sources. In contrast, an *A. rudis* individual can approach the bait, place a leaf, and rapidly depart before it is encountered. At a later time, it can return, quickly remove the leaf, and thus gain a portion of the resource with relatively low risk. *Aphaenogaster rudis* has been observed to place a leaf on a bait occupied by *C. ferrugineus* and later retrieve it when *C. ferrugineus* was on the opposite side of the bait. The behavior of *A. rudis* is similar when either *C. pennsylvanicus* or *F. subservicea* is present. Thus tool use allows *A. rudis* to obtain more food from such a source than it would obtain by drinking and thus increases its success in competing with these species.

Aphaenogaster rudis is also subordinate to *P. imparis* unless the latter is greatly outnumbered. However, if *A. rudis* places leaf fragments on a food before being excluded, *P. imparis* may eat all the available food but ignore the leaves. When *P. imparis* departs, *A. rudis* may retrieve the leaves. On 12 occasions, we have seen leaf-covered baits taken over by *P. imparis*. In such cases, the *P. imparis* individuals feed on the bait in their usual fashion. Occasionally, a leaf is knocked off the bait and a few individuals then glean some food from these pieces. Typically, however, the leaves are ignored and left at the bait. Presumably *A. rudis* could retrieve these at a later time, although this outcome has not been observed. Tool-covered baits have also been given to colonies of *C. pennsylvanicus* in the laboratory. Most of the food is eaten, but the tools and a moderate portion of the food under the tools are left and would thus be available for *A. rudis*.

Tool use appears to be a maximally efficient way of utilizing some food sources, regardless of dominance relationships. This behavior may be particularly adaptive for genera such as *Aphaenogaster* which have a relatively small gaster in which to carry food (7).

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8. We thank D. H. Morse for his encouragement. We are grateful to J. D. Allan, E. R. Buchler, D. E. Gill, D. H. Morse, E. O. Wilson, and two anonymous reviewers who kindly offered criticisms of the manuscript, although the conclusions remain our own. We thank S. Mann and S. Lilien who assisted in the initial observations, and D. R. Smith, U.S. National Museum, who kindly identified the ants.

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Oroville Earthquakes: Normal Faulting in the Sierra Nevada Foothills

Abstract. *Aftershocks of the Oroville, California, earthquake of 1 August 1975 define a 16- by 12-kilometer fault plane striking north-south and dipping 60 degrees to the west to a depth of 10 kilometers. Focal mechanisms from P-wave first motions indicate normal faulting with the western, Great Valley side downdropped relative to the Sierra Nevada block. The northward projection of the fault plane passes beneath Oroville Dam and crops out under the reservoir.*

On 1 August 1975, at 2020 Greenwich mean time, an earthquake of magnitude $M_L = 5.7$ (University of California, Berkeley), $M_L = 6.1$ (California Institute of Technology, Pasadena), and $m_b = 5.9$ (USGS National Earthquake Information Service) occurred in the Sierra Nevada foothills southeast of Oroville, California. The earthquake was felt strongly in Sacramento and was noticeable in Menlo Park, at a distance of 225 km. Taken together with the aftershocks, the Oroville earthquake is the most significant strain release episode in California since the 1971 San Fernando earthquake. The main shock epicenter (star in Fig. 1) was near the town of Palermo, 7 km south of Oroville and 11 km from the 235 m high Oroville Dam.

Because of the proximity of the earthquake to the dam and the possibility that the seismicity was induced by the 4.3 billion cubic meter reservoir, the U.S. Geological Survey (USGS) began deployment of 16 high-gain telemetered seismographs in the area on 2 August. The network was completed by 11 August and was augmented by data from a tripartite array of local stations, telemetered to Menlo Park through a data exchange with the California Department of Water Resources (CDWR). Ten strong-motion accelerographs were installed in the epicentral region within 48 hours of the occurrence of the main shock. The locations of the five instruments installed by personnel of the California Institute of Technology and the USGS are shown in Fig. 1. Five additional instruments were installed by the California Division of Mines and Geology. One hundred seventy strong-motion accelerograms of

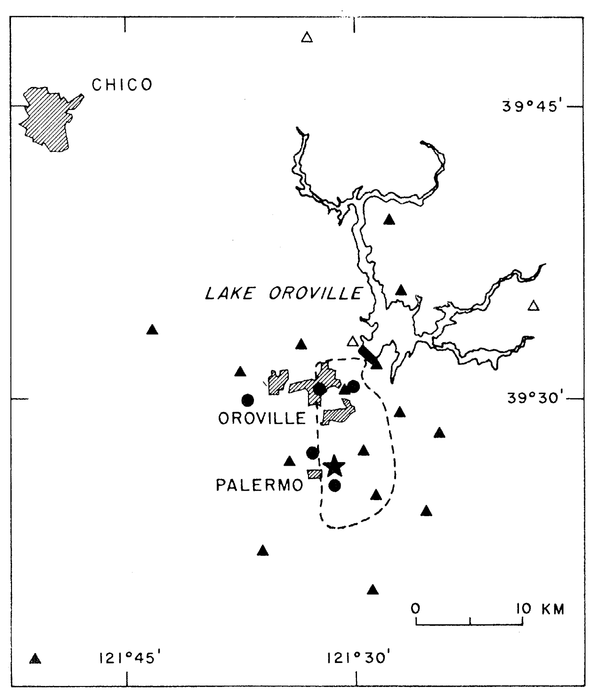

Fig. 1. Seismographic stations used in this study. Closed circles are strong-motion seismographs. Closed triangles are telemetered short-period seismographs installed by the U.S. Geological Survey after the 1 August 1975 earthquake. Open triangles are seismographs operated since 1964 by the California Department of Water Resources. The approximate epicenter of the main shock is indicated by a star. Distribution of aftershocks (August to October 1975) is indicated by the dashed line. The Oroville Dam is shown by the bar at the southwest corner of the reservoir.

earthquakes in the magnitude range $1.8 \leq M \leq 5.1$ were obtained through 20 August. Peak ground accelerations of 0.70, 0.42, 0.22, 0.19, 0.19, 0.10, and 0.05*g* were obtained for aftershocks of M_L = 4.7, 4.3, 4.0, 3.3, 3.2, 2.5, and 1.8, respectively, at hypocentral distances of 5 to 15 km. The peak ground acceleration recorded for the main shock at an accelerograph 2 km northwest of Oroville Dam was 0.12*g*.

This report deals primarily with the orientation of the fault plane and mechanism of faulting from 146 well-located (*1*) aftershocks during the period 5 to 11 August. These aftershocks (Fig. 2A) define an epicentral zone roughly 12 km long (north-south) by 7 km wide (east-west). Horizontal projections onto vertical planes were constructed for a number of azimuths of view. Assuming the aftershocks lie along a single planar surface, the plane appears best defined (Fig. 2B) looking due north or 5° east of north (N 5° E). The dip is approximately 60° to the west. The zone of aftershocks has an apparent thickness of about 2 km, with the upper edge of the hypocentral zone more sharply defined than the lower edge.

Composite fault plane solutions (lower hemisphere) for six aftershock subregions are shown in Fig. 2A. Assuming the westward dipping plane to be the fault plane, all fault plane solutions indicate normal faulting with the Great Valley side downdropped relative to the Sierra Nevada block. In detail, the solutions are different, indicating spatial variations in the strike and dip of the fault plane or direction of slip or both. Although the mean plane strikes north-south and dips about 60° to the west, local deviations as large as 22° in strike and 25° in dip occur. These deviations are significant, as the nodal planes are well constrained (± 5°) by the first motion data. Noteworthy in Fig. 2A is composite IB of earthquakes at the northwest edge of the aftershock zone. A nearly vertical fault plane strikes N 20° E and is consistent with the abrupt steepening of the aftershock zone at depth seen in Fig. 2B. Composite III of shallow ($1.9 \leq$ depth ≤ 3.5 km) events near a region of observed surface deformation (*2*) in the east-central part of the epicentral region shows a fault plane striking N 22° W and dipping 70° to the west.

A progressive extension of the aftershock region to the north and south during the period 5 to 11 August was noted. When considered with foreshock and main shock epicenters and earlier aftershock locations (*3*), a pattern of faulting is apparent, with rupture beginning at depth near the west margin of the aftershock zone and propagating upward to the east, then extending to the north and south. Since 19 August, Oroville aftershocks have been located on a real-time basis by using an on-line processor in Menlo Park. These later locations suggest a slow, continued northward extension of the aftershock zone (indicated by dashed outline in Fig. 1) at depth with shocks occurring as far north as the dam by October.

The proximity of the earthquake sequence to the Oroville Dam, the largest earth-fill dam in the United States, raises the obvious and important question of whether this earthquake sequence is causally related to the dam-reservoir system. Since Carder's observation (*4*) of increased seismicity rates near Boulder City, Nevada, temporally associated with the construction of Boulder Dam and the filling of Lake Mead, numerous instances of increased seismicity associated with reservoir filling have been reported (*5*), often in regions highly aseismic prior to reservoir filling. Damaging and locally destructive earthquakes have been spatially close and temporally related to the filling of large reservoirs, at Kremasta, Greece (1966), Lake Kariba, Zambia (1963), Koyna, India (1967), and Hsinfengkiang Dam, China (1962). The situation at Oroville is analogous to these case histories in several respects.

By California standards, the Oroville

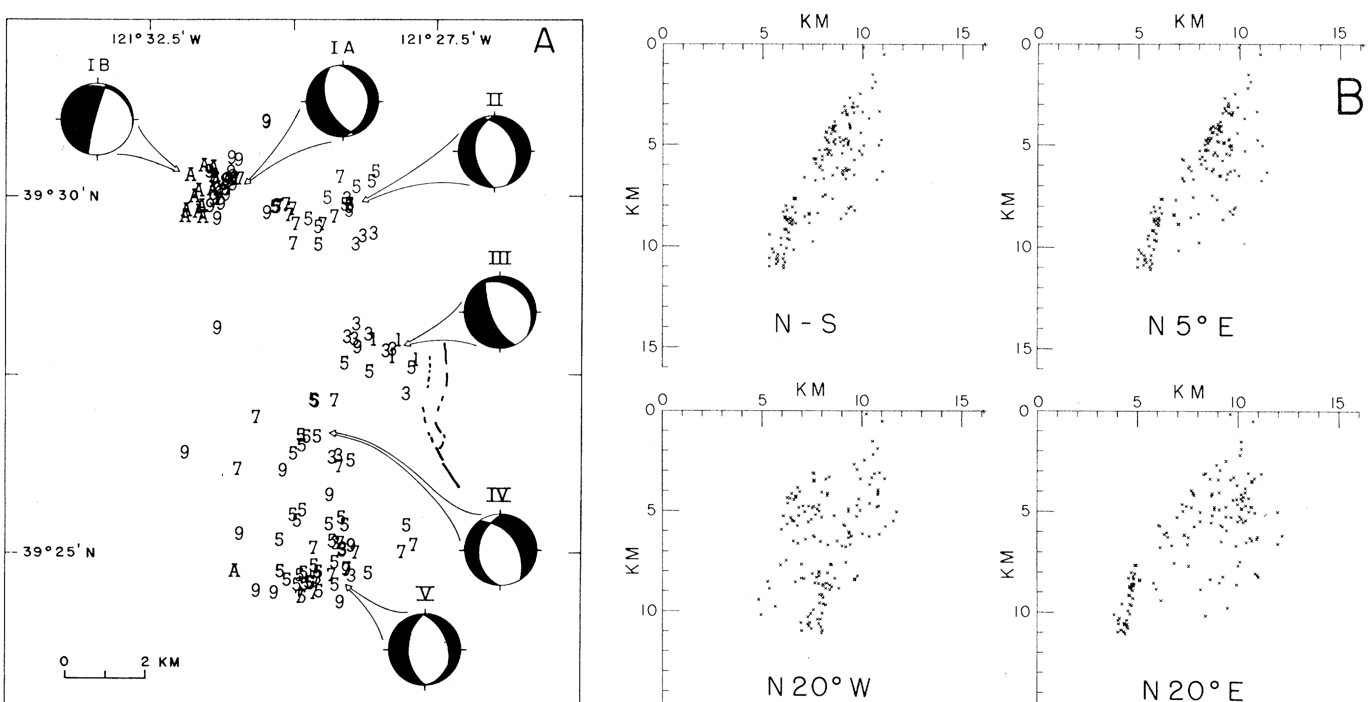

Fig. 2. (A) Epicenters of aftershocks during the period 5 to 11 August 1975. The number plotted is the focal depth in kilometers (*A* is 10 km). Fault plane solutions based on P-wave first motions are composites for events from zones indicated by arrows. Darkened areas of the equatorial projection plane are zones of compressional first motion for the lower hemisphere of the focal sphere, light areas are zones of dilatational first motion. The broken line marks the zone of apparent surface faulting. (B) Hypocentral vertical sections for selected viewing azimuths. There is no vertical exaggeration. Sections are centered (8 km on abscissa) at 39°27.5'N, 121°30.0'W.

area had been one of relatively low seismic activity. Forty earthquakes of magnitude ≥ 3.5 occurred within 100 km of Oroville in the years 1940 through 1974. None of the epicenters mentioned above is within 40 km of Oroville Dam, although earthquake locations in the Oroville area were not well determined until the installation of a short-period high-gain seismograph by CDWR near the dam site in 1963. Two additional stations were installed north and east of the reservoir in 1964. No significant seismic activity was noted in the vicinity of the dam-reservoir system (*6*) until 28 June 1975, when a sequence of small ($M \leq 3.5$) earthquakes occurred. In response to this situation, two portable seismographs were deployed by CDWR 30 km west and southwest of the dam. Seismicity continued at a low level until 1 August, when several foreshocks of $M_L \geq 3$ occurred in 5 hours preceding the main shock. The main shock was followed by a rather large number of aftershocks of $M_L \geq 4$, ten in the first 5 days following the main shock (*7*).

The Oroville earthquake sequence occurred well after filling of the reservoir was initiated in 1967. The reservoir was first filled to capacity in 1969. Normal seasonal fluctuation in reservoir level has been approximately 20 m, but in the winter of 1974–75 the level was lowered more than 40 m for maintenance purposes. The reservoir was rapidly refilled in the spring, with local earthquake activity beginning when the reservoir level was near maximum. In a review of seismicity associated with reservoir impounding, Simpson (*8*) has noted that in most instances earthquake activity has started soon after impounding, with the level of activity increasing as the water level increases. Most large shocks have occurred at or near the time of highest water level and have been associated with a long series of foreshocks and aftershocks. Large fluctuations in reservoir level subsequent to initial filling are sometimes accompanied by marked changes in seismicity. Extreme cases cited are at Contra, Switzerland, where the earthquake activity stopped when the reservoir was emptied and refilled, and at Vouglans, France, where activity began after a rapid emptying and filling of the reservoir 3 years after initial impoundment.

The sequence of events at Oroville suggests that if the earthquakes are causally related to the reservoir, weight-induced stresses are an unlikely explanation. In fact, these stresses have been shown (*9*) to oppose the inferred fault motion at Oroville, not induce it. An alternate explanation is that the increase in pore fluid pressure reduced the effective normal stress, and thereby the frictional resistance to fault motion. The inadvertent triggering of earthquakes by fluid injection at the Rocky Mountain Arsenal near Denver, and results of the earthquake control experiment conducted in an oil field at Rangely, Colorado (*10*), leave little doubt about the importance of fluid pressure in inducing shear failure in highly stressed rocks. Direct evidence as to whether fluid pressure variations induced by reservoir level changes have triggered earthquakes at Oroville (or elsewhere) is lacking. If weight-induced stresses near the Oroville reservoir are in opposition to tectonic stresses, this may explain the separation of the hypocentral zone from the reservoir. The time lag between initial reservoir filling and occurrence of the earthquakes could reflect the time required for a slowly migrating pore fluid pressure front to reach a region of high tectonic stress. The fault plane inferred from aftershock locations projects to the surface beneath the reservoir, possibly affording direct access of reservoir water to the shear zone on which the earthquakes occurred.

Since pore pressure variations also may play an important role in the mechanism of naturally occurring earthquakes (*11*), the discrimination of reservoir-induced earthquakes, other than by circumstantial spatial and temporal relationships, may not be possible without direct observation of fluid pressures in the hypocentral region over a period of years.

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References and Notes

1. Data were recorded on magnetic tape and arrival times read with an accuracy of ± 20 msec. Hypocenters were determined by using the Hypoellipse location program developed by J. Lahr and P. Ward of the USGS, assuming a linear increase in velocity with depth. Standard errors were generally less than 0.5 km in epicenter and 1.0 km in focal depth. The computed location of a calibration shot fired near Palermo on 23 October was 0.8 ± 0.4 km northeast of the actual shot point and at a depth of 1.1 ± 1.6 km.
2. Several kilometers of fresh surface ruptures, shown in Fig. 2, have been mapped by R. Sharp, M. Clark, and P. Harsh of the USGS (unpublished data). Geodetic measurements show a maximum of 17 cm of differential vertical movement since 1941, in a pattern consistent with normal faulting along the plane defined by the seismic data (J. Savage, USGS, unpublished data).
3. Hypocenters and magnitudes of earthquakes prior to 5 August were obtained from a list compiled at the Seismograph Station, University of California, Berkeley (UCB), on the basis of data from seismographs operated by UCB, California Department of Water Resources, and Woodward-Clyde Consultants.
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7. The UCB magnitudes were used for $M > 3.8$ in this study. An empirical relation of log coda length at station ORV to UCB magnitude for early aftershocks was used to determine magnitudes of events with $1.6 \leq M \leq 3.8$. The estimate of b in the relation $\log N(M) = a - bM$ (N is the cumulative number of events of magnitude $\geq M$) was 0.43 ± 0.19 for foreshocks and 0.61 ± 0.06 for aftershocks at Oroville, in contrast with b values greater than 1.0 for other earthquake sequences near reservoirs cited by H. K. Gupta, B. K. Rastogi, and H. Narain [*Bull. Seismol. Soc. Am.* **62**, 493 (1972)].
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12. We thank P. Morrison of the California Department of Water Resources, W. Savage of Woodward-Clyde Consultants, and T. McEvilly, B. Stump, and R. Urhammer of the Seismographic Station at the University of California for preliminary magnitude determinations and locations of foreshocks and earlier aftershocks. J. Ellis, S. Stewart, H. Mills, E. Taylor, C. McHugh, and many others at USGS sacrificed weekends and evenings to make this study possible. We also thank J. Savage for his interpretation of geodetic observations and P. Ward, C. B. Raleigh, and J. Eaton for their helpful comments and suggestions.

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