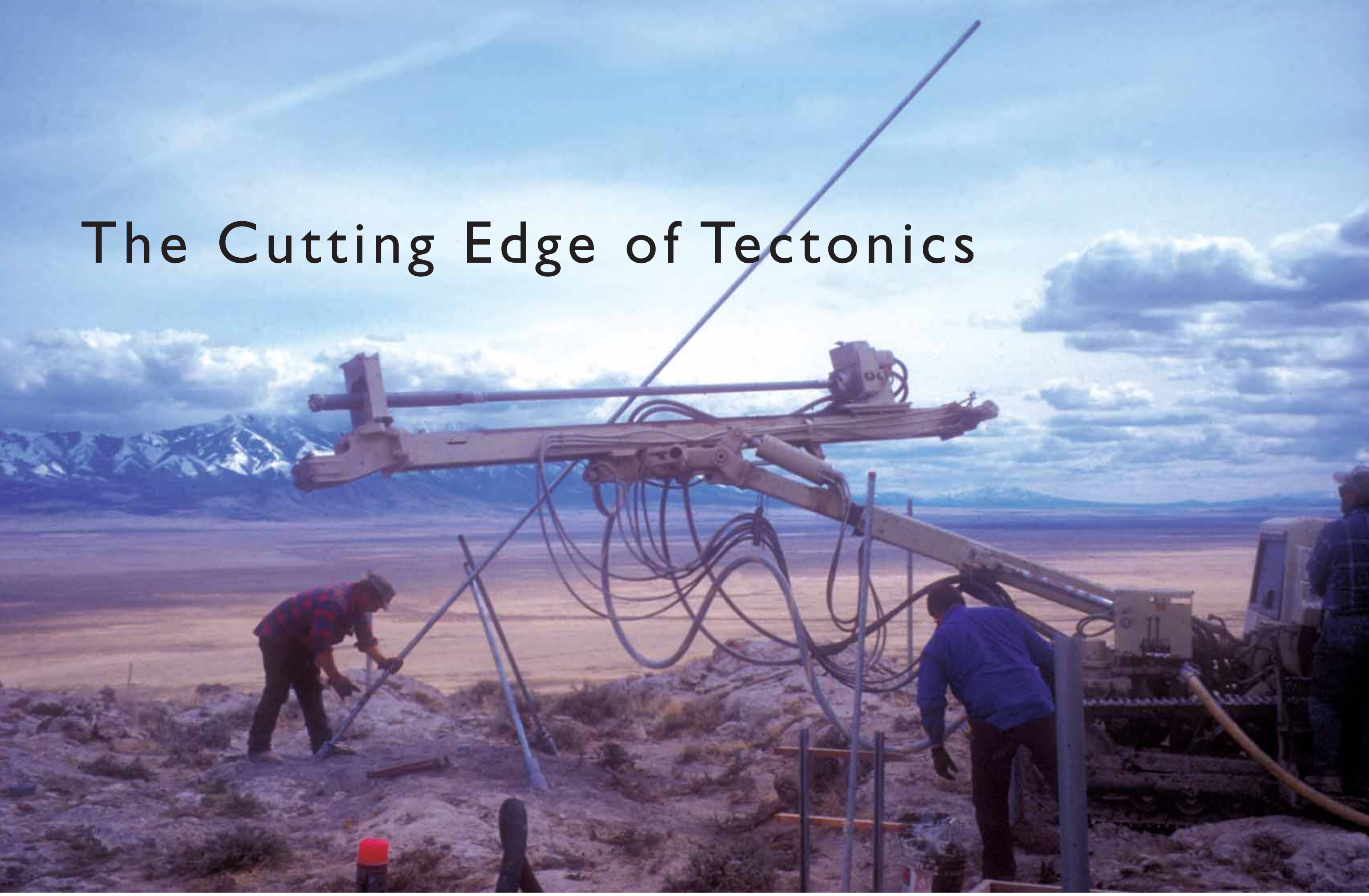


The Cutting Edge of Tectonics

by Brian P. Wernicke

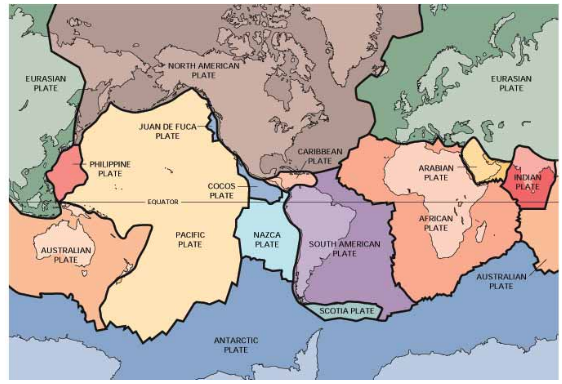
Installing a stable geodetic monument to hold a GPS antenna, above. Caltech has built a network of geodetic sites in the Basin and Range geological province of Nevada and Utah to measure the movement of this part of North America relative to the continental interior.

The term "tectonic" is often used as a metaphor for fundamental, unsettling change. Business analysts talk about "major shifts in the tectonic plates" of a certain market, or the "grinding tectonic shifts" of a recession. Most people don't think about the real thing very much, yet tectonic events like earthquakes and volcanic eruptions, with their associated tsunamis and mudslides, can wipe out tens or even hundreds of thousands of lives in just a few minutes. To match the death toll from the 1985 mudslide in Colombia triggered by the eruption of Nevado del Ruiz, or the 1999 Izmit earthquake in Turkey, the 9/11 bombers would have had to take down ten sets of twin towers, and to match that of the 1976 Tangshan earthquake in northern China, they would have had to level some 100 sets (at least 250,000 dead, just like that). The unspeakable horror of these disasters no doubt contributes to our tendency to keep them—and, by association, tectonics—out of sight and out of mind, except for the day they happen and perhaps a few weeks after. The contrast with plane crashes, terrorism, and even a run-of-the-mill homicide is our sense that tragedies caused by humans are somehow more preventable than those brought about by nature, even though the latter are far more devastating.

We can't eliminate natural disasters, but understanding them can equip us to bear them with comparative equanimity. In the case of earthquakes, a topic of great concern in Southern California, the better we can predict *what* will happen, even if not exactly *when*, the better we'll be able to take measures to mitigate the damage, with the peace of mind that we have not grossly underestimated or overestimated the danger. This is especially true of building codes, where overdesign can be a very costly waste and underdesign deadly, and also of our insurance system, where the optimum level of investment requires a quantitative understanding of long-term risk. The construction and insurance industries might one day be so finely tuned that a magnitude 7 quake could occur in a city of millions with only a few dozen lives lost, and a total unexpected cost to society of perhaps a few hundred million dollars—as opposed to losses measured in thousands or tens of thousands of lives, as at Izmit, or in tens of billions of dollars, as with the 1994 Northridge earthquake. In the case of Northridge, our building

From the standpoint of public benefit, the question “When is the big one going to hit?” may not be so important, because as you’ll see, it *is* going to hit. The really important question is “How big is big, and what do we need to do to cope with it?”

A dozen or so tectonic plates make up the earth’s outer crust.

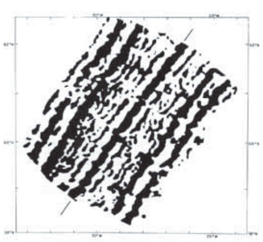


codes kept fatalities down to 61, but the harsh financial effects are still being felt by many of the uninsured. From the standpoint of public benefit, the question “When is the big one going to hit?” may not be so important, because as you’ll see, it *is* going to hit. The really important question is “How big is big, and what do we need to do to cope with it?”

To understand tectonic hazards, we must understand the phenomena behind them. We already know a lot about why and how earthquakes occur, but we are now at a threshold where we can begin to understand them at a much more fundamental and useful level than ever before. The discovery of the theory of plate tectonics in the 1960s was geology’s double helix, but just as knowing the structure and function of DNA has not cured cancer, understanding plate tectonics hasn’t explained why earthquakes happen or volcanoes erupt, much less how big such events might be, and with what frequency they might occur. So what *is* plate tectonics, and what exactly is needed to take the next big step?

Plate tectonics is simply the observation that the outer part of the earth is composed of a relatively small number of internally rigid plates that float on a relatively weak, fluid substrate, and move a few inches a year in relation to one another. We know this because as the plates spread apart, they leave a precise record of how and where they were created. They’re created at the midocean ridges, a huge system of mountains in the middle of the modern oceans that are volcanically active (*E&S* 2002, no. 3). For every kilometer that two plates move apart, a one-kilometer-wide, five-kilometer-thick batch of molten rock rises up from the mantle, cools, and solidifies to form new ocean crust. Particular mineral grains called magnetite within the newly forming rock align themselves parallel to the earth’s magnetic field at the time of cooling, so each bit of new crust along the ridge carries a record of the direction of the magnetic field at the time it formed. We know that this field reverses on a million-year timescale, so as the plates spread apart, they function as a magnetic recorder that can be read by towing a magnetometer over the ocean’s surface. Magnetic maps like the one bottom left show the history of reversals as stripes on the seafloor that look a lot like the bar code on an item you buy at the supermarket. Each of these stripes can be dated, because we know the times of the magnetic field reversals from studying rock strata that have accumulated on the continents, so by counting back from the midocean ridge, we can pin down precisely how the two plates on either side of a ridge moved apart through time.

The distribution of earthquakes across the globe also lends support to the theory of plate tectonics. Looking at the map below, it is immediately apparent that most of globe does *not* experience frequent earthquakes. The plates are basically stable, but there is deformation, manifested as earthquakes, where the plates are in contact at their boundaries, and there are also narrow, well-defined belts of earthquakes along the midocean ridges where the plates are moving apart.



Allan Cox: *Plate Tectonics and Geomagnetic Reversals*, 1973, W. H. Freeman & Co.

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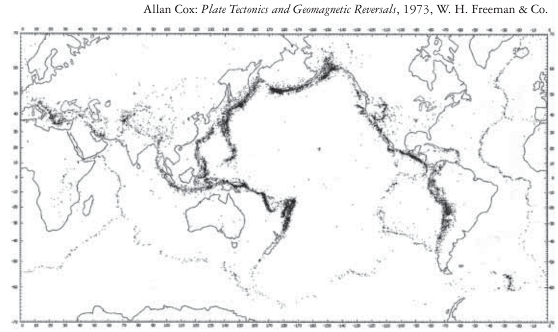
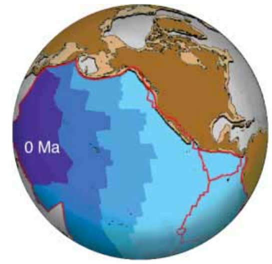
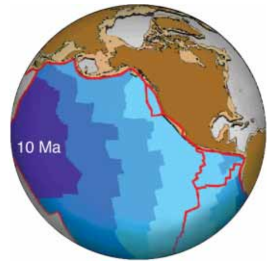
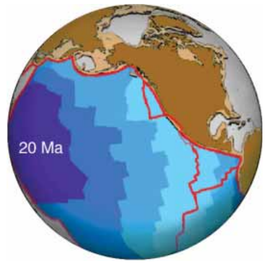
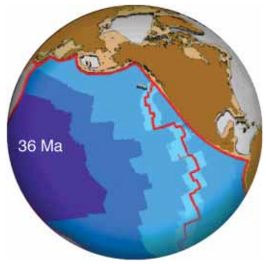


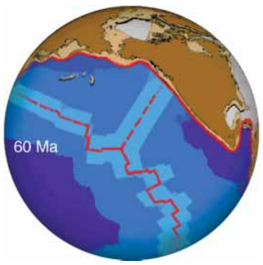
Global distribution of significant earthquakes between 1961 and ’67, above. The ocean floor has been conveniently bar-coded with magnetic stripes, left. This magnetometer reading was taken at the Reykjanes Ridge south of Iceland.

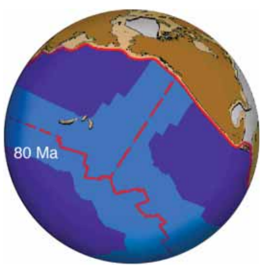










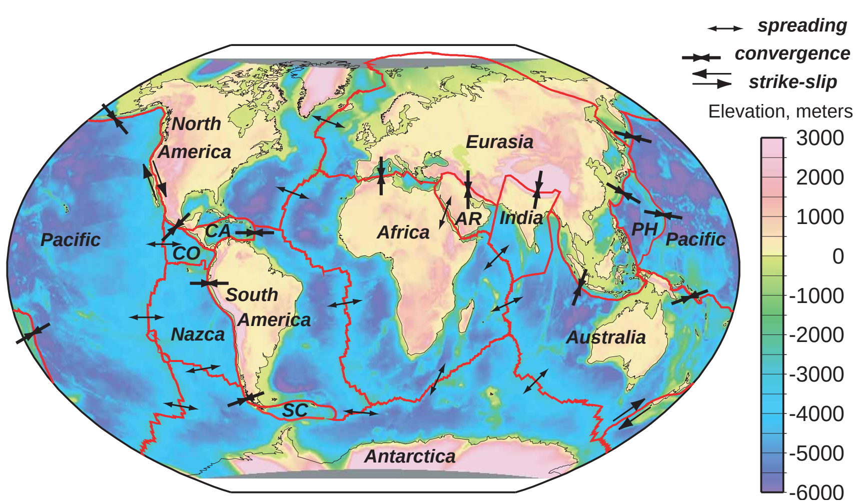


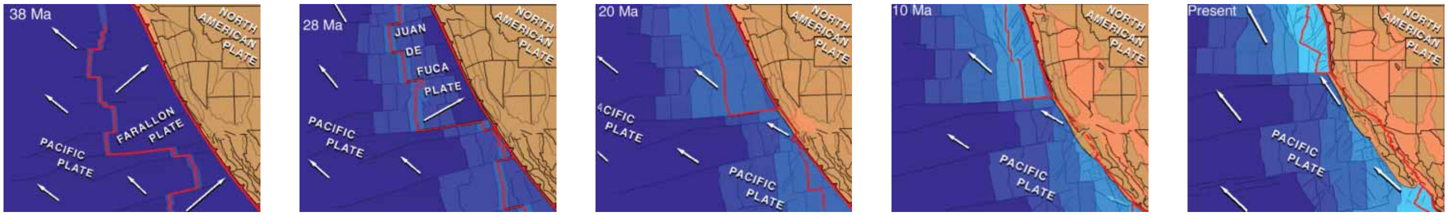
The modern picture of how the plates move with respect to each other is shown below. In addition to boundaries in the oceans where plates are spreading apart, there are places where plates slide directly past one another in a so-called strike-slip motion, and other places where plates converge. An oceanic plate often sinks back into the earth beneath a continental plate when the two meet, a process called subduction. And, as well as belts of earthquakes along each plate boundary, there are also belts of volcanoes. Along the mid-Atlantic ridge, for example, volcanoes and earthquakes are localized along the boundary between the North American and Eurasian plates (best observed in Iceland). Along the coast of Alaska, the Pacific plate plunges beneath the North American plate, creating large earthquakes such as the 1964 magnitude 9.2 Alaskan quake, and building a line of volcanoes on the North American plate stretching from the Aleutians to the interior of Alaska. In Southern California, the Pacific plate slides laterally past the North American plate, causing earthquakes on the San Andreas fault and on those faults beneath us in the L.A. basin.

We can now deduce quite accurately how the plates have moved over the last 200 million years by using the magnetic maps, as Professor of Geology and Geophysics Joann Stock (*E&S*, 1997, No. 3), and Professor Tanya Atwater of UC Santa Barbara, have done. The globes left and above are stills from Atwater's animation of the history of the Pacific Ocean plate boundaries from 80 million years ago to the present. The various shades of blue show the ages of the sea floor, with the lightest blue being the youngest. The Pacific spreading center created a lot of new plate, but the plate area created has been matched by the subduction of plates along the boundaries between the Pacific Ocean plates and North America. Plate motions like this are consistent with the global distribution of earthquakes and volcanoes—but knowing the motions doesn't predict that earthquakes and volcanoes should even exist. In fact the theory of plate tectonics doesn't predict anything other than the overall motion across the plate boundary, which as far as the theory is concerned could be a single, razor-thin, fault.

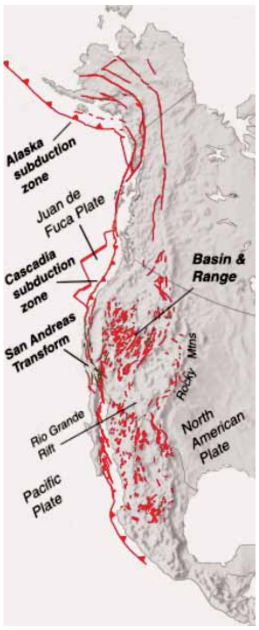
When we look in more detail at how plate boundaries evolve, especially where continents are involved, the picture becomes incredibly complex. For example, the plate boundary of western North America has a rather wide and complicated zone of faulting. Although some of these faults, like the San Andreas, clearly reflect the fact that the Pacific plate is moving northwestward at about five millimeters a year, the average rate of slip on

Above: Over the last 80 million years, the big spreading ridge in the Pacific Ocean added a lot of new (light blue) material to the Pacific plates and moved steadily closer to the North American plate. This animation, and the one at the top of the facing page, are at http://emvc.geol.ucsb.edu. Right: How the world's tectonic plates are moving in relation to one another.





Over the last 40 million years, the Farallon and Juan de Fuca plates have plunged below the North American plate, bringing the Pacific plate to the edge of the continent. Its movements since then have caused a lot of spreading (in pink) in the western part of the continent—just look at the growth of Nevada—and created the numerous faults shown in red on the map below.



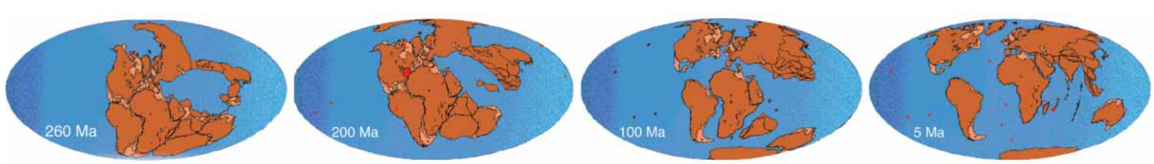
the San Andreas itself is only a fraction of the total plate motion, and the rest is soaked up by a complicated array of smaller faults (left). These include faults in Southern California that accommodate north-south convergence, called thrust faults, and faults across the Basin and Range province in Nevada and Utah that accommodate east-west stretching, called normal faults.

We can combine plate reconstructions with the geological history of the southwest to get a good picture of how this zone of faulting evolved, above. Over the last 40 million years, the ridge in the middle of the Pacific steadily approached North America. It collided with the continent between 10 and 20 million years ago, after which the boundary between the Pacific and North American plates widened, and the Pacific plate started to move obliquely away. This caused a huge area within North America to start spreading, creating the Basin and Range province of Utah and Nevada. Then, about 10 million years ago, the Pacific plate began to move more parallel to the coast, giving birth to the strike-slip San Andreas, tearing Baja California off the edge of the continent and driving it northward into the San Andreas, and creating the thrust faults in Southern California.

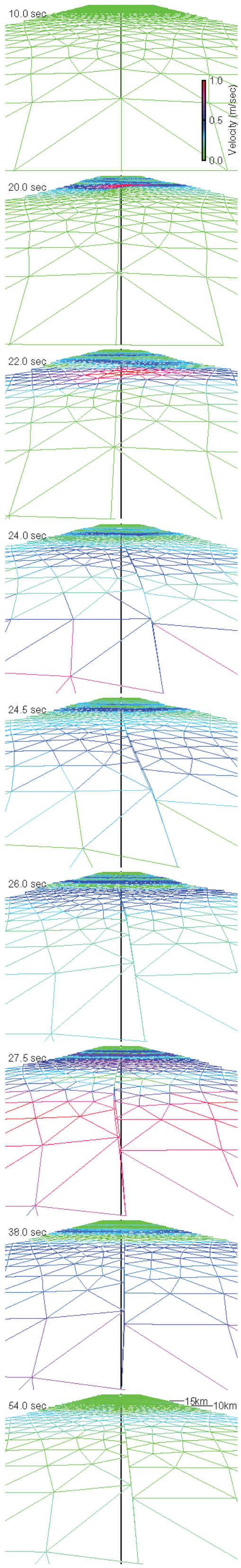
But, as I said earlier, plate tectonics is only a theory of motion, like Kepler's description of the solar system, and cannot be used to predict why there are earthquakes, how often they will occur, how big they will be, and why patterns of faulting along continental plate boundary zones are so wide and complicated. We need a theory of how motion is related to force, analogous to Newton's laws. In particular, we need a physical theory to account for both the slow, steady motion of plates on the one hand, and the rapid, nonsteady behavior of earthquakes on the other. There is reason for optimism that we can do this by using new methods of observation that bridge the huge gap in timescale between the two types of behavior.

To understand why plates move in the first place, it's helpful to take a really long view back. The earth formed about 4.5 billion years ago, yet the oldest magnetic stripes on the ocean floors are only about 200 million years old, which implies that if plate tectonics in its current form has been active through most of the earth's history, about 25 completely new oceans must have been created and destroyed. In the reconstruction of the history of the earth over the last 260 million years as based on plate tectonics (bottom), you can see that the continents were once assembled in one large, vaguely C-shaped mass known as Pangaea. Over the millennia, chunks were transferred from the southern part of the C-shape to the northern part (which eventually became Asia), and each time a piece was transferred a new ocean basin opened in its wake. There were also periods when huge volcanic eruptions poured out magma from the mantle. In a little over 200 million years, a lot of crust rose up, and a lot sank back down. In terms of physical theories that relate force and motion, we have a very good idea that what drives this is heat transfer from the interior to the exterior of the earth through a process called convection.

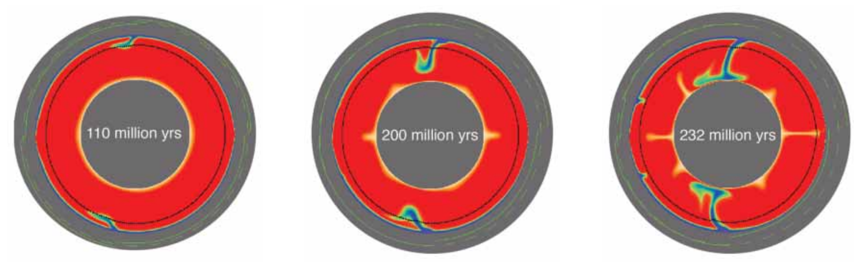
J. Besse & V. Courtillot: *J. Geophys. Res.*, 107, B11, art 2300 (2002)



Some snapshots of our planet at various times in the past, based on plate tectonics. A movie of this (and one showing how the landmasses will regroup in the future) can be found at http://www.ipgp.jussieu.fr/anglais/rub-terre/surface/time.html.



Left: Model of an earthquake on a strike-slip fault. The initial position of the fault is represented by the line down the center. Just behind the wave of strong ground motion, the fault swings rapidly from side to side until, 24 seconds after the start, it slips, and the horizontal lines crossing it break and realign. This all happens very quickly—the fastest waves are traveling at 3 feet a second. Below: Lava lamp earth.



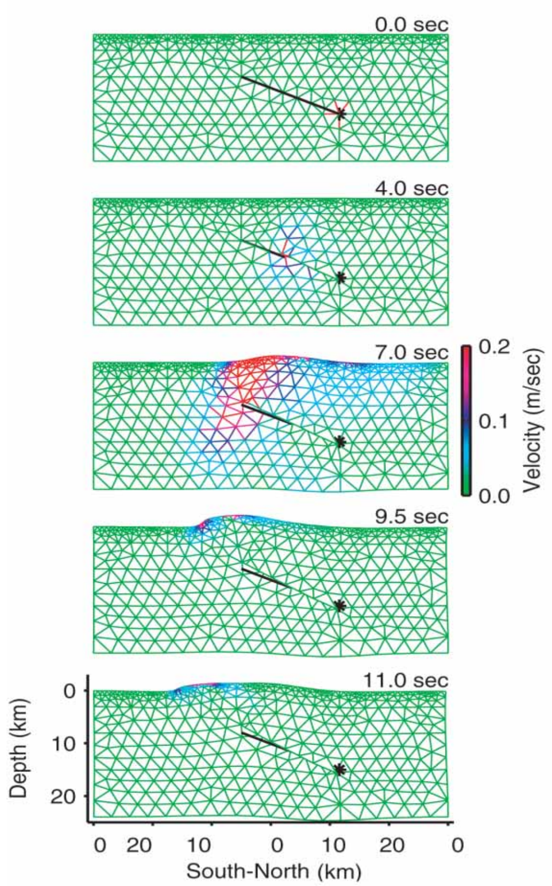
The same thing happens when water is boiled on the stove—the water sits still in the kettle as heat is added, but there's a point when the water at the bottom starts to rise up because it is hot and buoyant, and the cold water at the top sinks down because it is relatively dense. Lava lamps work on the same principle. In the model of convection in the earth's mantle developed by Professor of Geophysics Mike Gurnis and colleagues, above, the relatively cold, blue material represents subduction, the red material is intermediate in buoyancy, and the hot, yellow material is very buoyant. As the cold material sinks, hot material rises from the boundary between the mantle and the earth's molten iron core. (The full animation can be seen at http://www.gps.caltech.edu/~gurnis/Movies/movies-more.html.)

These examples show that we have the computational firepower to develop models of long-term processes such as plate motion, and that we can even make detailed models of individual plate boundaries. The timescales of these are in millions of years. In comparison, similarly sophisticated physical models developed by Brad Aagaard, of the USGS, and Tom Heaton, professor of engineering seismology, have timescales in seconds. Some stills of their animation of an earthquake on a strike-slip fault like the San Andreas (where one block suddenly moves horizontally relative to the other) are shown on the left. Such models of how the ground will move in response to a quake on a given fault help us to predict the worst of the shaking, or strong ground motion, of the earthquake, which is exactly what engineers need to know when designing buildings.

The challenge lies in bridging the gap between two sets of models with a difference of 13 orders of magnitude in time. The part of the spectrum we don't understand very well, mainly because we have very few observations, is the time ranging from decades to hundreds of thousands of years. If we can fill in this gap, we may be able to construct seamless physical models of how plate motions cause earthquakes, which in turn could give us a much better handle on answering questions about the frequency and strength of damaging quakes—the questions that matter most to society. New, improved ways of seeing where faults are, how often earthquakes occur on them, how fast they are moving, and how they moved in the past, make me optimistic that we can do it.

We cannot really understand the hazards of living in areas prone to earthquakes if we do not know where all the faults are. Many faults that generate large earthquakes don't rupture the surface cleanly when they move, and this is nowhere better demonstrated than beneath metropolitan Los Angeles. John Shaw at Harvard and Peter Shearer of the Scripps Institution of Oceanography studied the area around the 1987 magnitude 6 Whittier Narrows earthquake, and found a large blind-thrust fault. The red and white "beach ball" in the map below left on the facing page shows the epicenter of the quake, and the purple line down the middle shows the profile along which a seismic crew vibrated the ground with big trucks, listening carefully to the waves that bounced back in order to get an idea of the structure of the earth at depth. The green circles show oil and gas fields, and the blue lines are the depth contours of a large fault plane that was found. The cross section of this area (facing page, bottom center) showed that at the surface the sedimentary layers were flexed and folded, but deeper down, a group of reflections, shown in red, broke up the sedimentary layers along the line of the fault. This type of fault dies out upward, and has younger sedimentary layers draped over the top, so it's almost impossible to see at the surface. The fault plane lined up extremely well with the main rupture and aftershocks of the Whittier Narrows quake (facing page, bottom right), which must have been due to this thrust fault. With the fault's geometry known, a model of the type of

Airborne Laser Swath Mapping stripped bare the wooded Toe Jam Hill area of Bainbridge Island to reveal a prominent east-west fault line running across the top. The vertical stripes were scoured by glaciers.

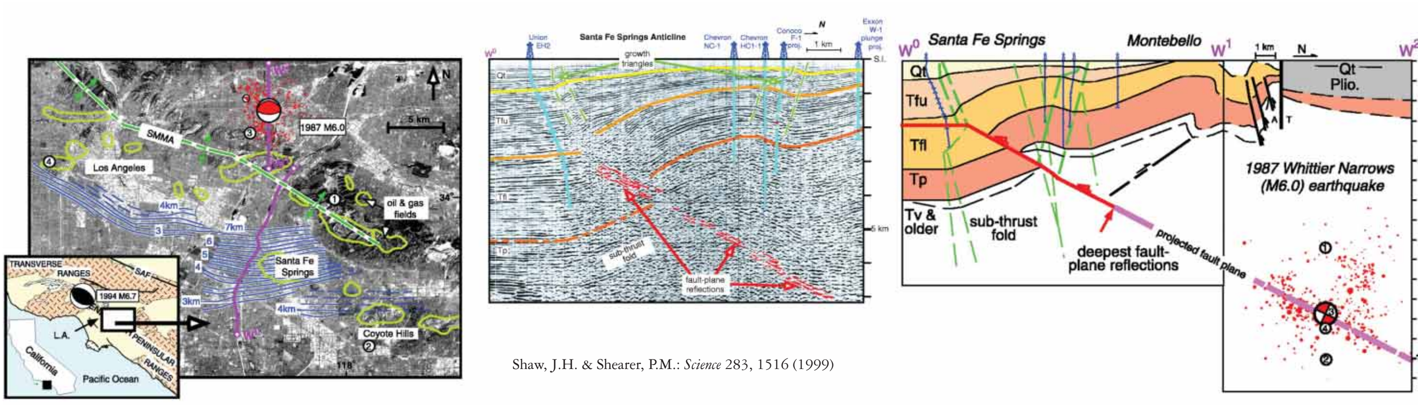


Above: In this model of an earthquake on a blind-thrust fault, the strong ground motions rush to the surface, where they crest like an ocean wave. Bottom, left to right: Seismic recordings taken at Santa Fe Springs, an area south of the 1987 Whittier Narrows earthquake (epicenter shown by the red and white "beach ball") revealed a blind-thrust fault hidden below ground (middle diagram), with the same strike and dip as the fault that ruptured in the Whittier Narrows quake, right.

shaking it might deliver was constructed, left. You can see that the rupture starts at depth, and moves up the fault plane in a wavelike fashion—faults like these are particularly dangerous because large vertical accelerations, reminiscent of an ocean wave, are generated near their upper tip, and these can be very damaging to buildings. Many built-up areas of the L.A. basin could be on top of such hidden faults.

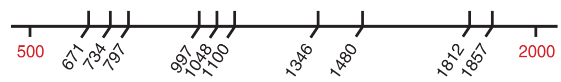
Even if faults *do* break the earth's surface, they can be very difficult to find, especially in areas covered with thick vegetation, like the Pacific Northwest. But a new technology called Airborne Laser Swath Mapping (ALSM) can image vegetated areas and return fine-scale topographic profiles that filter out reflections from the vegetation, enabling the creation of so-called "bald earth images." In the Toe Jam Hill area of Bainbridge Island in Puget Sound there was nothing obvious, either in aerial photos or when walking around on the ground, that suggested the presence of a fault. But ALSM revealed a scar across the north side of the island that turned out to be a strand of the active Seattle fault system.

Once we figure out where the faults are, we need to know how often they break. The times at which large earthquakes occurred on part of the



Shaw, J.H. & Shearer, P.M.: *Science* 283, 1516 (1999)

San Andreas fault have been determined by Sharp Professor of Geology Kerry Sieh and colleagues using carbon-14 dating. They found that over the last 1,500 years, the fault running along the southern margin of the Mojave Desert near Palmdale has ruptured 10 times, with an average frequency of about once every 150 years. The earthquakes have not been at all regular, but have occurred in clusters, with as little as 52 years



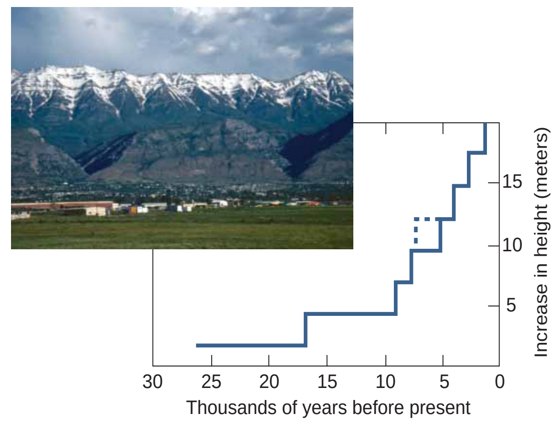
K. Sieh & S. LeVay: *The Earth in Turmoil*, W. H. Freeman & Co.

Near right: Dates of earthquakes on a section of the San Andreas fault close to Caltech. Far right: Over the last 26,000 years, earthquakes pushed the Wasatch Range up behind Salt Lake City. Each step in the graph represents one earthquake.

between some events, and as much as 332 years between others. Are we due for another one soon? Tough to say, but given this history it would not be anything like a surprise if one were to occur before you finish reading this article.

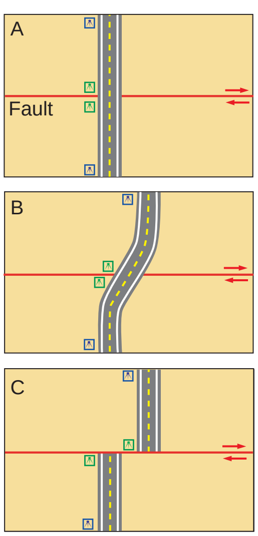
Jim McCalpin (of GEO-HAZ Consulting, Inc.) and colleagues have determined both the time of faulting *and* the amount of upward displacement of the mountains that occurred due to each event for the Wasatch normal fault in Utah. The Wasatch Range is being displaced upward relative to Salt Lake valley to accommodate the east-west stretching of the Basin and Range province. Looking at the plot left, which shows the upward motion, it can be seen that some six earthquakes have occurred in the last 9,000 years, giving a total upward movement of 16 meters (about 50 feet). In contrast, between 26,000 and 9,000 years ago there was only one earthquake, with a total motion over that time of only 3 meters (10 feet). It would appear that the region may be in the middle of a very busy period at the moment!

One way to try to understand how the past links with the present is to get a firm idea of how fast the blocks on either side of a fault are moving at present, using the techniques collectively known as geodesy. The concept is pretty simple. Faults tend to slip mainly during earthquakes, but in between these quakes the crustal blocks on either side of the fault continue to move very slowly and steadily. The regions of each block closest to the fault, however, are stuck—locked in place by the fault—and absorb energy through the accumulation of strain in the rock, much as a spring absorbs energy when extended or compressed. Using geodetic methods like the global positioning system (GPS), we can track the motions of points on either side of the fault to measure how fast this energy is building up. The greater the energy, the

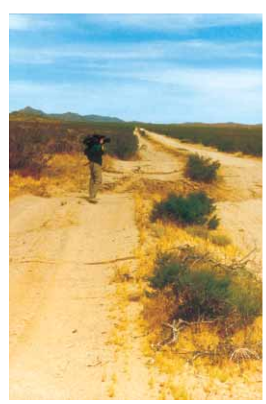


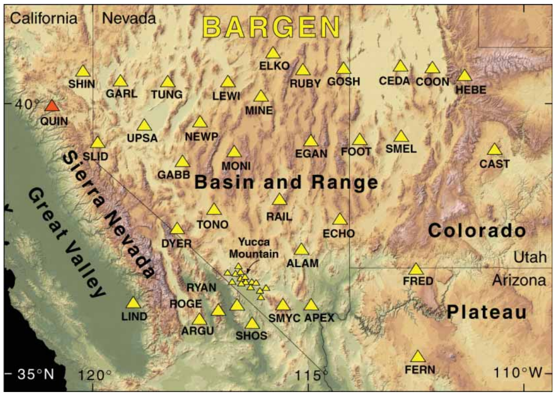
closer the fault is to failure. In the diagrams left, the blue GPS sites 20 kilometers from the fault move at a fairly steady rate just like the plates do. But the green sites close to the fault (about a kilometer away), where strain energy is building up, don't move as much, and the locked fault does not slip at all. When the next earthquake happens, the fault slips so as to line up the green sites with the blue sites again. When this happens, the strain energy built up in the crust is converted to heat and, regrettably, to the energy of seismic waves radiating through the crust. So the steadily moving geodetic sites see little or no motion during the earthquake, while sites closer to the fault feel a sudden jerk.

Over the last 10 years, a number of workers have built GPS-based geodetic networks around the world with the aim of seeing how things are moving. One example of a network of sites built by

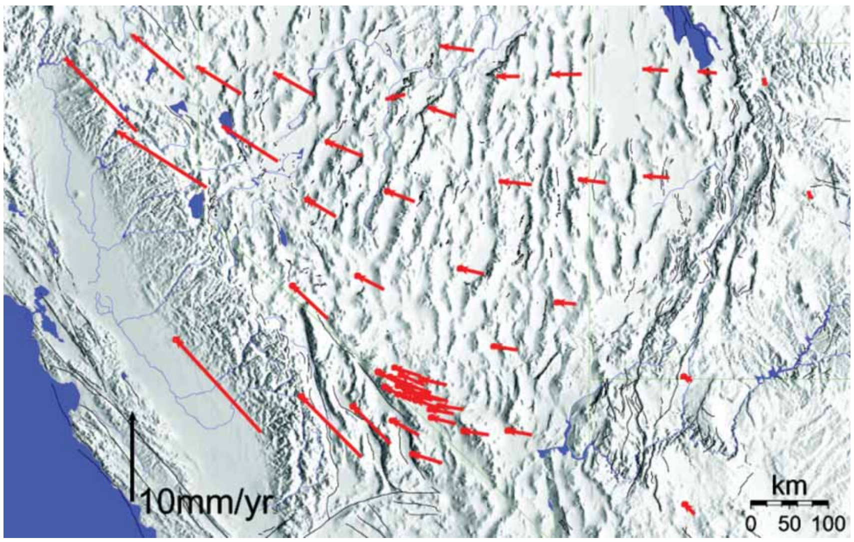


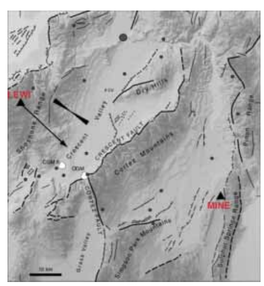
Left: A road with GPS sites along it is built across a strike-slip fault immediately after an earthquake (A). Red arrows show the direction the tectonic plates are moving. After a few years (B), the plates have moved quite some way past each other, taking the blue GPS sites with them. The green sites have moved apart much less, because the land they're on is locked by the fault. Eventually, there's another earthquake (C), the road is displaced, and the blue and green sites realign in one sudden jerk. This happened to the road in the photo, right, taken just after the '92 magnitude 7.3 Landers earthquake. The NBC news cameraman is standing in front of the fault where it crosses the road, which has been offset to the right on the far side.





Wernicke, B. et al.: *GSA Today*, November 2000.

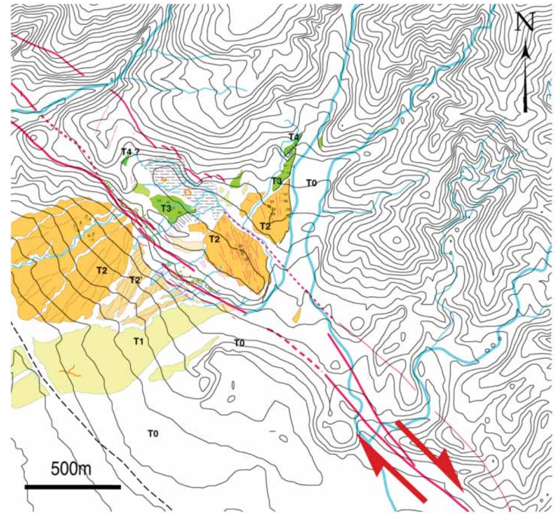




Top: Map showing the location of GPS sites in the BARGEN network. Above: The red arrows show the direction and rate at which each site is moving in relation to the center of the continent. Right: An oddity—site LEWI is moving toward MINE rather than away from it. Below: A typical GPS site in the BARGEN network.

Caltech is called the Basin and Range Geodetic Network, or BARGEN, where a GPS antenna mounted on an ultrastable monument has been erected at each site (left). We drill one vertical borehole and three slanting ones into the bedrock to a depth of about 30 feet, then slip steel posts down the holes (which is what we're doing in the photo on the front page of this article), grout them to the earth between 15 and 30 feet deep, and isolate the posts from the upper 15 feet of earth with foam-padded casing. The tops of the posts are welded together, and a GPS antenna is set on top, while a weatherproof box nearby houses the GPS receiver. This network has been in place since the late 1990s, recording the east and north components of motion. GPS can estimate position in this way to within about one millimeter each day, which means we can measure the relative rate of motion or velocity of any two sites to within a fraction of a millimeter a year. We use this information to make maps like the one on the left, of the direction and rate of movement of the geodetic sites. The red arrows, or vectors, show the velocity of the network relative to the interior of the North American plate. The size of the arrows increases steadily from east to west, indicating horizontal extension of the crust in the Basin and Range region. Then the arrows twist around, showing northwest motion in the region of the Sierra Nevada, as the sites begin to feel the northwesterly shearing strains associated with the San Andreas fault near the coast. There's an interesting exception to the pattern in north-central Nevada, where one site is moving much more slowly than the one directly to its east. Site LEWI is moving *toward* site MINE, which seems odd in a place like the Basin and Range where the crust is pulling apart on normal faults, not getting smashed together on thrust faults as in the Los Angeles basin. Between the two sites is a major normal fault, the Crescent fault, which is of the type that causes horizontal extension, in this case extension in exactly the same direction as the GPS results are telling us there is compression, northwest to southeast. Postdoc Anke Friedrich, now at Potsdam University in Berlin, has shown that the last major earthquake on this fault happened 2,800 years ago, so until that time sites LEWI and MINE must have been moving apart, to accumulate the strain that leads to an earthquake. Assuming the Basin and Range is generally an area of horizontal stretching, the faults between the two sites must now be *losing* strain energy, and accordingly will be much less likely to fail than faults nearby.

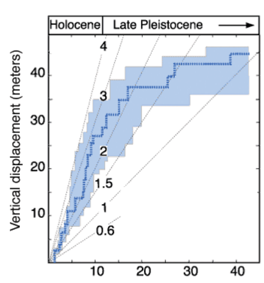
This example—and there are others like it—show that our simple idea of the seismic cycle has some major deficiencies. There appear to be processes at work on the decadal to millennial timescale that we are only just beginning to think about, as we start to understand the motions that occur at timescales longer than the earthquakes themselves and their immediate aftermath. Although highly



Cosmogenic nuclide dating enabled geologists to work out that the Biskra alluvial fan near Palm Springs, highlighted in orange, was formed by an ancient river 32,000 years ago. Between then and now, the San Andreas fault (red lines) has offset the lower part of the fan by an average rate of 22 millimeters a year.

accurate geodesy is part of the solution, we must also get a handle on how fast faults moved in the past. In general, we have only been able to date active fault motions accurately to the maximum age limit of carbon-14 dating, and then only in places where we could recover charcoal or other carbonaceous material. Faults like the San Andreas usually offset features in the landscape such as river channels and the sides of alluvial fans. Up until the mid-1990s, the surface of the offset alluvial fan near Palm Springs (above) would have been impossible to date, because it had no charcoal on it—and even if it did, its age might be well outside the range of precise carbon-14 dating. But a new dating method has recently become practical, based on the fact that very infrequent cosmic rays—generally neutrons—hitting the outer few centimeters of the earth's surface cause nuclear reactions in exposed rocks that produce distinctive isotopes of common elements called cosmogenic nuclides. These nuclides can be measured to determine how long the rock has been near the surface—think of it as measuring the rock's suntan. The method works over a time span of several thousand to a few hundred thousand years, whereas precision carbon-14 dating is limited to 30,000 years or less. Based on its cosmogenic nuclides, the Biskra alluvial fan formed about 32,000 years ago, while its offset shows that the average rate of movement of this part of the San Andreas has been about 22 millimeters a year over that time span. This method will make it possible to observe a broad range of average motion rates across most continental fault zones, contributing richly to filling in the gap between measurements at human and at plate-tectonic timescales.

One place where we are getting a glimpse of the transition from earthquake cycles to plate-tectonic timescales is the Wasatch region, where we have tentative ages for Wasatch fault movements covering the last 250,000 years. The graph on the far left shows the vertical displacement rate versus time for the Wasatch and two neighboring faults over the past 40,000 years, and the graph left compares this rate with an estimate of movements over the last 250,000 years. On average, these are very slow compared with recent rates, especially the rapid rates since 10,000 years ago.



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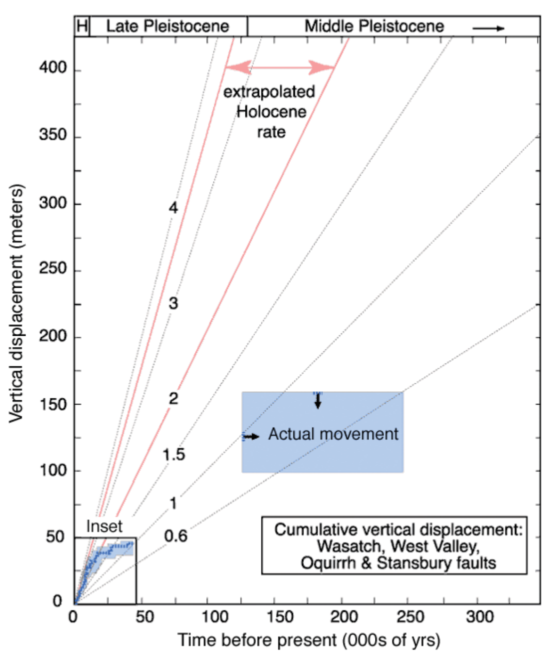

Far left: The rise in height over 40,000 years of the Wasatch fault and two others. Extrapolating the rate of increase in height calculated from this plot farther back in time, left, gives an overestimate of the rate of upward movement over the last 250,000 years (red lines). The actual rate of movement is shown by the blue box.

Mountain building in the Wasatch region viewed over three different timescales. The blue lines are changes in geological height, and the red dashed lines show geodetic motion. B is an enlargement of the lower 1/1000th of A, and C is the lower 1/1000th of B. In C, the blue line shows that there has only been one earthquake over the last 1,500 years, but the stepwise rise in geodetic motion shown by the red dashed line could be caused by other faults nearby.

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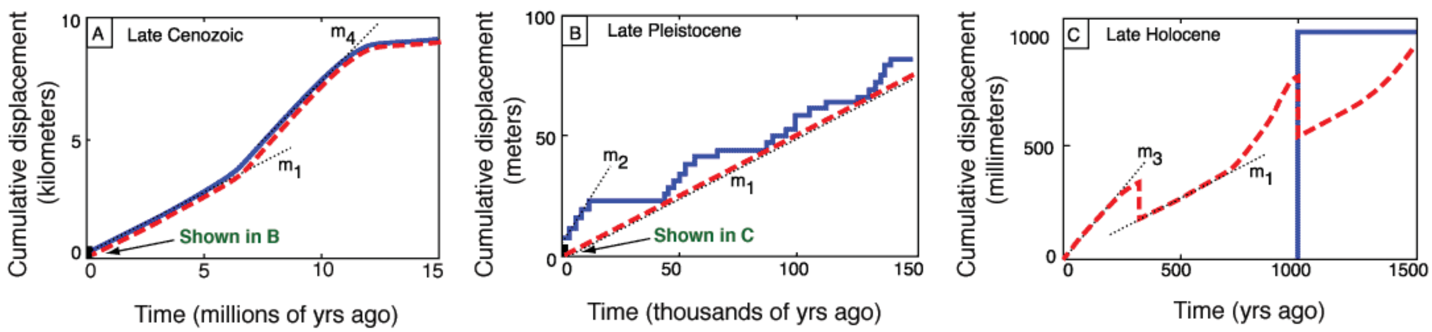

PICTURE CREDITS: 27 – USGS; 28, 29 – Tanya Atwater; 28 – Joann Stock; 30, 31 – Brad Aagaard, Tom Heaton; 30 – Shijie Zhong, Mike Gurnis; 31 – Puget Sound LIDAR Consortium; 32 – Jim McCalpin, GEO-HAZ Consulting; 34 – Kerry Sieh

Putting it all together, we can see the motion history across a millionfold difference in time. Kilometers of motion on the fault observed over millions of years (top left) show that there has been a general slowing of the average rate of motion since about 10 million years ago. The middle graph—the one we are most eager to fill in—looks at motions measured in meters over a few hundred thousand years. We're speculating that the geodetic rate may be rather smooth, but the earthquake strain release might be periodic, occurring in clusters every twenty to forty thousand years or so. If this is the case, what is it trying to tell us about the physics of how earthquakes really work? In the righthand graph, motions of millimeters or centimeters over hundreds or thousands of years are shown, but our knowledge of this is also incomplete. Here we see the strain accumulation between earthquakes, sudden jumps from nearby earthquakes, and large jumps from earthquakes on the fault nearest to the geodetic site.

The scientific community is presently gearing up to make observations on these timescales, and to develop models that explain the observations. EarthScope, a $200 million National Science Foundation initiative to investigate the structure and evolution of the North American continent, includes the installation of some 900 new GPS stations— similar to those in the BARGEN network—across the Pacific–North America plate boundary zone, which will yield an unprecedented view of active plate-boundary strain. Caltech itself is in the final planning stages for a "tectonic observatory" within the Division of Geological and Planetary Sciences that will focus on key plate boundaries around the globe. Using cosmogenic nuclide dating and other methods, we'll begin to unravel how different faults contribute to the evolution of plate boundaries in the way we've already started to do for the San Andreas and Wasatch faults.

With these and other data coming online over the next decade, we will be able to see in some detail the long-term behavior of plate boundaries, which should help us take the next big theoretical steps in understanding the physics of fault systems and earthquakes. I expect these advances to greatly improve our ability to determine the "tectonic climate" of the globe, and to help us make a realistic assessment of the measures necessary to cope with tectonic hazards. The famous dictum of Will Durant, "Civilization exists by geological consent, subject to change without notice," might then more aptly conclude "subject to change with all due notice." □

Chandler Family Professor of Geology Brian Wernicke, a native of Los Angeles, gained his BS at USC in 1978 and his PhD at MIT in 1982. After a year as an assistant professor at Syracuse University he joined Harvard, where he rose to associate professor in 1986, and full professor the year after. A year at Caltech as a visiting professor in 1990 was followed two years later by a more permanent move back to the action along the Pacific–North America plate boundary, to take up a professorship in geology. The plate boundary welcomed him with a magnitude 7.3 earthquake at Landers. Wernicke received a Presidential Young Investigator Award in 1985, and in 1991 he both received the Young Scientist Award of the Geological Society of America, the Donath Medal, and was elected a fellow of the society. He is married to another Caltech geologist, Professor of Geology and Geophysics Joann Stock. This article has been adapted from a Watson lecture given in May 2003; you can watch the entire lecture at http://atcaltech.caltech.edu/theater.