CHARACTERISTIC EARTHQUAKES AND SEISMIC GAPS

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Definitions

Fault slip. Relative motion, either steady or sudden as in earthquakes, between rock units on either side of a fault.

Rupture. Sudden fault slip in an earthquake.

Elastic rebound. Sudden release, as by an earthquake, of slowly accumulated strain energy.

Segment. A section of a fault or plate interface bounded by features thought to serve as strong barriers to earthquake rupture. Features postulated to form such barriers include changes in fault orientation or in rock type across parts of the fault, and intersections with other faults.

Characteristic earthquake. An earthquake rupturing an entire fault segment. Alternately, one of a sequence of earthquakes rupturing the same area of fault.

Recurrence interval. The time between characteristic earthquakes on a given segment or fault area.

Quasiperiodic. Occurring at approximately equal recurrence intervals.

Seismic cycle. A sequence of events on a segment starting with a large earthquake, followed by aftershocks, then by steady stress accumulation, and culminating with another large earthquake. The term “cycle” is sometimes but not always meant to imply quasiperiodic recurrence.

Seismic gap. A segment for which the time since the previous characteristic earthquake approaches or exceeds the average recurrence interval.

Introduction

The seismic gap hypothesis holds that most long-term geologic slip on faults or plate boundaries is accomplished by characteristic earthquakes on segments. Such quakes are presumed to reduce the stress substantially, necessitating a substantial recurrence time for elastic stress to recover before the next characteristic earthquake. The dates and rupture extent of past earthquakes may be determined by modern seismic networks; by historic reports of faulting, damage, or strong shaking; or by paleoseismic investigation of trenches across faults. The average recurrence time may be determined either from a sequence of dates of past characteristic earthquakes, or by the time required for steady slip on a fault to accumulate the slip experienced in a characteristic earthquake (Working Group on California Earthquake Probabilities, 1988, 1990).

History

Well before plate tectonics became accepted in the 1960s, Gilbert (1884) argued that large earthquakes should be separated by substantial time intervals. Reid (1910, 1911) proposed that faults slowly accumulate energy later released suddenly by earthquakes (“elastic rebound”), and that the time to a future earthquake could be estimated by surveying the strain released by a previous one. Fedotov (1965) noticed that most of the Kamchatka–Kurile trench in the northwest Pacific had been ruptured by earthquakes in the early twentieth century, with the exception of one zone southeast of Hokkaido. He concluded that a future earthquake was likely in that area, a forecast realized in 1973 when the Nemuro-oki earthquake struck with magnitude about 7.5 (Kasahara, 1981, 182).

Plate tectonics now provides a compelling, steady source of the strain energy driving elastic rebound, and
that fact led many to conclude that occurrence of large earthquakes must be separated by enough time to allow recharge. Scholz (1990, 260) remarked that “A tenet of plate tectonics is that the rates of plate motion must be steady over geologic time periods and must be continuous along plate boundaries. If it is assumed further that a significant portion of this motion must be released seismically, then it follows that segments of plate boundaries that have not ruptured for the longest time are those most likely to rupture in the near future. These places are called seismic gaps.” The seismic gap hypothesis was celebrated when Nishenko, 1989 published a list of 13 earthquakes that fit, at least approximately, the descriptions of previously expected earthquakes.

The seismic gap model has been applied to long-term forecasting of earthquakes in many regions (Sykes, 1971; Kelleher, 1972; Kelleher et al., 1973; McCann et al., 1979; Working Group on California Earthquake Probabilities, 1988, Nishenko, 1991). The model and its definition have evolved along with the quality and quantity of data that go into it. Fedotov (1965) defined the Nemuro-oki gap as the last remaining unbroken segment. McCann et al. (1979) used elapsed time and a color code to label segments around the Pacific Rim: more than 100 years had elapsed in red gaps, between 30 and 100 years in orange gaps, and less than 30 years in apparently safe green zones. In the most comprehensive forecast ever using the seismic gap model, Nishenko (1991) actually made testable probabilistic forecasts for about 125 plate boundary segments around the Pacific Rim. In that study he estimated the mean recurrence time and the elapsed time for each segment, and assumed that their ratio obeys a log-normal probability density function. With that information, he calculated the probability that each zone would be ruptured by a characteristic earthquake whose magnitude he also listed for each zone within 5-, 10-, and 30-year periods. A very similar model was used by the Working Group on California Earthquake Probabilities (1988) in its official earthquake probability estimates.

Assumptions
All the applications mentioned above share several important assumptions. First, their authors assume that faults and plate boundaries are segmented and that rupture does not cross segment boundaries. Second, they assume that each characteristic earthquake ruptures to both ends of its segment, reducing the stress to a uniform base level and beginning the process of stress recharge. Third, they assume that the time to the next characteristic earthquake depends almost entirely on the time of the previous one: not on other earthquakes, nonelastic stress redistribution, or other causes. To make useful forecasts, scientists must obviously be able to distinguish characteristic earthquakes from all others in order to know the elapsed time since the last one.

Small characteristic earthquakes
Recent studies in California (e.g., Nadeau and McEvilly, 1999), Japan (e.g., Igarashi et al., 2003; Okada et al., 2003), and elsewhere have identified sequences of small earthquakes fitting the alternative definition of “characteristic earthquake” above. In each sequence, the events are approximately the same size, and rupture approximately the same fault area. They recur at nearly equal time intervals or in some cases variable intervals consistent with variations in their size or in fault slip rate. In most cases, the slipped areas appear to be surrounded by areas where displacement occurs by steady slip rather than earthquakes. Because of that special circumstance, these small repeating earthquakes are not relevant to the discussion of seismic gaps.

Modified seismic gap hypothesis
As time, earthquake experience, and theoretical sophistication have accumulated, earth scientists have modified the seismic gap theory to rely less on the assumptions above. The Working Group on California Earthquake Probabilities (1990) allowed adjustments to account for stresses from earthquakes not on the relevant segment. The 1992 Landers, California earthquake (magnitude about 7) presented a particularly important observation. In that event, rupture jumped segment boundaries and even faults, making use of up to five faults mapped as separate before 1992. In a seismic hazard model produced by the Southern California Earthquake Center (Working Group on California Earthquake Probabilities, 1995), the seismic gap model was modified to allow rupture to jump segment boundaries with a modest probability. Later uses of the seismic gap model in California for official hazard estimates employ increasingly complex assumptions, especially about conditions under which rupture is likely to involve more than one segment (Working Group on California Earthquake Probability, 2002, 2008).

The more complex versions of the model raise interesting questions. What truly constitutes a segment? How effective are weak barriers in stopping rupture, and what controls their strength? Are the boundaries fixed in space, or can they move as stress conditions change? When rupture crosses a boundary, does it consistently continue to the next? If not, does it reset the stress and the clock on the partially ruptured segment? Do the elapsed times on adjacent segments control the probability that rupture will jump the barrier between them? If so, which segment is most important? Modelers must answer these questions, implicitly or explicitly, to forecast using the modified gap models. So far, there is no clear consensus on the answers.

Challenges to the seismic gap model
Despite some reported successes, the seismic gap hypothesis has often been questioned. Critics point to the difficulty of verifying the rather strong assumptions behind the hypothesis, and to its limited success in forecasting earthquakes.

The basic assumption that faults and plate boundaries are segmented has provoked significant debate. Even the few apparent successes (e.g., Loma Prieta, CA, 1989;
Parkfield, CA 2004; Chile, 2010), are equivocal at best. The rupture of the Loma Prieta earthquake was about the length of the nearest segment mapped by the Working Group on California Earthquake Probabilities (1988), but it shifted south and spilled over the southern segment boundary. Moreover, the event occurred near, but not actually on the San Andreas Fault for which the segment was defined. Before 2004, the Parkfield segment was defined in several different ways, so its location at Parkfield does not confirm the segmentation hypothesis (Jackson and Kagan, 2006). The 2010 Chile earthquake went well beyond the segment boundaries specified by Nishenko (1991). In addition, several events have clearly violated preassigned boundaries. The 1992 Landers quake was mentioned above, and the great Sumatra tsunami earthquake of 2004 breached several boundaries along its 1,300-km rupture zone (Nalbant et al., 2005).

The assumption that earthquakes rupture to both ends of segment boundaries also lacks verification. A basic problem is that the locations of segment boundaries are usually estimated inaccurately from the extent of past earthquake ruptures. For earthquakes identified by paleoseismic investigations, rupture can generally be pinpointed at only a few widely spaced locations. For historical earthquakes, rupture extent is typically estimated with great uncertainty from the extent of damage or reported shaking. Even for modern instrumentally recorded earthquakes, the extent of the aftershock zone or fault scarp may not accurately represent the rupture at depth where the elastic rebound occurs. In many cases, the extent of rupture for older earthquakes is assumed to be similar to that of the most recent event, a clear case of circular reasoning.

The connection between plate tectonics and earthquake recurrence referred to in the words of Scholz above depends on the assumption that characteristic earthquakes release most of the slowly accumulated fault slip. However, that assumption fails in many examples. For instance, the cumulative slip of the Parkfield, CA earthquakes since 1857, often regarded as an archetypical characteristic sequence, accounts for only a small fraction of expected slip at the long-term geological rate (Jackson and Kagan, 2006). In such cases, the alternative definition of characteristic earthquakes listed above, and the times of past events, may provide valuable information on the causes of some earthquakes but the direct link to plate tectonics is lost.

Proponents of the seismic gap theory cite many examples in which identified gaps have been filled by earthquakes. The positive examples are appealing but insufficient for two reasons. First, the definitions of gaps and forecasted earthquakes were quite general, making the target easier to hit at random. Second, they included only successes; a fair evaluation needs to consider failures as well.

Kagan and Jackson (1991, 1995), and Rong et al. (2003) applied statistical tests to the seismic gap theory as articulated by McCann et al. (1979) and Nishenko (1991). Earthquakes were actually more frequent in McCann’s green zones than in the red ones, opposite to what the gap theory assumes. The 1991 gap model implied far more earthquakes, in different places, than actually occurred. Kagan and Jackson (1995) and Rong et al. (2003) also tested a simple alternative to the gap model, assuming that earthquakes occur randomly in time and near past earthquakes. The alternative model fits the total number and the locations of future earthquakes much better than the 1991 gap model.

These statistical tests necessarily applied to the earlier versions of the gap hypothesis, in which segments were assumed to be independent of one another. Since then, more complex versions of the model have been applied. Most of these applications involve one or a few purported gaps with estimated recurrence times of decades or centuries. Published models generally do not provide probabilities for multi-segment ruptures, and they cannot be effectively evaluated until several seismic cycles have elapsed. To be rigorously testable, such a model must forecast a few tens of well-defined earthquakes. Unfortunately, no systematic, well-specified version of the more complex seismic gap model has been applied broadly enough to be tested.

Conclusions

The intuitively appealing seismic gap model encompasses the virtually unassailable principle that earthquakes release strain energy accumulated over a long time. Although many large events have occurred in previously identified gaps, the same is true of locations outside them. Simple versions of the gap theory, in which characteristic earthquakes occur on independent segments, are no longer tenable. Modified versions of the gap theory have not yet been formulated in a rigorously testable way.

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Cross-references

Earthquake Precursors and Prediction
Earthquake Rupture: Inverse Problem
Earthquakes and Crustal Deformation
Earthquakes, Energy
Earthquake, Location Techniques
GPS, Tectonic Geodesy
Great Earthquakes
Paleoseismology
Seismic Hazard
Seismicity, Subduction Zone
Seismology, Global Earthquake Model
Statistical Seismology

CONTINENTAL DRIFT

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Definition

Continental drift. The name given to the relative movement between continents.

Introduction

Apparently, continental drift was first postulated by Abraham Ortelius, who made one of the first atlases, in the third edition of his *Thesaurus Geographicus* (Ortelius, 1596) to account for the similarity between the coastlines of western Africa, western Europe, and the eastern Americas. During the next three centuries or so, several other thinkers used this morphological similarity to come to the same conclusion.

Alfred Wegener

Although Ortelius speculated that earthquakes and floods had torn the continents apart, Alfred Wegener, an Austrian meteorologist, was the first to systematically gather the geological evidence for continental drift in his synthesis (Wegener, 1929a), also translated into English (Wegener, 1929b), parts of which had been published as early as 1912 (Wegener, 1912).

Wegener was puzzled in particular by the present-day distribution of former ice-age deposits, or tillites, of Permo-Carboniferous age, now known to be about 300 million years old that are found today in South America, Africa, Antarctica, India, and Australia. Wegener’s meteorological background led him to assume that the present-day climatic zones, with cold polar regions and a hot tropical belt, was a fundamental property of the Earth’s atmosphere that had been established before these glacial deposits had formed and had persisted to the present-day. He realized that if all the southern continents had been joined together to form a supercontinent lying near the south geographic pole, then the present-day distribution of all the Permo-Carboniferous tillites would have a logical explanation. This supercontinent is known as Gondwana. But Wegener went further and postulated that the northern continents had also been joined to form a northern supercontinent known as Laurasia, which, with Gondwana, formed a huge continental area incorporating all the major continents, known as Pangea.

Wegener’s solution to the tillite distribution had a compelling elegance about it, partly because it also placed the Carboniferous forests of Europe and North America, (whose compressed remains gave the name to the Carboniferous period) in what would have been the tropical region of that time. However, elegance is not a scientific proof, and Wegener’s ideas were rejected by most geophysicists and many geologists, principally...
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