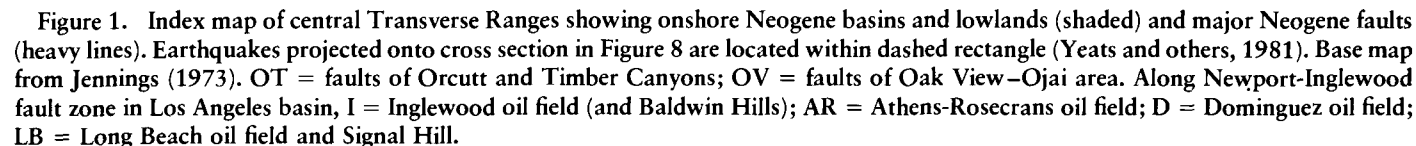


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There are exceptions to the common assumption that surface rupture by faulting is always accompanied by a damaging earthquake. Near Ventura, California, faults of the Oak View-Ojai area and Orcutt and Timber Canyons displace late Pleistocene and/or Holocene alluvial materials and soils by several tens of metres. The movement is almost exclusively along bedding planes in response to

flexural slip during folding. Therefore these faults constitute a ground-rupture hazard. However, because they do not extend downward to rocks of high shear strength which could store large amounts of elastic strain energy, they do not constitute a seismic-shaking hazard. In contrast, the Oak Ridge fault near the coast does not cut strata shallower than 1,250 to 1,500 m below the surface, although pressure ridges attest to recent activity. Similarly, the Newport-Inglewood fault between Long Beach and Inglewood oil



fields in the Los Angeles basin is expressed at the surface as a line of anticlinal hills rather than a throughgoing fault. Historical faulting at Inglewood and possibly at Rosecrans and Dominguez oil fields may be related to oil-field development rather than earthquake-related displacement. Those portions of the Oak Ridge and Newport-Inglewood faults pose seismic-shaking hazard but not ground-rupture potential from earthquakes alone. For planning purposes, it is necessary to distinguish faults with only ground-rupture potential or with only seismic shaking potential from the well-known faults with potential for both.

INTRODUCTION

Active faults pose two types of hazards to people and their structures: surface rupture and/or seismic shaking. Rupture of the Earth's surface along a fault zone is associated with fault motion that may be instantaneous or creeping, and which may or may not be accompanied by an earthquake. Seismic shaking occurs during sudden movement along a deep portion of a fault; such fault displacement may or may not be accompanied by surface rupture.

In an assessment of fault hazard, faults are presently classified

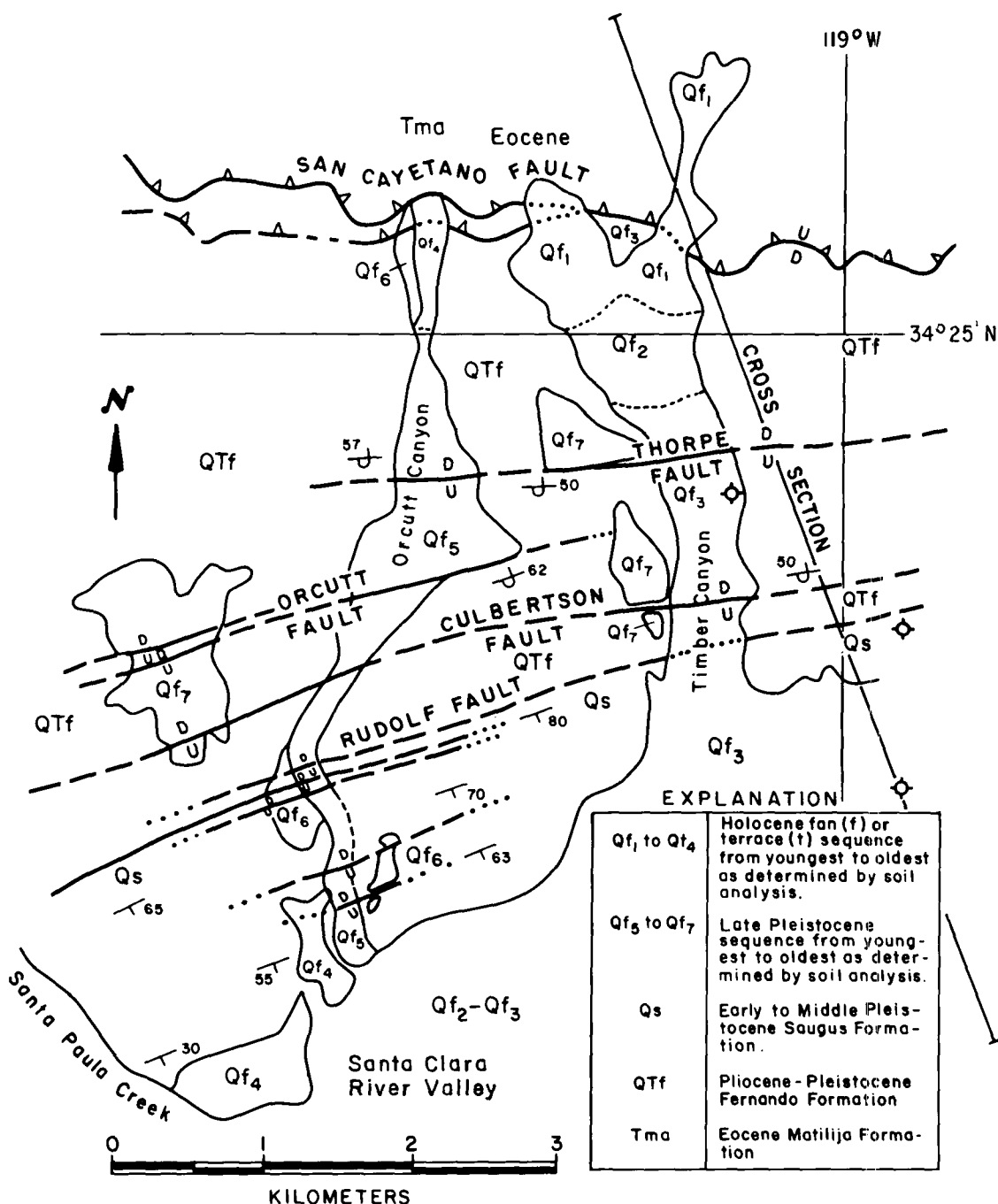


Figure 2. Map of Orcutt and Timber Canyons on the north flank of Santa Clara syncline. Decorated circles locate three Chevron wells identified in cross section in Figure 3 (after T. Rockwell, unpub.).

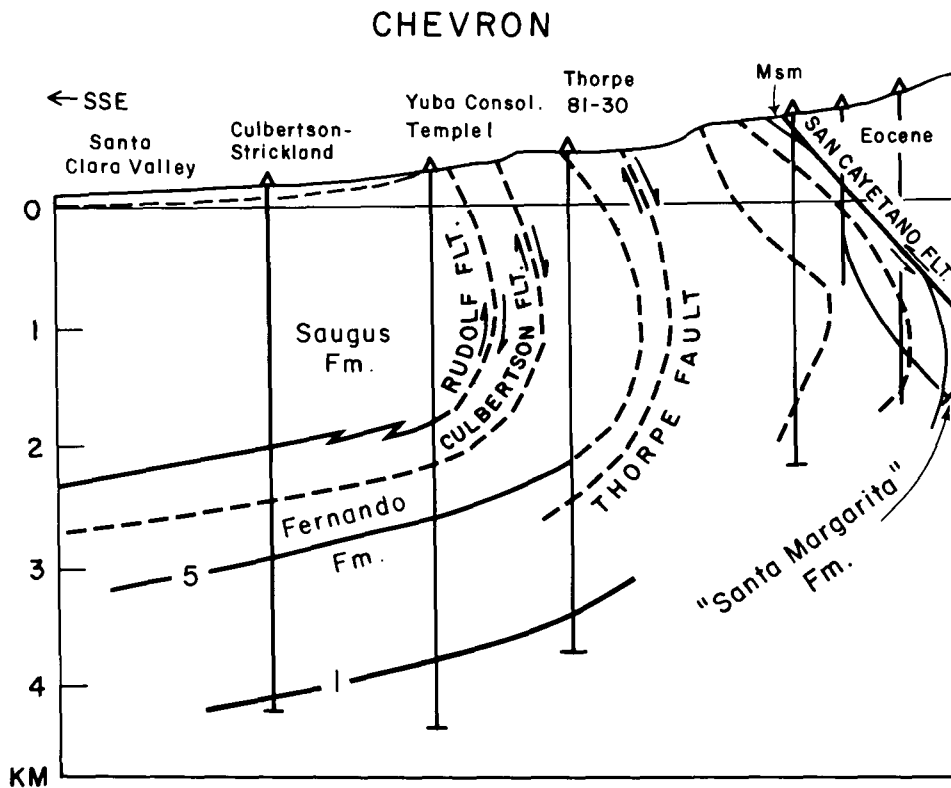


Figure 3. Cross section showing Culbertson, Thorpe, and Rudolf faults. Line of section shown in Figure 2. 1, 5 are microfaunal horizons taken from Yeats (1976). Msm = Santa Margarita Fm.

according to the recency of their movement with the implicit assumption that the younger the earth materials are that are offset by the fault, the more hazardous the fault is likely to be. In such assessments, ground rupture and seismic shaking are commonly treated together. However, in the Ventura region, we have identified faults which, on the basis of recency of movement, pose a ground-rupture hazard but, on the basis of their subsurface extension, do not pose a large-magnitude seismic-shaking hazard. In addition, we have identified faults in the subsurface which are pos-

sibly active but do not break the surface, suggesting a seismic-shaking hazard, but a relatively minor ground-rupture hazard.

In this paper, we describe three types of active faults on the basis of the type of hazard presented: (1) faults with ground-rupture hazard but minor, if any, seismic-shaking hazard; (2) faults with seismic-shaking hazard but slight or no ground-rupture hazard; and (3) faults with both ground-rupture hazard and seismic-shaking hazard. The faults discussed are located on Figure 1.

Flexural Slip Faults IDEALIZED DRAWING

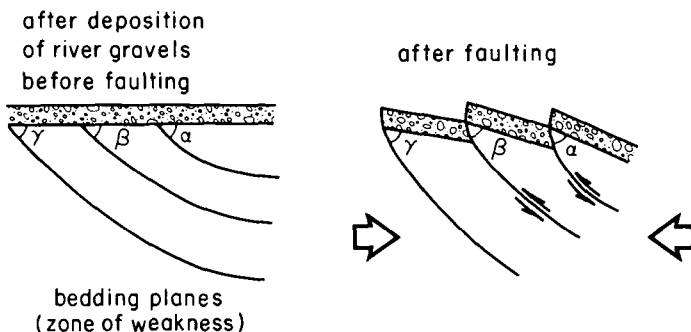


Figure 4. Diagram showing back-tilting of Oak View terrace along south-dipping bedding faults; this supports the argument that these faults flatten with depth (after Keller and others, 1980).

FAULTS WITH GROUND-RUPTURE POTENTIAL BUT MINOR, IF ANY, SEISMIC-SHAKING POTENTIAL

Faults of Orcutt and Timber Canyons

East of Santa Paula Creek, a thick Pliocene-Pleistocene sequence is folded into the asymmetric Santa Clara syncline, the north flank of which is exposed in the low hills north of the Santa Clara Valley (Fig. 2). Long, narrow alluvial fans of late Pleistocene to Holocene age unconformably overlie these steeply dipping strata.

The fans are cut by at least nine nearly parallel faults, all of which have the south side up, a sense of displacement opposite to that of the active San Cayetano fault to the north (Rockwell and Keller, 1980; Keller and others, 1980). The strike of these faults is parallel to that of the underlying steeply dipping strata so that displacement on the faults cannot be measured in the bed rock at the surface except where overlain by alluvial deposits. The faults have normal displacement where bedding is overturned and reverse displacement where right side up, indicating intrinsic control by bedding. Data from petroleum exploratory wells drilled in this area

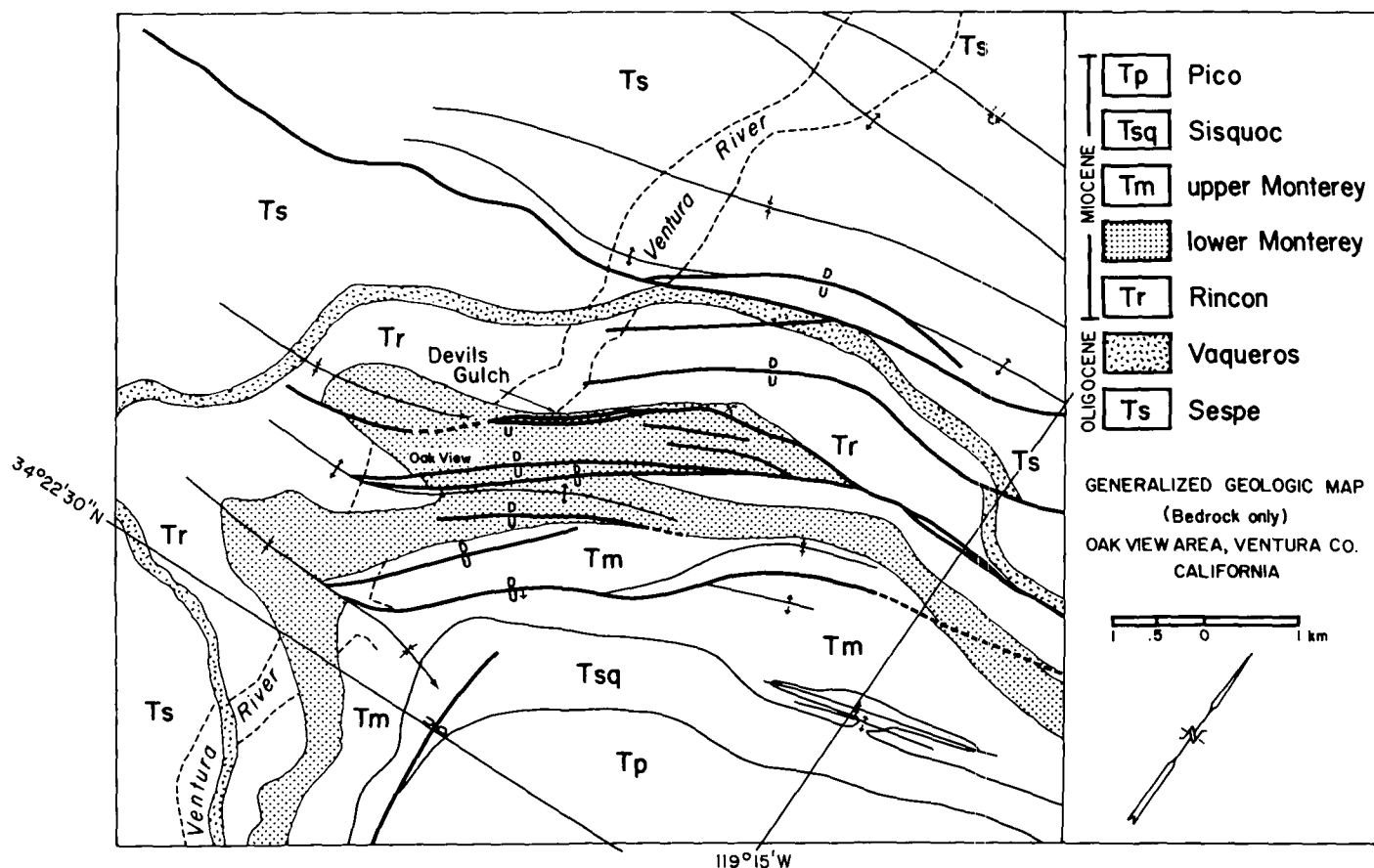


Figure 5. Tectonic map of part of Ventura River valley between Oak View and Ojai showing south-dipping faults (after Keller and others, 1980).

show that these faults do not offset bedding at depth (Fig. 3). The fan surfaces are faulted with greater separation for older surfaces, and the surfaces are tilted basinward, indicating a rotational displacement along the fault plane which is itself parallel to the curved bedding surfaces of the underlying strata (Fig. 4). The degree of tilt and the amount of separation are dependent upon the age of the surface. These faults are interpreted as bedding-plane faults which moved during flexural-slip folding of the Santa Clara syncline.

We conclude that the faults of Orcutt and Timber Canyons do not extend downward to rocks of such high shear strength that they could store enough elastic-strain energy to produce a damaging earthquake when the strain energy is released instantaneously. Continued north-south compression will accentuate the Santa Clara syncline, resulting in additional bedding slip on these faults and additional ground rupture. Accordingly, these faults constitute a ground-rupture hazard but not a seismic-shaking hazard.

Faults of Oak View-Ojai Area

At least seven recently identified faults cut Miocene strata (Monterey and Rincon Formations) and overlying Pleistocene terrace gravels and younger material in the Ventura River Valley between the towns of Oak View and Ojai (Clark and Keller, 1979, 1980; Keller and others, 1980). These faults strike northeast to east parallel or nearly parallel to bedding in the underlying Miocene

formations on the complex north limb of a large syncline (Fig. 5). The faults occur within a homoclinal sequence with older strata cropping out to the north. The faults dip southeast to south toward the axis of the syncline, show reverse separation, and are delineated by abrupt linear scarps that are several kilometres long and locally 50 m high.

Pleistocene gravels of the Oak View surface cap much of the area but are not shown on Figure 5 in order to emphasize the bed-rock structure. These gravels, previously known as the Oak View and older terraces (Putnam, 1942), have been correlated tentatively by soil profile development. A radiocarbon date for a sample from one site suggests the surface is about 40,000 yr old (Clark and Keller, 1979; Keller and others, 1980).

Multiple vertical offsets, as indicated by the large amounts of displacement of the gravels, have produced fault blocks that are tilted southeast away from the Ventura River toward the synclinal axis (Fig. 5), producing linear ponds, internal drainage, and drainage reversal (Clark and Keller, 1979). Tilting of the surface that overlies the fault blocks indicates that these are rotational faults which dip more gently with depth, and that faulting is the result of flexural slip during folding.

Holocene soil and colluvium are offset by at least one of the south-dipping thrusts near Devil's Gulch (Fig. 5), suggesting that the faults associated with flexural-slip folding are very young and should be considered active. Accordingly, these faults have

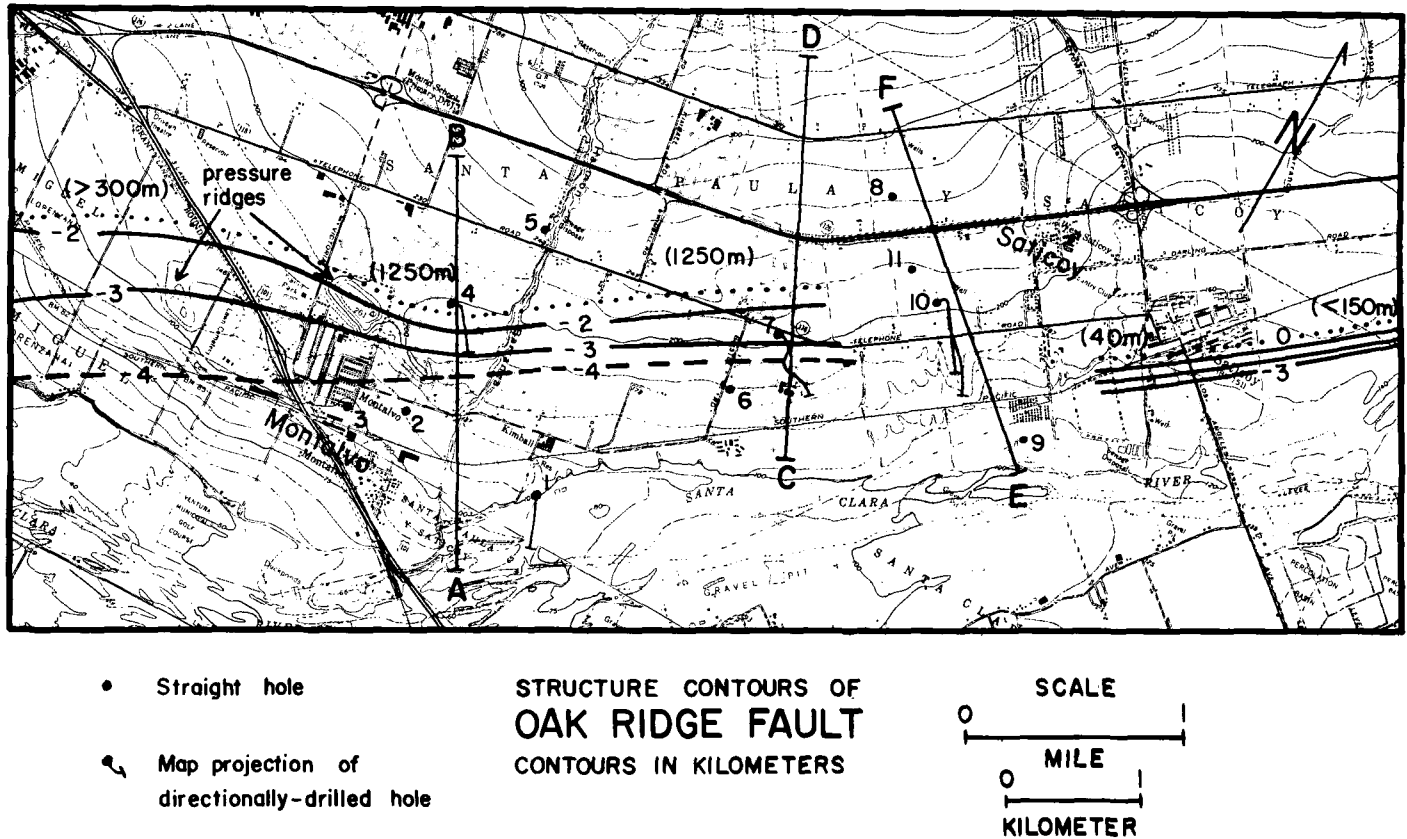


Figure 6. Structure contours on Oak Ridge fault near coast; contours in kilometres. Fault changes upsection to a monocline and is overlain by about 1,250 m of unfaulted strata. Dotted line is map projection of upward termination of fault. Numbers in parentheses give depth in metres of upward termination of fault. Two northwest-trending mounds east and west of Montalvo are en echelon pressure ridges, stepped to the left, containing deformed alluvium of Santa Clara River. A-B, C-D, E-F are cross sections shown in Figure 7. Along line of cross section E-F, the fault does not cut Pliocene strata at all. Farther east, at Saticoy, the fault is stepped right, dips very steeply south, and cuts strata fairly close to the surface. Filled circles with numbers locate wells used in cross sections in Figure 7.

ground-rupture potential, and in fact have produced at least 150 m of vertical displacement in the past 40,000 yr. However, because the faults are produced by flexural slip during folding, and the fault planes apparently do not penetrate downward to rocks of high strength, they have low potential for significantly hazardous seismic shaking.

We have demonstrated that fault movement associated with flexural slip during folding can produce ground rupture. Unfortunately, we have no data concerning when the rupture occurs. It seems reasonable to infer that surface rupture may take place during a large-magnitude earthquake along a nearby master fault. Therefore, the hazard associated with the ground rupture is a function of the earthquake activity of nearby master faults, and extrinsic seismic shaking will accompany the surface rupture. Because the faults flatten with depth and remain within the sedimentary sequence, ground rupture accompanying such faults is probably aseismic or accompanied by only low-magnitude earthquakes. In this case, the surface rupture would be an intrinsic consequence of local folding and uplift. In areas characterized by lower rates of uplift and folding, flexural slip might still occur, but surface expression would be more difficult to recognize. Thus, in evaluating the seismic hazard of an area characterized by faulting associated with flexural slip, it may be necessary to plan for occasional intrinsic slip

with ground rupture but no seismic shaking, as well as extrinsic seismic shaking and sympathetic ground rupture. We conclude that the potential hazard produced by shaking may be no greater or less at a particular site with or without the flexural-slip faulting. However, the recognition of the additional surface-rupture hazard is important and should be considered in land-use planning.

Aseismic faulting in the Houston, Texas, metropolitan area is triggered by withdrawal of ground water (Van Siclen, 1967). Normal faults in Gulf Coast oil fields (Cloos, 1968) are caused by regional gravity creep; they probably flatten with depth within the sedimentary section.

FAULTS WITH SEISMIC-SHAKING POTENTIAL BUT SLIGHT OR NO GROUND-RUPTURE POTENTIAL

Oak Ridge Fault

The Oak Ridge fault near Santa Paula (south of OT, Fig. 1) cuts nonmarine Pleistocene strata and landslide deposits which overlie these strata unconformably, but it does not appear to cut stream terraces of the Santa Clara River. Southwest of Saticoy (Fig. 6), the fault changes to a steep monoclinial flexure expressed in Pliocene

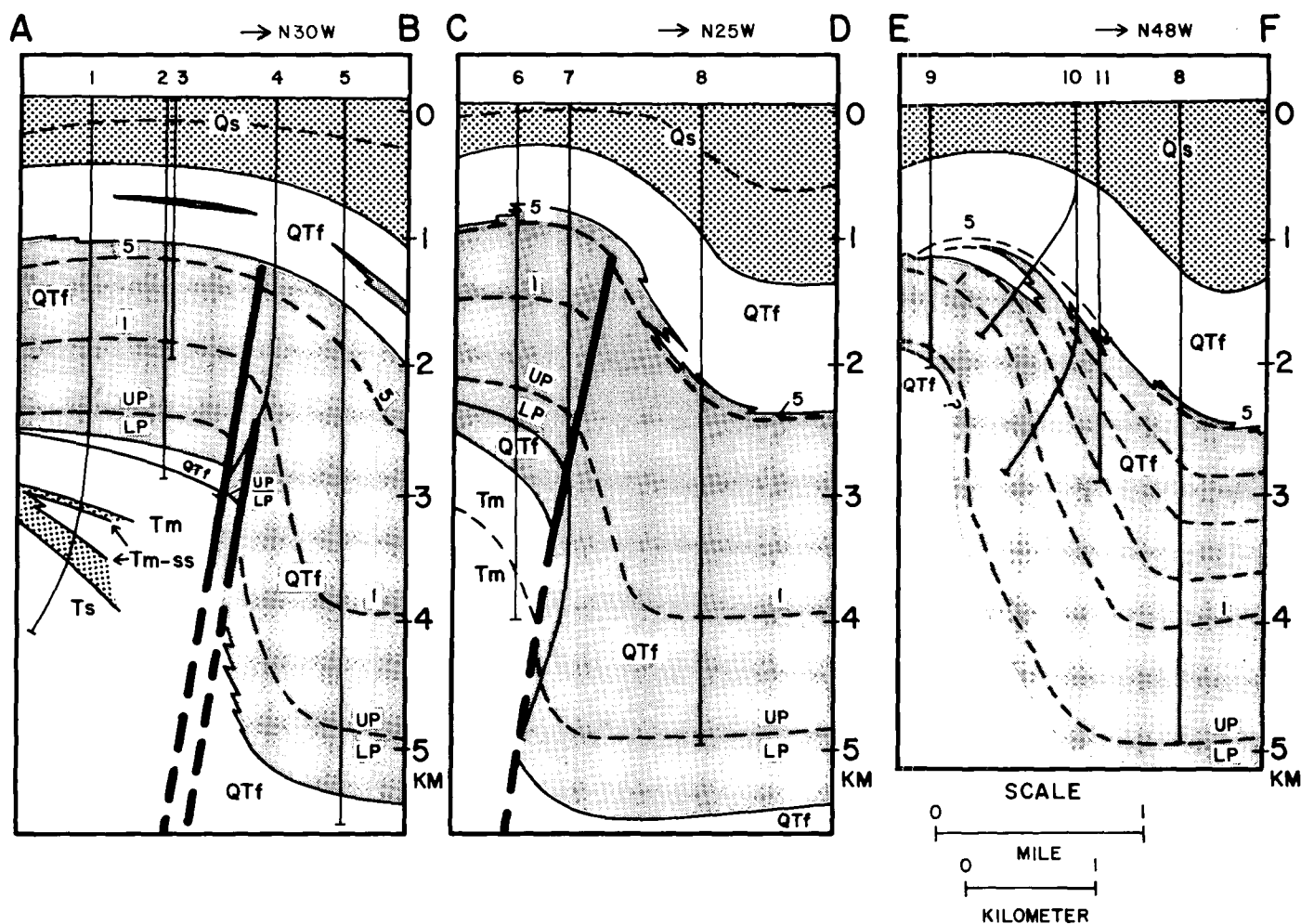


Figure 7. Cross sections across part of Oak Ridge fault. Sections located in Figure 6; north is to right. Fault penetrates to near micro-faunal horizon 5 in cross section A-B and C-D, but overlying strata are folded monoclinal without faulting. In cross section E-F, the entire Pliocene section is monoclinal and unfaulted; an erosional unconformity between horizons 1 and 5 indicates uplift of the south side of the Oak Ridge zone with respect to the north side. Coarse-dot pattern, Saugus Formation (Qs); fine-dot pattern, mainly sandstone turbidites of Fernando Formation (QTf); no pattern, mudstone of Fernando Formation. Other symbols: Tm, Modelo (Monterey) Formation of middle and late Miocene age; Tm-ss, basal shallow-marine sandstone of Modelo Formation; Ts, Sespe Formation. Vertical and curved lines numbered 1 to 11 identify wells used as control in cross sections; wells located by number in Figure 6.

and Pleistocene strata; the fault exists only in pre-Pliocene strata deeper than well control (cross section E-F in Fig. 7). Farther southwest, near the town of Montalvo, the fault cuts Pliocene strata but changes upsection to a monocline 1,250 m below the surface (Fig. 6). As shown in cross sections A-B and C-D in Figure 7, the Oak Ridge fault is associated with drag folding affecting strata of both the hanging wall and footwall. The fault displacement decreases to zero; at still shallower depths, only a steep monocline marks the position of the fault.

However, recent activity along this reach of the fault is indicated by two pressure ridges, one east and one west of the community of Montalvo (Fig. 6). These ridges trend east-southeast and are en echelon, stepped to the left. Deformed sediments in the ridges are undated but are apparently late Quaternary deposits of the Santa Clara River flood plain. Excavations for the sub-basement of an

office building on the edge of the western pressure ridge showed that unconsolidated sediments dip as much as 17° to the southwest. In this same excavation, $N5^\circ W$ -trending reverse faults with small displacement extend to within 7 m of the surface (E. A. Hall, unpub. data). These minor faults appear to be a secondary feature of the pressure ridge and are not a near-surface expression of the Oak Ridge fault, which strikes east-northeast in this area (Fig. 6). Quarrying in the eastern pressure ridge has exposed brown siltstone, sand, and gravel of the Saugus Formation dipping 43° SSW; this is overlain with angular unconformity by sand and gravel which are folded into an anticline with dips as steep as 17° to the north-northeast and south-southwest. Small-displacement faults dipping 37° to 60° south to south-southeast cut the siltstone and lower gravel beds; it is unclear whether the upper sand and gravel are also faulted. Comparison with Oak Ridge fault contours in Figure 6 and

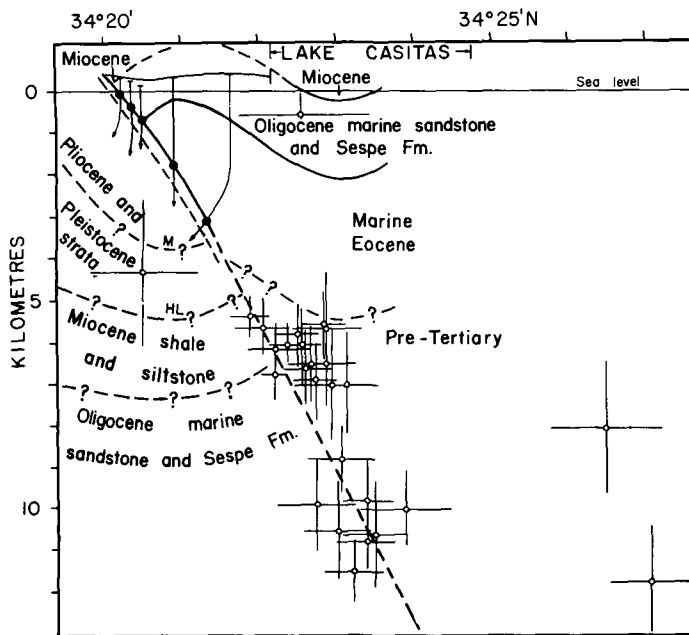


Figure 8. North-south cross section through Red Mountain fault showing surface and well control (well control shown by solid dots) and 1970–1975 earthquake hypocenters (open circles) projected onto section. Crosses around hypocenters give epicenter and hypocenter location error. Note absence of earthquakes shallower than 5 km, attributed to low strength of near-surface rocks (from Yeats and others, 1978, 1981).

with cross section A–B shown in Figure 7 shows that steeply dipping Saugus in the pressure ridge is underlain by nearly flat-lying Saugus; the faults are also surficial features not connecting directly to the Oak Ridge fault at depth.

The pressure ridges suggest that the Oak Ridge fault is active, despite the fact that it does not reach closer than 1,250 m to the surface. Thus, except for minor displacement related to the pressure ridges, faulting does not constitute a ground-rupture hazard, but it probably constitutes a seismic-shaking hazard. Seismic shaking can produce ground disruption due to lurching, liquefaction, and landsliding, but probably not disruption due to surface fault displacement.

Newport-Inglewood Fault Zone

In the Los Angeles basin, the Newport-Inglewood fault zone is seismically active and is the probable source of damaging earthquakes in 1920 and 1933. Two additional earthquakes in 1941 and 1944 produced damage to wells in the Dominguez oil field due to apparent movement along south-dipping reverse faults but did not produce surface rupture (see summary by Barrows, 1974). Barrows (1974) found no evidence that either the 1920 or the 1933 earthquake produced surface rupture, although both produced surface effects related to shaking. There may be a master, northwest-trending, right-slip fault in the basement, but there is no throughgo-

ing master fault in the overlying sedimentary sequence. Indeed, in that portion of the fault between Long Beach oil field and Inglewood oil field, there is little or no evidence for recent faulting, and the faults in the Dominguez and Athens-Rosecrans oil fields are predominantly east-trending reverse faults. The line of hills extending from Baldwin Hills in the northwest to Signal Hill to the southeast (and possibly to Newport Mesa even farther southeast) are probably pressure ridges along the fault zone, but they are not cut by a throughgoing master fault. It is noteworthy that earthquakes recorded in the Newport-Inglewood zone since mid-1971 occurred in crystalline basement but not in the overlying sedimentary sequence (Teng, 1975; Buika and Teng 1978).

Accordingly, the Newport-Inglewood fault has a demonstrated seismic-shaking potential, but it has not shown evidence of ground rupture, at least for the reach of the fault between Inglewood oil field (Baldwin Hills) and Long Beach oil field. On the other hand, surface faulting in the Baldwin Hills is probably related to development of the Inglewood oil field (Castle and Yerkes, 1969; Hamilton and Meehan, 1971); subsurface faulting in 1941 and 1944 in the Athens-Rosecrans and Dominguez oil fields may also be related to oil-field development rather than earthquake-associated displacements (Barrows, 1974).

Large shallow-focus earthquakes at Kita-Mino, Japan, in 1961 and Fukui, Japan, in 1948 were unaccompanied by surface faulting (Bonilla, 1979). Earthquakes in the eastern United States are commonly not associated with surface faulting; the New Madrid seismic zone is one of the best-known illustrations (Zoback and others, 1980).

Faults with Ground-Rupture and Potential Seismic-Shaking Potential

Faults of this third type are well known in the literature and will not be discussed in detail here. These include the San Andreas, San Jacinto, and Elsinore strike-slip faults and the San Fernando, Santa Susana, San Cayetano, and Red Mountain thrust faults. The Red Mountain fault is described briefly merely as an example; it is discussed in greater detail elsewhere (Yeats and others, 1978, 1981).

The north-dipping Red Mountain fault brings Eocene to Miocene strata southward over Pliocene and Pleistocene strata of the Cañada Larga syncline. Subsurface data indicate a dip of 50° to 60° to a depth of 3 km, and microseismicity data for the period 1970–1975 extend the fault to a depth of 12 km with only a slight increase in dip (Fig. 8). There were virtually no earthquakes recorded shallower than 5 km, suggesting that any fault displacement occurring at shallower depths was aseismic during the survey period (Fig. 8). Repeated surveys of bench marks on highways crossing the fault trace (Buchanan-Banks and others, 1975) show an uplift of about 200 mm of the Red Mountain anticline with respect to the coast in 34 yr, a rate of 6 mm/yr. Where the Red Mountain fault reaches the coast, it offsets a 40,000-yr-old terrace and is characterized by uplift rates of 4 to 10 mm/yr (Lajoie and others, 1979).

Thus, the fault has demonstrated microseismicity and is a candidate for at least a San Fernando-type earthquake of magnitude 6 to 7. Despite the evidence for historic uplift of the hanging-wall block with respect to the coast at the mouth of the Ventura River, there is no evidence of historic ground rupture, including that caused by

fault creep. Offset of the 40,000-yr-old marine terraces indicate that the fault has ground-rupture potential.

CONCLUSIONS

We conclude that in earthquake-hazard evaluation it is not sufficient to evaluate only the recency of movement and recurrence interval of earthquakes on a fault. It is also necessary to ascertain the capacity of a fault to produce surface rupture and/or seismic shaking. In many instances, seismic shaking is accompanied by surface rupture, but in others, seismic shaking may not be accompanied by surface rupture and vice versa. As shown in the cases presented here, geomorphic expression and geologic setting can aid in evaluating a fault as capable of seismic shaking or ground rupture or both. A fault which does not extend downward into rocks of high strength may produce surface rupture but probably not large-amplitude ground acceleration due to seismic shaking. A fault which ruptures at depth but on which the near surface displacement is warping or folding rather than faulting will produce seismic shaking but not surface rupture.

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REFERENCES CITED

- Barrows, A. A., 1974, A review of the geology and earthquake history of the Newport-Inglewood structural zone, southern California: California Division of Mines and Geology Special Report 114, 115 p.
- Bonilla, M. G., 1979, Historic surface faulting — Map patterns, relation to subsurface faulting, and relation to pre-existing faults: U.S. Geological Survey Open-File Report 79-1239, p. 36–65.
- Buchanan-Banks, J. M., Castle, R. O., and Ziony, J. I., 1975, Elevation change in the central Transverse Ranges near Ventura, California: *Tectonophysics*, v. 29, p. 113–125.
- Buika, J. A., and Teng, T. L., 1978, Recent seismicity and fault-plane solutions of the Santa Monica Mountains, Santa Monica Bay, and northern Los Angeles basin, in *Geologic guide and engineering geology case histories, Los Angeles metropolitan area*: Association of Engineering Geologists 1st Annual California Section Conference, p. 64–72.
- Castle, R. O., and Yerkes, R. F., 1969, Recent surface movements in the Baldwin Hills, Los Angeles County, California: A study of surface deformation associated with oil-field operations: U.S. Geological Survey Open-File Report, 300 p.
- Clark, M., and Keller, E., 1979, Newly identified zone of potentially active reverse faulting, western Transverse Ranges, California: *Geological Society of America Abstracts with Programs*, v. 11, p. 402.
- , 1980, Earthquake hazard evaluation of active faults near Ojai, California: *Geological Society of America Abstracts with Programs*, v. 12, p. 102.
- Cloos, E., 1968, Experimental analysis of Gulf Coast fracture patterns: *American Association of Petroleum Geologists Bulletin*, v. 52, p. 420–444.
- Hamilton, D. H., and Meehan, R. L., 1971, Ground rupture in the Baldwin Hills: *Science*, v. 172, p. 333–344.
- Jennings, C. W., compiler, 1973, State of California preliminary fault and geologic map: California Division of Mines and Geology Preliminary Report 13.
- Keller, E. A., Johnson, D. L., Clark, M. N., and Rockwell, T. K., 1980, Tectonic geomorphology and earthquake hazard north flank, central Ventura Basin, California: Final Technical Report to the U.S. Geological Survey, Contract 14-08-0001-17678, 167 p.
- Lajoie, K. R., Kern, J. P., Wehmler, J. F., Kennedy, G. L., Mathiesen, S. A., Sarna-Wojcicki, A. M., Yerkes, R. F., and McCrory, P. F., 1979, Quaternary marine shorelines and crustal deformation, San Diego to Santa Barbara, California, in Abbott, P. L., ed., *Geological excursions in the southern California area*: San Diego State University Department of Geological Sciences, p. 3–15.
- Putnam, W. C., 1942, Geomorphology of the Ventura region, California: *Geological Society of America Bulletin*, v. 53, p. 691–754.
- Rockwell, T., and Keller, E. A., 1980, Alluvial fan deformation along the San Cayetano fault, western Transverse Ranges, California: *Geological Society of America Abstracts with Programs*, v. 12, p. 150.
- Teng, T. L., 1975, Los Angeles Basin seismotectonics, in *Sycamore Canyon fault, Verdugo fault, York Boulevard fault, and Sierra Madre fault zone*: Association of Engineering Geologists Field Trip Guidebook, p. 58–66.
- Van Siclen, D. C., 1967, The Houston fault problem: American Institute of Professional Geologists, Texas Section, Proceedings of the Third Annual Meeting, p. 9–29.
- Yeats, R. S., 1976, Neogene tectonics of the central Ventura basin, in Fritzsche, A. E., Ter Best, H., Jr., and Wornardt, W. W., eds., *The Neogene Symposium: Pacific Section, Society of Economic Paleontologists and Mineralogists*, p. 19–32.
- Yeats, R. S., Lee, W.H.K., and Yerkes, R. F., 1978, Geology and seismicity of the Red Mountain fault, Ventura County, California [abs.]: *EOS (American Geophysical Union Transactions)*, v. 59, p. 385.
- , 1981, Geology and seismicity of the eastern Red Mountain fault, Ventura County, California, in U.S. Geological Survey Professional Paper (in press).
- Zoback, M. D., Hamilton, R. M., Crone, A. J., Russ, D. P., McKeown, F. A., and Brackman, S. R., 1980, Recurrent intraplate tectonism in the New Madrid seismic zone: *Science*, v. 209, p. 971–976.

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