Earthquakes in Stable Continental Crust

Earthquakes can strike even in stable crust, well away from the familiar earthquake zones at the edges of tectonic plates. What accounts for these enigmatic events?

by Arch C. Johnston and Lisa R. Kanter

Charleston, South Carolina, is a long way from earthquake country. The rim of the Pacific, the Mediterranean and central Asia experience most of the world's earthquakes, both spectacular and small. Yet in 1886 a quake several times larger than the event that struck San Francisco in October of last year severely damaged much of Charleston. Near the coast, the water-saturated soil liquefied and erupted in geyers of sand and mud. Scores of people were killed, and the devastation was so great that before it was slowed.

By most standards Charleston occupies a geologically quiet zone. Plate boundaries, where the 100-kilometer-thick plates of rock that make up the earth's outer shell collide, rift apart or slide past each other, are the scene of the most earthquakes and the most volcanism, active faults and most earthquakes. The San Andreas fault, for example, the boundary between the plate that carries most of North America and the plate underlying the Pacific Ocean, cuts directly through California. Yet Charleston lies well away from a plate boundary; the eastern edge of the North American plate is thousands of kilometers offshore, in the middle of the Atlantic Ocean. The area has not experienced the tectonic crust-deforming activity of a plate margin since the opening of the Atlantic some 180 million years ago.

The earthquake that collapsed buildings in Newcastle, Great Britain, in December of 1985 killed 116 people, and the city's recovery from the devastation of the Civil War, 20 years before, was slowed.

As the rifting begins, the continental crust becomes stretched and thinned, oceanic crust is riddled with faults and veined with volcanic rocks. Questions of seismic hazard, in fact, helped to motivate our own systematic study of these earthquakes, which was sponsored by the Electric Power Research Institute in Palo Alto, Calif., and done with Kevin Coppersmith and his co-workers at Geomatrix Consultants in San Francisco and Ann G. Metzger of Memphis State University.

We sought answers to two major questions: Just how much seismic activity does take place within the stable parts of continents? And are there specific geologic features that make some areas of stable crust particularly susceptible to earthquakes? We began by studying North America alone, but it soon became clear that the fairly short record of these rare events on a single continent would not provide enough data for reliable analysis. Hence, we decided to substitute space for time—to survey earthquake frequency and distribution in stable continental areas worldwide.

What counts as stable continental crust? The challenge was to identify the very quietest parts of continents, well away from the tectonic activity of plate boundaries. Clearly, the bedrock shields, some of them more than three billion years old, that form the ancient hearts of continents and the "platforms" of sediment-covered bedrock that surround the shields qualify as stable crust. At the other end of the spectrum, the plate boundaries themselves had to be excluded. After that, though, the choices of what to define as stable crust became more complex.

Tectonic activity driven by plate interactions can extend well away from plate boundaries. Where plates converge and an oceanic plate is subducted beneath a continental plate, volcanic activity and mountain building may take place in a band hundreds of kilometers wide on the overriding continent, as it does in the Andes. If both plates bear continents or continental fragments, the collision can produce a region of folded, uplifted and faulted terrain several thousand kilometers wide, typified by the Himalayas, the Tibetan plateau and central Asia as far north as Lake Baikal.

The converse process—the rifting of a continent to form two new plates—occurs by stretching the upper part of the continent. New ocean floor is generated at the ridge, where the ridge is subducted beneath a continental plate, in the Mid-Atlantic Ridge, where the new ocean floor is generated. It is an event of great interest to both private and public committees, on seismic hazards in the United States. A few years ago, a group of scientists at Stanford University in 1983 and moved to CERI in 1985. Johnston writes that F.A.U.L.T. is an acronym for Faults and volcanic activity are not the only events that can occur in continental crust.
volcanic material. Once a full-fledged oceanic spreading center develops between the rifted edges of the continent, the continental crust stops stretching. Its edges cool and subside, creating what are known as passive margins. As plate boundaries migrate and reorient themselves over geologic time, regions deformed by compression or stretching become part of the plates' stable interiors. They are no longer the scene of intense tectonic activity, even though they do still experience stresses—in general, compressive ones—transmitted from the distant edges of the plates. Along with the ancient shields and platforms, then, we counted as stable continental crust mountain belts older than about 100 million years (the Appalachians and Urals but not the Alps and Himalayas, for example) and passive margins older than about 25 million years (the margins of the Atlantic but not of the Red Sea). We also included ancient failed rifts, where a full-fledged spreading center did not develop and the stretched crust subsided into a broad valley or a sediment-filled trough. By these criteria nearly two thirds of all continental crust qualifies as stable.

To determine the earthquake activity within these least seismic parts of the continents, we could not rely on recent instrumental records alone; even global records are too sparse. We had to cast as wide a net as possible and include earthquakes in historical accounts. In North America such accounts begin in the 16th and 17th centuries, but in Europe they cover 1,000 years and in China more than 2,000.

Simply counting the events in the historical record was not enough; we needed a measure of their size. Current practice recognizes the moment-magnitude scale, devised by Hiroo Kanamori of the California Institute of Technology and Thomas C. Hanks of the U.S. Geological Survey, as the most reliable way to gauge earthquake size. Earlier scales, such as the Richter scale, rank earthquakes according to the amplitude of specific seismic waves, which can vary for an earthquake of a given energy depending on the wave frequency at which the amplitude is measured. The moment-

FAULT IN ANCIENT CRUST was the site of a 1988 series of moment-magnitude 6 earthquakes near Tennant Creek, in Australia's Northern Territory. The events are among the few recorded stable-continent earthquakes in which the surface ruptured. J. Roger Bowman of the Australian National University made the image.
magnitude scale, in contrast, is based directly on the physical process at the heart of an earthquake: the slip of rock along a fault.

The scale is based on seismic moment: the size of the force couple (two opposite forces) that caused the fault to rupture. Seismic moment is equal to the surface area of the rupture multiplied by the average displacement of the rock along the rupture and the rock’s rigidity. Moment magnitude (designated M) is linearly proportional to the logarithm of the moment, so that an event of M = 7 is 32 times larger than one of M = 6 and 1,000 times the size of an M = 5 event.

Seismic moment can be calculated even if the ruptured fault is inaccessible—hidden underwater or buried at a depth of many kilometers. Thanks to techniques developed by Keiiti Aki, who is now at the University of Southern California, and many later workers, an earthquake’s seismic moment, and hence its moment magnitude, can be determined from low-frequency components of seismic waves, which can be recorded at a distance by seismographs. Yet nearly half of the stable-continent earthquakes in our list, and the majority of the largest ones, took place before the invention of the seismograph in the late 19th century. We had to develop a way of estimating seismic moment from the evidence in historical accounts: “intensity areas,” or descriptions of an earthquake’s effects on people, buildings and the landscape and their areal extent.

Fortunately, we had both intensity areas and seismic moments directly computed from instrumental data for more than 50 stable-continent earthquakes. By applying statistical regression techniques to the data, we were able to develop a correlation between intensity areas and seismic moment for earthquakes in stable crust; we could then assign moment magnitudes to other events that lacked instrumental data. The largest stable-continent earthquakes on record turned out to be the great earthquakes centered in New Madrid, Missouri, during the winter of 1811–12, which had moment magnitudes ranging from M = 8.1 to M = 8.3.

In comparison, the largest earthquake recorded in any setting, the 1960 plate-boundary event in Chile, measured M = 9.5, or 63 times larger. (That magnitude represents an energy equivalent to that of an average hurricane but released in one or two minutes rather than over 10 days.)

The New Madrid events, however, may have been felt over a wider area than any other earthquake in history; the strong rock of plate interiors transmits seismic waves far more efficiently than the fault-laced crust near plate boundaries. Centered 1,000 miles inland, the New Madrid quakes damaged masonry as far away as the East Coast and collapsed scaffolding erected around the U.S. Capitol [see "A Major Earthquake Zone on the Mississippi," by Arch C. Johnston; Scientific American, April, 1982].

The Kutch, India, earthquake of 1819 ranks second to the New Madrid events in magnitude: M = 7.8, based on sketchy intensity areas. It also yields an independent check of our empirical correlation between intensity areas and seismic moment. In contrast to the faults responsible for most stable-continent earthquakes, which are deeply buried under the layers of sediment that cover much old crust, the fault rupture at Kutch reached the surface.

The effects were dramatic indeed. A scarp between six and nine meters high and at least 90 kilometers long was thrust up; it became known locally as the Allah Bund, or "Wall of God." Land to the north of the Allah Bund was elevated, while to the south what had been a low-lying rann—a salt flat that flooded periodically—was further depressed. Sindree Fort, built well before the event, had stood on a small rise in the rann. When the motion of the fault depressed the land to the south, the fort was so deeply submerged that soldiers had to escape by boat from the upper turret.

We might note that the juxtaposed uplift and submergence make the Kutch event one of the most vivid illustrations of the elastic-rebound theory of faulting. The theory (not formally elaborated until after the great San Francisco earthquake of 1906) holds that an earthquake is a sudden release of elastic strain built up in the rock; it predicts that rock on opposite sides of the fault will move in opposite directions. At Kutch, absolute sea level acted as a reference plane to dramatize the crust’s opposite vertical displacements.

<table>
<thead>
<tr>
<th>EVENT</th>
<th>HOST STRUCTURE</th>
<th>M</th>
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<tr>
<td>1. New Madrid, 1812</td>
<td>rift</td>
<td>8.3</td>
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<td>2. New Madrid, 1811</td>
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<td>3. New Madrid, 1812</td>
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<td>5. Baffin Bay, 1933</td>
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<td>6. Taiwan Straits, 1604</td>
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<td>14. Portugal, 1858</td>
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<td>15. So. Tasman Rise, 1951</td>
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Earthquake
Plate Boundaries
Rifted Stable Crust
Unrifted Stable Crust
Active Crust

**STABLE REGIONS** make up about two thirds of all continental crust. In defining stable crust, the authors excluded plate boundaries and broad, diffuse regions of active or recent deformation. The 15 largest earthquakes (on a scale of moment magnitude, M) ever recorded in stable crust (above) have all occurred where crust has been stretched and thinned over the past 250 million years.
More to the point, the obvious fault movement meant that we could calculate the seismic moment directly. The British had made careful measurements of the fault length and slip. To calculate seismic moment, we also needed to know how deep the rupture zone extended and the rigidity of the rock, but reasonable assumptions can be made for both quantities. The resulting moment was within a factor of two of the moment estimated from the intensity reports, which added to our confidence that we could adequately reconstruct seismic moment from historical accounts alone.

The New Madrid and Kutch earthquakes are only the most prominent elements in a data set of more than 800 stable-continent events of $M = 4.5$ or more. The number may seem large, but it is the sum of a global record covering centuries or millennia. (Many more earthquakes of $M = 4.5$ or greater take place along plate boundaries in just a year.) To find out just how seismic-moment release on stable continents compares with earthquake activity worldwide, we constructed a so-called frequency-magnitude diagram. Such a diagram has earthquake magnitude plotted on its horizontal axis and the number of events equaling or exceeding a given magnitude plotted on its vertical axis. If the vertical scale is logarithmic, frequency-magnitude plots for any given seismic zone yield a nearly straight line, sloping down from the smallest, most frequent events to very rare, catastrophic events.

Even if an earthquake catalogue overlooks very small events or covers too short a period to include very large ones, the consistent relation between frequency and magnitude means the plot can be extrapolated to estimate the frequency of earthquakes over a wide magnitude range. It is then straightforward to integrate the results to find the total seismicity—the rate at which seismic moment is being released—for the region covered by the data. Our calculations for stable continental crust yielded a total moment release of about $10^{26}$ dyne-centimeters (the conventional units of seismic moment) per year, or less than .5 percent of the global total.

No doubt our data set is incomplete. It probably includes every earthquake larger than $M = 7$ during the time of the records. Small and moderate-size events in remote regions may never have been recorded, however, which adds uncertainty to the frequency-magnitude diagram. Still, there is reassuring agreement between the seismicity figures and another source of information about processes in stable continental crust: independent measurements of the rate at which stable crust is being deformed.

Using signals from satellites or distant astronomical objects as references, geophysicists are now measuring tiny changes in distance between receiving stations thousands of kilometers apart as the intervening crust is stretched or compressed [see "Studying the Earth by Very-Long-Baseline Interferometry," by William E. Carter and Douglas S. Robertson; SCIENTIFIC AMERICAN, November, 1986]. For two stations separated by a zone of active tectonics near a plate boundary, the
deformation can amount to several centimeters a year. Stable continental crust also deforms in response to the compressive stresses transmitted from plate boundaries, but preliminary measurements suggest the rate is minuscule, about one part in \(10^{10}\) per year—perhaps a millimeter over thousands of kilometers.

If one assumes that all the stresses built up in this deformation are ultimately released in earthquakes (a reasonable assumption for the strong, brittle crust of continental interiors), it is possible to calculate how much seismic activity should accompany the deformation. B. V. Kostrov of the Soviet Academy of Sciences has shown that the moment-release rate is then proportional to the volume of crust multiplied by the rate of strain, or deformation. A strain rate of \(10^{-10}\) per year yields a predicted rate of moment release in stable continental crust that agrees nicely with what we calculated from our earthquake data set.

![Kutch Earthquake of 1819](image)

Kutch Earthquake of 1819 was unusual among stable-continent events in that the fault rupture reached the surface. It uplifted a scarp between six and nine meters high (the Allah Bund) across the salt flats known as the Rann of Kutch (above), in western India (left). Land to the north was uplifted; to the south the land subsided. Sindree Fort had stood on a rise (below); after the earthquake only the turret remained above water, as illustrated 19 years later from another angle (bottom). The woodcuts are from 1853 edition of Sir Charles Lyell’s classic book Principles of Geology.

Our figure for earthquake activity in stable crust is actually an average of a rate that varies widely from continent to continent. Antarctica and Greenland are quite devoid of significant earthquakes, perhaps because the massive ice sheets there stabilize any faults, inhibiting slip. The stable parts of South America and Asia (Siberia) are seismically quieter than the remaining stable continental regions. It may be that these variations reflect differences in average, continent-wide levels of stress—a possibility that might be tested by systematic comparisons of deformation rates within different continents.

Within the stable areas of a single continent, too, seismicity varies widely. To find out why, we worked with David B. Bieler, then at Memphis State, to analyze the tectonic history of stable continental regions and correlate it with earthquake distribution. One crustal characteristic stood out as a universal precondition for the largest stable-continent earthquakes.

Like many seismologists, we had expected stable-continent events to be associated with specific zones of weakness in the crust. Ultimately, of course, earthquakes in stable crust are the product of compressive stresses that originate at plate edges. Yet variations in the stress field within a continent seemed unlikely to be the sole explanation of the earthquake distribution. As Mary Lou Zoback of the USGS, Mark D. Zoback of Stanford University and others have shown from worldwide studies of earthquake faulting and of boreholes drilled into bedrock (which deform under the influence of the prevailing stress field), the compressive forces in continental interiors are consistent in orientation across vast areas.

Hence, an earthquake seemed to require a region weakened by past tectonics, where these stresses could be relieved. Crust dissected by old faults, such as an ancient mountains belt or a failed rift, might qualify. The pervasive compression within a continent might sometimes reactivate these old faults, causing them to slip and generate earthquakes.

Our findings largely bear out this reactivated-fault model. Areas that have undergone extension at some time in the past, such as passive margins and failed rifts, are more likely to experience an earthquake of any size than, say, ancient shields are. Of the more than 800 earthquakes we studied, almost half (49 percent) fell within such extended crust, even though it makes
RIFTED CRUST, the site of most large stable-continent earthquakes, forms over millions of years when extensional forces break up the brittle upper crust into blocks separated by active faults (1). Continued extension thins the crust, allowing magma to well up. If the stretching stops, the stretched crust remains as a failed rift (2a), in which new sediments accumulate. If the stretching continues, the continental crust eventually ruptures, giving birth to a spreading center at which new oceanic crust is produced. The stretched continental crust subsides, resulting in sediment-covered passive margin (2b).

The correlation grows stronger with increasing magnitude; whereas only 46 percent of earthquakes smaller than $M=6$ took place in extended crust, the figure is 60 percent for events between $M=6$ and $M=7$ and 100 percent for the largest events, of $M=7$ or more. A failed rift underlies the site of the New Madrid and Kutch earthquakes, for example, and the Charleston event took place on an extended passive margin. For all these largest events and most of the smaller ones on rifts or passive margins, the extension was comparatively recent—older than 25 million years (by definition) but younger than 250 million years.

The correlation between extended crust and earthquakes of moderate size would have been stronger had it not been for one continent full of exceptions: Australia. The ancient, unrifted crust of western and central Australia has experienced several earthquakes that rank among the largest events not associated with extended crust. The events, which took place in a remarkable 12-hour sequence...
SEISMIC ACTIVITY at plate boundaries and the associated active regions is compared with activity in several kinds of stable crust by a frequency-magnitude diagram. Earthquakes of all sizes are several hundred times more common at plate boundaries than they are in stable regions. Within stable crust, earthquakes take place more often in rifted areas; the correlation is the strongest for the largest events.

CONTINENT PEPPERED WITH EARTHQUAKES is Australia, which consists entirely of stable crust—an ancient core (pink) surrounded by somewhat younger crust (orange) and passive margins (red). A region of ongoing plate collision borders Australia to the north. Australia follows the general rule that the largest stable-continent earthquakes occur within crust that has undergone recent extension, but its largest onshore events have taken place in un rifted ancient rock and have produced surface faulting. The map, which shows both recent and historical events, is based on one in a series prepared by the authors for all the stable continental regions on the earth.
earthquake distribution, the events might seem to take place at random, as the smallest earthquakes in our record do.

The most important result of our study is that the largest earthquakes do not take place at random. Knowing that they are concentrated in failed rifts or passive margins is a promising start toward placing constraints on areas of earthquake risk. Yet it is hardly comparable to seismologists' ability to pinpoint earthquake-prone sites near plate boundaries, where many active faults are apparent at the surface and rupture often and regularly. Indeed, for many plate-margin faults it is possible to determine an approximate recurrence interval for major earthquakes, which can be as short as every 40 years or so. As a result, even though such earthquakes cannot yet be predicted with an accuracy of hours or days, they can sometimes be roughly forecast. The fault segment that was responsible for last year's earthquake south of San Francisco, for example, was identified in 1988 as being quite likely to sustain a large event within 30 years.

Forecasting stable-continental events—say nothing of predicting them—is a difficult problem. The deeply buried faults responsible for most of them cannot be identified at the surface, and the faults do not betray themselves by rupturing frequently. Of the 15 earthquakes of M = 7 or greater in our catalogue, none was a repetition of an earlier recorded event. It is also possible, however, that an earlier earthquake preceded the 1886 Charleston event by about 1,900 years. In excavations north of Charleston, S.C., the "sand blow" on the right (dated from bark fragments) is about 950 years old, the left one about 1,900 years. The earthquakes responsible had a source different from that of the 1886 Charleston event.

SOIL LIQUEFACTION can make it possible to date a large prehistoric earthquake. When a powerful earthquake shakes water-saturated sandy soil, the water pressure rises, and the soil becomes a viscous liquid that can erupt through overlying layers to the surface. The disturbed soil may trap organic matter that can be carbon-dated. In this excavation north of Charleston, S.C., the "sand blow" on the right (dated from bark fragments) is about 950 years old, the left one about 1,900 years. The earthquakes responsible had a source different from that of the 1886 Charleston event.