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Trapping an Earthquake

by *Karen McNally*

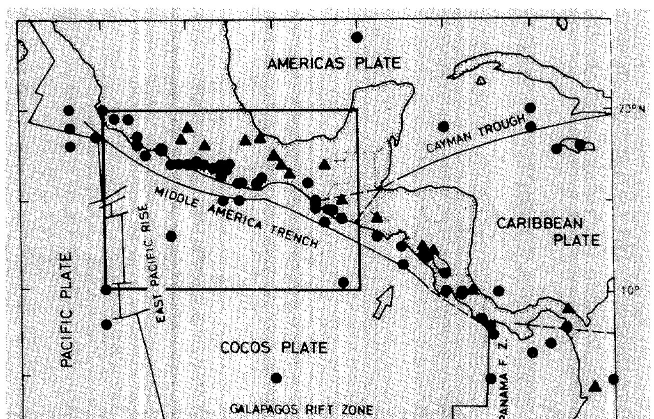
As a science, earthquake prediction is an infant — so young, in fact, that it is only just beginning to emerge from the realm of science fiction. The important way a science is distinguished from fantasies is by the application of the scientific method, that is, by the systematic collection and classification of data and the formulation and testing of hypotheses based on those data.

This is, of course, an academic definition, but it is also an accurate description of what happened that allowed us to "trap" the Oaxaca, Mexico, earthquake of November 29, 1978. In that instance, we had a case history of science in operation. There were data that led to the making of a scientific forecast that an earthquake would occur within a particular area. In response to that prediction, a group of seismologists from Caltech and the University of Mexico jointly placed seismographic instruments in the area to collect further data. Just about three weeks later, an earthquake of magnitude 7.8 occurred, precisely where it was expected. To help relate the size of this earthquake to others about which we have more knowledge, let me point out that this was close to the magnitude of the 1906 San Francisco earthquake and 120 times the size of the 1971 San Fernando earthquake.

The accurate prediction of the Oaxaca earthquake is of considerable interest to seismologists, of course, but it also has wider sociological implications. What happened to the people of that area of Mexico as a result not only of this carefully evaluated scientific prediction but also of a widely publicized non-scientific prophecy related to it could well be the script for what could happen under similar circumstances in, for example, southern California. In fact, what happened leads seismologists to urge the public and the appropriate governmental agencies to prepare for handling earthquake predictions as well as actual earthquakes.

The setting for the Oaxaca earthquake was along the west coast of Mexico. Here, deep in the Pacific Ocean, the Cocos Plate subducts, or dives, into the Middle America Trench and beneath the continent, producing many earthquakes in the process. The subduction of this plate is in conjunction with the East Pacific Rise, a spreading seafloor ridge that continues into the Gulf of California and extends northwestward to become a transform fault that we know as the San Andreas. While the motion of the San Andreas fault is different in that its two sides slide past each other, nevertheless it is an extension of the system that drives the Cocos Plate underneath the coast of Mexico and Central America.

In the period since about 1898 this area along the coast of Mexico has experienced more than 40 earthquakes of magnitude 7.0 or larger. In a similar period and over a coastal area about three-quarters as long, California has had 6 such earthquakes. If we normalize these numbers per square kilometer, we find that Mexico has five times as many earthquakes, which should make clear at least part of our motivation for going outside California to study earthquakes — that is, the availability nearby of extensive



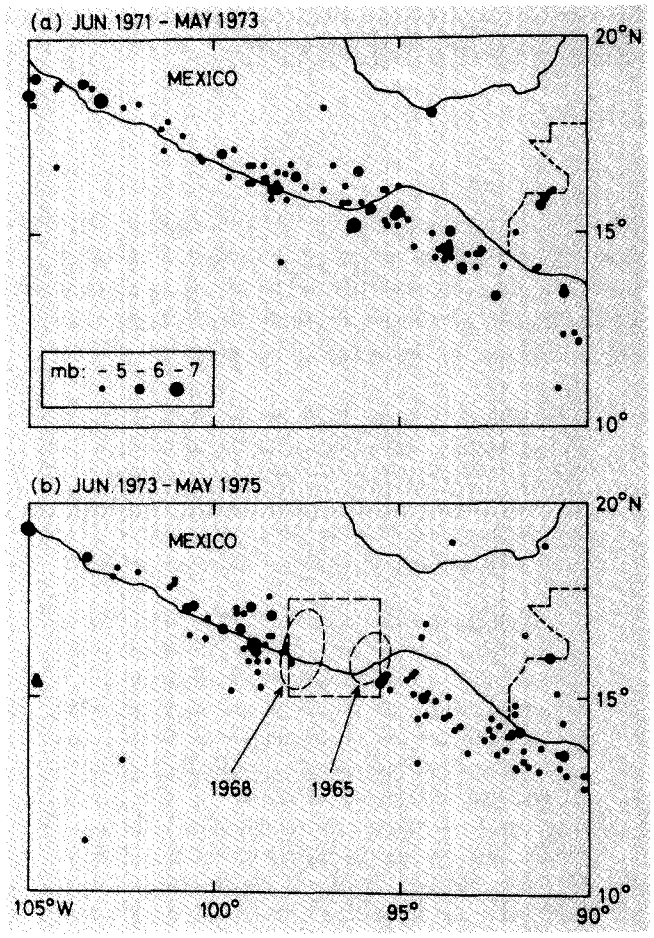
Mexico and Central America make a diagonal strip across this map, with the tectonic features that affect them on either side and the open arrow showing the direction of subduction of the Cocos Plate into the trench and beneath the continent. The black dots indicate the locations of large shallow earthquakes since 1898, and the triangles are for those originating deeper than 65 kilometers beneath the surface. The rectangle encloses the area within which the Oaxaca earthquake occurred last year. (After Ohtake, et al, 1977) material for research. We hope that when the next magnitude 7.0 or larger earthquake strikes California (and it will happen), we will have a better understanding of what to expect than we have had in the past.

Even though California has fewer large earthquakes than Mexico, we are fortunate in having an extremely dense array of seismographs, particularly in southern California where the density of the population gives rise to legitimate concern about the effects of large earthquakes on both structures and people. Instrumentation elsewhere in the world, unfortunately, is scarce, and data are basically lacking. This was certainly the situation in Mexico. But we were able to have an array of instruments in the field there by the first week of November of last year, so we have data from just over three weeks of detailed signals before the actual occurrence of the predicted earthquake, plus records of the seismic activity since.

A combination of circumstances led to the operation of a seismographic array by Caltech and the University of Mexico in the Oaxaca area at the appropriate time to trap this predicted earthquake. First, we knew about the forecast and that it was based on very thought-provoking data. Another related factor was that because an earthquake had recently occurred in the area in question, I was invited to give some lectures about Caltech's earthquake studies to a group of scientists (who also knew about the forecast) at the University of Mexico in August 1978. During one of these lectures, a second earthquake shook Oaxaca, and we decided to work together to try to discover what was occurring.

The forecast itself was made by scientists from the University of Texas in 1977, and it aroused great interest among the staff of Caltech's Seismological Laboratory. The evidence presented by the Texas group, which was so convincing to us, went something like this: Along the coast of Mexico earthquakes were fairly uniform in frequency between 1971 and 1973. In the area around Oaxaca from 1973 to 1975 they had suddenly ceased. In 1965 on one side of the area in question there had been an earthquake of magnitude 7.6, and on the other side of the area there had been one of about the same magnitude in 1968. The space along the subduction zone in between — a spatial seismic gap — had not broken.

As a matter of fact, in 1973 a group of seismologists from the Lamont Geological Laboratory had pointed out that this portion of the coastal region was a seismic gap area since no large ($M \geqslant 7$) earthquake had occurred there since a major episode of energy release in 1928 and 1931. They also pointed out that the average time periods between earthquakes of magnitude 7.0 or larger repeating at



These two earthquake patterns were significant in the development of the forecast of the Oaxaca earthquake — first, generalized earthquake activity along the coast between 1971 and 1973 (top) and second, the development of a seismic gap in a part of that area between 1973 and 1975 (bottom). The locations of the 1965 and 1968 earthquakes on either side of the gap and their aftershock areas are also shown. The size of the dots indicates the magnitude of the earthquakes. (After Ohtake, et al, 1977)

the same location was on the order of 30 years in this region. So the area seemed overdue for a seismic event.

The stopping of seismic activity between 1973 and 1975 in this area was considered by the scientists from the University of Texas to be significant anomalous behavior and possibly a prelude to a large earthquake. They based this conclusion in part on data from the 1965 and 1968 earthquakes. In both of those cases, activity stopped for a period of time, then resumed for a period, and then the main shock occurred. Looking at this particular seismic gap in the Oaxaca area in terms of both location and point in time, they noted the two-year-long cessation of activity, and forecast that a large earthquake was likely to occur following a resumption of seismic activity. They did not say definitely when it would happen nor precisely how large it would be, but they estimated it would be about the same size as those of 1965 and 1968.

At this point I want to shift gears and describe the effect of this prediction, plus a related prophecy, on the people of the State of Oaxaca, particularly those of the town of

Pinotepa. It may sound bizarre, but it happened, and who is to say it would not be similar in southern California under the same circumstances? The following account was written by two professors of geophysics from the University of Mexico: T. Garza and C. Lomnitz.

> On the 7th of February, 1978, two residents of Las Vegas, Nevada, sent a letter to the President of Mexico, which contained the following prediction, based on "demonstrated scientific facts": "Earthquake in the State of Oaxaca in the town of Pinotepa on 23 April 1978 and large quantities of water causing flooding."
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> A copy of this letter reached the office of the Mayor of Pinotepa a few days later. Some of the effects of the "prediction" were described in the local Pinotepa newspaper as follows: "After this announcement, there has been a tremendous commotion on the Oaxaca coast, to the point where many persons are fleeing their homes to emigrate to other towns in Mexico. . . . The psychosis caused by the alarming news has induced them to sell their properties to the highest bidder, thus destroying their homes. . . . At first it was a speculative news item, but so much has been written about it that it has brought damage to all of Oaxaca as well as to the neighboring states of Guerrero, Michoacan, Puebla, and others. . . . Unfortunately, there has been panic, particularly in Pinotepa and nearby coastal towns, and this is understandable because no one wishes to endanger their families; some local people have already sold their property, and people with money are buying land. . . . One wonders: Who are these people picking up cheap real estate along the Oaxaca coast?"
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> Meanwhile, a UPI press release from Austin, Texas, was headlined on the front page of a Mexican daily: "Texas U predicts big Mexico quake." This appeared to lend legitimacy to the prediction for April 23. The press report did not contain a specific date, but it was studded with phrases such as "A massive earthquake will occur soon in the state of Oaxaca," and "UT researchers expect the quake to be stronger than those that shook Managua and Guatemala," and so on. Verbatim quotes attributed to a reputable U.S. scientist appeared to confirm the earthquake threat to Oaxaca.
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> The American press caused speculation to flare up from Acapulco to Salina Cruz. One Acapulco local newspaper hatched a fantastic story, complete with "geological sections," claiming that a foreign power had buried half a dozen nuclear charges in a fault located off the Oaxaca coast, to be detonated on April 23 by a remote control from a plane flying at an altitude of 15,000 feet. Unfortunately, this story was widely circulated, if not actually believed. A surprisingly large number of people thought that oil or uranium had been discovered on the Oaxaca coast and that cheap leases were being sought by foreign nationals. The questions asked by reporters reflected similar beliefs.
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> Sunday, April 23, was a hot, sunny day in Pinotepa. The Governor of the State of Oaxaca had announced that he would be in attendance to preside over special festivities organized "to reassure the people of the Oaxaca coast that nothing was going to happen on that date with reference to the said earthquake." Folk dancing groups, musicians, and politicians had been brought in from the State Capital. The Mayor of Pinotepa told us that there had been no letup in seismic activity in recent years with reference to the seismic gap. "We feel some 50 or 60 earthquakes every year," he said. "If there had been a lull, people would have talked about it. We just had another shock four days ago." He proceeded to tell us that the two strongest earthquakes announced the beginning and end of the rainy season each year.
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> The Mayor was indignant about the prediction, which he claimed had caused more damage to Pinotepa than the 1968 earthquake. Though he used strong and profane language, he also claimed that the reports of widespread panic were exaggerated. "Those who left were mainly out-of-towners," he stated. "Only about 15 percent of the citizens of Pinotepa are economically well off and can afford to leave."
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> A stroll through the town revealed that perhaps 20 percent of the homes were shuttered, indicating that the residents were out of town.
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> The Governor arrived at 5 p.m. and proceeded to the Town Hall where a special exhibit (including a tent used for emergency housing) had been prepared by the Office of Urban Emergencies of the federal government. At 17:40:02 local time, while the Governor was being shown around the exhibit, an earthquake shook Pinotepa and startled the crowd inside the Town Hall. The shock felt like a nearby local earthquake and was not even recognized as an earthquake by some people though it caused the metal doors to vibrate audibly. The Governor and his party were unperturbed, and later denied they had felt an earthquake.
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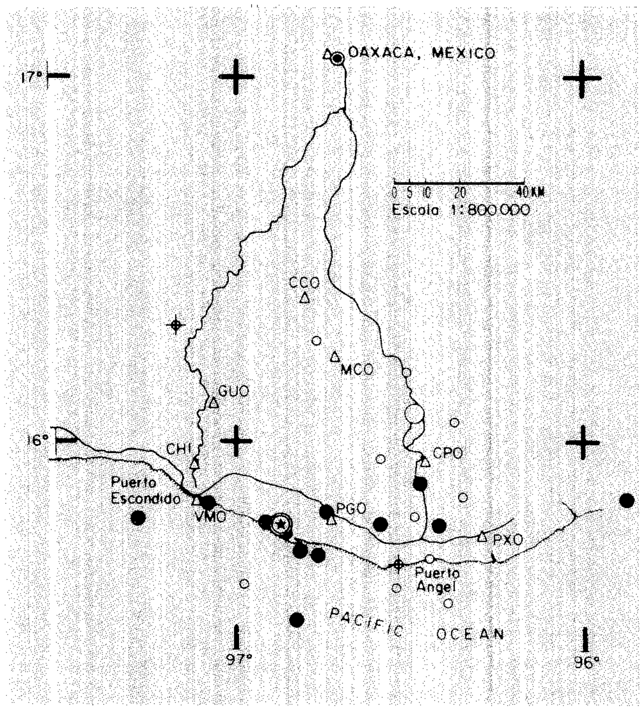
> The festivities proceeded as planned. Around 10 p.m. a merry public dance began in the town square. Shortly after midnight, the Governor looked at his watch and decided that it was time to return to Oaxaca City as the prediction had lapsed. Some local residents still took the small shock in the afternoon as proof that the prediction had been partially successful, but everyone was relieved that no disastrous earthquake and no tsunami had occurred.

For whatever it is worth as an object lesson, then, that is a description by a Mexican seismologist of the effects of



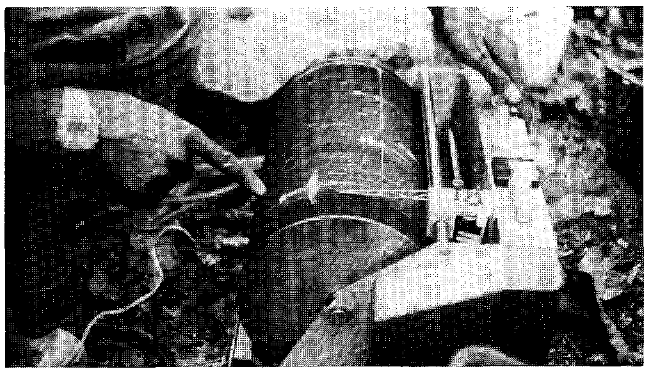
The route of the seismograph array (the stations are indicated by triangles) that trapped the Oaxaca earthquake started at Puerto Escondido, ran inland and upward 150 kilometers, and then turned back toward the coast, ending at Puerto Angel. The star is where the main shock occurred, and the black dots are the largest aftershocks within the following week. The open circles — in addition to the one around the main shock — show the locations of aftershocks as given by the standard worldwide network in the absence of local seismograph station data.

an earthquake prediction on a group of people who were not prepared to cope with it. Both Mexican and American seismologists did believe, however, that an earthquake really might occur near Oaxaca and that it was likely to be a large one. So we people at Caltech gathered our troops, our small budget, and some good equipment for working in Mexico, and joined with our colleagues from the University of Mexico to put out the array. Three weeks after it was in place, the earthquake occurred right in the middle of our net. Thus we had a complete history of what went on in those weeks before the main shock as well as after the main shock.

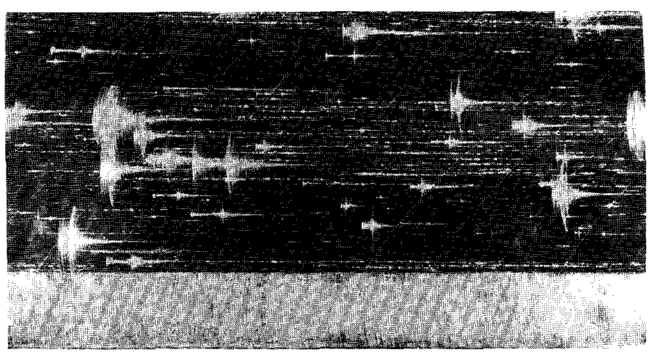
Our base camp was at Puerto Escondido on the coast of Mexico. From there, the stations of the array were strung out in a loop 150 kilometers up into the mountains above the coast and down again to Puerto Angel, some 100 kilometers east southeast of Puerto Escondido. Every station was an instrument that had to have its paper seismograms changed every one or two days, and that meant making it all the way around the loop for each change. It also meant crossing rivers where there were no bridges; it meant driving on roads that were often mere tracks through dense jungle; it meant a climb from sea level to 5,600 feet; and that meant at least eight hours of travel time — at about 11-13 miles per hour — plus the time it took to service the equipment.

The instrument we used was a battery-driven rotating drum. Around it was wrapped a piece of paper that had been smoked by holding it over a kerosene lantern. A needle, lightly in contact with the paper, scratched a record of any vibration felt by the instrument. This is one of the oldest forms of recording, recently brought into use for portable field array instruments. It is extremely simple, requiring very little except a suitcase to carry it, a source of smoke, and lacquer to coat the finished seismograms in order to fix the tracing. In this particular area there was one other requirement. Because of the intense heat in that area of Mexico at that time of the year, we had to construct foliage shelters over the instruments to keep them from malfunctioning.

After the earthquake occurred, there were — as one of the Caltech seismologists phrased it — "people ungrinding their axes." One of those people was the governor of Oaxaca. He was so pleased with our fine job of figuring out that there was going to be an earthquake that he just had to come right down to our base camp (where he had never been before), bring along his entire press group, and make a speech. Then a member of the opposition took the stand and said that there shouldn't be studies of earthquakes in this area when people are hungry. So our work became something of a political issue.



Above is a rotating drum covered with smoked paper on which a needle scratches the trace of vibrations felt by the seismometer. Below the actual tracing of the Oaxaca earthquake on a seismograph located at station PXO is so saturated that it looks like an almost solid band across the bottom of the strip of paper. The scattered tracings above that area are of the lesser shocks detected in the two days before the main shock.



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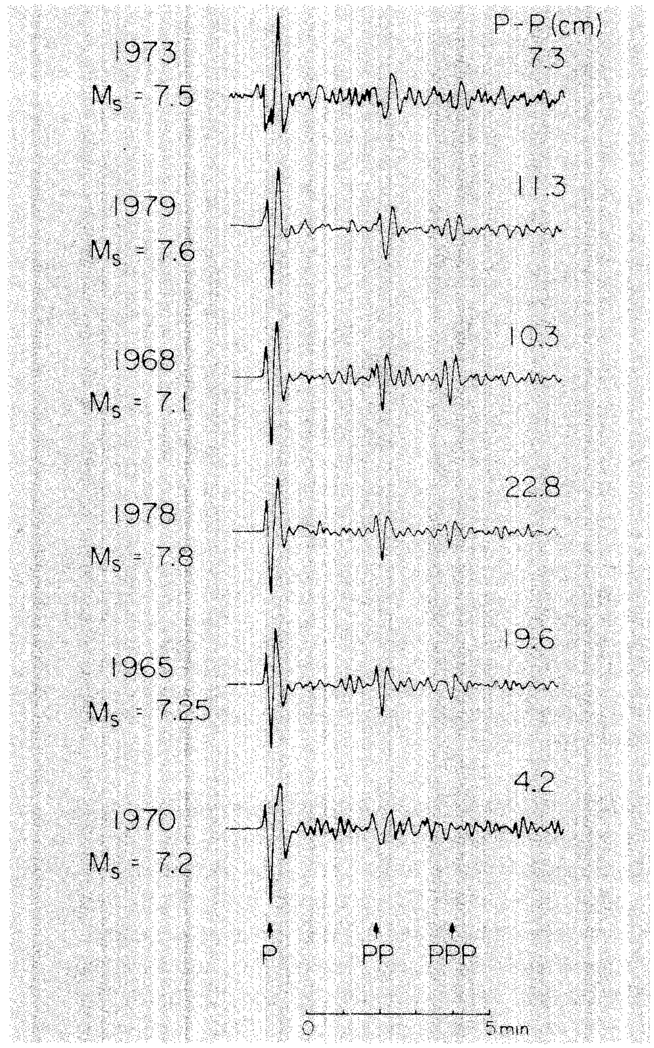
How much damage was caused by this very large earthquake? Amazingly little as far as we can tell, and much that was claimed by the local people was obviously in the hope of their getting the government to pay for repair of previously existing damage. Generally we have assumed that we have some ability to predict how damaging to structures an earthquake will be, based on its size. But this experience taught us that the matter is far more complicated than that. Are earthquakes along subduction zones typically low-damage tremors? Is there something in the way such earthquakes occur or the properties of the subduction zone or the nature of the failure itself that results in relatively small damage? We don't know the answers to those questions, but we are looking in a number of different ways at the data we have gathered to try to understand the main determining factors.

One of the first things to do was to compare the available records of the seismic wave forms obtained for other large earthquakes along the Mexican coast — in order, south to north, those of 1970, 1965, 1978, 1968, 1979, and 1973. We had records of the wave forms at teleseismic distances (that is, records obtained on instruments located at some distance from the actual event — at Caltech, for example, in the case of the Mexican earthquakes), and we could check them. All but one of these records showed extremely small, simple pulses in their first wave form. In contrast, the northernmost of these quakes showed an extremely complex pulse, indicating a ratcheting kind of effect as the earth broke and generated a high-frequency wave. Obviously, one of the first things for us to do in the light of that finding is to compare the damage reports for each of these areas in those earthquakes. We need to identify the areas of simple and complex sliding to see whether there is a correlation with the amount of damage.



Initial wave forms of six large earthquakes along the Mexican coastal subduction zone show small simple pulses in five cases, including the Oaxaca earthquake, while a 1973 event in northern Mexico produced a complex pulse. This may be correlated with the complexity of sliding and, consequently, the amount of quake-caused damage. [The magnitudes (M_S) given here for the 1965 and 1968 earthquakes differ slightly from those quoted in the text because they are from a different source.]

We already knew that the size of an earthquake is related to the area that slipped and the amount of slippage, and we were able to obtain comprehensive data on those factors in this earthquake because the field array gave us excellent constraints on the aftershock area. We found that this earthquake was what we call a low-stress drop earthquake, and this may be another ingredient in low-damage earthquakes.

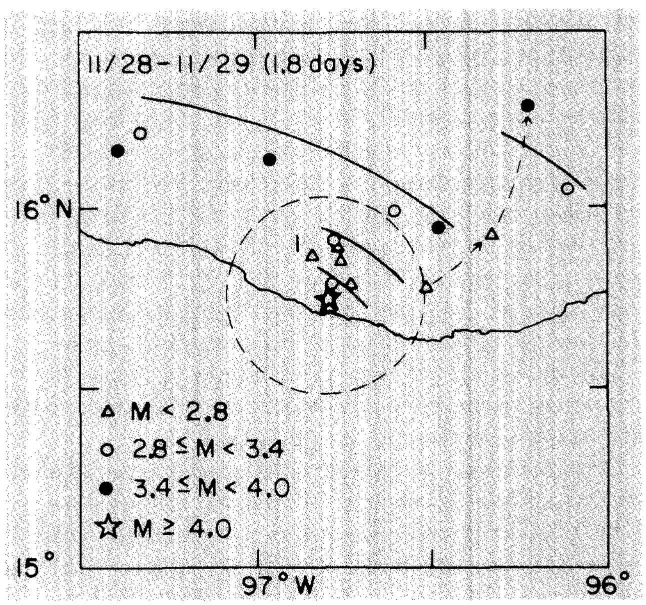
Since we had an array in place for this earthquake, we were also able to analyze the data to confirm the existence of tectonic plates, plot their depth at various distances inland, and determine the relation of the subduction failure to that depth. This is the first time this kind of information has become available in this region.

We have, of course, very well documented records of the foreshock activity in the last three weeks before this earthquake occurred. At first the seismic activity was quite low, with just a few events occurring at the edges of the area we were studying. Then a cluster of earthquakes broke the silence in the quiet region around the main shock. The quiescence then resumed within that area, but there was a much larger amount of activity around the periphery of the region. Nevertheless, within about a 30-kilometer radius of the main shock, nothing further occurred until, finally, in the last 1.8 days before the main shock, earthquakes again clustered in the quiet zone.

To concentrate on those last 1.8 days, a small event occurred very near the main shock region, and then activity began out at the edge of the region and migrated up-dip closer and closer to the center until 17 hours before the main shock. For those 17 hours, activity mostly stopped except for three events that moved out and down-dip back down the plate. The migration that moved inward seemed to originate at deeper points along the plate and move upward toward the point of the main shock.

The fault mechanism of an earthquake can be described as something like two pieces of foam rubber sliding past each other. There is a cut down the middle where, because of the friction along the cut, the pieces of rubber first stick and then slip as you slide them along. If you imagine a sphere around the central region of the foam rubber, you can see that as you push one side past the other, the impulse of the side that is not being pushed will be away from the sphere. Our data show us where there was push and where there was pull in this zone and that in the middle of the sphere is the earthquake source. From these data we have deduced that this earthquake (i.e., the main shock) was a thrust event, with the plate thrusting under the continental crust. Analysis of the foreshocks indicates that the mechanism of the activity at some distance from the main shock was different from the main shock itself. There seemed to be a kind of predictive slipping going on in the immediate region of the main shock, however, that emulated the subsequent fault mechanism of the main shock.

Our data on the foreshocks indicate a number of other significant factors. First, the average size of the events before the main shock clearly increased with time. Second, if you look at numbers of the events in the 32-hour period before the main shock, you can see that there is a strong increase and then a period of quiet. We were able to see clearly that in this last 32-hour period before the main shock there was a distinct clustering of earthquake activity that was quite different from any previous activity. It is encouraging in our efforts to make reliable earthquake predictions to think that if we had had similar data in advance of other earthquakes, we almost surely would have recognized the significant changes in activity from this kind of display.



The foreshocks of the Oaxaca earthquake illustrate the slipping during the last 1.8 days prior to the main shock (star). After a small event (1) near the center, shocks began on the outer edge (black and white dots) and migrated inward. For the last 17 hours all was quiet except for the three events moving outward (arrows).

This rise in earthquake activity and then a period of quiet before a main shock seems to be very common in foreshock sequences for earthquakes all over the world, but this is not a matter for as much optimism as it would seem we might expect. The fact of the matter is that if we had not had the instrumentation in place in this earthquake, we would not have recorded this foreshock activity elsewhere. All of these short-term foreshocks were smaller than the worldwide detection threshold. Our studies of earthquakes on that basis are mainly of those of magnitude 4.0 and larger. As far as we know, about 44 percent of all earthquakes are preceded by foreshock activity of this kind. What we learned from this earthquake is that we need much more instrumentation for increased detection to find out if foreshock sequences are more common than we have supposed.

Of course, in studying earthquakes and their failure mechanisms, seismologists are under the handicap of not being able to conduct earthquakes under varying conditions in order to find out what makes them happen. It's a circular situation. We have to study what happened before an earthquake in order to predict one, but we have to be able to predict one so we will know where to go to set up our instruments to get data to study. One thing we can do is to set up models to study in the laboratory, and one class of such models — called the dilatancy model — involves studying what happens to rock samples under stress. In this model (which has been developed both in the United States and in the Soviet Union) we measure the deformation of a sample of rock as we squeeze it. At first there are a series of small failures, creating microcracks in the rock sample. At a certain point, the density of microcracks becomes large and causes an increase in the volume of the sample. A coalescence of microcracks then takes place, and the size of fracturing events increases near what becomes the main fault plane, locally reducing the stress. The actual volume increase — or uplift — decreases again, and then failure may follow.

This suggests a number of things for earthquake studies;

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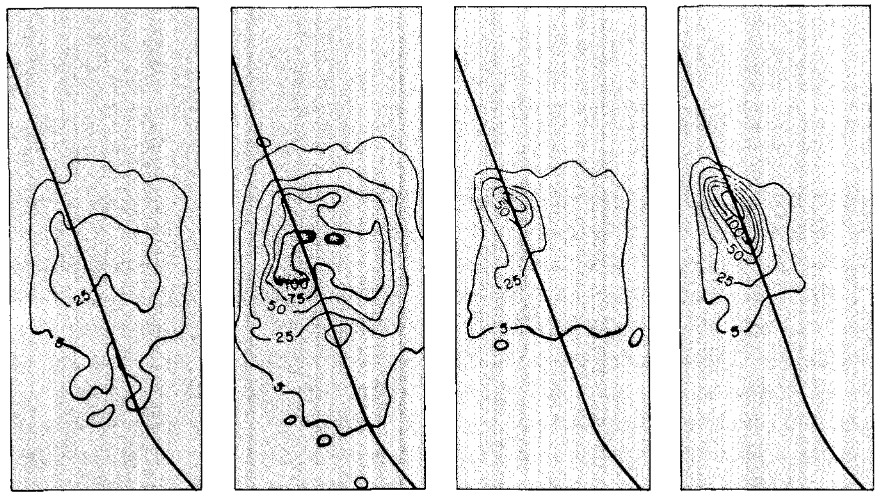

Microfracturing of a rock sample under pressure in the laboratory does not reproduce the period of quiet observed before the actual main shock of an earthquake. It does, however, illustrate the cluster of fractures (second frame — numbers on contour lines are the number of fractures) near the fault plane, which corresponds to observed activity. In the rock sample this is followed by a decreased frequency of events (third frame) and finally increasing activity just before failure. (Data courtesy of D. Lockner)

that, for example, we might observe uplift in the earth's crust before an earthquake. There have, indeed, been many observations of such uplift, but they are not well understood because their behavior is not consistent. We have all heard of the Palmdale uplift (or bulge) and because of the dilatancy model seismologists have been interested in and concerned about that uplift and what it may mean for a future earthquake on the San Andreas fault.

If we want to carry the analogy further, we can think of the microfractures in the rock sample as representing small earthquakes. An increase in microfracturing could represent an increase in activity in the last days before an earthquake. At present, laboratory models fail to predict the quiescent period of hours immediately preceding the final shock in a real earthquake.

If you look at rock fracturing within a sample in order to try to understand the time history of microfracturing, you can see several stages. First of all, there is a cluster of fractures corresponding to earthquakes near what becomes the fault plane. There are up to hundreds of events, followed by a quiet period when the frequency of events may drop to 50. In the last stage before the sample fails, microfracturing increases to 100 close to the fault plane. The clustering of microfracturing is certainly comparable to what is seen in the field, but what isn't comparable (perhaps because it is not observable on the kind of time scale we have in the laboratory) is the 30-kilometer-wide ring of quiet near the main shock. In the laboratory we can see nothing but increased concentrations of failures near the fault line.

The time scales for earthquake prediction are on the order of days to decades, and it is expected that the time period of this particular anomaly is related to the size of the subsequent event, but we really do not have enough data to be sure of that. If we bring to bear our data from the Oaxaca earthquake, we find that things are more complicated than we suspected. The scientists from the University of Texas showed a quiescent period beginning about 1973, but we later found that it had been quiet in the local area since 1966; the quiet area just became larger in 1973.

In terms of the seismic gap area and its relation to plate tectonics, the data are also somewhat confusing. You can take all of the sizes of large earthquakes along the coast of Mexico and Central America (since the size of an earthquake is related to how much slip there should be) and locate them along the trench at the edge of the Cocos Plate — and then look for a place where there has not been any slip. You have the known average plate rates (Central America — 7 to 9 cm per year; Mexico — 5 to 8) over a long period of time to check your work against — and then you come up with problems.

At some places the amount of slip we have measured in earthquakes actually corresponds with the long-term average plate rates; but at other places — particularly in Central America — it does not correspond at all. Even more disturbing, it turns out that subduction of sea floor topographic anomalies may lead to apparent seismic gaps of a different (or non-predictive) kind. Some of the areas that are quiet seismically actually coincide rather well with areas of prominent sea-floor topography, which means that in looking at seismic gaps we have to decide whether they will ever break. It is my present opinion, based on the study of modern data and of old Mexican journals dating back as far as 1542, that some areas being subducted under the continental shelf may never break in a large earthquake. So we need to find out which gaps are likely to break and which are not and what relation they have to the topographical properties along the trench.

So this is where we stand in earthquake prediction a year after the Oaxaca earthquake. We are still collecting data, still developing hypotheses and trying them out. Someday we will be much more sure of what it all means. When that day comes, we seismologists hope there will be an enlightened public, educated and able to cope with the implications of earthquake prediction. The importance of that is one of the most significant things to have learned from our trapping of the Oaxaca earthquake. □