sandy loam with slight clay, friable to firm with some very firm, with a reddish coating on the grains; and light-yellowish-brown (10 YR 6/4, dry) very friable to loose, sandy loam or sand with less clay than the red bands. The red bands are ½ to 3 inches thick, the light bands ½ to 5 inches thick.

(S16) II C_b horizon: (115-137 in.) dark-yellowish-brown (10 YR 4/4, moist) light sandy loam or loamy sand (less clay than above), massive to single grain, very friable, less than 1 percent scattered Monterey Shale fragments; this is an oxidized sand, which about 10 feet to the northis essentially unweathered and loose.

(S17) III B_b horizon: This is equivalent to all of unit Sd in trench B. Dominantly reddish-brown (2.5 YR 4/4, moist) sandy loam (medium), with more clay than overlying horizon, sand grains bear a colloidal stain but no visible clay films or bridges, friable where moist, hard to very hard where dry. Contains about 20 percent gray (5 YR 5/2-4/2, moist) mottles, not evenly distributed, mainly concentrated near the north side of the bedrock high (at station 53 ft.). Steeply oriented calcium carbonate veins, rarely containing a gray montmorillonitic clay seam, extend into bedrock near 53 feet, and extend up to, but not into, the overlying horizon. In the area of gray mottles, the $CaCO_3$ veins are largely restricted to the interior of the mottles.

<u>Profile 4</u>: Chernozem soil with a segregated C_{2ca}, equivalent to Profile 1, developed in clay (unit CF). Described on the west side of gully C about 150 feet southwest of trench F.

A horizon: (0-24 in.) sandy clay to clay, dark near-surface horizon, free of calcium carbonate.

C_{1ca} horizon: (24-28) in.) dark-colored horizon, sandy clay to clay, mycelium calcium carbonate.

C_{2ca} horizon: (48-about 108 in.) similar to overlying horizon except calcium carbonate is more abundant and occurs in numerous soft veins.

C_3 horizon: (108 in. +) lighter in color than overlying horizons, sandy clay to clay, free of calcium carbonate, and contains salts.

Profile 5: Chernozem soil developed in clay (unit C2). Described at station 50 feet in trench A (fig. 10).

(S1) A horizon: similar to A horizon of Profile 1.

(S4) C_{1ca} horizon: similar to C_{1ca} horizon of Profile 1.

(S5) C_{2ca} horizon: similar to C_{2ca} horizon of Profile 1, but finely jointed.

Profile 6: Prairie soil with well-developed textural B horizon in sand of marine terrace D (shoreline angle at about 110 feet altitude) on Point Dume. Described in roadcut on Fernhill Drive south of small creek between road intersections for which altitudes of 125 and 115 are shown on the topographic base map (see fig. 5; locality is unmarked but is approximately 4,950 feet N. 26° E. from BM 203 on tip of Point Dume). This soil is quite similar to those developed in marine sedimants of the 100-foot terrace near Santa Cruz and Half Moon Bay, California

A horizon: (0-18 in.) dark brown, heavy sandy loam.

B horizon: (18-66 in.) yellowish-brown sandy clay; becomes lighter in texture and color with depth, not subdivided.

C horizon: (66 in. +) oxidized sand.

Profile 7: Prairie soil with well-developed textural B horizon in sand and gravel (unit G-2(; described at station 335 feet in trench A (fig. 10).

(S1) A horizon: similar to A horizon of Profile 1.

(S9) B_2 horizon: high percentage of clay in sand and gravel.

(S10) C_1 horizon: oxidized sand and gravel.

(S11) C_{2ca} horizon: calcium carbonate in oxidized sand and gravel

Profile 8: Chernozem soil developed in sandy clay (unit C-6); overlies Prairie soil developed in sand. Described between station 250 and 290 feet in trench A (fig. 10).

(S1) A horizon: similar to A horizon in Profile 1.

(S6) C_{ca} horizon: light- to dark-brown sandy clay with gray mottles, fine mycelium calcium carbonate throughout and increasing with depth.

(S7) II A_{ca} horizon: dark-gray sandy clay, blocky to prismatic fracture, calcium carbonate in veins and nodules, the calcium carbonate here and in horizon below was derived from the overlying soil.

(S8) B_{2ca} horizon: reddish-brown sandy clay, blocky fracture, fine veins of calcium carbonate.

Profile 9: A weakly-developed Prairie soil in silty sand (unit Sd-3, containing mussel shells with a radiocarbon age of about 2,950 years) of Corral Canyon flood plain. Described at about station 200 feet on the northwest slope of trench 3.

A_1 horizon: (0-14 in.) dark-yellowish-brown (10 YR 3/4, moist) sandy loam, granular structure, well-defined boundary.

A_3 horizon: (14-26 in.) sandy loam, massive, a mixture of this and underlying horizon with color from both (could be, in part, an AB horizon), gradational boundary.

B horizon: (26-36 in.) dark yellowish-brown (10 YR 4/4, moist) sandy loam, massive, (a minimal color B horizon, slightly redder than underlying horizon), gradational boundary.

C_{ox} horizon: (36-39 in.) dark yellowish-brown (10 YR 4/4, moist) sandy loam, massive (oxidized sand).

C_{ca} horizon: (39 in. +) same color and texture as above, but has a very few small veins of mycelium calcium carbonate (probably less than 1 percent).

Profile 1 was described in trench B; it is also well developed at the south end of trench E; there, however, it grades northward in a distance of less than 4 feet to a slightly different soil (Profile 2), in which the calcium carbonate, although probably as abundant as in the C_{2ca} horizon of Profile 1, occurs in a network of fine rootlike veinlets (mycelium carbonate) rather than in thick veins along ped (or soil structural unit) boundaries. The two soils have a common base, and the cause of the difference in character of the C_{2ca} horizon is not clear. The only known differences between the parent materials of the two soils are a greater content of Monterey Shale fragments (about 10 percent rather than 1 to 3 percent), and less organic carbon (dark brown rather than gray-black color) in the parent material of soil Profile 2.

The upper part of Profile 3 in trench D, developed in clayey colluvium with 2 to 10 percent Monterey Shale fragments is almost identical to Profile 2. The C_{2ca} horizon which contains mycelium calcium carbonate rather than strongly segregated calcium carbonate, is quite similar, and is developed in similar clayey material that contains about 10 percent Monterey Shale fragments. Thus, the upper part of Profile 3 in trench D can be correlated with Profile 1 of trench B by means of the two profiles in trench E, which clearly represent two slightly different responses to the same kind and duration of soil-forming processes.

The A and C_{1ca} horizons developed in unit CF over the depression in trench B (fig. 11, 115 to 125 feet) can be traced laterally into the A and C_{1ca} horizons of Profile 1 in the south end of the trench; they are equivalent to horizons A and C_{1ca} of Profile 3. The apparent absence of a C_{2ca} horizon over the depression may be due to the thinness of the colluvium there and to difficulty in recognizing it in units Sd and G-1, which contain numerous veins of calcium carbonate.

Profiles 5 and 8, in the upper part of trench A, are similar to Profiles 1 and 2, and are developed in similar clayey parent material.

Prairie-Planosol Great Soil Group

The Prairie soil formed in the marine sands of terrace D on Point Dume (Profile 6) is typical of the unburied soils of the "100-foot" Sangamon(?) (fig. 53) terrace of coastal California (e.g., Half Moon Bay and Santa Cruz, California; see description of Watsonville soil, Wagner and Nelson, 1961). The primary features of the Point Dume soil are a thick A horizon, a clay-rich B horizon, and oxidation that extends well below the B horizon. This soil has probably required most of post-Sangamon time to form, some 100,000 years (fig. 53). Soils of similar development, but redder in color, are present in marine sand and gravel of terrace C in gully C, in stream terrace deposits at the south end of trench A (Profiles 7 and 8 in unit G-2, fig. 10), and in probable stream terrace deposits at the southwest corner of the coastal terrace just east of the mouth of Corral Canyon. These soils probably required a period of formation similar to that of Profile 6 (most of Sangamon time) prior to their burial by the clayey colluvial and alluvial material.

Two intervals of soil formation separated by an unconformity are probably represented in the sand of units Sd and Sd_1 that are buried by unit CF in trench D (fig. 12). The lower part of this profile (Profile 3, horizon III B_b) probably represents a weakly developed textural B horizon formed in fine-grained sand of unit Sd. The time required for the development of a profile with such a B horizon is uncertain, but the red color suggests that more than Recent time (approximately 10,000 years) was required. The A horizon that originally overlay this B horizon is missing; erosion prior to deposition of the overlying sand (unit Sd_1) is further indicated by calcium carbonate veins that extend upward to, but not into unit Sd_1. This younger sand bears an A horizon made up of material from the sand and the overlying unit (CF), a color B horizon, and an essentially unweathered C horizon (Profile 3, table 1). The B horizon grades laterally northward to a banded zone that consists of interbedded B and C horizon materials. If this banding is of pedologic origin, as it may well be, then more intense weathering is indicated than for that of the young soil in Corral Canyon (Profile 9) and it therefore required several thousand years to form prior to burial by unit CF.

Trench 3 provides exposure of a much younger soil (Profile 9) developed in silty, fine-grained sand of theCorral Canyon flood plain. Soil formation here has been restricted to development of an A horizon, oxidation of the sand, and formation of a minimal color B horizon (barely distinguishable to the eye) and of a minimal C_{ca} horizon. Mussel shells collected from the sand have a preliminary carbon-14 age of $2{,}950 \pm 300$ years BP (Before Present), which provides a maximum age for the soil.

Age of Profile 1

The age of the soil of Profile 1 (the time required for formation of the soil) is restricted by the age of the deposit in which it is formed, unit CF, and can be estimated by considering the rate of translocation of calcium carbonate downward through the soil.

Age of parent material.--The parent material of the soil is the sandy clay of unit CF, which was deposited by colluvial and alluvial processes on a complex surface underlain by bedrock, fluvial sand and gravel (unit G-3, trench E, fig. 13), and sediments of terrace C (units Sdm, G-1, Sd, and Sd_1, trenches B, C, and D, fig. 12). The unit may not everywhere be the same age. However, with local exceptions, there are no great lateral variations in the character of the deposit, and no natural boundaries within the deposit that could provide evidence of significant differences in age of the unit in different places. The maximum age of unit CF is restricted by the age of the well-developed soils formed in sand and gravel that it overlies. The time required for development of these latter soils (Profile 7, Profile 8, the soil formed in marine sediment of terrace C in gully C, and that formed in probable stream terrace sediment just east of the mouth of Corral Canyon), prior to their burial by unit CF, was probably most of post-Sangamon time (some 100,000 years).

The parent materials of the soils underlying unit CF are:

(1) marine sediments of terrace C, which is somewhat older than about 120,000 years;

(2) stream terrace deposits that (a) overlie bedrock at about altitude 137 feet, (b) probably were deposited by a stream graded to some part of terrace C or D, and (c) are therefore

probably some 120,000 years old, perhaps older; and

(3) sand and gravel that overlies bedrock at altitude 80 feet east of the mouth of Corral Canyon and is either (a) a stream terrace deposit associated with terrace D or (b) possibly a marine deposit of terrace D and (c) is in either case some 100,000 years old.

As these parent materials are in part and perhaps entirely Sangamon in age and a period equivalent to most of post-Sangamon time was required to form the soils in them prior to their burial, deposition of unit CF probably could have begun no earlier that late Wisconsin (fig. 53). Colluvial-alluvial deposits that overlie the soil developed in the sand and gravel just east of the mouth of Corral Canyon may not be as old as at other localities, for the soil formed therein is less well developed.

Organic carbon is present throughout much of unit CF and provides a basis for determining the age of the unit by means of radiocarbon dating. Organic carbon from two samples from the C_{2ca} horizon of Profile 1 in trench B (CW 116B and CW 117, fig. 11), which horizon probably contains several percent carbon (5 percent loss by ignition in CW 116B), was dated radiometrically. Preliminary determinations on the samples yield ages of 4,210 ± 300 years for sample CW 117 from the top of the C_{2ca} horizon, and 9,430 ± 400 years for sample CW 116B from the bottom of that horizon (table 5). The carbon in the deposit could have been derived from the sediment source area by erosion of soil, or in the depositional area by incorporation into the alluvial fan of organic carbon from vegetation growing on the fan. In either case fairly slow deposition would be required: lack of evidence for rapid erosion of bedrock (which would result in beds or lenses of bedrock fragments), also implies slow deposition. Downward movement of humic acid from the A horizon could also add carbon to the lower horizons, but treatment of sample CW 117 with sodium hydroxide revealed no humic acid. Monterey Shale, which underlies part of the probable source area of the deposit, may contain some carbon when fresh (Bramlette, 1946, p. 49, shows minor carbon in samples of Monterey Shale from other areas). However, carbon seems to have been oxidized and removed from the Monterey Shale in the Corral Canyon area, even from material well below the ground surface, leaving the rock white rather than black (the color of fresh Monterey Shale); this rock is therefore probably not a significant source of carbon. Rootlets of plants growing on the fan surface undoubtedly can add some zero-age carbon to the sediment, even to depths of 8 or 10 feet (such rootlets were observed in the exposures), but the samples were carefully treated to remove any rootlets present (large amount removed from CW 117; none were seen during treatment of CW 116B).

The radiocarbon age of unit CF is not greatly affected by contamination of the material with either zero-age carbon (from contemporary plant rootlets) or "infinite"-age carbon (as from Monterey Shale), even in amounts as great as 5 or 10 percent of the total carbon present (see table 5, contamination curves). The radiocarbon ages of unit CF thus appear reasonable within limits of perhaps ± 1,000 years. Deposition of the alluvial-colluvial material probably began some time in the late

Wisconsin and before some 8,000 to 10,000 years ago, and continued until after some 3,000 to 5,000 years ago.

Minimum time for translocation of calcium carbonate.--The age of soil Profile 1 can also be examined by a method proposed by Arkley (1963), in which a minimum age for a carbonate soil profile is based on the rate of carbonate translocation downward in the soil. The original distribution of carbonate in the parent material is estimated and compared with the present distribution in the soil profile to determine the amount of carbonate moved during soil formation. The rate of downward movement of water in the soil is approximated from climate data and the water-holding capacity of the soil; the solubility of the carbonate in this water is approximated using soil pH and surface temperature. The amount of carbonate moved, divided by the product of rate of water movement and solubility of carbonate, yields minimum time necessary for translocation. Because several of the parameters cannot be accurately determined, reasonable values (most resulting in minimum ages) are selected for some, and a range of values is considered for others.

If the calicum carbonate now present in the soil were evenly distributed through the soil, a concentration of 7.9 percent calcium carbonate would result. This can be considered the original homogeneous content of the deposit, although the original calcium carbonate content may have been less: one soil sample over bedrock north of trench B, in the general area from which sediment of the alluvial fan (unit CF) probably was derived, contains only 4.9 percent calcium carbonate (sample from Corral Canyon site, grid location N125,760, E066,360, fig. 4). If this value approximates the original concentration of calcium carbonate in the deposit, the rest could have been supplied by release of calcium from calcium-bearing silicates by weathering during soil formation. Assuming an original concentration of 7.9 percent, the amount of calcium carbonate added to the C_{2ca} horizon during soil formation is 9.6 gm/cm^2. (This refers to a column 1 cm square, extending the height of the soil horizon, see table 2.)

The amount of water that enters the C_{2ca} horizon from above each year is dependent on the precipitation, surface runoff, evapo-transpiration, and the available water-holding capacity of the soil above the C_{2ca} horizon. Average annual precipitation at the mouth of Corral Canyon is closely approximated by the 14.4 inches of the 25-year record at Oxnard (Dale, 1959); an isohyetal map of the Santa Monica Mountains, based on an 85-year record, but without a recording station at Corral Canyon, shows an average annual precipitation of 16 inches at the canyon mouth (Los Angeles County Flood Control District, Biennial Report on Hydrologic Data for 1957, Map III).

Very little is known about the details of the climate during Recent time in the Santa Monica Mountains coastal area. Evidence from the inland mountains and deserts of southern California indicates that Recent climates there have been both hotter and dryer and cooler and wetter than at present (Birman, 1964; Flint, 1957; Flint and Brandtner, 1961). In addition, there is some evidence of a general trend toward aridity in the southwestern United States during Pleistocene and Recent time (Hubbs, 1957, 1961). It is not known whether these various changes were accompanied by similar changes at Corral Canyon. To gain some local control on Recent climate, pollen from four positions in the 10-foot thick section of unit CF at the type locality of soil Profile 1 (226 feet in trench B) was examined by E. B. Leopold of the U. S. Geological Survey (see Appendix D). This analysis indicates that during the period of accumulation of the alluvial-colluvial material (unit CF) the pollen supplied to the area remained very constant in composition; of particular significance is the extreme scarcity of tree pollen (pine and cupressus). The surface (modern) pollen assemblage (surface sample, D 3898-D) is very similar to those of the deeper samples, and indicates a quite similar climate (including precipitation). The presence of about 8 percent tree pollen in the surface sample probably is of modern, local horticultural origin, although a slight increase of rainfall or change in wind pattern could also be the cause of this increase.

A fairly constant rate of precipitation is indicated by this preliminary pollen analysis for the period of deposition of the colluvial and alluvial material at Corral Canyon (Recent time). It is therefore reasonable to conclude that the average annual precipitation during the period of soil formation at Corral Canyon was similar to that of modern times; present precipitation may actually represent a slight increase. If the precipitation was lower during the time of soil formation, as possibly suggested by the pollen analysis, the value for present precipitation would be somewhat high, so that the calculations for the time required for translocation of calcium carbonate would represent minimum values (table 3).

Table 2.--Physical and chemical properties of soil Profile 1

Horizon (depth in inches)[1]	A (0-24 in.)	C_{1ca}(24-42 in.)	C_{2ca}(42-120 in.)
pH[2]	7.5	8.0	8.2
Bulk density (gm/cm^3)	1.42	[3] 1.51	1.72
Percent moisture content			
at minus 1/3 atm.	30.4	23.4	22.3
at minus 15 atm.	20.7	13.4	12.8
Available water-holding capacity			
(percent)	9.7	10.0	9.5
(in./horizon)	3.3	2.7	12.6
Present $CaCO_3$			
Soil weight (gm/cm^2)	85.5	68.5	336.5
Percent $CaCO_3$[4]	0.8	2.6	10.7
$CaCO_3$ weight (gm/cm^2)	0.7	1.8	36.0
Original $CaCO_3$			
Percent $CaCO_3$	7.9	7.9	7.9
Weight $CaCO_3$ (gm/cm^2)	6.7	5.4	26.4
Change in $CaCO_3$ (gm/cm^2)	-6.0	-3.6	+9.6

Laboratory analyses by G. Sposito, Department of Soils and Plant Nutrition, University of California, Berkeley.

1/ Sample localities: A - trench B at 122 feet; C_{1ca} - trench B at 122 feet; C_{2ca} - trench B at 223 feet.

2/ pH determined by glass electrode with water contact at the sticky point (see Jackson, 1958, p. 48).

3/ Bulk density for the A horizon considered representative. Five percent and 10 percent were subtracted from the original values of 1.59 and 1.91 for the C_{1ca} and C_{2ca}, respectively, to correct for voids due to soil structure.

4/ $CaCO_3$ identified by X-ray diffraction. Equipment difficulties yielded minimal values for sic duplicate samples of C_{2ca}; 10.7 percent is the most representative value.

In order to account for evapo-transpiration, a water balance was calculated on a monthly basis for the present climate (using data for Oxnard, which has a climate comparable to that at the mouth of Corral Canyon). Average monthly precipitation during the period May through October has never exceeded 0.4 inches (table 4). Because this is only a small proportion of the available water-holding capacity of the A horizon (table 2), and because potential evapo-transpiration is at its highest during this period (table 4), this summer dry season precipitation has no effect on translocation of calcium carbonate into the C_{2ca} horizon. According to the water balance calculations (table 4), the total quantity of water in the soil (storage) never exceeds the available water-holding capacity of the A and C_{1ca} horizons, so that no water reaches the C_{2ca} horizon to transport the calcium carbonate into it despite the water balance calculations; for this reason and in order that some provision for evapo-transpiration exceeded precipitation (table 4, April and November).

Two different values for the amount of water entering the soil are used in the translocation calculations (table 3): 14.4 inches, representing the present winter climate with no allowance for winter evapo-transpiration; and 12.2 inches, representing the present climate with some allowance for winter evapo-transpiration. In each case the water is considered to wet the A and C_{1ca} horizons once (available water-holding capacity of 6 inches), with the remainder entering the C_{2ca} horizon. No correction is here made for surface runoff, or for between-storms drying, which would require rewetting of the upper horizons before water could again move down into the C_{2ca} horizon.

Table 3.--Calculation of soil age from translocation of $CaCO_3$

	Cases, assuming different precipitations and pH[1/]					
	1	2	3	4	5	6
Change in $CaCO_3$ (gm/cm^2)	9.6	9.6	9.6	9.6	9.6	9.6
Precipitation (in./yr.)	14.4	12.2	14.4	14.4	12.2	12.2
AWC[2/] above C_{2ca} horizon	6.0	6.0	6.0	6.0	6.0	6.0
Water entering C_{2ca} horizon (in./yr.)	8.4	6.2	8.4	8.4	6.2	6.2
Water entering C_{2ca} horizon (cm/yr.)	21.3	15.8	21.3	21.3	15.8	15.8
pH	7.5	7.5	8.0	8.2	8.0	8.2
Solubility ($gm/cm^3 \times 10^{-4}$)	1.7	1.7	0.8	0.7	0.8	0.7
Age in years	2,650	3,570	5,650	6,440	7,600	8,700

1/ Case 1: Total winter precipitation 14.4 in., pH 7.5

2: Precipitation 12.2 in. (Dec. through March, see table 4), pH 7.5

3: Precipitation 14.4 in., pH 8.0

4: Precipitation 14.4 in., pH 8.2

5: Precipitation 12.2 in., pH 8.0

6: Precipitation 12.2 in., pH 8.2

2/ AWC: Available water-holding capacity

The solubility of calcium carbonate in the percolating water is dependent on temperature and pH. Limiting values of solubility (table 3) can be taken from the curves presented by Arkley (1963, p. 245) by using an approximate average temperature of 60°F (Stevenson, 1959, p. 18) and the pH of material from each of the soil horizons.

Based on the assumptions outlined above, the values obtained for the minimum time required for carbonate concentration in the C_{2ca} horizon range from 2,650 to 8,700 years (table 3) assuming present precipitation; assuming twice the present precipitation, comparable times would be 1,325 to 4,350 years. The most reasonable set of values for controlling factors pH of 8.0, representing that of the C_{1ca} horizon; solubility of 0.8×10^{-4} gm/cm^3 (temperature of 60°F), and a precipitation of 12.2 inches, which includes some provision for evapo-transpiration during the winter rainy season. The best estimate of the minimum time necessary for translocation of the calcium carbonate (the actual time must be greater) is thus 7,600 years (case 5, table 3). Considering the minimum character of this value, this is in good agreement with the 8 to 10 thousand-year radiocarbon age for the base of the parent material of the soil.

Table 5.--Radiocarbon dates from Corral Canyon site[1/]

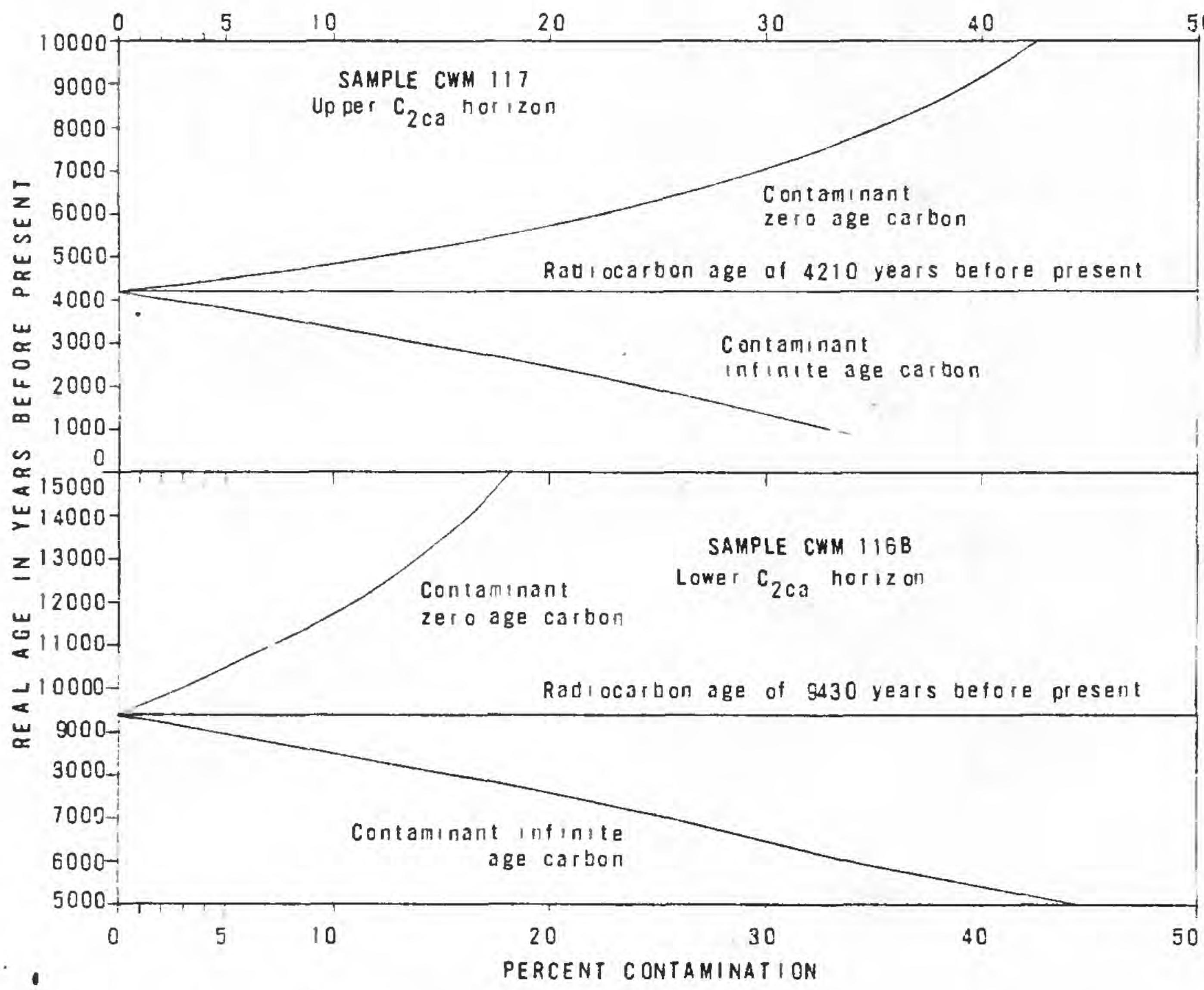
Lab. no.	Field no.	Sample and locality	Age (Years)
W1634	CW 126	Shells of *Mytilus californianus* and *Septifer bifurcatus* from silty sand (unit Sd-3), trench 3 (loc. A, fig. 8b)	2,950 ± 300
W1635	CW 128	Carbon from clay along slip surface, 80 feet, northwest wall of trench 3	[2/]2,280 ± 500
W1637	CW 117	Organic carbon in clay from top of C_{2ca} soil horizon, Profile 1, trench B (fig. 11)	[3/]4,210 ± 300
W1645	CW 116B	Organic carbon in clay from bottom of the C_{2ca} soil horizon, Profile 1, trench B (fig. 11)	[3/]9,430 ± 400

[1/]Preliminary ages and errors. Analyses by Meyer Rubin, U.S. Geol. Survey

[2/]Sample was too small and the error therefore large; carbon was diluted 2:1 with "dead" carbon.

[3/]Preparation of sample involved acidifying with hot HCl to remove carbonate, repeated mixing and decanting to remove rootlets (many in CW 117, none seen in CW 116B), followed by burning of the dry bulk sample in oxygen to extract all the carbon.

The real age of material may differ from radiocarbon age if contaminated by rootlets (zero-age carbon) or by dead carbon (infinite age) from Monterey Shale, as shown below.



Effect on real age of soil samples by contamination with zero- and infinite-age carbon. Based on Olson, [illegible], fig. [illegible].

Structure

The Corral Canyon site is within the Malibu Coast zone and is bisected the east-trending Malibu Coast fault. This fault and several chiefly north-dipping, dip-slip faults to the south separate the bedrock into east-trending bands 300 to 1,200 feet wide. North of the Malibu Coast fault the bedrock is asymmetrically folded and probably faulted, whereas south of it the bedrock is considerably faulted and locally prevasively sheared, as well as folded.

Faults

The Malibu Coast fault juxtaposes different stratigraphic sections and is inferred to be the surface expression of a crustal-block boundary fault that separates quite different basement rocks (see Regional geologic setting). In the Corral Canyon site, as elsewhere, the fault is very poorly exposed. However, in artificial exposures in Malibu Canyon, $2\frac{1}{4}$ miles east of Corral Canyon (fig. 5), the fault itself is a 25- to 75-foot-wide zone of very thoroughly sheared and brecciated rock. In the Corral Canyon site the fault trace is somewhat sinuous and dips northward between 45° and 80°. Relative displacement across the fault is inferred from structural and stratigraphic evidence to be chiefly dip slip with the north block upthrown.

Several other east-trending faults[1] (including those identified

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[1] For the purposes of this report a fault is defined as a surface or zone of discontinuity of tectonic origin along which permanent relative displacement has occurred; such displacement may range from inches to thousands of feet. This definition specifically excludes slip surfaces of landslide origin; landslides are superficial features of limited extent related to topography and are due to failure of unsupported material under its own weight.

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as faults A, E, And F) traverse parts of the Corral Canyon site south of the Malibu Coast fault (fig. 4): one (fault E) that bounds unit B on the south and is truncated by the Malibu Coast fault in Corral Canyon, and one (fault A) that bounds the main mass of Monterey Shale on the south, as well as shorter segments of faults exposed near the Pacific Coast Highway (fig. 4). These faults have north dips similar to the Malibu Coast fault (fig. 39). They juxtapose recognizably different stratigraphic units (of formational rank at a scale of 1:6,000) and they can therefore be traced for hundreds or thousands of feet, even in areas of poor exposure. That such contacts are faults can be determined by their interruption, reversal, or repetition of the normal stratigraphic sequence, truncation of local structure such as bedding, and rare exposures of sheared and brecciated rock that mark the faults themselves. These and most other faults in this area are subparallel to bedding in the adjacent rocks, so that determination of slip or even separation across the faults is commonly impossible. In the several cases where the normal stratigraphic sequence is not clearly reversed or repeated (as in the case of faults A and F), the amount of displacement or separation across the fault can be judged only qualitatively by the length of the fault and the thickness of shearing and brecciation that marks its trace. The shearing and brecciation along such faults is commonly several feet thick and the displacement is inferred to be on the order of the length of the faults, probably tens to hundreds of feet. The sense of displacement across faults in this area cannot be determined by correlation of recognizable points or lines across them, as such controls are commonly not exposed on both sides of the faults. However, the geometry of small-scale faults within the larger fault blocks indicates that movement has been chiefly dip slip, north side up (see Structure of plant site).

Folds

The Upper Topanga Formation in the Corral Canyon site appears to be folded throughout. Excellent exposures on Corral Canyon Road exhibit abundant medium-sized folds and most of the other exposures in the site also show folded rock. Determination of stratigraphic tops of beds (original upward direction) from sedimentary structures, and observation of small- and medium-sized folds in outcrop, indicate that the wave length and probably the amplitude of the folds range from several inches to more than a hundred feet; these dimensions are commonly several feet to some tens of feet. The folds vary greatly in shape as well as in size; they are commonly tight, overturned, asymmetric, and similar. The axial parts of many of the folds are cut by small faults that are subparallel to the axial surfaces of the folds. The fold axes plunge gently and the axial surfaces commonly dip northward, subparallel to the Malibu Coast fault.

Folds in the more deformed bedrock south of the Malibu Coast fault are more difficult to trace, because many of them are truncated by small-scale faults and broken up by pervasive shearing. As indicated by reversals in stratigraphic tops, the folding in unit B north of fault E is on a scale of 100 feet in wave length and amplitude. In the deformed Monterey Shale north of fault A folding is on a scale of several feet to tens of feet; in the pervasively sheared unit B south of fault A folding is on a scale ranging from inches to perhaps a hundred feet or so. The axes of almost all these folds are subparallel to the Malibu Coast fault and their axial surfaces dip northward subparallel to that fault.

Structure of the plant site

Bedrock in the plant site area was essentially unexposed until about 1,600 feet of test trench were opened there in January 1964 (fig. 7, test trench 1 and 2 on the east wall of the canyon, west wall trench, and the filled trench in the canyon bottom). Trenches 1 and 2 on the east wall of Corral Canyon exposed deformed unit B beneath surficial deposits for most of their length; the west wall trench also exposed bedrock for much of its length. The filled trench on the flood plain exposed alluvial deposits and the underlying bedrock, which was reportedly similar to that

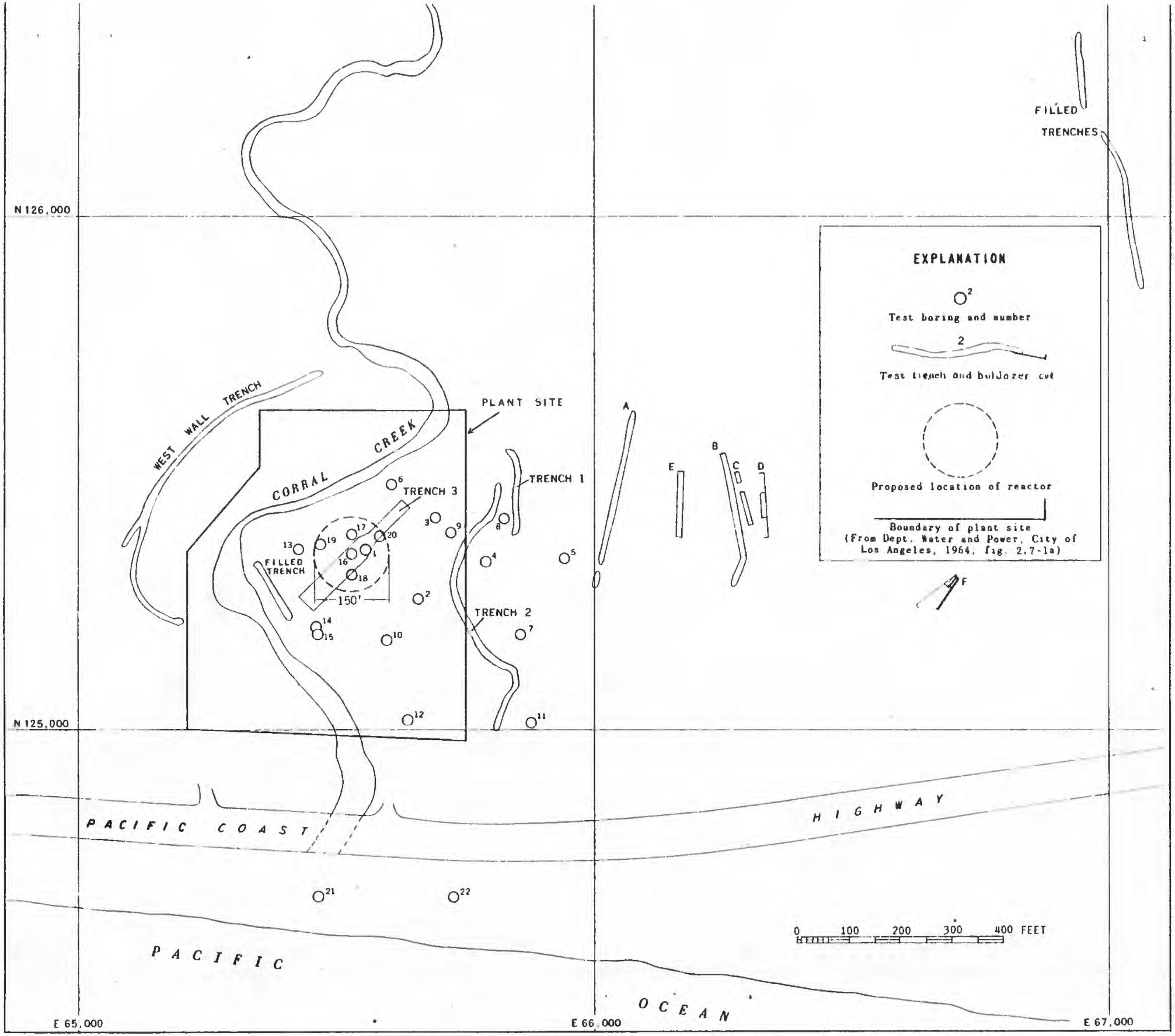

FIG. 7. MAP SHOWING PLANT SITE, PROPOSED LOCATION OF REACTOR, AND LOCATIONS OF TEST TRENCHES AND BORINGS

in the nearby creek exposure; this trench was not examined by the authors. About 615 feet of trench (trenches A and B, fig. 7) were opened on the terrace surface east of the plant site in November 1964; trench B, in addition to exposing deformed unit B rocks, also exposed bedrock faults associated with fault A, as well as marine disrupted terrace deposits. About 270 feet of trench, opened in April 1965, exposed flood-plain deposits and the underlying bedrock in the reactor location (trench 3, fig. 7). An additional 500 feet of trench were cut on the terrace surface east of the plant site (trenches C, D, E, and F, fig. 7) in April and May 1965; these exposed disrupted marine terrace deposits, unsuspected stream terrace deposits, and marine terrace deposits displaced by either a fault or a major landslide near the mouth of gully C. All of these test trenches provide excellent exposures of the bedrock and surficial deposits in and near the plant site; detailed maps were made of trenches 1, 2, 3, A, B, C, D, E, and F (figs. 8 through 15).

Bedrock of the plant site consists almost entirely of mudstone and interbedded sandstone. Almost all of the mudstone is broken by very closely spaced, anastomosing shear surfaces; the sandstone occurs partly as thin, persistent beds, but most of it occurs as shear-bounded fragments, pods, and blocks that are separated by sheared mudstone. Folds of various sizes are indicated by their observed axial areas and by reversals in the direction of tops of beds as indicated by sedimentary structures. The axes of most of the folds are gently plunging and trend subparallel to the Malibu Coast fault. Several small-scale faults, defined by zones of relatively closely spaced continuous shear surfaces, are exposed in the trenches. One such, fault F , has been traced across Corral Canyon through the reactor location (fig. 4). Most of the faults, shears, and axial surfaces of folds dip northward and trend eastward, subparallel to the Malibu Coast fault.

Shearing of mudstone.--The mudstone of unit B throughout the plant site area is characterized by anastomosing shear surfaces that pervade the mudstone and bound fragments, pods, and blocks of sandstone of various sizes (fig. 16); exposures are in cuts west of the mouth of Solstice Canyon, in the test trenches and numerous cores from test borings in and near the plant site, in the trenches east of the plant site, and at the mouth of gully A.

On the scale of a hand specimen (fig. 17), the shear surfaces generally form 1 to 3 sets that intersect at a low angle, and thus define rhomboid, lens-shaped, or somewhat irregularly shaped fragments. The surfaces are smooth and shiny, in contrast to the dull, fine-hackly fracture surfaces of unsheared rock. The persistence and spacing of the shear surfaces vary considerably. Gently curved surfaces 6 to 10 inches long are common and define lensoid fragments 3 to 10 inches long in the black plastic mudstone of unit m-6 (trench 3, fig. 8). Shears $\frac{1}{4}$ to 4 inches long are more common in the plant site area; much of the rock south of fault F is characterized by very short, closely spaced shears as much as $\frac{1}{2}$ inch long that define very small, densely packed fragments.

Fig. 16.--Sheared mudstone containing segmented sandstone beds; contact with thick block of sandstone is sheared. Shear surfaces, bedding, and long dimensions of sandstone segments dip steeply northward (right). Unit B exposed in test trench on the west wall of Corral Canyon near the plant site.

Fig. 17.--Sheared unit B mudstone containing small pods and irregular fragments of sandstone. Slick and striated shear surface at center and bottom center. Sample from test trench 2, east wall of Corral Canyon.

At magnifications of 10X to 20X the shear surfaces on samples from the trenches and from below sea level in borings 11 and 12 are distinctly shiny and range from planar to gently or sharply curved. Some of the surfaces are smooth; however, most of them bear ridges and grooves ranging in size from extremely small striations through those 1/100 to 1/10 mm in height and width, to larger discontinuous ridges and grooves up to 2mm in width (fig. 18). These linear structures are subparallel on any one surface, and different sets are generally oriented within about 30° of each other throughout a single sample. In some cases ridges that bear smaller striations maintain constant shape in cross section for the entire length of their exposure on a sample.

Many of the shear surfaces are quite evident in thin section;[1/]

[1/]Ten thin sections of unit B mudstone were examined: 4 samples of black mudstone (unit m-6 from station 126 feet in trench 3); 1 sample of olive-gray foraminiferal mudstone (unit m-7, near station 125 feet in trench 3); 2 samples from the contact between units m-6 and m-7 (station 125 feet in trench 3); 1 sample of "pinkish"-brown mudstone (unit m-5, near south end of trench 2); and 2 samples of black mudstone from borings: one from no. 9 at 11 feet below sea level, and one from no. 11 at 24 feet below sea level.

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they are variably marked by discontinuities in rock fabric and lithology, alinement of clay crystals parallel to the shears, truncation of formini-feral tests, and drag of rock fabric. In thin section many of the shears

Fig. 18.--Photomicrograph of well-developed striations on shear surface, fragment of unit B mudstone, from south end of the test trench 2, east wall of Corral Canyon.

are open cracks because of drying of the clayey rock during sample preparation, although some are still tight. Some of the shear surfaces extend across the width of the section as nearly straight lines, others are gently curved, and many intersect, branch, anastomose, and feather (figs. 19, 22d). The clay crystals along many of the shear surfaces are alined parallel to the surfaces (fig. 19), as indicated by mass extinction under crossed nicols. Such orientation of the clay is almost certainly the cause of the shine seen on the shear surfaces in hand specimen (fig. 17). Many of the shears are parallel or subparallel to the rock fabric (most probably a depositional fabric), whereas others cross and truncate the fabric at high angles (figs. 20, 21b, and 22d). Locally the fabric is dragged or folded against such truncating shears (figs. 20 and 21b).

Foraminifera are well preserved in much of the mudstone exposed in the south half of trench 3; in mudstone of unit m-7, which consists of about 5 percent foraminiferal tests, most of the tests are undeformed (figs. 21c, 22a). However, where shear surfaces intersect them, the tests are truncated (figs. 21a, 21d), and near the sheared contact between units m-6 and m-7 in trench 3 the tests are variably truncated, crushed, elongated, recrystallized, and comminuted (figs. 22b, 22c).

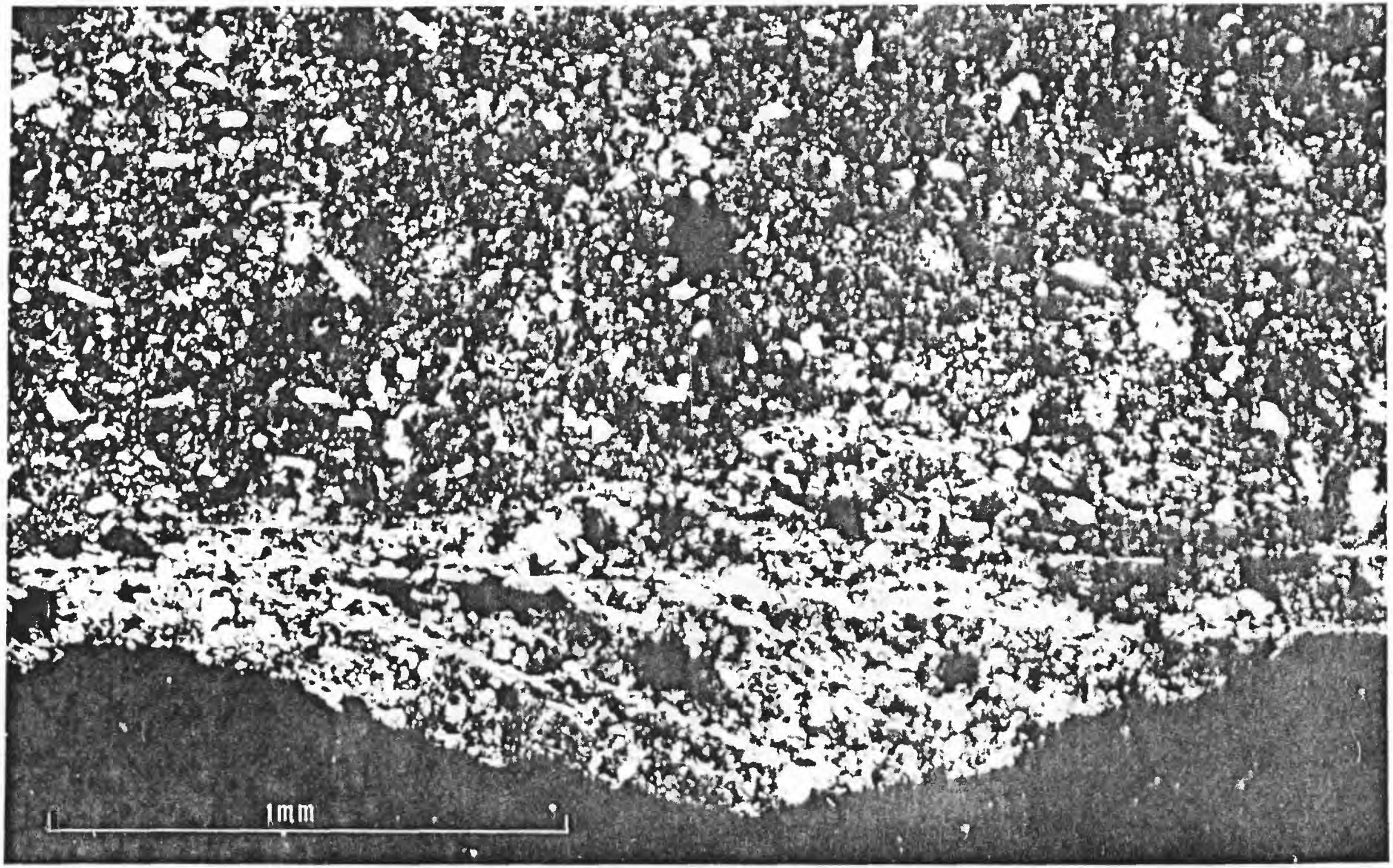


Fig. 19.--Photomicrograph of thin section showing shear surfaces with oriented clays, crossed nicols; unit B mudstone. The major shear surface, which bounds a mudstone fragment, crosses the lower part of the section; a weaker shear surface parallels the bounding surface within the body of the fragment. Several shear surfaces branch into the small piece of mudstone adhering to the larger one. Sample from south end of test trench 2, east wall of Corral Canyon.

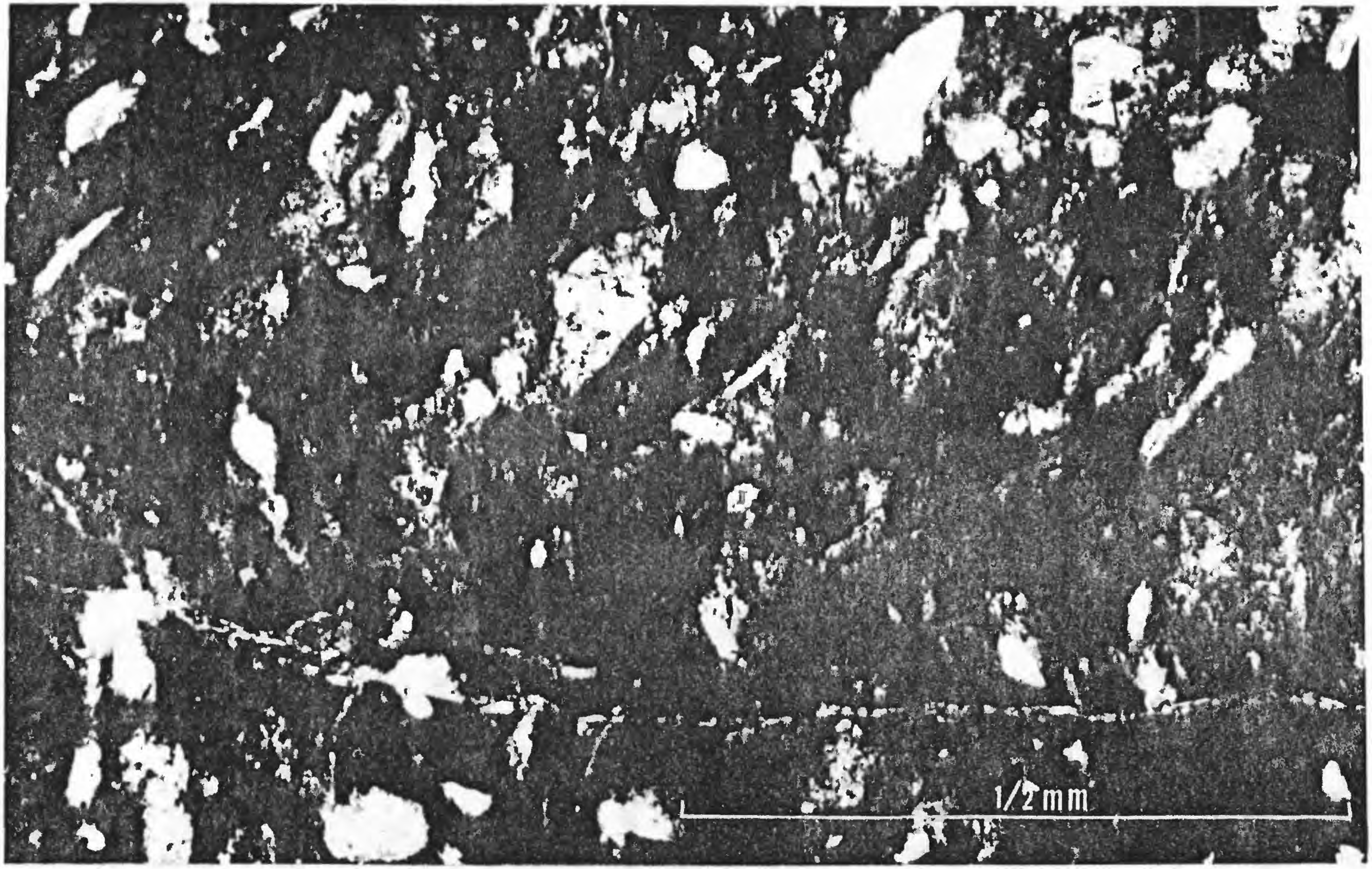


Fig. 20.--Photomicrograph of thin section showing truncated and dragged laminations on a shear surface in unit B mudstone, plane polarized light. Shear surface is bright line trending left to right near bottom of picture. Laminations trend down from upper right toward lower left, then bend toward lower right against shear surface. Sample from altitude minus 24 feet in boring 11, east wall of Corral Canyon.

The shear surfaces in bedrock exposed in trenches 1 and 2 (fig. 9) were carefully examined, and the orientations of the more persistent shear surfaces and well-developed sets of shear surfaces were measured at 37 stations distributed along the trenches (1 to 4 measurements per station). An orientation diagram (see explanation under Structural analysis) of poles to these shear surfaces (fig. 23) demonstrates a dominant, steep, north-northeast dip of the surfaces, plus some scattered very gentle and south dips. Inspection of other exposures in and near the plant site indicates that shear surfaces throughout that area (except in the toe of the landslide north of station 75 feet in trench 3) are similarly oriented. The gently dipping and south-dipping shear surfaces (of fig. 23) all occur south of station 250 in trench 2. These may well represent shear surfaces that have been folded and in places truncated by later shearing, as suggested by the shear surfaces between stations 520 and 550 that contain folds with northeast-dipping axial surfaces (figs. 9 and 24), and a folded sandstone bed and adjacent shear surfaces in the west wall trench (fig. 25). Nearly horizontal shear surfaces are also truncated by a northward-dipping shear surface in trench 2 (fig. 24).

Figure 21.--Sheared foraminiferal mudstone, unit m-7, at about station 125 feet, southeast wall, trench 3; photomicrographs (crossed nicols, X40) of thin sections (sample CW 138).

Figure 21a.--A complete section of a foraminifer (Bolivina sp.) is juxtaposed along shear "A" with another, truncated section of <u>Bolivina</u>; these may represent different sections of the same individual. Both tests are truncated by shear "B" such that the lower 1/4 of the more complete individual is missing. Long axes of tests parallel to dominant fabric of rock.

Figure 21b.--Shears "A" and "B" truncate rock fabric and lithology. Note drag at "C" in material between shears "A" and "B". End(?) view of *Bolivina* sp. with undeformed(?) flat side against shear "D".

Figure 21c.--Well preserved, undeformed Foraminifera: *Uvigerina* sp. at left, and *Bolivina* sp. at right.

Figure 21d.--Well-preserved *Bolivina* sp. truncated by shear "A" at apertural end. Long axis of test is parallel to the dominant fabric of the rock.

FIG 21

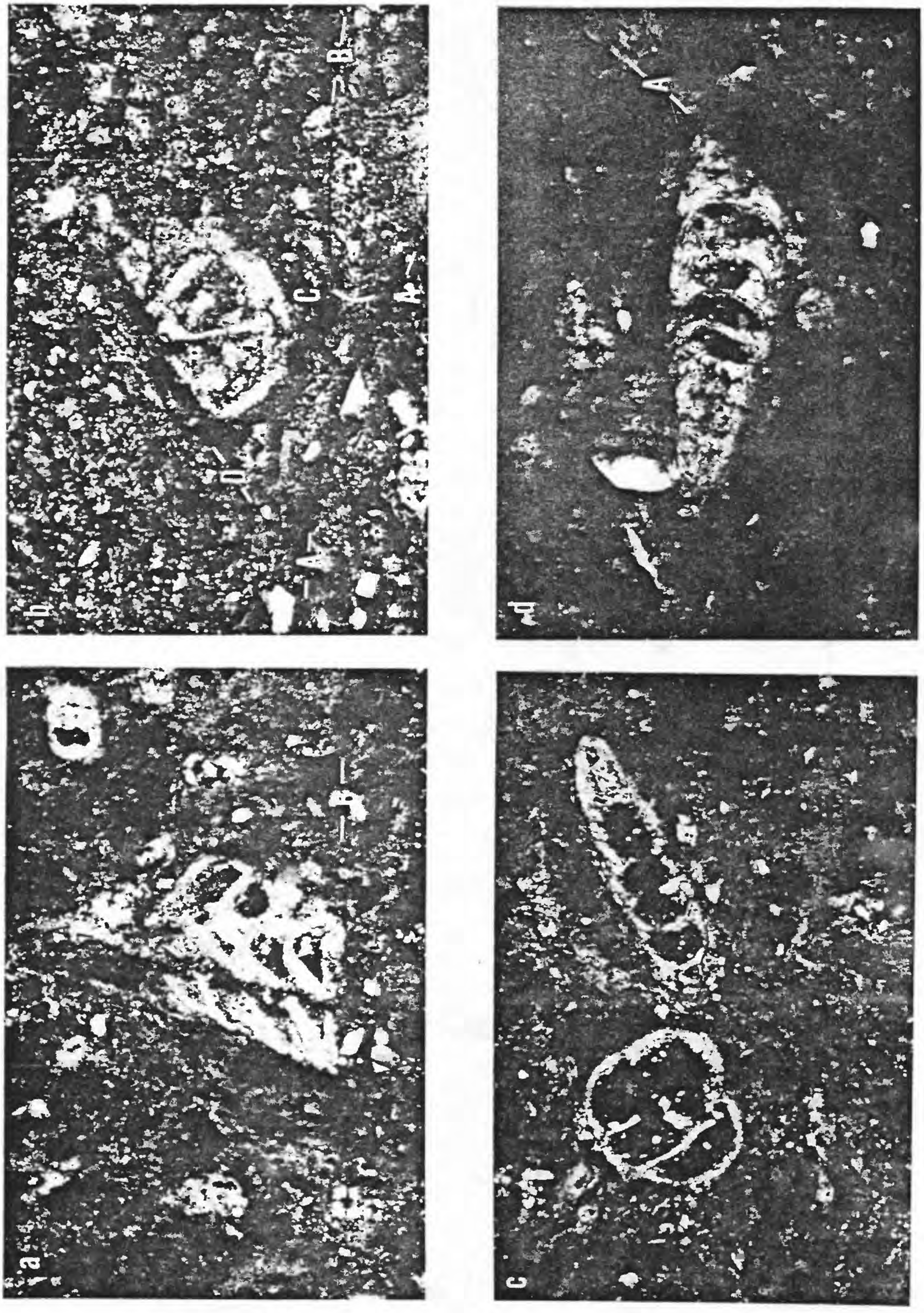


Figure 21

Figure 22.--Fig. 22a, sample CW 138 (as in fig. 21); figs. 22b, c, and d, sheared foraminiferal mudstone of unit m-7 at contact with unit m-6, station 127 feet on southeast wall, trench 3. Photomicrographs (crossed nicols, X40) of thin sections (sample CW 131).

Figure 22a.--Foraminifer (Nonion sp.), undeformed except for recrystallization and/or crushing at upper right edge.

Figure 22b.--Crushed and elongated foraminiferal test, probably truncated by shear "A"; another crushed test above shear "B".

Figure 22c.--Foraminiferal test is recrystallized, and truncated by shear "A". Light-colored areas marked "F" are other foraminiferal tests or fragments of tests.

Figure 22d.--Rock fabric and lithology are truncated by subparallel shears "A", "B" and "C".

FIG 22

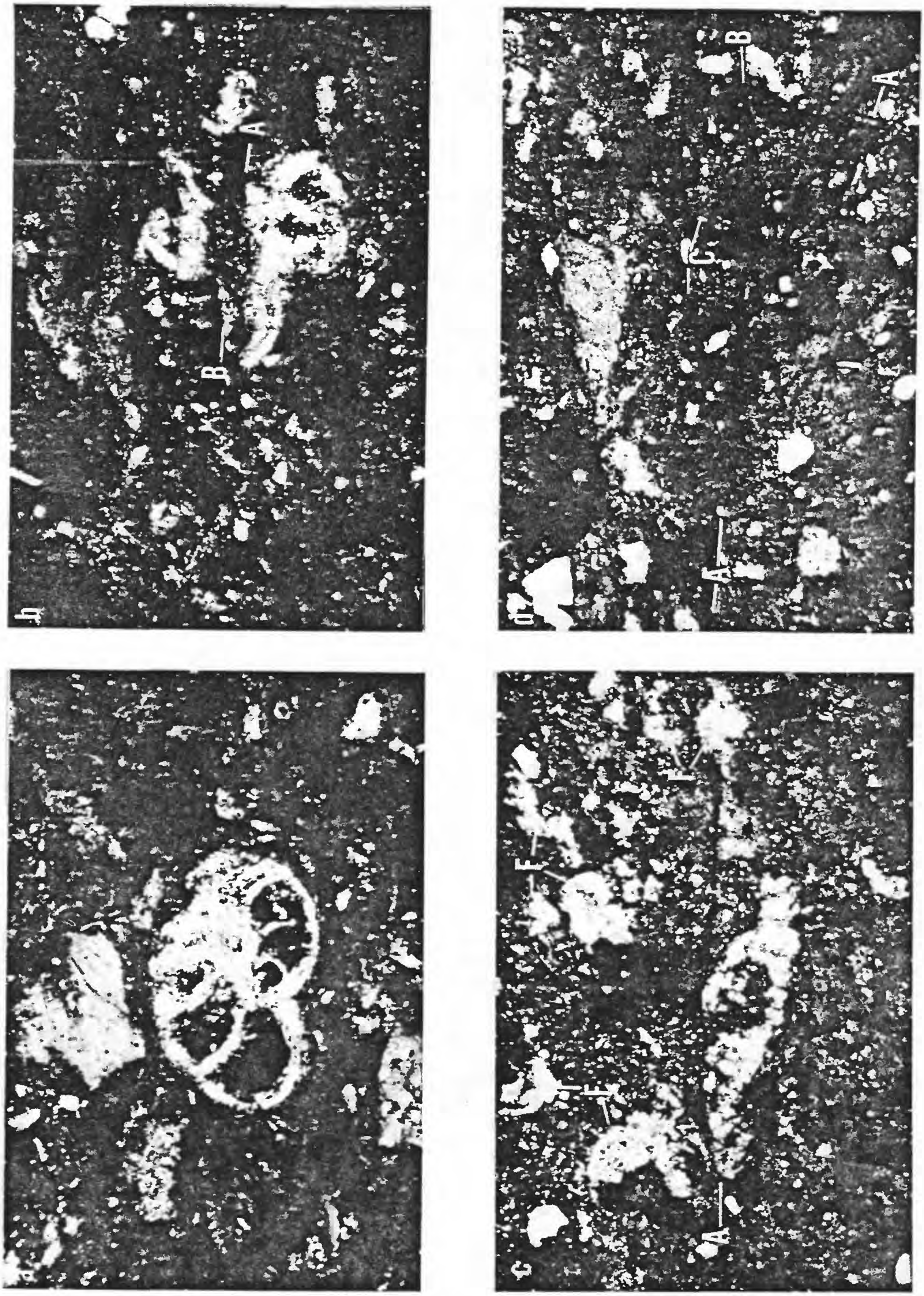


Figure 22

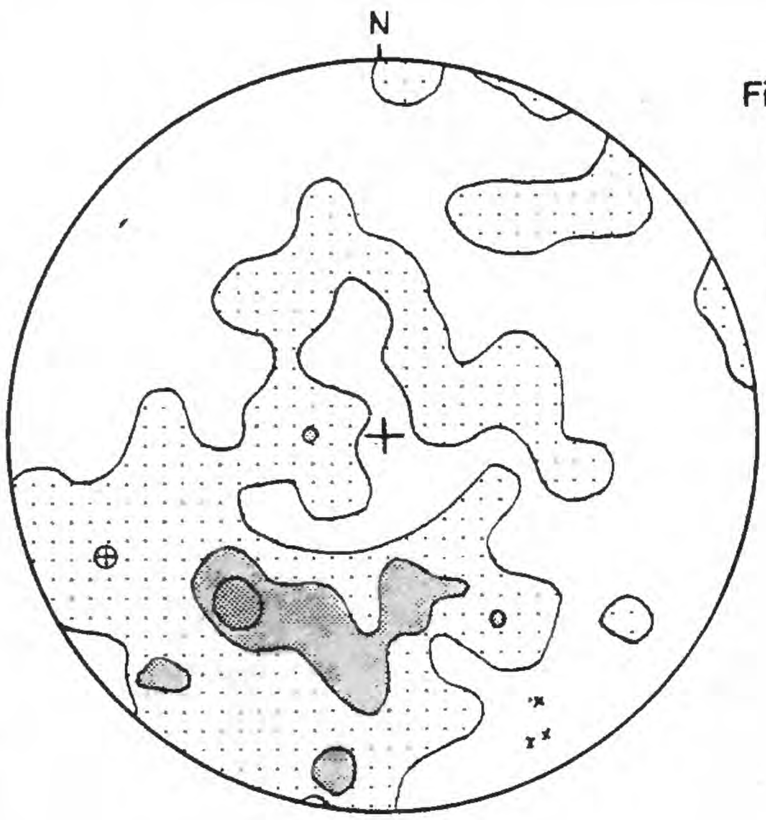


Fig. 23. Upper and lower test trenches, east wall, Corral Canyon: orientation diagram of 74 poles to shear surfaces, showing predominantly north to northeast dips.

Contours 8 %, 4 %, 0 % per 1 % area

x Axes of small folds in shear surfaces, between survey stations 1 and 2

⊕ Pole to axial surface of folds

Fig. 24.--Folded and locally shear-truncated shear surfaces in unit B mudstone near the plant site. Approximate form of a few of the folds in the shear surfaces shown by dashed lines. Traces of axial surfaces of the folds shown by dot-dash lines. Nearly horizontal shears are truncated by steeply dipping shear (solid line) at lower left. North is to left. Exposed near the south end of test trench 2, east wall of Corral Canyon.

Fig. 25.--Tightly folded thin sandstone bed and folded shears in unit B mudstone, south end of west-wall test trench; north to right. The light-colored sandstone bed is graded and cross-laminated and defines the fold: the upright upper limb is marked A-B, the tight axial area B-C, the overturned central limb (C-D) is repeated between E and F, and the upright lower limb is marked F-G. Note that fractures in the sandstone are everywhere approximately normal to bedding and that shears in adjoining mudstone parallel the fold, especially between E, F, and G.

Pods of sandstone and silt stone.--Fine- to coarse-grained, friable to hard sandstone is present in much of the sheared mudstone of the plant site area, but not as continuous beds of reasonably constant thickness. Rather, the sandstone occurs as discrete fragments, lenses, pods, and blocks less than an inch to more than 10 feet in length. These fragments were derived from sandstone beds that were 1/2 inch to at least 6 feet thick.

North of fault F (fig. 4) the pods are generally greater than 6 inches long, and are elongate parallel to their bedding, which is indicated within some of the pods by textural variations in the sandstone and by vary rare, undisturbed, thin mudstone interbeds. Bedding and apparent long and intermediate axes of the pods are parallel to each other and to other structures of the Malibu Coast zone: approximately east-west strikes and moderate to steep north dips. One prominent exception to this orientation is the bedrock in the toe of the landslide exposed north of station 75 feet in trench 3 (figs. 8a, 8b), which appears to have been considerably rotated about a near-vertical axis during movement of the landslide, thus changing the gross orientation of the structural elements. The sandstone pods commonly occur in the sheared mudstone either as isolated bodies (figs. 8 to 11, 16 and 17) or as adjacent but discrete bodies separated by thin seams of sheared mudstone (figs. 10,11, 35).

In cross section the sandstone pods range in shape from lensoidal, ellipsoidal and similar elongate, rounded forms (figs. 9, 11, 16, 30) to diamonds and other elongate, somewhat smoothed polygons (figs. 8a, 9 to 11, and 35). The vertical sections of sandstone pods that are commonly exposed in the north- or northeast-trending trenches are so shaped as are the few horizontal sections exposed on the floor of trench 3. The sandstone pods are bounded by shear surfaces that are regular and smooth to somewhat irregular in form; in some cases the bounding shear surfaces are displaced along surfaces that extend into the sandstone pods as fractures (for example, fig. 8a, station 53 feet). Curled sandstone bodies are present only in the axial areas of a few folds that have at least partially complete limbs (as in fig. 33); the only known exceptions are a small structure near the south end of the west-wall trench, illustrated by Hoffman and Smith (1965, fig. 8), and possibly an unusual feature in a thin sandstone bed near station 185 feet on the northwest face of trench 3, south of fault F (fig. 26).

In trenches 1, 2, and 3 (figs. 8 and 9), and especially in trench B (fig. 11), the sandstone pods shown as (unit sd-1) occur in zones separated by intervals of sheared mudstone with only minor sandstone. This suggests that the original distribution of sequences of sandstone beds with minor interbedded mudstone, relative to mudstone sequences with only minor sandstone, has controlled the present distribution of the sandstone pods.

Many of the sandstone pods are devoid of perceptible discrete internal fractures, but others contain a prominent set of fractures that is commonly normal to bedding and long dimensions of the pods (especially well developed in unit msd, fig. 8a); some of the fractures are stained by iron oxide. In a number of cases movement on these fractures has displaced the boundaries of the pods as much as 6 inches (fig. 35; pod at stations 12, 9 to 15 feet, trench 3, fig. 8a); in other cases movement has displaced

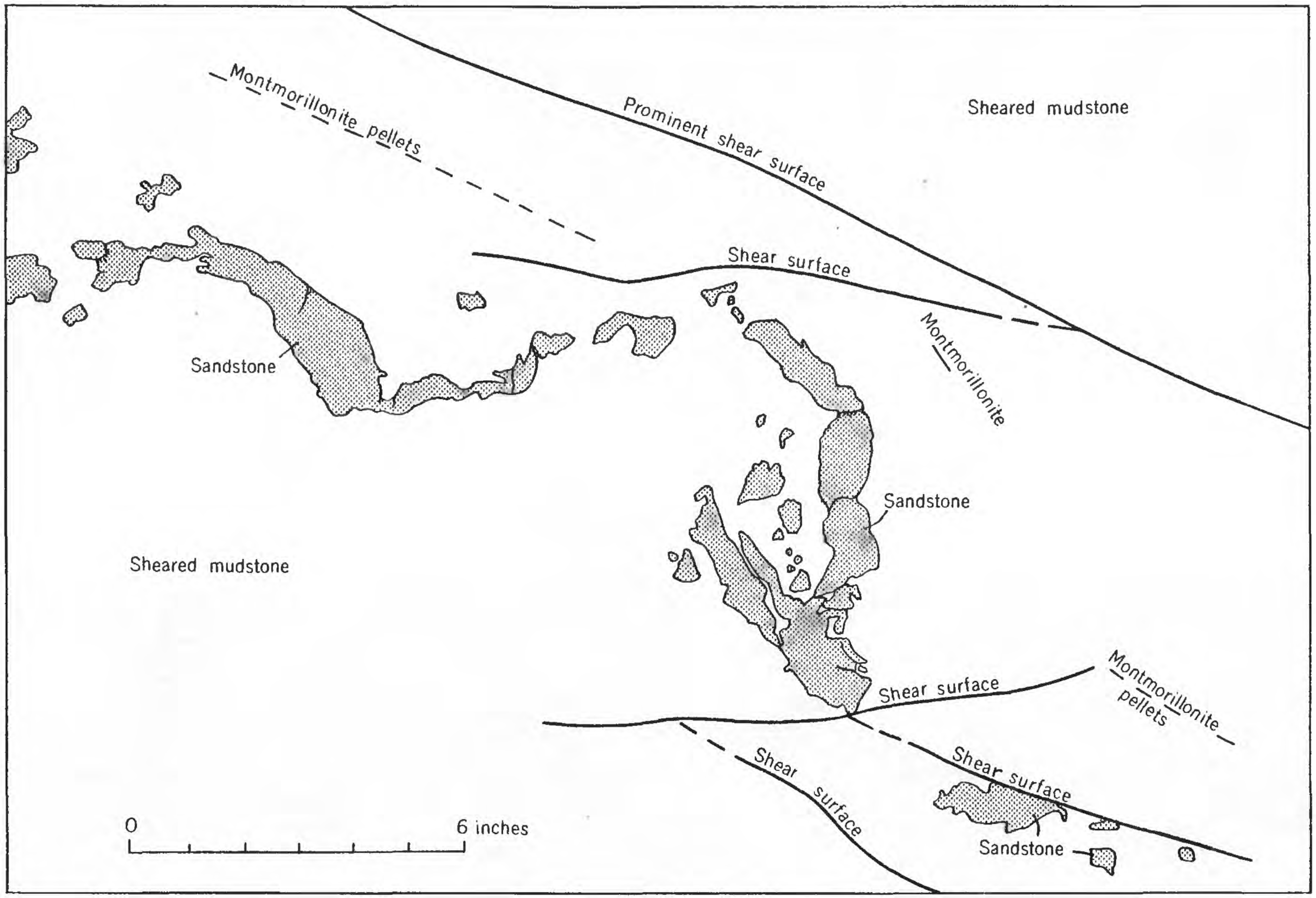


Fig. 26--Unusual "fold" in segmented thin sandstone bed in sheared mudstone of unit m-8 at 125 feet, northwest face of trench 3 (fig. 8e). This feature is not solely the result of bending around a fold axis and may actually be the result of disruption and repetition of the bed by shearing. Only the most prominent shears are shown; some of these, such as the upper one, are marked by thin seams of black sheared mudstone (this shear is also shown on fig. 8e). A band of pale greenish-yellow montmorillonite pellets is about 3 inches above the sandstone bed to the left and right of the "fold". Drawing traced from photograph.

the boundaries of mudstone fragments within the sandstone pods. In a unique exposure on the floor of trench 3 at station 25 feet a large sandstone pod is thinned at a zone of fractures (fig. 27); the fractures are normal to the length of the pod, are more abundant in the area of thinning, and many are stained by iron oxide. Outside the zones of abundant mudstone pods (as in unit sd-3, south end of trench 2, fig. 9) joints in the sandstone beds are normal to bedding.

Rounded pods of hard dolomitic(?) siltstone (unit st-1) are present in some of the unit B mudstone, especially near station 215 feet in trench 2 (fig. 9) and northeast of station 35 feet in trench 3 (fig. 8a). The hard siltstone pods, in contrast to the sandstone, are commonly broken by several sets of closely spaced fractures, so that they consist of masses of angular, approximately rectilinear fragments 1/4 to 3 inches long, which in most cases have not been greatly displaced relative to each other. In two cases (trench 2 at station 217 feet, fig. 9; and trench 3 at station 20 feet, figs. 8a and 28) a fracture normal to the long axis of a hard siltstone pod is intruded by the sheared mudstone that surrounds the pod. No certain examples of mudstone intrusion into sandstone have been observed. In one place a tongue of mudstone extends into a large sandstone pod (fig. 16), but this feature could have either formed by intrusion of mudstone into a fracture in the sandstone, or it may represent a flame structure formed during deposition.

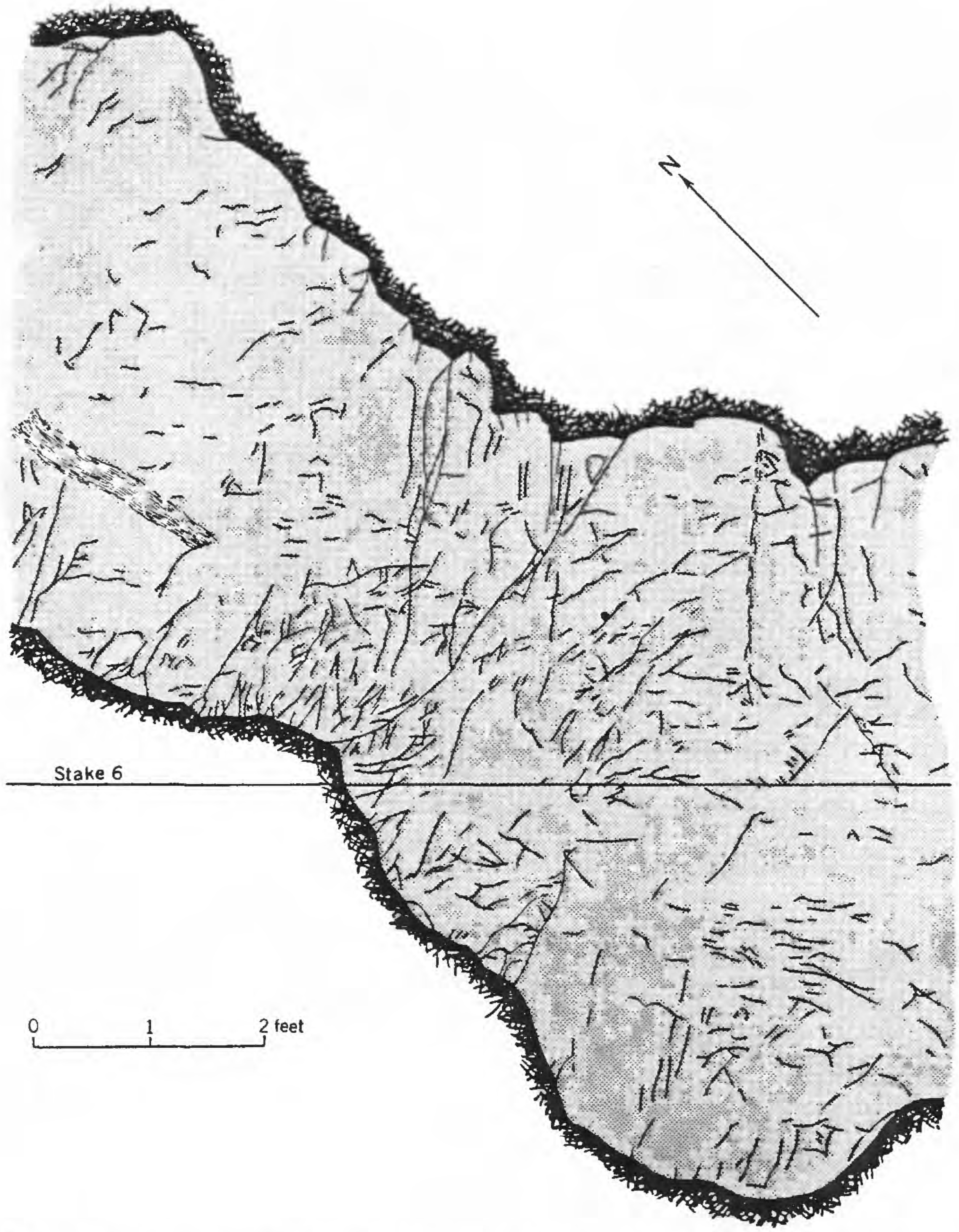


Fig. 27. Association of fractures and thinning in large sandstone pod exposed at 25 feet (stake 6) in the floor of trench 3. Fractures of the dominant set, approximately perpendicular to the boundaries of the pod, are abundant near the thinned central part of the exposed pod, but not elsewhere; they are sharply defined, are fairly persistent, and some are stained with iron oxide. The other main set, formed during excavation of the trench, is perpendicular to the length of the trench and consists of short, less well-defined breaks that are not stained and do not seem to penetrate deeply into the sandstone. Note the mudstone inclusion in the sandstone at left. Tracing from photograph after examination in the field. Contact between sandstone (dotted) and surrounding mudstone is approximately located because of tool smear.

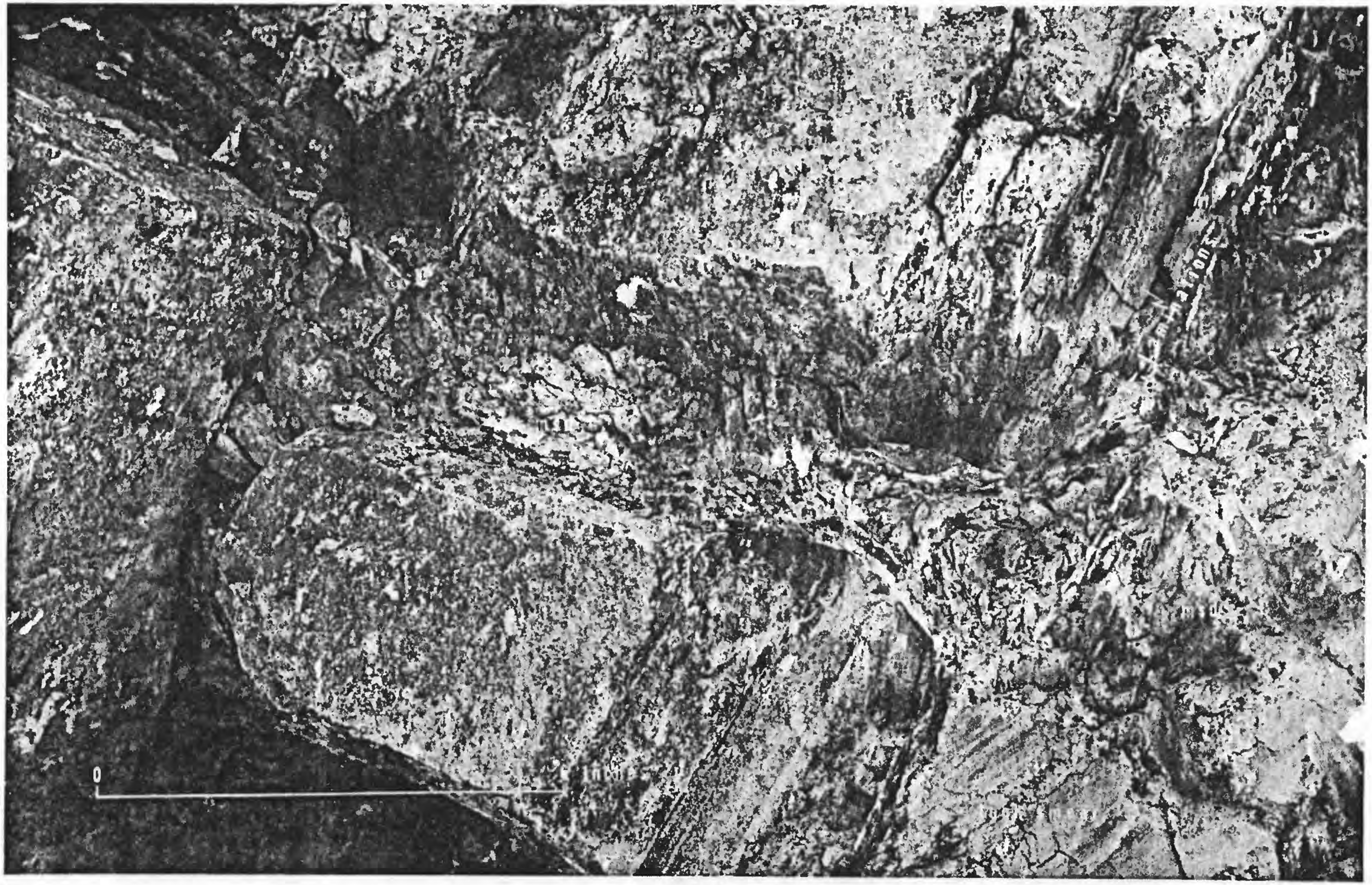


Fig. 28.--Rectilinearily-jointed dolomitic(?) siltstone concretion (st-1) at about 20 feet on southeast face of trench 3 (fig. 8a). Fracture is about 8 inches long and is intruded by sheared mudstone (unit msd). Note laminations at margin of concretion and fold in shears near base of intrusion. Mudstone at lower right is smeared by excavation tool.

South of fault F the large sandstone pods are generally absent. Instead, the finely sheared mudstone there contains fairly persistent, though perceptibly disrupted, thin sandstone beds (fig. 29) and some pods of tuff (fig. 8a). Unit m-6, exposed in trench 3, consists of plastic (when wet) black mudstone pervaded with persistent, closely spaced, gently curved shear surfaces, and contains abundant sandstone pods and fragments 1/16 to 10 inches long. The pods are somewhat elongate parallel to their bedding, and their long axes are commonly, though not entirely, parallel to each other and to the regional structure; both overturned and upright bedding is present. Many of these pods and patches of sandstone have rounded shapes, but close examination of their boundaries demonstrates that they are shear surfaces. In addition, one such pod (fig. 30), with an otherwise rounded shape, bears a partially detached segment. Where a pod of distinctive lithology occurred in unit m-6, no other pods of similar lithology were exposed within 3 or 4 feet. Close examination revealed numerous cases in which the pod boundaries were displaced along surfaces that extended into the surrounding mudstone as shear surfaces and into the sandstone as fractures. A few small, pale white pellets of "tuff" about 1/4 to 1 inch long are scattered through unit m-6 through other units exposed in trench 3 south of station 130 feet. Some of these pellets are coherent, whereas others are disrupted and strung out as trains of small, irregularly shaped pieces (fig. 32 shows a disrupted pellet).

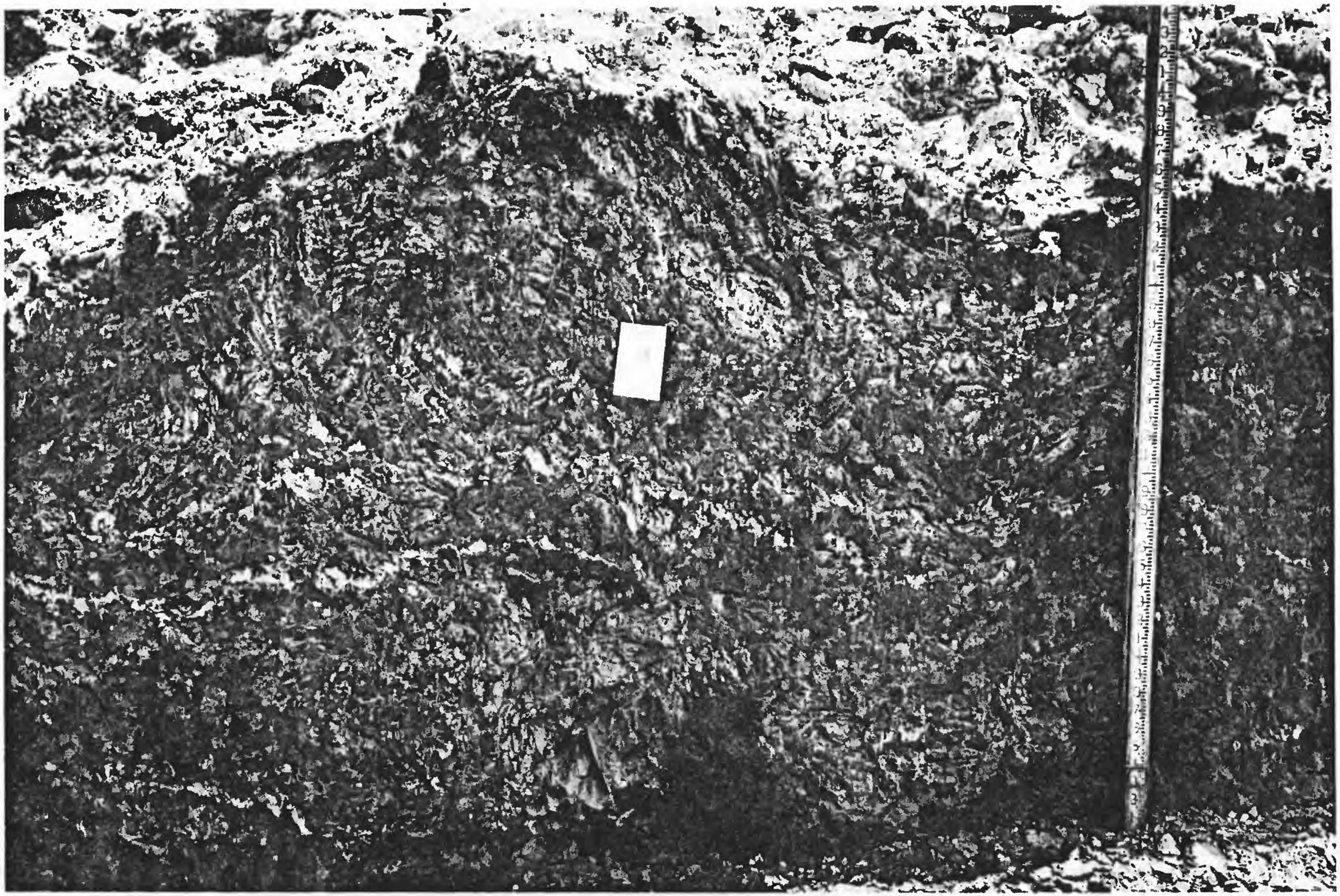


Fig. 29.--Disrupted thin sandstone beds in sheared mudstone, unit m-9 at 220 feet (stake 45) on southeast face of trench 3 (fig. 8a). Note that bedding defined by sandstone is folded to vertical to the right of rod (vertical bedding shown at 222 feet, fig. 8a). Rod scale in feet, tenths, and hundredths; thin linear marks were made by pick.

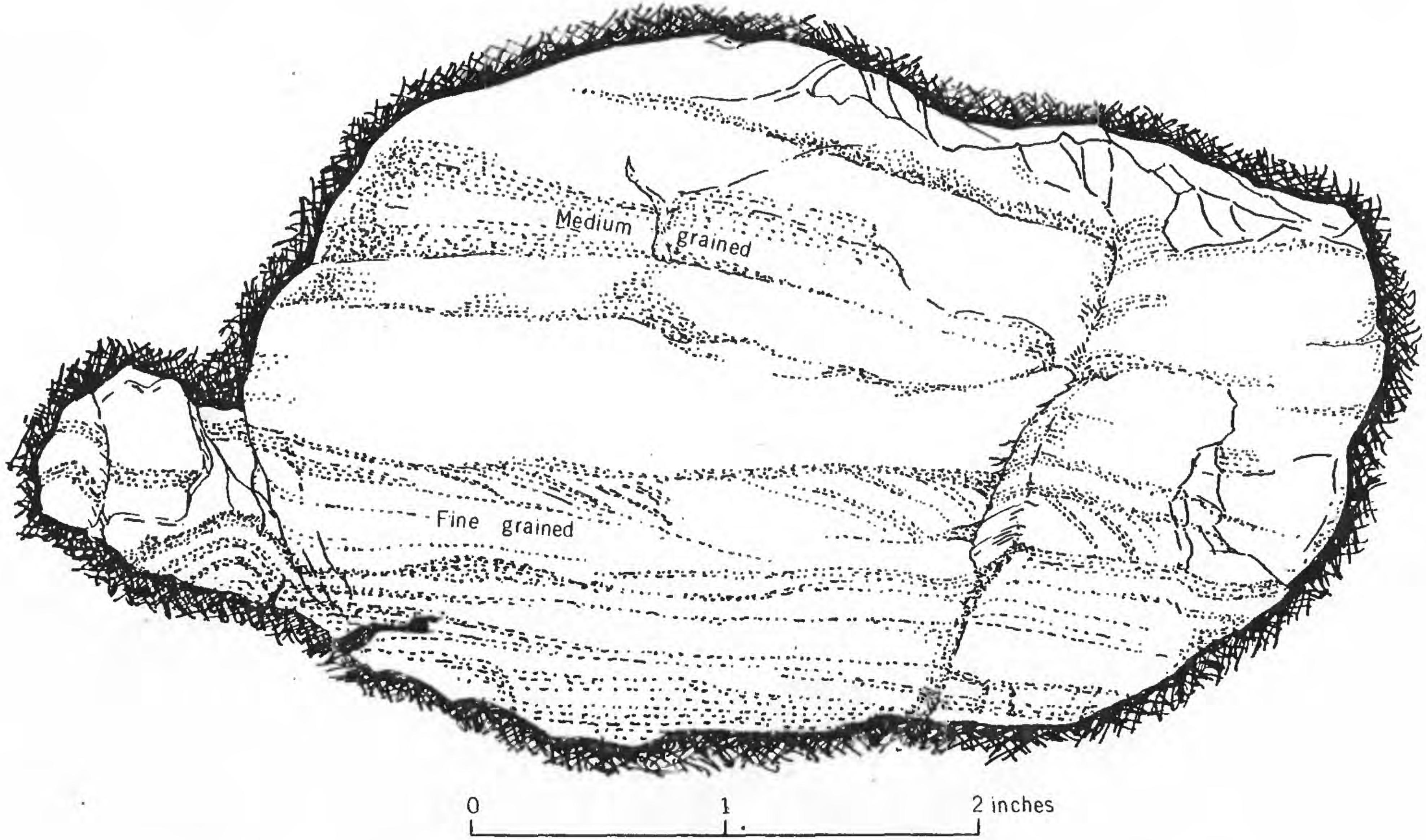


Fig. 30. Sandstone pod with subrounded shape defined by sheared boundaries; cross lamination and grading indicate that pod is overturned; partially detached segment at lower left has small fold and numerous fractures; one persistent fracture at right is normal to bedding. Pod is enclosed by sheared mudstone of unit m-6 at about 130 feet on northwest face of trench 3. Drawing from photograph.

Most of the bedrock in the plant site south of fault F contains no large sandstone pods and, therefore, probably contained no thick sandstone beds before deformation. Some of the fresh rock exposed in trench 3 south of the fault, although closely sheared throughout, is characterized by persistent bedding as defined by thin sandstone beds (fig. 29), vague color banding (fig. 31), and thin, discontinuous seams of greenish montmorillonite. The thin sandstone beds provide the best control on the extent and character of deformation of this rock. As is the case of the sandstone in bedrock north of fault F , the thin sandstones south of the fault do not form continuous beds of relatively constant thickness. Instead, they appear in section as trains of irregularly shaped patches and segments (fig. 29). In detail the boundaries of these patches consist of straight to gently curved shear surfaces that intersect at sharp angles (fig. 32). Individual shears extend into the mudstone as shiny surfaces, and into the sandstone bodies as fractures along which the sandstone is disrupted on a small scale (fig. 32).

Folds.-- Folds are present on at least three recognizable scales in bedrock of plant site; most of them have northward-dipping limbs and axial surfaces, and their axes trend easterly and plunge gently. Numerous small folds, with amplitudes and wave lengths between several inches and about 1 foot are indicated by preserved axial areas (figs. 25,33) and by reversals in the direction of tops as shown by sedimentary structures in sandstone beds (as at station 2 feet in trench 3, fig. 8a). An unusual feature south of fault F in trench 3 (fig. 26) involves a disrupted thin

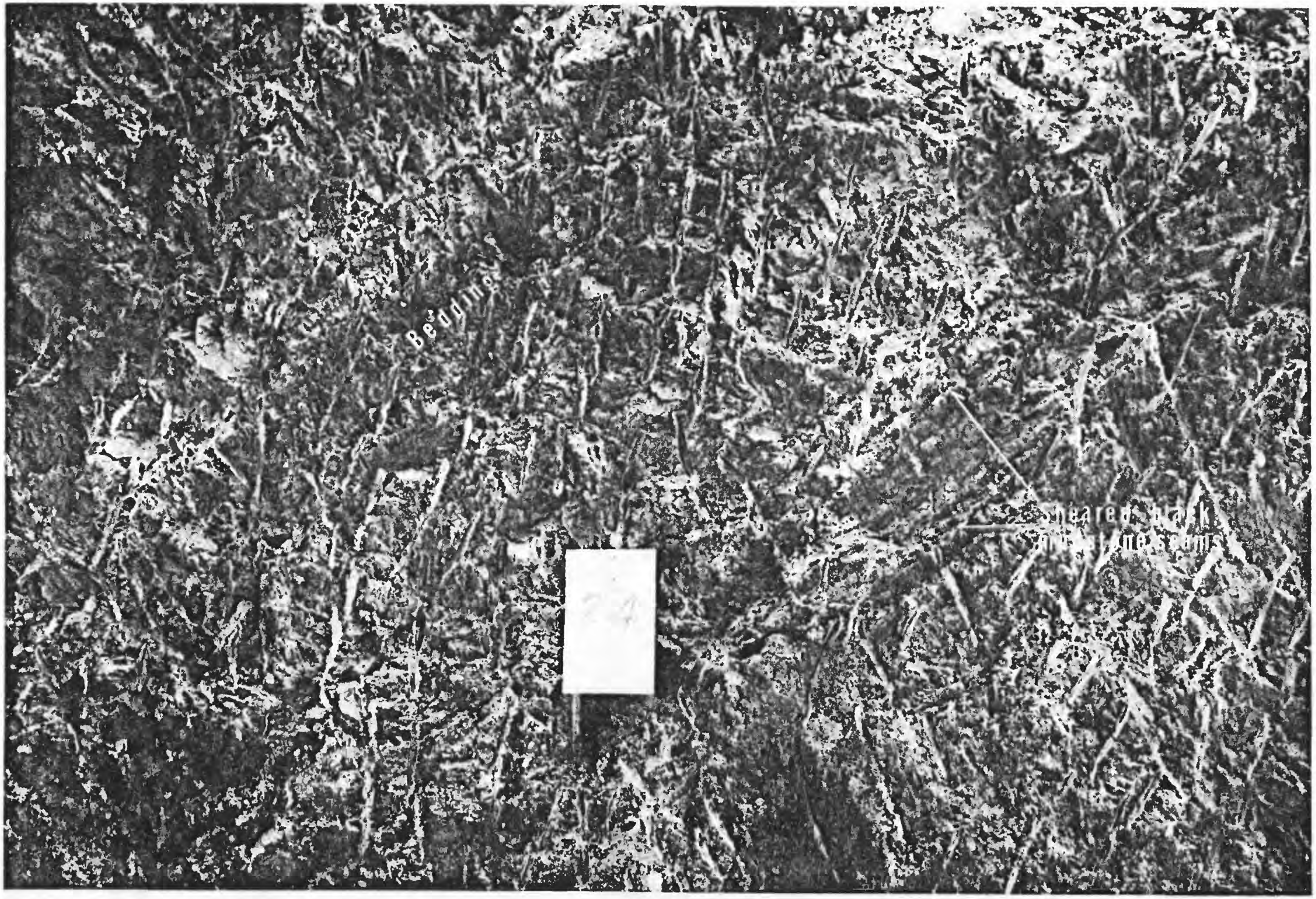


Fig. 31.--Banded mudstone, unit m-7 at 120 feet, southeast face of trench 3 (fig. 8a). Banding is due to variations in color (bedding) and parallel, thin black seams of sheared mudstone. Such sheared seams are represented as shear surfaces in the map of the trench face (fig. 8a).

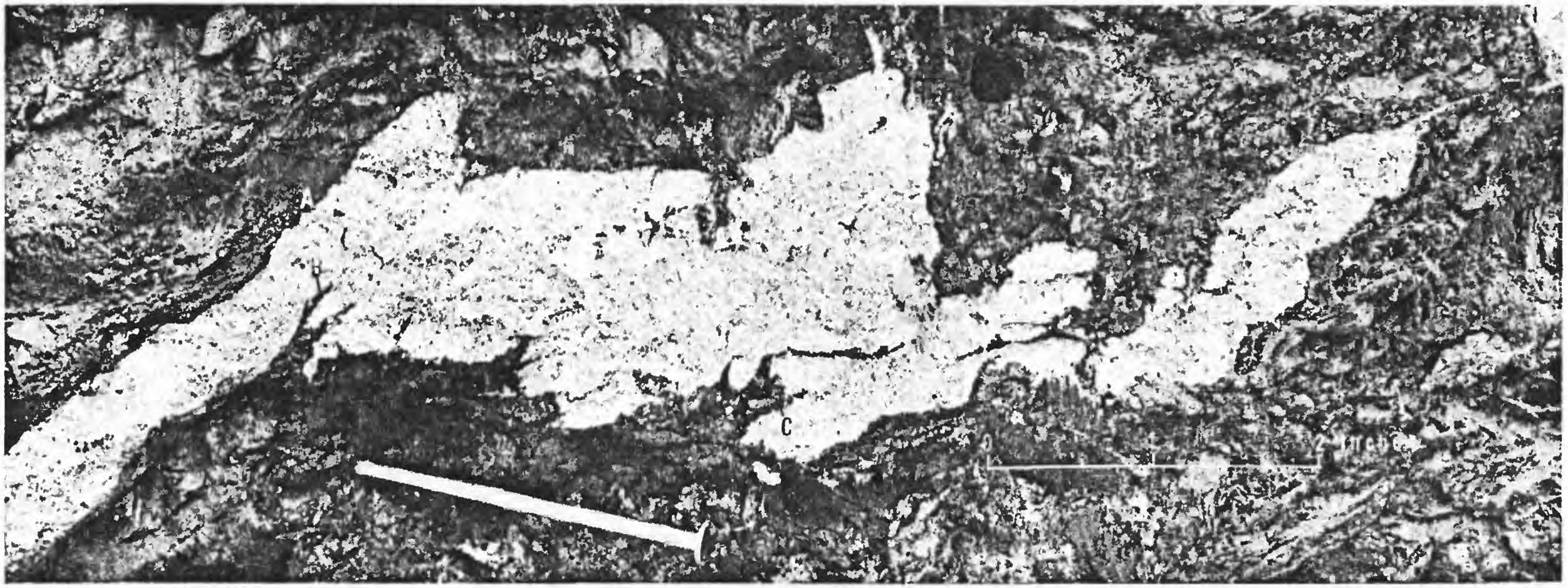


Fig. 32.--Shear-disrupted thin sandstone beds in mudstone, trench 3. Fig. 32a, unit m-9 at about 215 feet, and fig. 32b, unit m-8 at about 240 feet, southeast face (fig. 8a). Boundaries of sandstone segments are intersecting shear surfaces. A prominent orientation of the shear surfaces is parallel to the boundary of the sandstone segment at "A" (fig. 32a), the long dimension of the segments, and fractures within them, as at "B". The sheared boundaries of the sandstone segments extend into the mudstone as shear surfaces and into the sandstone as fractures, as at "B" and "C". Tuff pellets have also been disrupted, as in fig. 32b.

sandstone bed in mudstone; the disruption of this bed is more likely due to shearing than to folding.

A fold exposed in the west-wall trench has a wavelength measurable in feet; this fold involves at least three beds of sandstone between 1 and 3 feet thick (fig. 34). Thin mudstone beds at about station 220 feet in trench 3 define a fold of similar size (figs. 8a, 32).

Folding on a scale of hundreds of feet may be indicated by relations north and south of 150 feet in trenches 1 and 2 (fig. 9). North of that point the mudstone-sandstone section is overturned and faces south, as indicated by overturned graded beds; if the similar section south of that point faces north, as suggested by one upright bed then an overturned syncline with north-dipping limbs, and a half-wavelength of more than 90 feet is present.

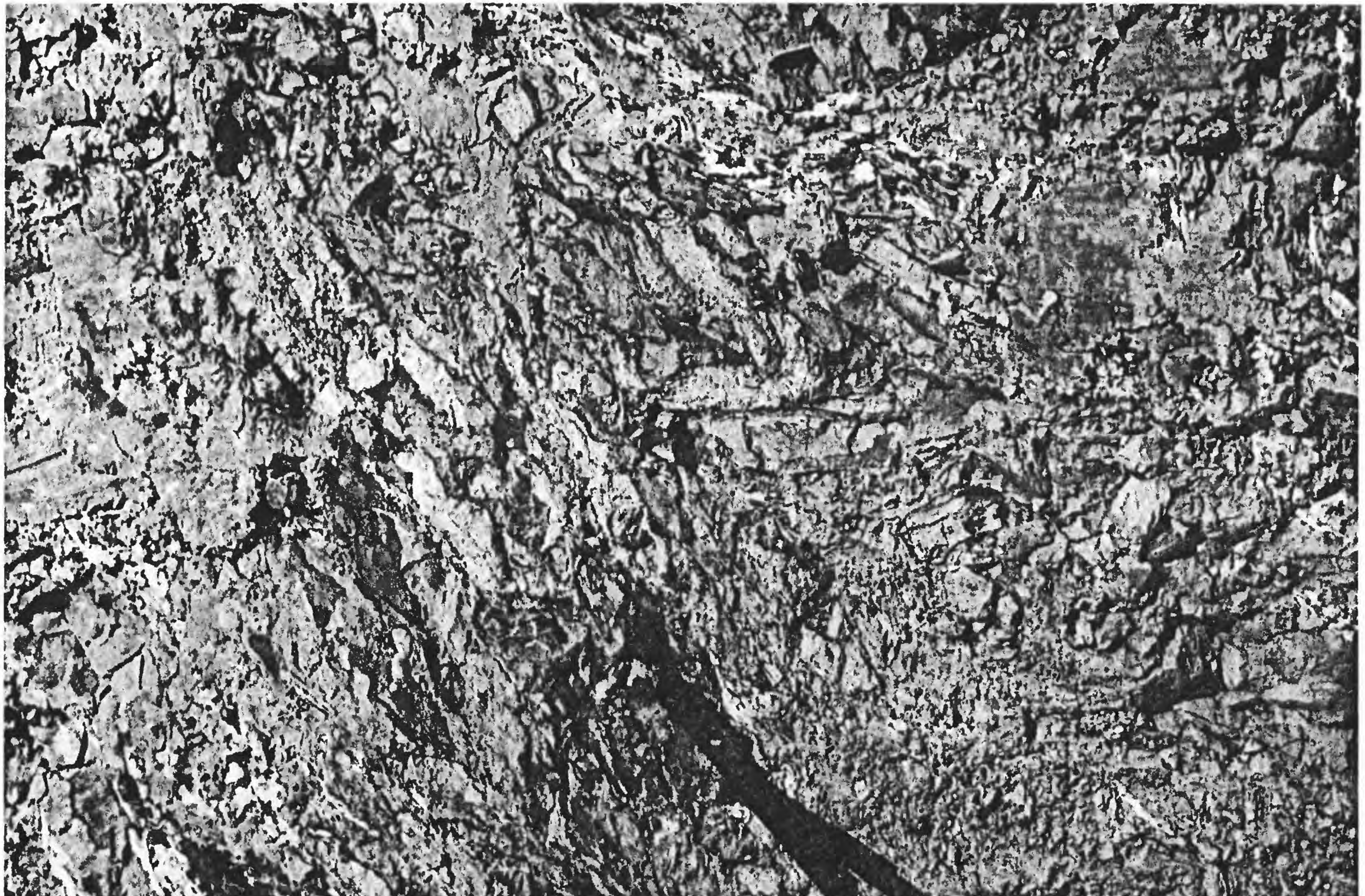


Fig. 33.--Small dismembered fold in thin-bedded sandstone and sheared mudstone of unit B near the plant site. Fold axis is approximately parallel to pencil below fold. Exposed in test trench on the west wall of Corral Canyon.

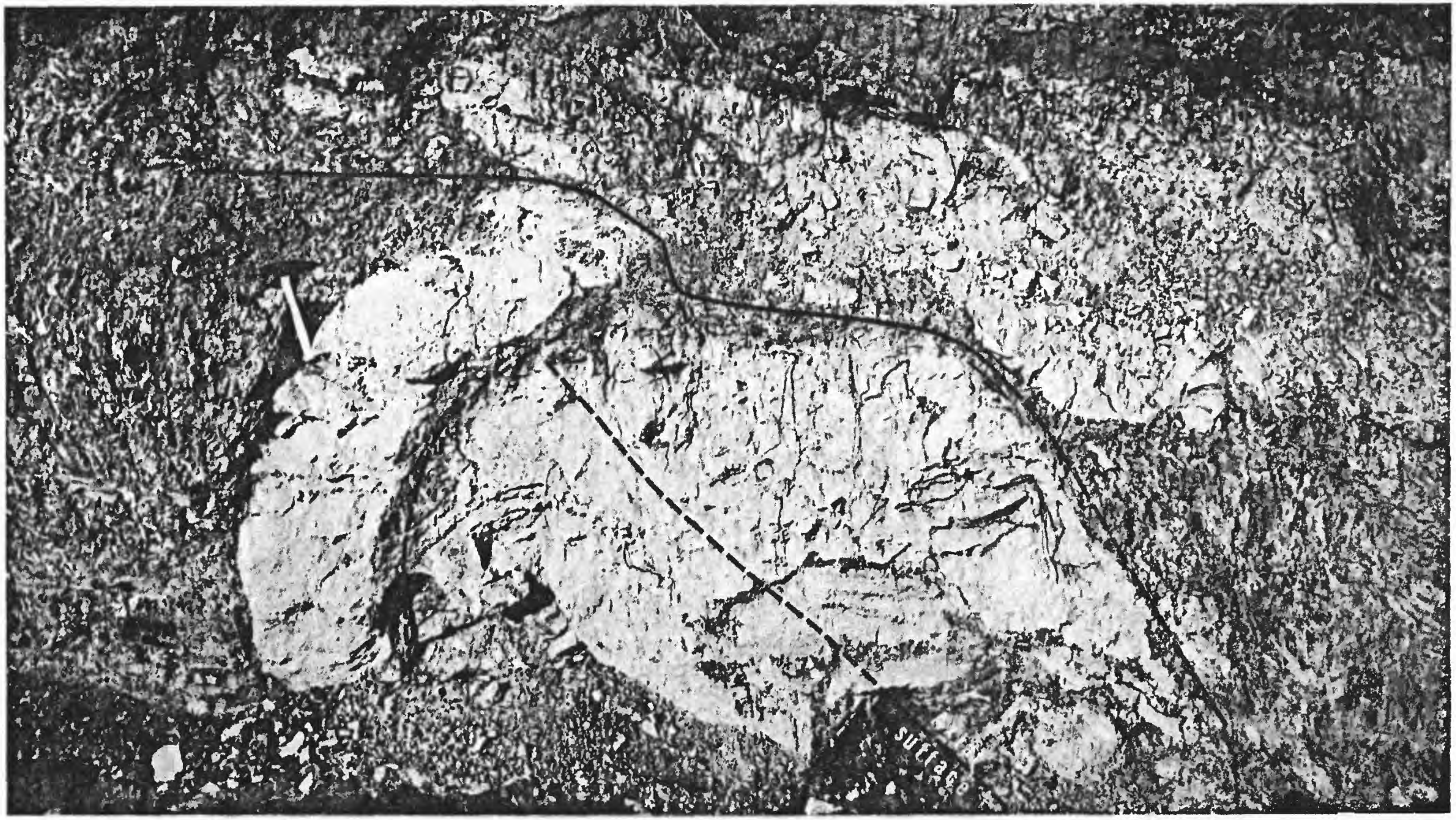


Fig. 34.--Anticline in unit B sandstone truncated by small, north-dipping thrust fault near the plant site. Axial surface of the fold dips northward (right). Exposed in test trench on west wall of Corral Canyon.

Faults.--The only known through-going fault of inferred relatively large displacement in the plant site area is fault A, the trace of which crosses Corral Canyon near the north boundary of the plant site (fig. 4). This fault is poorly exposed in the canyon, so that its position is largely inferred from the distribution of the Monterey Shale and unit B strata that it juxtaposes. Fault A is best exposed in a roadcut 3,000 feet east of the plant site, where it is a 10- to 15-foot-wide zone of sheared and brecciated rock (fig. 4). It is also exposed in gully B, and perhaps on the west wall of Corral Canyon. Relative displacement on fault A is probably many tens to some hundreds of feet; it is inferred to have been largely dip slip.

Trenches B, C, and D expose smaller-scale faults probably related to, but south of fault A. One of these, a 2- to 4-foot-thick, north-dipping zone of intensely sheared rock (unit m-4 at station 130 feet in the east face of trench B, fig. 11) separates distinct lithologic units (m-2 and msd) within unit B; this zone probably represents a fault with displacement of many feet. Another fault, at station 96 feet in the same trench, strikes N. 45° W., dips 78° to 90° S., and bears distinct mullion that pitch 9° SE, suggesting some component of lateral movement. Fault A probably underlies the resistant siltstone breccia (unit st-1) at 85 feet in trench B, and the untrenched ground between the upper and lower segments of trench C (fig. 12). Trench F (fig. 14) exposes a slip surface that juxtaposes rocks of unit B and Monterey Shale; if this is not fault A it is probably a feature controlled by that fault.

Fault F is an intraformational fault that was exposed in trench 3 (fig. 8) near the center of the reactor location; this fault is correlated with one exposed at station 250 feet in trench 2 (fig. 9) and with one exposed in the east bank of Corral Creek and the west wall of the canyon (fig. 4). This intraformational contact has also been recognized in six of the borings in the plant site area (see Jahns, 1965, for a three-dimensional diagram showing this contact). Where exposed, this contact consists of a zone of sheared rock of variable thickness and intensity of shearing. The rock north of the fault is mudstone that contains abundant medium to large sandstone pods (unit msd), whereas that south of the fault is less deformed mudstone, homogeneously sheared on a fine scale, that contains very little sandstone and minor amounts of volcanic rock and tuff; adjacent to the fault, severely sheared mudstone of unit m-6 contains numerous small sandstone pods as well as rare volcanic rock. In trench 3 fault F truncates the contact between units m-6 and m-7 at the base of the southeast face, and cuts out unit m-6 on the southeast face; on the northwest face and bench the location of the fault was not precisely established. The fault strikes about east-west and dips northward; it probably has dip-slip displacement on the order of at least tens of feet, presumably upper (north) block southward over lower block. A somewhat similar zone of gouge and penetratively sheared rock dips gently northward near 400 feet in trench 2 (fig. 9) and also probably represents a minor fault; additional evidence of this feature has not been exposed. At the south end of trench 3 (figs. 8b and 8c) a northwest-dipping fault, marked by a ½-inch- to 4-inch-thick zone of black plastic gouge, truncates structure in the lower block, cuts out stratigraphic section, and is gently folded.

Other small-scale faults are present throughout unit B strata in the vicinity of the plant site. A very low angle north-dipping fault in trench 1 is inferred to show some 6 feet of separation with the upper block displaced southward (see at stations 50 to 60 feet, fig. 9). The same sense of movement is also indicated by minor offsets of the north and upper boundary of a sandstone block just below this fault (see fig. 35, especially the inset). A fold on the west wall of Corral Canyon is truncated by a north-dipping, somewhat irregular fault on which the upper (north) block probably was displaced southward (fig. 34). In addition, there are numerous narrow, generally north-dipping zones of intensely sheared rock that can be traced across the faces of most of the trenches; these are considered to be very minor faults and especially well exposed in trench 3 south of fault F (fig. 8c).

The shear zones present in the rocks of unit B vary in thickness, continuity, and apparent displacement by several orders of magnitude. On thin section scale, movement on very small-scale shears has truncated foraminiferal tests and interrupted and deformed the rock fabric (figs. 19, 20, 21, 22). Very narrow zones of intensely sheared rock that can be traced for inches or a few feet disrupt sandstone beds a matter of inches (figs. 29, 32). At a different order of magnitude are the extensive zones of shears that form lithologic contacts, are as thick as about 3 feet, and truncate stratigraphic section (for example, the sheared contact

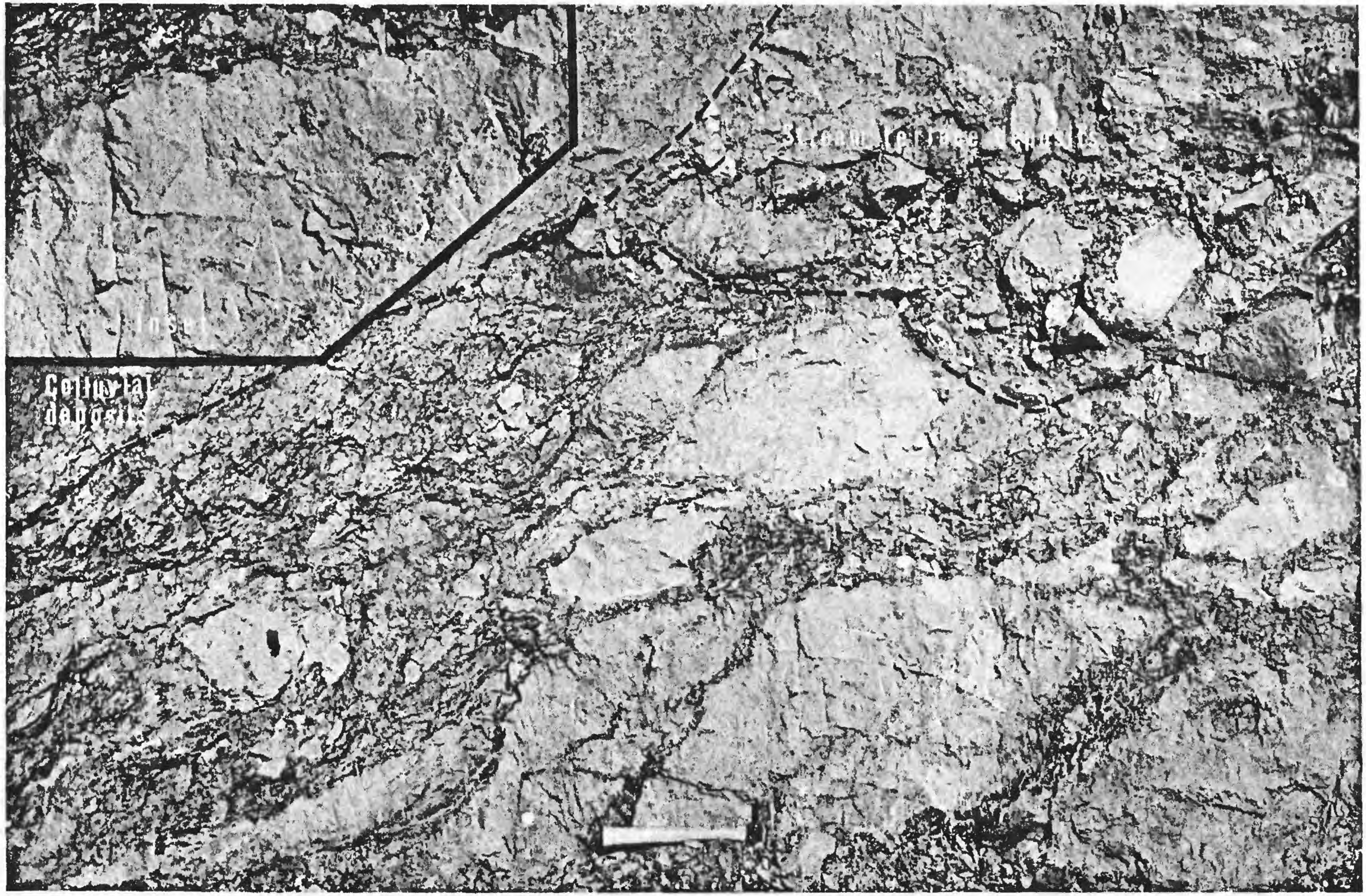


Fig. 35.--Blocks of unit B sandstone with partings of sheared mudstone, truncated by minor faults near the plant site. Bedding in the sandstone blocks dips northward (left), parallel to shear surfaces, and faces south (overturned). The small fault that truncates the sandstone block (center of photograph) has north-over-south sense of movement as indicated by minor displacement in top of sandstone block above hammer (see inset). Colluvial and stream terrace deposits overlie bedrock. North end of upper test trench on east wall of Corral Canyon.

between units m-7 and m-8, offset by the shear at station 160 feet on the southeast wall of trench 3, fig. 8c); separation on such features may locally exceed 5 feet. Apparent displacement on the shears and shear zones may thus be associated with the thickness and continuity of the sheared zone.

The faults that have been mapped vary considerably in thickness, continuity, and probable magnitude of relative displacement and geologic significance. The Malibu Coast fault is marked by a zone of sheared and brecciated rock tens of feet wide and has been mapped for a distance of more than 15 miles; it is a rock boundary of regional significance along which the relative displacement has been thousands of feet.

Most of the other faults shown on the areal geologic map (fig. 5) separate recognizably different stratigraphic units. These faults consist of zones of sheared and brecciated rock several feet wide that can be traced for hundreds or thousands of feet; they probably have relative displacements of the same order of magnitude.

Intraformational faults (such as fault F) and shear zones, such as many that are exposed only locally in or near the plant site, are recognized by their truncation of particular beds or lithologic units, and are marked by zones of sheared rock or breccia as thick as 3 feet. Intraformational faults may not be recognized in natural exposures and can therefore be traced for only relatively short distances; relative displacement on these faults is probably on the order of several to tens of feet.

Finally, the innumerable, locally continuous shear surfaces that pervade the mudstone of unit B in the plant site and elsewhere are also surfaces of displacement as indicated by slickensides, truncated Foraminifera, truncated fabric and lithologic units, and segmented sandstone beds; these are also small faults. Relative displacement on these very small faults probably ranges from less than an inch to perhaps several feet; displacement on any one such surface was probably quite small, but aggregate displacement across several feet of such sheared rock may total several feet.

STRUCTURAL ANALYSIS

Analysis of the bedrock structure of the Corral Canyon site and adjoining parts of the Malibu Beach quadrangle by means of orientation diagrams provides a concise graphic description of the local and areal structural geometry, as well as a means of comparing and interpreting the relations and origins of the different structural features.

Poles (perpendiculars) to bedding throughout selected areas were plotted on an equal-area net (lower hemisphere of a Schmidt projection) and the points in the resulting pattern were contoured on the basis of their density of distribution. Poles (β axes) were then constructed to great-circle girdles defined by the concentrations of poles to bedding. (For discussion of the method, see Turner and Weiss, 1963, especially p. 49-53, 58-62, 149-159). The resulting diagrams portray the combined spatial geometry of all the measurements of structural elements within the selected area.

The structural data were taken from two sources: the Preliminary geologic map of the coastal part of the Malibu Beach quadrangle (Schoellhamer and Yerkes, 1961, part of which has been revised for the east half of fig. 5); and the geologic map of the Corral Canyon site (fig. 4). None of the data on these maps were gathered with the intention of subjecting them to structural analysis. (Bedding attitudes selected during conventional mapping as representative of one or a series of outcrops do not provide as complete information for structural analysis as a number of readings taken at one locality to record significant variations from the representative attitude. It is possible that the nature of the rocks and the normal mapping methods employed result in a subjective bias against low dips).

That part of the Malibu Bowl thrust sheet shown on the preliminary Malibu Beach map was divided into two areas on the basis of homogeneity of structure (north and south areas, figs. 36 and 37). The north area was selected to contain a minimum of southward dips. The single maximum of the resulting orientation diagram (fig. 36) represents north-dipping beds. The east-west elongation of the maximum suggests fairly open folding of these beds around a gentle northward-plunging axis (β_1). Such folds are revealed on the Malibu Beach map by constructing form lines, everywhere parallel to the local measured strike of the bedding. The folds have half-wave lengths of about 500 to 2,500 feet and appear both as open bends in the form lines and as sharp bends or kinds.

The south area presents a very different structural picture (fig. 37) from that of the north area. The pattern of the north area (fig. 36), of north-dipping beds folded around gently north-plunging axes is present here (β_1 and corresponding great circle), but is nearly masked by a somewhat diffuse, generally north-south band containing several small maxima. The following elements (present in both figs. 36 and 38) can be recognized in the pattern of the south area (fig. 37): the great circle corresponding to β_1, a great circle corresponding to the gently east-plunging axis (β_{2a}), and one corresponding to the gently southeast-plunging axis (β_{2b}). In addition, there is evidence here of a great circle girdle representing a gently northwest-plunging axis (β_{2c}). This diagram of the south area (fig. 37) represents structure with the basic geometry of the north area

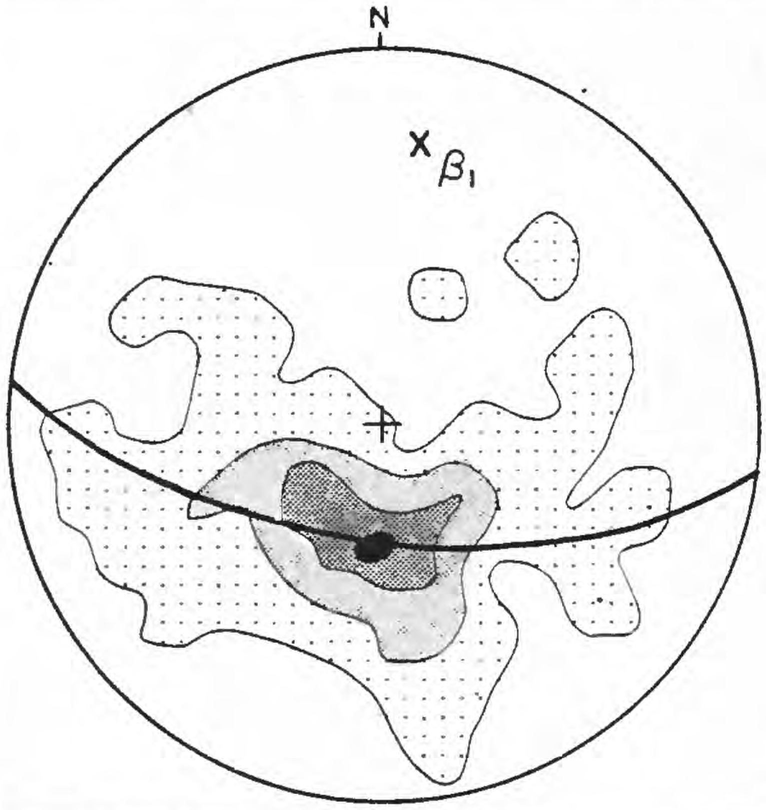
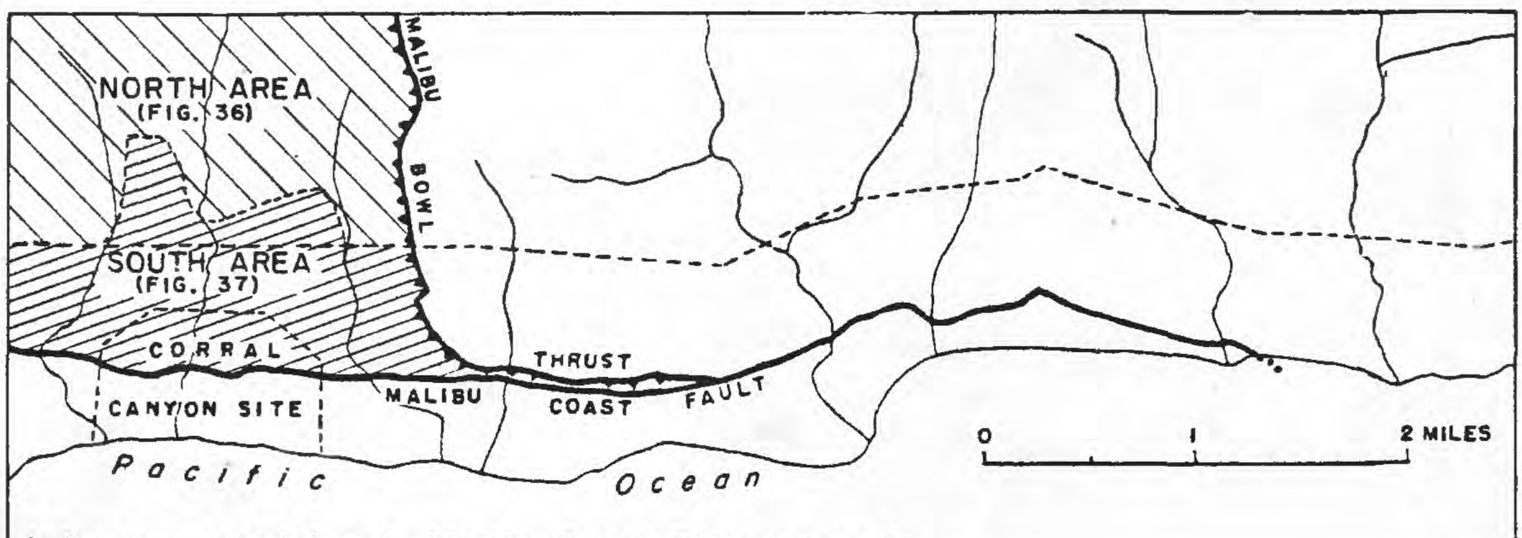


Fig. 36. Malibu Bowl thrust sheet-north area: orientation diagram of 176 poles to bedding, showing north-dipping beds folded around north-plunging axis (β_1).

Contours 12%, 8%, 4%, 0% per 1% area



Index map, coastal part of Malibu Beach 7-½' quadrangle

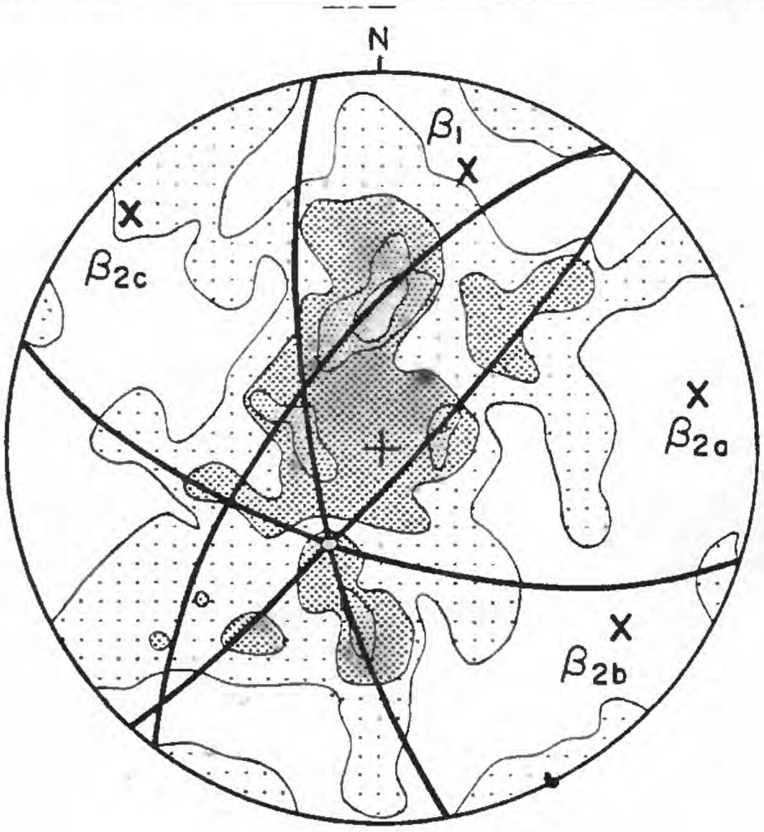


Fig. 37. Malibu Bowl thrust sheet-south area: orientotion diagram of 116 poles to bedding, showing north-dipping beds (β_1) greatly modified by folding around east-west to northwest-southeast axes ($\beta_{2a, b, \& c}$).

Contours 6%, 4% 2%, 0% per 1% area

(fig. 36), that has also been folded around gently plunging east-west and northwest- southeast-trending axes.

Data for the Corral Canyon site, a smaller area that straddles the Malibu Coast fault at the south edge of the Malibu Bowl thrust sheet, are provided by the geologic map of the site (fig. 4). In the orientation diagram for this area (fig. 38) a gently east plunging axis (β_{2a}) and one plunging east-southeast (β_{2b}) correspond to the two girdles defined by the north-south pattern. That folding has taken place around such axes is substantiated by the orientation of the axes of small folds (fig. 38), wave lengths 4 inches to about 15 feet, measured in the field (see figs. 33 and 34). These fold axes cluster near the trend of the β axes for the most part; however, in contrast to the β axes, they plunge gently both to the east and to the west. Although a girdle corresponding to a northwest-plunging β axis is not well developed in figure 36, such a girdle does occur in figure 37 (corresponding to β_{2c}).

It has been shown that half a mile north of the Malibu Coast fault (North area, fig. 36) the rocks dip northward and are slightly folded around gently north-plunging axes. Furthermore, 1 mile south and 3 to 4 miles west of Corral Canyon, the rocks also dip northward and are slightly folded around northward-plunging axes (inspection of unit Tm on Point Dume, fig. 5). Between these two areas, in the vicinity of the Corral Canyon site, the rocks have a different geometry, which shows that they are folded around east- to southeast-trending, gently plunging axes, and have both north and south dips. That this deformation pattern persists a considerable distance along the Malibu Coast zone is indicated

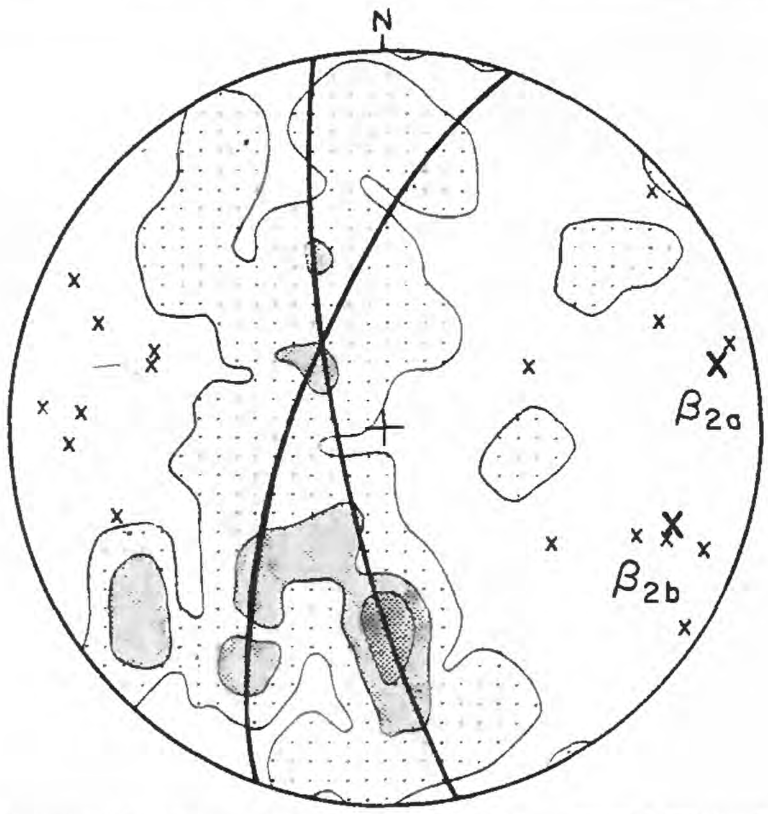
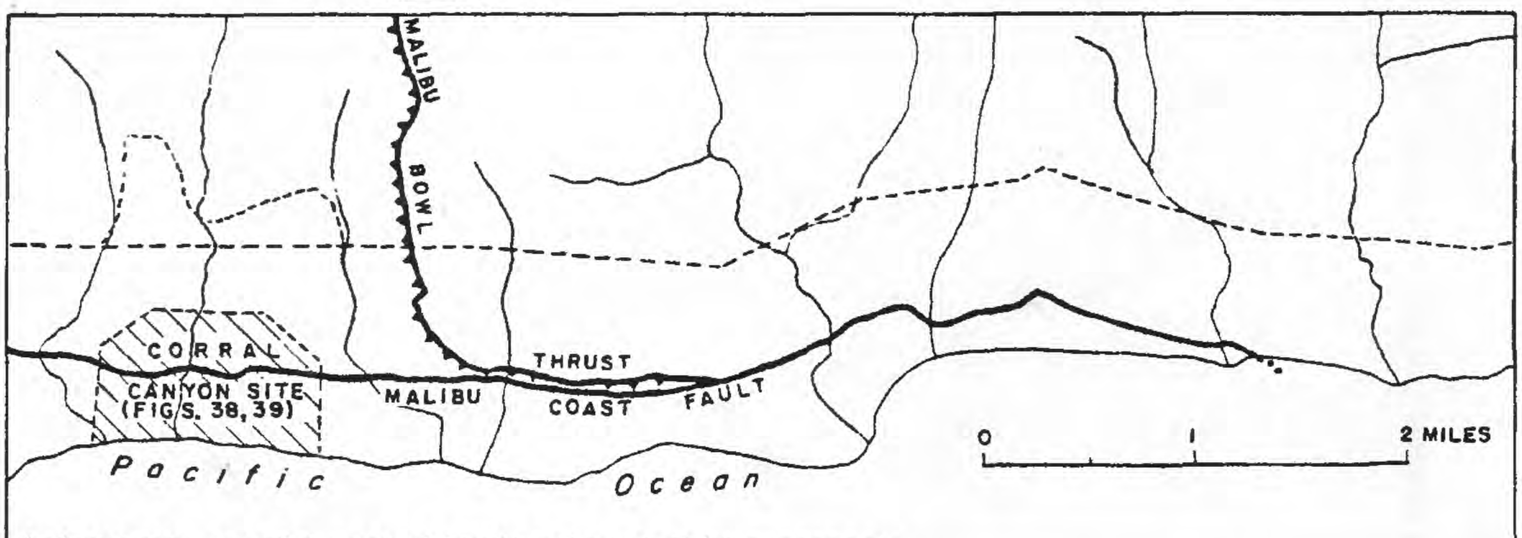


Fig. 38 Corral Canyon site: orientation diagram of 73 poles to bedding, showing bedding folded around east-west axes ($\beta_{2a\&b}$), and similarly oriented small fold axes.

Contours 8%, 4%, 0% per 1% area

x – axes of 18 small folds



Index map, coastal part of Malibu Beach 7-½' quadrangle

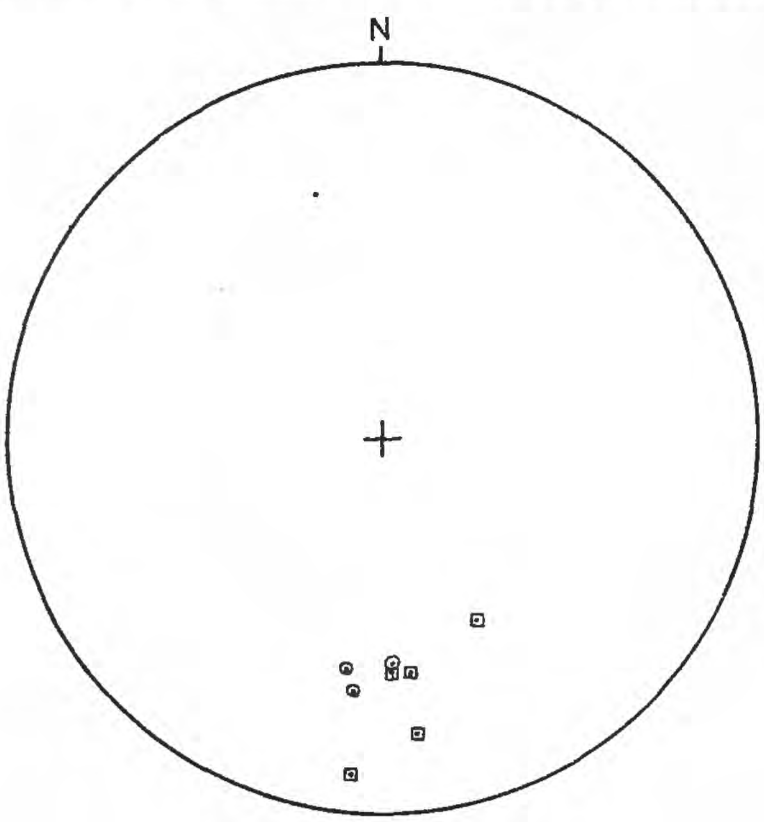


Fig. 39. Corral Canyon site: orientation diagram of 8 poles to major faults, showing north dips and east-west trends.

⊡ Malibu Coast Fault
⊙ Unnamed faults

by orientation diagrams for the east-trending bands just north and south of the Malibu Coast fault (figs. 40 and 41, respectively), which show both north and south dips, and weakly developed, discontinuous girdles that have gently east- and southeast-plunging β axes.

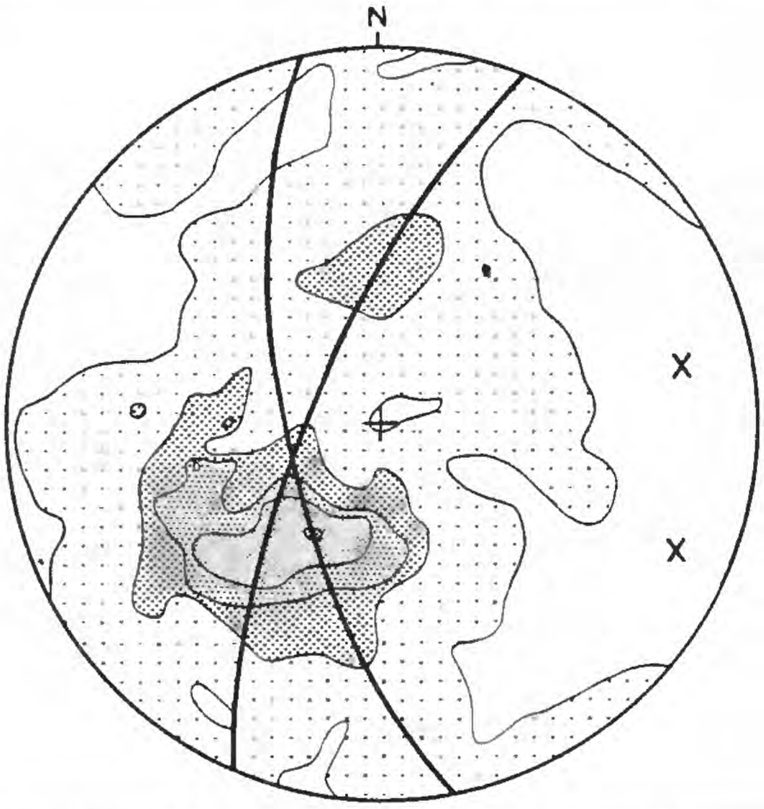
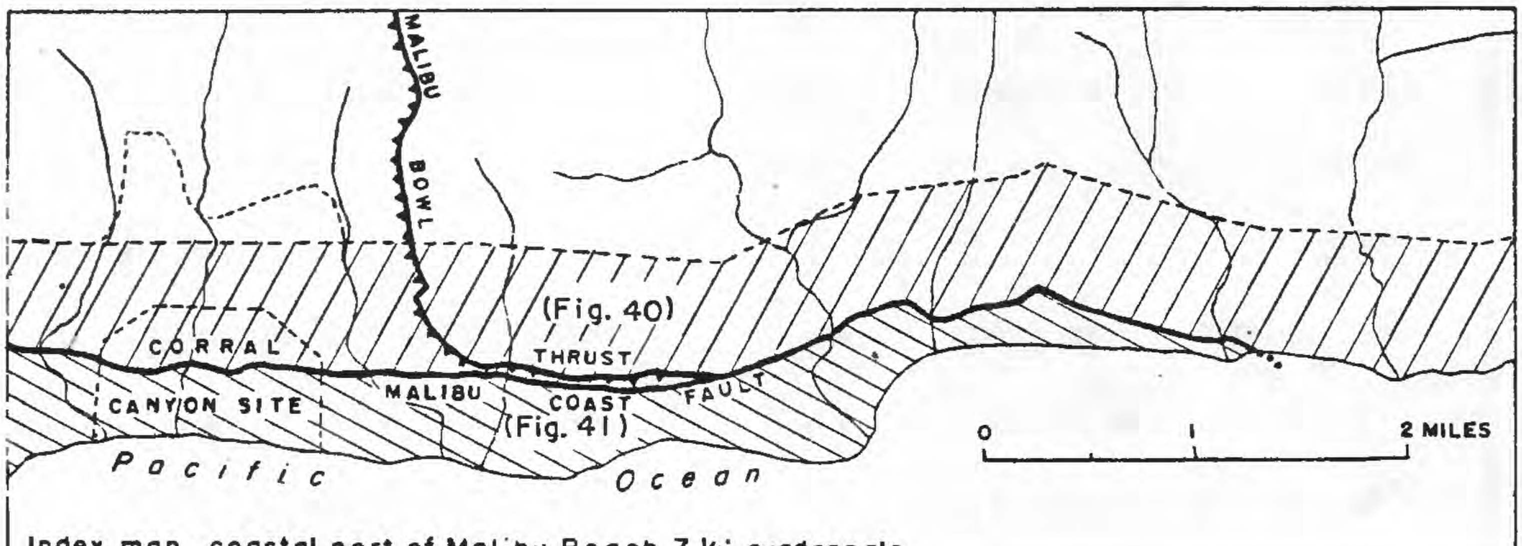


Fig. 40. East-west band north of Malibu Coast Fault: orientation diagram of 293 poles to bedding, showing north-to northeast-dipping beds modified by folding around east-west to northwest-southeast axes.

Contours 8%, 6%, 4%, 2%, 0% per 1% area



Index map, coastal part of Malibu Beach 7-½' quadrangle

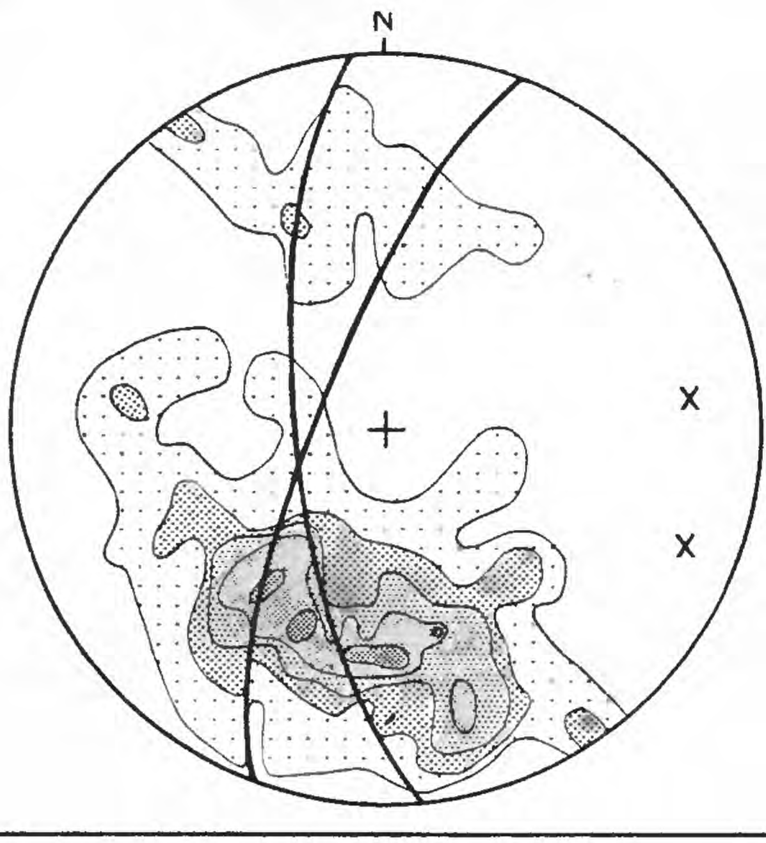


Fig. 41. East-west band south of Malibu Coast Fault: orientation diagram of 108 poles to bedding, showing north-to northeast-dipping beds modified by folding around east-west to northwest-southeast axes.

Contours 8%, 6%, 4%, 2%, 0% per 1% area

SUMMARY AND ORIGIN OF STRUCTURE

Origin of deformation

Setting, characteristics, and possible causes

The north-dipping Malibu Coast fault, which bisects the Corral Canyon site, lies within and near the north edge of the Malibu Coast zone of deformation and is the structural boundary between the unrelated stratigraphic sections of the Santa Monica Mountains part of the Transverse Ranges on the north and the Continental Borderland on the south. This fault and the spatially associated Malibu Coast zone of deformation are part of the east-trending Santa Monica fault system, which bounds the Transverse Ranges on the south for at least 145 miles from near Santa Cruz Island to the San Andreas fault. The active Newport-Inglewood zone of faults and folds forms the eastern boundary of the Continental Borderland block of Catalina Schist (or Franciscan) basement, of which the Malibu Coast fault is the inferred northern boundary. These two crustal boundary faults are considered to have operated as a system, allowing the Continental Borderland block to move northward along the Newport-Inglewood zone on the east and under the leading edge of the Transverse Ranges along the Malibu Coast fault on the north.

Analysis of bedding attitudes in the coastal part of the Santa Monica Mountains demonstrates that in a zone along the Malibu Coast fault (the Malibu Coast zone) both north and south, dips are present and represent folding around approximately east-trending, gently plunging axes (see Structural analysis); field observations confirm this style of deformation. In contrast, rocks north and south of this zone are considerably less deformed, and show only northward dips with some slight folding around gently north-plunging axes.

The pattern of bedding attitudes in the Corral Canyon site is the same as that of the Malibu Coast zone and field investigation demonstrates that the bedrock of the site (Upper Topanga north of the Malibu Coast fault and Monterey Shale and unit B to the south) is greatly deformed. Almost all structural elements in the Corral Canyon site are consistent with the pattern of deformation in the Malibu Coast zone: the folds plunge gently, have approximately east-trending axes and north-dipping axial surfaces; faults of several magnitudes strike approximately eastward and dip northward (Malibu Coast fault, fault A, fault F, and very small faults such as in trench 3); and the very abundant shear surfaces in mudstone of unit B show a similar orientation. Several small structural features in the plant site area, in addition to the gross stratigraphic and structural relations, indicate that the general sense of deformation was north side up and southward.

Unit B mudstone, which underlies the plant site and extends beyond the Corral Canyon site boundary to the east and west along the coast, exhibits a somewhat different style of deformation than do rocks of other lithology in the Malibu Coast zone. Because of poor natural exposures, these mudstones are best known from the excellent artificial exposures in and near the plant site. The unit B rocks of the plant site contain a number of small faults, as do the other rocks in the Malibu Coast zone (where exposures allow their observation). In addition, the sandstone occurs mostly as elongate pods and lenses, rather than in relatively continuous beds, and all of the mudstone contains innumerable flat to curved, shiny, striated surfaces, herein termed shear surfaces. The origin of those shear surfaces has been considered (Cleveland and Troxel, 1965; Hoffman and Smith, 1965; Jahns, 1965) to be chiefly the product of submarine slumping of unconsolidated sediment, complicated by the effects of swelling and shrinking of montmorillonitic clays in the bedrock after consolidation and later exposure to weathering processes near the ground surface. Under such an interpretation the structural features of the bedrock in the plant site would not be the result of the tectonic activity that produced the various structural features in bedrock throughout the Corral Canyon site and the Malibu Coast zone, as well as the nearby Malibu Coast fault itself. In contrast, Kamb (1965), and the present authors consider essentially all the structural features of bedrock in the Corral Canyon site to be tectonic in origin and to be a direct result of the tectonic environment in which the Malibu Coast fault and the other structural features of the Malibu Coast zone formed. Judgments as to the probability and possible location of future faulting depend in part on determining the origin of the structural features of the bedrock in the plant site (see Location of future faulting; also Jahns, 1965, p. 5; and Hoffman and Smith, 1965, p. 24), for if these features are demonstrated not to be the direct result of tectonic deformation, then it can be inferred that the bedrock has been little affected by its tectonic and structural environment since middle Miocene time.

Sedimentary material can be deformed as newly deposited, water-rich, fluid or plastic sediment; during lithification; or after consolidation into well-indurated sedimentary rock. The deforming movements may originate tectonically, that is, from within or below the earth's crust (crustal tectonics); they may be due to the effects of gravity acting on very large masses of rock (gravitational tectonics of Hills, 1963, p. 336); or they may be the result of small-scale gravity sliding related to local topography, either on the sea floor or on the subaerial surface.

Tectonic movements of crustal or subcrustal origin may fold, fracture, shear, and fault rocks of the crust, crumple a broad sedimentary basin into a thick mass of folded and faulted rock, elevate mountain ranges, form great fault blocks, and drive a great fault like the San Andreas, as well as produce a myriad of smaller structural features.

In contrast, submarine slumping, a type of penecontemporaneous deformation (approximately contemporaneous with deposition), involves downslope transport and accompanying deformation of masses of relatively unconsolidated, generally plastic sediment by slumping and sliding, due to their own weight, on the sea floor in the basin of deposition (see, for example, Potter and Pettijohn, 1963, Chap. 6). Such deformation can be described in terms of two end-member types: (1) transport of the material along a discrete sole or slip surface, with minor concurrent rupture and folding within the mass; and (2) transport accompanied by plastic deformation throughout, including variably pervasive folding, rupturing, rotation, and mixing within the flowing mass.[1] The deposits

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[1] It is important to distinguish the process here called submarine slumping from that of sediment movement by turbidity currents. Although many turbidity currents are probably initiated as slumps, they move across the sea bottom, in the manner of fluids, with relatively high energy, transporting and fairly thoroughly mixing the contained sediment. Each turbidity current is probably responsible for the deposition of one bed. Evidence of deposition by turbidity currents, including such structures as graded bedding, flame structures, and contained mudstone fragments, in no way implies any history of gravitational instability of the sediment at its site of deposition.

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resulting from submarine slumping can achieve quite large dimensions, probably exceeding more than 100 feet in thickness and more than a square mile in area (Jones, 1939, describes slump deposits of quite large size). These slump deposits, formed on the sea floor at the interface between sediment and water, may be buried by continuing deposition in the area. Such burial provides the only indisputable evidence of deformation by submarine slumping: if the deformed beds are clearly overlain at an unconformable, depositional contact by undeformed beds of the same lithologic unit, then the deformation must have occurred during deposition of the unit.

Under some circumstances, gravity transport of consolidated and partially consolidated sedimentary material can also occur on a grand scale, moving masses hundreds to thousands of feet thick and many square miles in area for distances of tens of miles. Products of such deformation range from great thrust sheets of coherent, relatively unbroken rock, to chaotic sheets that consist of variously bent, folded, and segmented blocks, plates, and irregular bodies of stratified rock ranging in size from less than a foot to several miles, all in a variably abundant matrix of sheared mudstone (for example, the argille scagliose of the Apennines, see Merla, 1952; Maxwell, 1959; and Page, 1962). This kind and scale of deformation, by some termed gravitational tectonics (Hills, 1963, p. 336), has some properties of both submarine slumping and tectonic deformation.

Finally, it seems possible that incompletely lithified sediments can be involved in major tectonic deformation of a sedimentary basin, resulting in tectonic deformation of soft sediments.

To determine the major cause of deformation of the unit B mudstone and sandstone that underlies the plant site, it is first necessary to establish whether the material was soft or indurated at the time of major deformation, and then to establish which of the pertinent deforming processes have been operative. In the absence of the very few kinds of evidence that are in themselves conclusive (as is the case at Corral Canyon) any attempt to distinguish the major cause of deformation requires consideration of both the detailed and the general evidence from the particular rocks, and especially their relation to the structure of the surrounding rocks and the regional structure (Potter and Pettijohn, 1963, p. 143-144).

The manner of deformation of the sandstone beds, once continuous and of fairly constant thickness (see Structure of the plant site, and fig. 42), as well as that of the surrounding mudstone, indicates the degree of induration of those materials at the time of major deformation. The sandstone occurs as pods, blocks, and irregularly shaped fragments ranging from less than an inch to more than 10 feet in length. All but the smallest pods are elongate parallel to the bedding within them, and are oriented approximately parallel to each other and to the regional structure. Thin sandstone beds south of fault F in trench 3 are disrupted into trains (in section) of irregularly shaped fragments. The boundaries of the sandstone pods and fragments are shear surfaces; in some cases such shears extend into the sandstone as fractures, on some of which movement has been recorded by displacement of the pod boundaries. Fractures are present in many of the sandstone pods, and most are oriented approximately normal to the bedding in the pods and to their length. In one case a concentration of such fractures is spatially related to thinning of a thick, large sandstone pod (fig. 27). Hard, dolomitic(?) siltstone pods are jointed both normal and parallel to their bedding and length, and in two cases such fractures perpendicular to pod length are intruded by sheared mudstone. The few folded sandstone beds contain fractures oriented approximately normal to bedding throughout the fold.

The dominant tectonic processes recorded in the bedrock are fracturing of indurated sandstone and siltstone and formation of parallel sandstone pods and fragments by extension and segmentation of once-continuous beds. There are no structures indicative of fluid or small-scale plastic deformation of the sandstone and surrounding mudstone.

The common structures resulting from such deformation--fluidal and disharmonic folds, curls, swirls, contortions, crinkles, mixings, "marblings", pebbly mudstones, slump overfolds, and similar structures--are almost entirely lacking in these rocks. The "rolled sandstone body" illustrated by Hoffman and Smith (1965, fig. 8) is the only known structure that may be indicative of such an origin.

The mudstone that contains the pods and disrupted beds of sandstone is neither massive nor structureless, either in surface outcrop, test trenches, or in the borings. Instead, the mudstone everywhere contains innumerable, closely spaced, shiny, striated surfaces, shear surfaces that truncate rock fabric, lithology, and foraminiferal tests on a microscopic scale. On a larger scale, sandstone beds have been disrupted along the shears (figs. 29, 32). Displacement along these surfaces is suggested by the slickensides, and is required by the truncated rock features and disrupted sandstone beds.

These shear surfaces define small fragments of mudstone within which there is little or no evidence of deformation. Within the fragments fresh fractures are typical of undeformed mudstone, the rock fabric is relatively coherent, shear surfaces are poorly developed if at all, and foraminiferal tests are undeformed (figs. 21, 22; Albee, 1965).

Although the orientations of shear surfaces vary considerably, resulting in lens-shaped fragments, their distribution is not random. Surfaces measured in trenches 1 and 2 show a strongly preferred orientation (fig. 23; approximately east-trending strike, north-northeast dip); visual inspection of shear surfaces in the other trenches indicates that they have similar orientations.

The shears are surfaces of weakness in the bedrock, along which the fresh rock commonly breaks when crushed or torn by hand, and along which the rock parts when it shrinks upon drying. There is no megascopic or microscopic evidence to indicate any significant healing of these fractures after their formation, as would be expected if considerable lithification of the material had followed their formation. (By healing is meant the development across the shears or fractures of rock strength similar to that in other directions in the rock).

The abundant structural features present in the bedrock of the plant site all indicate failure of relatively brittle rock; little evidence was recognized that indicates deformation of fluid or plastic sediment. The processes capable of deforming such rock are gravitational tectonics, crustal tectonics, and possibly, swelling of clays in the zone of weathering.

Shear surfaces.--The shear surfaces in the mudstone are considered by Hoffman and Smith (1965, p. 11), Jahns, (1965, p. 4), and Cleveland and Troxel (1954, p. 16) to be the product, respectively, of desiccation cracking and redeposition of clays; of alteration, wetting and drying, and normal slacking; and probably of release of swelling stresses resulting from cyclic hydration and dehydration. These authors consider the shear surfaces to be the product largely or entirely of shrinking and(or) swelling of clays in the bedrock in the zone of weathering. Deformation by swelling clays is considered by these authors to account for only the abundant shear surfaces in the mudstone. (Shear surfaces are referred to as parting surfaces by Hoffman and Smith, 1965, p. 10; and Cleveland

and Troxel, 1965, p. 16; they are distinguished by the latter from minor shears, which probably are equivalent to the very small faults of this report.) Some other cause is required to account for much of the deformation of the sandstone beds.

It has been stated or implied that the abundance of parting surfaces (herein termed shear surfaces) in the mudstone decreases with depth (Hoffman and Smith, 1965, p. 10; Jahns, 1965, p. 4). However, examination of the cores of mudstone from borings in and near the plant site (courtesy of Converse Foundation Engineers) indicates that, although the surfaces may be less obvious with depth, they are present in similar abundance in all the cores to the greatest depth penetrated (about 67 feet below sea level in boring 5, east of the canyon wall).

Near the ground surface the mudstone is weathered, as indicated by the "pinkish"-brown, gray, and greenish-gray rock colors and general presence of gypsum and jarosite(?). In contrast, below a poorly defined, but shallow depth in the bedrock (about altitude 20 feet in trench 3; below the bedrock exposures in the other test trenches; below depths of 10 to 25 feet, Jahns, 1965, p. 4) the rock is olive to gray black, lacks gypsum and jarosite(?), and contains pyrite at least locally (observed in sandstone and as euhedral crystals on shear surfaces in mudstone, and distinguished by X-ray diffractometry in two fresh mudstone samples, CW 135 and CW 138, in trench 3). The presence in all but near-surface bedrock of dark rock color and pyrite, which are unstable in the oxidizing environment of the weathering zone, indicates that cyclic drying and wetting of the bedrock, accompanied by such an exidizing environment, has not penetrated more than a few tens of feet into the bedrock.

It is unknown whether shear surfaces such as those present in unit B mudstone could result from swelling during relief of load by erosion of overburden and entry of ground water into the bedrock; little is known concerning the structural features that would result from such processes acting on clay-rich bedrock. It seems reasonable that peak swelling pressures would progress downward from the ground surface during relief of overburden load and entry of water as a wave front subparallel to that surface, so that most of the swelling of the entire rock mass known to contain shear surfaces would not occur simultaneously. Any hypothesis of swelling pressures as the cause of the shear surfaces must account for (1) the preferred orientation of the shear surfaces approximately parallel to the regional structures and oblique to both the ground surface and the inferred downward-moving front of peak swelling pressures; (2) the closely spaced, anastomosing character of the shear surfaces in both weathered and fresh rock; (3) the similar abundance, spacing, and orientation of the shear surfaces in both weathered rock and in deeply buried, black, unaltered rock well below the zone of weathering; and (4) the general lack of crushing of delicate foraminiferal tests in rock between shears, rock that should have participated in any homogeneous swelling.

It should be noted that some surfaces similar to the bedrock shear surfaces have been observed in clayey surficial deposits, especially in the buried A horizon (S7, fig. 10) exposed in trench A; these surfaces, although similar in appearance to the bedrock shears, do not resemble them in abundance, spacing, or orientation.

To account for the shear surfaces in the mudstone by shrinking or swelling of clays in the zone of weathering requires that two different deforming processes have acted on the rock to produce the structural features here described. The segmentation of the sandstone beds into pods has required movements of many feet in some cases, a distance too great to be a reasonable result only of the swelling of clays. Aside from this shortcoming, the evidence here reviewed casts some doubt that significant swelling and(or) shrinking of clays has occurred throughout the bedrock known to contain shear surfaces.

Sandstone pods.--The sandstone pods of unit B resemble boudins, and the deforming process considered responsible for boudinage structure (Ramberg, 1955) may well have had a major role in producing the structural features now observed in bedrock of the plant site. The mudstone can reasonably be considered to have been less competent than the interbedded sandstone. Upon compression the mudstone failed by shear fracture along a myriad of closely spaced intersecting surfaces, and in a gross sense flowed plastically to produce extension, probably in two dimensions. This extension placed the sandstone beds under tension, resulting in fracturing normal to bedding and ultimately in separation of segments of the sandstone beds; mudstone moved in between the segments as they parted (see Ramberg, 1955, fig. 6c). The result would be much like the present state of the bedrock in the plant site. The shear surfaces are subparallel to bedding, but intersect at low angles to define lens-shaped mudstone fragments. This process would account for the lack of evidence for any considerable rotation of the sandstone blocks.

There is little direct evidence of this process in the bedrock of and near the plant site. However, in some cases several pods of similar lithologies are near each other, and could have been derived from the same bed. Concentration of sandstone pods in zones suggests only limited transport, normal to stratification, of original sets of sandstone beds. In similarly deformed unit B mudstone west of Corral Canyon, a series of three sandstone pods, clearly derived from one bed, record the kind of segmentation here described (fig. 42).

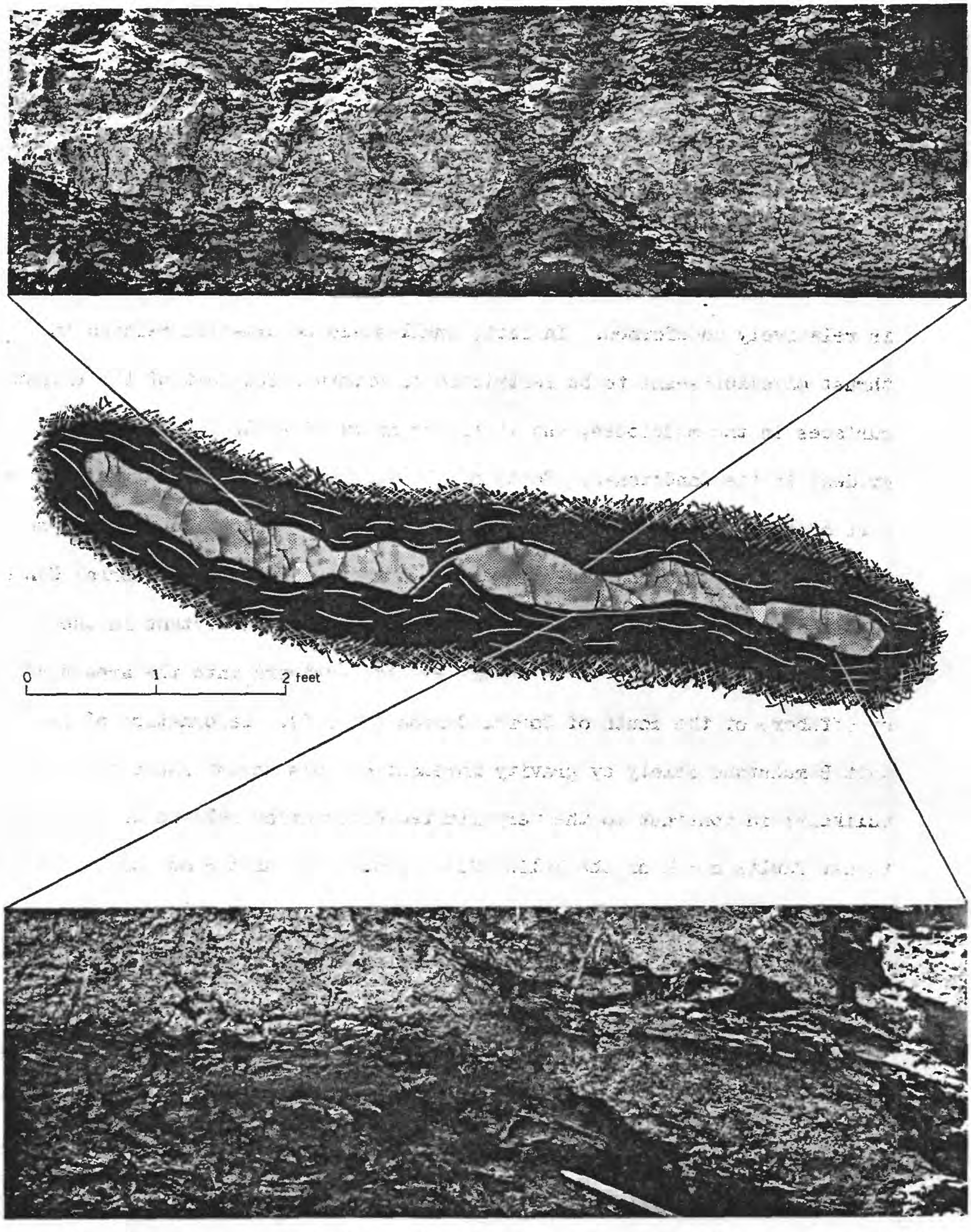


Fig. 42.--Segmented sandstone bed in sheared unit B mudstone, exposed 100 feet north of thrust fault at head of landslide on the coast about 7,200 feet west-southwest of the mouth of Corral Canyon (see fig. 5). The sandstone bed has been segmented by lateral extension of the bed in surrounding mudstone. Shear surfaces in the mudstone are subparallel to the sandstone and bend into the areas of separation (see upper photograph). Fractures in the sandstone are normal (in section) both to bedding and to the direction of extension. Center drawing traced from photograph.

Regional aspects of deformation.--At least three thick and extensive thrust sheets of major significance are present in the rocks north of the Malibu Coast fault in the central Santa Monica Mountains; these may well be gravity slides (Yerkes and others, 1964; Campbell, Yerkes, and Wentworth, ms. in preparation 1965). The rock within the thrust sheets is relatively undeformed. In fact, small-scale deformation related to thrust movement seems to be restricted to within a few feet of the thrust surfaces in the mudstones, and little or no small-scale deformation is evident in the sandstones. South of the Malibu Coast fault in the eastern part of the Point Dume quadrangle $1\frac{1}{2}$ miles west of Corral Canyon, the mass of unit B rock that contains the deformed mudstone exposed at Corral Canyon is directly underlain by a thrust fault of considerable extent in the Malibu Coast zone; this thrust fault extends eastward into the area near or offshore of the mouth of Corral Canyon (fig. 5). Deformation of the unit B mudstone solely by gravity movement of this thrust sheet seems unlikely; in contrast to the very limited deformation related to the thrust faults north of the Malibu Coast fault, the unit B mudstone section (probably at its thickest at Corral Canyon), is intimately deformed throughout its entire structural thickness. In fact, as indicated by exposures in trench 3, the structurally higher bedrock is more greatly deformed, whereas rock high in a gravity thrust sheet could be rafted along without major intimate internal deformation. In addition, there is considerable evidence that this thrust fault is related to Malibu Coast fault deformation, and is not a gravity thrust: it is younger than the probable gravity thrusts north of the Malibu Coast fault as it involves rocks equivalent in age to those that unconformably overlie the thrust-faulted rocks north of the Malibu Coast fault; and its position, structural geometry, and sense of movement, as well as the deformation of the rocks structurally above and below it, are at least consistent with Malibu Coast fault deformation.

Interpretation.--The geometry of the structural elements of the bedrock in and near the plant site is neither chaotic nor unique. Almost all the faults, folds, bedding, sandstone pods, and shear surfaces show generally east-trending strikes and north dips. Deformation in soft sediment slumps is commonly chaotic, so that folds and beds have little or no geometric order: structural elements in known slump deposits commonly have no necessary relation to tectonic structures of the general area (Potter and Pettijohn, 1963, Chap. 6). In very large gravity slides, however, some order to such structures may exist (for example, Page, 1962). But both of these mechanisms, regardless of the degree of internal order of structures, leave unexplained the similarity in geometry of structural elements within the plant site and those in other stratigraphic units in the Corral Canyon site and throughout the Malibu Coast zone.

Tectonic movement along the crustal boundary represented by the Malibu Coast fault could provide a common tectonic origin for the structural features present throughout the Malibu Coast zone; such movement would be expected to produce some degree of structural homogeneity. North-over-south thrusting along the Malibu Coast fault would result in compression of the rocks in the Malibu Coast zone and in translation of the upper (north) block up and over the lower (south) block. Such a process would produce small faults with sense of displacement similar to that of the Malibu Coast fault, and gently plunging folds that trend approximately parallel to that fault. All rocks in the zone should be similarly deformed, as indeed is the case, rather than only a single stratigraphic unit. Some variation in style and degree of deformation would be a reasonable result of the different physical properties of the different rock lithologies that have been deformed: thus, unit B north of fault E is composed largely of sandstone, is jointed, folded on a large scale, and contains some small folds and faults; Monterey Shale is folded, faulted, and brecciated; and in contrast, the clay-rich unit B mudstone south of fault A is intimately sheared as well as faulted.

The deformation of unit B bedrock in the plant site is inferred to be the product both of north-over-south translation and of compression approximately normal to stratification. North-over-south translation is indicated by (1) the general stratigraphic and structural relations across the Malibu Coast fault; (2) by a similar sense of movement on some smaller structural elements in unit B; and (3) in part by the gently plunging, generally east-trending axes of small folds and their generally north-dipping axial surfaces.

The most reasonable model for the major deformation of the rocks of the plant site is north-over-south translation that resulted in folding, some faulting and shearing, and two-dimensional extension of the mudstone along innumerable shear surfaces that produced the boudinage structure of the sandstone. The major deformation of the rocks of the plant site, and of the entire Malibu Coast zone, is thus considered to be the product of deformation related to north-over-south thrust deformation along the Malibu Coast fault.

AGE OF STRUCTURAL FEATURES

Santa Monica fault system

The major amount of movement on important known faults of the Santa Monica fault system occurred between late Miocene and late Pleistocene time, although some relatively minor faulting locally displaced upper Pleistocene deposits (see below under that heading). Direct geomorphic evidence of faulting along mainland parts of the system is lacking. However, both Santa Rosa and Santa Cruz Islands (fig. 1) contain at least one prominent through-going, eastward-trending fault at which stream courses are deflected in a left-lateral sense (Kew, 1927; Rand, 1931); these faults may be related to the Santa Monica fault system.

On a regional scale contemporary activity of the Santa Monica fault system may be inferred from its seismicity. As shown by the analysis of Allen and others (in press), the Santa Monica fault system west of the Newport-Inglewood zone occupies the approximate center of an east-trending band of moderate seismic strain release (fig. 43). The calculated strain release for that part of the system west of about longitude 118°45' (west boundary of Malibu Beach quadrangle) is larger than that of the Transverse Ranges to the north or the

Continental Borderland to the south by a factor of about 4; it is smaller than that of the Santa Barbara area to the northwest and the Los Angeles area to the southeast by at least the same factor. The analysis of Allen and others is based on records of seismicity for 1934 to 1963, and therefore excludes several pre-1934 large-magnitude earthquakes in the Los Angeles and Santa Barbara areas. If corrected to include these shocks, the strain-release map would accentuate the contrast between these areas and the Santa Monica fault system area. Release of strain implies accumulation of strain across the system; however, there has been no investigation made of the amount or rate of local strain accumulation in the Santa Monica fault system.

The records of the Pasadena Seismological Laboratory of California Institute of Technology have been examined by J. H. Healy of the U. S. Geological Survey (written communication, 1964) for data on epicenters of shocks within 100 km (62 miles) of the Corral Canyon site. All known epicenters of shocks greater than Magnitude 2 since 1933, plus those of known shocks prior to 1934, are plotted (fig. 44). This plot shows that numerous small-magnitude shocks (none greater than M 4.7) have occurred along the trend of the Santa Monica fault system in the last 30 years; there is no historic record of a larger shock along the trend. The known error in location of these epicenters (a circle of error with a radius of 5 km or more), the shallow, but unknown depth of their foci (probably in the range of 8 to 12 km), and the known or inferred northward dip of faults of the Santa Monica system, all prevent confident association of any epicenter or group of epicenters with a

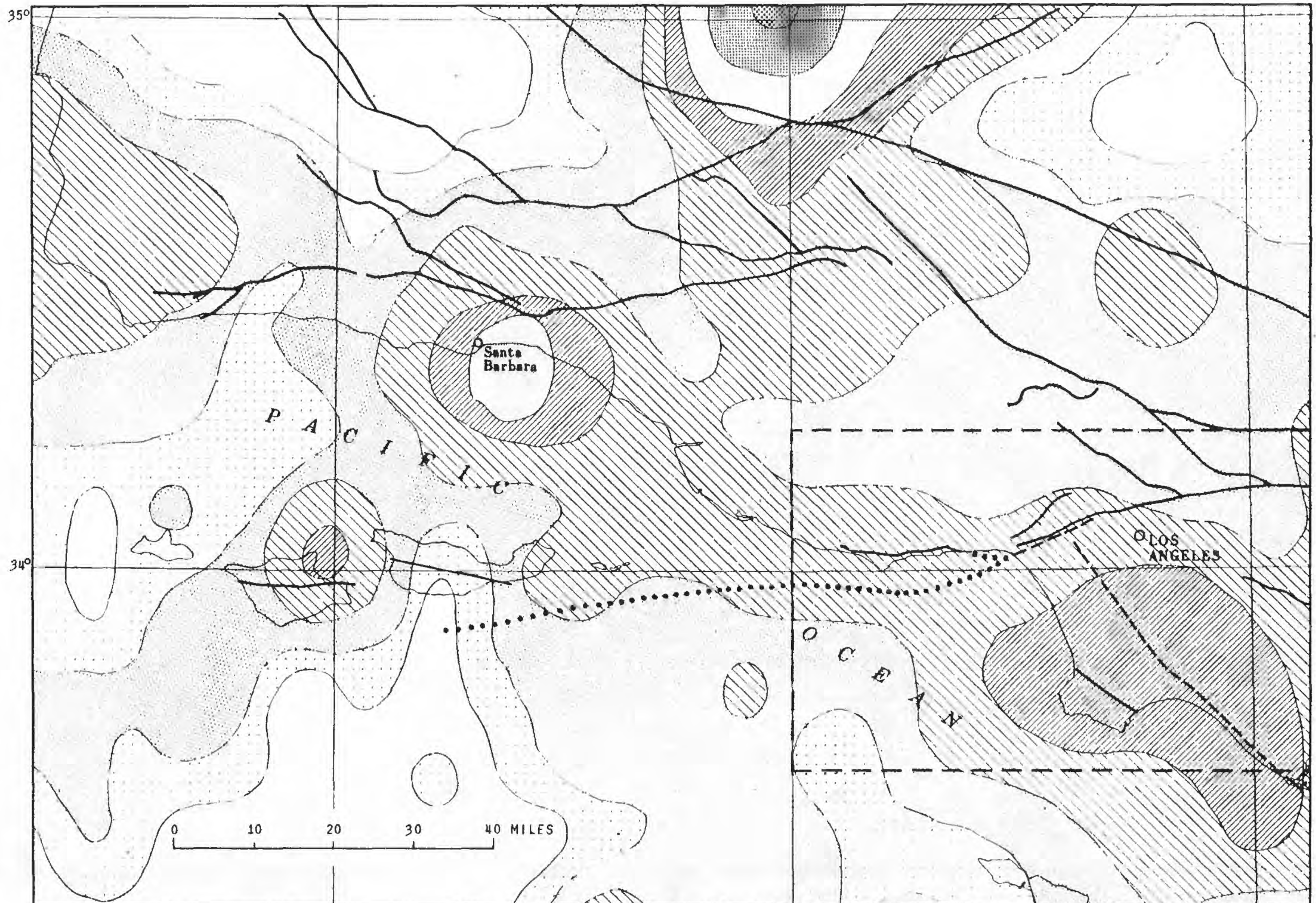


Fig. 43. Strain-release map of part of southern California, 1934 to 1963. Reproduced with permission from Allen, St. Amand, Richter, and Nordquist, in press, pl. 1. Rectangle at lower right outlines "Los Angeles area" of those authors. See facing page for explanation.

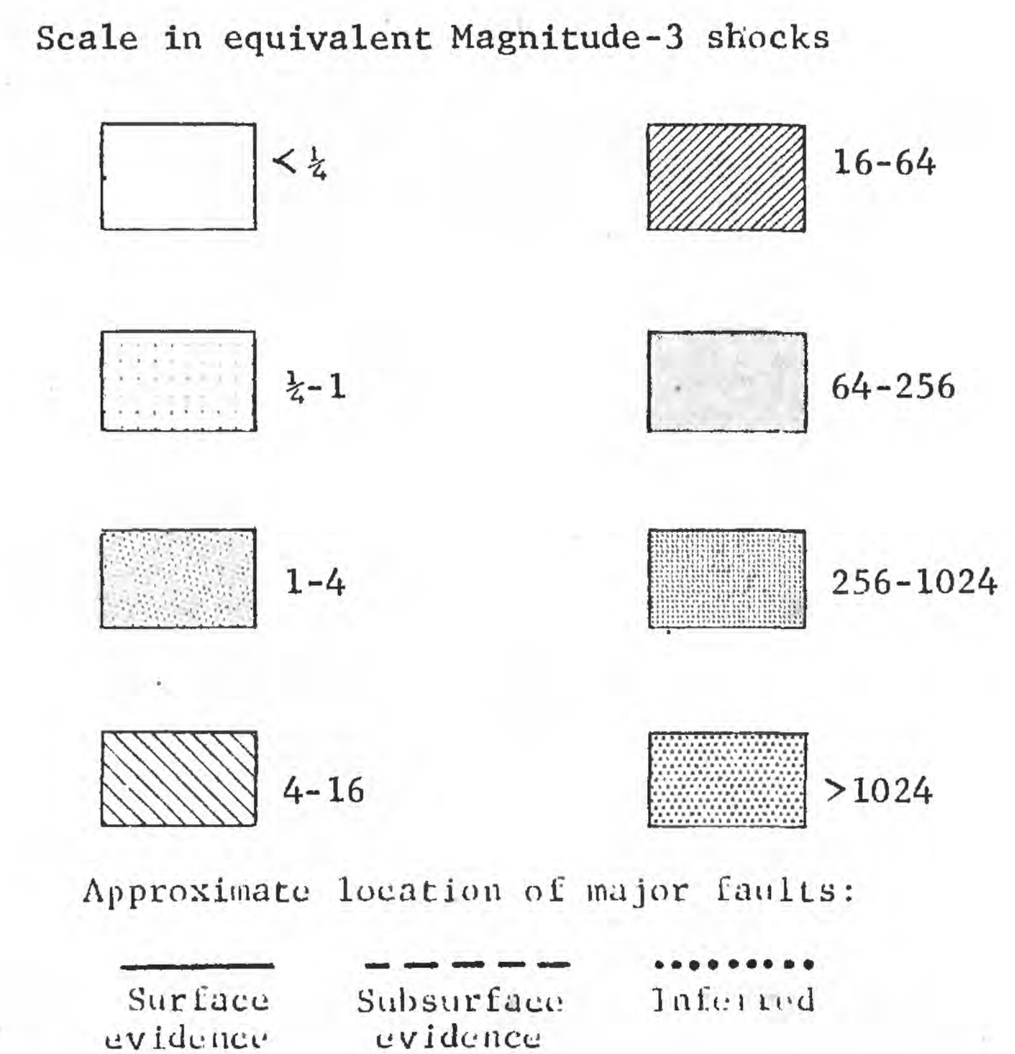


Fig. 43.--Reproduced from part of plate 1 of "Relationship between seismicity and geologic structure in the southern California region" by C. R. Allen, P. St. Amand, C. F. Richter, and J. M. Nordquist, in press. Location and representation of faults modified for this report. Seismic strain release has been calculated by Allen and others from the Richter magnitudes of earthquakes recorded during 1934 to 1963; it is expressed as an equivalent number of Richter Magnitude-3 shocks in such a manner that two earthquakes differing by one unit in magnitude will differ by a factor of about six in strain release, and a Magnitude 7.0 shock will be equivalent to about 1,000 shocks of Magnitude 3.

 (next page 141)

particular fault. On the basis of this record the Santa Monica fault system is inferred to be a source of continuing minor seismic activity (U.S. Coast and Geodetic Survey, 1964), but has not been considered by seismologists to be a prominent source of seismic activity in southern California (Richter, 1959, fig. 6).

On the basis of its continuing minor seismic activity, strain release, inferred strain accumulation, and its inferred relation to the known-active Newport-Inglewood zone of the western Los Angeles basin, the Santa Monica fault system west of the Newport-Inglewood zone is a moderately-active structural feature.

Malibu Coast fault

The age of the Malibu Coast fault is restricted by the youngest bedrock it cuts, upper Miocene Monterey Shale, and its local burial by upper Pleistocene coastal terrace deposits (6 miles west of Corral Canyon and 1.5 miles east, fig. 5) that are probably not displaced by the fault. Major displacement along the fault in this area therefore occurred between late Miocene and late Pleistocene time. However, the base of the terrace deposits is poorly exposed in this area, and displacement of a few feet could be concealed; furthermore, no terrace deposits extend across the fault in the Corral Canyon site, so that later movement there would not be recorded. The base of the Recent stream deposits where they extend across the fault is nowhere exposed. There is, however, no topographic expression of post-Pleistocene displacement along the trend of the fault in the central Santa Monica

Mountains; the trace of the fault can be located only by careful mapping of the bedrock units that are juxtaposed by the fault and that underlie the mantle of surficial material.

If the fault at locality 6 west of Santa Monica (see following discussion of Faults that displace upper Pleistocene deposits and fig. 3) is the eastward extension of the Malibu Coast fault, then in an area 12 miles east of Corral Canyon the fault was active during late Pleistocene time.

Point Dume fault

The east-trending fault exposed only at the tip of Point Dume (fig. 5), herein called the Point Dume fault, probably lies within the Santa Monica fault system. This fault juxtaposes middle Miocene rocks (unit B volcanics and sedimentary rocks on the south, against Monterey Shale on the north) and is unconformably overlain by marine sediments of the upper Pleistocene marine terrace D (about 120,000 years old). Limits on the age of this fault are thus similar to those on the Malibu Coast fault: the interval between late Miocene and late Pleistocene time.

Offshore escarpment: the Anacapa fault

A prominent, east-trending, south-facing, submarine topographic escarpment about $2\frac{1}{2}$ miles south of Point Dume (Emery, 1960, Chart 1) has been attributed to an east-trending, through-going fault named the Anacapa fault by Hill (1928). This feature probably is a fault scarp or modified fault scarp, as are numerous other escarpments of the Continental Borderland (Emery, 1960, p. 77-80). A fault origin, rather than an erosional origin, is suggested for these features by their straightness, steepness and height, common trends, steplike profiles, and linear depressions at the base (Emery, 1960). Where it is best developed, the Anacapa escarpment has relief of about 2,000 feet and a southward slope of 15° to 23°. This is comparable in form to the south front of the Santa Monica Mountains, which has similar relief and a southward slope of 8° to 13° (see Emery, 1960, fig. 48, for a north-south topographic profile just west of Point Dume). The Anacapa scarp is probably underlain by bedrock of Miocene or younger age (Emery, 1960, fig. 62), which thus limits the maximum age of the escarpment. There is little available evidence that bears on its minimum age: its steepness relative to the mountain front may well be due to less modification by erosion because of its submarine environment.

Newport-Inglewood zone

Faults of the Newport-Inglewood zone exhibit right-lateral displacement of 3,000 feet to a "few miles" (Hill, 1954; Rothwell 1958) in rocks of Pliocene age. Movement along the zone late in geologic time is indicated by little-modified fault scarps (Poland and others, 1959, p. 70-76) and by uplift and arching of upper Pleistocene marine and younger nonmarine deposits in hills along the zone. Although no surface faulting has occurred along the zone during historic time, contemporary tectonic activity is indicated by earthquake-related, right-lateral displacement of oilfield facilities in the subsurface (Bravinder, 1942); and by numerous seismic shocks with epicenters along its trend (fig. 44), which include the destructive Long Beach earthquake of 1933 (Richter, 1958, p. 497).

Malibu Coast zone

Faults and folds in the Malibu Coast zone of deformation involve rocks chiefly of late Miocene age or older both north and south of the Malibu Coast fault. West of Santa Ynez Canyon (fig. 3) there are no deposits in the zone that record the interval between late Miocene and late Pleistocene time; however, numerous small-scale pre-Recent faults in or near the zone displace upper Pleistocene terrace deposits at several localities distributed along the length of the zone (see discussion under Faults that displace upper Pleistocene deposits, and fig. 3). There is no geomorphic or geologic evidence of faulting along the zone during Recent time. In the Corral Canyon site the youngest known faults are overlain by undisturbed Recent deposits and(or) undisturbed soils that required most or all of Recent time to develop (see Soils, and later discussion under Upper Pleistocene deformation).

In the coastal area east of Topanga Canyon (the area that includes the locality where upper Pleistocene terrace deposits are faulted along a possible extension of the Malibu Coast fault; see locality 6, fig. 3, and later discussion under heading Upper Pleistocene deformation) the only topographic features that might be related to fault displacement of the ground surface (1) occur only on mesa-like or ridge-top remnants of coastal terraces generally higher than altitude 200 feet; (2) are underlain by pre-Recent deposits; (3) have subdued relief and quite gentle slopes, indicating that considerable time must have been required for erosional modification of any preexisting scarp; and (4) include no known fault displacement of deposits of Recent geologic age (such as stream, flood-plain, or landslide deposits). At locality 6 of faulted upper Pleistocene deposits (fig. 3) at least 15 of the total of 120 feet of vertical separation recorded in the exposure occurred prior to deposition of younger late Pleistocene strata. The stratigraphic, structural, and geomorphic evidence along the trend of the Malibu Coast zone between Topanga Canyon and Santa Monica indicates that folding and faulting in that area were related to differential uplift of the coastal margin, in part preceded and in part followed deposition of the nonmarine cover of the lowest emergent marine terrace, and the youngest faulting apparently took place before the beginning of Recent time (J. T. McGill, written communication, 1965).

Physiographic features.--Faulting that affects the ground surface commonly forms distinctive topographic features, such as fault scarps, offset drainage, and undrained depressions, which under favorable climatic conditions can persist for thousands of years before being destroyed by continued erosion of the landscape. Four of the nine main stream courses that cross through the Malibu Coast zone to the sea in the Point Dume-Malibu Canyon coastal area show eastward, left-handed deflections, subparallel to the trend of the Malibu Coast zone. These deflections in Escondido, Latigo, Solstice, and Puerco Canyons (see fig. 49) range in length from 400 to about 2,100 feet. This sense of deflection of the stream courses is consistent with the left-lateral strike-slip displacement postulated for the Malibu Coast fault (Corey, 1954, fig. 1), and therefore suggest that the stream courses may have been displaced by fairly recent strike-slip fault movement in the Malibu Coast zone. In three of these four canyons, the Malibu Coast fault is north of the deflection, and therefore cannot be responsible for their formation. The deflection of these four stream courses constitutes the sole evidence for recent strike-slip fault movement in the Corral Canyon area, whereas several lines of evidence indicate that the deflections are best attributed to other factors. Although there are four streams with eastward deflections in this area, there are five other stream courses of similar size, including Corral Canyon, that lack such features; furthermore, there is no other topographic evidence that could represent the effects of recent strike-slip movement in the Malibu Coast zone.

A more satisfactory explanation for the eastward deflections of the stream courses is found in the location of erosion-resistant bodies of the deformed Monterey Shale and unit B volcanics in the Malibu Coast zone (fig. 49; note that all the deflections are spatially related to these resistant rocks). The consistent sense of deflection may reflect the influence of ancient spits built by eastward longshore drifting of sediment along the coast when the Pleistocene sea stood higher relative to land. The deflections are entrenched into the upper Pleistocene coastal terraces, indicating that they existed at or soon after the time of emergence of the terraces. Thus, the deflections are most likely pre-Recent in age.

The south front of the Santa Monica Mountains has been interpreted as a scarp closely associated with active uplift of the mountain block along the Malibu Coast zone (Kamb, 1965). The evidence cited for this interpretation consists chiefly of the variable width of the emergent marine terrace platforms between the present shoreline and the base of the mountain front, as compared at Point Dume (total width of platforms about $2\frac{1}{2}$ miles) and at Corral Canyon (total width about 500 feet). However, the remnants of the lower of the emergent marine terraces (terraces C and D) north of Point Dume are wide because the point itself, $1\frac{1}{2}$ miles south of the otherwise uninterrupted east-west trend of the coastline (fig. 1), is underlain by resistant volcanic rock (fig. 49) that has protected these terraces from removal by continuing marine erosion (as was noted by Davis, 1933, P. 1092). In contrast, marine erosion during terrace M time caused retreat of the seacliff at the longitude of Point Dume to a position north of and parallel to the trend of present east-west coastline. The retreat of the terrace M seacliff was probably due to a lack of protection from marine erosion by the resistant volcanic rock now exposed at the tip of Point Dume. The south front of the mountains clearly represents the inland limit of marine erosion that formed the higher terrace platforms. The position of this limit was controlled largely, if not entirely, by the narrow, east-trending belt of resistant rocks (siliceous Monterey Shale and unit B volcanic rocks) that almost everywhere lies immediately south of the Malibu Coast fault (figs. 5, 49).

The south front of the mountains may represent a fault scarp, considerably modified by subaerial erosion, that is related to uplift of the mountains along the Malibu Coast zone. If so, such a scarp is older than terrace M (more than a maximum of 280,000 years), for the terrace transgresses the Malibu Coast zone just west of Malibu Canyon (fig. 49) and west of Point Dume without recognizable differential displacement. The postulated fault scarp cannot therefore be attributed to active uplift of the Santa Monica Mountain block along the Malibu Coast zone, nor has perceptible relative uplift of the Mountain block occurred along the zone since formation of the terraces.

Upper Pleistocene deformation.--Upper Pleistocene deformation in the Malibu Coast zone includes fault displacement of coastal terrace deposits and warping of terrace C in the Point Dume-Malibu Canyon coastal area.

Faults that displace upper Pleistocene deposits.--Upper Pleistocene terrace deposits have been faulted at seven known localities in or near the Malibu Coast zone east and west of the Corral Canyon site (fig. 3), as well as within the site. The occurrence of these localities along some 20 miles of the zone suggests that other faults of similar age and character are present in the area, but have not been recognized because of the general lack of good exposures.

Localities east and west of Corral Canyon site.--Locality 1: Upper Pleistocene nonmarine terrace deposits are caught in a fault sliver about 12 feet in exposed height between two south-dipping faults; the sliver is bounded by middle Miocene volcanic rocks (figs. 45 and 46). Located 3.8 miles west of the mouth of Corral Canyon in the Malibu Coast zone; 1.2 miles northwest of Paradise Cove (fig. 5).

Locality 2: The base of upper Pleistocene coastal terrace deposits is vertically separated about 8 feet by reverse faults (unpub. detailed mapping of J. T. McGill; Yerkes and others, 1964). Located at Parker Mesa, about 9.6 miles east of the mouth of Corral Canyon.

Locality 3: The base of upper Pleistocene coastal terrace deposits is vertically separated about 14 feet by a fault that dips 40° east-southeast (unpub. detailed mapping of J. T. McGill; Hoots, 1931, pl. 16). Located on the east wall of Santa Ynez Canyon, about 10.5 miles east of the mouth of Corral Canyon.

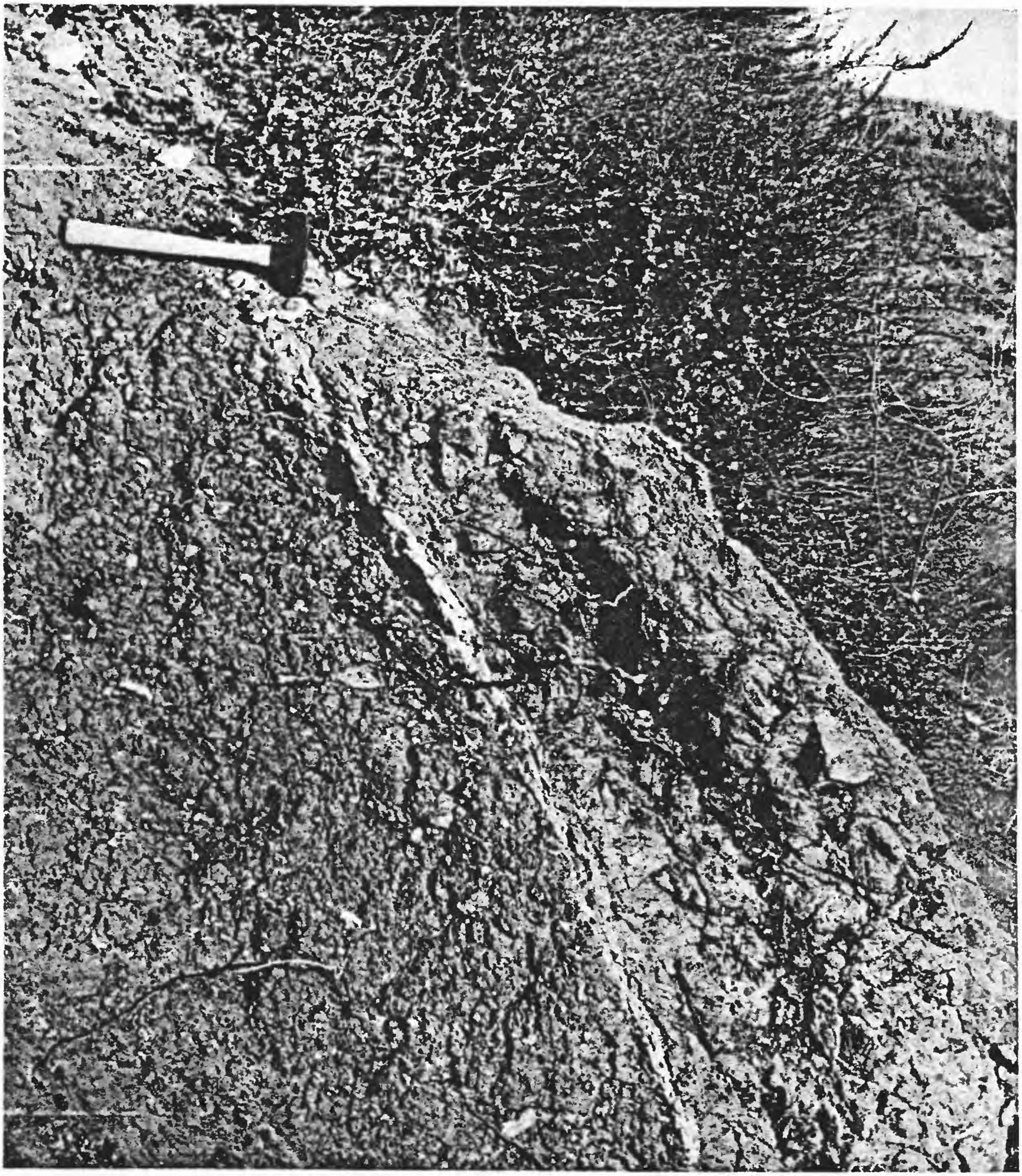


Fig. 45.--Details of fault (white line extending diagonally downward to right from hammer) that juxtaposes upper Pleistocene terrace deposits on left against middle Miocene volcanic rocks on right. Locality is 3.8 miles west of Corral Canyon in Point Dume quadrangle (locality 1 of fig. 3). See figure 46 for general view of fault sliver, and figure 5 (1.2 miles northwest of Paradise Cove) for geologic relations.

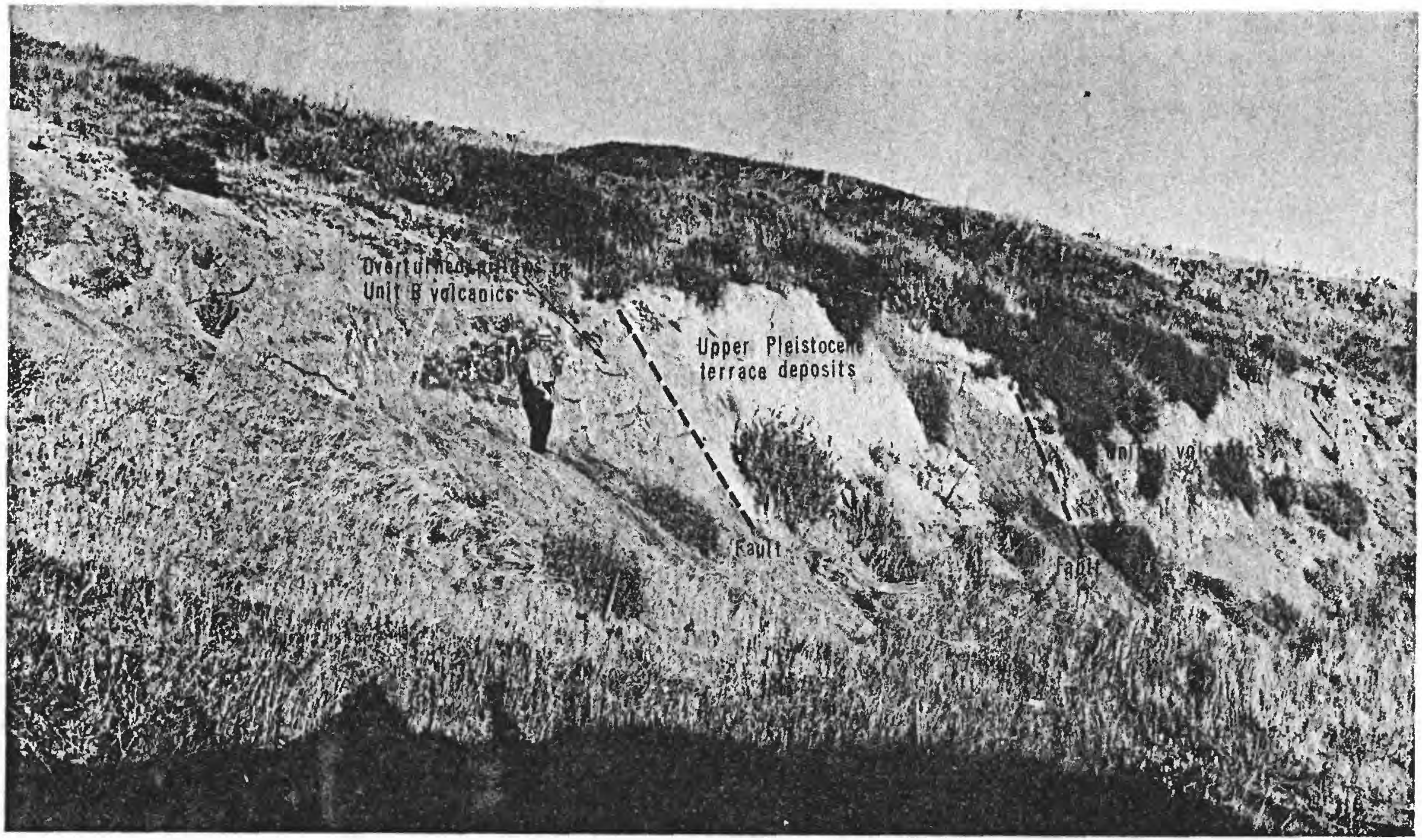


Fig. 46.--Sliver of upper Pleistocene terrace deposits faulted into overturned middle Miocene volcanic rocks at locality 1 (fig. 3), 3.8 miles west of Corral Canyon. Details of fault at right shown in figure 45.

Locality 4: The base of upper Pleistocene high-level coastal terrace deposits is vertically separated at least 8 feet by a reverse fault that trends N. 38° W. and dips 67° S. (unpub. detailed mapping of J. T. McGill). Located about 11 miles east and 1 mile north of the mouth of Corral Canyon.

Locality 5: The base of upper Pleistocene terrace deposits is vertically separated at least 18 feet, and probably about 35 feet, by a steeply north(?)-dipping fault. A small hill with relief of about 20 feet above the surrounding terrace surface and underlain by an anticline in bedrock was exposed immediately south of the fault, but was removed by grading operations in 1945 (unpub. detailed mapping and written communication of J. T. McGill). Located about 3,000 feet east and 400 feet north of the intersection of Pacific Coast Highway and Sunset Blvd., 10.8 miles east and 0.5 mile north of the mouth of Corral Canyon.

Locality 6: The base of upper Pleistocene coastal terrace deposits is cut by two branches of a fault with aggregate vertical separation of about 120 feet (unpub. detailed mapping of J. T. McGill; see Hoots, 1931, pl. 16, for field relations). One fault at this locality is vertical and the other dips about 55° north; at the level of Pacific Coast Highway the faults juxtapose marine Pliocene strata on the north with marine and nonmarine upper Pleistocene deposits on the south; these faults may represent an eastward extension of the Malibu Coast fault (fig. 3). Located in the seacliff at the mouth of Potrero Canyon (between Temescal and Santa Monica Canyons), 12 miles east of the mouth of Corral Canyon.

Charcoal from marine terrace sand displaced by this faulting was dated by radiocarbon methods at greater than 35,000 years by the U. S. Geological Survey (sample W-1034, Ives and others, 1964, p. 50). On the east wall of Potrero Canyon at this locality marine terrace sands are preserved on the bedrock platform on the downthrown (south) side of the vertical fault, but are missing because of erosion within about 100 feet of the fault on the upthrown (north) side. The stratigraphic and structural relationships here indicate that at least 15 feet of vertical separation occurred on the fault prior to deposition of the overlying marine(?) and nonmarine deposits. The latest movement on this fault was parallel to the dip, as shown by slickensides (J. T. McGill, written communication, 1965).

A very gentle, smooth, scarplike slope is present on the coastal terrace surface just east of the mouth of Potrero Canyon; it is alined with, and just north of the probable trace of the vertical fault exposed in the seacliff at locality 6. The slope is inclined as much as 8° to 10° southward, thus interrupting the general 2° southerly gradient of the terrace surface, and it has a relief of about 25 feet in a horizontal distance of about 400 feet. This scarplike slope may have resulted chiefly from folding of the marine terrace platform and its covering deposits rather than from long-continued erosion of a once-vertical fault scarp (J. T. McGill, written communication, 1965).

Locality 7: A very subdued east-trending low scarp about 0.4 miles long is alined with the features of locality 6 about 14.6 miles east of the mouth of Corral Canyon (Poland and others, 1959, pl. 2); this feature may be related to the faults exposed at locality 6.

The age of faulting at these localities can be established only within broad limits. The maximum age of faulting (or age of youngest faulted deposits) is more than 35,000 years, the age of faulted marine sand at locality 6. The minimum age of faulting (or age of oldest undisturbed deposits that overlie the faults) is reasonably well controlled only at Corral Canyon (for details see later description in this section, Deformation of terrace C in the Corral Canyon site), where the basal part of undisturbed nonmarine alluvial-colluvial terrace cover is about 10,000 years old.

The youngest faulting known in the Malibu Coast zone is late Pleistocene, pre-Recent in age as indicated by:

1. Topographic features, which might be related to fault displacement of the ground surface in the area between Topanga Canyon and Santa Monica, are underlain by deposits of pre-Recent age and have subdued relief and very gentle slopes, implying a considerable period of time during which erosion modified any pre-existing scarps;
2. All known cases of faulted upper Pleistocene deposits occur only on mesa-like or ridge-top remnants of coastal terraces;

3. Where Recent nonmarine terrace cover has been preserved and exposed, as in the Corral Canyon site, it is not displaced by faults in underlying deposits; and

4. Stream, flood-plain, and stream terrace deposits are not known to be displaced on the projections of faults.

Deformation of terrace C.--Terrace C is one of several emergent marine terraces that characterize the Point Dume-Malibu Canyon coastal area. This area is part of that described by Davis (1933), who differentiated two main coastal terraces, Malibu (terrace M of this report) and Dume (terrace D of this report). Terrace C was first recognized when its buried shoreline angle was exposed in test trench B at the Corral Canyon site. In order to determine the relations of this terrace to Davis' terrace sequence, the shoreline angles of the terraces in the Point Dume-Malibu Canyon coastal area were mapped and their altitudes determined by jacob staff and rod (fig. 49). The accuracy of location of the shoreline angles varies due to poor exposures and the limited number of control points. The limits of error for the altitude of the "C", "S", and "P" control points (fig. 49) range from about ±0.5 feet for the shoreline angle of terrace C in gully A to as much as ±7 feet for the "P" point on terrace C in Marie Canyon. Average error of altitude for surveyed control points is probably about ±2.5 feet.

The map (fig. 49) shows that the altitude of the shoreline angle of terrace M is about 260 feet, that of terrace D is about 110 feet, and that terrace C is intermediate between terraces D and M, with shoreline angle between 151 and 176 feet altitude. The map further indicates that terrace C is warped in the Point Dume-Malibu Canyon area. The shoreline angle of this terrace rises rather uniformly eastward from about 160 feet altitude on Point Dume (fig. 49) to 176 feet in trench B at the Corral Canyon site (fig. 11), and thence slopes downward uniformly to the east to an altitude of about 170 feet in gully A, to about 160 feet in Marie Canyon, and to about 151 feet in Malibu Canyon. Thus, terrace C attains its maximum altitude (for a total of 25 feet relief in a distance of 2 miles) in the Corral Canyon area, where the terrace platform is also disrupted by faulting and possibly by landsliding. The altitude of the shoreline angle of the next higher terrace (M) is poorly defined, consequently it cannot be determined whether it is warped to the same or a greater extent than terrace C. The platform of the lower terrace (D) has been destroyed by coastal erosion in the Corral Canyon area; however, the relative position of the shoreline angle of this platform in the Point Dume area suggests that this terrace is less deformed than terrace C.

The age of shell material from marine deposits on terraces D and C has been determined (see Coastal terrace deposits under heading Geology of the Corral Canyon site; and Appendix C). Shells from deposits on terrace D at locality M 1710, $1\frac{1}{2}$ miles west of Corral Canyon, have an estimated maximum age of 130,000 years; and shell material from deposits on terrace C at gully B, Corral Canyon site, have an estimated maximum age of 280,000 years. It is believed that differences in ages determined by this method (Uranium series disequilibrium) are probably real, thus reinforcing the long-standing belief that the higher, more dissected marine terraces in an elevated sequence are older than the lower terraces.

Deformation of terrace C in the Corral Canyon site.--The gently sloping, relatively smooth terrace surface east of Corral Canyon conceals a record of complex upper Pleistocene events (exposed in the test trenches, figs. 10 to 14) that include (1) planation of the marine platform of terrace C and deposition of marine deposits on the platform; (2) landsliding of Monterey Shale that toed above the old sea cliff of terrace C and accumulation of Monterey Shale rubble near the old seacliff; (3) disruption of the marine platform and the overlying sand and gravel along steep rupture surfaces near the shoreline angle and coincident(?) disruption (with at least 17 feet of vertical separation), on a gently north-dipping slip surface, of the terrace platform and marine terrace deposits in gully C; (4) formation of a soil on the sand, followed by erosion, which truncated the soil and the record of the disruption; (5) deposition of more sand and formation of a soil on that sand; (6) stream erosion of the southwest part of the terrace platform by an ancient channel of Corral Creek; (7) accumulation over most of this area of brown to black sandy clay by colluvial-alluvial processes following truncation of older soils and units; (8) formation of a Chernozem soil on the colluvial-alluvial unit; and (9) dissection of the coastal terrace by gullies A, B, and C. Because of the likelihood that terrace C was disrupted chiefly by faulting, the details of these events, insofar as they can be determined, are important in order to establish their sequence and relative ages.

The bedrock platform and marine deposits of terrace C are well exposed in trenches B, C, and D (fig. 12) as well as in the bulldozer cuts and farther south in gully C (fig. 14); an exposure of the shoreline angle of terrace C, at an altitude of 176 feet, is also present in trench B. For most of its exposure the contact between the sand and gravel and the underlying bedrock (rubble near trench F) is abrupt and sharply defined, and is quite flat and lacking in irregularities.

The sand and gravel overlying the bedrock platform of terrace C is of three types. The sediment overlying the north end of the platform exposures in trenches B, C, and D (unit Sdm) and the lower part of the deposit in gully C is loose, quite well sorted, crudely bedded, fresh colored, and lacks clay. Fossils indicative of a shallow-water nearshore marine environment were present in the marine sediment in trenches B and C, gully B, and in a temporary trench (excavated and filled during excavation of trench F and associated cuts), in gully C (Appendix B: samples CW 115, C-2, and Y CC-11E). In contrast, the upper part of the deposit in gully C contains a well-developed soil profile (Soils-Prairie Planosol Great Soil Group) in which the B horizon is oxidized and contains considerable clay. The third type (unit G-1) is south of unit Sdm in trenches B, C, and D; it is not obviously marine as is Sdm, and was initially considered to be a separate deposit, probably of different origin. This unit (G-1) contains abundant clay, is moderately to poorly sorted, and in all exposures exhibits south-dipping imbrication of the gravel, but lacks fossils and perceptible bedding. Consideration of these features and their physical continuity with unit Sdm (no well-defined contact between the two units) leads to the conclusion that unit G-1 is probably marine. The differences in character between the two may be due largely to the addition of clay to unit G-1 during soil formation; unit Sdm, in contrast, was probably shielded from such changes by its cover of Monterey Shale rubble (units T and rbl).

Rubble that consists almost solely of angular fragments of Monterey Shale in a matrix of finer fragments of shale, clay, and powdery calcium carbonate overlies the marine sand and gravel (unit Sdm) near the old seacliff in trench B. In trench D the rubble interfingers with the marine sediment, and in trench B similar tongues of Monterey Shale fragments extend into the marine sand and contain a matrix of well-sorted sand. Thus, at least some of the Monterey Shale rubble (units T and rbl) is contemporaneous with deposition of the marine sediment. Tongues and lenses of the rubble also occur higher, within the sand of unit Sd.

The source of this rubble is clearly the Monterey Shale present up slope (trenches B and C), north of fault A. Exposures in trenches A, E, and B indicate that thin-bedded, blocky-jointed Monterey Shale, identical in lithology to the rubble material, is involved in a landslide that extends at least across those three trenches (see fig. 4 and later section on Landslides). The toe of this landslide is exposed in trenches A and E, and its base in trench B lies 15 feet north of the old seacliff of terrace C (at station 85 feet, fig. 11). Movement of this landslide could well have supplied the debris of which units T and rbl are composed, although creep and fragment-by-fragment accumulation may also have been involved.

A fairly homogeneous deposit of sand (unit Sd) overlies the marine sand and gravel of terrace C in trenches B, C, and D. The sand is reddish brown, slightly silty, fine- to medium-grained, and moderately sorted. It extends northward over the Monterey Shale rubble and contains tongues and lenses of that rubble. The exact contact of unit Sd with unit G-1 in trench B is not obvious, but is marked by an absence of gravel above the contact and a change from medium- and coarse-grained sand below to fine- and medium-grained sand above. In trench C and the northern part of trench D gravel extends up into the basal 6 to 12 inches of unit Sd: both the matrix contact and the top of the gravel are mapped there (fig. 12). The gradational contact with the sand and gravel (unit G-1) below indicates that probably no great time break separated the deposition of the two units, which further substantiates the approximate contemporaneity of deposition of units T and rbl with units Sdm and G-1.

The depositional origin of unit Sd is not entirely clear; however, the gradational contact with marine sediment below, the fine grain size and fair sorting of unit Sd, and the presence of probable dune or beach sand above (see later description of unit Sd_1), combined with a lack of organic material, bedding, and gravel lenses, indicates that it is probably of beach or dune origin, rather than an alluvial or colluvial deposit. The presence of a few percent angular Monterey Shale fragments in the sand and its moderate sorting favor a beach origin,whereas the tongues and lenses of Monterey Shale and rubble and lack of fossils may favor a dune origin. The red-brown color and very slight clay content are the result of soil formation on the sand.

Trench D exposes a more complex sequence of surficial deposits than do the other trenches. Well-sorted, fine- to medium-grained sand (Sd_1) overlies unit Sd at a fairly flat contact. In trench D the contact is sharp only at the north end (solid line, fig. 12), and somewhat gradational elsewhere. In a temporary exposure between trenches C and D this contact was flat and sharply defined, and exposed for some 25 feet in north-south direction. The loose, clean, well-sorted character of this sand suggests dune or beach origin. Soil formation has resulted in a reddish-brown color and very slight clay content in the upper part of the unit.

The contact between units Sd and Sd_1 is an unconformity as shown by truncation of a soil horizon (horizon S 17, a "B" horizon; see Profile 3, table 1; and fig. 12); truncated vertical veins of calcium carbonate that extend up to, but not into unit Sd_1; and the sharp nature of the contact. The agent of erosion is unknown; wind erosion could be involved, but if unit Sd_1 is marine, then marine erosion is indicated.

Although the bedrock platform at the base of the marine sand and gravel of terrace C is quite flat and regular for much of its exposed extent, prominent exceptions are the zone of disruption exposed in trenches C and D and about 20 feet south of the terrace C shoreline angle in trench B (fig. 12), and the disruption that has occurred on the slip surface exposed in trench F and the related cuts (fig. 14).

In trench B the otherwise regular contact between bedrock and the overlying marine sand and gravel (units Sdm and G-1) is interrupted between 117 and 123 feet (fig. 11) by a depression that is U-shaped and about 4 feet wide by 3 feet deep in north-south section on both faces of the trench. At the north edge of the depression bedrock overhangs the sand and gravel, and forms an acute angle of about 50° with the bottom of the depression (figs. 11 and 47). The south wall of the depression is vertical and is nearly coincident with a vein of powdery calcium carbonate that extends from a fault in bedrock upward through units G-1 and Sd, a distance of about 9 feet.

The bedrock platform exposed in trenches B, C, and D and the contact between the overlying units (G-1 and Sd) are disrupted along several vertical to steeply north-dipping slip surfaces (fig. 12). In bedrock these slip surfaces form lithologic boundaries, are marked by very thin zones of gouge or intensely sheared rock, veins of powdery calcium carbonate, and are consequently mapped as small-scale faults (calcium carbonate veins are not indicated in the figures where they occupy known faults in bedrock). In the unconsolidated surficial deposits (units G-1 and Sd) the slip surfaces are generally poorly defined: locally they clearly are very narrow zones that disrupt the texture of the sand, and in a number of places they are occupied by veins of powdery calcium carbonate (such veins also occur where there is no evidence of a rupture). In some places the slip surfaces form steep contacts between bedrock and unit G-1 and between units G-1 and Sd, locally with evidence of disruption of the sediment along them; in other cases the location of the slip surfaces can only be inferred between displaced contacts. The slip surfaces in the sand and gravel are not marked by slickensides; the granular, unconsolidated sediment does not support such evidence of shearing within it.

The slip surfaces can be correlated in a general way between trenches B and C (trench C is about 20 feet east of B; see fig. 7) and between trenches C and D (trench D is about 40 feet east of trench C) and have fairly consistent apparent senses of movement.

The most prominent slip surface, at about station 54 feet in the three trenches (fig. 12), generally forms the north margin of unit m-4; the apparent sense of movement is south-side-up (as seen in north-south section) with vertical separations ranging from 1½ to 3 feet on the bedrock surface and ½ to 4 feet at the top of unit G-1.

In trenches B and C the slip surface at station 54 feet in part forms the south boundary of a depression in the bedrock surface; in trench B the depression is U-shaped and about 4 feet deep and 3 feet long; in trench C the depression is roughly V-shaped and about 1½ feet deep and 1 foot wide at the top. In trench D the north side of the depression is absent; rather, the slip surface at 54 feet forms a north-facing step with relief of about 2½ feet at the bedrock surface. The north side of the depressions in trenches B and C coincides with north-dipping faults that form sheared lithologic boundaries in bedrock, and on which the bedrock surface overhangs the surficial sand and gravel (unit G-1; fig. 12). In trench B this overhang forms an acute angle of about 50° with the bottom of the depression (figs. 11 and 47); in the extreme apex of the overhang several small pebbles from unit G-1 were found on the slip surface almost, if not entirely enclosed within the mudstone of the bedrock.

Some evidence of deformation is found in the sand and gravel (units Sdm, G-1) that overlie the depression in trench B. Many of the cobbles and boulders in and above the north side of the depression have long axes that lie at unusually steep angles for primary deposition (45° to 80°; south-dipping). In addition, slightly south of the depression,

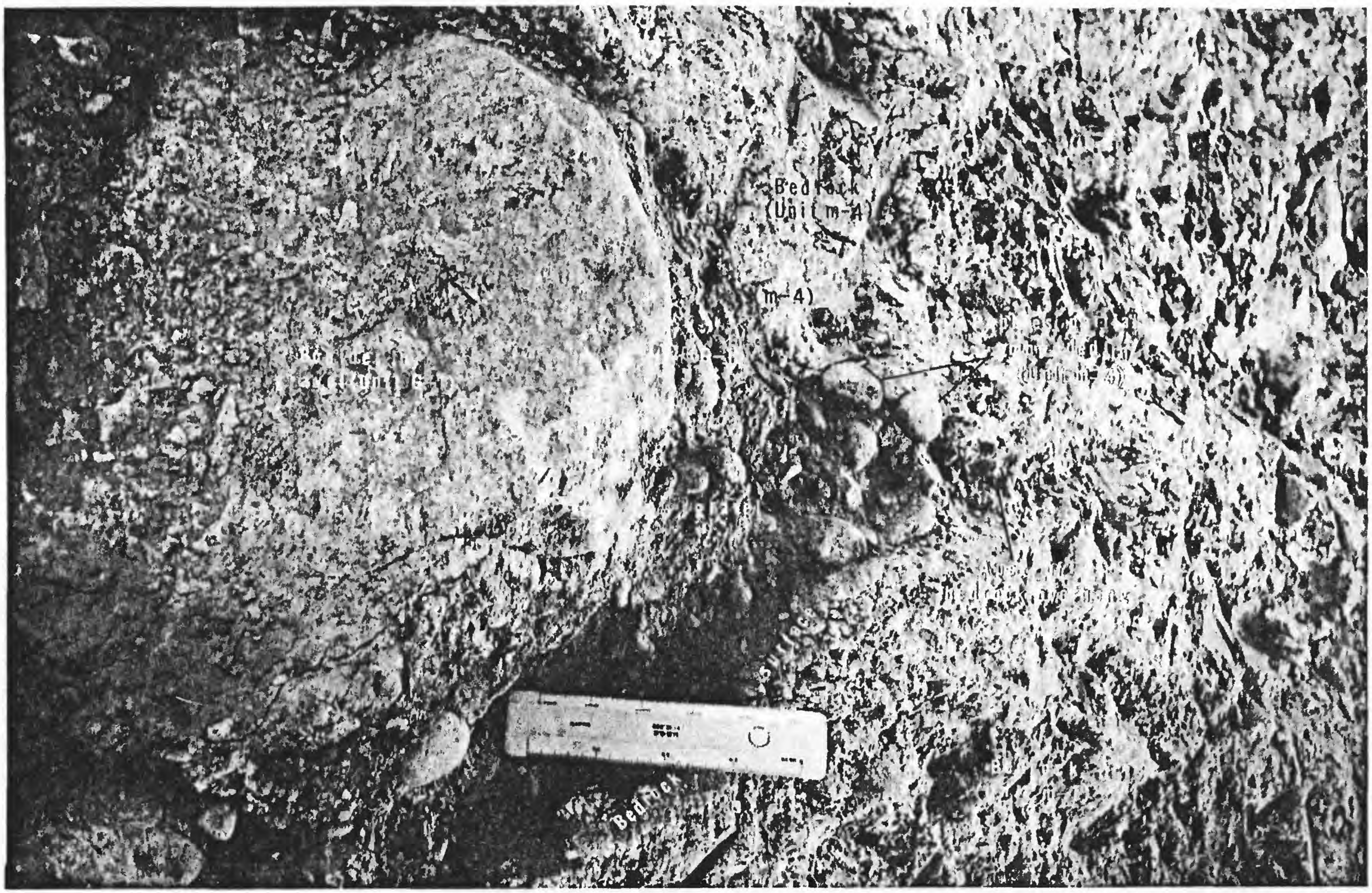


Fig. 47.--Overhanging bedrock at base of north side of the bedrock depression in test trench B, viewed toward northwest (at 118 feet, west wall, fig. 11; note that this face is viewed toward east in fig. 11). Sand and gravel of surficial deposits (unit G-1) overlie bedrock (unit m-1) along a flat contact at the scale (7 inches long); the axis of the boulder at left is near vertical. Sand and gravel extend into the apex of the acute angle (at right) formed by the flat contact and the south edge of the overhanging bedrock at upper center. Above the apex the bedrock partially encloses two pebbles of unit G-1.

near station 129 feet (fig. 11) a cobble and a boulder in unit G-1 are broken into 3 and 2 pieces, respectively, and displaced north-side-down. The upper contact of unit G-1 over the south edge of the bedrock depression in turn exhibits a small, steep-sided depression that is probably a reflection of the displacement that formed the bedrock depression.

A large slice of bedrock (unit m-4) is raised relatively up and southward along a second, north-dipping slip surface that is present in all three trenches 4 to 10 feet south of the prominent slip surface at station 54 feet. The bedrock platform is vertically displaced between 2 and 8 inches on this north-dipping surface. An 8-inch, south-facing step in the upper contact of the sand and gravel (unit G-1) at station 64 feet in trench C may correlate with this second slip surface. The 2 foot-high, rounded "step" or bulge in this contact at a similar position in trench D, although clearly not ruptured, could well be the result of intergranular movement of the sediment. This bulge may thus be related both to the north-dipping slip surface at station 58 feet in the bedrock in trench C, and to the bedrock high at about station 54 feet in trench D; the latter may also represent an upward, plastic bulging of bedrock. Such mass deformation of the bedrock, accompanied by deformation of the sand and gravel (unit G-1) could account for the greater thickness of that unit at and south of the bedrock bulge than the thickness north of it. The bedrock high is probably a very local feature, for within 3 feet from its exposure on the east wall of trench D it is a small vertical tongue of crumbly mudstone bedrock about 6 inches wide at the base and 2 inches wide at the top, which extends about 18 inches above the general level of the bedrock platform. This tongue of bedrock is the only evidence of disruption of the bedrock surface on the west wall of trench D, although the upper contact of unit G-1 is separated 2 feet vertically, north-side-down, at the prominent slip surface at station 54 feet. The bedrock high in trench D might possibly be a primary erosional feature on the marine-cut platform, but if so it would be the only such bedrock high known on that surface over the considerable extent of exposure of the platform, and would not be consistent with other relationships herein described.

The exposures in trenches C and D demonstrate that the bedrock depression in trench B cannot be due to an erosive origin. The relative positions of the disruptions are consistent from trench to trench; displacements are present not only at the bedrock surface, but at the upper contact of the sand and gravel; and the sharp delicate shapes of the features in the soft mudstone would be unlikely to survive significant erosion.

North-south compression, possibly with a small component of lateral movement, could account for much of the deformation indicated by the evidence in these trenches; such compression could relatively lift the slice of bedrock (unit m-4) between the two slip surfaces like a "pumpkin seed", and locally squeeze it out of shape to produce the bedrock high in trench D and the bulge in the overlying sediment. Such deformation could have been followed by the displacement that formed the north side of the bedrock depression in trenches B and C. This interpretation would not directly account for the fact that on the west face of trench D the upper contact of the sand and gravel (unit G-1) is separated on the slip surface about 2 feet vertically (up on the south, as on the east face of the trench), whereas its base (contact with bedrock) is only locally interrupted by the 18-inch "tongue" of bedrock previously described, and otherwise forms a relatively uninterrupted surface. Perhaps some small component of lateral movement is required on the slip surface to account for this feature.

In the model of the deformation here described the bedrock responded to the deformation by rupture and slip along discrete surfaces; the relatively unconsolidated surficial sand and gravel probably failed in part by intergranular movement and in part by slip along discrete surfaces.

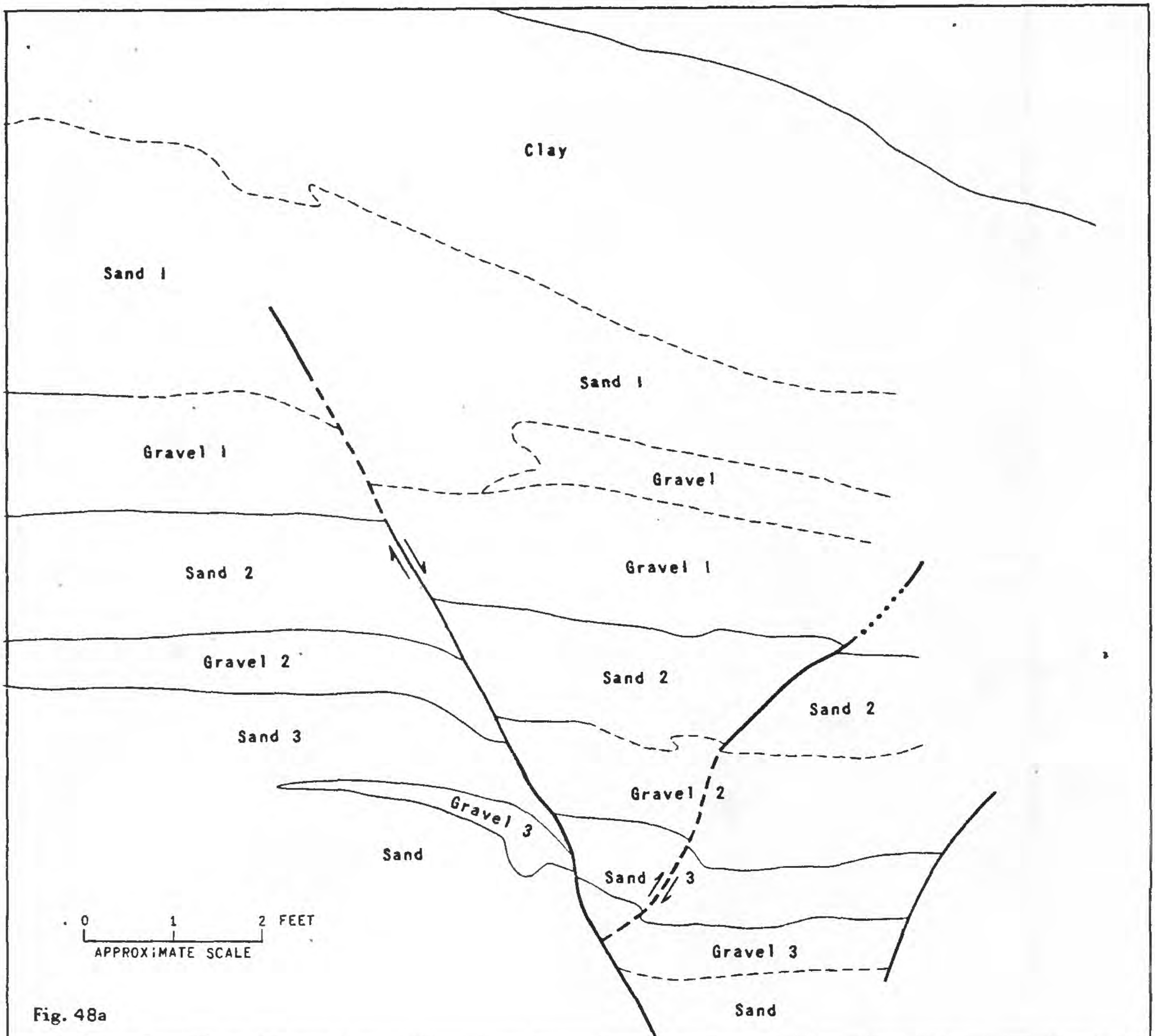
A slip surface along which rubble of Monterey Shale has moved relatively southward up and over marine deposits of terrace C is exposed in bulldozer cuts and trench F in gully C (fig. 14). The slip surface separates very compact rubble of Monterey Shale from underlying sheared black mudstone of unit B in trench F; on the walls of the bulldozer cuts in the gully the Monterey Shale rubble overlies the marine sediment at the slip surface, which is there marked by a zone of powdery calcium carbonate, rare fragments of unit B mudstone, and disturbed sand of the marine terrace deposits immediately below. Although coincident with the projected trace of fault A, the slip surface in gully C has a more easterly strike, N 65° to 85° E, and dips 30° to 45° northward.

A sharply defined, fairly flat contact without small irregularities, a marine platform, is cut on the Monterey Shale rubble, and is overlain by a normal, undisturbed section of marine sand and gravel of terrace C (this sediment contains shell fragments and a few pholad(?)-bored boulders of Monterey Shale). Below the slip surface to the south similar sediment is exposed, and in an earlier cut (now backfilled) the normal base of this sediment on the marine platform over unit B mudstone and sandstone was exposed at about altitude 140 feet. Thus, the vertical separation of the marine platform across the slip surface is about 17 feet (fig. 14).

The northern part of the marine platform and overlying marine deposits dip gently northward, and as exposed in the bulldozer cut in the east wall of the gully the stratigraphic units within the marine sand and gravel bend near the slip surface (fig. 14, station 75 feet), as if drag-folded by the movement of the slip surface. Thus, displacement on the slip surface occurred after the marine platform was cut on bedrock and the marine sediment was deposited; the marine sediment was moved with the upper, upthrown block without much internal deformation.

Age restrictions on the deformation near the shoreline angle of terrace C in trench B and the deformation for which evidence is exposed in gully C are similar. In both cases deformation post-dates the marine deposits of terrace C, because they are disrupted; the disruption is therefore less than a maximum of 280,000 years old (see coastal terrace deposits). The disruption near the shoreline angle in trench B does not disturb unit CF or soil Profile 1 developed in it, and therefore is older than some 8 to 10 thousand years (see section on Soils). The minimum age of this disruption is further restricted by the time necessary for the formation of the unconformity between units Sd and Sd_1 (trench D), deposition of unit Sd_1, and development of the soil in that sediment (Profile 3, S13 through S16, table 1, and fig. 12). The time required by these processes is unknown, but the soil formed in unit Sd_1 probably required several thousand years to form (see Prairie Planosol Great Soil Group). The exposures are not adequate to demonstrate whether the slip surface in gully C disrupts or is truncated by the alluvial-colluvial deposits that underlie the coastal terrace surface east and west of gully C and(or) the Chernozem soil (Profile 4; equivalent to Profile 1). However, the complete lack of topographic expression of the deformation on the coastal terrace east and west of gully C strongly suggests that the disruption in gully C preceded deposition of the alluvial-colluvial deposits. Thus the deformation of terrace C, both near the shoreline angle (in trenches B, C, and D) and in gully C, is late Pleistocene - post terrace - C marine deposits in age (less than a maximum of 280,000 years old), but predates the alluvial-colluvial deposits and soil Profile 1 (more than about 8 to 10 thousand years BP); deformation in both areas could have been coincident in time.

In the mouth of gully B a bulldozer cut exposed several small slip surfaces showing vertical separations as great as about 1 foot in very friable sand and gravel of terrace C (fig. 48). These slip surfaces could not be traced downward to the bedrock platform, which was barely



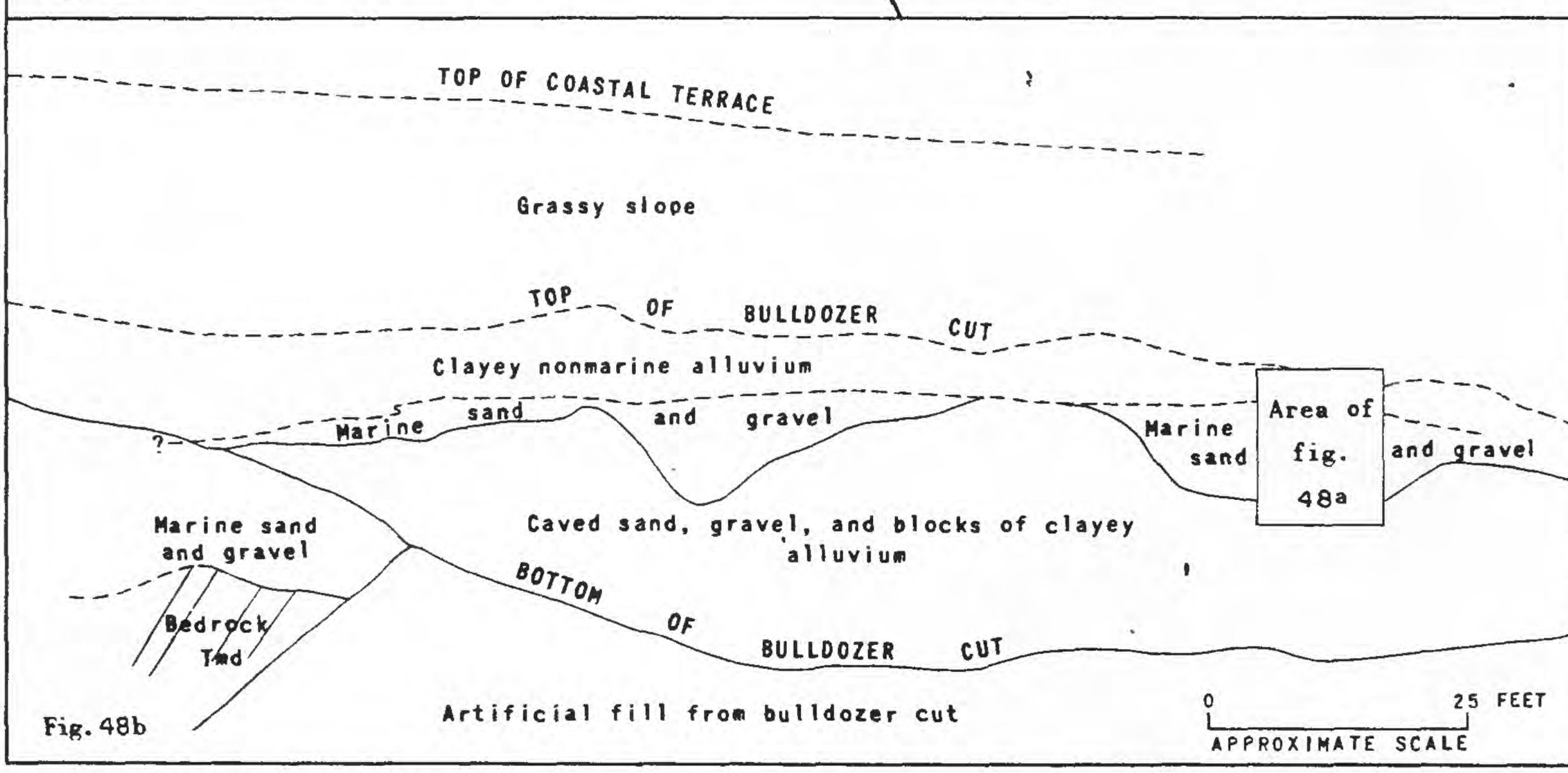


FIG. 48. TRACING OF PHOTOGRAPHS, SHOWING DISPLACEMENTS IN MARINE TERRACE DEPOSITS, EAST WALL OF GULLY B AT MOUTH, IMMEDIATELY NORTH OF AND ABOVE FAULT "A"

exposed at the bottom of the cut, nor was any disruption of the bedrock surface observed (observations were very brief; caving of the excavation prevented careful examination of the bedrock surface). These displacements could be due to slight movement of the sand toward gully B, possibly to movement very early in the history of the deposit (Hoffman and Smith, 1965, p. 22; Cleveland and Troxel, 1965, p. 13), or might be related to warping of the terrace.

The evidence of disruption as exposed in the trenches B, C, and D provides no basis on which to distinguish between landslide or tectonic fault origin of the disruption of terrace C. The displacements near the shoreline angle could be due either to faulting or to relative movement of blocks within a landslide, the sole of which would underlie the exposures in the trenches. The toe of the landslide of Monterey Shale, exposed in the north part of trenches B, A, and E, is north of the disruption here described (see section on landslides below) and therefore cannot be responsible for the disruption. Cleveland and Troxel (1965, p. 28 and plate) have postulated a large landslide that would include the disrupted terrace C platform near the shoreline angle; however, except possibly for the slip surface in gully C (see below) there is no relevant evidence for such a landslide (see section on landslides below).

The displacement in gully C could also be due either to faulting or landsliding. If this displacement is of tectonic origin, it would be consistent with north-south compression, and its location on the projected trace of fault A would be a reasonable place for such displacement to occur.

However, displacement of marine terrace deposits is not present on the eastward extension of fault A in gully B; the projected east-trending strike of the slip surface in gully C would be well to the north of the projected southeastward trace of fault A. The rubbly nature of the Monterey Shale above the slip surface in gully C might be equally expectable whether the displacement were of landslide or fault origin; southward movement of the upper block over the lower block would also be reasonable in either case.

If the slip surface in gully C represents the sole of a landslide near its toe, the landslide is probably a very large one, because the slip surface dips steeply (33° north) at the bottom of trench F; however, there is no topographic evidence whatsoever to indicate the possible boundaries of such a slide. If such a large slide existed, it could reasonably contain the disruption features near the shoreline angle of terrace C. Only a rotational-slump landslide could be expected to have a sole dipping as steeply as 33° upslope near its toe. Rotational slumping of the bedrock bearing the platform of terrace C northwest of gully C should result in a back-tilt or northward slope of the terrace platform, whereas the platform actually slopes southward where exposed in the trenches (fig. 12). Furthermore, the altitude of that shoreline angle, 176 feet above sea level, is the highest known for terrace C in the Point Dume-Malibu Canyon area (fig. 49, and see above). If this part of the terrace is within a rotational slump and north of the axis of rotation, it would have moved downward during landslide movement, and therefore would have been even higher prior to landsliding; in contrast, north-south compression might well be expected to locally raise the shoreline angle (by folding and(or) faulting).

The available evidence does not permit a satisfactory selection of either landslide movement or tectonic movement as the cause of the disruption of terrace C in the Corral Canyon site, nor is it necessary for the disruptions near the shore angle and in gully C to be synchronous or even of the same origin. However, the evidence available seems weighted toward a fault origin, possibly synchronous for both features.

Known upper Pleistocene deformation in the Corral Canyon site and in the Malibu Coast zone consists chiefly of faulting and local warping of marine terrace platforms and their marine deposits, which are more than 35,000 and less than a maximum of 280,000 years old. The disruptions are present only on topographically elevated coastal terraces, are locally overlain by undisturbed non-marine cover (about 10,000 years old at Corral Canyon), and have no known topographic expression that can be attributed to Recent faulting. Younger deposits at lower altitudes, such as stream terrace deposits, flood-plain deposits, and stream deposits, are nowhere known to be disturbed. All known deformation in the Malibu Coast zone is late Pleistocene, pre-Recent in age (more than about 10,000 years old).

GEOLOGIC FACTORS THAT SHOULD BE CONSIDERED DURING ENGINEERING DESIGN AND CONSTRUCTION

The Corral Canyon site is in a seismically active region that will experience earthquakes in the future. It is located in a zone of tectonic deformation adjacent to one of southern California's major faults, and is possibly subject to faulting of the ground surface. The predominant bedrock of the plant site is relatively weak mudstone that is susceptible to swelling and shrinking during change in load or moisture content; slopes underlain by this rock may be subject to failure by landsliding. The proposed location of the reactor is in the mouth of a moderate-size canyon (drainage area about 3.6 square miles) that is capable of directing floods and flood debris through the plant site. The plant site is also near sea level, adjacent to the Pacific Ocean, and within reach of any large tsunamis or very large storm waves that strike this part of the coast. Marine currents transport sand along the coast, which must be crossed by pipes for cooling water. The expected occurrence and extent of these geologic phenomena in the Corral Canyon site during the next 50 years are relevant to engineering design and construction of the proposed plant at Corral Canyon and are discussed below.

Future faulting of the ground surface

The Corral Canyon plant site is located in the Malibu Coast zone of deformation and within 1,000 feet of the Malibu Coast fault, a major fault in the Santa Monica fault system. Thousands of feet of horizontal crustal shortening took place across the Malibu Coast fault between late Miocene and late Pleistocene time. The general structural and tectonic environment that produced this and related rock deformation probably still exists, as indicated by the evidence for late Pleistocene faulting in the Malibu Coast zone, continuing seismic activity associated with the Santa Monica fault system, and the inferred relation of that fault system to the known-active Newport-Inglewood zone of faults and folds. The entire southern California region is one of active tectonic deformation, as expressed by numerous earthquakes and infrequent fault rupture of the ground surface (see Allen and others, in press).

The general tectonic activity of southern California is well established. Richter (1958), Hill and others (1964), and Allen and others (in press) have assembled data on seismically active faults and known surface faulting associated with earthquakes in this region. The Corral Canyon site is within about 40 miles of the San Andreas fault zone, the nearest segment of which was faulted at the surface for a distance of many miles during the great 1857 Fort Tejon earthquake. This earthquake was the last major shock on the San Andreas fault in southern California north of the Imperial Valley. Other seismically active faults or areas of seismic activity that are near the Corral Canyon site include the Channel Islands-Santa Barbara area and the Santa Ynez fault, at least 50 miles to the northwest (no known surface faulting during historic time, but several large earthquakes), and the Newport-Inglewood zone of the western Los Angeles basin, about 20 miles to the east-southeast (no known surface faulting during historic time, but destructive earthquakes as late as 1933 and subsurface displacement during an earthquake in 1941). In comparison to these faults and seismic areas, the Santa Monica fault system has been less active seismically by a factor of 4 or more in terms of strain release during the 1934-1963 period (Allen and others, in press); the area along the central and western Santa Monica Mountains part of the system has in turn been more active than adjoining areas to the north or south by the same factor (see fig. 43). Detailed reports on seismic shock and ground acceleration in the Corral Canyon area have been made by Benioff (1965), Housner (1963, 1965), and the U. S. Coast and Geodetic Survey (1964).

Probability of future faulting

Judgment as to probability and location of future faulting of the ground surface in the Santa Monica fault system and Malibu Coast zone in the central Santa Monica Mountains area can be based only on the known geologic and seismic records. The geologic record of the Malibu Coast zone in this area is incomplete due to the absence of deposits representing Pliocene and lower Pleistocene time, the interval during which much of the deformation occurred in the Malibu Coast zone. Furthermore, upper Pleistocene and Recent deposits are only locally preserved and well exposed. The period of seismic record at best is only 200 years, and the period of good instrumental record is only about 30 years. These incomplete or short term records of past geologic events do not permit valid quantitative prediction of future events.

Minimum probability of future faulting.--The Santa Monica fault system is tectonically active at depth, as indicated by its inferred relation to the known-active Newport-Inglewood zone and its seismic activity, which indicates accumulation and release of strain at depth. This evidence of tectonic activity, when coupled with the evidence of known late Pleistocene faulting in the Malibu Coast zone and the lack of knowledge concerning frequency of large earthquakes and surface faulting in the Santa Monica fault system, dictates the conclusion that there is some probability of surface faulting during the next 50 years in the Santa Monica fault system.

Location of future faulting.--The location of any future faulting in the Santa Monica fault system can be judged only qualitatively on the basis of limited evidence for the varying degrees and time relations of deformation in different parts of the system.

The Malibu Coast fault forms a regional rock boundary; it was the locus of major tectonic movement amounting to many thousands of feet between late Miocene and late Pleistocene time. Considerable movement during this period is also represented by the numerous folds, faults, and abundant shear surfaces that characterize the Malibu Coast zone.

Most of the known tectonic activity in the Santa Monica fault system in the central Santa Monica Mountains area was restricted to the interval between late Miocene and late Pleistocene time. The youngest known tectonic activity near the ground surface in the fault system in this area was minor faulting that took place during late Pleistocene time in the Malibu Coast zone.

The character of deformation has varied considerably across the trend of the exposed part of the Santa Monica fault system. South of the Malibu Coast zone, on Point Dume, the bedrock is homoclinally tilted northward, locally folded, and locally cut by steep faults. Future faulting in this or a similar structural block would probably follow the few existing faults, rather than propagate through unfaulted rock. In contrast, rocks in the entire exposed Malibu Coast zone are variably--locally tightly--folded, faulted, and sheared. The through-going faults in this zone were clearly preferred surfaces of displacement at depth. This preference would probably exist at the ground surface as well, but to a lesser degree because of lack of confining pressure. A fault rupture propagating upward through this rock might therefore migrate from a through-going fault into adjoining rock, especially where the rock is already sheared and faulted.

The age relations and degrees of deformation in various parts of the Santa Monica fault system indicate that any future faulting is at least as likely to occur within the Malibu Coast zone, the only part of the system where evidence for upper Pleistocene faulting is recognized, as outside it.

Maximum probability of future faulting.--The record for Recent time contains no known geologic or geomorphic evidence of faulting at the ground surface in the Malibu Coast zone. The length of this geologic record (about 10,000 years) when compared to 50 years, suggests that the probability of faulting at the ground surface in Corral Canyon during the next 50 years is very low.

Surface faulting in California and Nevada has commonly been associated with earthquakes of Magnitude 6 or greater, so that judgment of the probability of future surface faulting should be based in part on the probability of occurrence of large-magnitude shocks in the Santa Monica fault system. The historic records indicate that surface faulting might accompany a shock of Magnitude 5.5 to 5.9 centered near Corral Canyon, could well accompany one of Magnitude 6.0 to 6.4 in that vicinity and can be expected to accompany a shock of Magnitude 6.5 or greater (Allen and others, in press; Oakshott and Tocher, 1960; Tocher, 1958).

The seismic record of the Santa Monica fault system has been reviewed (under Age of structural features). Based on this record, the system is considered to be one of continuing minor seismic activity, with the greatest shock recorded having Magnitude 4.7.

The detailed seismic record for southern California dates from 1934, and the record for reasonably well-located large shocks dates from about 1900. As a consequence of the short duration of the record, the recurrence interval of seismic shocks, especially those of large magnitude, is unknown, or at best can only be approximated for the southern California region. The records do not permit valid extrapolation for parts of the region such as the Santa Monica fault system, except possibly in the case of Los Angeles area as a whole. On the basis of their analysis, Allen and others (in press, table 2) suggest that for the entire 8,900 km^2 Los Angeles area, the "once-per-year" earthquake has Magnitude 4.2 and the "once-per-hundred years" earthquake has Magnitude 6.3. However, these figures can be applied only to the entire 8,900 km^2 area; they cannot be applied directly to a small part of the area, such as the Santa Monica fault system.

Estimates of the largest shock to be expected on the Santa Monica fault system range from an implied Magnitude 5.5 (U. S. Coast and Geodetic Survey, 1964, p. 3, 6) to a maximum ever to be expected of Magnitude $7\frac{1}{4}$ (Benioff, 1965, p. 8). The available record (see Allen and others, in press) is not sufficient to establish for this fault system the recurrence interval of possible large-magnitude (M. 6 or greater) shocks. This interval is greater than the approximately 200 years of historic time, and the lack of surface evidence of faulting suggests that the interval may exceed the approximately 10,000 years of Recent time. The recurrence interval of large shocks in the Santa Monica fault system, although unknown, is thus probably quite large; the probability that such a shock will center near Corral Canyon during the next 50 years is therefore very low.

The lack of any known evidence of Recent surface faulting in the Malibu Coast zone coupled with the very low probability of a large earthquake near Corral Canyon during the next 50 years, lead to the conclusion that the probability of permanent displacement of the ground surface by faulting at Corral Canyon during the next 50 years is very low (this same very low probability was described in the U. S. Geological Survey report of 1964 (Yerkes and Wentworth, 1964) as negligible, which was used in that report in the sense of very low.). In the assessment of this probability, no judgment of public risk is intended or implied; that is, no judgment is made that faulting of the ground surface at the Corral Canyon site is or is not a geologic phenomenon of consequence in any particular utilization of the site.

Landslides

Landslide deposits occupy about one-third of the Corral Canyon site and involve all stratigraphic units. Each of the three largest landslides has an area of about 1,000,000 square feet, several are 100,000 to 300,000 square feet in area, and smaller slides are abundant.

The existence of landslides and the location of their boundaries were determined in the field by examination of the ground and of aerial photographs. Fresh headwall scarps, diagnostic cracks in the ground surface, irregular hummocky topography, and exposed soles (the sole is the surface on which a landslide has moved) were used as criteria definitive of landslides. Critera suggestive of landslides include anomalous, relatively flat slopes that interrupt steep slopes and are accompanied by bulging slopes below (fig. 51).

Two types of slope failure have been recognized in the Corral Canyon site: slumps or multiple slumps, and debris slides. Slumps consist of one or more relatively large slices of bedrock that have moved downslope as units (fig. 51) and have not been internally deformed to any great extent by their movement. Debris slides consist of chaotic masses of small, independent fragments and typically have undulating, hummocky topography; these slides may form in part by flowage.

Physiography, composition and structure of bedrock and surficial deposits, degree of water saturation of bedrock and surficial deposits, and seismic shock may contribute to the initiation, acceleration, or rejuvenation of landslides in this area. Corral Canyon contains an intermittent creek that tends to undercut the canyon slopes. The walls of the canyon are commonly quite steep, rising 100 to 600 feet at slopes of 20° to 40° on the east side, and to a similar height at slopes of 15° to 30° on the west side. The south-facing coast rises at slopes of 12° to 30° from the eroding shoreline to an altitude of about 90 to 140 feet at the seaward edge of coastal terrace C. These slopes have locally failed, as indicated by the many landslides on them. Some of the landslides in the Corral Canyon site formed on slopes as low as 25°, whereas other slopes as steep as about 40° have not failed.

The rocks of unit B are especially susceptible to failure by landsliding. The bedrock in the plant site area has relatively low strength because the interbedded sandstones and mudstones are folded and sheared and contain significant quantities of montmorillonite (swelling clay; table 7). The surface traces of mapped faults are also preferred locations for landslides; the traces of the Malibu Coast fault and fault A are concealed by landslides on the walls of Corral Canyon.

During the rainy season the Corral Canyon area is subject to relatively short, intense rainstorms that are capable of saturating the ground. Such saturation is a major cause of slope failure, because it results in a substantial increase in the weight of potentially unstable ground, as well as a decrease in rock and soil strength.

Corral Canyon is in an area of known seismic activity and will be subject to seismic shock in the future. Seismic vibration, especially if superimposed on water-saturated ground, can initiate, accelerate, or rejuvenate landslides in the Corral Canyon site; a landslide can be rejuvenated in segments, as at the head of gully B (fig. 5).

The soles of some of the smaller slumps in the Corral Canyon site were observed; these consist of one or more closely spaced surfaces of rupture with undeformed bedrock above and below. The large landslide west of the mouth of Corral Canyon has been explored by six test borings. One of them (L2, fig. 4) bottomed in bedrock at an altitude of minus 49 feet; although no obvious surfaces of rupture were detected by in-hole inspection, the sole of the landslide is inferred to be at minus 4 feet.

Some of the landslides have relatively fresh scarps or cracks at the top, or are crossed by pavement that has been disrupted, expecially near the margins of slides; these are tentatively considered to be active. Little is known concerning rates of movement of any of the slides.

The two large landslides that flank the mouth of Corral Canyon (frontispiece) may be moving seaward; they have unsupported toes at or near the shoreline, and in part have resulted from removal of support by coastal erosion of unit B rocks. Continued minor or local activity involving these two slides can probably be expected; rejuvenation or acceleration of movement might result from a combination of saturated ground and seismic shock. Enlargement by headward migration would be possible under these circumstances; lateral migration would be less likely. It is unlikely that the toes of these two slides extend far offshore. The sea bottom off Corral Canyon slopes very gently; water depth 1,500 feet offshore is about 35 feet (U. S. Geol. Survey topographic quadrangle, Solstice Canyon, 6' series, 1932). In addition, the sole of the landslide west of the canyon mouth has been interpreted to be at minus 4 feet (in test boring L2) at a distance of about 100 feet north of the shoreline.

A slip surface exposed near station 80 feet in trench 3 strikes about N 70° W across the trench and dips 30° to 37° northward. On the southeast face of the trench the slip surface juxtaposes clayey surficial deposits (unit Sd-4) on the north over bedrock (unit msd) on the south, whereas on the northwest face of the trench the slip surface juxtaposes bedrock (unit msd) on the north over young sand and gravel on the south (units Sd-3 and G-4, figs. 8b and 50). Two bulldozer cuts (cuts 1 and 2, northwest of trench 3, fig. 8b) exposed the same slip surface, which there also juxtaposes bedrock (unit msd) over sand and gravel (units Sd-3 and G-4). In detail, the slip surface is somewhat irregular in form (see map of vertical face, cut 2, fig. 8b), but a structure contour constructed on the slip surface at altitude 25 feet shows that the general strike of the surface changes from about N 70° W in trench 3 to N 30° to 40° W where exposed in the bulldozer cuts;

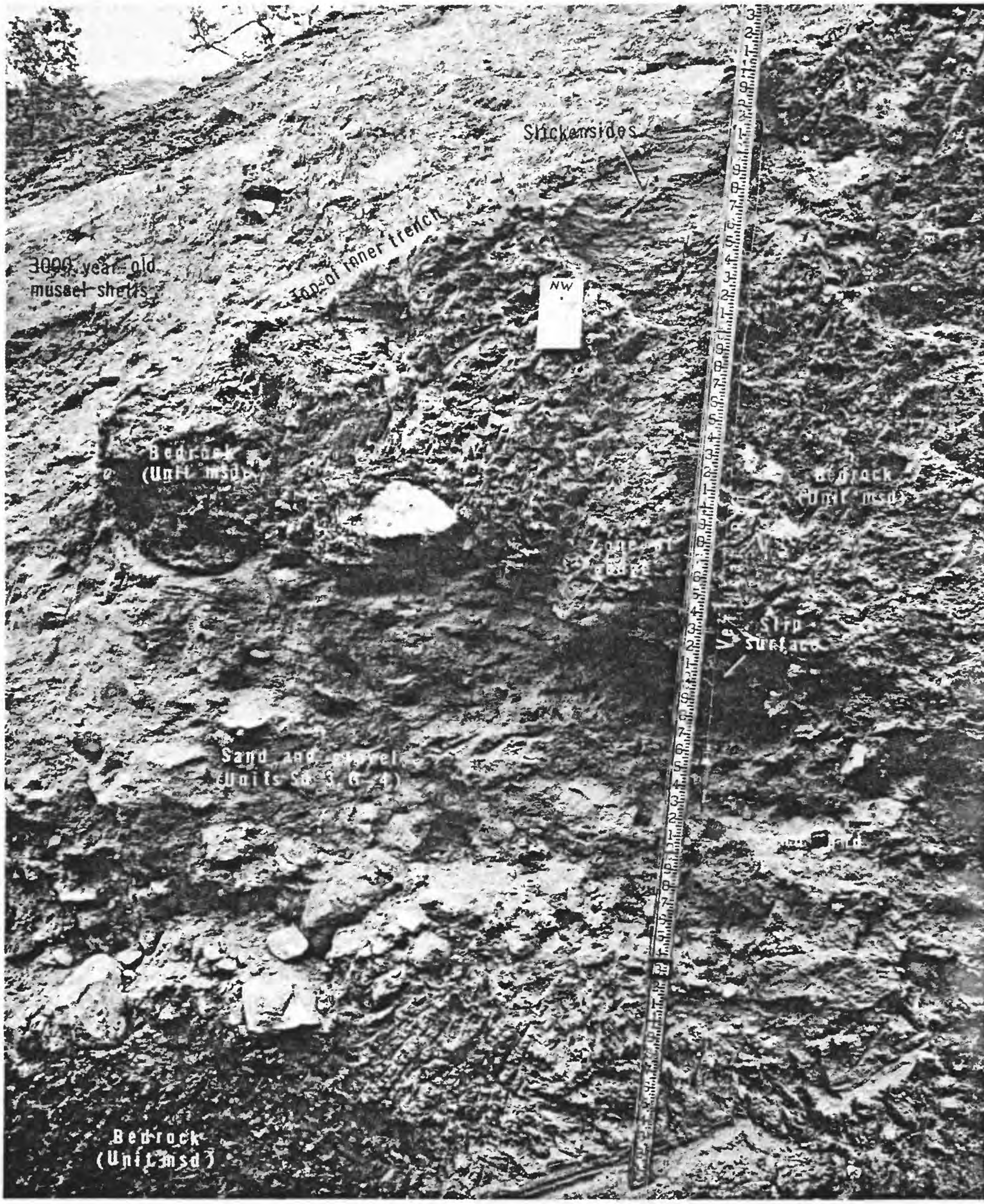


Fig. 50.--Toe of buried landslide exposed at about 80 feet, northwest face of trench 3 (fig. 8b). Middle Miocene bedrock (msd) has overridden Recent flood-plain deposits (Sd-3 and G-4) that contain shells dated by radiocarbon at about 2,950 years before present. Slip surface (at 3.1 feet on rod) is marked by local gouge; see fig. 8b for map of slip surface.

associated with this change in strike is a change in dip from 30° to 37° northward to a gentle 14° northeastward. It was impractical to trace the slip surface farther to the west or northwest because it is truncated by relatively young sand and gravel near the bottom of Corral Canyon.

Two sets of striations on the principal slip surface, one set on an adjacent, related slip surface, and a set at station 40 feet on a possibly related slip surface trend between N 47° W and N 90° W, and plunge between 11° and 23° westerly; striations on the principal slip surface at its northwesternmost exposure near bulldozer cut 2 have a similar trend, but plunge southeastward (fig. 8b). The nearness of steeper slopes on the east wall of Corral Canyon, the westerly trend and gentle plunge of striations on the slip surface, the northwestward curve in strike of the principal slip surface as it is traced toward the canyon bottom from the east, and the reversal in position of juxtaposed bedrock material and surficial deposits between the two sides of trench 3 indicate that the bedrock mass north of and above the slip surface moved westward from the east wall of Corral Canyon as a landslide. The trend of the trace of the slip surface can be projected eastward upslope from the exposure in trench 3 to coincide with a subtle, arcuate depression near the edge of the main coastal terrace surface, which probably represents the head of the landslide (fig. 2). The reversal of plunge of the striations on the slip surface near bulldozer cut 2 suggests that this part of the feature is in the toe of the landslide, and that movement here had an upward component.

Shells from locality A in unit Sd-3 below the slip surface (figs. 8b and 50) have a radiocarbon age of about 2,950 years; the landslide is thus Recent in age. The toe of the landslide has been truncated and eroded to a depth of some 17 feet at a position 70 to 80 feet south of the present Corral Creek, and the slip surface is buried near the trench by as much as 12 feet of surficial deposits.

An extensive gently sloping surface is present at about altitude 300 feet above a prominent bulge on the east wall of Corral Canyon about 1,000 feet north of the Malibu Coast fault (figs. 4 and 51). The surface slopes toward the canyon and is underlain by very poorly exposed, folded sandstone and siltstone of the Upper Topanga Formation Folds in this formation vary considerably in trend but average east-west, hence their attitude in the bedrock underlying the gently sloping surface cannot be used either to demonstrate or disprove a landslide origin for the topographic feature. The gently sloping surface is similar in altitude to several other smaller surfaces present on spurs on the west wall of the canyon. These surfaces may therefore represent remnants of an ancient stream terrace of Corral Canyon. If the large feature on the east wall is a landslide, it probably formed a dam in Corral Canyon, has since been disected to a depth of about 100 feet, and is therefore relatively old.

A bedrock platform preserved at altitude 80 feet at the east edge of the mouth of Corral Canyon has been interpreted as due to landsliding from a higher altitude (Cleveland and Troxel, 1965). The presence in

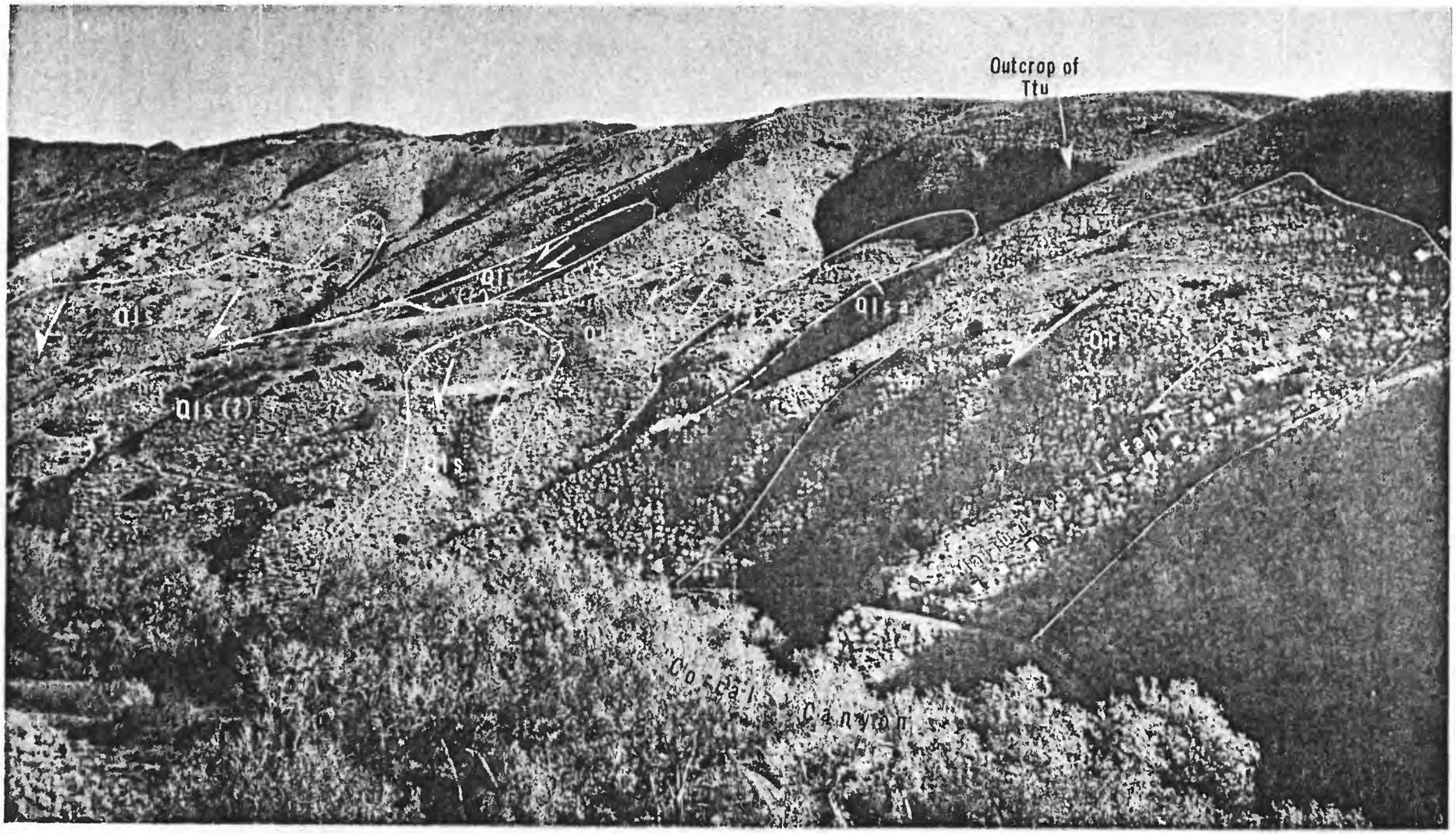


Fig. 51.--East wall of Corral Canyon north of Malibu Coast fault. Bulging slope at right is formed by landslide that conceals the trace of the Malibu Coast fault; bedrock to north is folded sandstone and siltstone of the Upper Topanga Formation (Ttu); landslide below outcrop of Ttu (Qlsa) is probably active. Large questionable deep slump slide (**Q**ls ?) at left and center may be an old landslide or a remnant of a high-level stream terrace that lacks deposits; if this feature is a landslide it probably dammed Corral Creek when it moved.

trench E of stream terrace deposits on bedrock at altitude about 130 feet and more than 500 feet east of present Corral Creek (fig. 13) indicates that the entire bedrock platform between Corral Creek and trench E has been extensively modified by stream erosion; the southwestward slope of the coastal terrace is therefore probably due to removal by erosion of stream terrace deposits, rather than to landsliding. Other features cited as evidence that the east wall of Corral Canyon is underlain by a large landslide include the presence of marine terrace deposits on the 80-foot platform at the canyon mouth (inferred to have been dropped down from a higher altitude), pull-away features at the head of the landslide exposed in trenches A and B, and disturbance of the bedrock in trenches A, B, 1 and 2. As shown elsewhere (under Coastal terrace deposits and Stream terrace deposits) the sand and gravel on the 80-foot platform more likely correlates with stream terrace deposits exposed at altitude 95 feet in trenches 1 and 2 (fig. 9); the pull-away features in trenches A and B are best attributed to the landslide, the sole of which is exposed in trenches A and B (see below); and the disturbance of unit B bedrock south of that landslide is similar in degree to that of unit B mudstone-sandstone sequences throughout the plant-site area.

Parts of an ancient, buried landslide (see fig. 4 for inferred boundaries) are exposed in test trench A (stations 15-190 feet, fig. 10), test trench E (stations 0-90 feet, fig. 13), test trench B (stations 0-80 feet, fig. 11), and the north ends of trenches C and D. This landslide heads at altitude about 240 feet and toes at about altitude

170 feet (see stations 160-190 feet, trench A). In trench A the toe of the landslide is overlain by a well-developed soil profile that is correlated with soil Profile 1 in trench B (stations 120-270 feet, fig. 11), which required most of Recent time to form (see Soils). A rubble unit in trench B (unit T) may have been derived from this landslide; the rubble is interbedded at its south margin with fossiliferous Upper Pleistocene marine deposits (unit Sdm), which have a maximum estimated age of 280,000 years (sample CW 115, Appendix C). The marine deposits and underlying bedrock platform are displaced on slip surfaces exposed by trenches B, C, and D. If these slip surfaces are faults (see Upper Pleistocene deformation), the buried landslide probably predates the youngest known faulting in the Corral Canyon area; both this landslide and the disruption of the terrace deposits are late Pleistocene in age.

Seaward movement of part or all of the plant site by landsliding seems quite improbable in view of its low altitude, the very gentle slope of the sea floor offshore, and the northward dip of structural features in the area.

Landslides on the walls of Corral Canyon near the plant site are small. However, the bedrock is sheared mudstone and sandstone of unit B that is readily susceptible to slope failure; cuts with slopes steeper and(or) longer than natural slopes now standing near the plant site may fail.

Corral Canyon could be dammed by landslide debris upstream from the plant site during a period of high runoff. If ponded flood waters then overflowed and quickly eroded such a dam, a major flood, possibly on the order of 10,000 cfs, could result near the canyon mouth. Determination of this value was based on an assumed dam height of 100 feet in Corral Canyon about 1,500 feet north of the plant site.

Preliminary plans (Dept. Water and Power, City of Los Angeles, 1964) propose a culvert to divert the creek water about 800 feet north of the plant site. The culvert would rest on the west wall of the canyon and may require a debris dam to prevent blockage of the culvert. The possibility should be considered that landslides could be initiated or rejuvenated during construction of these facilities, or following completion of a debris dam, by saturation of slopes by ponded flood waters.

Floods and flood debris

The Santa Monica Mountains are subject to both disastrous brush fires and to short, intense rainstorms. Rainstorms that can saturate the ground and then provide flood-stage runnoff can be expected in the Corral Canyon area. Peak discharges for a 50-year flood at the mouth of Corral Canyon may range from 1,500 cfs for normal watershed conditions to about 3,000 cfs for a burned-over watershed. Large quantities of debris may be carried downstream by flood runoff and deposited in the creek channel, on the flood plain, and in drainage structures.

History

Average normal seasonal precipitation over the 85-year period 1872 to 1957 is about 16 inches at the mouth of Corral Canyon and 23 inches at its head (Los Angeles County Flood Control District, Biennial Report on Hydrologic Data for 1957, Map III). Seasonal precipitation for the period 1932 to 1963 in the Corral Canyon area has ranged between 6.14 inches (1961) and 44.58 inches (1941) (see table 6), and has fallen almost entirely during the period October to April.

The March 1938 rainstorm resulted in floods as severe as any previously recorded in Los Angeles County and these floods moved the largest volume of flood debris then recorded by the Los Angeles County Flood Control District. Erosion rates, determined from observations at 16 debris basins of the Flood Control District at various locations in the County range from 27,000 cubic yards per square mile of drainage area (maximum vegetation cover and minimum disturbance by man) to 100,000 cubic yards per square mile, with an average of 60,000 cubic yards per square mile (Burke, 1938). These floods followed a six-day rainstorm, which began on February 27, 1938, and totaled 10.28 inches in Escondido Canyon, about 2.5 miles west of Corral Canyon (table 6). The seasonal totals for the two rain gage stations nearest the Corral Canyon site (table 6) show that the 10-inch rainfall of that rainstorm was only about 40 percent of the 1938 seasonal total of 26 inches. This seasonal total was nearly equaled by the precipitation of the 1932, 1935, 1937, 1943, 1944, and 1956 seasons; it was exceeded by the precipitation of the 1941, 1952, 1958, and 1962 seasons.

Table 6.--Seasonal rainfall totals (inches) for two rain gage stations near the Corral Canyon site

Year	Station 2 (inches)	Station 1028 (inches	Year	Station 2 (inches)	Station 1028 (inches)
1932	1/ 11.36	No record	1948	08.50	No record
1933	1/ 9.79	do	1949	2/ 12.47	do
1934	1/ 09.05	do	1950	16.22	18.96
1935	23.03	do	1951	11.22	12.04
1936	18.53	do	1952	34.25	36.86
1937	25.07	do	1953	14.53	14.89
1938	25.67	do	1954	18.85	19.93
1939	18.45	do	1955	2/ 15.52	2/ 15.52
1940	19.29	do	1956	22.71	23.12
1941	44.58	do	1957	14.38	16.35
1942	16.53	do	1958	29.33	2/ 37.80
1943	20.91	do	1959	7.79	10.00
1944	21.92	do	1960	11.95	14.40
1945	17.64	do	1961	6.14	7.36
1946	14.93	do	1962	27.23	36.62
1947	16.24	do	1963	14.51	17.78

1/ Record incomplete

2/ Record partly estimated

Each season year is October 1 to September 30, listed opposite the terminal year. Station 2 (after 1947 termed Station 2B) is located in upper Escondido Canyon, about 2.5 miles north of the coast and about 2.5 miles west of Corral Canyon. Station 1028 (1028B in 1957-58, and Station 1028C after 1958) is located 3 miles north of the coast in Corral Canyon. From Los Angeles County Flood Control District, 1933-1964.

Rainstorms of the 1952 season produced destructive runoff and spectacular slope failures and debris flows in the Santa Monica Mountains. This season followed a 7-year period of general drought. By January 1, 1952, 50 percent of normal seasonal precipitation had fallen, and by January 15, 67 percent had been recorded. Most of the increase for the season resulted from the rains of January 12 and 13. This increase was followed on January 15 to 18 by two rainstorms during which an additional six inches of rain fell in the Corral Canyon area. In spite of the fact that these two rainstorms were separated by a 24-hour, rain-free period, the saturated watersheds responded quickly with severe runoff and slope failure. Peak discharge from Corral Canyon during this period was estimated at 687 second-feet. "Had the rainfalls been more intense and of greater volume, a major flood could easily have developed" (Burke, 1952). The average rate of debris production (based on results from 28 debris dams and debris basins of the Los Angeles County Flood Control District) for these rainstorms was about 5,785 cubic yards per square mile. The most spectacular damage was caused not primarily by floods, but by debris flows and landslides.

Estimated flood magnitude-frequency

An analysis of the flood magnitude-frequency relationship in Corral Canyon has been provided by L. E. Young of the U. S. Geological Survey, who studied the records of annual peak discharges from 24 stream-gaging stations in the Los Angeles area. Individual flood magnitude-frequency curves were constructed for each of 24 gage sites. Two of these gage sites, Zuma Canyon and Topanga Creek, are in the Santa Monica Mountains. From these 24 individual frequency curves, regional relationships were developed between floods of selected frequency of occurrence and physiographic characteristics of the watersheds. Estimates of flood magnitude-frequency for ungaged Corral Canyon (fig. 52) were then based on the regional relationships.

Figure 52 shows the estimated flood magnitude-frequency relationship of Corral Canyon for recurrence intervals between 10 and 50 years. The frequency curve has been extrapolated to a recurrence interval of 100 years, but should be used with caution above a recurrence interval 50 years because the analysis is based on only about 50 years of streamflow records. It is emphasized that recurrence intervals are average figures; thus a 50-year flood, which is the discharge that has one chance in 50 of being exceeded in any one year, may not be exceeded in a given 50-year period or it may be exceeded several times.

The discharges of figure 52 apply only in the case of normal vegetative cover in the basin. An increase in peak discharge of as much as 100 percent for a 50-year flood may occur if it immediately follows complete destruction of the vegetative cover by fire (Rowe and others, 1954, p. 26). This increase in peak discharge is reduced as vegetative cover is re-established.

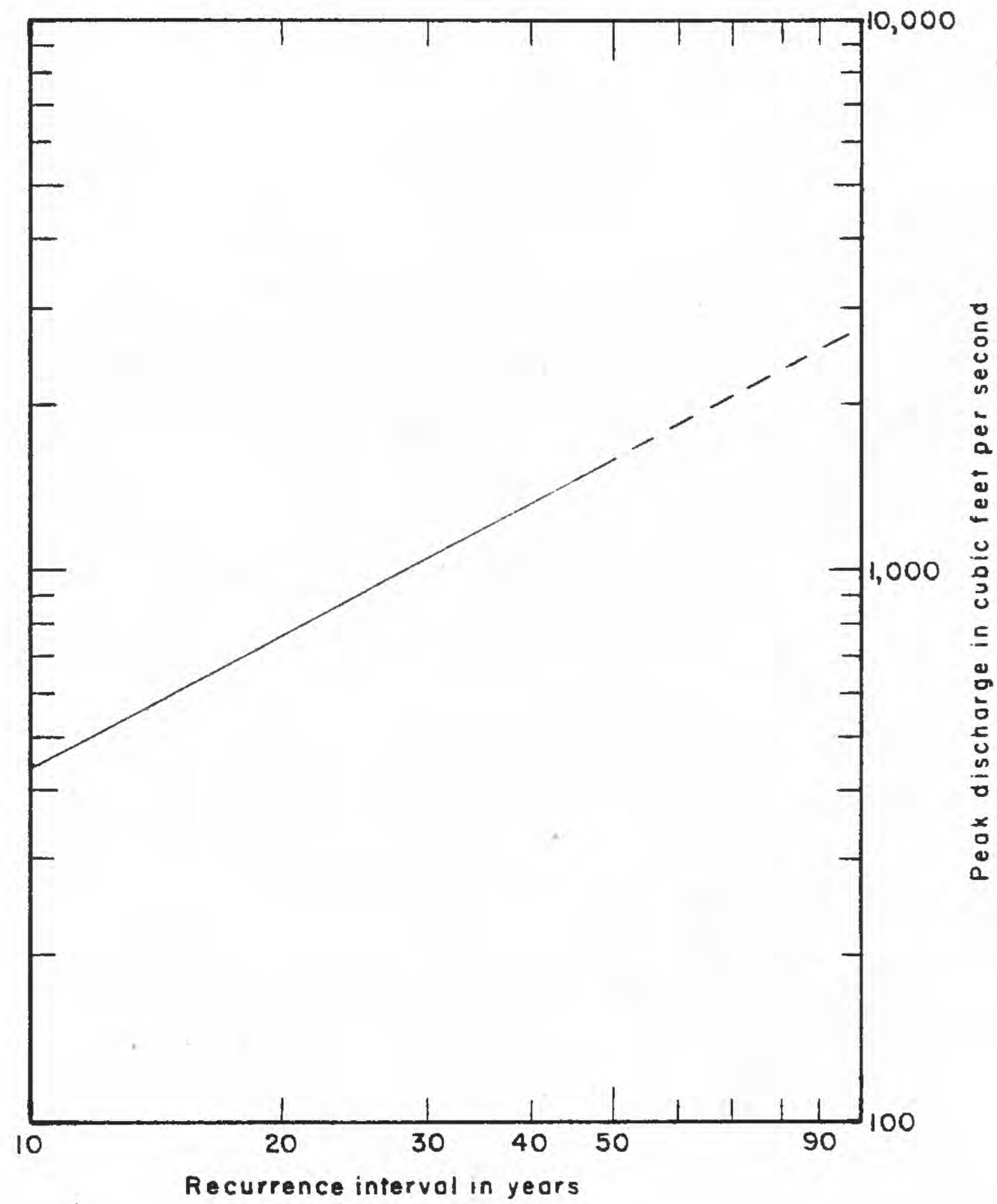


Fig. 52. Estimated magnitude and frequency of annual floods in Corral Canyon. Data supplied by L. E. Young, U. S. Geological Survey.

Clays in rocks of the site

A preliminary investigation indicates that significant amounts of montmorillonite clays are present in bedrock and surficial deposits of the Corral Canyon site as determined by X-ray diffraction study of 15 samples (table 7). The proportion by weight of clay minerals in nine bedrock samples ranges from a low of 15 to 25 percent to a high of 40 to 90 percent. The clay minerals content of six samples of surficial deposits is about 10 percent for three samples and between 15 and 40 percent in the others. Free swelling tests (no load applied) for four of these samples showed Y3b-1 expanding about 100 percent, AK-42b expanding 10 percent, and no swelling in samples AK-42a and AK-46b.

Clays, particularly those of the montmorillonite group, where subject to repeated wetting and drying, contribute materially to the relative weakness of the bedrock and overlying surficial deposits. The stability of the slopes, cuts, and fills in the graded site will be influenced by the abundance and swelling capacity of the montmorillonite clays. The swelling capacity of such clays varies, depending on the types of cations (sodium, calcium, magnesium) that occupy the cation exchange sites in the crystal lattice.

Offshore geology

Large-diameter pipes to provide cooling water for the proposed plant will extend approximately 1,500 feet offshore from the site and will be buried in the sea floor. Their installation and stability will be affected by the topography and geology of the bedrock and the properties and thickness of surficial deposits.

The sea floor in this area has a uniform, gentle, seaward slope; water depth 1,500 feet offshore is about 35 feet. The bedrock geology of the offshore area can be inferred only by projecting eastward the features exposed in the Point Dume quadrangle west of the site (see fig. 5). On this basis offshore facilities will be founded on sedimentary and volcanic rocks of unit B in the Malibu Coast zone; contacts between different rock units will be faults. The toes of the two large landslides that flank the canyon mouth should be located in order to determine their relation to proposed locations of offshore facilities.

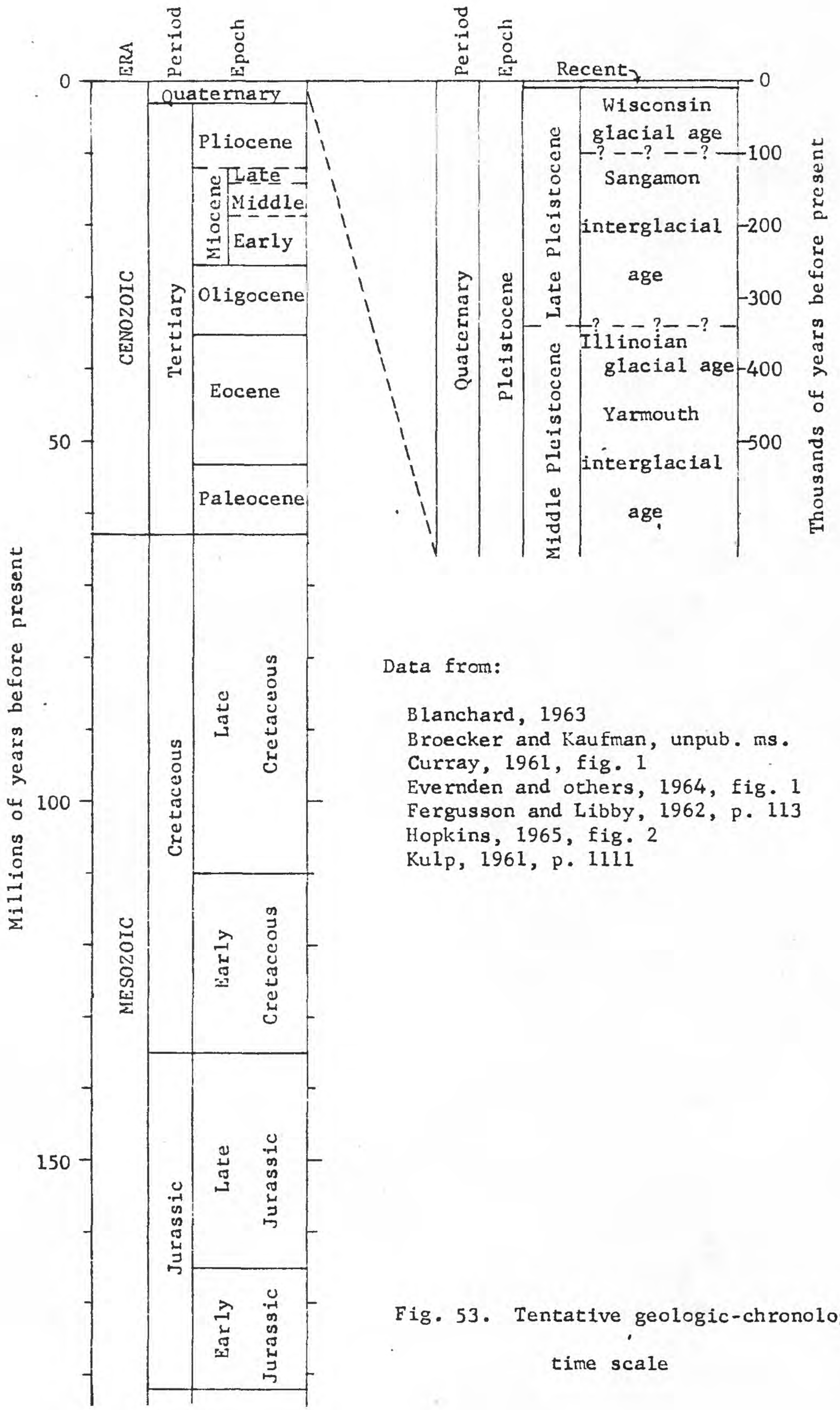
Marine processes

Storm and seismic sea waves will affect the safety and efficiency of both offshore and onshore facilities of the plant; littoral drifting may affect offshore facilities such as cooling-water pipes.

The plant site is located within 500 feet of the shore and will be graded to an altitude of 35 feet (Dept. of Water and Power, City of Los Angeles, 1964, fig. 2.7-1b). Infrequent storms at sea create waves as high as 26 feet along the southern California coast, as well as long-period waves that wash exceptionally high on the beaches (Emery, 1960, p. 117). Such waves are capable of considerable erosion of the shore and damage to shore structures.

In its general exposure to the open sea on a south-facing shoreline the Corral Canyon site resembles areas west of Santa Barbara, which may have experienced tsunamis as high as 30 to 50 feet following the earthquakes of 1812 (Richter, 1958, p. 113). Tsunamis of lesser magnitude have been recorded along the southern California coast in 1854, 1855, 1872, 1885, 1946, and 1957. Although those recorded have been relatively small, the occurrence of infrequent large tsunamis off the Pacific Coast of South America suggests that such low areas as Malibu Beach could suffer great damage from a tsunami (Emery, 1960, p. 124).

Littoral drifting includes both longshore and beach drifting--lateral movement of sediment along the coastline in the breaker zone and tidal zone due to longshore currents generated by wave action. Eighteen weekly observations of longshore currents in the surf zone, between August and December 1964, at five locations between Paradise Cove (3.5 miles west of Corral Canyon) and Malibu Colony (2 miles east of Corral Canyon) were made by Horrer (1965). During this period the average speed of the longshore currents was 0.15 knot, direction was eastward 85 percent of the time and westward 15 percent of the time. Eastward littoral drifting of sediment occurs along this part of the coastline at an unknown rate. At Port Hueneme near Oxnard, 27 miles northwest of the Corral Canyon site, littoral drifting is predominantly southward at a rate of 500,000 cubic yards per year; at Santa Monica, 14 miles east of the Corral Canyon site, littoral drifting is southward at a rate of 270,000 cubic yards per year (Johnson, 1956). A simple interpolation between these two rates to determine the rate of littoral drifting at Corral Canyon may not be even roughly approximate because of the unknown influence of Point Dume and the submarine canyon opposite Zuma Canyon west of the point. However, several lines of evidence show that sediment does pass eastward around Point Dume (Handin, 1951, p. 52; Trask, 1955).



Data from:

Blanchard, 1963
Broecker and Kaufman, unpub. ms.
Curray, 1961, fig. 1
Evernden and others, 1964, fig. 1
Fergusson and Libby, 1962, p. 113
Hopkins, 1965, fig. 2
Kulp, 1961, p. 1111

Fig. 53. Tentative geologic-chronologic time scale

REFERENCES CITED

Addicott, W. O., 1964, Pleistocene invertebrates from the Dume terrace, western Santa Monica Mountains, California: Southern California Acad. Sci. Bull., v. 63, pt. 3, p. 141-150.

Albee, A. L., 1965, Testimony in the matter of Department of Water and Power, City of Los Angeles, Malibu Nuclear Plant Unit No. 1: [mimeo.] Rept. to U. S. Atomic Energy Comm., Docket No. 50-214, Feb. 1965, 10 p.

Allen, C. R., St. Amand, P., Richter, C. F., and Nordquist, J. M., 196_, Relationship between seismicity and geologic structure in the southern California region: Seismolog. Soc. America Bull. (In press)

Arkley, R. J., 1963, Calculation of carbonate and water movement in soil from climatic data: Soil Science, v. 96, p. 239-248.

Bailey, T. L., 1954, Geology of the western Ventura basin, Santa Barbara, Ventura, and Los Angeles Counties [California], Map Sheet no. 4 of Jahns, R. H., ed., Geology of southern California: California Div. Mines Bull. 170, scale 1 in. to 6 mi.

Barbat, W. F., 1958, The Los Angeles Basin area, California, in Weeks, L. G., ed., Habitat of oil--a symposium: Tulsa, Okla., Am. Assoc. Petroleum Geologists, p. 62-77; also in A guide to the geology and oil fields of the Los Angeles and Ventura regions: Am. Assoc. Petroleum Geologists, Ann. Mtg., Los Angeles 1958, p. 37-49.

Benioff, Hugo, 1965, Testimony in the matter of Department of Water and Power, City of Los Angeles, Malibu Nuclear Plant Unit, No. 1: [mimeo.] Rept. to U. S. Atomic Energy Comm., Docket No. 50-214, July 1, 1965, 6 p.

Birman, J. H., Glacial geology across the crest of the Sierra Nevada, California: Geol. Soc. America Spec. Paper 75, 80 p.

Blanchard, R. L., 1963, Uranium decay series disequilibrium in age determination of marine calcium carbonates: [unpub.] Ph.D. thesis, Chemistry Dept., Washington Univ., St. Louis, 164 p.

Bramlette, M. N., 1946, The Monterey formation of California and the origin of its siliceous rocks: U. S. Geol. Survey Prof. Paper 212, 57 p.

Bravinder, K. M., 1942, Los Angeles basin earthquake of October 21, 1941, and its effect on certain producing wells in Dominguez field, Los Angeles County, California: Am. Assoc. Petroleum Geologists Bull., v. 26, no. 3, p. 388-399.

Broeker, W. S., and Kaufman, Aaron, 196_, An evaluation of absolute ages for the elevated marine terraces of the Palos Verdes Hills area based on uranium series inequilibrium in mollusks: [unpub.] ms. in press; cited with written permission of authors.

Burke, M. F., 1938, Flood of March 2, 1938: Los Angeles County Flood Control District.

_____1952, Report on floods of January 15-18, 1952: Los Angeles County Flood Control District.

Buckman, H. O., and Brady, N. C., 1960, The nature and properties of soils: New York, The Macmillan Co., 567 p.

Campbell, R. H., Yerkes, R. F., and Wentworth, C. M., 196_, Structural elements of the central Santa Monica Mountains, California: U. S. Geol. Survey report in prep. 1965.

Cleveland, G. B., and Troxel, B. W., 1965, Geology related to the safety of the Corral Canyon nuclear reactor site, Malibu, Los Angeles County, California: [mimeo.] Rept., Resources Agency of California Div. Mines and Geology, Feb. 1965, 37 p.

Converse Foundation Engineers, 1963, Preliminary submarine investigation--proposed nuclear power plant No. 1--Corral Canyon--Los Angeles County, California: [unpub. report of investigation] conducted for Department of Water and Power, City of Los Angeles, July 9, 1963.

Corey, W. H., 1954, Tertiary basins of southern California, [Pt.] 1 in Chap. 3 of Jahns, R. H., ed., Geology of southern California: California Div. Mines Bull. 170, p. 73-83.

Curray, J. R., 1961, Late Quaternary sea level: a discussion: Geol. Soc. America Bull., v. 72, no. 11, p. 1707-1712.

Dale, R. F., 1959, Climate of California, in Climate of the State: U. S. Weather Bur. Climatography U. S., no. 60-4, 37 p.

Davis, W. M., 1933, Glacial epochs of the Santa Monica Mountains, California: Geol. Soc. America Bull., v. 44, no. 10, p. 1041-1133.

Dudley, P. M., 1954, Geology of the Long Beach oil field, Los Angeles County [California], Map Sheet no. 34 of Jahns, R. H., ed., Geology of southern California: California Div. Mines Bull. 170.

Durrell, Cordell, 1954, Geology of the Santa Monica Mountains, Los Angeles and Ventura Counties [California], Map Sheet no. 8 of Jahns, R. H., ed., Geology of southern California: California Div. Mines Bull. 170.

Durrell, Cordell, 1956, Preliminary report on the geology of the Santa Monica Mountains, in Los Angeles Forum: Pacific Petroleum Geologist (News letter Pacific Soc., Am. Assoc. Petroleum Geologists, Los Angeles, Calif.), v. 10, no. 4, p. 1-3.

Emery, K. O., 1960, The sea off southern California, a modern habitat of petroleum: New York, John Wiley and Sons, Inc. 366 p.

Evernden, J. F., Curtis, G. H., Savage, D. E., and James, G. T., 1964, Potassium-argon dates and the Cenozoic mammalian chronology of North America: Am. Jour. Sci., v. 262, no. 2, p. 167.

Fergusson, G. J., and Libby, W. F., 1962, UCLA Radiocarbon dates I: Am. Jour. Sci., Radiocarbon Suppl., v. 4, p. 109-114.

Flint, R. F., 1957, Glacial and Pleistocene geology: New York, John Wiley and Sons, Inc., 553 p.

✓ Flint, R. F., and Brandtner, Friedrich, 1961, Climatic changes since the last Interglacial: Am. Jour. Sci., v. 259, no. 5, p. 321-328.

Grim, R. E., 1962, Applied clay mineralogy: New York, McGraw-Hill Book Co., Inc., p. 247-251.

Handin, J. W., 1951, The source, transportation, and deposition of beach sediment in southern California: U. S. Dept. of the Army, Corps of Engineers, Beach Erosion Board, Tech. Memo. 22, 113 p.

Hill, D. M., Lao, C., Moore, V. A., and Wolfe, J. E., 1964, Earthquake and epicenter fault map of California, in Crustal strain and fault movement investigation: California Dept. Water Resources Bull. 116-2.

Hill, M. L., 1954, Tectonics of faulting in southern California, [Pt.] 1 in Chap. 4 of Jahns, R. H., ed., Geology of southern California: California Div. Mines Bull. 170, p. 5-13.

Hill, R. T., 1928, Southern California geology and Los Angeles earthquakes: Los Angeles, Calif., Southern Calif. Acad. Sci., 232 p.

Hills, E. S., 1963, Elements of structural geology: New York, John Wiley and Sons, Inc., 483 p.

Hoffman, R. A., and Smith, J. L., 1965, Testimony in the matter of Department of Water and Power, City of Los Angeles, Malibu Nuclear Plant Unit No. 1: [mimeo.] Rept. to U. S. Atomic Energy Comm., Docket No. 50-214, Feb. 15, 1965, 37 p.

Hoots, H. W., 1931, Geology of the eastern part of the Santa Monica Mountains, Los Angeles County, California: U. S. Geol. Survey Prof. Paper 165-C, p. 83-134.

Hopkins, D. M., MacNeil, F. S., Merklin, R. L., and Petrov, O. M., 1965, Quaternary correlations across Bering Strait: Science, v. 147, no. 3662, p. 1107-1114.

Horrer, P. L., 1965, Testimony in the matter of Department of Water and Power, City of Los Angeles, Malibu Nuclear Plant Unit No. 1: [mimeo.] Rept. to U. S. Atomic Energy Comm., Docket No. 50-214, March 10, 1965, 19 p.

Housner, G. W., 1965, Testimony in the matter of Department of Water and Power, City of Los Angeles, Malibu Nuclear Plant Unit No. 1: [mimeo.] Rept. to U. S. Atomic Energy Comm., Docket No. 50-214, March 10, 1965, 5 p.

Hubbs, C. L., 1957, Recent climatic history in California and adjacent areas, in Craig, H., ed., Conference on Recent Research in Climatology, Proc., Scripps Inst. Oceanography, March 25-26, 1957: Comm. on Research in Water Resources, California Univ.

Hubbs, C. L., 1961, Quaternary paleoclimatology of the Pacific Coast of North America, <u>in</u> California Cooperative Oceanic Fisheries Investigations, Reports, v. 8: Marine Research Comm., State of California.

Ives, P. C., Levin, Betsy, Robinson, R. D., and Rubin, Meyer, 1964, U. S. Geol. Survey radiocarbon dates VII: Am. Jour. Sci., Radiocarbon Supplement, v. 6, p. 37-76.

Jackson, M. L., 1958, Soil chemical analysis: Englewood Cliffs, New Jersey, Prentice-Hall, Inc., 498 p.

Jahns, R. H., 1965, Testimony in the matter of Department of Water and Power, City of Los Angeles, Malibu Nuclear Plant No. 1: [mimeo.] Rept. to U. S. Atomic Energy Comm., Docket No. 50-214, March 10, 1965, 5 p.

Jenny, Hans, 1941, Factors of soil formation: New York, McGraw-Hill Book Co., 281 p.

Johnson, J. W., 1956, Nearshore sediment movement: Am. Assoc. Petroleum Geologists Bull., v. 40, no. 9, p. 2211-2232.

Jones, O. T., 1939, The geology of the Colwyn Bay district; a study of submarine slimping during the Salopian period: Quarterly Jour. Geol. Soc. London, v. 95, p. 335-376.

Kamb, Barclay, 1965, Geology of the Corral Canyon site in relation to the proposed nuclear reactor: [mimeo.] Rept. to Tuttle and Taylor, attorneys for Marblehead Land Co., Malibu, Calif., 40 p.

Kew, W. S. W., 1927, Geologic sketch of Santa Rosa Island, Santa Barbara County, California: Geol. Soc. America Bull., v. 38, no. 4, p. 645-653.

Kleinpell, R. M., 1938, Miocene stratigraphy of California: Tulsa, Okla., Am. Assoc. Petroleum Geologists, 450 p.

Knapp, R. R., chm., and others, 1962, Cenozoic correlation section across Los Angeles basin from Beverly Hills to Newport, California: Am. Assoc. Petroleum Geologists, Pacific Section.

Kulp, J. L., 1961, Geologic time scale: Science, v. 133, no. 3459, p. 1105-1114.

Los Angeles, City of, Department of Water and Power, 1964, Sixth amendment to application for construction permit and facility license for Malibu nuclear power plant--unit no. 1: [unpub.] report, August 21, 1964.

Los Angeles County Flood Control District, Hydraulic Division, 1933-1964, Seasons of 1931-32 to 1962-63 (1933, 1935, Rainfall and runoff report; 1937, Rainfall, runoff, and dam operation; 1939-64, Annual and biennial reports on hydrologic data): Repts. on hydrologic data.

Maxwell, J. C., 1959, Turbidite, tectonic and gravity transport, northern Apennine Mountains, Italy: Am. Assoc. Petroleum Geologists Bull., v. 43, p. 2701-2719.

McCulloh, T. H., 1960, Gravity variations and the geology of the Los Angeles basin of California: Art. 150 in U. S. Geol. Survey Prof. Paper 400-B, p. B320-325.

Merla, G., 1952, Geologia dell' Appennino Settentrionale: Soc. Geol. Italiana, Boll., v. 70 (1951), p. 95-382; English summary, p. 360-365.

Morrison, R. B., 1964, Lake Lahontan: geology of the southern Carson Desert, Nevada: U. S. Geol. Survey Prof. Paper 401. 156 p.

Oakeshott, G. B., and Tocher, Don, 1960, Surface faulting in recent earthquakes, Western Cordillera [abs.]: Geol. Soc. America Bull., v. 71, no. 12, pt. 2, p. 2038.

Olson, E. A., 1963, The problem of sample contamination in radiocarbon dating: Ph.D. thesis, Columbia Univ., fig. 3, Graph for quantitative consideration of sample contamination.

Page, B. M., 1962, Geology south and east of Passo della Cisa, northern Apennines: Bollettini Soc. Geol. Italiana Boll., v. 81, p. 1-48.

Poland, J. F., Garrett, A. A., and Sinnott, Allen, 1959, Geology, hydrology, and chemical character of ground waters in the Torrance-Santa Monica area, California: U. S. Geol. Survey Water-Supply Paper 1461, 425 p.

Potter, P. E., and Pettijohn, F. J., 1963, Paleocurrents and basin analysis: Academic Press, Inc., chap. 6, p. 143-172.

Putnam, W. C., 1954, Marine terraces of the Ventura region and the Santa Monica Mountains, California, [Pt.] 7 in Chap. 5 of Jahns, R. H., ed., Geology of southern California: California Div. Mines Bull. 170, p. 45-48.

Ramberg, Hans, 1955, Natural and experimental boudinage and pinch-and-swell structures: Jour. Geology, v. 63, p. 512-526.

Rand, W. W., 1931, Preliminary report of the geology of Santa Cruz Island, Santa Barbara County, California: Mining in California, v. 27, no. 2, p. 214-219.

Reed, R. D., 1933, Geology of California: Tulsa, Okla., Am. Assoc. Petroleum Geologists, 355 p.

Richmond, G. M., 1962, Quaternary stratigraphy of the La Sal Mountains, Utah: U. S. Geol. Survey Prof. Paper 324, 135 p.

Richter, C. F., 1958, Elementary seismology: San Francisco, Calif., W. H. Freeman and Co., 768 p.

_____ 1959, Seismic regionalization: Seismolog. Soc. America Bull., v. 49, no. 2, p. 123-162.

Rothwell, W. T., Jr., 1958, Western Los Angeles basin and Harbor area, in A guide to the geology and oil fields of the Los Angeles and Ventura regions: Am. Assoc. Petroleum Geologists, Ann. Mtg., March 1958, p. 65-73.

Rowe, P. B., Countryman, C. M., and Storay, H. G., 1954, Hydrologic analysis used to determine effects of fire on peak discharge and erosion rates in southern California watersheds: U. S. Dept. Agriculture, California Forest and Range Experiment Sta., Forest Service.

Schoellhamer, J. E., and Woodford, A. O., 1951, The floor of the Los Angeles basin, Los Angeles, Orange, and San Bernardino Counties, California: U. S. Geol. Survey Oil and Gas Inv. Map OM-117, scale 1 inch = 1 mile.

Schoellhamer, J. E., and Yerkes, R. F., 1961, Preliminary geologic map of the coastal part of the Malibu Beach quadrangle, Los Angeles County, California: U. S. Geol. Survey open-file map, Sept. 6, 1961, scale 1:12,000.

Schoellhamer, J. E., Yerkes, R. F., and Campbell, R. H., 1962, Preliminary geologic map of the coastal part of the Point Dume quadrangle, Los Angeles County, California: U. S. Geol. Survey open-file map, Aug. 20, 1962, scale 1:12,000.

Shepherd, F. P., and Emery, K. O., 1941, Submarine topography off the California coast canyons and tectonic interpretation: Geol. Soc. America Spec. Paper 31, 171 p.

Slemmons, D. B., Jones, A. E., and Gimlett, J. I., 1965, Catalogue of Nevada earthquakes 1852-1960: Seismolog. Soc. America Bull., v. 55, p. 537-583.

Smith, M. B., 1964, Map showing distribution in configuration of basement rocks in California: U. S. Geol. Survey Oil and Gas Inv. Map OM-215.

Stevenson, R. E., 1959, The marine climate of southern California, <u>in</u> Oceanographic survey of the Continental shelf area of southern California: State Water Pollution Control Board, Publ. no. 20, p. 3-58.

Thornthwaite, C. W., and Mather, J. R., 1957, Instructions and tables for computing potential evapotranspiration and the water balance: Drexel Inst. Technology, Centerton, New Jersey, v. <u>X</u>, no. 3, p. 185-311.

✓ Tocher, Don, 1958, Earthquake energy and ground breakage: Seismolog. Soc. America Bull., v. 48, p. 147-153.

Trask, P. D., 1955, Movement of sand around southern California promontories: U. S. Dept. of the Army, Corps of Engineers, Beach Erosion Board, Tech. Memo. 76, 60 p.

Turner, F. J., and Weiss, L. E., 1963, Structural analysis of metamorphic tectonites: New York, McGraw-Hill Book Co., Inc., 545 p.

U. S. Department of Agriculture, 1951, Soil Survey Manuel: U. S. Dept. Agric., Agricultural Handbook 18, 503 p.

U. S. Coast and Geodetic Survey, 1964, Report on the seismicity of the Malibu, California area: [unpub.] Rept. to Div. of Licensing and Regulation, U. S. Atomic Energy Comm., June 1964.

Wagner, R. J., and Nelson, R. E., 1961, Soil survey of the San Mateo area, California: U. S. Dept. Agriculture, Soil Survey Series 1954, no. 13, 111 p.

Wentworth, C. M., and Yerkes, R. F., 1965, Geologic investigations, December 1964 to March 1965 at the proposed nuclear power plant site, Corral Canyon, Los Angeles County, California: [unpub.] U. S. Geol. Survey Rept. to U. S. Atomic Energy Comm., March 1965, 27 p.

Woodford, A. O., 1960, Bedrock patterns and strike-slip faulting in southwestern California: Am. Jour. Sci., v. 258-A (Bradley Volume), p. 400-417.

Woodford, A. O., Schoellhamer, J. E., Vedder, J. G., and Yerkes, R. F., 1954, Geology of the Los Angeles basin [California], [Pt.] 5 _in_ Chap. 2 _of_ Jahns, R. H., ed., Geology of southern California: California Div. Mines Bull. 170, p. 65-81.

Woodring, W. P., Bramlette, M. N., and Kew, W. S. W., 1946, Geology and paleontology of Palos Verdes Hills, California: U. S. Geol. Survey Prof. Paper 207, 145 p.

Yerkes, R. F., Campbell, R. H., Schoellhamer, J. E., and Wentworth, C. M., 1964, Preliminary geologic map and sections of southwest part of the Topanga quadrangle, Los Angeles County, California: U. S. Geol. Survey open-file map, scale 1:12,000.

Yerkes, R. F., and Wentworth, C. M., 1964, Geologic report on the proposed Corral Canyon nuclear power plant site, Los Angeles County, California: [unpub.] Rept. of U. S. Geol. Survey to U. S. Atomic Energy Comm., Dec. 1964, 93 p.

Appendix A

Foraminiferal collections from the Corral Canyon site; identified by P. B. Smith, U. S. Geological Survey

Locality 1, test trench 3 (fig. 8c); field no. CC/50-1:

Bolivina advena striatella Cushman
B. imbricata Cushman
Buliminella curta Cushman
Uvigerinella californica Cushman
Valvulineria miocenica Cushman
V. californica Cushman
Cassidulina cf. C. crassa d'Orbigny
Robulus sp.

Age: Luisian (late middle Miocene)

Locality 2, test trench 3 (fig. 8c); field no. CC/50-2:

Bolivina advena striatella Cushman
Uvigerinella californica Cushman
Valvulineria miocenica Cushman

Age: Luisian stage (late middle Miocene)

Locality 3, test trench 3 (fig. 8c); field no. CC/50-3:

Bolivina advena striatella Cushman
Buliminella curta Cushman
Valvulineria miocenica Cushman
Uvigerinella californica Cushman

Age: Luisian stage (late middle Miocene)

Locality 4, test trench 3 (fig. 8c); field no. CC/50-4:

Bolivina advena striatella Cushman
Uvigerinella californica Cushman
Valvulineria miocenica Cushman
V. californica Cushman
Planulina sp.

Age: Luisian stage (late middle Miocene)

Locality 5, test trench 3 (fig. 8c); field no. CC/50-5:

Bolivina advena striatella Cushman
B. imbricata Cushman
B. guadaloupae Parker
Buliminella curta Cushman
Uvigerina subperegrina Cushman and Kleinpell
Uvigerinella californica Cushman
Valvulineria miocenica Cushman
V. californica Cushman
Gyroidina rotundimargo R. E. and K. C. Stewart

Age: Luisian stage (late middle Miocene)

Locality 6, test trench 3 (fig. 8c); field no. CC/50-6:

Bolivina advena striatella Cushman
B. guadaloupae Parker
Buliminella subfusiformis Cushman
Uvigerinella californica Cushman
Nonion costiferum (Cushman)
Valvulineria californica Cushman
V. miocenica Cushman
Elphidium cf. E. crispum (Linné)
Gyroidina rotundimargo R. E. and K. C. Stewart
Cassidulina cf. C. crassa d'Orbigny

Age: Luisian stage (late middle Miocene)

Locality 7, test trench 3 (fig 8c) field no. CC/50-7:

Bolivina advena striatella Cushman
Buliminella subfusiformis Cushman
Uvigerinella californica Cushman
Valvulineria californica Cushman
V. miocenica Cushman
Hanzawaia sp.

Age: Luisian stage (late middle Miocene)

Locality 8, test trench 3 (fig. 8c); field no. CC/50-8:

Bolivina advena striatella Cushman
B. guadaloupae Parker
B. imbricata Cushman
Uvigerina subperegrina Cushman and Kleinpell
Uvigerinella californica Cushman
Buliminella curta Cushman
Valvulineria miocenica Cushman
V. depressa Cushman
Baggina robusta Kleinpell
Gyroidina rotundimargo R. E. and K. C. Stewart
Hanzawaia sp.
Lagena spp.
Globigerina spp.

Age: lower Luisian stage (late middle Miocene)

Locality 9, test trench 3 (fig. 8c); field no. CC/50-9:

Bolivina advena striatella Cushman
B. imbricata Cushman
B. guadaloupae Parker
Uvigerina subperegrina Cushman
Uvigerinella californica Cushman
Valvulineria depressa Cushman
Planulina sp.
Lagena sp.

Age: lower Luisian stage (late middle Miocene)

Locality 10, test trench 3 (fig. 8c); field no. CC/50-10:

Bolivina advena striatella
B. imbricata Cushman
Buliminella subfusiformis Cushman
Valvulineria californica Cushman
V. miocenica Cushman
V. depressa Cushman
Uvigerina subperegrina Cushman and Kleinpell
Uvigerinella californica Cushman

Age: lower Luisian stage (late middle Miocene)

Locality 11, test trench 3 (fig. 8c); field no. CC/51-7:

Bolivina advena striatella Cushman
B. imbricata Cushman
Uvigerinella californica Cushman
Valvulineria miocenica Cushman
Cassidulina cf. *C. crassa* d'Orbigny
Gyroidina sp.

Age: Luisian stage (late middle Miocene)

Locality 12, test trench 3 (fig. 8c); field no. CC/51-1:

Bolivina advena striatella Cushman
B. imbricata Cushman
Buliminella subfusiformis Cushman
Uvigerinella californica Cushman
Valvulineria californica Cushman
V. depressa Cushman
V. miocenica Cushman
Baggina robusta Kleinpell

Age: lower Luisian stage (late middle Miocene)

Locality 13, test trench 3 (fig. 8c); field no. CC/51-2:

No identifiable Foraminifera

Locality 14, test trench 3 (fig. 8c); field no. CC/51-1a:

Bolivina advena striatella Cushman
B. imbricata Cushman
B. guadaloupae Parker
B. cf. *B. rhomboidalis* Millett
Uvigerina subperegrina Cushman and Kleinpell
Uvigerinella californica Cushman
Valvulineria californica Cushman
V. miocenica Cushman
Baggina robusta Kleinpell
Nonion costiferum (Cushman)
Cibicides sp.
Globigerina spp.

Age: Luisian stage (late middle Miocene)

Locality 15, test trench 3 (fig. 8c); field no. CC/51-3:

Bolivina advena striatella Cushman
B. guadaloupae Parker
B. imbricata Cushman
Buliminella curta Cushman
Uvigerina subperegrina Cushman and Kleinpell
Uvigerinella californica Cushman
Valvulineria miocenica Cushman
V. depressa Cushman
V. californica Cushman
Globigerina spp.

Age: lower Luisian stage (late middle Miocene)

Locality 16, test trench 3 (fig. 8c); field no. CC/51-4:

Bolivina advena striatella Cushman
B. imbricata Cushman
Uvigerinella californica Cushman
Valvulineria miocenica Cushman
V. depressa Cushman

Age: lower Luisian stage (late middle Miocene)

Locality 17, test trench 3 (fig. 8c); field no. CC/51-5:

Bolivina advena striatella Cushman
B. guadaloupae Parker
B. imbricata Cushman
Uvigerina subperegrina Cushman and Kleinpell
Uvigerinella californica Cushman
U. obesa Cushman
Valvulineria californica Cushman
V. miocenica Cushman
Epistominella subperuviana (Cushman)
Cibicides sp.

Age: Luisian stage (late middle Miocene)

Locality 18, test trench 3 (fig. 8c); field no. CC/51-6:

Bolivina advena striatella Cushman
B. imbricata Cushman
B. guadaloupae Parker
B. marginata gracillima Cushman
Uvigerinella californica Cushman
Valvulineria miocenica Cushman
Anomalina salinasensis Kleinpell
Pullenia miocenica Kleinpell
Gyroidina sp.
Planulina sp.

Age: upper Luisian stage (late middle Miocene)

Locality 2-1, test trench 2 (fig. 9); field no. Y326F

Nonionella sp.
Globobulina pacifica Cushman
Uvigerinella californica Cushman
Valvulineria miocenica Cushman
Lagena sp.
Bolivina advena striatella Cushman
Globigerina bulloides d'Orbigny

Age: Luisian? (middle Miocene)

Locality 2-2, test trench 2 (fig. 9); field no. Y320D

Valvulineria californica obesa Cushman
Bolivina advena Cushman
Nonion costiferum Cushman
Baggina californica Cushman
Hanzawaia sp.
Buliminella curta Cushman
Robulus sp.
Hemicristillaria beali (Cushman)
Uvigerinella californica Cushman

Age: middle Miocene, probably Luisian stage

Locality 2-3, test trench 2 (fig. 9); field no. Y326B

Valvulineria miocenica Cushman
V. californica Cushman
Baggina robusta Kleinpell
Siphogenerina collomi Cushman
Bolivina advena striatella Cushman
Uvigerinella californica Cushman
Gyroidina rotundimargo R. E. and K. C. Stewart
Planulina sp.
Bolivina imbricata Cushman
Epistominella relizensis Kleinpell
Cassidulina cf. *C. crassa* d'Orbigny
Pullenia miocenica Kleinpell
Globigerina bulloides d'Orbigny

Age: upper Luisian stage (late middle Miocene)

Locality 2-4, test trench 2 (fig. 9); field no. Y318A

Siphogenerina collomi Cushman
Valvulineria californica Cushman
Baggina californica Cushman
Bolivina advena striatella Cushman
Hemicristillaria beali
Valvulineria miocenica Cushman
Uvigerinella californica Cushman
Bolivina cf. *B. vaughani* Natland
Pullenia miocenica globula Kleinpell

Age: upper Luisian stage (late middle Miocene)

Locality 2-5, test trench 2 (fig. 9); field no. Y326C

Uvigerinella californica Cushman
Valvulineria miocenica Cushman
V. californica appressa Cushman
V. depressa Cushman
Bolivina imbricata Cushman
B. advena striatella Cushman
Gyroidina rotundimargo R. E. and K. C. Stewart
Cassidulina panzana Kleinpell
Buliminella subfusiformis Cushman
Epistominella relizensis Kleinpell
Baggina californica Cushman

Age: lower Luisian stage (late middle Miocene)

Locality 2-6, test trench 2 (fig. 9); field no. Y326E

Valvulineria depressa Cushman
V. miocenica Cushman
Bolivina advena striatella Cushman
B. cf. B. vaughani Natland
Buliminella curta Cushman
Baggina californica Cushman
Uvigerina subperegrina Cushman and Kleinpell
Cassidulina cf. C. crassa d'Orbigny
Buliminella subfusiformis Cushman

Age: lower Luisian stage (late middle Miocene)

Locality 2-7, just westof mouth of Corral Canyon (fig. 4); field no. Y321C

Uvigerinella californica Cushman
Bolivina advena Cushman
Valvulineria araucana Cushman
V. miocenica Cushman
Buliminella curta Cushman

Age: middle Miocene, probably Luisian stage

Appendix B

Megafossil collections from Corral Canyon site; identified by W. O. Addicott, U. S. Geological Survey.

CW-115. From bulldozer cut in gully B at north (left) edge of marine sand and gravel shown in fig. 43.

Tivela stultorum; fragments
Olivella biplicate; 3 specimens

CW-126. From 90 feet on northwest wall, trench 3, altitude about 25 feet, in unit Sd-3 (fig. 8b). Collection in part courtesy of Converse Foundation Engineers.

Age: radiocarbon age of about 2,950 years BP

Ecology: marine; largely intertidal; the invertebrates are common constituents of kitchen middens.

Gastropods:

Acmaea sp. - 1 specimen
Olivella cf. *O. biplicata* (Sowerby) - 1 specimen

Pelecypods:

Mytilus californianus Conrad - abundant
Septifer bifurcatus (Conrad) - 10 values

Amphineuran:

Mopalia muscosa (Gould) - 5 valves

Vertebrate (Identified by C. A. Repenning):

Toe bone of a small Pinneped (seal or sea lion)

C-2. From unit Sdm at about 42 feet in trench C (fig. 12). Collection courtesy of Converse Foundation Engineers.

Age: Pleistocene to Recent

Ecology: marine, intertidal to shallow inner sublittoral

Gastropods:

- *Calliostoma* sp.
- *Lacuna* sp.
- *Tegula gallina* (Forbes)
- unidentified trochid

Appendix C

Estimates of ages for samples from elevated marine terraces based on uranium series disequilibrium, determined by J. N. Rosholt, U. S. Geological Survey.

Sample CW 115. Bulk sample of shell fragments from marine sand at altitude about 135 feet, terrace C, east wall of gully B near mouth, Corral Canyon site; estimated maximum age 280,000 years; probably is significantly older than two samples listed below.

Sample M 1710A. Specimen *Tivela stultorum* (aragonitic) from the U.S.G.S. Cenozoic (late Pleistocene) locality M 1710, 2 miles west of Corral Canyon on Pacific Coast Highway (see fig. 5), from marine deposits on terrace D (110-foot). Estimated maximum age 130,000 years; may not be significantly different in age from sample M 2017 below.

Sample M 1710. Specimen of *Florimetis biangulata* (aragonitic) from Palos Verdes Sand, on lowest emergent "100-foot" terrace, southeast corner of Olive and Pacific Streets, San Pedro, California. Estimated maximum age 110,000 years.

Appendix D

Preliminary pollen analysis of unit CF by E. B. Leopold, U. S. Geological Survey.

Samples from 226 feet in trench B, depths from ground surface as indicated. A sample from adjacent bedrock mudstone contained no pollen. U.S.G.S. Paleobotanical locality No. D3598.

	Depth below ground surface:			
	96 in. D3598-A	84 in. D3598-B	24 in. 3598-C	0-2 in. D3598-D
trees and shrubs				
Pinus	0.9		1.9	7.2
Cupressus type	0.9	0.9	5.6	0.9
Quercus (oak)				2.7
Juglans (walnut)				0.9
Alnus (alder)				1.8
Rhus				0.9
herbs				
Chenopodiaceae (salt bush family)				14.3
Compositae (sunflower fam.)	90.0	88.2%	56.5	28.6
Gramineae (grasses)			1.9	
Euphorbia		0.9	3.8	34.9
Erodium				2.7
Eriogonum	0.9			0.9
undetermined				
dicotyledons	5.5	2.7		5.3
monocotyledons	1.8	7.2	30.2	
total pollen counted	110	109	106	112