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The California Earthquake Advisory Plan: A History

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ABSTRACT

Since 1985, the California Office of Emergency Services (Cal OES) has issued advisory statements to local jurisdictions and the public following seismic activity that scientists on the California Earthquake Prediction Evaluation Council view as indicating elevated probability of a larger earthquake in the same area during the next several days. These advisory statements are motivated by statistical studies showing that about 5% of moderate earthquakes in California are followed by larger events within a 10-km five-day space–time window (Jones, 1985; Agnew and Jones, 1991; Reasenberg and Jones, 1994). Cal OES issued four earthquake advisories from 1985 to 1989. In October 1990, the California Earthquake Advisory Plan formalized this practice, and six Cal OES Advisories have been issued since then. This article describes that protocol's scientific basis and evolution.

Electronic Supplement: Table listing earthquakes of magnitude ∼5 and larger in and near California between 1 January 1985 and 31 December 2015.

INTRODUCTION

California faces enormous hazard from the strong earthquakes that will inevitably strike its population centers. Such events have low daily probabilities and remain unpredictable, all but precluding advance warning. Yet statistical studies since 1985 have shown that a moderate earthquake in California has about a 5% chance of being followed by a larger event occurring nearby within several days (Jones, 1985; Agnew and Jones, 1991; Reasenberg and Jones, 1994). Emergency managers can exploit this brief period of elevated hazard to take advance actions that enhance preparedness, and to craft public announcements that could lessen the impact of a major seismic event (Jordan *et al.*, 2014; Goltz, 2015).

Temporary earthquake probability gains following potential foreshocks have also been demonstrated statistically in Nevada (Savage and dePolo, 1993), Japan (Maeda, 1996), and, for large earthquakes, worldwide (Reasenberg, 1999). Only California, however, has a protocol for using these findings to promote public safety. The purpose of such protocols became clear in 2009, when three months of vigorous seismicity near L'Aquila, Italy, culminated in an **M** 5.9 earthquake on 6 April that killed 297 people (Jordan, 2013). Although seismologists on a government-appointed commission knew that the elevated seismicity indicated a larger earthquake was temporarily more likely, nonscientist officials had announced publicly on March 31 that the seismic activity posed no danger (Jordan, 2013). Seismologists were accused of criminal negligence and manslaughter for providing incomplete, imprecise, and contradictory information (Hall, 2011) that led residents to remain in seismically vulnerable buildings.

Almost 25 years before the L'Aquila earthquake, the state of California had implemented protocols that enable emergency managers to take advance actions when a potential foreshock to a damaging earthquake occurs. This protocol, formalized as the California Earthquake Advisory Plan, continues to be used today but seems little known among earthquake scientists. The history presented below draws on records maintained by the California Geological Survey, California Office of Emergency Services (Cal OES), and the personal files of one of us (J. G.) who served as Executive Secretary of the California Earthquake Prediction Evaluation Council (CEPEC) from 1986 to 1993 and as Cal OES *ex-officio* representative to CEPEC from 2007 to 2011. We hope this account of California's approach to advising the public of temporarily heightened earthquake probability can inform future efforts to utilize earthquake science for public safety.

SCIENTIFIC BASIS AND INCEPTION OF THE ADVISORY PLAN

In the 1970s, optimism about earthquake prediction capability led to concerns of detrimental societal responses to such predictions (Geschwind, 2001). Following public responses to several earthquake forecasts, officials at Cal OES and at California Division of Mines and Geology (CDMG; now California Geological Survey) sought expert earthquake-science advice. In particular, Cal OES, responsible for advising the California Governor whether conditions warrant proclaiming a State of Emergency, wanted rapid access to experts who could judge

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whether smaller earthquakes on faults that had generated damaging events in the past might be foreshocks.

The California Earthquake Prediction Evaluation Council (CEPEC)

Cal OES established CEPEC as an informal advisory committee in 1974, chaired by California State Geologist James E. Slosson. Although its name implies that CEPEC reviews only predictions, the council also reviews research or data that suggest an increase in seismic or volcanic potential affecting California. Currently, California remains the only state with a formal body of this type. (The National Earthquake Prediction Evaluation Council [NEPEC] is a Federal Advisory Committee that advises the Director of the U.S. Geological Survey [USGS] on similar matters outside California, but NEPEC has rarely met in urgent sessions to evaluate potential foreshocks.)

By 1976, CEPEC had evolved into a formally appointed body of nine scientists with expertise in geology, volcanology, seismology, and geophysics (CEPEC, 1977). The California State Geologist, as Chair of CEPEC, interfaces between these scientists and the California state emergency management agency, screening information that may have public policy implications. CEPEC members are recommended by the Director of Cal OES, in consultation with the State Geologist, and appointed to four-year terms by the Governor. CEPEC always invites an executive-level representative from Cal OES to monitor CEPEC meetings for policy issues, including closed rapid assessment scientific discussions, but some meetings have taken place without such a representative present.

The first prediction that CEPEC evaluated was in 1976, when seismologist James Whitcomb hypothesized that anomalous seismic velocity changes near Palmdale, California, might be precursors to an **M** 5.5–6.5 earthquake within the next year. Chaired by Acting California State Geologist Thomas E. Gay, CEPEC did not endorse this prediction, but judged the data sufficiently suggestive to warrant further scientific investigation (Ingram, 1983; Geschwind, 2001). Prior to CEPEC's evaluation, OES Director Charles Manfred had already written local governments and state agencies urging them to review and update their emergency plans (CEPEC, 1976), and OES took no further action.

The California State Geologist, with approval from the Director of the California state agency responsible for emergency management, has authority to convene CEPEC for a rapid assessment conference call when increased earthquake activity in or near California raises the probability of a larger earthquake that could affect population centers in California. As of 2015, the criteria for convening CEPEC are met by earthquakes larger than **M** 5, or for three or more closely-spaced closely-timed events larger than **M** 3.5 (J. Parrish, written comm., 2015). The State Geologist will also consider convening CEPEC in rapid-assessment mode if recognized earthquake experts so urge, even if these criteria are not met. There is no automatic mechanism to trigger a CEPEC teleconference. From 1986 through 2016, CEPEC has convened for 17 rapid assessments.

CEPEC's rapid assessment conference calls are confidential, as is the written summary statement that CEPEC sends to Cal OES, recommending whether to issue an Advisory. Therefore, we cannot describe the scientific arguments on which individual CEPEC recommendations were based. The Director of Cal OES has discretion as to whether to act upon CEPEC's recommendation, and is responsible for transmitting Advisories to local jurisdictions.

CEPEC members are immune from legal liability in their deliberations regarding specific earthquake predictions or assessments of related research. At the time of this writing, CEPEC has never invoked this immunity.

Foreshock Probability Research

USGS seismologist Lucy Jones (1985) first established the statistical foundation for earthquake advisory statements in California. Based on an analysis of all southern California earthquakes with $\mathbf{M} \geq 3$ between 1932 and July 1983 (4811 events), Jones (1985) estimated the probability that an $\mathbf{M} \geq 3$ earthquake in southern California will be followed by a larger magnitude event within 5 days and 10 km to be ~6%. Further, Jones showed that the probability that an earthquake would be followed by an $\mathbf{M} \geq 5$ mainshock increases with the magnitude of the foreshock from less than 1% at **M** 3 to 6.5% for $\mathbf{M} \geq 5$. The probability of a larger follow-on earthquake is the highest immediately after the candidate foreshock, with a significant percentage of the increased probability concentrated in the first 30 min.

Another way to view the Jones (1985) result is that during the five-day 10-km time–space window, the most probable outcome is that no larger shock will occur: 94% of advisory statements based on these statistics would be false alarms. Despite these odds, California state officials decided that advisories motivated by potential foreshocks were still worthwhile. From an emergency management viewpoint, even the low probability of a significant earthquake is actionable if the potential consequences include damage and casualties. Preparedness and mitigation actions need not be extreme, and can be scaled to a low probability of occurrence, as discussed below and described by Reitherman (1986) and Goltz (2015).

No reliable identifying characteristics of foreshocks are known in advance of the mainshock; Cal OES relies on CEPEC's judgment in deciding whether to issue an Advisory. Table 1 includes all of the earthquakes and earthquake swarms for which CEPEC has been convened for rapid assessment. Figure 1 is a map of earthquakes $\mathbf{M} > 5$ that have affected California since 1 January 1985, indicating which were assessed by CEPEC; these events are also listed in Ⓔ Table S1, available in the electronic supplement to this article. We selected the case histories described here to illustrate the advisory protocol's use and evolution since 1985.

PREPLAN ADVISORIES 1985–1990

California's first four earthquake advisories, which predated the formal Advisory Plan, revealed the difficulties of coordinating

Table 1
Earthquakes and Earthquake Sequences That Have Prompted Review by the California Earthquake Prediction Evaluation Council (CEPEC), or That Are Described in the Text for Other Reasons

Date and Time (yyyy/mm/dd hh:mm:ss.ss)	Latitude Longitude (°)	Depth (km)	Magnitude	Location	Action
1985/06/18 00:12:55.23 UTC 1985/06/17 05:12 p.m. PDT	32.691 −117.15	5.34	M_L 3.7	San Diego	Advisory 1
1985/06/18 03:22:28.67 UTC 1985/06/17 08:22 p.m. PDT	32.679 −117.151	5.06	M_L 3.9	San Diego	
1985/06/18 04:28:15.28 UTC 1985/06/17 09:28 p.m. PDT	32.684 −117.152	5.34	M_L 3.7	San Diego	
1986/07/08 09:20:44.56 UTC 1986/07/08 02:20 a.m. PDT	33.999 −116.608	9.47	M_L 5.6	North Palm Springs	CEPEC review, no advisory recommended
1986/07/20 14:29:45.44 UTC 1986/07/20 07:29 a.m. PDT	37.5667 −118.4382	5.04	M_L 5.9	Chalfant Valley foreshock	
1986/07/21 14:42:26.00 UTC 1986/07/21 07:42 a.m. PDT	37.538 −118.4428	8.8	M_L 6.4	Chalfant Valley	Advisory 2
1987/10/01 14:42:20.02 UTC 1987/10/01 07:42 a.m. PDT	34.061 −118.079	8.88	M_w 5.9	Whittier Narrows	CEPEC review, no advisory recommended
1987/10/04 10:59:38.19 UTC 1987/10/04 03:59 a.m. PDT	34.074 −118.098	7.72	M_L 5.3	Whittier Narrows aftershock	
1987/11/24 01:54:14.66 UTC 1987/11/23 05:54 p.m. PST	33.09 −115.792	10.85	M_w 6.2	Elmore Ranch	
1987/11/24 13:15:56.71 UTC 1987/11/24 05:15 a.m. PST	33.015 −115.852	11.18	M_w 6.6	Superstition Hills	CEPEC review, no advisory recommended
1988/06/10 23:06:43.05 UTC 1988/06/10 04:06 p.m. PDT	34.943 −118.743	5.9	M_L 5.4	Tejon Ranch	CEPEC review, no advisory recommended
1988/06/27 18:43:22.33 UTC 1988/06/27 11:43 a.m. PDT	37.1283 −121.895	12.63	M_L 5.3	Lake Elsman	Advisory 3
1989/08/08 08:13:27.39 UTC 1989/08/08 01:13 a.m. PDT	37.1482 −121.9268	13.41	M_L 5.4	Lake Elsman	Advisory 4
1989/10/18 00:04:15.19 UTC 1989/10/17 05:04 p.m. PDT	37.0362 −121.8798	17.21	M_L 7.0	Loma Prieta	
1992/04/23 04:50:23.23 UTC 1992/04/22 09:50 p.m. PDT	33.96 −116.317	11.63	M_w 6.1	Joshua Tree	Advisory 5
1992/04/25 18:06:05.18 UTC 1992/04/25 11:06 a.m. PDT	40.3353 −124.2287	9.86	M_w 6.7	Cape Mendocino	
1992/04/26 07:41:40.09 UTC 1992/04/26 00:41 a.m. PDT	40.4325 −124.566	18.82	M_w 6.5	Cape Mendocino aftershock	
1992/04/26 11:18:25.98 UTC 1992/04/26 04:18 a.m. PDT	40.3828 −124.555	21.71	M_w 6.6	Cape Mendocino aftershock	CEPEC review; nonadvisory statement
1992/06/28 11:57:34.12 UTC 1992/06/28 04:57 a.m. PDT	34.201 −116.436	1.1	M_w 7.3*	Landers	Advisory 6
1992/06/28 15:05:30.73 UTC 1992/06/28 08:05 a.m. PDT	34.203 −116.827	3.63	M_w 6.3	Big Bear	
1994/01/17 12:30:55.39 UTC 1994/01/17 04:30 a.m. PST	34.213 −118.537	18.2	M_w 6.7	Northridge	
1998/08/12 14:10:25.14 UTC 1998/08/12 07:10 a.m. PDT	36.7545 −121.4615	8.82	M_w 5.1	Near San Juan Bautista	First aftershock forecast; U.S. Geology Survey-Caltech statement

(Continued next page.)

Table 1 (continued)
Earthquakes and Earthquake Sequences That Have Prompted Review by the California Earthquake Prediction Evaluation Council (CEPEC), or That Are Described in the Text for Other Reasons

Date and Time (yyyy/mm/dd hh:mm:ss.ss)	Latitude Longitude (°)	Depth (km)	Magnitude	Location	Action
2001/11/13 20:43:14.95 UTC 2001/11/13 12:43 p.m. PST	33.3172 −115.7002	5.55	M_L 4.1	Bombay Beach swarm	Advisory 7
2003/12/22 19:15:56.24 UTC 2003/12/22 11:15 a.m. PST	35.7005 −121.1005	8.38	M_w 6.5	San Simeon	CEPEC review of **M** 8 prediction
2004/09/28 17:15:24.25 UTC 2004/09/28 10:15 a.m. PDT	35.8182 −120.366	8.14	M_w 6.0	Parkfield	
2007/10/31 03:04:54.81 UTC 2007/10/30 08:04 p.m. PDT	37.4335 −121.7743	9.74	M_w 5.5	Alum Rock	Advisory 8
2009/03/24 11:55:43.93 UTC 2009/03/24 04:55 a.m. PDT	33.3172 −115.7282	5.96	M_L 4.8	Bombay Beach swarm	CEPEC recommends advisory, but not issued
2009/03/25 07:51:23.01 UTC 2009/03/25 00:51 a.m. PDT	33.2900 −115.7213	4.40	M_L 3.6	Bombay Beach swarm	
2009/03/25 19:59:44.10 UTC 2009/03/25 12:59 a.m. PDT	33.2920 −115.7197	6.50	M_L 3.7	Bombay Beach swarm	
2009/03/26 03:25:21.98 UTC 2009/03/25 08:25 p.m. PDT	33.2930 −115.7215	7.38	M_L 4.0	Bombay Beach swarm	
2009/04/08 22:04: 2.36 UTC 2009/04/08 03:04 p.m. PDT	33.3180 −115.7227	4.11	M_L 3.5	Bombay Beach swarm	
2010/06/15 04:26:58.24 UTC 2010/06/14 09:26 p.m. PDT	32.705 −115.9113	8.99	M_w 5.7	El Mayor Cucapah aftershock	Advisory 9
2012/08/26 19:31:23.04 UTC 2012/08/26 12:31 a.m. PDT	33.0172 −115.5537	8.26	M_w 5.3	Brawley	CEPEC review
2012/08/26 20:57:58.22 UTC 2012/08/26 01:57 p.m. PDT	33.0185 −115.5403	8.22	M_w 5.4	Brawley	No advisory recommended
2014/08/24 10:20:44.06 UTC 2014/08/24 03:20 a.m. PDT	38.2155 −122.3117	11.21	M_w 6.0	South Napa	CEPEC review; statement
2016/09/26 14:31:08.8 UTC 2016/09/26 7:31 a.m. PDT	33.2976 −115.7137	2.2	M_w 4.3	Bombay Beach swarm†	Advisory 10
2016/09/27 03:23:58.58 UTC 2016/09/26 8:23 p.m. PDT	33.2998 −115.7123	4.84	M_w 4.3		
2016/09/27 03:36:15.15 UTC 2016/09/26 8:36 p.m. PDT	33.3058 −115.7010	2.52	M_w 4.1		
2016/09/27 03:46:30.30 UTC 2016/09/26 8:46 p.m. PDT	33.3080 −115.6973	3.1	M_w 3.5		
2016/09/28 01:05:51.51 UTC 2016/09/27 6:05 p.m. PDT	33.2987 −115.7118	7.03	M_w 3.6		
2016/09/28 01:13:04.4 UTC 2016/09/27 6:13 p.m. PDT	33.2988 −115.7053	6.85	M_w 3.5		

Information is from the Advanced National Seismic System (ANSS) catalog (NCEDC, 2014) except as noted. Magnitudes are not necessarily the same as the magnitudes upon which advisory-related decisions were based. PDT, Pacific Daylight Time; PST, Pacific Standard Time.
*see Data and Resources.
†ANSS Comprehensive Earthquake Catalog (ComCat); search performed 20 December 2016.

scientific assessments with emergency management actions. During this period, CEPEC was chaired by James F. Davis, who served as California State Geologist from 1978 to 2003.

Advisory 1: 17 June 1985 San Diego Bay Sequence

San Diego, California, residents felt three earthquakes on the evening of 17 June 1985 (M_L 3.7 at 5:12 p.m. Pacific Daylight Time [PDT], M_L 3.9 at 8:22 p.m. PDT, and M_L 3.7 at 9:28 p.m. PDT). This swarm and an M_L 3.3 earthquake on 21 June 1985 are ascribed to the Rose Canyon fault zone, which passes beneath the city of San Diego (Grant and Shearer, 2004).

An **M** 7 earthquake on the Rose Canyon fault was one of seven scenario earthquakes for which probable effects on population centers had been evaluated by the USGS in 1981 (USGS, 1981). That report assigned an earthquake of this magnitude a very low probability of occurring before 2001 (0. 01% chance per year). Nevertheless, USGS scientists were concerned that a larger earthquake (**M** ≥ 5), endangering San Diego, might follow the 17 June 1985 events (Goltz, 1985). The evening of 17 June 1985, the USGS communicated an advisory to Cal OES, labeled "For Internal Use Only: Not for Release to Press or Public." The account below is condensed from Goltz (1985).

As a state agency, Cal OES had no plan for responding to this unprecedented message from the federal USGS, and San Diego County officials only learned of the advisory informally upon contacting Cal OES for information about the earthquakes. After several conference calls, San Diego County Office of Disaster Preparedness (ODP) was given responsibility for deciding how to proceed.

San Diego County officials weighed several factors. The USGS request that the information not be released and the reluctance of Cal OES to issue a warning exposed the County to possible legal liability if it issued a warning that led to adverse outcomes. Public information needed to be crafted carefully to avoid overreaction. After consultation with Cal OES, San Diego County ODP issued an earthquake potential advisory at 5 p.m. Pacific Standard Time (PST) on 18 June 1985, 24 hr after the swarm began: "According to the United States Geological Survey, there is a slight increase in the probability of a potentially damaging earthquake in San Diego. This statement is based on historical data on the type of earthquake swarms we had yesterday. One in twenty of these swarms has been followed by a damaging earthquake of Richter magnitude 5.0 or greater within a five day period."

Numerous phone calls to San Diego County ODP soon revealed that the public equated the earthquake potential advisory to an earthquake prediction. Rumors arose that the probability of a larger earthquake was 20%, that the expected earthquake would be **M** 8.3 or larger, and that the beaches and city were being evacuated. San Diego County ODP responded with press releases requesting the populace to check back with them to verify information. Further confusion developed on 20 June 1985, when newspapers, citing a Caltech seismologist, reported that the advisory had been downgraded, although San Diego County ODP had reaffirmed that the advisory remained in effect.

After conferring with the USGS, San Diego County issued a public statement at 5 p.m. PDT on 21 June 1985 stating that, barring increased seismic activity, the advisory would be cancelled at midnight PDT on 22 June 1985. There were no damaging follow-on earthquakes in the immediate San Diego area.

The San Diego advisory abruptly exposed the challenges of issuing a public earthquake warning: appropriately phrasing the warning, providing sufficient public information, dealing with rumors, and updating and cancelling the warning. Lacking previously developed procedures, scientists and public officials had to devise a plan for evaluating and communicating seismic observations and crafting an appropriate alert during the hours when a larger earthquake was most likely to follow the 17 June seismicity.

CEPEC Deliberations on How to Respond to Potential Foreshock Activity

Possibly prompted by the 1985 San Diego advisory, CEPEC formed a committee to advise OES on feasibility of preplanned seismic response policies, chaired by Karen McNally of the University of California at Santa Cruz. Reporting back in November 1986, the committee recommended collecting research papers on faults with seismic gaps, and maintaining a database of knowledgeable researchers who could be reached on short notice by CEPEC.

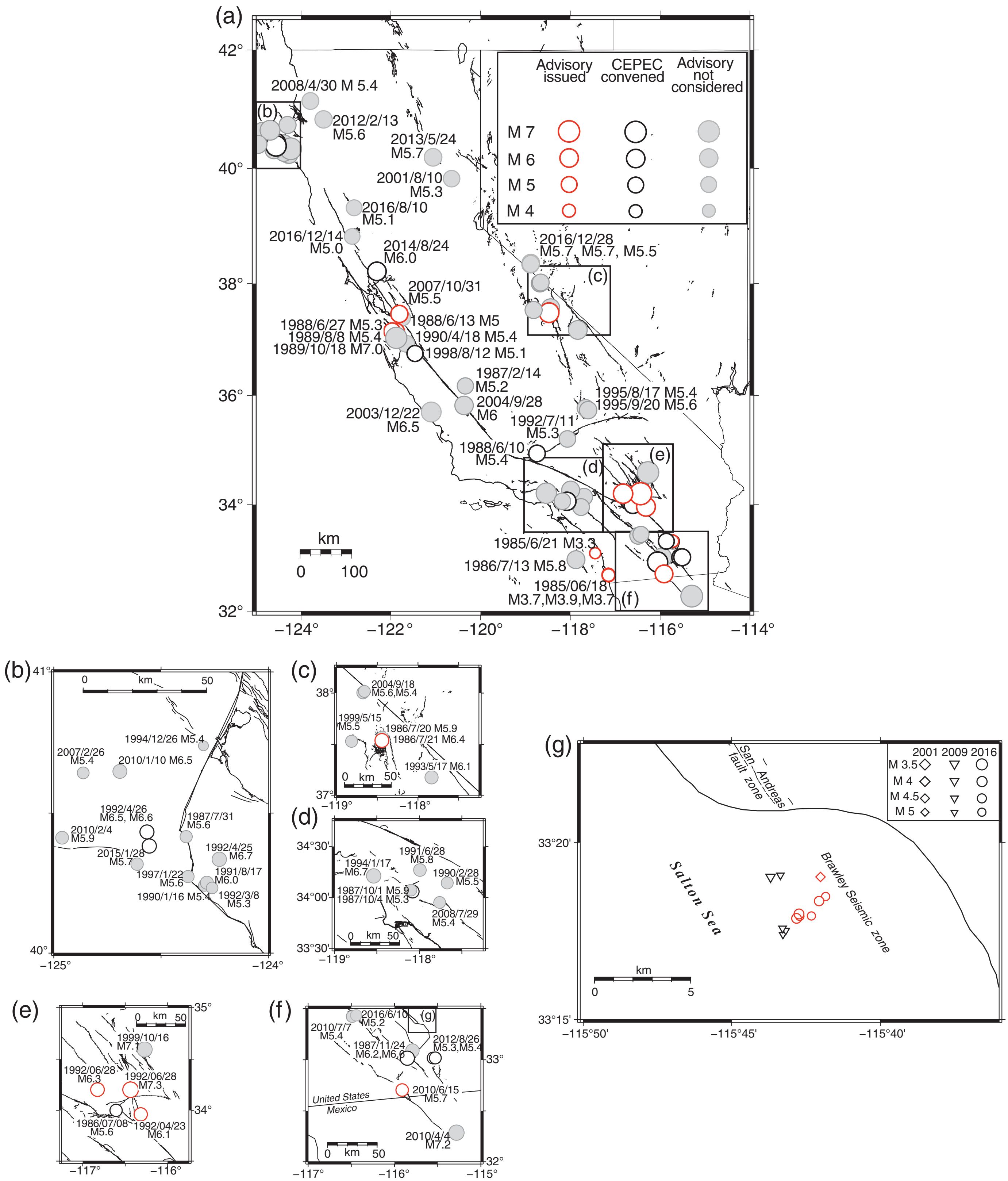
Accompanying the minutes to a December 1987, CEPEC meeting was a handwritten document by Karen McNally, reviewing foreshock activity prior to 11 earthquakes of **M** ≥ 7 in California, beginning with the 1857 M_w 7.9 Fort Tejon earthquake, and concluding: "It would be prudent for OES to be on alert for ∼72 hours following moderate earthquakes **M** ≥ 5.5 within 30-50 km of the ends of known seismic gaps. Local emergency officials might be notified. (Public announcement not necessarily needed.) **M** ≥ 5.0-5.4 might also warrant alert in these locations - if there aren't too many false alarms for OES practicality. The case histories are too few (for **M** ≥ 7 earthquakes) to use a purely statistical approach. The above advice is based on a cautionary premise."

The 1987 McNally document recommends an alert period and magnitude threshold similar to those of Jones (1985). McNally was presumably aware of the Jones (1985) paper, for which the dataset included fewer than 10 **M** ≥ 7 earthquakes after 1932.

Four Nonadvisory Earthquakes 1986–1988

Between 1986 and 1988, CEPEC evaluated four southern California earthquake sequences and decided against recommending advisories.

The first two—the 8 July 1986 M_L 5.6 North Palm Springs earthquake (Jones *et al.*, 1986) and the 1 October 1987 M_w 5.9 Whittier Narrows earthquake (Hauksson and Jones, 1989)—were themselves damaging, but in locations not believed capable of generating much larger earthquakes. No larger events followed. However, an M_w 5.3 aftershock three



▲ **Figure 1.** Map showing epicenters of earthquakes **M** 5 or greater in and near California from 1 January 1985 through 31 December 2016. Information is from the Advanced National Seismic System (ANSS) catalog (Northern California Earthquake Data Center [NCEDC], 2014) except as noted in the footnotes to Table 1 and Ⓔ Table S1 (available in the electronic supplement to this article): (a) California and surrounding regions; (b) Cape Mendocino; (c) Chalfant Valley; (d) Greater Los Angeles; (e) eastern California shear zone; (f) southernmost California; and (g) Salton Sea, events with magnitude greater than 3.5.

days after the Whittier Narrows earthquake caused additional damage, injuries, and one fatality (Stover and Coffman, 1993).

In the third of these sequences, the M_w 6.2 Elmore Ranch earthquake at 5:54 p.m. PST on 23 November 1987 was followed 11.4 hr later by the M_w 6.6 Superstition Hills earthquake, 9 km to the southwest (Wald *et al.*, 1990). Had CEPEC been convened before the second of these two events, their ability to identify a potential foreshock would have been tested. As it happened, CEPEC met after the mainshock, and their judgment that no larger earthquake would follow proved correct. Their decision may have been based on an absence of known faults in that area extensive enough to host a larger earthquake.

The fourth of these earthquakes was the M_L 5.4 Tejon Ranch earthquake on 10 June 1988, only a few kilometers from the Mojave segment of the San Andreas fault, which ruptured in the great 1857 M_w 7.9 earthquake. This fault segment was considered unlikely to re-rupture after only 131 years of quiescence—an assumption since revisited, for example, by Scharer *et al.* (2010). Though one may wonder whether CEPEC would have decided differently in light of later research, their 1988 judgment was correct: no larger earthquake occurred.

Advisory 2: 21 July 1986 Chalfant Valley Earthquake Sequence

This vigorous earthquake sequence began with an M_L 5.9 foreshock on 20 July 1986, 24.2 hr prior to the M_L 6.4 mainshock (Savage and Cockerham, 1987). CEPEC convened on 21 July 1986, after this mainshock, and recommended that an earthquake advisory be issued. This advisory, dated 22 July 1986, was a letter to William M. Medigovich, Director of Cal OES, from Dallas L. Peck, Director of the USGS, stating: "It is our assessment that the region of Chalfant Valley, from Bishop north to the Nevada border, may experience additional earthquakes similar to the July 21 event during the next few days." The letter described likely damaging effects of such an earthquake, and stated that an update would follow on 24 July 1986. No additional earthquakes $\mathbf{M} \geq 6$ occurred.

Some alarmed speculation and rumors arose in the town of Bishop, California, prompted by the letter's statement that the Chalfant Valley had been recognized to have the potential for generating a magnitude-7 event (Ramos and Reich, 1986). The public may also have been reacting to Cal OES placing two Army National Guard helicopters, a medical evacuation helicopter, a communications van, and a fuel tanker on standby in Bishop.

Bishop residents in 1986 reacted much like those in San Diego in 1985 in seeing the advisory as a prediction, with ensuing rumors of a much higher probability of a larger ($\mathbf{M} \sim 7$) earthquake than scientists had actually warned of. And again, CEPEC's recommendation had come after the mainshock, missing a 24.2-hr window between the M_L 5.9 foreshock and the M_L 6.4 mainshock, during which an advisory, if issued, would have been fulfilled.

Advisories 3 and 4: The 1988 and 1989 Lake Elsman (Lexington Reservoir) Earthquakes

Scientific consensus is that the 1988 and 1989 Lake Elsman earthquakes in Santa Clara County, California, were foreshocks of the damaging 18 October 1989 M_L 7.0 Loma Prieta earthquake (Sykes and Jaumé, 1990; Perfettini *et al.*, 1999). Harris (1998a,b) provides thorough accounts of the advisories prompted by these two events.

The first Lake Elsman earthquake (M_L 5.3) occurred during the morning of 27 June 1988 (Olson, 1990). That afternoon, USGS seismologist Alan Lindh informed California State Geologist Jim Davis that the earthquake was the largest since 1906 to have occurred at the northern end of the southern Santa Cruz Mountains segment of the San Andreas fault. Noting that the Working Group on California Earthquake Probabilities (WGCEP, 1988) had assigned this segment a 30% probability of an **M** 6.5–7 earthquake in the 30-year period from 1988 to 2018, USGS seismologist Lindh told California State Geologist Davis that this M_L 5.3 event could be a foreshock to an **M** 6–6.5 earthquake.

CEPEC convened, concluded that the probability of a larger earthquake on this segment of the San Andreas fault was temporarily elevated, and recommended that Cal OES send an earthquake advisory to local governments, but not announce this to the public via a news release (for details, see appendix 2 of Harris, 1998a). The following day, however, California state officials did issue a news release.

The earthquake advisory was for five days, consistent with the time window used by Jones (1985) for southern California foreshocks, although no northern California earthquakes had been part of the Jones (1985) foreshock study. The aftershock sequence of the M_L 5.3 Lake Elsman earthquake was not very vigorous, and the advisory expired on 2 July 1988.

The second Lake Elsman earthquake (M_L 5.4) occurred on 8 August 1989 (Olson, 1990), within 10 km of the 27 June 1988 M_L 5.3 earthquake, prompting Cal OES to issue another CEPEC-recommended five-day advisory. No unusual activity followed in those five days, so this advisory also expired.

The next notable seismic activity in the area was the Loma Prieta mainshock itself (M_L 7.0) on 18 October 1989 (Olson, 1990). It ruptured a 35-km-long patch on a steeply dipping fault subparallel to and just southwest of the San Andreas fault, extending northward to within 15 km of the Lake Elsman epicenters. The two Lake Elsman earthquakes, 16 months and 2.5 months prior to the mainshock, were retrospectively recognized as foreshocks.

FURTHER STATISTICAL STUDIES OF EARTHQUAKE SEQUENCES

Reasenberg and Jones (1989) presented a method to estimate probabilities of not only a larger follow-on earthquake but also of aftershocks. They introduced a conceptual framework in which foreshocks, mainshocks, and aftershocks are not intrinsically different, so that it is only a matter of chance whether or not the mainshock (the largest event) is the first earthquake in the sequence.

Next, Agnew and Jones (1991) analyzed foreshock probabilities for the entire San Andreas system, assigning higher probabilities of being a foreshock to events on or near faults where a mainshock is regarded as about due. (Time-dependent probabilities of specific California mainshocks had been developed by WGCEP, 1988.) Agnew and Jones (1991, p. 11,960) hypothesized that "the large characteristic earthquakes on a fault zone are not simply the largest members of the total population of earthquakes there, but are somehow derived from a different population. Foreshocks to such events can thus reasonably be regarded as also being a separate class of events from the background earthquakes." However, they acknowledged that foreshocks lack features distinguishing them from background events.

Agnew and Jones (1991) pointed out that fault segments known to have produced great earthquakes historically now have little background seismicity, and they argued that the probability that an event is a foreshock is higher when background activity is lower. Michael (2012) pointed out that this proposal implied earthquakes should be more capable of triggering other earthquakes in locations with lower background activity, but in southern California he found no evidence for that behavior.

DEVELOPMENT OF THE CALIFORNIA EARTHQUAKE ADVISORY PLAN

By 1990, California state emergency management officials and CEPEC scientists had learned to collaborate effectively, despite their distinct professional cultures. Scientists prefer to speak accurately and to withhold judgment when large uncertainties exist, whereas emergency managers, more concerned with not being blindsided, prefer uncertain information to no information at all. Earthquake scientists, who lack expertise in devising appropriate ways to manage preparedness and public information, may view a chaotic large-scale evacuation as the only possible response to an earthquake advisory (e.g., Wang and Rogers, 2014). In contrast, emergency managers are schooled in a broad spectrum of mitigation measures. For example, in the case of low-probability events, they may recommend only that their own agencies prepare internally, facilitating a possible event response without elevating public concern (for a list of potential actions, see Reitherman, 1986). The California Earthquake Advisory Plan was therefore based on a principle that has now been articulated in the post-L'Aquila earthquake report by the International Commission on Earthquake Forecasting for Civil Protection (2011): that of "transmitting scientific information about future earthquake occurrence to decision-makers in a way that appropriately separates hazard estimation by scientists from the public protection role of civil authorities."

In October 1990, the formal Advisory Plan was published (State of California, Governor's Office of Emergency Services, 1990b), both as an appendix to the California Short-Term Earthquake Prediction Response Plan (State of California, Governor's Office of Emergency Services, 1990a) and as a stand-alone document, developed by emergency management consultants Terrence Haney and James Powers. The Short-Term Earthquake Prediction Response Plan recommends graduated response procedures tied to potential impacts and probabilities of occurrence should a scientific earthquake prediction be validated by CEPEC. The Advisory Plan addresses anomalous seismic activity (e.g., an $\mathbf{M} \geq 5$ earthquake on a fault known to have generated large damaging earthquakes in the past) that could be precursory within a short time span to a stronger potentially damaging event.

Earthquake Advisories are "statements by Cal OES regarding scientific assessments that, within a specified period [usually 3–5 days], there is an enhanced likelihood for damaging earthquakes to occur in areas designated in the Advisory" (State of California, Governor's Office of Emergency Services, 1990b, p. 3). The California Earthquake Advisory Plan, which recommends actions appropriate if the estimated probability within 72 hr of a damaging earthquake of $\mathbf{M} > 5$ does not exceed 25%, has been exercised frequently. Were circumstances to indicate that the probability of such an event were greater than 25%, it is likely that the more extensive actions prescribed in the Short-Term Prediction Response Plan would instead be implemented, but that has never happened.

In addition to formalizing the previously developed protocol for convening CEPEC to assess potential foreshocks, the Advisory Plan specifies procedures to be followed by Cal OES: sending checklists of actions to local jurisdictions in the affected region, notifying state and federal agencies with emergency response functions, and formulating a release to the media and public. The Advisory Plan includes standard message content for communicating the Advisory, and for continuing or cancelling the Advisory (with CEPEC's concurrence).

Also in 1990, the USGS was refining a separate protocol for assessing possible increases in mainshock probabilities on the southern San Andreas fault (Jones *et al.*, 1991; Jordan and Jones, 2010). This USGS "short-term earthquake hazard assessment" defines alert levels D, C, and B, corresponding to progressively larger magnitude potential foreshocks in this region, which are assigned higher probabilities of being followed by a mainshock than events of the same magnitude elsewhere in California. In keeping with the principle of separating the roles of scientists from those of emergency management officials, CEPEC reviewed a draft of this USGS geographically targeted plan in 1990, and requested revisions to "avoid any confusion regarding the distinction between actions taken at certain alert levels by the USGS of a scientific nature and those of the State of a public safety nature."

OPERATING UNDER THE ADVISORY PLAN 1990–2016

After October 1990, a procedure was in place whereby CEPEC would rapidly evaluate anomalous seismic activity, and Cal OES would carry out predefined actions upon accepting a CEPEC-recommended Advisory. Yet the Advisory Plan did not eliminate the need for CEPEC to evaluate, and Cal OES to respond to, situations that had not specifically been covered by published statistical analyses.

25 April 1992 M_w 6.7 Cape Mendocino Earthquake

The tectonically complex, seismically active Mendocino Triple Junction (MTJ) is the northern terminus of the San Andreas fault, where it meets the Cascadia subduction zone to the north and the Mendocino oceanic transform fault to the west (Bakun, 2000). The statistical analyses of Jones (1985) and Agnew and Jones (1991) did not include earthquakes from the MTJ that were not on the San Andreas fault system.

On 25 April 1992, the M_w 6.7 Cape Mendocino earthquake occurred at 11:06 a.m. PDT, reaching Mercalli intensity VIII and causing damage valued at \$48–\$66 million (Oppenheimer *et al.*, 1993). CEPEC did not convene, however, until two aftershocks of M_w 6.5 and 6.6, 13 and 17 hr later, respectively, had caused fires and additional damage (Oppenheimer *et al.*, 1993). CEPEC crafted a statement (not an Advisory) that Cal OES issued on 26 April 1992, warning that more strong aftershocks could hit the Humboldt County area. No further damaging events occurred after this warning.

Detailed analysis (Oppenheimer *et al.*, 1993) revealed that the 1992 Cape Mendocino earthquake was a thrust event on the Cascadia subduction interface. CEPEC's decision not to issue an Advisory for this earthquake predates consensus that Cascadia has potential to host an earthquake **M** 8 or larger (Atwater *et al.*, 1995).

Advisory 5: The 23 April 1992 M_w 6.1 Joshua Tree Earthquake and Advisory 6: The 28 June 1992 M_w 7.3 Landers and M_w 6.3 Big Bear Earthquakes

According to Jones (1994, p. 892), the Joshua Tree earthquake "had a probability of 21% of being a foreshock to a San Andreas mainshock within the next 3 days. On this basis, the state of California issued an advisory warning of the potential of a damaging earthquake on the San Andreas within 3 days." (p. 892). No such earthquake occurred, however, and the Advisory expired.

But two months later, at 04:57 a.m. PDT on 28 June 1992, the M_w 7.3 Landers earthquake ruptured a series of faults of the Eastern California shear zone, north-northeast of the Joshua Tree epicenter (Hauksson *et al.*, 1993). The Landers earthquake was preceded by a swarm of foreshocks over 7 hr, but the largest was of M_L 3.4 (Dodge *et al.*, 1995), too small to convene CEPEC. The Landers mainshock was followed after 3 hr by the M_w 6.3 Big Bear earthquake at 8:05 a.m. PDT, which, though unquestionably an aftershock, ruptured a separate fault 30 km west of the Landers rupture zone (Hauksson *et al.*, 1993).

CEPEC convened shortly after the Big Bear earthquake, and Cal OES issued an Advisory mid-morning of June 28. This Advisory made the unprecedented recommendation of "no unnecessary travel until further notice," due to road damage and landslides in the epicentral areas. The travel ban was reportedly unpopular and Cal OES rescinded it at 5 p.m. PDT the same day.

Concern rose considerably on 29 June, when an M_w 5.5 Landers aftershock occurred on the San Andreas fault zone near Indio at 9:01 a.m. PDT. That evening, CEPEC reviewed strain changes recorded at Piñon Flat Observatory (Wyatt *et al.*, 1994), considered stress changes imposed by the Landers and Big Bear events (Harris and Simpson, 1992; Stein *et al.*, 1992), and concluded that 193 km of the San Andreas fault between Cajon Pass and Bombay Beach could have been significantly destabilized. From Jones (1994, p. 893): "Concern about the possibility of a major San Andreas earthquake was so high that ... (CEPEC) recommended that the state of California prepare for an imminent earthquake alert if an $\mathbf{M} \geq 6$ earthquake were to occur 'on or near' the southern San Andreas fault."

On 1 July 1992, CEPEC and Cal OES adopted a temporary protocol informally called the go-to-war scenario (Jordan and Jones, 2010), whereby certain events such as an **M** 6.0 event within 3 km of the southern San Andreas fault would prompt Cal OES to implement plans for a 25% chance of a major earthquake. Although no Advisory was officially extended, Caltech and USGS scientists agreed to remain in a 24/7 heightened mode of monitoring.

At least one spate of rumors arose during the aftershock sequence: when the USGS announced that it was upgrading the Landers earthquake from **M** 7.3 to 7.5, some people believed scientists and officials were concealing the full extent of the hazard (Reich, 1992).

The go-to-war scenario officially ended in February 1997, when CEPEC members' consensus was that the probability of a large earthquake on the southern San Andreas fault had returned to pre-1992-Landers–Big Bear sequence levels (Minutes, 28 February 1997 CEPEC meeting). At the time of this writing, the feared southern San Andreas event has not occurred.

The decision to enact the go-to-war scenario was not based on rigorous statistics: the Landers aftershocks had increased the background seismicity rate, violating an assumption of the Agnew and Jones (1991) analysis. Jones (1994) extended that methodology, arguing that the elevated background activity lowered the probability that an **M** 6 aftershock would be a foreshock. However, she also noted that the Landers sequence imposed static stress changes that presumably brought the southern San Andreas fault closer to failure, a principle that is currently being evaluated for use in forecasting the evolution of earthquake sequences (e.g., Segou *et al.*, 2013; Nic Bhloscaidh *et al.*, 2014).

It became apparent retrospectively that the Joshua Tree earthquake had been a Landers foreshock: although the two earthquakes' epicenters were 35 km apart, seismic swarms had occurred between the Joshua Tree epicenter and the southern end of the future Landers rupture in the nine weeks between those events (Hauksson *et al.*, 1993). Because the Joshua Tree–Landers–Big Bear sequence occurred off the San Andreas system, where no authoritative probability estimates existed, its implications for the probability of a major earthquake could be assessed only qualitatively. Nevertheless, CEPEC exercised its judgment by recommending a heightened state of alert, which Cal OES accepted and followed.

The 1994 Northridge Earthquake: No Foreshocks

The devastating 17 January 1994 M_w 6.7 Northridge earthquake, on a subsurface thrust fault, had no foreshocks within a 30-km radius that justified convening CEPEC (Hauksson *et al.*, 1995). Jones (1984) had previously found that, of the four **M** ≥ 5 California mainshocks before 1980 with reverse-faulting mechanisms, none had foreshocks. The Northridge earthquake underscores that even perfect identification of foreshocks would provide advisories for fewer than half of damaging earthquakes.

Implementation of Aftershock Forecasts

In 1996, the Northern California Seismic Network (NCSN, operated by the USGS and the University of California at Berkeley) began planning to augment its reports for earthquakes **M** ≥ 4 with seven-day aftershock probabilities, calculated automatically following the Reasenberg and Jones (1989, 1994) methodology. NCSN's draft wording alluded to the possibility of a larger follow-on event with the statement "Usually, aftershocks are smaller than the mainshock…." After CEPEC discussed the algorithms, protocol, and text between December 1996 and October 1997, the threshold for automated aftershock reports was raised to **M** ≥ 5, and NCSN's template, while retaining the probability of a larger mainshock, was revised to emphasize that a larger mainshock would probably not occur.

The CEPEC-approved protocol was exercised on 12 August 1998, when an automated aftershock warning was linked on the NCSN's public website to the Preliminary Earthquake Report for an M_w 5.1 earthquake near San Juan Bautista, California. CEPEC recommended that USGS and Cal OES issue a "Joint Summary Statement," specifically stating that it was not an earthquake Advisory. The Joint Summary Statement gave a 5%–10% seven-day probability of another earthquake of **M** ≥ 5.1. That estimate, based on the Reasenberg and Jones (1994) aftershock statistics, was at least as high as the foreshock probability implied by the Agnew and Jones (1991) methodology.

Advisory 7: 13 November 2001 Bombay Beach Swarm

On 13 November 2001, a microearthquake swarm near Bombay Beach, California, began with an M_L 2.4 event at 5:54 a.m. PST, continuing with several events M_L 3 and larger. Bombay Beach is at the southern terminus of the Coachella segment of the San Andreas fault, for which WGCEP (1988) had estimated a 40% chance of an **M** ≥ 7.5 earthquake before 2018. Consequently, events **M** ≥ 3.1 here are assigned up to a 1% 72-hr probability of being followed by an **M** 7.5 earthquake, rising to as much as 5% for an **M** 4.2 event (Jones *et al.*, 1991). The swarm prompted CEPEC conference calls at 9:30 and 11 a.m. PST that morning. At 2 p.m. PST, following an M_L 4.1 event at 12:43 p.m. PST, Cal OES issued an Advisory for a possible major southern San Andreas earthquake. The M_L 4.1 earthquake proved to be the largest of the swarm, however.

According to Jordan and Jones (2010, p. 572), "The public scarcely noticed this Level C alert, and there was little media interest in the situation." Nevertheless, by taking the preparatory actions specified in the Advisory plan, Cal OES had readied itself to respond quickly had a major earthquake occurred.

22 December 2003 M_w 6.5 San Simeon Earthquake

The San Simeon earthquake occurred on a previously unknown thrust fault subparallel to the San Andreas fault in central California (Hardebeck *et al.*, 2004). Despite the event's magnitude, CEPEC was not convened, possibly because no larger earthquake was known to have occurred on this fault.

On 6 January 2004, newspapers reported that University of California, Los Angeles, scientist Vladimir Keilis-Borok claimed to have predicted the San Simeon earthquake and was citing that success to support his new prediction that an earthquake of **M** ≥ 6.4 would occur by 5 September 2004 in a region including the southeast Mojave Desert as well as an area south of that (Wolpert, 2004). CEPEC, chaired by Acting California State Geologist Michael S. Reichle, met 20 February 2004, to discuss this new prediction, and declined to either validate or invalidate it (California Department of Conservation, 2004). The predicted southern California earthquake did not occur. However, a summary of CEPEC's deliberations states that the 2003 San Simeon earthquake had satisfied a June 2003 prediction by the Keilis-Borok team (California Earthquake Prediction Evaluation Council, 2004).

28 September 2004 M_w 6.0 Parkfield Earthquake

The Parkfield segment of the San Andreas fault had been densely instrumented since 1985 in anticipation that an **M** ∼ 6 event would occur before 1993, and a separate protocol for the USGS to communicate directly with Cal OES in the event of possible foreshocks and/or anomalous crustal deformation was in place for Parkfield (Bakun *et al.*, 2005). The M_w 6.0 Parkfield earthquake did not occur until 28 September 2004, however, and was not preceded by any foreshocks or other precursory phenomena. The potential for a Parkfield rupture to extend further southwest along the San Andreas fault had been noted (Harris and Archuleta, 1988), and a Parkfield earthquake was a foreshock to the 1857 M_w 7.9 Fort Tejon earthquake (Meltzner and Wald, 1999). Nevertheless, with a detailed response plan in place, a sparse and earthquake-aware local population, and intense scientific attention to a long-awaited Parkfield **M** ∼ 6 event, convening CEPEC was judged unnecessary (J. Parrish, written comm., 2015).

Advisory 8: 31 October 2007 M_w 5.5 Alum Rock Earthquake

The 2007 Alum Rock earthquake occurred 15 km northeast of San Jose on the Calaveras fault (Oppenheimer *et al.*, 2010). In response to this event, CEPEC was convened by current California State Geologist John G. Parrish, who has served since 2005. As recommended by CEPEC, Cal OES issued an Advisory of a heightened chance of a damaging earthquake along the Hayward and/or Calaveras faults. No such earthquake occurred before the Advisory expired.

Online commentary during this Advisory, the first since broadband Internet service had become widely available, offers some insight into public reaction. Web searches did not uncover any undue overreaction to the Advisory, but a reposting of the Cal OES Advisory statement on FreeRepublic.com (2007) elicited the following comment: "I'm probably missing something but how can the probability be significantly increased for (sic) above the normal level of a damaging quake while at the same time have an overall low likelihood?" This question, which emergency managers and scientists often struggle to answer, received three helpful replies:

- "Because the basic probability of a large quake at a moment in time is very, very low. Several times greater risk can still be a low probability. It is (sic) not as goofy as it sounds.: -)"
- "The normal probability level is even lower."
- "If you buy one lottery ticket, your odds of winning are low. If you buy a hundred lottery tickets, your odds of winning have gone up a hundredfold—a significant increase—but they're still low."

Some additional comments at this site were frivolous, but several urged preparedness, and none indicated a lack of respect for earthquake science. In fact, one states, referring to CEPEC: This is an official advisory body of legitimate scientists. There is a heightened risk of a far more serious quake on either Calaveras or Hayward for the next few days, if this is a foreshock.

A Restructured Emergency Management Agency Does Not Issue a CEPEC-Recommended Advisory: March 2009 Bombay Beach Swarm

In March 2009, another microearthquake swarm began near Bombay Beach, California, including three $\mathbf{M} > 3$ events within 30 min of each other on 21 March. A subsequent M_L 4.8 event on 24 March 2009 was the largest earthquake ever recorded within 10 km of the southern half of the Coachella segment of the San Andreas fault (Jordan and Jones, 2010). By this time, the Uniform California Earthquake Rupture Forecast, v.2 (Field *et al.*, 2008), had estimated a 24% probability of an $\mathbf{M} \geq 7$ earthquake on the Coachella segment before 2038.

CEPEC met by teleconference three and a half hours after the M_L 4.8 earthquake on 24 March 2009, and recommended that an Advisory be issued, stating: "CEPEC believes that stresses associated with this earthquake swarm may increase the probability of a major earthquake on the San Andreas Fault to values between 1 to 5 percent over the next several days."

However, as of 1 January 2009, Cal OES had been reorganized, merged into the California Governor's Office of Homeland Security, and renamed the California Emergency Management Agency (Cal EMA). New managers at Cal EMA, just 2.5 months into their assignments, had not been briefed on the Earthquake Advisory Plan. Although prepared to respond to a damaging earthquake, they had not anticipated receiving information that the probability of a future damaging earthquake was elevated, and, as a result, did not issue an Advisory. Instead, on 24 March 2009 they sent a Preparedness Advisory, including CEPEC's statement, to potentially affected counties in southern California, recommending that they "reach out to agencies and jurisdictions … to raise their awareness of today's events" and "ensure the readiness of systems essential to emergency operations and remind the public about the importance of being prepared for earthquakes." This Preparedness Advisory did not include the specific actions or wording specified in the Advisory Plan.

In 2013, Cal EMA was renamed Cal OES and became an agency reporting directly to the Governor. The protocol for handling Advisories has been clarified, but the situation that developed after the governmental restructuring illustrated the challenge of keeping a protocol alive as organizations evolve.

Advisory 10: 26 September 2016 Bombay Beach Swarm

On Monday, 26 September 2016 at 4:03 a.m. PDT, a third microearthquake swarm began beneath the Salton Sea near Bombay Beach, California, just south of the 2001 swarm and north of the southern edge of the 2009 swarm (SCSN, 2016; Fig. 1g). Two **M** 4.3 events and an **M** 4.1 event occurred at 07:31 a.m. PDT, 8:23 p.m. PDT, and 8:36 p.m. PDT, respectively. The Los Angeles Times (2016) reported that retired USGS seismologist Lucy Jones tweeted that evening that magnitude 4 earthquakes near the San Andreas "increase the chance" of a big earthquake "a little bit. But we have swarms without big [earthquakes]—most likely nothing more will happen."

The following day, 27 September, at 8:30 a.m. PDT, CEPEC convened a conference call at the urging of Cal OES Director Mark Ghilarducci. More than 150 microearthquakes had occurred, most of $\mathbf{M} < 2$, and television news broadcasts had reported on the swarm an hour earlier (KTLA, 2016). As in 2001 and 2009, CEPEC recommended that Cal OES issue an Advisory, stating that, based on several models, "stresses associated with this earthquake swarm may increase the probability of a major earthquake on the San Andreas Fault to values between 0.03 percent and 1.0 percent for a **M** 7.0 or larger earthquake occurring over the next week (to 09:00 hrs PDT, Tuesday, October 4, 2016)" (CEPEC, 2016).

Cal OES issued the recommended Advisory, and on the afternoon of 27 September, held a conference call with emergency managers in eight southern California counties to discuss the earthquake swarm. Cal OES also posted a notice on their public website at 10:45 p.m. that evening, but that notice rephrased CEPEC's statement as having concluded "that stresses associated with this recent earthquake swarm may increase the probability an additional earthquake as large, or larger, than the September 26 magnitude 4.3 occurring over the next week." Cal OES corrected that notice on 30 September to state the following, consistent with reflecting CEPEC's actual conclusion verbiage: "This advisory was updated to clarify that CEPEC specifically evaluated the potential for the earthquake swarms to trigger a larger earthquake (**M** 7.0+) on the San Andreas Fault. Scientists estimated values between 0.03 percent and 1.0 percent possibility of that happening." (California Office of Emergency Services, 2016).

Major news outlets reported CEPEC's conclusion after this update, with one article posted that morning, 30 September, quoting Lucy Jones' tweet that the swarm "is over and risk mostly gone" (CBS Los Angeles, 2016).

DISCUSSION

When a potential foreshock has temporarily elevated the probability of a damaging earthquake, California has been able to alert the public without significant adverse reaction by exercising its Earthquake Advisory Plan. As of December 2016, 10 advisories have been issued, but no mainshock has occurred during any of them. This outcome is consistent with the approximate 5% probability that an earthquake is a foreshock to a mainshock within the time–space window identified by Jones (1985). Although such peer-reviewed statistical findings on foreshock occurrence constitute the scientific basis for the Advisory Plan, CEPEC has often exercised scientific judgment when deciding whether to recommend an earthquake Advisory. In particular, from the potential foreshocks they have evaluated, CEPEC scientists have winnowed out several events that they decided were probably not foreshocks. The vigor of the aftershock sequence and possible observations of aseismic deformation are among the factors that CEPEC has considered (J. Parrish, personal comm., 2012), although these features have not been shown to reliably diagnose foreshocks. CEPEC has also assessed swarms consisting of events smaller than those included in statistical analyses. As of this writing, no damaging earthquake has occurred before which CEPEC had met and recommended against an Advisory.

Advisories need to be issued much more rapidly. Each of the 10 advisories recommended by CEPEC was publicly issued hours after potential foreshocks occurred. Unfortunately, these time lags are long compared with the less than 30 min interval between foreshock and mainshock for about half the events studied by Jones (1985). Also, the two largest foreshocks of the 1857 M_w 7.9 Fort Tejon earthquake preceded the mainshock by 2 and 1 hr, respectively (Meltzner and Wald, 1999). More recently, foreshock–mainshock intervals for the 1986 M_L 6.4 Chalfant Valley and 1987 M_w 6.6 Superstition Hills earthquakes were 24.2 and 11.4 hr, respectively, yet advisories could not be issued before those mainshocks because CEPEC did not convene until after they had occurred. The protocol whereby CEPEC's summary statement is transmitted to Cal OES for issuance could be made more efficient, though must continue to honor the key principle of separating scientists' responsibility (using their expertise to judge how seismic activity is likely to evolve) from emergency managers' responsibility (deciding the best way to use that information to promote public safety). In our current Internet and social media environment, the public wants instantaneous information following earthquakes, and information voids can be filled with unscientific speculation and misinformation.

Damaging mainshocks have also occurred more than a few days after foreshocks. CEPEC addressed this reality following the 1992 Landers earthquake by recommending the go-to-war scenario, in which seismologists and emergency managers maintained heightened vigilance after public advisories expired. Deployment of additional seismic or geodetic monitoring stations could exploit these long foreshock–mainshock intervals not only to benefit emergency preparedness but also to advance scientific understanding of how the events in an earthquake sequence are linked.

Little effort has been made to determine whether issuing advisories has reduced the risk of losses in earthquakes. Do advisories promote preparedness or stimulate constructive actions such as voluntary seismic retrofitting? Do negative outcomes such as rumors have significant consequences? Do successive unfulfilled advisories reduce public confidence in earthquake science or lead to a cry wolf syndrome? Future earthquake advisories should be better documented and their benefits (or lack thereof) evaluated. Even if CEPEC deliberations must remain confidential to encourage frank exchange of scientific ideas, summary reports should be prepared and archived. Social science research is needed to facilitate continual improvement in the usefulness of advisories to the public at risk.

The Advisory Plan could be adapted for use outside of California. Where seismicity rates are lower, historic and instrumental earthquake catalogs generally include too few events for robust earthquake statistics. However, CEPEC has successfully assessed several situations outside the scope of statistical studies. People everywhere inevitably crave earthquake forecast information whenever seismic activity begins, and it is in everyone's interest that earthquake scientists and public officials provide authoritative information.

The appropriate division of responsibilities between earthquake scientists and emergency managers is a key feature of the Advisory Plan that can be implemented anywhere. The Plan specifies that forecasting the behavior of seismic sequences must be done by earthquake scientists, while designing appropriate responses to such forecasts is the job of experts in emergency management, informed by social science research. This separation of scientific forecasting from decision making by stakeholders has also been recommended by the International Commission on Earthquake Forecasting for Civil Protection (2011) in the wake of the 2009 L'Aquila earthquake.

The California Earthquake Advisory Plan is a pioneering effort to derive public safety benefits from uncertain earthquake science, supplemented by expert judgment. Implementing, maintaining, and improving such a protocol for collaboration between earthquake scientists and emergency managers provides a necessary framework for advising the public during situations of elevated earthquake probability.

DATA AND RESOURCES

All data used in this article came from published sources listed in the references. Some plots were made using the Generic Mapping Tools v.4.2.1 (www.soest.hawaii.edu/gmt, last accessed February 2014; Wessel *et al.*, 2013). The data on the Landers earthquake are obtained from scedc.caltech.edu/significant/landers1992.html (last accessed May 2016).

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