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THE HONEYDEW EARTHQUAKE

August 17, 1991

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Photo 1. Dust from landslides in the King Range triggered by the August 17 earthquake. Photo taken on Elk Ridge about 15 miles east of Honeydew 15 minutes after the earthquake. *Photo by Bill Eastwood.*

The Honeydew is one of many northern California earthquakes. This article describes the effects of the Honeydew earthquake, while Sources of North Coast Seismicity (page 40) summarizes the seismic record and tectonics of this part of California...editor.

INTRODUCTION

The north coast of California was shaken by a unique series of four large earthquakes in July and August of 1991 (Figure 1). Three of the earthquakes (July 12, surface wave **magnitude*** (M_s)= 6.9; August 16, M_s=6.3; and August 17, M_s=7.1) were located in the Gorda plate off the northern California and southern Oregon coast (Gee and others, 1991; Nabelek, 1991), the region which has produced the majority of the area's historic damaging earthquakes (Smith and others, 1981; also see Dengler and others, this issue). The magnitudes of these events are not unusual for the Gorda plate, but the short time intervals are unprecedented in the historic record.

On August 17 at 12:29 p.m., nearly 21 hours after the August 16 and 3 hours before the August 17 plate events, a much more unusual earthquake occurred on land about 7 miles (11 km) south of Petrolia and west of Honeydew (McPherson and others, 1991; Oppenheimer and Magee, 1991). This magnitude 6.2 event, the Honeydew earthquake, was the largest on-land earthquake in the continental United States during 1991. This earthquake is important because: 1) It was the largest earthquake on land in the vicinity of the Mendocino triple junction in this century; 2) The shallow depth of focus (7 miles, or 12 km) suggests a previously unrecognized source for damaging earthquakes in the region, which has now produced three damaging earthquakes in slightly over a two-year period[1]; 3) The earthquake produced a conspicuous zone of northwest oriented surface cracks which coincided with a previously recognized shear zone; 4) The epicentral region has undergone a very high rate of Quaternary uplift and the proposed style of faulting for the Honeydew earthquake is consistent with uplift of this region; 5) A large region surrounding the epicenter experienced changes in ground water and stream flow related to the earthquake.

* Terms in **boldface** type are in the glossary on page 38.

1 Magnitude 5.3 earthquakes occurred in the same area on January 16, 1990 and March 7, 1992. Both earthquakes produced peak intensities of Modified Mercalli III.

This report summarizes surface phenomena observed during the 2 weeks following the earthquake (Photo 1), presents an isoseismal map constructed from field data and individual survey responses, and proposes a simple fault model for the earthquake.

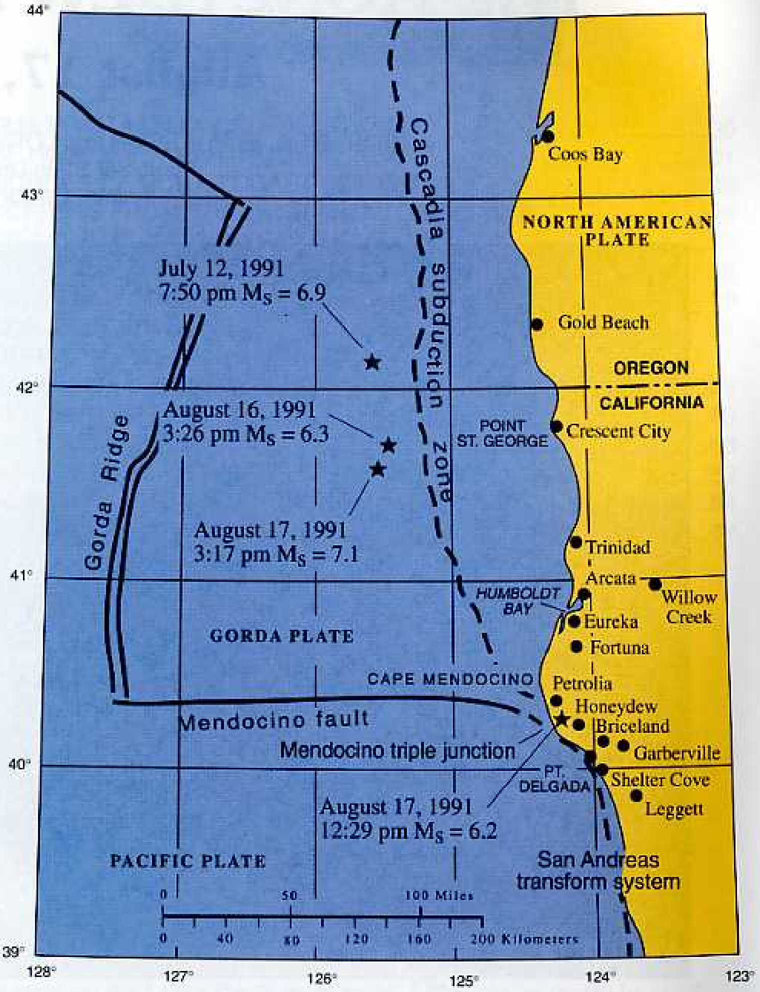

Figure 1. Location map of large earthquakes in the north coastal California area during July and August 1991. Times are Pacific Daylight Time. Epicenter locations and magnitudes from the National Earthquake Information System (NEIS), 1991.

GEOLOGIC SETTING

The Honeydew earthquake occurred about 15 miles (25 km) southeast of Cape Mendocino in the vicinity of the Mendocino triple junction (Kelsey and Carver, 1988; Clarke, 1992), the region where the Gorda, Pacific, and North American plates meet (Figure 2). North of the triple junction, coastal tectonics are dominated by the convergence of the Gorda and North American plates along the Cascadia subduction zone. To the south, tectonics are controlled by the San Andreas fault system and the right-lateral transform motion of the North American and Pacific plates (Kelsey and Carver, 1988). The Mendocino fault, extending due west of Cape Mendocino, forms the boundary between these two tectonic regimes.

Northwest of the Mendocino triple junction, the southern end of the Cascadia subduction zone bends eastward and comes onshore in the vicinity of the Petrolia Shear Zone (Clarke, 1992). The boundary between the Gorda and Pacific plates, the Mendocino fault, can be followed eastward along the base of the Gorda Escarpment offshore to about 124° 45' longitude, but landward its location becomes less certain. Seismicity trends of shallow earthquakes (McPherson, 1989; Oppenheimer and Magee, 1991) suggest that the Mendocino fault follows the Mattole River Canyon and eventually joins the Cooskie Shear Zone as proposed by Clarke (1992). Therefore, two of the three plate boundaries that form the triple junction come onshore near two previously recognized on-land shear zones, the Cooskie and Petrolia shear zones.

The boundary between the Pacific and North American plates is a broad zone of faults parallel to and east of the San Andreas fault (Kelsey and Carver, 1988; Eaton, 1989). The surface rupture of the San Andreas fault during the 1906 earthquake can be traced from south of San Jose northward to Pt. Arena (Lawson, 1908). From Pt. Arena, the San Andreas fault is thought to run offshore to just south of Pt. Delgada (Griscom, 1973; McCulloch, 1989). North of Pt. Delgada, the San Andreas fault is not well defined, but may run parallel and close to the coastline, curving westward to join the Mendocino fault (McCulloch, 1989), or across land southeast of Pt. Delgada, eventually joining the Mattole shear zone (McLaughlin and others, 1988).

The Mendocino triple junction, because it consists of poorly delineated plate boundaries, is not a single point but rather a region bounded on the northeast by the Petrolia shear zone, on the south by the Cooskie shear zone, and on the west by the coastline (Figure 2). The epicenter of the Honeydew earthquake is within this region, and therefore must be considered a triple junction event.

The rocks of the King Range Terrane, with peaks reaching over 4,000 feet (1,200 m), are within a few miles of the coast, south of the Mendocino triple junction. McLaughlin and others (1982) have suggested that the King Range Terrane was obducted (thrust) onto northern California along a southwest-dipping reverse fault as recently as 2 million years ago. Subsequent folding and uplift are recorded by marine terraces along the coast (LaJoie and others, 1982; McLaughlin and others, 1983; Merrits and Bull, 1989) and fluvial terraces to the east near Garberville (Bickner, F., Humboldt State University, Arcata, California, oral communication, 1992). Studies using **fission tracks** (Dumitru, 1991) and stream profiles (Merrits and Vincent, 1989) corroborate the late Holocene history of rapid uplift in the region.

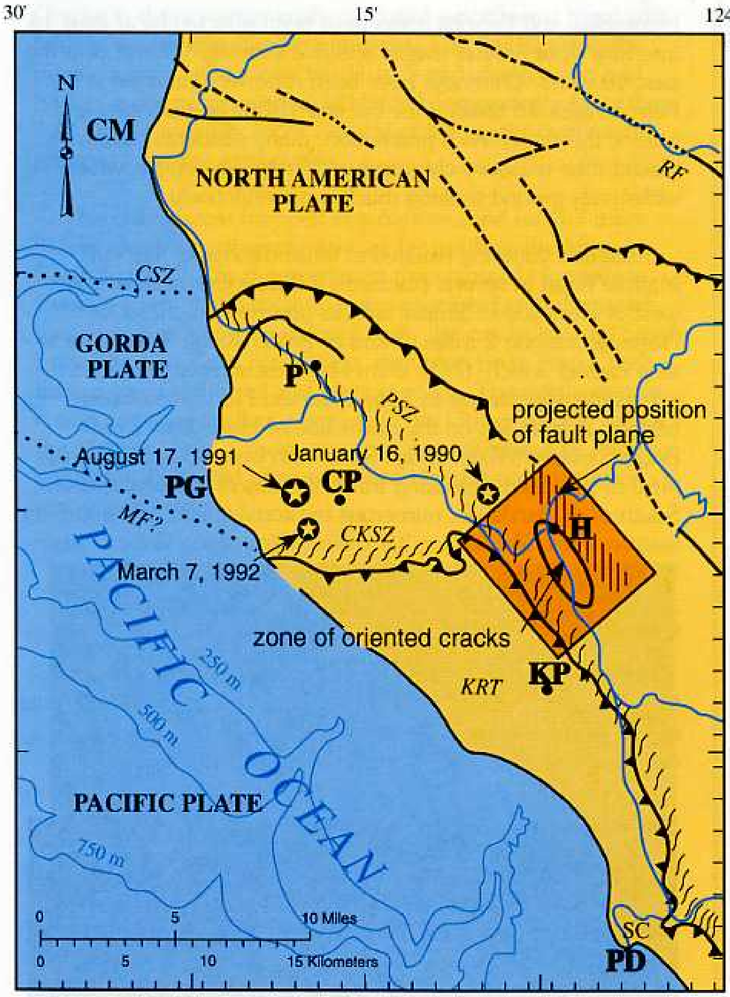

Figure 2. Simplified geologic sketch map of the epicentral region of the Honeydew earthquake (after McLaughlin and others, in press; Clarke, 1992). Towns: P = Petrolia; H = Honeydew; SC = Shelter Cove. Geologic features: KRT = King Range Terrane; PSZ = Petrolia shear zone; CKSZ = Cooskie shear zone; RF = Russ Fault; MF = Mendocino fault; CSZ = Cascadia subduction zone boundary. Geographic features: CM = Cape Mendocino; PG = Punta Gorda; PD = Point Delgada; CP = Cooskie Peak; KP = King Peak. Stars mark the epicenters of the January 16, 1990, August 17, 1991, and March 7, 1992 earthquakes. The region of oriented surface cracks and the projected surface position of the fault plane are also shown. The brown rectangle is enlarged in Figure 3.

THE AUGUST 17th HONEYDEW EARTHQUAKE

The Honeydew earthquake was felt as far away as San Francisco, 185 miles (300 km) to the south. It produced strong ground-shaking (intensity IV or greater) over an area of nearly 3,860 square miles (10,000 km^2). Residents of the epicentral area reported 6 to 10 seconds of violent ground motion that was strong enough to cause some people to fall to the ground. Debris was shaken from both live and dead trees. Rockfalls were common and landslides were reactivated over a large region. As the shaking subsided, dense dust clouds rose, giving some observers the impression of a major forest fire, prompting several calls to the California Division of Forestry (Photo 1).

In the 2 weeks following the earthquake, we conducted field investigations of the effects of strong motion in the remote epicentral area. We were interested in studying this earthquake because its epicenter was on land and shallow. Beginning 2 days after the earthquake, we mapped surface features and damaged structures on 7-1/2-minute quadrangles, primarily along roads. Residents were interviewed and many invited us to look at features on their property. The region covered by the most detailed field mapping is shown in Figure 3.

There are several obstacles to the study of earthquake effects in remote areas. There is a tradition of self reliance and many residents have strong feelings about their privacy and trespassing. During the early stages of the field study, one of us was rudely alerted by gun shots fired overhead. We found it essential to respect the local population, to explain what we were doing and why, and to let the word-of-mouth network spread the information about our study. A local radio station continually reported our progress, thus involving the residents and keeping their interest high. Most people were very cooperative and consequently we have a network to rely on after future earthquakes[2].

During field studies, it became clear that the amount of damage and the peak intensity were higher than initial estimates. The Humboldt County Office of Emergency Services (OES) has two volunteers (in Petrolia and Shelter Cove) to cover about 965 square miles (2,500 km^2) of very rugged terrain and poor roads. The OES estimated county road and bridge damage at $45,000 to $75,000, and private property damage at $50,000 (Mike McGuire, Humboldt County OES, 1992, oral communication). We estimate the private sector damage to be several times higher than the OES estimate because many residents did not report damage to uninsured structures.

The National Earthquake Information Service (NEIS) assigned a peak intensity of VII to the Honeydew area, based on postmaster survey responses (NEIS, 1991). However, effects observed during field work and interviews with residents convinced us that this intensity estimate was too low. To clarify the peak intensities and regional intensity distribution, we found it necessary to change the Modified Mercalli scale to account for the lack of masonry structures and large structures of any kind in the epicentral area. We put together an intensity questionnaire more suitable to a rural area and surveyed more than 300 north coast residents.

Damage

Structural damage was concentrated in a 3-mile (5-km) radius zone centered near the town of Honeydew. Houses inadequately attached to foundations, and mobile homes on post

[2] This network enabled us to construct a preliminary isoseismal map within 2 weeks of the area's damaging March 7, 1992 event.

Honeydew and Petrolia areas have been affected by at least 14 intensity VI or greater events and five intensity VII events in the past 40 years. Chimneys have been reported damaged in the Petrolia area 16 times since the late 1800s (see Dengler and others, this issue). As a precaution, many residents have replaced their masonry chimneys with metal stovepipe, which withstands ground shaking much more effectively.

Roadbed slumping resulted in tensional cracks that cut Mattole Road in several places on a 3-mile (5-km) stretch just west of Honeydew. Similar failures occurred southeast of Honeydew along 2 miles (3 km) of Wilder Ridge Road. The settling caused 3-inch- (7- to 8-cm-) high escarpments to form across the approaches to Bear Trap and Honeydew Creek bridges. A landslide on the north side of Honeydew Creek Bridge covered Wilder Ridge Road with over 600 cubic yards (460 m^3) of debris, blocking traffic the day of the earthquake. South of the landslide, numerous tensional cracks and slumping features were obvious for 3.7 miles (6 km) along Wilder Ridge Road.

Oriented Surface Cracks

A linear zone of surface cracks was observed along Wilder Ridge Road about 4 miles (6 km) south of Honeydew. Individual cracks were typically 30 to 65 feet (10 to 20 m) long. They occurred along the ridge and on the ridge flanks (Figure 3).

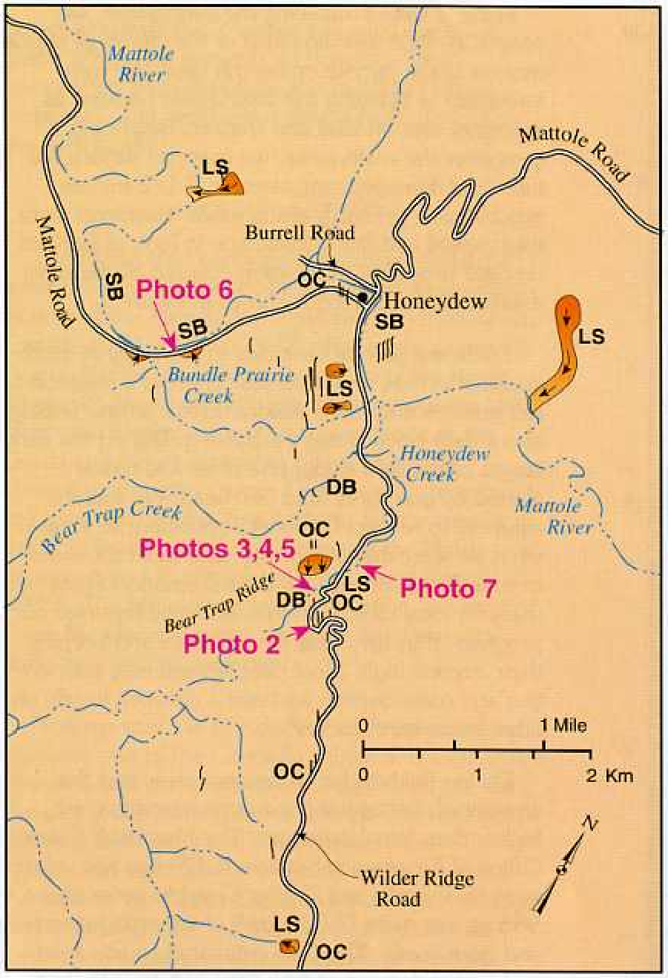

Figure 3. Simplified field map of the epicentral region. Mapped surface effects: LS = reactivated landslides; DB = displaced boulders; SB = **sandblows**; OC = oriented cracks. Viewpoints of photos 2–7 in this article are also marked.

Photo 2. Oriented tensional crack along Wilder Ridge Road, 4 miles (6.4 km) south of Honeydew. Crack orientation is approximately N 30° W, with the downslope side having moved up forming an east-facing scarp. *Photos by Robert C. McPherson unless otherwise noted.*

and cinder block foundations had the most damage. We interviewed, or received survey responses from, 53 residents in the Honeydew, Wilder Ridge, Panther Gap, and Petrolia areas. Of these, 33 reported structural damage, some as far away as Ettersburg, about 10 miles (16 km) to the southeast. At least a dozen structures in the Panther Gap, Wilder Ridge, and Honeydew areas were jarred from their foundations, resulting in considerable structural damage. One mobile home, resting on cinder blocks, had been strapped to the ground with taut cables but was damaged when the cinder blocks disintegrated. Well constructed homes with shear bracing and proper bolting suffered little or no structural damage. In the region of strongest shaking, nearly all unattached objects were thrown from shelves and table tops.

At least 15 chimneys were down or damaged in the Petrolia-Honeydew area. Incidence of chimney damage was lower, however, than one might have expected from observations of damage by previous earthquakes. Residents of the

Cracks in this zone generally exhibited a northwest trend with both left- and right-stepping patterns. The cracks along the ridge showed 1/2 to 2 inches (1 to 5 cm) of extension and had, in some cases, a small left-lateral component of less than 1/2 inch (1 cm) (Photo 2). Several of the cracks continued growing after the earthquake.

The cracks were mapped in a narrow zone for 3.7 miles (6 km) along a northwest trend, as far north as the Mattole River (Figure 3). To the northwest they crossed Honeydew Creek (Photo 3), where they were associated with displaced boulders. North of Honeydew Creek, the cracks crossed Smith Etter Road on Bear Trap Ridge, disrupted Bear Trap Creek, then cut across Burrell and Mattole roads. The northernmost cracks cut a young fluvial terrace in the Upper North Fork of the Mattole River. Cracks were obscured in places by large landslides, but could always be found by sighting northwest across each slide.

Photo 3. Northwest oriented tensional crack crossing the bed of Honeydew Creek. This crack was associated with displaced boulders (see Photos 4 and 5).

Displaced Boulders

Disrupted streambed cobbles along the cracks across Honeydew Creek were the clearest indicators of strong motion. Cobbles and boulders up to 3 feet (1 m) in diameter, 50 to 115 feet (15 to 35 m) from the cracks, were thrown from their positions. These cobbles, which before the event had been imbedded a few inches (several centimeters), showed primarily westward displacements (Photos 4 and 5). More large boulders than smaller ones were dislodged. Several boulders were flipped, with some displaced 10 inches (25 cm). Similarly, logs near the cracks in the streambed were displaced and rotated to the west. Disrupted boulders were also found near tensional cracks in Bear Trap Creek, the next drainage to the northwest. The narrowness of the zone of disrupted stream-channel boulders suggested that strong ground-motions had been focused in this region.

Water Flow Changes

After the earthquake, which occurred during the driest time of the 6th year of drought, most of the residents in the epicentral area noted an increase in flow in the Mattole River and in many streams. The Mattole River flow increased steadily from 28 cubic feet (0.8 m^3) per second prior to the earthquake to 82 cubic feet (2.3 m^3) per second in the 6 days following the earthquake (Figure 4). The only precipitation during this period was a small storm on August 26. The earthquake-induced flow, after reaching a peak, waned to pre-earthquake levels in about 60 days.

Many residents also reported changes in their well levels and springs. Most reported increased flows after the earthquake. The community of Briceland, whose water system was nearly dry prior to the earthquake, enjoyed a copious supply for several weeks after the temblor (Peter Ryce, Briceland water system, oral communication, 1992). A few residents noticed decreased flows, and one reported that the location of one spring changed entirely. Another landowner's reliable cold spring, over 500 feet (150 m) above the Mattole River, became "river water warm one half hour prior to the quake."

Liquefaction

Liquefaction of loosely consolidated water-laden sediments can result in surface ejection of water and sand along tensional cracks. This type of surface response to vibration occurred in

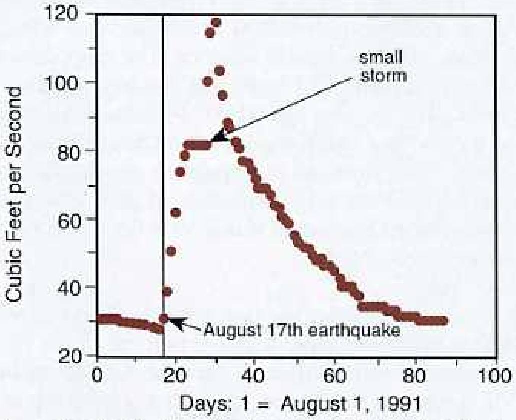

Figure 4. Mattole River hydrograph for August - October 1991. Gauging station is near the mouth of the Mattole River to the southwest of Petrolia. Pre-earthquake flow averaged about 30 cubic feet (0.8 m^3) per second. During the 6 days following the August 17 earthquake, flow increased to 82 cubic feet (2.3 m^3) per second and stabilized for 4 days. A small storm on the 26th of August produced a small storm peak. The flow gradually returned to pre-earthquake levels in about 60 days (U.S. Geological Survey, unpublished data, 1991).

Photo 4. Displaced stream cobble in Honeydew Creek. This cobble has been displaced to the west.

the Mattole River and Honeydew Creek channels where, moments after the shaking subsided, the water became turbid. This initial muddying was caused by liquefaction of the riverbed sediments, not from land sliding into the stream from the surrounding hills (although landslides provided a subsequent muddying of the flow). Sand and turbid water were ejected from tensional cracks along the dry sections of the river channel. Some vents were marked by a group of cobbles surrounded by fine sand, with a periphery of finer, brown-stained material (Photo 6).

Intensity Survey

An isoseismal map (Figure 5) of the Honeydew earthquake was constructed from more than 300 written surveys, telephone interviews, and field reconnaissance. The map shows a somewhat elongated area of intensity VIII shaking, trending north-northwest. The western boundary of the zone is uncertain because it coincides with the edge of the King Range National Conservation Area, an unpopulated, roadless region for which we have no detailed information on ground shaking. The boundary between intensities V and VI is uncertain because of a similar lack of data.

The VIII zone encompasses the region of mapped surface cracking. Within this zone, more than 50 percent of the survey respondents reported some structural damage. Our decision to assign an VIII value was also supported by the statements of several residents who described this event as stronger than any other they had experienced in their 40 or more years in the area. The size of the intensity VIII zone is comparable to the one mapped for the magnitude 5.9 Whittier Narrows earthquake of October 2, 1987. The Whittier Narrows earthquake also had a similar depth and focal mechanism and its intensity VIII zone is likewise located up-dip from the hypocenter (Hauksson and others, 1988).

Figure 5 also shows regions of mapped broken trees, rockfall, landslides, and reported changes in water flow described above. The arrows on the map show the direction of ground motion inferred from the motion of objects during the earthquake. The single-pointed arrows denote directions determined from heavy object displacement (Photo 7). For example, if a wood stove was found west of its usual place, the arrow points east because the ground and foundation under the stationary stove moved east. The double-pointed arrows show the direction that hanging or shelved objects moved. The intensity VIII zone shows a consistent pattern of ground-east motion. Elsewhere the pattern is less clear. Both north-south and east-west motions were reported in the Petrolia and Point Delgada areas. Motion near Garberville was predominantly north-south.

RELATION OF FAULTING AND SURFACE PHENOMENA

The most striking feature of the Honeydew earthquake was the concentration of structural damage, landslides, gravity slumping, rockfalls, and sandblows in a narrow zone 6 miles (10 km) east of the epicenter (Photo 6). Within this zone, tensional cracks formed along a narrow northwest trend, and were followed for approximately 4 miles (6 km). The first motions recorded by seismographs suggest that slip occurred at depth along a northwest-trending reverse fault, having either a northeast or southwest dip of 45 degrees (Oppenheimer and Magee, 1991). Since the area has southwest-dipping reverse faults (McLaughlin and others, 1988), the southwest dip is the more plausible.

The pattern of strong ground-motion effects can be explained in two ways. Both explanations involve reverse slip on a fault that does not reach the surface. The concentration of effects near Honeydew may be due to the focusing of strong

Photo 5. Displaced stream cobble in Honeydew Creek. The base of this cobble had been imbedded in the streambed before being displaced to the west.

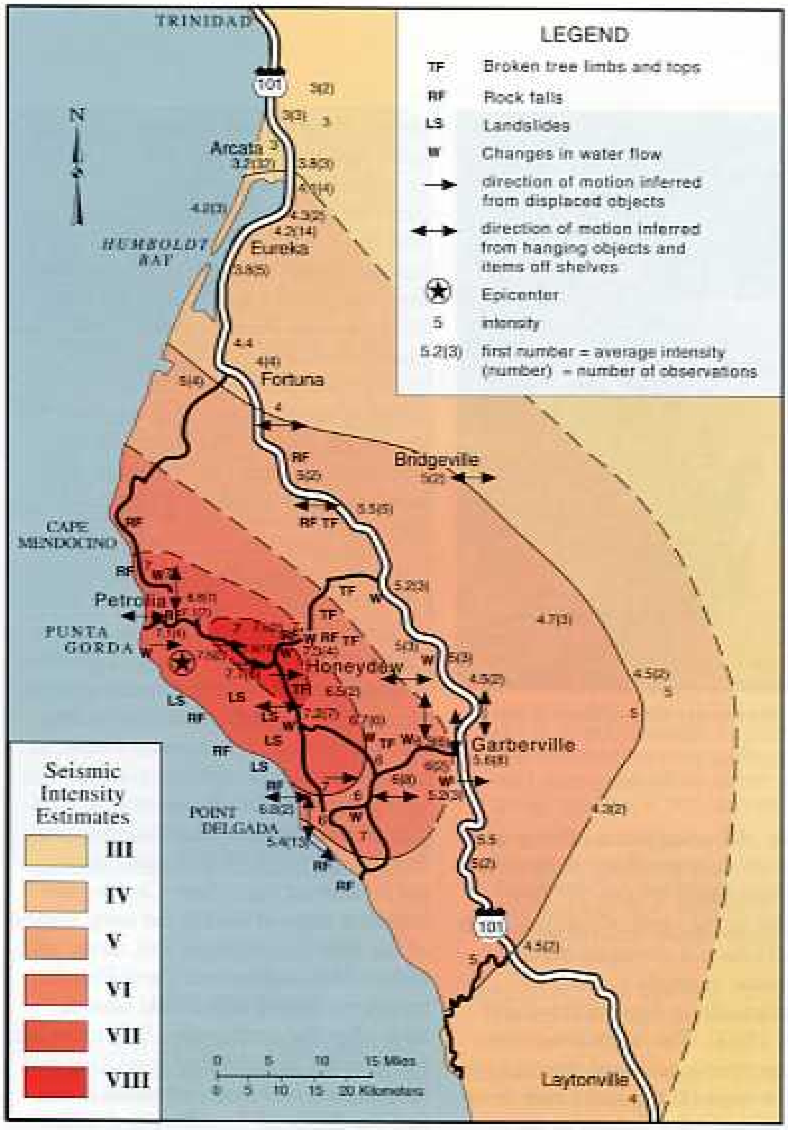

Figure 5. Isoseismal map of the August 17 earthquake.

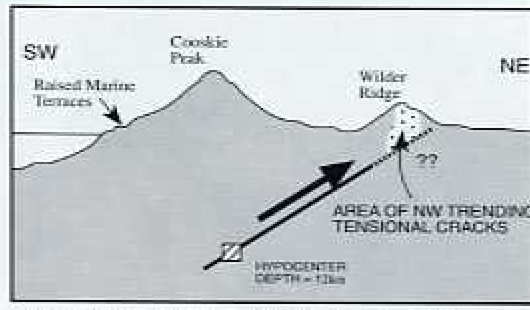

Figure 6. Simplified model of fault motion during the Honeydew earthquake. The shaded square shows the position of the hypocenter (about 7 miles [12 km] under Cooskie Peak). First-motion studies (Oppenheimer and Magee, 1991) and surface features suggest that the hanging wall of the fault moved up and to the east during the earthquake. The fault rupture stopped before reaching the surface. The mapped zone of oriented cracks near Honeydew may represent nose failure in the hanging wall.

motions in the up-dip region 6 miles (10 km) from the epicenter. These effects are similar to those of the Whittier Narrows earthquake which produced an isoseismal pattern resembling the one produced by the Honeydew earthquake (Hauksson and others, 1988). The focused shaking could have caused the tensional cracks along Wilder Ridge as the ridge spread laterally in response to strong ground-motion. (Numerous surface features produced by the 1989 Loma Prieta earthquake are thought to have formed in this manner [Hart and others, 1990; Ponti and Wells,

Photo 6. Sandblow in bed of Mattole River, near junction with Bundle Prairie Creek. Length of this blow is 3 feet (1 m).

Photo 7. Displaced concrete lid in vicinity of Honeydew. Lid has moved west relative to the tank.

1991].) This explanation, however, does not easily explain the narrowness of the zone of disruption, nor does it provide a mechanism for the cracks which crossed two ridges and two stream channels in the vicinity of Bear Trap Creek.

A more plausible scenario is that as the slip propagated up-dip, it caused the block of land containing Cooskie Peak to suddenly move up and to the east, motion consistent with the region's uplift history. The nose of the hanging wall fails in a tensional manner producing the northwest-trending tensional cracks (Figure 6). In this model, the projection of the fault would intersect the surface east of the zone of cracks, just southeast of a mapped northwest-trending, southwest-dipping reverse fault (Figure 2). Tensional failure in the nose of hanging walls of reverse faults is a common occurrence; a classic example is the 1980 El Asnan earthquake in Algeria (King and Vita-Finzi, 1981). This mechanism also explains the strong eastward-directed jolt that was felt near Honeydew Creek (and displaced many heavy objects to the west), and offers an explanation for crack formation in valleys as well as ridges.

Whether the observed effects were due to focusing, nose failure, or a combination, the Honeydew earthquake suggests that the triple junction is a source of potentially damaging earthquakes (see Dengler and others, this issue). The recurrence intervals and greatest magnitude for this type of earthquake are unknown. It seems unlikely that the Holocene terraces in the Cape Mendocino area (LaJoie and others, 1982) could have been formed by magnitude 6 earthquakes. This suggests that the region could suffer larger events with greater impact on the more populated Eel River Valley and Humboldt Bay areas.

GLOSSARY

Fission tracks: The paths of radiation damage made by nuclear particles in a mineral or glass by the spontaneous fission of uranium-238 impurities. Fission tracks have been used to determine ages from 20 years to 1.4×10^9 years.

Sandblow: A sand deposit left by the ejection of sand and water during vibration-induced compaction of saturated sediments.

Magnitude: The measure of the strength of an earthquake, or the strain energy released by it, usually expressed by the Richter magnitude scale. Each whole number step of magnitude on the scale represents a ten-fold increase in the size of the waves on a seismogram and about a 31-fold increase in energy release. Magnitudes determined within about 400 miles (600 km) of an epicenter are local magnitudes. Surface-wave and body-wave magnitudes are measured from seismograms recorded farther away. Energy magnitudes are determined from fault dimensions, displacement, and rigidity. These four magnitudes are usually similar for the same event.

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Robert McPherson was the chief seismologist for the Humboldt Bay Seismic Network, a 16-station array operated by TERA Corporation as part of a seismic safety study for the Humboldt Nuclear Power Plant. He currently lectures at Humboldt State University, Arcata and works as an independent consultant.

Lori Dengler is a geology professor at Humboldt State University, Arcata. For 7 years she has been researching historic seismicity of California's north coast area. She has worked with emergency planning personnel and educators in community and State earthquake awareness and preparedness programs and now directs a regional center for CALEEP (California Earthquake Education Project). Application of geophysical techniques to the study of near-surface processes is an ongoing research interest.

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