Despite differences in approach, Nishenko and Sykes [this issue] come to conclusions much like those of Kagan and Jackson [1991]. We appear to agree on the following:

The seismic gap hypothesis deserves a rigorous test. The spatial and temporal boundaries of the gaps, and the qualities of gap-filling earthquakes, must be specified.

The color map of McCann et al. [1979, hereafter referred to as MNSK] does not successfully forecast most large ($M_S \geq 7$) earthquakes in the ensuing decade. Specifically, green zones are not safe from large earthquakes, and red zones are not more likely than the others to have large earthquakes.

Earthquakes since 1979 do not statistically support the seismic gap hypothesis that red, orange, and green zones are successively less hazardous, compared to the null hypothesis that red, orange, and green zones are equally hazardous. This conclusion holds for our test catalog, as well as Nishenko and Sykes' catalogs of large and very large earthquakes (their Table 1).

The antithesis (that red, orange, and green zones are successively more hazardous) fits the data better than the gap hypothesis for all the catalogs above except Nishenko and Sykes' larger earthquakes (their Table 1, $M_S \geq 7.5$). However, the null hypothesis cannot be rejected for any of the catalogs.

We still disagree on several issues: (1) the importance of testing the original 1973 [Kelleher et al., 1973] and the MNSK 1979 versions of the gap hypothesis, (2) how to determine whether an earthquake is in a given zone, (3) what kinds of earthquakes are forecast by the seismic gap hypothesis, (4) the relative hazard for red and orange zones, and (5) whether the seismic gap hypothesis can now be rejected. Let us discuss these in order. We use the following definitions: large, applied to earthquakes, means $M_S \geq 7.0$; larger means $M_S \geq 7.5$; hazard means the probability that an earthquake will occur.

ARE THE 1973 AND 1979 GAP HYPOTHESES MOOT?

Much has been learned about earthquakes since 1979, and the seismic gap hypothesis has evolved in sophistication. Nishenko and Sykes devote much of their comment to discussion of deficiencies of the 1979 hypothesis and modifications that can now be made to improve the model. We now have more information about the source zones of pre-1979 earthquakes, and Nishenko and Sykes suggest that we might retroactively adjust some zone boundaries before testing the 1979 forecast. Also, new gap models allow for different mean recurrence times for different zones. Nevertheless, the earlier gap models must still be tested, in their original form, against the data. If a forecast model is abandoned before enough earthquakes occur to test it, then it lacks scientific meaning because it is not falsifiable.

Retroactive adjustment of a model before testing is not permissible, even if additional information was, in principle, available in advance. Many pre-1979 earthquakes might be relocated, possibly leading to a complete revision of the 1979 seismic-gap map. This procedure invites bias. MNSK used historic recurrence information only qualitatively in defining their seismic gaps. More detailed gap models [Lindh, 1983; Sykes and Nishenko, 1984; Nishenko and Jacob, 1990; Nishenko, 1991] use estimated mean recurrence times explicitly. These versions will presumably be tested when enough earthquakes have occurred, but they are not ripe for testing now.

Some have accepted the seismic gap hypothesis prematurely. Nishenko [1986, 1989] reported that several earthquakes in seismic gaps confirmed the 1979 and earlier versions of the hypothesis. He did not report failures. Apparently on the basis of this perceived success, several official reports on earthquake hazards, including the Working Group on California Earthquake Probabilities [(WGCEP) 1988, 1990] used the seismic gap hypothesis to estimate seismic hazard. Now Nishenko and Sykes contend that even the 1979 version cannot be tested for want of enough earthquakes. No version of the seismic gap hypothesis has been confirmed statistically.

ASSIGNING EARTHQUAKES TO ZONES

We assigned earthquakes to zones by overlaying a map of earthquakes on the color map of MNSK. Nishenko and Sykes protest this procedure because the color map lacks the detail of the monochrome figures in MNSK. However, the more detailed maps in MNSK do not show the seismic zones as closed areas, so that one must make arbitrary decisions to assign earthquakes to specific zones. Furthermore, MNSK did not assign seismic potential categories to the segments indicated in the detailed figures, and these segments do not match the zones shown on the color map or described in the text. The small scale of the color map does allow errors of assignment. Our procedure randomizes these errors, and moving the few debatable earthquakes into "redder" zones does not change the outcome substantially [Kagan and Jackson, 1991]. In the future, seismic gap and other forecasting hypotheses should include a numerical algorithm for assigning zones.

WHAT KINDS OF EARTHQUAKES ARE FORECAST BY THE SEISMIC GAP HYPOTHESIS?

Nishenko and Sykes claim that we tested "a very different hypothesis" than that of MNSK, because we ignored
and limitations, verbatim from MNSK [pp. 1085-1087]:

advance, and this was not done. Here are the assumptions
esis to be testable, its terms must be specified adequately in
interpretation of "assumptions and limitations" in MNSK.

It would be pointless to discuss our differences on individ-
earthquakes that occurred within their zones, based on their
variations in magnitude, focal mechanism, fault complex-
ity, and other complications. They reject over half of the
earthquakes that occurred within their zones, based on their
interpretation of "assumptions and limitations" in MNSK.

This difficulty is not semantic but rather
reflects the failure of earthquakes to conform to the simple
assumptions behind the seismic gap theory. In reality, the
plate boundary is a broad zone of complex deformation on
many faults. Earthquakes with diverse mechanisms on faults
subparallel to the "main" boundary faults affect the stress
environment within the plate boundary and contribute to
plate motion. Where does one draw the lines?

MNSK and Nishenko and Sykes [this issue] failed to draw
such lines. It is irresponsible of Nishenko and Sykes to ac-
cuse us now of a "glaring error" in assigning a zone to the
Costa Rican earthquake of April 22, 1991. This event oc-
curred well within the boundaries of an orange zone shown
in the color map of MNSK. Because of a typographical error
we listed the earthquake in zone O-6 instead of O-13 [Ka-
gan and Jackson, 1991, Table 4], but this is irrelevant to
the dispute. If the plate boundary, by their definition, does
not include the Panama fold and thrust belt, MNSK should
have drawn the map accordingly.

MNSK clearly stated in several places that their forecast
applied to large ($M_s \geq 7$) earthquakes, yet Nishenko and
Sykes suggest that different size criteria should apply to dif-
ferent zones. What are these size criteria? Nishenko and
Sykes now suggest that an earthquake may "partially fill"
ap. Should these partial earthquakes be counted in test-
ing the gap hypothesis, even if they are smaller than the
"characteristic" earthquake for a full gap?

Given the ambiguities in the MNSK hypothesis, differ-
ences in assignment are inevitable. We presumed that the
seismic gap hypothesis should describe a large majority of
earthquakes within the designated zones. Surely, WGCEP
[1988, 1990] made the same presumption when they used
the seismic gap hypothesis to evaluate seismic hazards in
California. The U.S. Geological Survey (USGS), too, must
have made the same presumption when they suggested us-
using the original MNSK color map to design experiments to
observe large earthquakes in the near field [Hanks, 1985].

Now Nishenko and Sykes propose to exempt a majority of
events, even within the specific zones of MNSK. Table 1

\begin{table}[h]
\centering
\caption{Earthquakes From 1979 to 1988}
\begin{tabular}{lcc}
\hline
Category & $M_s \geq 7$ & $M_s \geq 7.5$ \\
\hline
Total & 76 & 20 \\
Not in zone & 36 & 10 \\
In zone, ineligible & 22 & 3 \\
In zone, eligible & 18 & 7 \\
Green & 8 & 3 \\
Orange & 10 & 4 \\
Red & 0 & 0 \\
\hline
\end{tabular}
\end{table}

provides the only indication of these widths, yet Nishenko
and Sykes object to its use because of its low resolution.
This is a clear recognition of the difficulty in defining the

plate boundary. This difficulty is not semantic but rather

\begin{table}[h]
\centering
\caption{Earthquakes From 1979 to 1988}
\begin{tabular}{lcc}
\hline
\end{table}
apply to a minority of the earthquakes within the specified zones.

The Relative Hazard for Red and Orange Zones

Nishenko and Sykes discuss at length the fact that orange earthquakes outnumber red ones. They suggest that red zones may have fewer earthquakes above magnitude 7 because they have larger, less frequent earthquakes. MNSK discussed this suggestion as well [pp. 1085-1089] but they never imply from this that orange zones should be more hazardous. They state [p. 1085] that red zones (category 1) "are those in which a great event is known to have occurred in the area but not within the last 100 years." Orange zones (category 2) "also appear to have a high potential for the occurrence of future large shocks. Many of the latter gaps, however, probably will not be sites of large shocks for the next few tens of years since a long time is needed to build up high tectonic stresses." The retrospective suggestion that orange zones are more likely to have \( M \geq 7 \) earthquakes than red zones is consistent with the data, but not with the MNSK hypothesis. Earthquakes since 1973 do not confirm the suggestion that red zones should have larger events: Table 3 of Nishenko and Sykes shows one red, eight orange, and six green events greater than magnitude 7.5 since 1973. The largest event (using \( M_5 \)) was in an orange zone, and the next largest was in a green zone. Nine of the 15 larger events were larger than the sole red event.

The suggestion that the red zones have longer characteristic earthquakes implies a permanent difference from other zones. For example, red zones should be substantially longer than the others. Suppose green and orange zones are characterized by magnitude 7.5-7.7 earthquakes [Nishenko and Sykes, this issue] and red zones by magnitude 8.5. Then using the scaling relationships between magnitude, seismic moment, slip, rupture length, and rupture width from Scholz [1990], the red zones should be 4 to 15 times longer than the others (depending on whether the slip is proportional to rupture length or width). But the average length of a red zone is comparable to that of the green and orange zones. Finally, the largest historic earthquakes [Pacheco and Sykes, 1992] were the 1960 Southern Chile, 1964 Central Alaska, and 1957 Central Aleutian earthquakes, which occurred in green zones.

Can the 1979 Seismic Gap Hypothesis Be Rejected?

If the seismic gap hypothesis is to be scientifically interesting or useful for policy decisions, there should be some substantially higher probability (at least double) of a large earthquake in the redder zones. We tested the following hypotheses: (1) Red zones are twice as likely to suffer large earthquakes as green zones. (2) Red zones are twice as likely to suffer large earthquakes as orange zones. (3) Orange zones are twice as likely to suffer large earthquakes as green zones.

The earthquake data in Table 1 do not support any of these three hypotheses, and in fact the reverse of 1 and 2 would be in better agreement. We tested 1, 2, and 3 separately against a null hypothesis, that the zones were equally hazardous, using Nishenko and Sykes catalogs of "eligible" earthquakes only, and their values for the numbers of zones (17 red, 53 orange, and 55 green). We used Cox and Lewis' [1966, equation 9.2.3, p. 225] test for comparing intensities of two Poisson processes.

The hypotheses above can be tested unambiguously only for the MNSK map during the period 1979-1988, because only for that map do the zone specifications and time interval of Nishenko and Sykes correspond to those in the original publication. Hypothesis 1, which we regard as the weakest hypothesis that would have any scientific or planning consequences, can be rejected at the 96.9% confidence level for \( M \geq 7.0 \) earthquakes. Any stronger version of 1 could be rejected at a higher confidence level (for red equals 4 times green, the confidence is 99.8%). Hypotheses 2 and 3 can be rejected at the 98.4% and 74.9% confidence levels, respectively. For larger events, the confidence levels for 1, 2, and 3 are 78.9%, 86.2%, and 53.6% respectively, reflecting the small number of such events. The stronger version of 1, with red equal to 4 times green, can be rejected at 91.1% confidence for larger events. Thus any meaningful interpretation of the MNSK model can be rejected now for large \( (M \geq 7) \) earthquakes.

Nishenko and Sykes give in Table 3 a count of earthquakes in various zones from 1973 to 1989. We are not sure how to interpret the zone assignments for the earthquakes before 1979, because Nishenko and Sykes apparently use the zone definitions of MNSK but the earthquakes predate publication of MNSK. If we take the counts at face value, the gap hypotheses 1, 2, and 3 can be rejected at 99.1%, 99.0%, and 96.4% for \( M \geq 7 \), and 81.9%, 91.6%, and 65.5% for \( M \geq 7.5 \). Because the 1973-1989 catalog contains more events, the gap hypotheses can be rejected with more confidence.

Conclusions

Inadequate definitions of seismic gaps and eligible earthquakes cause most of the differences of opinion regarding earthquake assignment and testing of the seismic gap hypothesis. The seismic gap model cannot achieve scientific validity until these definitions are provided. Nishenko and Sykes [this issue] reject over half of the large earthquakes in the identified hazard zones of McCann et al. [1979] using post facto interpretations of the assumptions and conditions in MNSK. Even the selected data of Nishenko and Sykes justify rejecting the MNSK hypothesis for \( M \geq 7 \) earthquakes at the 95% confidence level if the hazard for a red zone is assumed to be double that of a green zone. Zones that have had recent large earthquakes are definitely not immune from further large earthquakes, either "eligible" or "ineligible".

Seismic gap models that explicitly use mean recurrence times for individual zones cannot yet be tested because too few earthquakes have occurred. These models, too, suffer from inadequate definition of seismic gaps and eligible earthquakes. No version of the seismic gap hypothesis has yet shown a significant statistical advantage over a reasonable null hypothesis.

References


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