Earthquake Cycles and Rupture Patterns: Insights and Models from Paleoseismic Data

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Abstract

Paleoseismic studies yield observational data on the temporal and spatial rupture characteristics of moderate to large magnitude earthquakes over multiple rupture cycles. Such data are essential for developing predictive models of earthquakes at scales of time and magnitude that affect society. Therefore, paleoseismic data has been influential in assessing seismic hazard and developing models of fault behavior over multiple earthquake cycles. The models can be loosely categorized as deterministic, variable behavior, and clustered. Deterministic models include fault segmentation, characteristic slip, and time predictable behavior. Non-deterministic models include irregular recurrence, variable slip and variable rupture patterns. Several data sets suggest that ruptures are temporally clustered.

Introduction

Moderate to large magnitude crustal earthquakes typically generate surface rupture or induce permanent changes in the landscape and local environment. Such earthquakes are potentially catastrophic if they occur in populated areas. They are also important because they account for the bulk of seismic moment release along individual faults [1]. Earthquake cycles, or successive surface ruptures, occur on the order of hundreds of years for the fastest-moving faults to thousands or tens of thousands of years for more numerous but less active faults [2]. Modern observation and analysis of seismicity has occurred for a small fraction of this time. Therefore, there are few observations on the spatial and temporal characteristics of fault ruptures over multiple seismic cycles [3]. Such observations are essential for developing predictive models of fault behavior over scales of time and magnitude that have a significant impact on society.

Paleoseismology is the study of pre-historic or pre-instrumental earthquakes preserved in the geologic and environmental record[4]. Paleoseismic investigations provide data on the temporal patterns of earthquake recurrence, variations of rupture displacement over space and time, and information on rupture termination [5,6]. Therefore, paleoseismic data has been influential in assessing seismic hazard and developing models of fault behavior over multiple earthquake cycles.

The global paleoseismic data set is much smaller than other data sets in observational seismology and geophysics. Only a few faults world-wide have records of ruptures spanning 10 or more cycles. However, the amount of paleoseismic data has increased markedly in the last decade and generated several earthquake records suitable for developing and testing theoretical or computational models of fault behavior[7].

Models based on paleoseismic data can be loosely categorized as deterministic, non-deterministic, and clustered. Examples of deterministic models include fault segmentation, characteristic slip, time predictable and slip predictable behavior. Variable behavior models include irregular recurrence, variable slip and variable rupture patterns. Several data sets suggest that ruptures are temporally clustered. Selected models developed from or tested against paleoseismic data are summarized here, and described more fully in [5].

Deterministic models

Deterministic models of fault behavior were developed from early paleoseismic investigations with very small data sets. The models are attractive because they are simple and potentially useful for prediction. Efforts at prediction such as the Parkfield earthquake prediction experiment and forecasting earthquakes on the San Andreas fault in California were based primarily on these models [5].

Fault segmentation

Segmentation models assume that faults are divided into discrete, identifiable sections that behave distinctively over multiple rupture cycles (e.g. [1]). Fault segments are convenient units for computational simulation of earthquake ruptures. Segment boundaries are thought to control the termination and initiation of fault ruptures and therefore limit the magnitude and rupture pattern of an earthquake. Fault segments are defined based on structural discontinuities and changes in strike as well as by paleoseismic data [1,2,3] and slip rate.

Only a few segment models have been tested against rupture patterns of historic earthquakes [3] with mixed results. Preliminary tests of segment models using paleoseismic and historic rupture data suggests that the models may be more applicable to normal faults than strike-slip faults [5]. Many more observations are needed to test segmentation hypotheses and their utility for simulating earthquake cycles.

Characteristic slip

The characteristic earthquake model [1] is probably the most influential model of fault rupture and earthquake recurrence developed from paleoseismic data. The characteristic earthquake concept was formulated from extensive studies of normal faults in the Wasatch fault zone, western U.S., and from early paleoseismic data on the behavior of the San Andreas fault in California. It has been widely applied for seismic hazard assessment and analysis of fault mechanics.

The basic tenet of the model is that most surface slip on a fault occurs in *characteristic earthquakes*. Characteristic earthquakes are the result of *characteristic slip*: at a specific location along a fault, the displacement (slip) is the same in successive characteristic earthquakes. This implies that characteristic earthquakes have similar rupture patterns and that a fault can be divided into segments that behave characteristically. Each segment would have a distinctive or "characteristic" rupture pattern and magnitude. Characteristic slip requires variable slip rate along a fault to account for different amounts of total slip.

According to the characteristic slip model, most seismic moment is released on a fault by repetition of characteristic earthquakes of approximately the same magnitude. This causes a kink in the recurrence curve known as *characteristic recurrence* due to the high number of relatively large magnitude characteristic earthquakes.

Recent paleoseismic studies of the San Andreas fault and other faults reveal complexity in spatial and temporal rupture patterns that was not evident when the characteristic earthquake model was first proposed [8]. Debate about the applicability of the characteristic earthquake model for forecasting and modeling earthquakes is likely to continue.

Time predictable model

Paleoseismic investigations are the main source of data for measuring or estimating recurrence times and average recurrence intervals. Assuming the slip rate of a fault is constant over the period of observation and there is no creep, then recurrence time is a linear function of displacement. If displacement occurs in constant-size (characteristic) earthquakes, then the recurrence time can be "predicted" from the amount of slip (displacement) in previous earthquakes. The time-predictable model was developed from observations of uplifted coastal terraces in Japan[9]. The model has been applied to forecast earthquakes, and to estimate the dates of paleo-earthquakes from measurements of previous co-seismic displacements.

Clustering models

Temporal and spatial clustering is a well-known property of historically observed earthquakes. Early paleoseismic data sets were too small to test temporal clustering hypotheses for paleo-earthquakes. Several recent paleoseismic studies suggest quasi-periodic or clustered recurrence of surface ruptures within the boundaries of measurement uncertainty [5,6]. At several investigation sites along the San Andreas fault previous ruptures have been reported to occur in an irregular pattern or in temporal clusters. Temporal and/or spatial clustering of surface ruptures has also been proposed to describe recent surface ruptures of normal faults in the Basin and Range, and paleo-earthquakes in the eastern California shear zone, USA. Historic and prehistoric records of earthquakes spanning thousands of years in Turkey and Iran suggest that large earthquakes were triggered by previous ruptures to form temporal clusters or cycles of damaging earthquakes. Although these results are very intriguing, larger paleoseismic data sets are needed to conduct statistically significant tests of clustered recurrence.

Variable behavior models

Several paleoseismic data sets suggest that fault rupture patterns in time and space are irregular or variable, but the small size of the data sets and uncertainty in the data make it difficult to recognize patterns, if they exist. Space-time diagrams of rupture patterns have been prepared by compiling the dates of paleo-earthquakes at different locations along a fault, or system of faults. Error bars on the dates of earthquakes create uncertainty in correlating ruptures and lead to non-unique solutions. However, repetition of regularly spaced, identical earthquakes has been ruled out for several faults using such data.

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