= 1) quantile points at the selected times, S, corresponding to the expected probability and ±1 SD (Table 1). The standard error in P rapidly decreases with increasing time after the mainshock due to the inclusion of current data. For example, at $S = 1$ day after the mainshock, the ±1 SD range about the generic 1-day interval probability (0.052) is 0.034 to 0.075 (Table 1).

Rydelek suggests estimating parameters from subsets of the a priori data corresponding to particular tectonic regions. While this approach has potential merit, it was not very successful for the California data. Parameter estimates for subsets of the data corresponding to the strike-slip regime of central California, the compressional regime of southwestern California and the strike-slip and extensional regime of eastern California do not differ significantly from each other, with one exception. The a value for sequences in eastern California is significantly higher than in central or southwestern California, which indicates a higher productivity of aftershocks there. In future applications of our method to other areas, however, a search for regional or tectonic subsets of earthquake sequences that significantly differ in some parameter values could provide an improvement over the single generic model approach.

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REFERENCES AND NOTES

1. P. A. Reasenberg and L. M. Jones, *Science* **243**, 1173 (1989).
2. Model parameters a, b and p, defined in (*1*), describe the total number, magnitude distribution and time distribution of the aftershocks, respectively.
3. As defined in (*1*), M_1 and M_2 are, respectively, the lower and upper limits of a magnitude range, and S and T are, respectively, the lower and upper limits of a time interval, for which P is computed.
4. In practice, observation of earthquakes within the central and southern California U.S. Geological Survey networks is complete above approximately magnitude 1.5.

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California Aftershock Hazard Forecasts

The first practical application for our model for real-time probabilistic hazard assessment (*1*) was provided by the 6 March 1989 *M*4.7 Obsidian Butte earthquake sequence in the northern Brawley Seismic Zone at the southern end of the Salton Sea, California (Fig. 1). The earthquake sequence was initially very active and included a relatively high proportion of large-magnitude aftershocks ($a = -0.5$, $b = 0.6$). As a result, the model-estimated probability for a larger ($M \geq 4.7$) earthquake during the first week in the sequence was relatively high—on the order of 0.30. Scientists familiar with the Brawley Seismic Zone generally felt that this estimate was reasonable. We did find, however, that other factors, in addition to those considered in the model, also warranted consideration.

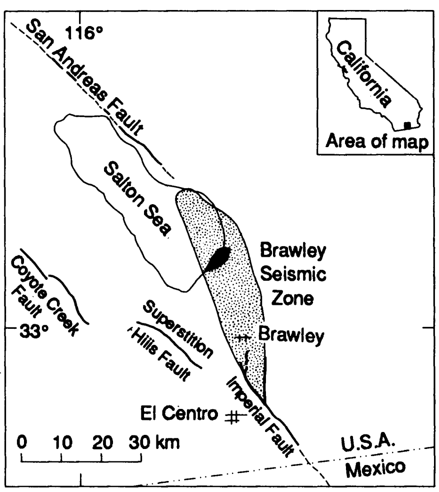

Fig. 1. Aftershock zone (black area at south end of the Salton Sea) of the 1989 Obsidian Butte earthquake sequence. The Brawley Seismic Zone (shaded area) is the site of numerous earthquake swarms in the cross over region between the San Andreas and Imperial faults.

One factor was the proximity (18 km) of the Obsidian Butte earthquakes to the intersection of the Brawley Seismic Zone and the San Andreas fault and the possibility that a great ($M \approx 8$) earthquake might be triggered by the Obsidian Butte sequence. The concensus was that the distance to the San Andreas fault was too great to warrant an upward revision of the model probability estimate for a great earthquake.

Another factor was that the Brawley Seismic Zone may not be capable of producing very large earthquakes because it is composed of numerous small faults, rather than a continuous long fault. If we assume that the largest possible earthquake in the Brawley Seismic Zone is *M*6.2 (the magnitude of the largest known historic event), then the model-estimated probability of a $M \geq 4.7$ earthquake decreases from 0.30 to 0.26.

The U.S. Geological Survey used the model to issue frequent public forecasts during the 17 October 1989 Loma Prieta earthquake sequence of probabilities of strong aftershocks within a day, a week, and 2 months. While this earthquake produced fewer aftershocks than expected for a generic *M*7.1 earthquake, the final model parameters determined for it ($a = -1.67$, $b = 0.75$, $p = 1.19$) all differ by less than 1 SD from their respective generic values (*2*, figure 1). We reported 24 hours after the earthquake that the chance of a $M \geq 5$ aftershock in the next day was 0.13 (none occurred). One week later that probability had decreased to 0.05, while the probability of a $M \geq 5$ aftershock over the next 2 months was 0.50 (none occurred). Forecasts were made first daily, and then less frequently, through 30 November 1989. These were issued to federal, state, and regional government agencies and were widely reported by Bay Area printed and electronic media. Public demand for and interest in aftershock forecasts was greatest immediately after the earthquake and remained high for about 2 weeks, decreasing as the felt aftershocks subsided.

Some local and regional government agencies requested model results particular to their needs during the first week of the sequence. The Port of Oakland requested estimates of probabilities for strong aftershocks in order to decide whether and when to reoccupy a damaged structure. The San Francisco Fire Department requested probabilities of strong shaking in the Marina and China Basin districts to guide decisions about equipment deployment and staffing levels in these damaged areas. Within the U.S. Geological Survey, scientists coordinating the regional deployment of strong motion portable seismographs frequently consulted model results in planning their experiment design and field strategy.

Our experience with the Obsidian Butte sequence and the Loma Prieta sequence has shown that the model can provide important information for real-time hazard assessment for earthquake sequences. Sensible real-time assessment of the seismic hazard during future earthquake sequences in California should also take into account relevant regional factors, including proximity to stressed fault segments, fault complications or gaps, and possible regional limitation of the maximum possible earthquake size.

In the Loma Prieta sequence, we found that regularly released short-term forecasts of expected aftershock activity were useful in meeting the high public demand for earthquake hazard information after a strong earthquake. We also saw that the press and public can easily misunderstand a probabilistic forecast; such public statements should be simple, clear, and consistent. Overall, however, we feel that our use of model probabilities to forecast the continuing earthquake hazard after the Loma Prieta earthquake was generally understood and widely accepted by the public, the press, and other government agencies.

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REFERENCES AND NOTES

1. P. A. Reasenberg and L. M. Jones, *Science* **243**, 1173 (1989).
2. P. A. Reasenberg and M. V. Matthews, *ibid.* **247**, 343 (1990).

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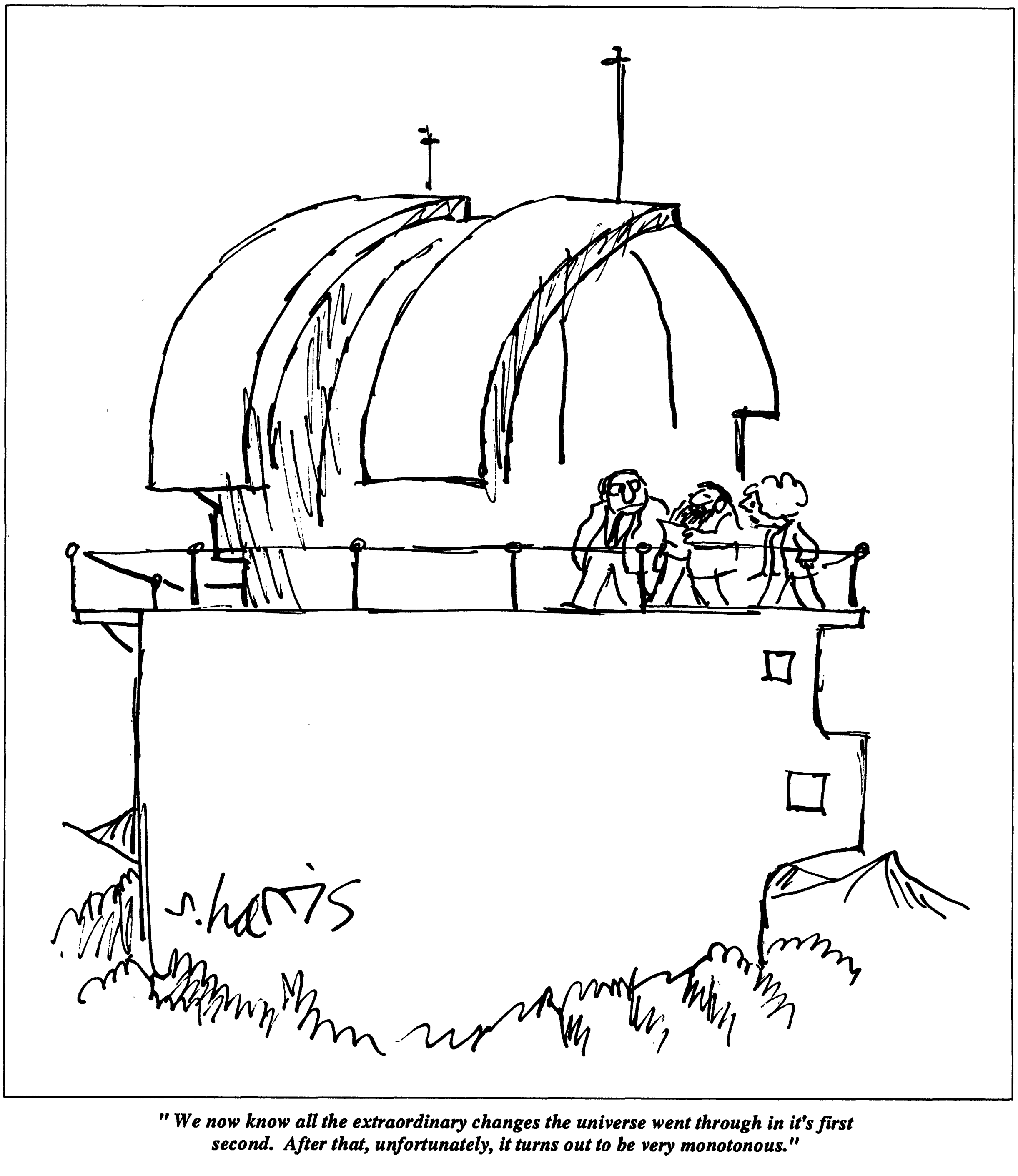

" We now know all the extraordinary changes the universe went through in it's first second. After that, unfortunately, it turns out to be very monotonous."