UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

SEISMIC ENVIRONMENT OF THE BURRO FLATS SITE, VENTURA COUNTY, CALIFORNIA

(A brief, limited literature review)

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by

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Summary and introduction

A limited review of available literature suggests that the maximum horizontal ground acceleration at the Burro Flats site from earthquakes in the region could range from less than 0.1 to 0.49 g. A magnitude 8 earthquake on the nearby San Andreas fault could produce ground accelerations in the range 0.18 to 0.31 g, and an expectable larger earthquake on that fault could produce larger accelerations. Ground motion from possible smaller but closer earthquakes ranges up to 0.49 g for an earthquake of magnitude 6.5 on the adjacent "Burro Flats fault".

Estimation of these accelerations is dependent on determining the geologic environment of the site, the appropriate earthquake magnitudes to be assigned significant faults in that environment, and the attenuation of shaking between the earthquake epicenters and the site. The site lies within a tectonically active region--the historically active San Andreas fault is only 34 miles to the northeast, and lesser faults showing evidence of late Quaternary displacement are located closer to the site. Evidence for youthfulness of these lesser faults varies, and except for the active Newport-Inglewood zone and the Santa Ynez fault, they qualify as possible

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[1] Since this report was written in 1969 the nearby San Fernando earthquake of 1971 has occurred, and knowledge of the relation of earthquake magnitude, fault distance, and base rock acceleration has increased considerably (see, for example, USGS Prof. Paper 733 and Page and others, 1972, respectively).

but as yet-unproven active faults. All known faults with appropriate length to site-distance ratios that are reasonably classed as late Quaternary faults are discussed, and are included as potential earthquake generators.

Earthquakes of appropriate magnitude to be assigned to each fault are determined by assuming rupture in one event of half the map length of the fault, and applying relations (determined by several authors) between earthquake magnitude and rupture length in historic events to determine magnitudes. These magnitudes are, for the purposes of this brief review, probably reasonable estimates of the capabilities of each fault, although earthquakes of larger magnitude are possible. Accelerations are then determined by assuming earthquakes of the above determined magnitude placed at the closest point to the site on the fault trace, and applying attenuation curves of three different authors.

Considerable uncertainty is inherent in the rough estimates of seismic accelerations made herein, for they are dependent on a chain of judgments, each of which, in itself, is uncertain. Present knowledge of the geology of the region is incomplete, so that geometry and structural relations of the faults are in part uncertain, and much evidence bearing on the youth of the faults has yet to be gathered and evaluated. Estimation of earthquake magnitude is also uncertain, and even assuming that approximate magnitude is known rather than estimated from fault length, estimates of maximum ground acceleration may differ greatly depending on the authority used. Further consideration of ground acceleration at the site might refine the estimates made herein and resolve the apparent contradictions between the authorities cited. Attention to frequency and duration of strong shaking would also be appropriate.

This study was undertaken at the request of A. J. Pressesky, Assistant Director for Nuclear Safety, Division of Reactor-Development and Technology, U.S. Atomic Energy Commission, in March, 1969. It is based on a brief review of pertinent literature to which the authors had immediate access during the few weeks (April-May, 1969) available for report preparation. Because the report is limited both in scope and thoroughness, it must be considered no more than a first estimate of the tectonic and seismic environment of the Burro Flats site, and should not be considered sufficient, in itself, as a basis for design. The report is intended, however, to indicate the breadth of inquiry that is necessary in the consideration of ground acceleration at sites in California, and to indicate the incomplete status of geologic mapping and other geologic studies in the region. The report describes the tectonic environment of the Burro Flats site, discusses 10 pertinent faults individually, and presents possible earthquake magnitudes for those faults and resultant potential ground accelerations at the site.

Regional tectonic environment

The geologic environment of the Burro Flats site, as briefly developed below, indicates that significant seismic shaking at the site may result from nearby earthquakes of moderate size or from more distant earthquakes of larger size. Thus, not only local geology and possible local earthquakes, but regional geology and accompanying possible larger earthquakes must be considered in determining the seismic conditions at the site. Of immediate importance is the San Andreas fault, which is historically active and generally considered an impending source of a great earthquake in this region.

The Burro Flats site in the Simi Hills is within the well-known southern California region of active tectonism and seismicity (fig. 1; Allen and others, 1965). This region is dominated by the San Andreas fault system, which consists of the San Andreas fault itself and several other major faults west of it. These other faults are spaced 20 to 25 miles apart and trend northwestward to abut the south margin of the Transverse Ranges. The east-trending Transverse Ranges form a structural province that lies athwart the northwest trend of the San Andreas system. West of the San Andreas and San Jacinto faults the province is crossed only by the northwest-trending San Gabriel fault. Surface faulting and major earthquakes have occurred in some abundance in the region during the short period of historic record, with faults of the San Andreas system predominating over Transverse Range structures (Allen and others, 1965, fig. 5; Dickenson and Grantz, 1968, last plate - Historically and recently active faults of the California region).

Especially notable historic earthquakes in the region, for present purposes, are the great Fort Tejon earthquake of 1857, which was accompanied by surface rupture on the San Andreas fault (fig. 1); the 1933 Long Beach earthquake of magnitude 6.3 on the Newport-Inglewood Zone; and the 1952 Kern County earthquake of magnitude 7.7, which was accompanied by surface rupture on the White Wolf fault (fig. 1). Lesser earthquakes have occurred throughout the region, but with irregular areal distribution. According to records at the California Institute of Technology, no earthquake as large as magnitude 4 has occurred near the Burro Flats site, at least since reasonably good records began in 1933 (Yerkes and Wentworth, 1965, fig. 44; site is located 8 miles northwest of Woodland Hills).

Because the historic seismic record is much too short to be used alone to estimate future seismicity, the geologic history recorded in the rocks must be consulted as well. Although this geologic record is very incomplete, and of much poorer resolution than the historic record, it may be quite important. However, consideration of the geologic record does not guarantee that all presently operative faults can be recognized, and the very incomplete state of geologic mapping and other study further hinders such recognition. The White Wolf fault, for example, would not have been confidently identified by most geologists as an active fault prior to the 1952 Kern County earthquake, despite the presence of a steep mountain front just behind the fault. This event should be a reminder of the difficulty of recognizing active faults, even where the geologic record is considered along with the historic record.

The geologic history of the Burro Flats area indicates much late Cenozoic* tectonism, including probable late Quaternary* displacement on several faults near the site (which are named on the larger map of fig. 1). Northwest of the site the south side of the late Cenozoic Ventura basin is marked by the Santa Rosa fault. The San Fernando Valley, in part fault-defined, lies to the east of the site, and to the south, the south margin of the Transverse Ranges structural province is formed by the Malibu Coast fault and others of the Santa Monica fault system. Farther south lies the

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*Late Cenozoic is used here to refer to the past 13 million years or so--post middle Miocene time; late Quaternary refers to the past few hundred thousand years--late Pleistocene and Holocene (Recent); and Holocene refers to the past 10,000 years.

Explanation for Figure 1

Map Units

Qa	Quaternary alluvium
Qt	Quaternary terrace deposits
QP	Pliocene and Pleistocene deposits
PM	upper Miocene and lower Pliocene deposits
M	middle and lower Miocene rocks
Mv	Miocene volcanic rocks
Øc	Oligocene nonmarine rocks
E	Eocene rocks
Ep	Paleocene rocks
Ku	Upper Cretaceous rocks
JT	Jurassic-Triassic rocks

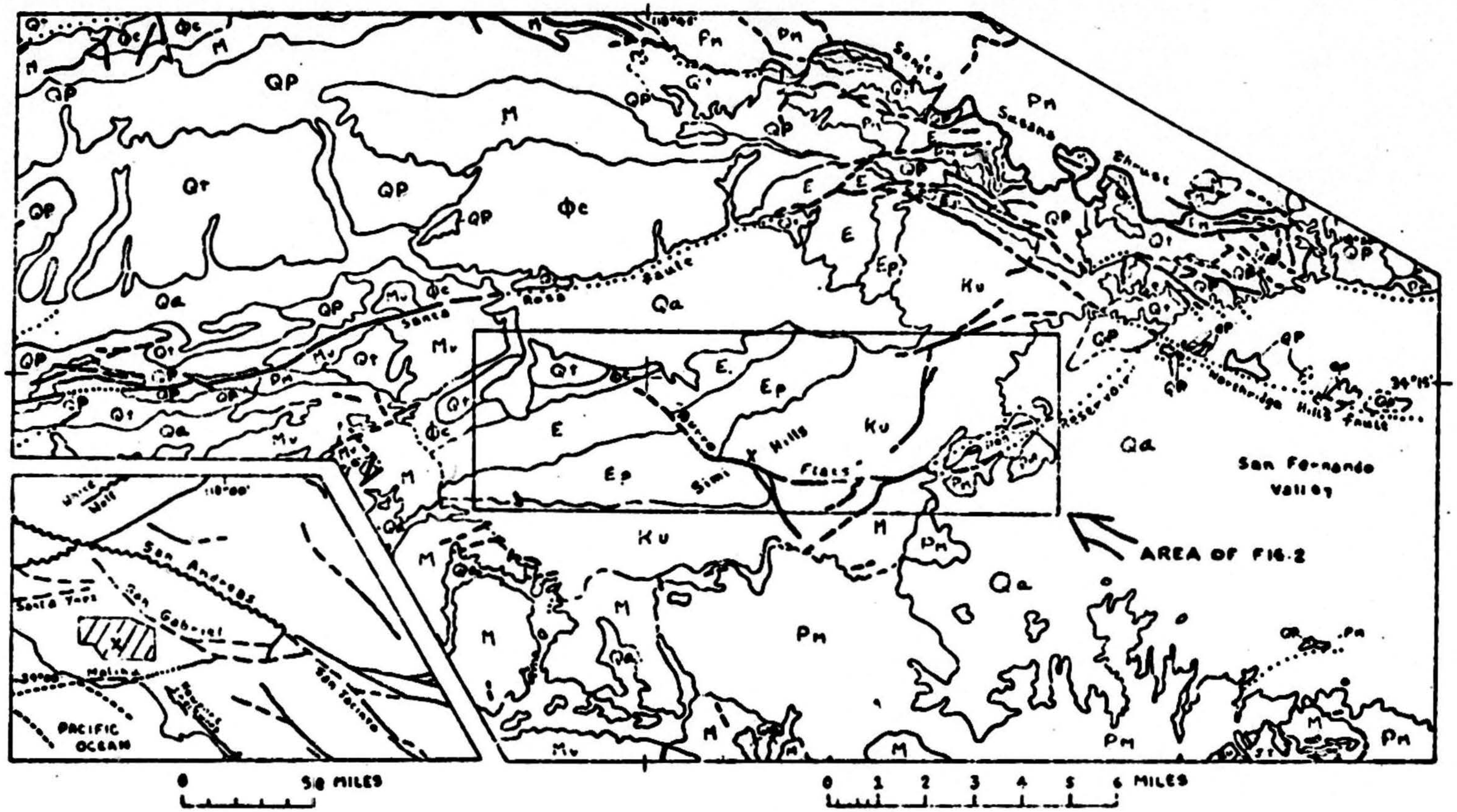

Fig. 1. General geologic environment of Burro Flats site (indicated by 'x'). Small inset map shows the relation of the site to faults with historic surface displacement (〰〰) and other large faults in southern California (modified from Dickenson and Grantz, 1968); more detailed map shows bedrock geology and relation of site to nearby late Quaternary faults, which are named (geology from Jennings and Strand, 1969).

structurally defined Los Angeles basin of late Cenozoic age, crossed by the northwest-trending Newport-Inglewood zone.

Positive identification of specific faults as active, or as sufficiently active to be of concern for a particular engineering problem, is not possible except for those few faults that have exhibited repeated activity in historic or very recent geologic time. For at least some purposes, faults lacking evidence of such recent movement may be important, and consideration of their geologic history as recorded in the rocks, albeit incompletely, is their only means of identification. In the following discussion, all faults exhibiting evidence of late Quaternary movement with appropriate length to site-distance ratios are included as worthy of consideration, and no attempt is made to evaluate their relative or absolute likelihood of future displacement. The discussion, therefore, is in no way comprehensive, although it should provide a rough approximation of the real geologic environment.

San Andreas fault.--This active master fault traverses 800 miles of western California, and passes within 34 miles of the Burro Flats site. It has been the locus of two great earthquakes during historic time, and present evaluations (Allen, 1968, p. 76, Richter, 1964, p. 7) suggest that the most likely place for the next great earthquake is the fault segment that generated the Fort Tejon earthquake of 1857, which lies opposite the Burro Flats site. Surface rupture has accompanied the larger and some of the smaller historic earthquakes on the fault. Marked topographic evidence of fault disruption of the ground surface testifies to persistence of this activity back at least into the recent past (Ross, 1969; Wallace, 1968), and geologic evidence indicates persistence of right slip for many tens of millions of years (Dickinson and Grantz, 1968, p. 117-119). Geodetic measurements reveal that deformation across the fault system is continuing today (Dickinson and Grantz, 1968, p. 1), indicating that future earthquakes can be expected.

Santa Ynez fault.--This is a major active fault in California that trends eastward for about 82 miles along the north margin of the Transverse Ranges, and approaches within 30 miles of the Burro Flats site at its eastern end (fig. 1; Jennings, 1959; Jennings and Strand, 1969). It has a total displacement measurable in miles, and bears evidence of quite youthful movement.

The fault is nearly parallel to the historically(?) active left-lateral Big Pine fault 12 miles to the north (fig. 1), and exhibits sufficient evidence of recent movement for Dibblee to conclude (1966, p. 66) that "the Santa Ynez fault and associated subsidiary faults constitute a major active fault system." The fault is the site of fairly consistent left-lateral stream offsets, and Page and others (1951, p. 1769) report furrowing of the ground surface, ponding of slope wash, and vague indications that in one place terrace deposits may be faulted. Thus it must be concluded that the Santa Ynez fault has been active in late Quaternary time, and probably in Holocene time as well.

Like the San Andreas fault, the Santa Ynez fault is a steep fault with a relatively straight trace, and is marked by a zone of shearing as wide as 1,500 feet and numerous elongate fault slivers (Page and others, 1951, p. 1722; Dibblee, 1966, p. 67). According to Dibblee (1966, p. 67), displacement across the fault is probably at least several miles, with significant components of both dip-slip and left-lateral strike-slip.

Newport-Inglewood zone.--This active structural zone, probably a part of the San Andreas fault system, has undergone major right slip, and seems to separate continental from Franciscan basement at depth. From a point about 20 miles southeast of the Burro Flats site it extends southeastward for 45 miles across the Los Angeles Basin, and continues on for an unknown distance beneath the Pacific Ocean. Abundant evidence of late Quaternary displacement exists along the zone, and it is considered the source of the 1933 Long Beach earthquake (Richter, 1958, p. 497).

The zone consists of a complex of interrelated faults and folds in a sedimentary section about 12,000 feet thick, which extends down into basement rock as a relatively simple fault zone. The Newport-Inglewood zone does not extend northwestward beyond the Malibu Coast fault, but rather merges with that fault to form a coherent structural system (U.S. Geological Survey, 1965). This system has allowed Franciscan terrane of the continental borderland to move northwestward along the Newport-Inglewood zone and down beneath the leading edge of the Transverse Ranges along the Malibu Coast fault (Yerkes and Wentworth, 1965, p. 24-25).

Considerable attention was given the geologic history of the Newport-Inglewood zone during consideration of the Corral Canyon (Malibu) and Bolsa Island reactor sites (Yerkes and Wentworth, 1965, fig. 1, p. 24-25, and 145; Castle, 1966, p. 19-38). An advisory committee to the Secretary of the Interior (Seed, 1967) recommended that, for the Bolsa Island site, a magnitude 8 earthquake be assumed on the Newport-Inglewood zone. This high magnitude was purposely intended to be very conservative, and is not used herein, although a long submarine continuation of the zone might make such a great earthquake less conservative.

San Gabriel fault.--This is a major fault in the San Andreas fault system that has undergone 20 to 30 miles of right slip. The fault is 74 miles long (including its southern branch), and passes within 16 miles of the Burro Flats site. Opinion differs over the present tectonic vitality of the San Gabriel fault, but the available evidence requires that in this report it be considered a potential generator of future large earthquakes.

The San Gabriel fault has been studied in detail by Crowell (1950, 1952, 1962) along its northwestern part, where geologic evidence suggests that the fault absorbed much of the right slip of the San Andreas fault system during Pliocene and earliest Pleistocene time. Crowell considers displacement on the San Gabriel fault during this period to have totaled 20 to 30 miles right slip and locally more than 10,000 feet dip slip. The fault is presumed to connect at its northwestern end with the San Andreas fault beneath the Frazier Mountain thrust, and extends 56 miles southeastward to Tujunga Canyon, where it branches. The northern branch trends eastward for 30 miles towards the San Jacinto fault (an active fault in the San Andreas fault system), but is truncated by the left-lateral San Antonio fault north of Ontario (Rogers, 1969). The southern branch is formed by the Sierra Madre Fault, 18 miles long, which may connect with the Santa Monica fault system north of Monrovia. The San Gabriel fault and its southern branch are treated in this report as one fault 74 miles long.

At its northwestern end the San Gabriel fault is overlapped by late Pliocene strata, suggesting termination of movement by that time. However, according to Crowell, evidence of later movement is present both there, and to the southeast where Plio-Pleistocene strata are displaced. The northern of the two southeastern branches does not seem to disturb probable late Pleistocene terrace deposits (P.L. Ehlig, California State College at Los Angeles, oral communication, 1969). However, the Sierra Madre fault (the southern branch) does displace late Quaternary terrace deposits (Metropolitan Water District, 1966 and 1967).

Crowell concluded (1962, p. 6) that the San Gabriel fault is now inactive, as Richter apparently also did in 1958 (p. 441). No large earthquakes have definitely been attributed to the San Gabriel fault in historic time, and the trace of the fault has no apparent influence on the pattern of strain release shown by Allen and others (1965) for the period 1934 to 1963. However, in 1964 Richter (p. 8) included the San Gabriel fault on a map showing "the larger geological faults in and around California which are known to be earthquake sources from either historical or geological evidence", which is reasonable, considering the late Quaternary displacements on the Sierra Madre fault mentioned above. It is possible that differing conclusions concerning the present tectonic vitality of the San Gabriel fault may be due to different criteria used in identifying a fault as active. In any case, for present purposes the fault formed by the San Gabriel fault and its southern branch is considered a possible generator of large earthquakes.

Malibu Coast fault.--As a member of the Santa Monica fault system this north-dipping fault forms part of the south margin of the Transverse Ranges structural province, and in concert with the right-lateral Newport-Inglewood zone, it has undergone thousands of feet of thrust movement. The Malibu Coast fault (labeled "Malibu" on fig. 1) extends westward for

30 miles from the Newport-Inglewood zone along the south margin of the Santa Monica Mountains, passes within 13 miles of the Burro Flats site, and may continue westward beneath the Pacific Ocean for 15 or more miles. Several lines of evidence suggest that the fault has potential as a future generator of large earthquakes.

The Malibu Coast fault is a north-dipping thrust that separates sedimentary sections of different characters, and is inferred to separate continental from Franciscan basement at depth (Yerkes and Wentworth, 1965, fig. 3, and p. 20-23; Campbell and others, 1966, figs. 2, 3, and p. C10). With the Newport-Inglewood zone it forms a coherent structural system that has allowed Franciscan terrane of the continental borderland to move northwestward along the Newport-Inglewood zone and down beneath the leading edge of the Transverse Ranges along the Malibu Coast fault (Yerkes and Wentworth, 1965, p. 24-25).

Possible tectonic activity of the Malibu Coast fault was a subject of considerable debate in the U.S. Atomic Energy Commission Safety and Licensing hearing in 1965 on the Corral Canyon (Malibu) reactor site. The fault displaces late Pleistocene coastal terrace deposits 120 feet at one locality, and several other small, late Quaternary faults associated with the Malibu Coast Fault are cited by Yerkes and Wentworth (1965, fig. 3, and p. 151-156). Yerkes and Wentworth (1965, p. 8) concluded that there is a real but low likelihood of a large magnitude earthquake on the Malibu Coast fault in the next 50 years. This conclusion was based on the evidence of late Quaternary movement; a band of moderate strain release shown by Allen and others (1965, plate 1) along the trend of the south margin of the Santa Monica Mountains, due to small earthquakes; and the structural relation of the Malibu Coast fault with the active Newport-Inglewood zone. The commissioners of the Atomic Energy Commission, in their decision concerning the Corral Canyon reactor site (U.S. Atomic Energy Commission, 1967, p. 12), concluded that "we are not persuaded by the record that because there has been no surface faulting at the site for 10,000 or more years the probability of ground displacement during the lifetime of the facility can be disregarded in its design." Thus, at least for the particular reactor installation therein considered, the possibility of surface faulting--and therefore an earthquake of significant size--was considered to be reasonable by the commissioners.

Santa Rosa fault.--This fault (also known as the Simi fault, and at the northeast end, as Las Llajas fault) lies 5.5 miles northwest of the Burro Flats site, where it extends northeastward for 20 miles parallel to structure in the late Cenozoic Ventura basin. Little is known of the fault from the published literature, but it must at least tentatively be considered to have had late Quaternary displacement.

The fault as shown on the state map (Jennings and Strand, 1969) is based on an unpublished map by T. L. Bailey, on which the relations between faults and late Quaternary deposits are not presented. The fault is a northwest-dipping thrust fault according to Grivetti (1958, p, 163-4), and this sense of displacement is also suggested by the distribution of stratigraphic units on the state map. This geometry seems to associate the fault with Ventura basin structure, so that it probably is a relatively young fault.

Northridge Hills fault.--This fault trends northwestward for 12 miles along the south margin of the Northridge Hills and on into Cretaceous and lower Tertiary rocks to the northwest (Jennings and Strand, 1969; fig. 1, this report), thus reaching within 6.25 miles of the Burro Flats site. Details of the fault do not seem to be well known, but a late Quaternary age for the fault is indicated by its displacement of terrace deposits along the Northridge Hills (California State Water Rights Board, 1962, vol. I, plate 4, unit Qoal).

In the subsurface in the Northridge Hills the Modelo Formation is separated (displaced) 500 to 1,000 feet across the fault, with the north side relatively downthrown (California State Water Rights Board, 1962, vol. II, p. A-24). This apparent sense of displacement is the reverse of the south-side-down indication on cross section A-A' of the same reference (vol. I, plate 5A). The latter sense is also suggested by the south-side-down separation of the base of the unconsolidated alluvial valley fill inferred from Plate 6 of that reference (vol. I). The southeastern end of the fault is buried by alluvium and extension of the fault eastward is possible, but unknown.

Santa Susana thrust.--Along the south margin of the eastern end of the Ventura basin, 8 miles north of the Burro Flats side, late Cenozoic rocks have been thrust southward along the 15-mile-long Santa Susana thrust for at least 1-1/2 and possibly 5 miles (Winterer and Durham, 1962, p. 334-336; Jennings and Troxel, 1954, p. 54). Terrace deposits are overridden by the thrust (Jennings and Troxel, 1954, fig. 28 and map 22), which indicates a late Quaternary age for the fault.

Considerable horizontal shortening is indicated by juxtaposition of unlike stratigraphic sections across the fault. The gentle north dip of the fault near the ground surface, which results in a very sinuous surface trace, steepens greatly within several thousand feet, although at greater depth a hypothetical northward flattening is suggested (Winterer and Durham, 1962, plate 45; Jennings and Troxel, 1954, fig. 28; Hazzard, 1944).

Reservoir-CE fault.--At the west end of the San Fernando Valley northeasterly trending faults extend through Chatsworth Reservoir, continue northeastward to abut the Northridge Hills fault, and may also continue southwestward to an apparent termination near the base of the Modelo Formation (fig. 1, base of unit PM = base of Modelo Formation). This version of the alternative fault patterns yields a fault 9 miles long that is herein termed the "Reservoir-CE fault". The midpoint of the fault, in the reservoir, is 5 miles from the Burro Flats site, and the southwestern end approaches within 3.5 miles of the site. Two independent, though somewhat uncertain, lines of evidence suggest late Quaternary displacement on the fault.

Structural relations along the fault are not well known, and two alternatives are possible. At the reservoir the faults juxtapose Cretaceous and Miocene bedrock and are downthrown on the southeast. Evidence for the fault northeast of the reservoir comes from water well data (California Water Rights Board, 1962, vol. I, plates 4, 6 and p. 38). These data indicate that the fault has dropped the bedrock down on the southeast to form a groundwater cascade about 80 feet high within the alluvial valley fill. The "Reservoir fault" may continue southwestward as fault segment CE on fig. 2 and truncate the "Burro Flats fault", CG. Alternatively it may extend westward as the "Burro Flats fault", and either truncate fault segment CE, or branch at C and be mechanically continuous with both CE and CG. Continuation as segment CE is quite reasonable considering the presence of the fault at B, which could not easily connect with the "Burro Flats fault" using the map pattern shown by Conrad (1949). Relations at the southwestern end of this fault (fig. 1) are also poorly known. The fault seems to be unconformably overlain by upper Miocene Modelo Formation in one interpretation (Jennings and Strand, 1969; and see fig. 1, this report), and to terminate in middle Miocene Topanga Formation in another (California Water Rights Board, 1962, vol. I, plate 4). The former depiction seems inconsistent with the evidence for late Quaternary displacement farther northeast, and the latter suffers at least from the possible misidentification of the stratigraphic unit concerned. In fact, the fault could displace the base of the Modelo Formation.

Evidence for probable late Quaternary displacement is present in two places along the fault. At the northeast end the offset at the base of the alluvium probably represents late Quaternary faulting of both bedrock and the overlying alluvium. However, these relations could conceivably represent alluvial burial of a preexisting fault or faultline scarp in Cretaceous sandstone. At the east end of the reservoir Conrad's map (1949), although cartographically obscure in some critical spots, seems to show terrace deposits to be offset by a fault (fig. 2, loc. A). This fault probably is related to the larger faults shown passing under the reservoir, so that its evidence of young faulting would apply to those larger faults.

These two independent, though somewhat uncertain, indications of late Quaternary displacement on the northeast end of the fault must be applied to the southwestward and(or) the westward continuations of the fault as well.

Burro Flats site

The Burro Flats site[1] is located about 1,000 feet north of the "Burro Flats fault" on a large, benchlike surface in the Simi Hills (fig. 2; Hoffman, 1964, Drawing 1). The northwest-dipping Cretaceous bedrock beneath the site is hard sandstone in thick, massive beds with thin to several-feet-thick interbeds of siltstone. Several sets of joints are present (Hoffman, 1964), which are prominent on aerial photographs of the area (R. B. Saul, California Division of Mines and Geology, oral communication, 1969).

The topographic flat apparently is not an alluvial surface underlain by thick unconsolidated sediment, but rather is an erosional feature mantled by residual soil and some slope wash. Borings on 100 to 120 foot centers at the site show the top of weathered bedrock to be 0.5 to about 14 feet below the ground surface, overlain largely by firm natural soil and 0.5 to 6.5 feet of uncompacted fill (Crandall and Associates, 1968).

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[1] This site is herein assumed to be delineated by F, G, 22nd, and 24th streets on Burro Flats, as identified by comparison of Plate 1 of Crandall and Associates, 1968, with the 1967 photorevision of the 1952 U.S.G.S. Calabasas, California, 7 1/2' quadrangle, 1:24,000 scale, and as shown on fig. 2 of this report.

Hoffman (1964, p. 2), referring to the street block immediately south of the present site, describes an 18-foot-thick surface section consisting of 2 feet of medium soft silt, 7 feet of moist, firm to very firm silty clay, and 9 feet of slightly moist, very firm to medium hard "clayey silt-sand" (weathered bedrock) grading downward to fresh bedrock. Crandall and Associates indicates that the uncompacted fill and surface silt soils are not satisfactory foundation materials, but that "below depths of roughly two feet, the natural soils are firm, and the proposed facility may be supported on conventional spread footings established in the firm natural soils" (1968, p. 3). It is assumed, therefore, that soil amplification of seismic waves would not be significant at the Burro Flats site, and that consideration of seismic motion of the bedrock will suffice.

Burro Flats fault.--This fault cuts the late Cretaceous to early Tertiary rocks near the Burro Flats site, and has a displacement of a few thousand feet. Conrad (1949, p. 27) considered the fault to be downthrown on the south, dip slip, and probably nearly vertical. Its extent and structural relations are uncertain, in part because of insufficient geologic mapping in the area. However, it may well be mechanically continuous eastward with the "Reservoir fault", in which case a probable late Quaternary fault 6 miles long passes within about 1,000 feet of the site.

A brief geologic study of a proposed nuclear reactor site in the street block just south of the present Burro Flats site (Hoffman, 1964) provides a geologic map of the immediate site area at 1:1,200 scale, and conclusions concerning the history of the Burro Flats fault. These conclusions warrant further consideration in the light of presently available information. Hoffman concludes (p. 5) that the "Burro Flats fault" is "inactive and has not moved for a period of millions of years." His judgment is based on one of two alternatives: (1) the fault is unconformably overlain by Oligocene Sespe Formation at its western end (loc. G, fig. 2), and therefore has not been operative since deposition of those sediments 25 to 40 million years ago; or (2) the fault does not extend as far west as the base of the Sespe Formation, "and was therefore only a minor rupture associated with regional uplift." However, the unconformity suggested by Hoffman is not required by the geologic relations as currently known, and the suggested regional uplift must be demonstrated to be millions of years old for the conclusion of inactivity to be valid. Conrad suggests (1949, p. 35) that intermittent uplift during Pleistocene and Holocene time has occurred.

The structural geometry utilized by Hoffman includes termination of the "Burro Flats fault" at a "northwest trending cross fault" on the east. Although the Northridge Hills fault (fig. 1, this report) could fit this description, this configuration would require consideration of the relations along the "Reservoir fault", and would make the "Burro Flats fault" larger and more important than Hoffman seems to imply. It seems more likely that Hoffman's "northwest" should read north<u>east</u>. In this case connection of fault segment EC with the fault at D (fig. 2, this report), such as is shown in the map compilation of California Water Rights Board (1962, vol. 1, plate 4), might be the cross fault referred to. However, the most recent field work (Conrad, 1949) shows the "Burro Flats fault" to extend eastward to the "Reservoir-CE fault" (fig. 2), and without information this depiction is at least a reasonable alternative to truncation by the above mentioned fault DCE.

Large displacement on the "Burro Flats fault" at its west end (G) could require unconformable relations with the Sespe Formation. To examine this possibility, a vertical cross section was constructed approximately along the trace of the fault, and distances between correlative horizons were determined along horizontal and vertical lines, as well as perpendicular to bedding[1]. This construction assumed the fault to be vertical, or nearly so. This assumption appears reasonable, because Conrad considered that to be the case, and Hoffman (1964, p. 4) reports a steep southerly dip for the fault. The possible amount of slip for the Paleocene strata (Tmz) and the Eocene strata (Td) determined by this method ranges from 1,000 to 5,000 feet, depending on slip direction and correlation datum used (Table 1). Regardless of the slip direction assumed, the slip decreased westward from the Paleocene datum to the Eocene datum. Comparison of this relation with map position suggests that slip becomes very small in the vicinity of the base of the Sespe Formation (G, fig. 2), especially if the slip approximates dip slip rather than strike slip, as was suggested by Conrad.

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[1] Because of its absence on the south side of the fault, unit Tms was assumed absent on the north side of the fault as well for the purpose of the construction. The base of unit Td was assumed to be midway between the contacts of unit Tms.

Table 1.--Possible slips across the "Burro Flats fault"

Datum used	Slip, in feet		
	Maximum horizontal	Maximum vertical	Maximum perpendicular to the strata
Middle of Td	2,700	1,200	1,000
Middle of Tmz	5,000	2,600	2,300

The small slip on the "Burro Flats fault" at G, determined by extrapolation of the figures of table 1, is insufficient to require that the base of the Sespe Formation unconformably overlie the fault. Further uncertainty is introduced by the possibility of a gradational base of the Sespe Formation in this area (I. P. Colburn, California State College at Los Angeles, oral communication, 1969), for this would suggest the absence of an unconformity at that horizon. As alternatives to the unconformable relations, the fault may not reach the base of the Sespe Formation, or it may extend past, and displace, that contact. Minor offset of the contact might not be easily recognized, because a thick soil covers bedrock in the area (Conrad, 1949, p. 26), and the contact may be gradational. Thus, the west end of the fault may well lie near the base of the Sespe Formation, as is assumed herein, but no age relations can be inferred from this, because at present the true structural relations there are unknown.

Mechanical continuation of the "Burro Flats fault" eastward as the "Reservoir fault" is suggested both by the general map pattern (fig. 1 and 2) and the eastward increase in apparent slip along the fault (near the reservoir, late Miocene rocks are in contact across the fault with Cretaceous rocks). This possibility was referred to under "Reservoir-CE fault" above, and would require that evidence of late Quaternary age of the "Reservoir fault" be applied westward to the "Burro Flats fault." This composite fault, then, would have a length of 12 miles, and is referred to as "Burro Flats-Reservoir" in table 2 and 3. The relative likelihood that this, or the "Reservoir-CE" configuration, is the actual case cannot be determined from present information.

If future rupture along the "Burro Flats-Reservoir fault" is a reasonable possibility, then subsidiary faulting might also be considered. I. P. Colburn of California State College at Los Angeles reports (oral communication, 1969) that geologic mapping northwest of the site indicates the presence of a fault that may well pass through the site (see note at F, fig. 2, this report). Most subsidiary faulting probably would be expected to follow existing faults (Bonilla, 1967, p. 29), so that the detailed geology in the vicinity of the site could be significant.

Estimates of earthquake magnitude

Estimates of the magnitude of earthquakes that could be generated by the several faults described above are listed in table 2, and are based largely on fault lengths and on empirical data which relates earthquake magnitude to length of surface rupture for historic events on other faults. Only for the San Andreas fault are historic events on the fault sufficient to allow magnitude estimation without recourse to the fault-length technique.

Four magnitude estimates are listed in table 2 for each fault. Each estimate was derived from empirical relations between magnitude and rupture length established by one of several investigators. Rupture of the whole length of a fault in a single event seems unlikely, and comparison of historic rupture lengths to length of mapped faults in southern California (Allen and others, 1965, fig. 4) suggests that rupture of only half the

Table 2.--Estimated earthquake magnitudes for specific faults

These magnitudes were determined by assuming rupture of half the fault length, and using relations between earthquake magnitudes and rupture length in historic events as determined by the cited authors. Magnitudes determined using this method are, for the purposes of this brief review, probably reasonable estimates of the capabilities of each fault, although earthquakes of larger magnitude are possible.

Fault	Half Length (miles)	Estimated Magnitude Using Methods of Cited Authors				
		Iida (1965)	Tocher (1958)	Bonilla (1967)	Albee and Smith (1967)	Average
San Andreas						8.25[a]
Santa Ynez	41	7.5	7.2	7.6	7.8	7.5
Newport-Inglewood[b]	23	7.3	7.0	7.2	7.3	7.25
San Gabriel	37	7.4	7.2	7.5	7.7	7.5
Malibu Coast[b]	23	7.3	7.0	7.2	7.3	7.25
Santa Rosa	10	7.0	6.7	6.7	6.6	6.75
Northridge Hills	6	6.8	6.5	6.3	5.8	6.5
Santa Susana	7.5	6.9	6.6	6.5	6.2	6.5
"Reservoir-CE"	4.5	6.7	6.4	6.1	4.7[c]	6.0
"Burro Flats-Reservoir"	6	6.8	6.5	6.3	5.8	6.5

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a. Maximum instrumentally determined magnitude for historic earthquakes on this fault.

b. Lengths used for these faults are minima. Information from offshore would probably require use of greater lengths, which would result in higher assigned magnitudes for these two faults.

c. Extrapolation of fig. 4 of Albee and Smith, 1967.

fault length or less is a more likely case, as pointed out by Albee and Smith (1967, p. 432). Half the fault length is used herein[1].

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[1] Cursory comparison of data from Bonilla, 1967, and original literature indicates that the ratio of length of surface rupture to length of the whole fault for about 10 historic North American events ranges at least from 0.02 to greater than 0.75. In the absence of more thorough investigation of this ratio and its possible dependence on kind of faulting, the value of 0.5 used herein must be considered only approximate at best.

Magnitudes determined using this method are, for the purposes of this brief review, probably reasonable estimates of the capabilities of each fault. However, larger magnitudes are possible, because ruptures longer than half the fault length may occur, and because the magnitude-rupture length data include magnitudes greater than the average for given rupture lengths.

Iida (1965, p. 120) found $M = 0.76 (\log L) + 6.07$ (M being magnitude, and L length of rupture, in kilometers) for 64 world-wide events from 1811 to 1964. Tocher (1968, p. 150), using 10 events in California and Nevada, found $M = 0.9 (\log L) + 5.6$ (L in kilometers). The combination of two empirical equations of Bonilla (1967, p. 18 and 26) yields $M = 1.51 (\log L) + 5.14$ (L in miles) for about 20 events in western North America. The fourth estimate was made using the graph of Albee and Smith (1967, figs. 4 and 6), which is based on 17 events in California and Nevada.

The four estimates for each fault were combined by averaging and rounding off to the nearest quarter magnitude to yield an estimated maximum earthquake magnitude for each fault (table 2). The earthquake magnitude assignable to the San Andreas fault must equal or exceed the magnitude of the 1906 San Francisco earthquake, M 8.25 (Bolt, 1968). However, because magnitudes greater than 8 are not shown on the magnitude-acceleration graphs used below, magnitude 8 has been used as a minimum reference for the San Andreas fault.

Acceleration factors at the site

Estimates of maximum horizontal ground acceleration (as a fraction of acceleration of gravity) that might occur at the site are shown in table 3, assuming earthquakes of estimated magnitudes as shown in table 2, and with epicenters located on the faults at points closest to the Burro Flats site. Accelerations at the site were read from three different sets of curves: two that relate acceleration, earthquake magnitude, and epicentral distance, and one that relates acceleration and epicentral distance directly. The curves of Housner (1965, fig. 7) are based on accelerations measured at various sites, nearly all of which are underlain by "relatively deep alluvium" (Housner, 1965, p. III-100). The curves of Seed and others (1968, fig. 17) yield much lower values for the same magnitudes and epicentral distances than do those of Housner, probably in large part because they are intended to indicate acceleration in rock and do not include the influence of any alluvial deposits. The curves and equation of Cloud (1968) are intended to show how the upper limit of maximum acceleration decreases with distance from the epicenter and are based on records from sites having a wide range in depth to

Table 3.--Estimated site accelerations for specific earthquakes

These accelerations were determined by assuming an earthquake of magnitude listed in table 2 placed at the closest point to the site on the fault trace, and applying the attenuation curves of the cited authors. The accelerations should not be considered sufficient, in themselves, as a basis for design.

Fault	Assigned Magnitude	Epicentral Distance (mi.)	Estimated Acceleration (a/g) Using Methods of Cited Authors		
			Seed and others (1968)	Housner (1965)	Cloud (1968)
San Andreas	8.25	34	no information		
	8	34	.18[a]	.31[a]	.24[a]
Santa Ynez	7.5	30	.13	.29	.26
Newport-Inglewood	7.25	25	.13[c]	.31[c]	.29[c]
San Gabriel	7.5	16	.24	.37	.35
Malibu Coast	7.25	13	.21[c]	.36[c]	.36[c]
Santa Rosa	6.75	5.5	.17	.33	.43
Northridge Hills	6.5	6.25	.14	.31	.42
Santa Susana	6.5	8	.13	.30	.41
"Reservoir-CE"	6.0	3.5	<.1	.27	.46
	6.0	5[b]	<.1	.27	.44
"Burro Flats-Reservoir"	6.5	.19	<.1	.32	.49

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a. These accelerations are minima only, for a magnitude of at least 8.25 should be used for the San Andreas fault.

b. 5 miles, assuming the epicenter to be at the approximate midpoint of the fault.

c. These accelerations are based on minimum fault length, and in all likelihood should be larger (see footnote b, table 2).

bedrock. As shown in table 3, values obtained from Housner and Cloud are more nearly in agreement with one another than with values obtained from the curves of Seed and others.

Because rock underlies the Burro Flats site at a very shallow depth, and the curves of Seed and others apply exclusively to rock motion, their curves might be considered the most appropriate for the site when evaluating earthquakes on the more distant faults. However, their curves are weighted averages of other curves which differ greatly from one another at distances less than about 12 miles from the epicenter (Seed and others, 1968, fig. 13-16). Even the largest values given on these other curves for a magnitude 6.5 earthquake (Seed and others, 1968, fig. 13) have been exceeded in recent earthquakes. The magnitude 5.5 Parkfield earthquake of 1966 generated a short-duration acceleration pulse of 0.4 g at a site on rock 4 miles from the causative fault (Cloud and Perez, 1967, table 2, fig. 5). A magnitude 6.5 earthquake at Koyna, India, in 1967 produced a short-duration acceleration of about 0.62 g at a distance of about 18 miles. Although the recording was made within a concrete dam, the motion was measured parallel to the stiff longitudinal section of the dam, and therefore was considered equivalent to that of the ground beneath the dam (Ambraseys and Sarma, 1968; Ambraseys, 1969). These reports do not indicate the nature of the dam foundation, although presumably the dam was founded on rock.

Several factors which are important in design are not considered herein, because the intent of this report is only to give a first approximation of ground accelerations that might occur at the site. Among those factors not included are the duration of strong shaking and the effects of epicentral distance and earthquake magnitude on the predominant frequencies of ground vibration.

Explanation for figure 2

Approximate geologic map of Burro Flats and vicinity, compiled from Nelson (1925) west of Burro Flats site and Conrad (1949) east of the site, with comments added. The geology has been transferred to modern 1:24,000 topography from the original maps, which are on older, smaller scale bases, so that locations are only approximate. Bold letter symbols are keyed to the text.

EXPLANATION

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Fault	Contact

Dashed lines represent poorer quality of location than solid lines. Dotted where concealed, queried where original map impossible to read with confidence.

dip and strike of bedding

dip and strike of bedding estimated from configuration of contact

Map Units (Formations according to Nelson (1925) and Conrad (1949))

Qal	Quaternary alluvium
Qt	Quaternary terrace deposits
Tm	Miocene Modelo Formation
Tt	Miocene Topanga Formation
Ts	Oligocene Sespe Formation
Ttj	Eocene Tejon Formation
Td	Eocene Domengine Formation
Tms	Eocene Santa Susana Formation
Tmz	Paleocene Martinez group
Kc	Cretaceous Chico Formation
Tb	Mafic flows and intrusives

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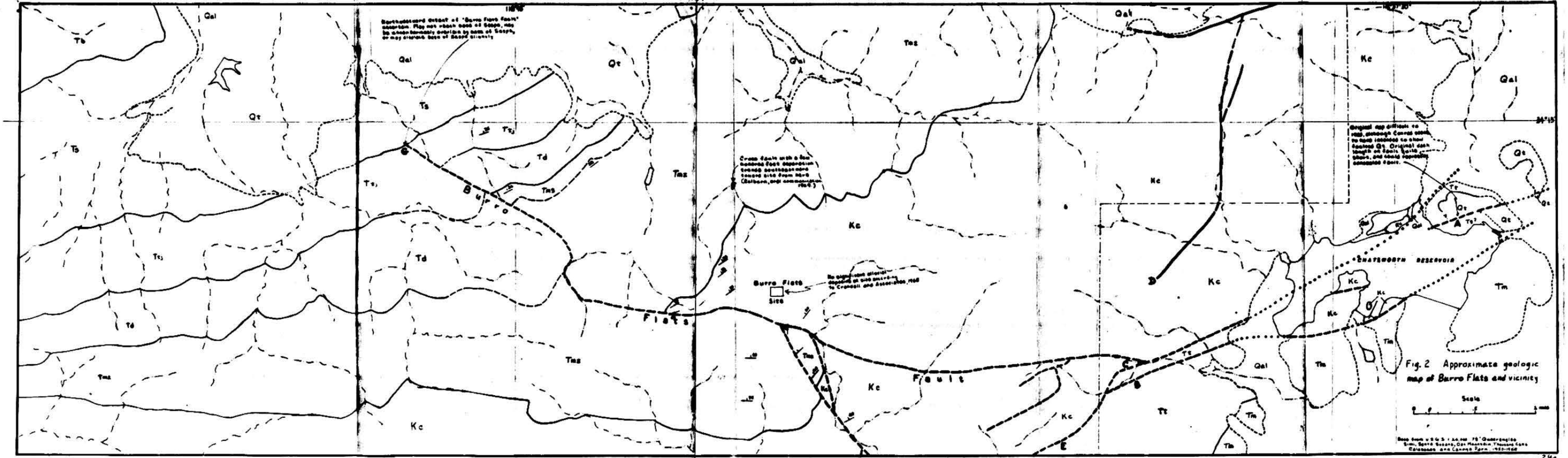

Northeastward extent of "Burro Flats fault" uncertain. May not reach base of Sespe, may be unconformably overlain by base of Sespe, or may displace base of Sespe slightly

Cross fault with a few hundred feet separation trends southeastward toward site from here (Balbora, oral communication 1969.)

No significant alluvial deposits at site according to Crandall and Associates, 1968

Original map difficult to read, although Conrad seems to have intended to show faulted Qt. Original dash length on fault quite short, and could represent concealed fault.

Fig. 2 Approximate geologic map of Burro Flats and vicinity

Base from U.S.G.S. 1:24,000 7½' Quadrangles
Simi, Santa Susana, Oat Mountain, Thousand Oaks
Calabasas and Canoga Park, 1950-1968