



[Back to the deformation and Stress Change Modeling home page](#)

R. Stein and R. S. Yeats,

Hidden Earthquakes, *Sci. Am.*, 260, pp. 48-57, June, 1989.

Read a review of this paper in [Time Magazine](#)



Hidden Earthquakes

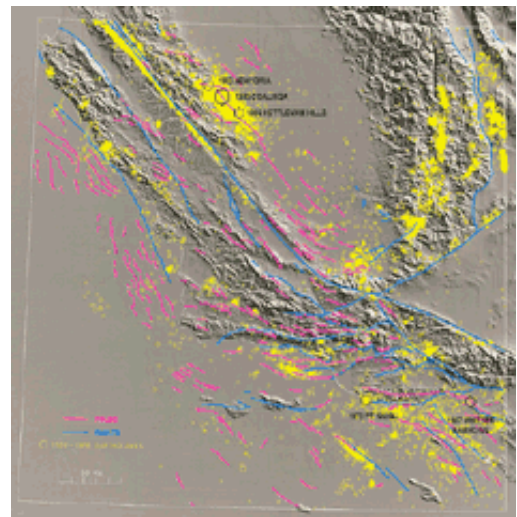
Large earthquakes can take place not only on faults that cut the earth's surface but also on "blind" faults under folded terrain

by Ross s. Stein and Robert S. Yeats

An erupting volcano makes its role as a conduit for magma and ash from the interior of the earth unmistakable. The connection between a scarp face and the active fault that sculpted it is less obvious; in fact, the association between earthquakes and such ridges was first made only a century ago. Gently rolling or folded terrain is perhaps the least forbidding landscape, evoking slumber rather than danger. In Matthew Arnold's words:

*To a boon southern country he is fled,
And now in happier air,
Wandering with the great Mother's
train divine. ..
Within a folding of the Apennine.*

But Italy's northern Apennine mountains - one of the many fold belts that girdle the globe - are not still. Rather these mountains are built by earthquakes along faults hidden well under the landscape. Such earthquakes, which unlike their more familiar counterparts do not rupture the earth's surface, we term "surface-folding" earthquakes, or "fold" earthquakes for short. They have only recently become the object of study by investigators.



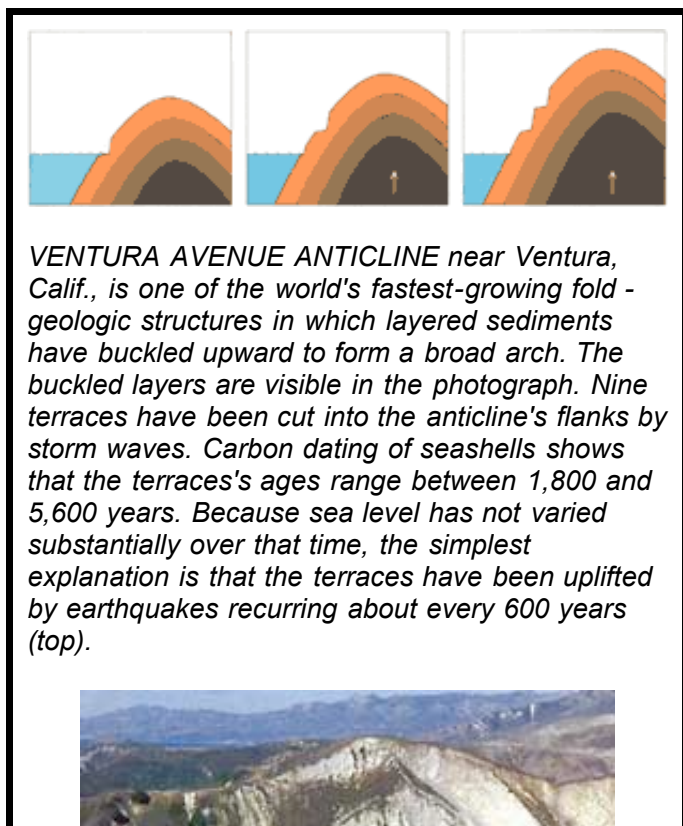
EARTHQUAKES in southern California from 1980 to 1986 are displayed on this topographical map. The yellow circles represent the 23,000 shocks that registered between 1.5 and 6.5 on the moment-magnitude scale M . Many of the earthquakes are concentrated along surface faults (blue lines), in particular the San Andreas. Others, however, appear to be associated with folds (red lines). The association is explicable if folds marks the location of active "blind" faults that do not extend to the surface. Recent earthquakes (hexagons) that have uplifted folds confirm this

The fundamental premise of earthquake-hazard reduction in the U.S. is that most earthquakes take place along active faults that suddenly fail and slip. Large earthquakes take place along large faults, and large faults, it is widely held, cut the earth's surface. Geologists recognize faults that have displaced young surface deposits as having recently been active and deem them the most likely to rupture again.

This reasoning has yielded profound insights into earthquake behavior, making it possible to situate critical facilities—such as power plants and dams—away from active fault sites, to identify sites with high seismic potential and to make probabilistic forecasts of earthquake size and frequency [see "Predicting the Next Great Earthquake in California," by Robert L. Wesson and Robert E. Wallace; SCIENTIFIC AMERICAN, February, 1985].

Yet in California most small earthquakes do not occur along faults that cut the earth's surface. Only 50 years ago this fact was ascribed to an inadequate number of seismometers. Now, however, 700 seismometers are in operation in California, and coverage is more complete than in any other area of the world with the possible exception of Japan. Certainly many micro-earthquakes take place along active faults, such as parts of the San Andreas. But a greater number do not correspond to any known surface fault.

Many of the earthquakes that are not associated with surface faults occur under folds - geologic structures formed when layered sediments are buckled upward in an arch called an anticline. The presence of an anticline reflects crustal compression as two moving tectonic plates collide, in much the same way a carpet wrinkles when pushed across the floor. That so many small earthquakes nucleate on faults hidden under folds is remarkable and unexpected. The more important question, though, is whether such active folds conceal large faults, which in turn could provide the sites for large shocks.



VENTURA AVENUE ANTICLINE near Ventura, Calif., is one of the world's fastest-growing fold - geologic structures in which layered sediments have buckled upward to form a broad arch. The buckled layers are visible in the photograph. Nine terraces have been cut into the anticline's flanks by storm waves. Carbon dating of seashells shows that the terraces's ages range between 1,800 and 5,600 years. Because sea level has not varied substantially over that time, the simplest explanation is that the terraces have been uplifted by earthquakes recurring about every 600 years (top).

By virtue of hindsight it appears that during the past half century large fold earthquakes have taken place in Japan, Argentina, New Zealand, Iran and Pakistan, giving an apparent affirmative answer to the question. The evidence for these events, however, is sparse and subject to interpretation. Yet since 1980 four major events have unequivocally established the reality of fold earthquakes. A fifth event may soon be added to the list.

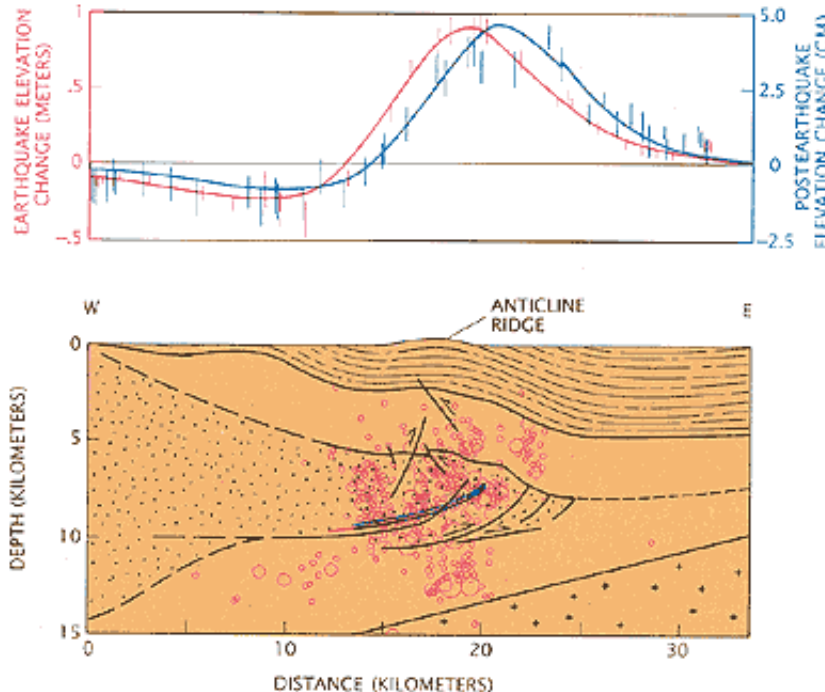
The first of these shocks took place in 1980 in El Asnam, Algeria. It measured 7.3 on the moment-magnitude scale (a successor to the Richter scale, designated M), killed 3,500 people in three North African cities and dammed a major river. The second and third earthquakes, the 1983 M = 6.5 Coalinga shock and the adjacent 1985 M = 6.1 Kettleman Hills event, shook areas of California. Because these sites are remote, the earthquakes caused only modest damage and one death, but the areas did include several major toxic-



waste storage sites, and in the small town of Coalinga, 75 percent of the unreinforced buildings were demolished. The next shock struck within California's populous Los Angeles basin on October 1, 1987. Although this $M = 6.0$ Whittier Narrows quake was only one tenth the size of the Coalinga event, it caused 10 times the damage - \$350 million - and took eight lives. The fifth, candidate event was the tragic 1988 Armenian earthquake, which claimed at least 25,000 lives.

The most obvious feature of the three California earthquakes was that none of the faults that slipped cut the surface of the earth. In the Algerian event the fault did cut the earth's surface, but the amount of fault slip at ground level was far less than the amount of slip at the depth of the earthquake's focus, about 10 kilometers down. These observations suggest that in fold earthquakes the slip diminishes from earthquake level toward ground level, and so there is little, if any, rupture of the surface

A second feature was that all four earthquakes took place under young anticlines - anticlines that are less than several million years old. Taken with the third and most revealing observation - that at each site the fold rose perceptibly during the earthquake - this suggests not only that young anticlines mark potential earthquake sites but that folds are actually the geologic product of successive earthquakes. If the pattern of diminishing fault slip toward the surface holds in general, then folds should enable us to divine the history of the hidden, or "blind," faults below.



COALINGA EARTHQUAKE of $M = 6.5$ in 1983 took California by surprise because it was not associated with any surface fault. The deformation of the overlying fold (plotted against distance from an arbitrary origin) is shown by the red vertical lines in the top panel. The red curve represents the deformation produced by a model blind fault, shown in red in the bottom panel. Deformation in the four years since the event is shown in blue in the top panel.

ongoing deformation indicates that the fault continues to propagate into the fold's core, as shown by the blue curve in the bottom panel. Seismic profiling reveals many faults deep in that region of the anticline (short lines, bottom panel). Small displacements along them during the 1983 event may explain the widely distributed pattern of aftershocks (circles) that followed the main shock (largest circle). Such a pattern contrasts strongly with that of a surface-fault earthquake, in which all the aftershocks are aligned with the fault.

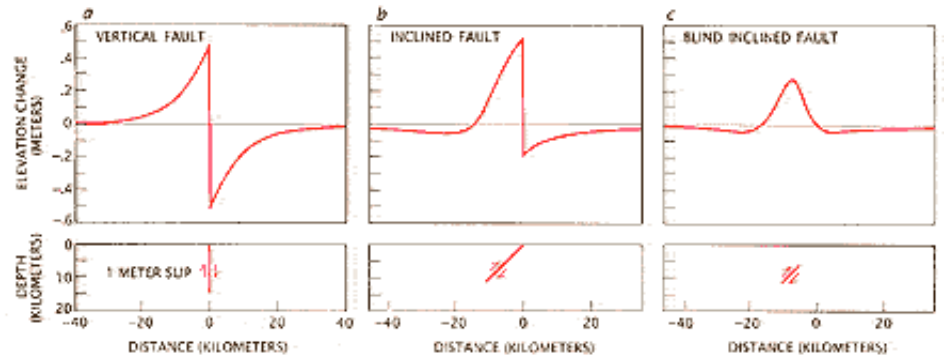
Unsurpassed data from seismology, geology and geodesy - the measurement of the shape of the earth's surface - make the Coalinga event the most vivid illustration of a fold-related earthquake. Anticline Ridge, a 750-meter-high fold (appropriately named by the petroleum geologists who discovered oil there in 1898), grew 75 centimeters during the earthquake [see illustration above].

The youngest folded sediments are less than two million years old, which indicates that the fold began to form since that time. If a 75-centimeter growth is typical for events at the Coalinga site, then Anticline Ridge could have been built by roughly 1,000 ancestral earthquakes of magnitudes from $M = 6$ to $M = 7$ recurring every 1,000 to 2,000 years.

The Coalinga event also differed from surface-fault earthquakes in the pattern of its aftershocks. Typically the aftershocks of surface-fault earthquakes are aligned along the plane of the fault itself. On the other hand, the aftershocks at Coalinga - and of fold earthquakes in general - are distributed much more diffusely, both above and below the fault plane. What does this tell us?

Carl M. Wentworth, Jr., of the U.S. Geological Survey and Mark D. Zoback of Stanford University have investigated the deep geologic structure at Coalinga with the help of data from oil-well drill holes, seismic-refraction profiling (based on the travel time of sound waves excited by a controlled explosion as they traverse the structure) and seismic-reflection profiling (based on the timing of sound waves that are generated by orchestrated thumping of the ground and reflected off buried strata). Their results suggest that the core of the Coalinga anticline is riddled with faults, many of which exhibit displacements that make up a small fraction of the displacement along the major fault lying at a greater depth.

The majority of structures imaged by these techniques are "reverse" faults, steep faults along which the younger strata are pushed over the older beds below, like a carpet pushed up a tilted floor. When reverse faults are less steeply inclined, they take on the name "thrust" faults. The main Coalinga shock appears to have nucleated on one of the major blind thrust faults. Many of the aftershocks, however, appear to be the



ELASTIC MODEL demonstrates how a blind fault deep underground (bottom panels) can deform the earth's surface (top panels). The faults are cut into the earth to a depth of 15 kilometers, much like slices that have been made by a knife in a rubber block. The left side of the block moves upward one meter with respect to the right side. If the fault is vertical (a) and extends to the surface of the earth, the surface deformation is one meter at the fault axis and asymptotically approaches zero far from the fault. If the fault is inclined 45 degrees (b), the total surface displacement is only 70 percent (cosine 45 degrees) as large. If the fault does not reach ground level (c), the fault is termed blind, and the slip results in a fold at the surface.

result of slip on the smaller reverse faults. The pattern stands in strong contrast to that of a surface-fault earthquake, in which the aftershocks generally take place along a single plane (as can be seen along the San Andreas fault in the illustration on pages 48 and 49).

How does one measure the displacement of faults hidden beneath the surface? The location and amount of slip cannot in fact be observed directly, but they can be deduced from surface measurements with the help of a simple elastic model of the earth's crust. One treats the crust as an elastic solid with an embedded cut - similar to a stiff block of rubber that has been sliced with a knife. When the two faces of the cut are slid past each other, the rubber is strained and its surface is deformed. This elastic analysis was first developed to understand angstrom-sized flaws in crystals but has since been extended to study ruptures of faults 1,000 kilometers long.

By such methods we have discovered that the fault displacement at Coalinga, which was about 3.5 meters at the earthquake depth of nine kilometers, diminished upward, giving rise to folding at shallower depths, and disappeared at a depth of about six kilometers. After the earthquake the fault continued to slip: over the next four years the surface fold deformed by another 10 percent, and the axis of uplift shifted several kilometers eastward [see illustration on preceding page]. The simplest explanation for this observation is that the fault tip is propagating upward and eastward into the core of the anticline. The fault migration is due to the fact that the stress imparted by the earthquake is greatest just beyond the tip of the fault. Any visitor to Independence Mall in Philadelphia has observed the phenomenon: curators of the Liberty Bell were compelled to drill a cylindrical hole at the end of its famous crack to distribute the stress evenly and prevent this national treasure from splitting in two.

Given the tendency of fault tips to propagate, one might well wonder why the great majority of thrust faults, such as the one beneath Coalinga's Anticline Ridge, do not extend all the way to the surface. Through analysis of oil-well logs John Suppe of Princeton University has identified active folds in Taiwan that result from slip along deeply buried faults. He has also examined ancient folds, in which the overlying sediments have been exposed, thereby exhuming the faults beneath. The studies reveal that these faults form at depths of 10 to 20 kilometers and propagate slowly toward the surface over millions of years. Consequently many faults are undoubtedly still propagating to the surface and have not yet signaled their presence. Other, inactive faults will remain invisible until they are exposed by erosion of the overlying rocks. This pattern contrasts with that of the more familiar faults, where "what you see is what you get"; such faults either propagate to the surface rapidly or propagate downward.

By modeling the fault-propagation process, Suppe has also found that as the faults migrate, so do the fault propagation folds, which grow in amplitude and change shape [see illustration on opposite page]. The postearthquake deformation at Coalinga shown on the preceding page supplies a remarkable snapshot of the process envisaged by Suppe: as the fault tip propagated to the right, the fold also migrated in that direction.

One example of a fold-related earthquake would not constitute a class. Yet the Coalinga event was not an isolated case; in fact, it was the second of a trio of related events that took place along the same blind thrust fault, the first being the

October 25, 1982, New Idria earthquake to the north



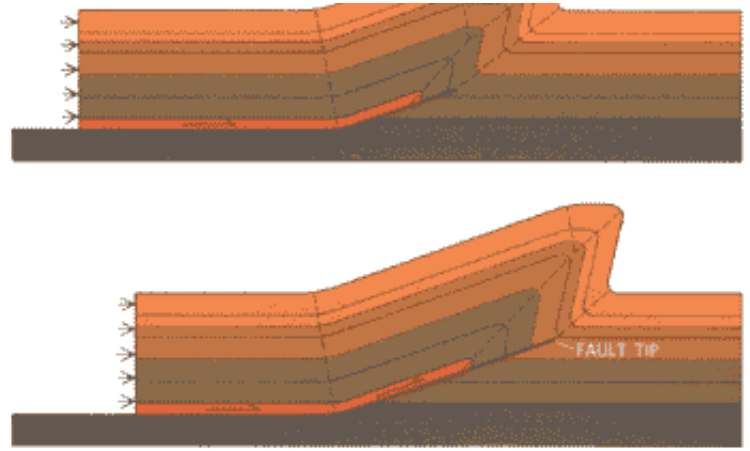
and the third being the August 4, 1985, Kettleman Hills earthquake to the south. The three earthquakes were sudden responses to northeast-southwest compression along what is evidently one regional thrust fault approximately 100 kilometers long. The fact that the earthquakes proceeded from north to south suggests that a slip on one patch loads an adjacent patch to the south, which ruptures next. Although the south half of this string of anticlines has not produced a large historical earthquake, it must be viewed as a candidate for a future shock. Repeated earthquakes along the blind fault must have taken place to build this long chain of folds.

Stronger evidence for this point of view comes from the 1980 $M=7.3$ El Asnam earthquake in Algeria. The earthquake was produced by a three to six-meter slip on a reverse fault several kilometers underground. Only in the central segment of the fault did much of the slip (two meters) reach the surface. Geoffrey c. P. King, now of the U.S. Geological Survey, Claudio Vita-Finzi of University College, London, and J. C. Ruegg and his colleagues at the Institute of Physics of the Globe in Paris showed that an anticline associated with the fault was uplifted five meters during the earthquake and that the adjacent valley buckled downward one meter [see top illustration on next page]. As a result the Cheliff River, which flowed through a gorge it had hewn through the growing anticline, was dammed. Within days after the earthquake the Cheliff River swelled into a lake.

Before the river cut through the fold 40 centimeters of silt had accumulated in the lake, leaving a permanent mark in the geologic record. Mustapha Meghraoui of the University of Paris and his colleagues have excavated the underlying deposits and found that over the past 6,000 years there has been a succession of six such short-lived lakes, each marking the onset of sudden flooding. The best explanation is that these lakes were the products of surface-folding earthquakes. The El Asnam site not only furnishes evidence for a single fold earthquake but, more important, contains an archive of fold earthquakes, once again providing evidence that anticlines are built by a series of discrete events.

El Asnam displays further evidence that it has experienced repeated earthquakes. Small, secondary faults on the top of folds can also slip during an earthquake in response to the buckling of the fold. If they do, the slips form an accessible record of past quakes, which can be dated by applying carbon-14 methods to the surrounding sediment. Such dating was carried out by Meghraoui and his colleagues on secondary faults in the El Asnam region, and the results are consistent with the lake-sediment record.

The small but ominous Whittier Narrows event, which took place in 1987 in the Los Angeles metropolitan area, rounds out the recent evidence for fold earthquakes. Like its larger predecessors, this earthquake appears to be the product of a tear in a stack of sediments that are being compressed in a geologic vise between two moving crustal plates. By graphically unfolding the buckled strata in the Los Angeles basin, Thomas L. Davis and Jay Namson of Davis and Namson Geological Consultants in Los Angeles have argued that the basin has been shortening at the rate of about a centimeter per year for the past 2.2 million



FAULT-PROPAGATION FOLD was modeled by John Suppe of Princeton University. The rock slips along a horizontal fault in a weak stratum and deforms (top). The fault then splays upward and propagates into the overlying beds (middle). Continued displacement of the rock along the fault causes the fold to grow upward, widen and change shape (bottom). Such a process may be active in the Coalinga fold. Several effects that influence the geometry of folds, including the buoyancy and elasticity of the crust, sedimentation and erosion, have been neglected.

years, which represents 20 percent of the entire plate motion of the western U.S. concentrated in a zone 50 kilometers wide. In other words, Los Angeles may be losing one-quarter acre each year to active surface folding, which may explain the concentrated and enigmatic seismicity of the basin.

Like its predecessors the Whittier Narrows earthquake also lifted its associated anticline, the Santa Monica Mountains fold. And like the New Idria, Coalinga and Kettleman Hills shocks, the Whittier Narrows event seems to mark an extensive blind fault. Evidence from the alignment of small-to-moderate earthquakes (advanced by Egill Hauksson of the University of Southern California and Lucile M. Jones of the U.S. Geological Survey) suggests that the Whittier Narrows event is but one of several earthquakes that have taken place along a blind fault running for 150 kilometers beneath the California coastline. The $M = 5.6$ earthquake on February 21, 1973, at Point Mugu took place at the western end of the proposed fault and shares many attributes with the larger fold-related earthquakes: it accommodated crustal compression, uplifted the Santa Monica Mountains by 35 millimeters, left a diffuse zone of aftershocks and showed no surface-fault slip.

In the preceding discussion much of the evidence for fold earthquakes may have seemed indirect: projection of surface deformation to greater depths and examination of aftershock distribution. More direct evidence can be obtained only with access to the interior of an anticline, and direct access is possible only when a fold has been extensively plumbed for oil. The Ventura Avenue anticline, which is punctured by more than 1,400 wells drilled to a depth of as much as 6.6 kilometers, is among the best studied - and also fastest-rising - folds in the world and so is ideal for close inspection.

The Ventura Avenue anticline, located on the southern California coast, has uplifted former deep-water sediments and exposed these folded layers in cliffs near the coastline. Although no major earthquakes have been registered along the Ventura Avenue anticline, its structure and prehistoric record tell us much that is pertinent to the other earthquake sites we have discussed.

Like many anticlines the Ventura Avenue structure traps oil and gas that migrate into its core. The logs of the oil wells that have been drilled into the Ventura Avenue anticline enable us to view it in cross section [see bottom illustration at left]. The curvature of the strata is broad at the surface but becomes progressively tighter at greater depths. At about four kilometers below ground level, the fold exhibits a sharp kink, underlain by mechanically weak rock. An exploratory well 6.6 kilometers deep penetrated enough of the weaker rock to demonstrate that the strata below the kink are not folded at all. This evidence suggests that beneath the fold lies a nearly horizontal thrust fault. Smaller, steeply inclined reverse faults extend upward from the base of the anticline to ground level.

The Ventura anticline appears to have been uplifted by slip on the Barnard thrust fault that branches off the Sisar fault at the base of the fold. The slip of the internal reverse faults also seems to result from motion along the Barnard fault. Farther to the north, slip on the Barnard fault exceeds that on the Sisar fault, causing the strata to be jammed together and bowed upward. This close inspection of the Ventura anticline shows that it not only hides a major thrust fault at the depth of the greatest slip but also harbors myriad smaller reverse faults within its core. These structural features are remarkably similar to those inferred from seismic imaging and geodetic measurements at the Coalinga and Kettleman Hills folds.

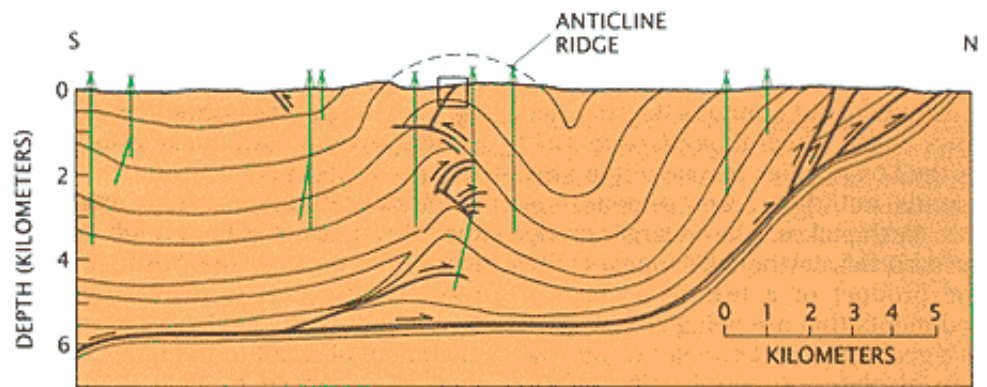
The internal structure of the Ventura Avenue anticline helps to explain several shared features of the Coalinga, Kettleman Hills, Whittier Narrows and El Asnam earthquakes: although the greatest slip takes place on the major fault at the fold base, slip on the abundant small reverse faults scattered throughout the core may well account for the diffuse distribution of aftershocks that characterizes fold earthquakes.

Another observation from Ventura Avenue helps to explain a second distinguishing feature of most fold events, which we have not yet mentioned: the faults ruptured slowly. Although not all fold-related earthquakes are slow, almost all slow earthquakes are fold-related. Goran Ekstrom of Columbia University has shown that the Kettleman Hills rupture took about four times longer (16 seconds) than is typical for a surface-faulting earthquake of the same size. John L. Nabelek of Oregon State University found that at the northern segment of the El Asnam site, where the aftershocks were most dispersed and negligible reverse faulting cut the surface, the seismic rupture took twice the expected time. At Coalinga the seismic rupture time was normal, but the fold continued to grow after the earthquake at an exponentially decaying rate, which was a result of continued slow slip and propagation of the blind thrust fault.

The slow rupture time may be explained by the high fluid pressures registered in boreholes at the Ventura Avenue, New Idria, Coalinga and Kettleman Hills sites. Robert F. Yerkes of the U.S. Geological Survey has shown that the fluid pressure there exceeds hydrostatic pressure below three kilometers. The folds seal in the fluids, whereas surface faults provide a source of leakage. High fluid pressure in the rock fractures reduces the frictional resistance of the rock to sliding, thereby enhancing its susceptibility to both faulting and folding. Diffusion of the pore fluid after the rupture alters the friction along faults, inhibiting slip on some fractures and promoting it on others. The result is a spread of rupture times that can manifest itself as a slow, or prolonged, earthquake.

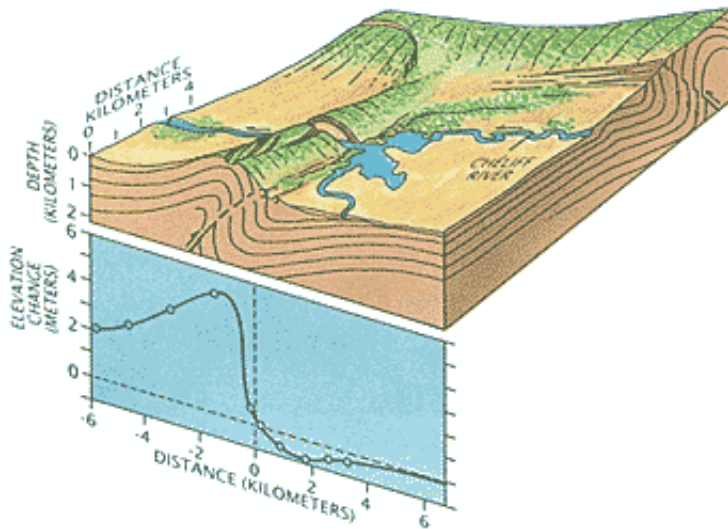
We claim that folds are built - at least in part - in a punctuated fashion by successive earthquakes over hundreds of thousands or millions of years, rather than by slow, steady deformation. The Ventura Avenue anticline also provides persuasive evidence for this point of view.

The anticline is only 200,000 to 300,000 years old; during that period it has been growing at one of the fastest rates in the world. Kenneth R. Lajoie and Andrei M. Sarna-Wojcicki of the U.S. Geological Survey have identified nine marine platforms on the flank of the anticline, the youngest one lifted two meters above sea level, the oldest raised 20 meters. Each of these terraces was cut by storm waves at or near sea level and strewn with seashells. Carbon dating of the shells yields ages of 1,800 years for the youngest terrace and



INTENSE FRACTURING pervades the core of the Ventura Avenue anticline. Such fracturing, caused by bending of the strata, produces many faults (purple lines). Analysis of data from oil wells (vertical green lines) drilled into the anticline shows that the fold flattens at a depth of about six kilometers. This is best explained by the presence of a nearly horizontal fault, or thrust fault, at the fold's base. Movement along faults that diverge from this main fault causes the fold to buckle and grow as does the model on the preceding page. The box indicates the region shown on page 50.

5,600 years for the oldest. Because sea level is known from independent evidence to have been within a meter of its current height during the past 7,000 years, the terraces could not have been cut during periods when sea level was higher than it is now; rather the land has been rising. The preservation of nine separate platforms suggests that this uplift was not gradual but sudden. As in the case of the El Asnam lakes, the simplest explanation for this giant flight of stairs is uplift produced by repeated earthquakes.



EL ASNAM EARTHQUAKE of $M = 7.3$ in 1980 dammed Algeria's Cheliff River. The river had cut a gorge through the fold at the earthquake site, but during the event the ground rose five meters, blocking the flow. Silt accumulated in the transient lake that was created thereby; excavations under the new silt layer revealed evidence for six such short-lived lakes over the past 6,000 years. They are likely to have been the product of fold-related earthquakes that have recurred every millennium. The graph shows the change in elevation of the ground across the fold; the uplift pattern's similarity to the shape of the fold suggests that such events actually built the fold.

Monica Mountains fold (which, at Whittier Narrows, is almost completely buried by sediments shed by the San Gabriel Mountains) is less than 3.3 million years old. The average uplift rate is therefore about 0.5 millimeter per year. During the Whittier Narrows earthquake, however, the fold grew 50 millimeters at the earth's surface. If fold growth is caused entirely by earthquakes, then an earthquake should recur at this site every century. Yet the section of fault that slipped during the 1987 earthquake was about five kilometers long, only about 3 percent of the length of the entire blind fault, which may be as long as 150 kilometers. Consequently, if all parts of the fault are equally likely to slip in an $M = 6$ earthquake, shocks should strike the Los Angeles basin and the adjacent coastline every three to five years. Clearly this has not happened: an average of just one shock of magnitude greater than or equal to $M = 6$ has been recorded every 25 years in this corridor since Los Angeles was settled in the early 19th century.

One possible explanation for the discrepancy is that most of the fault slip and fold growth is in fact steady: stress does not accumulate but is continuously relieved by creep. The thrust faults beneath many folds lie at depths of 12 to 15 kilometers, where the crust may reach a temperature at which the quartz component of the rock becomes ductile and facilitates creep. If the faults undergo steady slip, then the folds above may

We have argued that the El Asnam, Coalinga, Kettleman Hills and Whittier Narrows earthquakes provide indisputable evidence that folds grow during large earthquakes. Moreover, the prehistoric record at El Asnam and Ventura Avenue also illustrates that such events have recurred. Yet most earth scientists have viewed folds as evidence for steady, progressive deformation that need not be punctuated by earthquakes. The difficult question, then, is: Are the cases we have discussed the exception or the rule? In other words, is fold growth dominantly steady and aseismic or do most actively growing folds in fact conceal seismic faults?

If one were to ask the same question about motion along active faults that cut the earth's surface, the answer would be that few faults are seen to undergo steady slip, or creep; the rule is that creep is uncommon in the uppermost 15 kilometers of the crust. There are of course notable exceptions, the central 300 kilometers of the San Andreas fault among them. Worldwide, however, most faults exhibit the stick-and-slip behavior that gives rise to earthquakes.

Nowhere is this question more important than in the Los Angeles basin. The 1.5-kilometer-high Santa

also deform progressively. Although there is no direct evidence for steady fold growth, stable sliding has been simulated in rock samples in the laboratory, and as much as half of the slip on the interface between tectonic plates along the plate boundaries around the Pacific Ocean is aseismic.

We think it is more likely that the folds grow intermittently through earthquakes that are larger than the Whittier Narrows event but that are much less frequent. Earthquakes of magnitudes greater than $M = 7$ recurring every several hundred years could account for the fold growth, and the scenario would be consistent with the absence of smaller events during the brief recorded history of the Los Angeles basin.

It is incumbent on seismologists to distinguish between the two competing explanations; their consequences are dramatically different. If earthquakes larger than the 1987 event are possible beneath the Santa Monica Mountains fold, then Los Angeles's greatest earthquake threat may come not from a future $M = 8$ shock on the San Andreas fault, 50 kilometers to the north, but from a smaller earthquake originating under downtown Los Angeles.

Several tools are now at our disposal to probe the Los Angeles basin as well as other active fold belts around the world. They include seismic-reflection profiling, geodetic measurement of the present rate of fold contraction and uplift, examination of the logs from thousands of oil wells and geologic investigations to identify the fastest-growing surface folds.

Although southern California has served as a focal point for efforts to study fold-related earthquakes in the U.S., evidence indicates that such events have struck throughout the world's active fold belts and therefore endanger a much larger population [see illustration on page 55]. In addition to North Africa, the site of the El Asnam earthquake, events of magnitudes from $M = 7$ to $M = 7.8$ have taken place on blind faults in northern India, New Zealand, Argentina, Canada and Japan. Countries such as Chile, Yugoslavia, Taiwan, Iran and Pakistan may also be subject to highly damaging fold events.

The most recent - and among the most tragic - example of a fold earthquake claimed worldwide attention just six months ago. We are of course referring to the December 7, 1988, $M = 6.8$ earthquake in Spitak, Armenia, which killed at least 25,000 people. The earthquake struck in one of the world's most intensely folded and seismically active regions, the Lesser Caucasus Mountains of the Soviet Union. The main shock was the result of slip on a reverse fault beneath a youthful anticline. Rupture along a surface fault was found, but it extended for only eight to 12 kilometers, whereas aftershocks were distributed over a 50-kilometer-long zone beneath the fold. This suggests that little of the slip that caused the earthquake reached the earth's surface. As with the other fold earthquakes we have discussed, the aftershock pattern was also diffuse rather than aligned along the fault plane, as it would have been in a surface-fault earthquake. The preliminary evidence therefore indicates that the Spitak event was fold-related.

The size and destructive character of the Armenian earthquake could not have been predicted on the basis of its short surface fault, but the fold provided a clue that seismologists must not, in the future, overlook.



ARMENIAN EARTHQUAKE SITE was mapped by Landsat in 1987 and later color-enhanced for the Soviet Mission in Washington, D.C. The main 1988 shock (large white circle) occurred near a limited surface fault (heavy blue line) not far from the town of Spitak. A string of folds (red line) mapped by Soviet geologists 25 years before the earthquake is seen to be aligned with the widespread aftershocks (small white circles), which were recorded by a U.S. National Academy of Sciences - U.S. Geological Survey seismic team at the invitation of the Academy of Sciences of the U.S.S.R. The limited surface rupture and the close association of the fold and aftershocks suggest that the earthquake was fold-related. It is not clear whether the major but heretofore unverified fault (thin blue line) slipped during the event.

ROSS S. STEIN and ROBERT S. YEATS collaborate on the study of earthquakes because, as Stein puts it, "two heads are better than none." Yeats is professor of geology at Oregon State University and past chair of the department. He received a Ph.D. from the University of Washington in 1958 and then went to work as a petroleum geologist for the Shell Oil Company. In 1967 he joined the faculty at Ohio University and in 1977 went to Oregon. For relaxation he plays the piano. Stein received a B.Sc. at Brown University in 1975 and a Ph.D. at Stanford University in 1980. In 1981 he took his present position as a geophysicist at the U.S. Geological Survey in Menlo Park, Calif. Since 1987 he has also been an editor of the Journal of Geophysical Research. For relaxation, Stein says, he eats lasagna baked by Yeats.