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Earthquake Prediction Research Funding: Senate Bill 22X

Joint Committee on Science and Technology

CALIFORNIA LEGISLATURE

JOINT COMMITTEE ON SCIENCE AND TECHNOLOGY

SENATOR JOHN GARAMENDI, CHAIR

Interim Hearing on

EARTHQUAKE PREDICTION RESEARCH FUNDING: SENATE BILL 22X

November 16, 1989
California Institute of Technology
Pasadena, California

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HEARING

STATE OF CALIFORNIA

JOINT COMMITTEE ON SCIENCE AND TECHNOLOGY

EARTHQUAKE PREDICTION RESEARCH FUNDING:

SENATE BILL 22X

Thursday, November 16, 1989
1:30 p.m.
BAXTER LECTURE HALL
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CA

CHAIRMAN: HONORABLE JOHN GARAMENDI

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Senator Rebecca Morgan
Senator Art Torres

Assemblyman Sam Farr
Assemblyman Charles Quackenbush
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STAFF:

Masako Dolan
Principal Consultant
Karen Thiel
Senior Consultant
Gladys Ikeda
Senior Consultant
Fusha Hill
Secretary

HEARING TRANSCRIPT

<u>HEARING TRANSCRIPT</u> (cont'd)

CHAIRMAN JOHN GARAMENDI: We have a very full agenda for the day. We have fourteen witnesses. In looking at the resumes and the backgrounds of the witnesses, we have, gathered in this room, the best of California's, if not the world's, seismologists. I don't mean that just to play upon your good will, but rather to express our sincere appreciation for your attendance at the hearing.

You have all been deeply involved in earthquakes, seismology, tectonics and other matters of the earth for years and you have a wealth of information. And on behalf of the Joint Committee on Science and Technology, I want to welcome each and every one of you to this hearing on Earthquake Predictions.

The earthquake is a uniquely frightening natural disaster. More than one person in this room has told me already today that they are scared to death of earthquakes. My suggestion that they move from California didn't meet with much enthusiasm on their part because many of us want to live here for reasons that have to do with employment, lifestyle, environment and we're willing to put up with earthquakes.

But they come without warning, or so we have always feared. Earthquakes alone can cause devastation and death without allowing us, at least at the moment, any chance, no matter how small, to do something to save ourselves from the grasp of the earthquake.

This is not a new subject for this Committee. We have explored this topic before. We've held previous hearings which featured information on the need for earthquake research and the Committee has sponsored legislation in this area, including most recently, SB 22X, which is Special Session legislation dealing with the matter of earthquake prediction.

Given the enormous devastation of the October 17th disaster, it's obvious to me that anything we can do to find meaningful ways to alert people is an expenditure well-worth it. Every Californian -- all 28 million of us -- knows that we live in earthquake country. Each of us can predict with 100 percent accuracy that there will be an earthquake. But where will it be, when and in what magnitude will it occur? Until now we thought that we were at nature's mercy. However, many of you here in this room have been trying to find ways to allow people to anticipate earthquakes and to take some precautions against them. You're -- many of you -- in the business of earthquake prediction. Some of you have spent your careers analyzing and studying the movement of the earth -- its plates -- in hope of discovering the secrets that lie therein. I understand that you've made great advances. We'd like you to share that information with us. Through disciplines like paleoseismology and neotectonics, you've been charting the course of faults. (And I'm not referring to legislative or political faults.) You've recorded the faults that exist here in our earth's crust and you're making estimates of where they will move and when. Everyone within this room has spent a lot of time on this subject. Please share your information with us.

Some questions that we do have we'd like to put to you.

* What do we know about earthquakes and how they are caused in California?

* To what degree can we now predict earthquakes?

* What steps can we take now to improve the prediction-ability?

* Will we ever get predictions to the point where we will be able to sound the alarm just before the big one occurs?

* Even if we cannot get predictions down to that level of precision, what practical use can we make of long-range predictions?

* What value lies in such predictions?

* Finally, what can the state government do to assist you in your work? What kind of support do you need from the state government?

We await your testimony. We'd appreciate all of you keeping in mind that we're numerous and try not to wander too much and I'll keep that in mind also.

To lay the groundwork and the background for all of this, Bill Iwan, a member of the Seismic Safety Commission is here. He's a professor of Engineering. My understanding is he had to walk across campus to get here. Bill, we can see you down there.

BILL IWAN, PH.D.: Thank you. Mr. Chairman and Committee Members, I am Wilford Iwan. I'm a member of the Seismic Safety Commission and also I'm on the Engineering Faculty here at Cal Tech. Thank you for inviting me to come and address you on behalf of the Seismic Safety Commission. We're pleased that the Committee is concerned about the technology related to the earthquake safety problems and is holding this particular hearing.

Let me begin by stating that the Seismic Safety Commission supports continued earthquake prediction research, but believes that this research must be undertaken within the context of a comprehensive and balanced seismic safety program. Such a program must consist of at least three essential elements. First is hazard identification, second is hazard mitigation, and third is emergency preparedness and response. To the extent that earthquake prediction contributes to and supports these elements, we support further efforts in this area.

The first element that must be a part of the program is hazard identification. Of course, the goal of hazard identification is to identify and quantify the earthquake hazard. This involves a number of different aspects. First, it involves understanding the causes and nature of earthquakes. The objective here is to determine the likelihood of the occurrence of an earthquake on a particular fault of a particular magnitude in a given time. Necessarily this involves a great deal of research in the basic earth sciences areas and our research today has contributed greatly to our understanding of the nature and causes of earthquakes. We believe that additional research on earthquake prediction, will also contribute to our understanding of the nature and causes of earthquakes.

But if earthquake prediction becomes a practical reality, it will enable us to sharpen this identification beyond our present probabilistic definitions of the earthquake hazard to definitions that are more precise. However, this process raises a considerable number of questions, as well, such as how precise will that determination be? How reliable will the predictions be? What kinds of faults will we be able to predict earthquakes associated with? How long will it take for us to do this? And how much will it cost?

In this regard, I think it's important that we keep in mind that we already have more information about the earthquake hazard potential in California than we have been able to act upon so far. For example, we know there's a very high probability of the occurrence of a magnitude 7 earthquake on the Hayward Fault. But as we've seen in the last couple of weeks of testimony in the Commission, we really have not taken the steps that we need to take to mitigate against that known earthquake hazard.

Earthquake hazard identification also requires that we understand how seismic waves are modified by their path from the site to the source or from the source to the site, and in the local site conditions. The objective here is to identify those sites that are most hazardous and to quantify this hazard.

We have seen graphically in this earthquake and Loma Prieta that the effects of different soil conditions can have a very pronounced effect on the ground shaking. We've seen amplifications of a factor of three or four -- in some cases possibly larger. There's also some evidence that local topography has a strong influence on the nature of the ground shaking.

A lot more research is needed in this area. It's possible that earthquake prediction research could give some information in this area, but it's not one of the strongest areas of contribution.

We also need to know more about how soils and manmade structures respond to earthquake shaking. We need to be able to identify those conditions or those structures that represent the greatest risks in a future earthquake and to somehow quantify this risk.

We also need to be able to assess the risk that structures have after one earthquake for the possible damage that they might incur after an aftershock.

We certainly need better ways to analyze and to predict the behavior of soils. We've seen liquefaction in the Loma Prieta earthquake. We need to know more about when and how liquefaction takes place. We also need to know more about structural response to identify those structures that might collapse, like the Cypress Viaduct structure.

This is another area where considerable research is needed and I might just say here that we appreciate the efforts of the Chairman and this Committee in introducing legislation that would give California a stronger earthquake research program and we pledge our support to continue to work with the Chairman to see that California does exercise the appropriate leadership in doing earthquake research. We simply cannot rely upon the federal government to continue to support all of that research.

The second element of any good seismic safety program is mitigation. The goal is to find and to implement effective economically and socially acceptable ways to mitigate the hazards associated with the earthquake and reduce the risk to an acceptable level. This is no easy task. In fact, we can't even seem to agree on an acceptable level of risk. We feel that it's unacceptable if we lose life in an earthquake. It's somehow acceptable if we have some structural damage. But we're not sure just what degree of economic impact is acceptable. We first need to find out what's acceptable and then we need to reduce the risk to that acceptable level.

Clearly, earthquake prediction could play a role in hazard mitigation. Just what that role would be is not so clear. It might be simply motivational to begin to make people do the things that they knew they should have done and put off doing. On the other hand, by giving us a sharper definition of the hazard in terms of space and time of occurrence, we could take certain steps to minimize the loss of life. However, I think we should note, that even with prediction and the associated movement of people around and so on, I think we would all believe that it's unacceptable if we lost any significant portion of our infrastructure.

For example, if we lost a significant portion of our housing stock, or if we lost certain critical facilities like power plants, water treatment plants, hospitals, dams or if we lost a significant portion of our production capability. So even if we had 100 percent earthquake prediction, we must adopt other methods of mitigation as well, in order to minimize the effects of an earthquake to our built environment and our population.

The third essential element of a seismic safety program is emergency preparedness and response. Here, again, earthquake prediction could play an important role. We could keep people away from areas of high risk and thereby probably minimize the loss of life.

In this regard, the idea of real time earthquake monitoring, which will also be discussed in this hearing, is an interesting possibility. The use of early warnings, as well as the traditional earthquake prediction might also be useful.

But we must keep in mind, I think, that we just simply can't evacuate whole cities. And even if we could evacuate whole cities and we asked the people to return to rubble, that would be unacceptable. So again, even with earthquake prediction, we must do the other mitigation strategies that we know can be undertaken to protect our built environment.

Earthquake prediction is no substitute for a balanced program of preparedness which involves public awareness, public education, private sector actions, local, state, and federal government actions. We need to have all of these factors working if we're going to have an effective emergency preparedness program.

In the final analysis, the Commission believes that earthquake prediction research must compete for the limited seismic safety resources with other strategies based upon how well it will contribute to the hazard identification, mitigation and emergency preparedness and response. The competing strategies include the retrofit of unsafe buildings, or highway bridges, or dams, or other structures; the design and construction of safer -- that is, lower risk -- new structures and facilities; better earthquake preparedness through education; land use planning, occupancy restrictions and so on; a better emergency response through improved communication systems; more response resources and improved planning; and better recovery planning, taking into consideration insurance, tax credits and so on.

Finally, I think it should be noted that in many cases, we already have adequate knowledge of the earthquake hazard potential. In fact, we already have identified the risk. We already have identified mitigation strategies. We know that the risk is unacceptable. But we simply have not yet made the commitment to do anything about the problem.

So whether or not we have earthquake prediction, we do need to have action to begin to take steps that we know will make a difference. We know, for example, that unreinforced masonry buildings are hazardous. We know that non-ductile concrete frame buildings are hazardous. We know that certain highway structures are hazardous. Yet somehow we have not acted forcefully enough to make a major impact as we should have in those areas.

For example, it's been 18 years since we saw the damage to highway structures in the San Fernando Earthquake and we still have not solved the problem of our highway structures.

In conclusion, the Seismic Safety Commission believes that our first priority must be to take action to mitigate our known seismic safety hazards. Where it is necessary to do research to get this going, we need to get that research under way. If we now have the technology to do it, we need to make the commitment of resources to get the job done. We owe it to the people of California not to wait any longer.

After that we need to consider all of the other activities that will help reduce the earthquake risk, including earthquake prediction. And we look forward to this hearing and to the clarification of the issues involved in that particular area of technology. Thank you.

CHAIRMAN GARAMENDI: Bill, thank you very much. You've been a consistent and constant witness at our hearings and I appreciate your testimony once again. The role of the Seismic Safety Commission is not fully understood by Californians. But I hope it will become clear through the hearings that the Commission is undertaking, that you and the other members are participating in now, that this is an excellent process and will undoubtedly provide a great deal of information. On the legislative side, we anxiously await the outcome of your hearings and your additional recommendations to the State. You and your other members of the Commission have been a consistent and constant herald, whose voice, unfortunately, is not heard in every appropriate office of government in California. So stay with it. Eventually, perhaps, as a result of the past disaster, the voice will be heard.

CHAIRMAN GARAMENDI: I may have some additional questions and we may want to come back to you a little later.

Thomas Heaton is the scientist in charge of the Pasadena Office of the U.S. Geological Survey. Thomas? I think you're our next witness.

While you're coming up, Tom, I want to introduce to the audience my staff, who has been responsible for putting together the hearing. Karen Thiel, a consultant to the Committee, is on my right and she was the one most directly responsible. Masako Dolan, on my left, is the Chief Consultant of the Committee. And together, primarily with Karen's work, this hearing has been put together and all of you have been assembled. So, Karen and Masako, thank you very much. Now, Tom.

THOMAS HEATON, PH.D.: Thank you for the opportunity to give my views. I have fairly strong views, having been in this field for quite a while and I'll keep my comments very brief and general, but specific. And...

CHAIRMAN GARAMENDI: That will be interesting. So please... (laughter)

DR. HEATON: Well, as I see it, the earthquake prediction problem is -- I don't really care for the word prediction. I would prefer to say that the problem is to utilize information that's available at any given instant to minimize our risk. That is, we need to go out and learn whatever we can about earthquakes, monitor earthquake activity and then utilize the information to decrease our risk. And strategies have been developed to do just that. And those strategies include long-term risk estimates. Those would include studying active faults, identifying which are the active faults and, by the way, Bill is right, we have identified numerous active faults, but I think there are many problems remaining to be solved in this area.

The next area is short-term risk estimation. That is, if something changes in the earth. For instance, the earthquake activity in the Los Angeles region has mysteriously doubled within the last three years. And we don't know the reason for it. We don't know the significance of it. But certainly we ought to. And if there is some activity -- for instance, suppose there was an earthquake right now in Pasadena. What should we tell the public about the potential significance of that event? What information should we provide in the short-term as things change. And that's along the lines of traditional earthquake prediction. We do have some strategies to deal with, I won't go into the details, but they're described in a document I'll mention.

The third strategy is to provide rapid estimates of the distribution of shaking immediately following a significant earthquake. And I think we've seen time and again that despite many efforts, when there is a significant earthquake, there is often a failure of our infrastructure. There have to be many emergency response actions taken. And there's always a lot of chaos immediately following earthquakes. There's not much information available. Everyone is -- 15 million people are trying to provide information and it's very difficult to get an assessment of what it is that has just happened after a major earthquake. There should be methodologies and there are strategies available to provide, within minutes, some sort of gross distribution of the shaking pattern so that more efficient emergency responses could be taken.

And then another strategy is to provide very short term warning of imminent strong shaking. And that's this notion that seismic waves travel slower than radio waves and that we could have some little black boxes that would be predicting five to ten to even as much as 60 seconds ahead of the shaking. About when the shaking would occur, when it would arrive, how big it would be and how long it would last. And that could trigger certain actions such as shutting down elevators or shutting down transit systems. It may even involve turning on a speaker system to tell us that the earthquake will start to shake here in ten seconds and hopefully it would say it will be over in five seconds and it will be a mild shaking and don't worry about it, but... So that's another strategy.

CHAIRMAN GARAMENDI: After you get yourself off the ceiling.

DR. HEATON: That's right.

CHAIRMAN GARAMENDI: By the way, don't worry.

DR. HEATON: So, I think the point I want to make is that there are a number of strategies that we know about for dealing with the earthquake problem over a variety of time scales and they're described in a USGS circular. It's called the National Seismic System Science Plan and I'd like to leave a copy of that with you and it describes those strategies.

Despite the fact that we have the strategies, systems to utilize these strategies are really not currently implemented. We say we've been in a research mode, but actual application of these strategies has really yet to be seen. And I think that's much of what Bill Iwan told you.

I think there's a very serious misconception among many people in the public that whatever can be done about this earthquake problem is being done. I think people figure this is such a big problem that if they knew what to do, they would do it. The only reason it isn't being done is because they don't know what to do. Well, that's wrong. I mean, we have many strategies to deal with these problems and there are many things that should be done that aren't.

Let me put up my next transparency. I'm not sure my colleagues from central California will agree with this, but in my opinion, it's important to recognize that there's a very serious imbalance between earthquake science resources, both equipment and personnel, between central and southern California. Seismologists and seismometers are a little bit like water in this state. Most of them are in the north, whereas most of the consumption's in the south. And... (laughter) I don't think most people really understand that the reason for it is people and a variety of reasons. But the biggest reason for it is because the Western Regional Office of the U.S. Geological Survey, which is the biggest participant in this research, is located in the Bay Area and there are over 200 people who work on earthquakes in that office and those working on earthquakes in southern California probably number less than fifty. So there's an imbalance there.

The next point is that earth scientists got together last spring and had a long conference about what the strategies should be in southern California and a proposal was put together for a Southern California Earthquake Center, whose goal it is to develop and implement the types of risk reduction strategies that I mentioned in that first transparency. That group came up with a plan and right now it's in the talking stage. The plan was presented to the Department of Interior, who, before the earthquake, at least, didn't show much enthusiasm for it in this current time of fiscal trouble.

I would urge that one thing that the State could do would be to give strong support, both from the State and strong support for cooperation with federal agencies to set up some sort of a Southern California Earthquake Center and I think these goals can be achieved. Thank you.

CHAIRMAN GARAMENDI: Don't run off. Tom, the Southern California Earthquake Center proposal translates into money. What kind of money are you talking about? How much money are you talking about?

DR. HEATON: Well, let me say in increments and currently, the total amount of money being spent on the earthquake program in southern California by the U.S. Geological Survey, I believe, is estimated to be about $3 million, is that right? So you could talk about any amount of money, I mean. But currently it's about $3 million that -- there's a proposal out for about $5 million a year to the NSF. and I don't know how that will fare, frankly. The USGS originally was proposing $15 million a year through the Department of Interior for the Southern California Earthquake Center. That was viewed as politically impossible and then pared down to $5 million a year and the last word that I heard was that even $5 million a year was just not a viable amount.

CHAIRMAN GARAMENDI: What did it mean to California when the Earthquake Research Center wound up in Buffalo, New York?

DR. HEATON: That center was primarily concentrated on the one aspect of engineering. And I think it definitely hurt that type of research in California, although it probably had beneficial aspects for the rest of the country. I mean, it's important to recognize the other parts of the country do have an earthquake problem. But, I think it certainly hurt California's ability to understand its earthquake hazards.

CHAIRMAN GARAMENDI: The Southern California Earthquake Center would focus on what kind of studies?

DR. HEATON: It would focus on studies of ground motions in southern California. How the waves travel through southern California. The physics of the earthquake process in southern California. And then it would focus on developing -- the final strategy here is to develop a time-varying risk model. A model of what the risk of going over certain levels of ground motion is as a function of time and that -- to actually develop such -- it's a computer model, but to develop such a model, you need to understand many things about the physics of the earthquake process.

CHAIRMAN GARAMENDI: You said at the outset you had strong views. Do you believe it's possible to predict earthquakes, both as to location and time?

DR. HEATON: My own view is that we will be able to reliably, and by that I would mean, over, say, 75 percent reliability -- give time, place and magnitude, where the time is down to days or even weeks. I don't believe we have a strategy to do that. I don't know how to do it and I'm not sure that anyone does know how to reliably say when an earthquake will occur. But I think it's important to not let that get in the way of understanding that there are many other useful strategies that must be recognized. I think sometimes people look at the earthquake prediction problem and say, "Well, they're doing whatever they can to predict the earthquake. They can't predict it. Therefore, everything is being done." That's not the case.

CHAIRMAN GARAMENDI: I think that's very clear and I suspect most of you will probably make that point over and over again that prediction is one part. But we do know with certainty that we're going to have earthquakes in California. And part of the prediction issue, as I see it, is to predict where they're going to be, which is, I suspect, what you're talking about with your Southern California Earthquake Center, understanding the structures of the geology in this area.

DR. HEATON: Yes, I think one thing we hoped ten years ago that there were some schemes and strategies out there that you would just put in some data and out would pop a prediction. Looking into those further, it's become clear that there is no magic bullet now and there's none foreseeable on the horizon. But we need to understand the physics of the process. As we understand the physics better, the -- foretelling the future will become clearer. We'll get better at saying what will happen in the next X number of years and perhaps even weeks.

CHAIRMAN GARAMENDI: One of the things I'd like to try to accomplish in this hearing and probably in a subsequent meeting, at which we'll probably invite -- well, we will invite all of you -- is the prioritization of where the money should be spent. Predictions, remedial strategies, and so forth -- things that have already been discussed. What's the priority? If we have $10 to spend, where do we spend the first dollar and the last dollar? And so forth.

One quick question to you and it deals with -- back to predictions. Some folks think that the gravitational pull of the moon and the sun are important in this process and can set off earthquakes. Could you comment on that?

DR. HEATON: Well, it's curious that you would ask me that. I've spent several years of my career studying that problem and my conclusion is that the tides have little or no predictive value. I do not believe that it's possible to predict earthquakes using tides, at least with any strategy that I've seen so far to date.

CHAIRMAN GARAMENDI: I understand that you're the author of a paper on the subject some years back and you've changed your views, I guess, over the period of years.

DR. HEATON: Well, I wrote one paper which had a positive conclusion that said it appeared that there was correlation and that was based on looking at a set of data and looking for a pattern. And then when I went to apply the same pattern to another set of earthquakes, it didn't work. So it taught me that if I go to Las Vegas and look for patterns, I shouldn't use them to bet my money with 'cause it doesn't always work so well.

CHAIRMAN GARAMENDI: The article in the magazine, Geology, July 1989 by Robert Wing, "Strong Correlation Between Earthquakes and Earth Tides in the Eastern United States"?

DR. HEATON: Well, it's based on a very small number of earthquakes and they found that if they looked for certain -- they took many tidal parameters and found if they grouped the earthquakes in a certain way, they could find a correlation. But it really doesn't mean much until you have a completely new set of earthquakes to test that hypothesis on. And we see that all the time where people believe they found some method by looking at past patterns, but when they go use it on a different data set, it doesn't work.

CHAIRMAN GARAMENDI: Well, you've just excited Karen. She's a researcher and she loves to look at past history and try to predict the future and she's just whispering in my ear, "Yeah, yeah, yeah."

MS. KAREN THIEL: It's called "predictive validity".

CHAIRMAN GARAMENDI: "Predictive validity" is the phrase she's using. Incidentally, the bill that we've introduced on this subject matter would provide the Seismic Safety Commission with the task of prioritizing. And that's where the meeting's going to come about. Tom, thank you very much for your testimony.

Some of the more interesting data that's been developed in this whole area in the last few years is the Parkfield Study and the Hayward Fault Studies. We're now going to explore those two studies or those two areas and the studies that have been done on them. Allen Lindh, Chief Scientist of the Parkfield Prediction Experiment of the U.S. Geological Survey and Tom McEvilly, Professor of Seismology, Assistant Director of the Seismology Station at U.C. Berkeley and Director of the Earth Science Division of the Lawrence-Berkeley Laboratory.

CHAIRMAN GARAMENDI: So, Allen, you're first.

ALLAN LINDH, PH.D.: Thank you. Could I have slides, please? I'll try to get through them in a hurry. I'm not quite sure how much background you all have on Parkfield, so I'll give a quick overview. If at midway through it you don't want to hear anymore, I trust you'll tell me.

Parkfield's a great small town about midway between San Francisco and Los Angeles. It's right beneath the dot, basically, labeled 1857 because it's right at the north end of the section of the San Andreas that failed in the great 1857 Fort Tejon Earthquake. And it's a very pretty little valley. Lot of nice people live in it. Fortunately they're good, tough California ranchers, including William Clark, Ronald Reagan's long-time Chief of Staff. And it's a great place to do an earthquake prediction because the people who live there aren't afraid of very much and they sure aren't afraid of earthquakes.

This is just a satellite view showing the line of epicenters of yellow dots running across the figure from upper left to lower right is the San Andreas Fault. The red dot in the middle is where the 1966 Parkfield Earthquake started and it extended about 20 kilometers down the fault. The big blob of yellow up in the upper right-hand corner is the aftershocks of the Coalinga Earthquake.

CHAIRMAN GARAMENDI: You may be interested in this -- if I could just interrupt.

DR. LINDH: Sure.

CHAIRMAN GARAMENDI: We've had one of our more interesting days today. This morning's testimony -- this morning's hearing was on a Space Policy for California and the use of satellites for this particular kind of study was mentioned. Please continue.

DR. LINDH: I personally think they're invaluable. There's so much difference between a computer plot and a picture of what things really look like. From my personal point of view, they're essential.

The prediction at Parkfield is largely the work of Tom McEvilly and his students over the years. Starting from 1967, they developed what was a compelling case for a long sequence of earthquakes at Parkfield, the most recent in 1966 and an approximate periodicity with earthquakes every 22 years and even seismologists can add 22 to 1966 and get 1988. We're currently a year overdue, but when you look at the scatter and the numbers, we really didn't expect it to occur with a precision better than two to three years. So we're not breaking out into a cold sweat quite yet. And we expect it to occur in the next year or two.

This is a cross section in the fault plane. The red blob shows where the greatest motion occurred from left to right across the figures, approximately 30 kilometers. So a patch approximately 30 kilometers in the plane of the San Andreas failed, extended to 10 or 12 kilometers depth and had about a half meter of slip. The yellow circles on it are the aftershocks. And as you can see, the aftershocks pretty well outline the area that slipped in 1966.

Our strategy today is really twofold. You just boil it down to the essentials. We're looking for slip somewhere in this patch that will occur before the next earthquake and we're looking for foreshocks at the left-hand edge of the picture where we know the last two Parkfield Earthquakes both had very significant foreshock sequences.

This is just a similar cross-section now, showing, from current data, the patch that we believe is locked and accumulating strain and the white circles are the seismicity that we recorded in the last 20 years or so. The black area is the portion we expect to slip and basically we are looking for slip -- some premonitory slip on the edge of that patch or foreshocks at the left-hand edge of the figure. And we have a pretty good guess as to where the foreshocks were precisely in 1966, so our efforts are focused there.

And, thanks to the money that the State provided in conjunction with federal funds for the last four or five years, we've now had an intensified monitoring effort there, which basically, from my perspective, consists of four really important parts. One is the seismic instrumentation -- seismometers of various kinds scattered over the ground. I believe we now have overall the best seismic array in the world focused on the Parkfield area, and thanks to the work that Tom and Peter Malin at UCSB have been involved in, we quite reliably locate earthquakes down to below magnitude 0.5.

This is a plot showing where the strain meters are. The other main part of our strategy, besides recording small earthquakes, is to look for very small changes in the strain field. As the two plates move by one another, we get a very consistent long term pattern. We look for very small changes in that. I think we also have the best array of strain meters in the world deployed in that region. And this is, again, a cooperative effort with people at the Carnegie Institute in Washington and at Queensland University in Australia. And we monitor the changes in strain in the ground day to day at about one part per billion level.

And this is one of the other main pieces. This is the two-color laser which is really the prettiest thing that we do. In fact, it's the only thing that has any aesthetic appeal. And this allows us to measure the distance between the mountain tops in the Parkfield area to a precision of about one millimeter, which means that week to week, we actually see plate tectonics happening. We really see the mountaintops moving by one another and the gentleman running the laser there on the left is Duane Hohman, the school teacher in the one-room Parkfield School, who is really the heart and soul of the program, figuratively and literally.

We also have water wells. Deep water wells in or near the fault zone which provide quite precise strain meters.

The strategy since we -- as Tom emphasized several times -- since we don't know how to predict earthquakes, we've had to take a very empirical approach. We simply monitor everything we can. We try to characterize the signals we see week in, week out. We try to identify things that look anomalous and we assign levels of concern to them. We've made up some little formulas that allow us to combine these different levels of concern and I really think of it as like the little arrow that one sees outside the State Forestry Office telling you if the fire danger is low, medium or high.

At Parkfield, so far, we've only had what we call D and C Level Alerts. D's are very common, C's are less common. They don't stop in 1988. We just haven't updated this slide. But if it was updated, it would look exactly like what you see there. When we get to a Level B Alert, that will come close to constituting a prediction. At Level A, the State has sort of hard-wired a procedure by which a public warning will be issued. So far we've had no B's or A's, so we've had no false alarms.

And the procedure by which the data is analyzed as it comes to Menlo Park via various means -- satellite, microwave and radio. We monitor it with computers. We have people on call 24-hours a day so when something changes our beepers go off [sound of his beeper heard] and we log onto a computer terminal. We feel realistically that we can pass the signal to Sacramento within five to ten minutes if something very short term happens and they can go, then, to the counties and to the local radio stations. It is conceivable that with very good luck, a public warning could be on the street within 15 to 30 minutes after we had seen something so compelling, we thought the earthquake was imminent.

However, the reality is, of course, that we have not yet predicted the earthquake. The earthquake hasn't occurred and, of course, we don't have any idea whether we really will or not. So the question is have we done any good?

In my opinion, we have been on a great shake-down cruise for instrumentation. By putting a lot of instruments in one place and making people work hard on them. Those of us involved in it have a real clear concept now -- what works -- and win, lose or draw in the Parkfield Experiment, the next time we put out an instrumentation array like that, it will be better and cheaper.

I think we've learned a great deal from our cooperation with all the other institutions involved. This -- any relationship is tough. A tough relationship like we've had with our University and State and other colleagues has, I think, been a learning experience for all of us. And I think the inescapable conclusion is that we all can work together and that we all bring different talents and strengths and that cooperatively we're a lot better than we are individually.

I think our relationship to the State has been a real eye-opener for all of us. Five years ago, if you asked people about earthquake prediction, they'd start telling you horror stories about what might happen if you even started talking about earthquake prediction. And they quite often would make disparaging comments about bureaucrats and politicians -- everybody's favorite targets. And they would tell you how these people were not capable of dealing with the stresses that would be involved in an earthquake prediction.

Boy, has that ever not been the case. The State Office of Emergency Services and CEPEC -- Dick Andrews, Mike Guerin, Jim Davis, the Head of CEPEC. When you go to them with a concern about something, they don't damp your fears. They talk to you. They get people together and talk and in the case of the recent advisories that were issued following magnitude 5's in the Bay Area, it was very clear that as the process went up the political ladder, there was growing resolve on people's part to take concrete action in response to the threat.

I personally think the most important thing we've learned at Parkfield is that people are not afraid, at least, to try to predict earthquakes and if we make scientific progress, in fact, that will be communicated to the public.

As to whether scientifically we're learning anything -- it is my opinion at this point -- and this may be self-serving -- that the process of trying to predict things involves moving onto another level in science. That, as long as science consists of picking daisies and trying to characterize them, there's one level of science that takes place. But when you get on to putting your ideas on the line, putting out good instrumentation and doing experiments where you can fail, you kick the process up a level and at the level of science, you can expect data that over the long term really increases.

The other thing is, I think when people start to practice earthquake prediction -- like doctors or generals -- nobody wants a theoretical doctor when they're sick. They want a real doctor who practices. And they'd like to fight wars with generals who have fought wars. I believe the process of predicting earthquakes is at least as tough as medicine and almost as tough as war and I think the process of trying to predict them will, in fact, create a cadre of people who have the experience to do that.

The other benefit, as far as I'm concerned, is that I think people listen better when you talk about prediction. In the end, the earthquake problem in California is one of education. Clearly we have the money in this state to deal with most of the hazards that exist. It's my opinion that until people understand the problem, it is unlikely that forthright social action will be forthcoming.

It's my experience that the attempt to predict something -- the attempt to do better science with a hard edge on it -- is simply more interesting. It's more interesting to the press. I think it's more interesting to the people who are at risk in the state. It's my opinion that even if you were determined -- if you thought there was little chance you could predict earthquakes, you might still go ahead and make the effort because you would become a very visible symbol of trying to do something about the problem and in the process of trying to do something about it, I believe you would further public understanding a great deal. Thank you.

CHAIRMAN GARAMENDI: Thank you very much. The Parkfield Experiments seem to me to be the most extensive effort underway in perhaps, America, if not the world, to use instrumentation to study and to predict. Is that the case?

DR. LINDH: Yes. The only real rival would be the Tokai Gap Experiment in Japan where they're expecting a magnitude eight earthquake south of Tokyo. It's a much tougher problem because the fault is beneath the ocean. It's a very big earthquake. Very great social consequences. They have a somewhat higher level of effort than we do, I think, because of the great risk their society is at.

CHAIRMAN GARAMENDI: It appears as though your efforts are entirely in instrumentation. Are you using any of the other methods of prediction or studying any of the other methods of prediction that have been discussed -- animal behavior, tides, so on and so forth.

DR. LINDH: No.

CHAIRMAN GARAMENDI: You're not attempting to tie any of that into it?

DR. LINDH: We do have a few other things -- magnetometers, geochemistry, which are at a somewhat lower level -- related to our confidence that they will produce something. Animals, tides, fortune tellers have been tried extensively in this country and elsewhere with little success. And in the real world, you've got to make decisions. You've got finite resources and finite people to work on them and it's not that we know there's nothing to them. It's that when you get down to the hard edge and have to make decisions, you have to put your money on the best bets. That's what we've done.

CHAIRMAN GARAMENDI: The work at Parkfield, I assume, is transferable if, when the earthquake occurs, you will have proved one thing or another -- at least shown it to have some validity or none.

DR. LINDH: One thing we've learned is you've got to get off the surface, so unfortunately most of the instruments at Parkfield will be part of the earth for millions of years to come. They're cemented down thousands of...

CHAIRMAN GARAMENDI: No, I wasn't referring so much to the actual instrumentation, but the -- the methodology -- the type of instruments -- the technology that you're developing there -- the information you're developing there -- I assume that that could be transferred and used elsewhere in other parts of the state or wherever else.

DR. LINDH: I believe that's what my esteemed colleague, Tom McEvilly, is about to talk about with the Hayward Fault. I think it's been a great shake-down cruise for what works and what doesn't.

CHAIRMAN GARAMENDI: Let's talk about the Hayward Fault. Tom?

THOMAS MC EVILLY, PH.D.: I can save five minutes because Allan did such a marvelous introduction of Parkfield, but the message that I want to bring to your Committee is that I believe, and I think that it's a defensible and a fairly widely-held view that it's appropriate and urgent at this time to apply the technology developed and demonstrated in the Parkfield Prediction Experiment to the Hayward Fault. And a summary of what I have to say is right here. And it doesn't take a whole lot more than that. It's appropriate because the use of borehole high resolution seismic monitoring systems and accurate geodedic methods for observing crustal deformation have been demonstrated to be the front line technologies in earthquake prediction research. And it's urgent because of the unique hazard of the Hayward Fault which is known to be great, but very poorly understood, in terms of both the long term slip rates that -- the long term behavior of the fault -- and the recurrence time of the major earthquakes of which we just have the two, 1836 and 1868.

Now, behind that first page on the handout -- the testimony I gave, which I'm not going to read to you -- it's not necessary -- there is a description of a project that we termed the Hayward Fault Surveillance Project. And it involves the application of these specific two areas of technology and research to the Hayward Fault, which, as everyone here, I'm sure, realizes runs the length of the east bay communities in the San Francisco Bay Area.

And what we're proposing consists of three elements. A network of broad -- of borehole-installed seismic sensors, a global positioning system receiver network for the satellite deformation monitoring system, and a rapidly accessible data base and on-line computational system. And right up front, the estimate of the cost of this installation -- of building this facility would be approximately twelve and a half million dollars. It will take two or three years to put it in. To maintain and operate and to keep the data available to the hands of the decision-makers and the researchers in this field, wherever they may be -- in the Bay Area, in California or anywhere in the world -- probably will take about $3 million a year -- just for the operational costs.

Now, clearly it's an opportunistic move to come before you and to make a proposition like this, but I subscribe completely to Al Lindh's previous assessment of the Hayward Fault being a tremendous shake-down of this capability.

I can show you a couple of more figures of what the plan involves. I'm going to skip the Parkfield review because it's been done, basically, by Al. I will show you one Parkfield figure just to show the sorts of things that... (pause)

Thanks. This is an example of the sort of resolution that the borehole emplace network of ten stations at Parkfield over about 20 kilometers is doing in terms of allowing us to pinpoint the physical properties of the subsurface in the nucleation zone of where we expect the earthquake. This is a cross-section across the fault zone illustrating the seismic velocities that are determined in a rather elaborate mathematical inverse problem that is run on about 400 earthquakes in the sequence. And it shows a clear velocity anomaly from almost any perspective that you attempt to image it at the site of the expected nucleation zone of the coming magnitude six earthquake.

These sorts of things require the borehole emplacements. They require the high resolution of very precise timing capabilities of a millisecond, you know, rather than tens of milliseconds and the quiet high sensitivities that we're capable of getting deep in the earth. In the transfer to the Hayward, I estimate we're going to have to be down on the average of about 2,000 feet just to get away from the culturally-generated noise along the stretch. It's occupied its entire length by metropolitan centers, one after the other and a few million people.

The next one, Rob. The other element in it, besides the borehole network, is a global positioning system fixed network. I show this courtesy of Arrow Services, who installed one a year ago -- a year and a half ago in Japan for the Japanese, south of Tokyo, in the extremely dangerous Izu Peninsula area where large earthquakes are expected -- to monitor the crustal deformation. That's the network of global positioning system satellite receivers that are used in -- in real time determination of the deformation. It's -- it's a big two-color laser system essentially. But instead of the two-color laser, it's using the constellation of GPS satellites that are up there for navigational purposes.

The next one shows some results. These are two figures I got from Professor Fugiwara in Japan, who has submitted a paper to Nature which should be coming out in a month or so on the performance of this network and the recent eruption of an earthquake -- the Taji Earthquake off the Izu Peninsula. And at three scales, this figure shows, in the upper left, first of all, where it is. The lower left where it is with respect to Tokyo and the bottom is the blow-up of the box right off the east coast of the peninsula showing the earthquake. And it shows two of the GPS stations, HTS and ITO, north and south of the volcano. This is a new volcano that started acting up and erupted. I don't know that it's new, but it erupted earlier this year.

The next picture shows the performance of the network in terms of the -- the absolute position -- the relative positions of ITO and HTS -- those two positioning sites. And the behavior of the network prior to the -- to the eruption which is the big arrow on the right -- towards the right end of these figures. And you see the precursory activity -- precursory deformation for a couple of weeks before the eruption when the swarming began.

The -- I put this up because of the stability of the system. And this is really a relatively poor constellation that they've had to work with in Japan at low -- low angles and usually only for satellites. The stability of those lines prior to it represent centimeter horizontal control on the line links. In other words, it's possible to pinpoint HTS and ITO to approximately -- to an uncertainty of about plus or minus a half centimeter. And this is what we're shooting for on the Hayward in terms of the GPS installation.

Rob, I think there's a map of the potential GPS sites.

CHAIRMAN GARAMENDI: Before we move on to the Bay Area, the facilities there in the Tokyo area indicated ten days or so before the earthquake, there was a significant movement between those two positions. Is that what I saw?

DR. MC EVILLY: That's right. But that was a volcanic eruption.

CHAIRMAN GARAMENDI: Before?

DR. MC EVILLY: No, no -- it ended with the volcanic eruption.

CHAIRMAN GARAMENDI: Yes. It ended with some occurrence. Some geological occurrence.

DR. MC EVILLY: That's right.

CHAIRMAN GARAMENDI: Did the Japanese government issue any warnings or did they just begin to really focus when they saw these kinds of things occurring?

DR. MC EVILLY: I don't know. I just got these two days ago. I called and asked if they had anything and he said, "Oh, by the way, I have a paper that shows it and I'll send you two figures." I don't know what they did with that information. It's offshore, so it wasn't felt to be the hazard of a magnitude 8 earthquake. It was pretty well understood that what was going on was undoubtedly of volcanic nature.

CHAIRMAN GARAMENDI: The hypothesis here is when these things begin moving as they did here, something's going to happen.

DR. MC EVILLY: Oh, yes. Absolutely.

CHAIRMAN GARAMENDI: Now, let's see what happens in the Bay Area.

DR. MC EVILLY: Well, the Bay Area -- what we proposed in or postulate might be the right way to go about this -- is to span from the coastline to essentially the far East Bay out as far east as, let's say, Mount Diablo. So you cross the major faults in the Bay Area with approximately 20 of the stations, which are on-line real time and are transmitting their data in some hardened manner to the computing facility we're talking about. The little blue squares -- they're hard to pick out, but there are 20 of them scattered around.

The reason for this installation is to place the Hayward Fault in its appropriate context in terms of the distribution of the strains throughout the major faults in the Bay Area. The last figure I have, Rob, is a similar thing for the Borehole Seismographic Stations -- whoops, it's on its side -- there you go -- which are much more...

DR. MC EVILLY: That's right. (laughs) Which are much more concentrated, of course, along the Hayward Fault. This represents approximately four or five Parkfield network strips -- just strung end to end, essentially, along the fault zone with everything we've learned there applied to the date acquisition and on-line processing. And I should think that we probably can get deep enough to drop the high frequency noise from the surface enough that we probably can do equivalent resolution that we're doing at Parkfield.

So this is the proposal. It's not cheap. But I think there's some strong feeling that this is the appropriate transfer of technology from the Parkfield Prediction Experiment to a specific Bay Area one. And the Hayward Fault is selected because of the extreme risk associated with it and the fact that the seismicity on it is well-defined. The fault is well-defined and it would be very easy to transfer Parkfield right to it. It's not a defuse zone. It's a very clearly defined fault zone. Thank you.

CHAIRMAN GARAMENDI: This proposal that you have presented here, I understand, has taken the form of a piece of legislation introduced by Senator Bill Lockyer who represents the Hayward area. It also could be part of the proposal or one of the research activities undertaken under our legislation. Either way, we're aware of this and the Legislature will be dealing with this in some detail in the next three months, I should think.

My daughter tells me to pay great attention to this. She lives in a sorority that is on top of the fault in Berkeley -- next to the stadium.

DR. MC EVILLY: She may be our greatest supporter. (laughter)

CHAIRMAN GARAMENDI: She is clearly a supporter. When she found out about this, she wanted to know what I was going to do about it. Which brings us to Mr. Henton's comment -- Heaton's comment about southern California? Indeed, we haven't forgotten about southern California. Our next set of witnesses are interested in a Southern California Earthquake Center. So what's good for the north ought to be good for the south. Let's figure out what this Center's all about. We've had a little bit about this. Let's have more.

Tom Henyey? Did I do that right, Tom? And Egill Haukkson. Tom is Professor of Geophysics, Chair of the Department of Geological Sciences at the University of Southern California and Egill is Research Professor, Department of Geological Sciences, University of Southern California. Tom, please.

THOMAS L. HENYEY, PH.D.: Well, Senator I'd like to thank you for the opportunity to appear here before you and your interest in earthquake hazard mitigation in California. Of course, I'd like to take the opportunity to talk to you a little about the Southern California Earthquake Center. As such, I'm not going to deal specifically with prediction, but, of course, this Center has as one of its primary objectives, the whole issue of earthquake prediction.

I'd like to go back to a comment made by Bill Iwan about prediction being a competing strategy. I don't view it as competing. I view prediction as a complementary strategy to the other strategies. And I think it's perhaps better to think of it this way and I would no more forego predicting or forecasting a warning of earthquakes than I would say strong storms or things along those lines. So I think that prediction is something that we want to continue to dwell on in the earth science community and in its benefits to society.

The new initiative to which we've been referring here -- the Southern California Earthquake Center -- and Tom Heaton has already said something about this -- is comprised of members primarily from the southern California academic community in a partnership with the U.S. Geological Survey. It's not an earthquake engineering operation as the entity in Buffalo, but rather it is an earth science operation, and as such, it's complementary to let's say, the Buffalo operation, or, as I like to think, to our own operation here in state -- the Curee organization, which you may or may not be familiar with.

This Center was conceived earlier this year prior to the October 17 Loma Prieta Earthquake. Federal funding for the center is currently being solicited through the National Science Foundation's Science and Technology Centers Program and through the U.S. Geological Survey's National Earthquake Hazards Reduction Program.

We envision -- and I think you asked about these numbers earlier -- we envision that between about five and ten million dollars per year will be a minimum required to make this a viable operation. We have asked for $5 million from the National Science Foundation and funding on that order is being asked for from the U.S. Geological Survey.

This is a very delicate marriage, if it works between the Foundation and the Interior Department. We don't know whether it will work or not but we anticipate going on with Center activities nevertheless.

I don't want to take up a lot of time talking to you in detail about the specific nature of the proposed Center, although I'd be happy to do this at some time if you so desire. I'd like to describe, however, the basic mission of the Center and provide some rationale for this Center in southern California, and also for some of the things that the State might become involved in.

My interest in the Center should in no way be translated into an advocacy for reprogramming funds -- federal funds or state funds or what have you, from northern California to southern California, or to develop a primary focus for earthquake studies in southern California versus northern California. Quite the contrary, I'm an advocate for a balanced statewide program. Federal resources and any new state dollars for research on seismic hazards, particularly in our metropolitan areas, should be appropriately partitioned within the state.

This overhead shows then, the participating organizations.

So why an earthquake center in southern California? Well, Tom Heaton has already touched on some of the rationale for this. There are perhaps three points that could be made here. Based on plate tectonic, motions, the locations of active faults, strands, vis-a-vis population centers, and the record of historical earthquake occurrences lead us to believe that the earthquake risk for the immediate future is probably greater in southern California than anywhere in the United States.

Number two, a very large and outstanding segment of the earthquake scientific community is based in the various academic institutions in southern California.

And third, as Tom Heaton pointed out, the current research effort in dollars expended in southern California is not, we believe, commensurate with the region's earthquake risk.

I'd like to develop the third point a little bit and, again, I may be going over some ground that Tom went over, but I think this is perhaps worth doing. As you're probably aware, the bulk of the federal funding for earthquake research in California comes from the U.S. Geological Survey's National Earthquake Hazard Reduction Program. These funds support both programs internal to the Survey, as well as external to the Survey in academia.

Currently about 60 percent of the USGS program in California is focused in the northern part of the state -- in the area we would consider here in southern California to be north of the Tehachapi Mountains. And most of the scientists involved in the activity are also in that area. Fewer than twenty USGS scientists are presently in the southern California area.

This current balance of effort does not agree well, as Tom indicated, with the balance of population and the development going on in California, which is tilted toward the southern part of the state. Although the potential for large earthquakes in the two parts of the state is commensurate, for the immediate future, we believe that the risk is greater in southern California.

The proposed Southern California Center would draw together the data, intellectual resources of various university groups, with a core group of USGS personnel. Such a partnership, including the California Division of Mines and Geology and other state agencies, and perhaps even the private sector, would attack major problems with a more integrated approach. Sharing common data collection, archiving and processing facilities; bringing together teams of researchers, not only from different disciplines, but also from different institutions.

In addition, the Center would serve as a major regional resource of earthquake information, much as that Center does -- the Northern California Center in Menlo Park does.

As envisioned, although the principal focus of the Southern California Earthquake Center would be on the territory of southern California, participation would not be limited to institutions from southern California or to scientists from southern California. We already have scientists from M.I.T. and Columbia and even from northern California involved in the Center and Center planning.

Lessons learned from the relatively frequent large earthquakes in California will also have application in northern California and throughout the country. In short, we believe southern California is an excellent study center for a -- or study area for a major center.

I'd like to finish my comments with a more specific description of the Center and how the State might participate. First, I'd like to show a diagram of the Center. I think, Rob, you may have had that up there earlier. It looks a little bit complicated, but let me just briefly describe it. Everything inside the big dotted line in the middle is the Center, composed of the U.S. Geological Survey, a set of core institutions, a set of participating institutions, and the California Division of Mines and Geology. The difference between participating and core really is a level of activity and involves also some focus on southern California institutions.

Essentially, resources would flow from the Department of Interior, the National Science Foundation and, hopefully, the State of California to the Center and out of the bottom, information would flow directly to emergency response groups and the risk assessment and hazard mitigation activities, either directly, or through other groups, such as SCEPP (Southern California Earthquake Preparedness Project) or the Curee organizations, with then feedback to the Center, which would help guide the Center's activities -- that is, the information needed by the user community would guide the Center activities.

If I could have the next one, Rob. This basically is the best I could do to summarize the mission. And I think everybody who's participating in the Center has their own concept of what the Center is and what its primary mission is. We've discussed this many times over and we've come up with a notion of a master model. That is, the Center will develop, refine and apply -- and when we say apply, we mean here, transfer to the user community. That is, it's about time we begin transferring information that we have to make it available to those who need this kind of information through what we call a master model.

And the master model really consists of the following elements showed as the bullets there, a combination of existing knowledge of the earthquake process, and further knowledge to be gained through research activities. And then it consists of a framework in which geologic, geodedic, geophysical and seismological information pertinent to earthquakes in southern California would be integrated for the purpose, now, of developing methodologies for predictions of impending events, as well as predictions of strong ground motions. And then this master model will be constantly updated as new information becomes available and it will be refined and worked on according to the feedback process from the user community.

Finally, on this last overhead, we can see some of the expected contributions from a Southern California Earthquake Center. And these are not contributions which are new to any of us. But the hopes are that we can improve our space time, probabilistic estimates of major earthquake occurrences, long term, which we're beginning to make headway on, but gradually moving into short term and imminent; improved prediction of strong ground motion in southern California based on typical earthquakes. Rapid estimation of the distribution of strong ground motion following major earthquakes and then some other things that are also important, such as a system which was set up in the Bay Area to warn of aftershocks to the people working on the Cypress Viaduct; immediate earthquake epicenter magnitude and source characteristics for people who are concerned where the damage may be the greatest; and then, of course, a post earthquake briefing and scientific command center.

Well, so it can be seen that the Center will consist of a variety of activities, including scientific analysis, data collection and interpretation, and we feel, very importantly, the application or technology transfer of our information. All of these activities require manpower. But it's perhaps the data collection, specifically, using advanced technologies, that strain our budgets, but without which we cannot expect to move our understanding of the earthquake process forward.

It is here the support of the State in concert with federal funds can make a significant contribution to the research effort. That is in providing for much wider monitoring of our most active and hazardous faults.

A proposal after the Whittier-Narrows Earthquake here in southern California was put forth -- and you may remember that -- with Assemblyman Katz' help -- to improve instrumentation along the hazardous Elysian Park Seismic Trend or structural trend in the Los Angeles metropolitan area. And now after the Loma Prieta Earthquake, a proposal to instrument the Hayward Fault in the east Bay Area has emerged. These are two examples where additional state funding, not only would be considered by the scientific community as serious steps toward major scientific payoff, but also would be seen by the public as a positive step by the State toward earthquake hazard mitigation in our two most populous metropolitan areas. And also by the federal government as a realization by the State that it must bear a fair share of the burden of such efforts within its own boundaries. Thank you.

CHAIRMAN GARAMENDI: A question, if I might. Have you or your colleagues made any presentation to the local governments in southern California?

DR. HENYEY: We have begun working with Councilman Hal Bernson. He has been briefed on this Center. We have also had a briefing with technical personnel in the city and county, namely engineering people -- with Caltrans, the City Engineer of Los Angeles and the County Engineer of Los Angeles County. So the answer is, yes. We are, in fact, beginning to talk with these individuals.

CHAIRMAN GARAMENDI: The same question I had meant to put to your colleague from northern California, but I neglected to. Tom McEvilly, have you talked to the Bay Area local governments?

DR. MC EVILLY: To some extent. The Chancellor's Office at the University was making some phone calls on that and I don't know how far they got, but the University itself is doing something.

CHAIRMAN GARAMENDI: Okay. What will need to be done here for both of these projects is to secure the involvement of the local governments, as well as the state and the federal government. It is appropriate in my mind that the state government take the lead. I've never believed that anybody else ought to lead us, although there are other people who think differently than I do. But it seems to me the state government ought to take the lead, but there is some local and federal participation involved here and we'll see what we can do to help pull some of this together.

Now, I believe that Dr. Haukkson is also a participant in this part of the testimony, so Doctor, if you'll care to join us, and Tom, thank you very much for explaining the project.

EGILL HAUKKSON, PH.D.: Thank you, Mr. Chairman. I'm going to talk about something more specialized which is going to be a project within the Southern California Earthquake Center if it gets funded. Could I get the slides, please?

The project I'm going to talk about involves the varied faults in the Los Angeles basin. This map shows earthquakes of magnitude 5 and greater in the greater Los Angeles area since 1930. And we see that we have about one earthquake of magnitude 5 or greater every six or seven years. The two biggest earthquakes are the 1971 San Fernando Earthquake and the 1933 Long Beach Earthquake that are shown here shaded in green and the surface ruptures are shown shaded in red.

These two earthquakes and many of the other ones occurred on previously mapped faults. The October one, the 1987 Whittier-Narrows Earthquake did not occur on a mapped fault and it's shown here in the eastern Los Angeles basin. It caught us by surprise and made us think that perhaps all the fault maps published by the State of California were not absolute truth and some of them perhaps needed updating.

Much of what we know about the Whittier-Narrows Earthquake is derived from seismology or data collected by the existing seismic networks. Here is shown the fault plane. The earthquake occurred at about ten miles depth or in the depth range of 14 to 16 kilometers. And the fault plain dips gently to the north or about 30 degrees and it's quite clear that this earthquake was associated with what we call a buried fault or a blind fault and it was not associated with the Whittier Fault.

Now, the earthquake did not rupture the surface, but it caused uplift of the surface area about the epicenter. And the top will show uplift data and you see in the bottom cross-section the epicenter doesn't start on a fault. And what happened in the earthquake was that movement on the fault caused folding or buckling of the sediments up above. And we see that the uplift is about 50 millimeters or two inches above the epicenter.

So this immediately said yes, that a way of identifying buried or hidden faults is to look for buckling of the sediments in the surface. This has been seen in other earthquakes, such as the 1983 magnitude 6.5 Coalinga Earthquake. It caused uplift of about three feet, which is shown as the red data on the top panel and down below we show a cross-section through the epicenter zone. And the Coalinga Earthquake caused uplift and buckling of the Coalinga ridge.

Another example is the 1980 El-Asnam Earthquake in Algeria that amounted to 7.3. It caused uplift of near surface sediments of about 15 feet. Here you see the river that has gorged through the sediment. It got dammed up by the uplift and later investigations have shown that such uplifts have occurred about six times in the last 6,000 years, so the repeat time in this case is about a thousand years.

Now I have searched through the literature for data on folding or buckling of the sediments in the Los Angeles basin and there's abundant data on that from oil company data and investigations that have been done to mark the oil fields in the Los Angeles basin. I've also gone through the earthquake data base that we have for the last 12 years and I've found all the earthquakes that have shown similar fault movement as the Whittier-Narrows Earthquake, i.e., thrust faulting or you can think of it as earthquakes with vertical fault movement.

I've been able to identify two zones of thrusting and folding, one on the east and the north side of the Los Angeles basin, and one on the southwest side. The Los Angeles basin itself is indicated in the middle here with depth to basin contours of eight and ten kilometers. So as the Los Angeles basin is being squeezed by north-south compressive forces, we see that the flanks of the basin itself are being buckled and folded and that's why we have the earthquakes.

I should just point out that earlier today Al Lindh pointed out that in Parkfield they have such good instrumentation that they can work with earthquakes of magnitude .5 or less. In the Los Angeles basin we have such bad instrumentation that we have to limit ourselves to work with earthquakes of magnitude 2.5 or greater.

If we look at this on a more familiar map, then I have drawn on here the surface faults such as the Whittier Fault and the Newport-Inglewood Fault. I've also shown on here the two new zones of thrust faulting -- the Elysian Park Fault and Thrust Belt and the Torrance-Wilmington Fault and Thrust Belt.

If we now think about this for a minute, then the Whittier-Narrows Earthquake ruptured about three mile length of the Elysian Park Fault system. The total length of the system is about 60 miles. So it ruptured about five percent. The total length of the Torrance-Wilmington Fault and Thrust Belt is about 40 miles.

Other faults that have been known for a longer time and have been better studied, such as the San Andreas Fault or for that matter, the Hayward Fault, we know fairly well the slip rate. We know the length and width or depth. And we know their sedimentation. So we have an approximate idea what the long term earthquake hazard is.

In this case, we don't have the foggiest idea. We don't know how these faults are segmented in -- with any certainty, so we don't know whether we are just dealing with a whole bunch of magnitude 6 earthquakes like the Whittier-Narrows Earthquake or whether we could have say, a magnitude 7.1 such as the Loma Prieta Earthquake right beneath downtown Los Angeles, which would be where Elysian Park is.

We also have very limited information on how fast these faults are moving. It's quite possible that they're moving as fast as say, 20 to 30 percent of the speed of the fault itself, but we need to know how fast they're moving in order to be able to quantify the earthquake hazard they present to the Los Angeles area.

This particular problem of buried faults is not a piddly local problem for the Los Angeles basin. It is a California problem. Here you see the Los Angeles basin in the lower right-hand corner and earthquake epicenters plotted in yellow and the red lines are fault axis or indicate the location of faults throughout southern California and central California, and in blue we see the earthquake faults that are thought to be most dangerous.

So you see, if you add faults beneath all of those red lines, that we have more than doubled the available faults for having earthquakes on. The big blob of yellow earthquakes up in the corner -- center of the picture -- are Coalinga and Kettleman Hills aftershocks.

Now, this is not only a California problem. It's also a worldwide problem. On this slide we show the fault and thrust belts shaded in brown and you see the area in North Africa where I showed a picture from the El-Asam Earthquake, southern Europe and Armenia, which had the earthquake about a year ago that killed about 25,000 people.

In many respects this is a very fitting project for the Southern California Earthquake Center in that a big part of the Center will be scholarly exchange with other countries -- scientists coming to the Center to bring new information and new insight and also staying at the Center to learn about the ongoing activity at the Center. Thank you.

CHAIRMAN GARAMENDI: Those are some very sobering charts and diagrams and maps. Let me review some of your testimony so that I might have it straight in my mind. The Wilmington-Torrance and the Elysian Park Fault/Thrust Belts lie deep beneath the surface of the earth. Is that correct?

DR. HAUKKSON: Yes, the Elysian Park and Torrance-Wilmington Fault and Thrust Belts lie at a depth of somewhere between five and twelve miles.

CHAIRMAN GARAMENDI: And the Elysian Park Belt was responsible for the Whittier-Narrows Earthquake?

DR. HAUKKSON: Yes. The Whittier-Narrows Earthquake occurred on the Elysian Park Fault.

CHAIRMAN GARAMENDI: And we know virtually nothing about these two belts.

DR. HAUKKSON: Well, we know they exist. And there's a lot of oil company data there on the geology about it -- it's both data collected at the surface -- like seismic reflection data. There's data that's collected from oil well drilling. And some people have looked at varying amounts of these data, but no one has really yet put it all together. And perhaps we have to collect some more data to get the whole picture.

CHAIRMAN GARAMENDI: But...

DR. HAUKKSON: But the point I would like to bring across is that these are important fault trends and our knowledge of them is ten steps behind our knowledge of let's say, the San Andreas or the Hayward Faults. So we feel it's important that we kind of catch up here.

CHAIRMAN GARAMENDI: The Southern California Earthquake Center would presumably be studying these, plus the other kinds of faults that are in the area. Is that correct?

DR. HAUKKSON: Yes, that's correct. We, in southern California, do not so much favor a Parkfield approach, in that if we pick a fault, we are 99 percent sure that the next big earthquake is not going to be on the fault we picked. So -- (laughs) -- we would prefer to take a more regional approach and try to distribute our instruments throughout the region and study several faults simultaneously.

CHAIRMAN GARAMENDI: The faults that -- the earthquakes that might occur on these faults are estimated to be in the 5 and up range, or 5 magnitude?

DR. HAUKKSON: We know for sure that the Whittier-Narrows Earthquake of magnitude 5.9 occurred on the Elysian Park trend. It's quite possible that we could have earthquakes like the 1971 San Fernando earthquake and we cannot exclude that we could say, have a 7.7 earthquake like the 1952 Kern County Earthquake on the Elysian Park trend. But if we did more studies, collected more data and analyzed those data, we might, perhaps, be able to narrow down this range and come up with realistic estimates of what is the hazard. Because the Whittier-Narrows Earthquake, which was a small earthquake that caused $360 million-worth of damage and we see the Loma Prieta as maybe up to somewhere between five and ten billion. So...

CHAIRMAN GARAMENDI: Yes, the return on a $12 million annual investment is enormous, isn't it?

DR. HAUKKSON: Yes.

CHAIRMAN GARAMENDI: Let's see. That's about a dollar per person in the basin.

DR. HAUKKSON: Yes.

CHAIRMAN GARAMENDI: Not so much money when one considers the potential damage. Thank you very much for your testimony. The Southern California Earthquake Research Center proposal will certainly be on the agenda of the Legislature for the coming year, either put there by this Committee or by other members of the Legislature, probably from southern California.

I believe we are now going to talk about Cal Tech. Let's talk about our host for a few moments -- in a nice way, if we might. There are three scientists from the Institute of Technology's Seismological Laboratory who are with us. Dr. Robert Clayton, Hiroo Kanamori and Don Anderson. The Acting Director, a Professor of Geophysics and a Professor of Geophysics. All here at the California Institute of Technology. Dr. Clayton, are you with us yet? Well, yes, there you are. Doctor, your turn.

ROBERT W. CLAYTON, PH.D.: Thank you, Senator, for this opportunity. I was asked to speak here in my role as Acting Director of the Seismological Laboratory. This is a job I've held for two weeks. I think who you really want to talk to is my predecessor, Don Anderson, who is sitting right up there, who held the job for 21 years. So if you're looking for a historical point of view, I suggest you direct the questions to him.

My personal research really is on the periphery of earthquake prediction. And what I can offer you is my observations in watching my colleagues struggling with this problem. Perhaps sort of a stand-back look at what I think might help them in doing their job.

First problem I encounter with this is the definition of earthquake prediction. If you use a dictionary-type definition, you might think it's something like time and place earthquake predictions based on well-established and well-understood precursory phenomena. The two operative words there being well-established and well-understood. I don't believe we've got a significant notch up on either of those and so I have a lot of problems with that strict definition of it.

I would offer for your consideration some revised lesser goals of that activity -- earthquake forecasting. I think this is a very legitimate and proper activity. This is the type of thing where Kerry Sieh, for example, has done a lot of research in this area -- whereby looking at the historical record one is able to determine past occurrences of earthquakes and based on that type of information, trying to predict zones of risk and possibly when, over many years, large earthquakes might occur in those types of zones.

Another form of prediction I would say is important is trying to answer the question what happened right after an event and in the prediction mode, what is going to happen next? This is after the shaking has taken place and you're trying to tell people what to expect next.

We experienced this -- I, personally, -- in the Whittier Earthquake and I'm sure the people up north struggled with this question during the Loma Prieta Earthquake.

It's the kind of question when the school teacher from across Cal Tech -- there's one kitty-corner to us here -- says, I've got 900 kids standing out in the school yard. What's next? That's what we would like to try and answer.

Also, I think, it's in the realm of technology to consider in very quick time, to assess the region of large and intense after shaking. To remotely assess where the damage probably occurred in a large earthquake.

The next step up in that type of a thing would be something I would call real time seismology -- that is, given that the event happened somewhere, it will take time for the damaging waves of the earthquake to propagate out. We could probably sense those types of waves and offer warnings from a few seconds to maybe a couple of minutes to critical facilities so they could take some appropriate action. I think that is in the realm of what we could possibly achieve with prediction.

In watching my colleagues work on these types of questions, I see time and again the most frustrating thing they have to deal with is the instrumentation. They are looking at, I believe, fairly inadequate records of these earthquakes and trying to say something intelligent about it.

Based on that, I have, I think, two recommendations. I think, apart from my association with the Seismological Laboratory, you might consider these unbiased, since I wouldn't directly use these. But I think it's fairly clear in my mind that a array of broad band seismic instruments distributed over the state -- say 20 to 40 such instruments -- would prove invaluable for earthquakes. Had such an array been in place in the Loma Prieta Earthquake, I believe, we could have said much more rapidly what had happened. Maybe the earthquake itself would have taken out a few of the close instruments, but the remaining ones in the state could have answered that question, I think.

I, on a personal note, sat with many people on October 17th, set to watch the World Series and instead, spent many hours that evening in frustration trying to figure out what had happened to Santa Cruz, where my daughter lives. No information was coming in on Santa Cruz, which turned out to be virtually the epicenter of the event.

The other project that I think has a lot of merit to it is the GPS Network. This is the Global Positioning Satellite measurements to make quick and accurate geodedic measurements around the state. Tom McEvilly indicated a network like this for the Hayward Fault. Certainly consideration of this has been given for southern California.

There's really two components of that. One is a fixed fiducial network, which serves both as the backbone to allow densifying with portable instruments and also is a real time monitoring system to check for rapidly occurring displacements across faults. If I had to pick two projects that I would say could help the earthquake studies, I would pick those two.

As for the expertise in earthquakes, I wish to defer to my colleagues, Hiroo Kanamori and Don Anderson. With that, I would stop.

CHAIRMAN GARAMENDI: Dr. Clayton, the GPS Network for the state would be based on instruments located, as I suppose, in the Tokyo area, using satellite telemetry of one sort or another? Is that what you were talking about here?

DR. CLAYTON: Yes. In fact, I see Duncan Agnew up there. He is what I would consider an expert on this type of thing. But there have been plans drawn up for fixed stations and also increasing the portable stations.

CHAIRMAN GARAMENDI: Karen just tells me we will have testimony on that in a few minutes. Doctor, thank you very much. Professor Kanamori. Did I say that correctly?

HIROO KANAMORI, PH.D.: Well, yes.

CHAIRMAN GARAMENDI: More or less. (laughter) Thank you for your tolerance.

DR. KANAMORI: I guess for the last perhaps five years or so there have been a few long term predictions -- sometimes forecasts. And the one on the left is more or less what we have been using and which has been very successful. In this case, so that the range of time is more like 40 years or so. Sometimes it can be ten years, sometimes it can be hundred years.

In terms of the size of earthquake to be predicted, we normally talk about half a unit or so range and then in terms of place, there's always some certainty about 30 miles or so. And the probability -- it is very difficult to give any fixed number and what I meant by 50 percent is it's pretty uncertain. I don't think we can really give a very precise number to it. But, in general, this kind of a long term forecast has been, to some extent, successful. Not always. And in particular, in the last Loma Prieta Earthquake, up to superficially, it was very successful.

However, one problem is the way the public perceives prediction is slightly different. Say suppose if I am not a seismologist and if I don't know anything about seismology, and if someone told me about prediction, I would perhaps say a time has to be precise to be within a few days, otherwise it doesn't make any sense to me. And maybe in terms of magnitude, it has to be half a unit or so. And place has to be within ten miles or so to be useful. And the probability -- it has to be really more like 90 percent or 80 percent. It has to be reasonably certain, otherwise I wouldn't take it very seriously.

So there is some gap between the public perception and sort of a forecast the seismologists have been talking about. And this is a rather important point. And at this moment, long term forecasting has been done very successfully, but I don't think seismology, as it stands, can make very precise predictions like the one listed on the right.

And these uncertainties arise from a variation in strengths of crust. We don't know exactly what it is. But we know that there is substantial variation. So the timing of failure varies considerably.

And there is a major triggering effect. If one segment of fault breaks, it might trigger adjacent segments. For that reason, size can be very uncertain. And also we have only incomplete knowledge of physics, so it's very difficult to make precise prediction on the basis of physics.

Well, given these uncertainties, well, the question is whether seismology is useful or not. And I want to address this question. I don't think at this present time we can make very precise predictions. And even in the next decade or so, I'm not even sure whether we can approach the kind of prediction listed on the right.

So given these uncertainties, what can we do as seismologists to minimize seismic hazard? Well, there is one thing which we can do after a major earthquake and that's what Robert mentioned -- real time information service. And when I say real time information, the information includes location of the earthquake, a magnitude -- how large the earthquake is, and rupture pattern -- in which direction the fault ruptured. This is sometimes very important to us as seismic damage. And these things are very important to allow effective emergency services. Our people can go to the right spot to do effective emergency services. And also to forecast what will happen next. This is, again, as Dr. Clayton mentioned, very often, immediately after a large earthquake, we are asked by the public what's going to happen next? And without precise information about the type of earthquake that has happened, it's very difficult to give that kind of information. So these data are critically important for rapid earthquake emergency response service.

And research and facilities needed for that -- obviously, we need very effective real time network and robust communications, which wouldn't fail during the post-seismic period. By using data from some other global stations, like Japan, Europe, and other parts of the United States, we can determine our seismic parameters very quickly by the currently available methodology. However, using more regional data, we still don't have anywhere established methods. So it requires development of methodology for real time seismology. And of course, I know that to do this we need global and regional networks. And some of them are now being built. But, obviously, it's not quite complete. But the most important thing is we need human brains to do this.

And, as was discussed earlier, currently seismological research is grossly under-funded and really it's very important to develop human resources so that we can do state of art seismology. And also one other important thing is to archive all the data. This doesn't sound very exciting. However, our experience tells us that whenever we have an earthquake we really want to know exactly what happened before in the same area. In order to have that kind of information very quickly, archiving old data is exceedingly important. And with the current computer system, we can develop very efficient data bases so that we can retrieve all data very quickly to be used for hazard assessment.

What can we do before a large earthquake? Of course, we can do planning based on long term forecasts and also we can estimate ground motion for specific events and also, according to that estimate, we can do some retrofitting of weak structures. And these things are obviously very important and the research and the facilities to do that, we need broad based seismic studies because we need to really understand the nature of earthquakes -- the physics of earthquakes. Without that knowledge, it's very difficult to estimate ground motions and to do effective planning.

And also we need to evaluate the main effect and side effects. Over and over again, we have seen very dramatic side effects -- the most dramatic ones in recent years are the Mexico City and San Francisco area ones. And we need regional networks to do this, as well as portable instruments to do effective side effect estimation.

And again, we need development of human resources. But I really want to emphasize here that it's very important to have seismologists and engineers working together. Of course, in many places this has been done. But in order to really use seismology for effective hazard reduction, it's very important for seismologists and engineers to work together because the exchange of information is critically important.

Well, so this is the focus that I have discussed. One problem is that seismological research is grossly under-funded. I have been looking at the National Science Foundation's Seismology Program for the last few years and it has been $4 million for the past decade or so. And it's only a third or a quarter of the research money we needed. And secondly, our present facilities in seismology, particularly in the United States, is unfortunately far behind currently available technology except for a few cases. And if these problems are corrected, seismologists will be able to take full advantage of modern technology and will be able to contribute significantly towards comprehensive seismic hazard reduction.

And let me just spend two more minutes to discuss part of a global network, as well as a one station network telescope which is operated by Cal Tech. And I'm not going to talk about details. This has a state of the art sensor and recording system. So basically we can record all possible ground motion from small to large, from very high frequency to very low frequency. And one important aspect is this has a local data storage and modem so that people can dial up to this system to retrieve seismic data.

Basically this is a list of our people who called into our station after this earthquake and the earthquake occurred at 0004GMT and within the first 24 hours, almost 20 to 30 people called into our station to retrieve actual seismic data so that they could do very quick analysis. And if you look at the name of the people, it's rather interesting. Of course, Cal Tech people called in and then Harvard people called in and the USGS and the people from Japan called in and people from Italy -- Rome -- called in. And also a lot of people from the east coast called in. And all of these people could have access to our data -- our real time data, within the first 24 hours or so. And they could use this data to analyze and then to come up with the seismic source parameters. And these source parameters turned out to be actually very important. But within the past few years, we have had only limited success. So we thought maybe this earthquake is more like a San Andreas-type of earthquake, so we came up with the mechanism on the left. But of course, this is based upon only one and a half stations worth with data. But immediately, as we had additional data, we found that this mechanism isn't quite appropriate. And by adding another set of data, we came up with the mechanism on the right, which is probably fairly close to the most recent mechanism.

So with this kind of system, within a few hours, perhaps in this case, maybe ten hours, we could come up with the correct source parameter, as well as rupture length and to some extent, depth estimate. And the one important thing is that we don't believe that it is coming out for one person because we always make mistakes. However, in this case there are more than ten groups working in the country as well as in the world. And this information has been exchanged very quickly using FAX. So on the following day, we are reasonably confident that this mechanism was right, as well as other source parameters. So this kind of real time seismology is really very important to provide key information to the people in the local area.

So my feeling is just modernizing existing facilities would really make a great contribution to seismology and also towards effective hazard reduction. I guess I'll stop here.

CHAIRMAN GARAMENDI: Professor, thank you very much. At some point I'm going to begin the digestion process of all of this information and perhaps I'll begin that as we move towards the termination of our testimony here. Mr. Anderson -- Professor Anderson, the previous Director. Thank you.

DON ANDERSON, PH.D.: I don't really have any prepared statements because I knew most of what I wanted to say would already have been said. And that's quite true. So let me just cover some major points that I think have been left out a little bit and maybe some things that need to be emphasized a little bit more.

Rob mentioned that I might give a little bit of the history of Cal Tech. Cal Tech's been, or rather the Seismological Laboratory has been recording earthquakes in California -- and in fact around the world -- for more than 60 years. And it joined Cal Tech in about 1936 and has been the Seismological Laboratory of Cal Tech since that time. We've been doing research in earthquakes and also training seismologists and I'm happy to see that two-thirds of your witresses, in fact, are Cal Tech graduates or somehow associated with Cal Tech.

And that leads me to a point that in order to understand earthquakes, in order to predict earthquakes, you need instrumentation and you need research. We do not know yet how to predict earthquakes, but we now have a pretty good idea of what's required in order to predict earthquakes. We have the instrumentation that I think is necessary and we just need to wheel them out -- to put it out and let good people look at it for awhile, in order to develop the understanding that is then required to have sensible earthquake engineering codes and also to develop methods of predicting earthquakes. So the first message is we need research and seismology and we need much better instrumentation in seismology in order to take the next step.

The second message is that what we learn in northern California is not necessarily transferable to southern California. This is a question that you asked, Senator. Northern California has simple fault lines and simple strike slip structures, by and large, although you did see some folding type structures and some thrust type structures. And even this latest earthquake had a large thrust component and apparently wasn't a simple strike-slip event as we expected in northern California. Southern California is full of buried faults and thrust structures and things that aren't nearly as simple. And as was also mentioned by Egill, we need to take a more regional approach.

So the approach that we've taken here at Cal Tech is to design a regional array using broad band instruments that are also connected with global positioning satellite detectors so that we can monitor ground motion or a very large frequency and amplitude band in southern California so that virtually any earthquake of magnitude 4 or so and above will give detectable signals over a large number of these instruments. It's our feeling that we need this modern instrumentation in order to understand earthquakes fully and in order, perhaps, to find precursors that are not evident right now in data that isn't nearly as good as far as the band width or the dynamic range.

One point I would like to make is that the funding level is very much lower than is optimal for trying to understand earthquakes, particularly in an area that is as prone to earthquakes as California. And we can no longer look to Washington or the federal government for all the funds in research and instrumentation in the earthquake business. We've tended to rely on the USGS, but their funds are limited and their obligation is nationwide, including Alaska and Hawaii both of which have large earthquake problems.

To illustrate this point, I was on my way to Washington -- I was driving to the airport, as a matter of fact, when the Whittier Earthquake occurred. When I got to the airport and saw how serious it was, I canceled my reservation and came back and immediately started writing a proposal to Cal Tech to try to raise private funds for this -- this array, which we now call Terascope -- this broad band array to be installed in southern California, which includes the GPS receivers, because I knew the federal government was saturated. They literally could not afford this amount of money. I felt the need was so great that we couldn't wait for the State Legislature's wheels to progress. So I figured we could approach private foundations and get the money faster because it was, in my view, such an urgent matter.

We've had one of these stations running now for about two years and Hiroo Kanamori has shown you some of these results. The results are very, very exciting. It's my belief that when we get about ten of these stations running, we will have a break through in seismology. We'll know so much more about earthquakes than we know now with our present old-fashioned instrumentation. And it will be a model for the whole state.

I think we should have 40 or so of these scattered around the state and we're talking about $10 million. These are not conventional short period instruments. These are instruments that will tell you what's happening between earthquakes. It'll tell you the very long period motions that are associated with earthquakes and perhaps very long period precursors that have been happening all along, but which we could never detect because of the technology.

I'd like to also emphasize that there's a very important research and training and educational aspect in all of this. We've got to continue to do active research in earthquakes. We've got to train the best seismologists and we do this both at the state schools and the private schools.

In southern California, for example, Cal Tech and USC are examples of private universities that have very active research programs in earthquakes. Some of the more important people in earthquake seismology are in the private universities. Of course, some of the more important people are also in the public universities. But any legislative solution has to recognize the role that the private universities play in the earthquake business.

For example, since the 1920s, Cal Tech has been responsible for earthquake information in southern California and Berkeley, a public university, has been in charge of earthquake information in northern California. The USGS has been moving into central California, so now we have three organizations that are really responsible for earthquake information -- one federal, one state and one private university.

That's really most of the message I wanted to make. I think I would like to emphasize one more time that there's been a lot of attention to northern California -- not enough money in northern California, but in contrast, southern California has really been getting much less attention. Berkeley and Santa Cruz have good, well-financed research programs and, of course, the USGS is headquartered in Menlo Park and they're putting a lot of instruments in the -- in Parkfield and in northern California. Southern California, in many respects, has been neglected and the problems are just as severe and the population density, of course, gets -- gets even higher.

So I would like to emphasize that southern California is not only a different cultural part of the state, it's also a different geological part of the state and we need to devote resources to southern California as well. And that's really the message I wanted to make. Thank you.

CHAIRMAN GARAMENDI: Thank you very much. I'm reading with considerable interest, the handout that you provided in the information on Terascope. I think I will save this question for -- we have three more witnesses. I'd like to go through those witnesses and then -- five more witnesses -- oh, my. Turn the page. There's five more witnesses. My apologies. Let's go through them and I'll save my question. I'll ask my question now to all of you and -- and then you can respond, perhaps in writing, or after the last witnesses.

Our next witness is Kerry Sieh. Thank you, Kerry. Professor of Geology here at California Institute of Technology. My question -- well, I'm going to save it. Kerry, go ahead.

KERRY SIEH, PH.D.: I'd like to start by stepping back 18 years. If we'd been sitting here 18 years ago and you'd been asking us questions about where the next earthquakes are going to happen, when they're going to happen, how big they're going to be? There would be a deafening silence. We've learned a tremendous amount in 18 years.

Could I get the first slide, please? About 20 years ago, when plate tectonics became the model for how California was falling to pieces, tremendous opportunities came about to understand what happened when the great earthquakes happened in California in the 1800s and 1900s -- early 1900s.

We knew when the San Fernando Earthquake happened -- you can see the damage area there in the little hatchered box. We knew that there had been great earthquakes in California and we knew that the three great earthquakes -- the biggest earthquakes, had had damage areas shown in the colored patches. In 1906 the damaged region was roughly in the area of the orange patch. In 1857, our southern California equivalent of the San Francisco Earthquake, fortunately happened 50 years earlier when there was only 4,000 people in town. Damage there is shown in the orange -- or the high shaking area is shown in orange or yellow and then the 1872 earthquake which occurred on a fault in the Owens Valley.

We knew nothing about whether the earthquake -- the next earthquake to come was going to be in the Santa Cruz Mountains or a repeat of 1906 or how often 1906 ought to repeat itself. Or how often 1857 ought to repeat itself. Or if the segments shown in red -- the portion uncolored shown in red -- was -- was that even seismic? Could we even have a great earthquake in the Palm Springs area along the San Andreas fault. Some people said the San Andreas fault in the Palm Springs area -- Riverside area -- San Bernardino area -- was dead. And there was another fault called the San Jacinto that was the active structure.

Well, what we know now is considerably more. This is a figure taken from a report that a number of us put together a year and a half ago -- government, private university and public universities -- in response to the request of the Director of the Geological Survey. And what this figure shows is that we believe there are several segments along the San Andreas Fault -- and here we're only looking at the San Andreas for the moment -- that have a very high potential for breaking. And we have several segments that have a very low potential for breaking.

The northern most segment of the San Andreas that has a high potential had an earthquake a couple of weeks ago. In general that earthquake was forecast, not only by this group, but in other publications by other scientists over the past five years. That's a tremendous success in my opinion, in spite of the fact that some of the details weren't quite what we thought. We knew we had a tiger. We didn't realize it was green.

Just going down from northwest to southeast, let me just talk briefly about the forecast we've made. Part of the reason I'm going back into what we have forecast is because I think that we have a tremendous track record here. Seismologists working with geologists, working with geophysicists -- we have a lot to say. We have learned a lot in the last ten, fifteen, twenty years. I think we have the potential for learning as much or more in the next ten or twenty years, if we have adequate public support.

The segment of the fault that broke in 1906 included the North Coast segment, the San Francisco Segment and the south Santa Cruz Mountain Segment. We strongly believe that the North Coast segment will not break again within the next thirty years. Probably not, in fact, within the next 100 years, because we know from geological evidence that earthquakes happen there only about every two to three hundred years. We think that the San Francisco peninsula and south Santa Cruz Mountains segments have high potential. We thought they did. Because the slip there in 1906 was so little and the slip rate is so high, that there ought to be earthquakes about every 100 years or so.

The central creeping segment of the fault northwest of the Parkfield area that Al Lindh talked about, is creeping at a rate that we know from geological studies and geodedic studies -- we know from geodedic studies that it's creeping at a rate of about 34 millimeters a year -- an inch and a half. We know from geological studies over the last few millennia, it's been moving at about the same rate. So that means there's no strain accumulating. There's no potential for a great earthquake there. So we can unforecast an earthquake for that area.

The Parkfield Segment -- we have a very high likelihood of a magnitude 6 in the next thirty years. In fact we probably have a high probability of two in the next thirty years.

The Chalome Segment is a segment that had relatively low slip in 1857. We think that it's about due for an earthquake. It might very well combine with the Parkfield Segment and produce a magnitude seven, an earthquake about the same size as the one that happened a couple of weeks ago and this is an earthquake significantly larger and a damage potential to the area around San Luis Obispo, Paso Robles and surrounding communities.

The Carrizo Segment is a segment that had huge offsets in 1857 -- we know from offset little streams. And that segment we just discovered this week, in fact. We finally got our results back from some of our excavations and we found that, in fact, the last earthquake there prior to 1857 was about 1480 A.D. Prior to that, the previous earthquake was about 1200 A.D. So we have about a 300-year interval between earthquakes there and it's extremely unlikely that in the next thirty years Taft or Maricopa or Bakersfield are going to have to worry about a monster earthquake generating from that segment of the fault.

It's also good news because we now believe much more strongly that the Parkfield Earthquake and the Parkfield-Chalome Earthquake -- if it occurs -- will not trigger a great earthquake along the Carrizo and Mojave Segments like it did in 1857. So we don't think now the repeat of either the 1857 earthquake or the north coast -- or the 1906 earthquake is going to happen in the next thirty years. The Mojave Segment, for various reasons I'll get into later, has a probability of somewhere around thirty percent in the next thirty years. The Coachella Valley Segment has the highest probability, at least as judged by this committee, of breaking within the next thirty years.

All these segments are large. All of them could fail separately or they could fail in unison. If the southern three segments failed in unison, we'd probably have a magnitude 8 earthquake. If they failed separately, we'd probably have a mere 7.5.

Let me go through now a little bit of discussion of the Carrizo Segment and the Mojave Segment, Senator Garamendi, so you'll understand a little bit about what -- how we do what we do and then I want to go to the L.A. basin and amplify some of the comments that Egill Haukkson made.

The San Andreas Fault, as seen here on this plastic relief map, runs from the upper left corner west of Bakersfield, along through the Mojave Desert, along through the

Palmdale area, and then down through the right center part of the photograph, passing out to the Imperial Valley as it goes through San Bernardino.

The portion of the fault off to the left we call the Carrizo Segment. The portion off to the right is called the Mojave Segment. These two segments behave differently, we think. They happened to fail together in 1857, but based on the prehistoric behavior, it looks as if the segment to the left, further away from L.A., is going to lie dormant. It's going to be a slumbering giant for at least another century or so. The segment to the right -- we're not quite so sure about.

Let's look for a second at that northern or left-most segment. Here's what the fault looks like when you're flying -- well, probably, in fact, when you flew down today from -- if you flew down from San Francisco, anyway, you would have flown over this part of the fault. Off in the haze, which is the marine layer, not smog, of course, is the Los Angeles. area.

Well, those small little streams down in the lower part of the screen, tell us what happened in the last earthquake. We've made a lot of hay out of those little streams. We could make an awful lot more hay if we had better seismic instruments and if we had better geodedic instruments. And that's the sort of thing that Hiroo Kanamori was talking about, that Don Anderson was talking about. We've learned a lot from the dirt. We could learn a lot more by making sure that we're prepared to collect sophisticated data when future large earthquakes happen.

We missed a lot of good information in the Loma Prieta Earthquake because we simply haven't had the money to do what we would want to do or the manpower. We, nonetheless, will learn a lot from the Loma Prieta Earthquake, but we could have learned it on a magnitude of more.

Anyway, that segment, again, I think will be dead for another 100 years -- 150 years. This segment between Lancaster, Palmdale and the Los Angeles basin is not quite so promising in terms of the length of its hibernation. Again, this segment broke with several meters of offset in 1857. The lower portion of the slide here, moving up to the left towards San Francisco -- the upper portion of the slide -- the Mojave Desert and the southern and Sierra Nevada, moving to the southeast.

At a place just near the right edge of the -- well, near Palmdale, actually, north of Los Angeles, we have a record of prehistoric earthquakes. The fault lines you can see breaking this vertical cut into the layers and, I won't go through the details, but there are a lot of places in this section of layers of marsh peats and black and river sands and tan where, if you have the magic eyes of a geologist, you can see prehistoric earthquakes. The record of prehistoric earthquakes for this segment looks like this. The vertical axis is the time period from 400 A.D. to 2000 A.D. and the horizontal axis is just the earthquakes that occurred -- the prehistoric earthquakes occurring in sequence. Each bar and each letter represents a prehistoric earthquake that occurred long before instrumental records were available -- before instruments were recording them.

Up at the top -- event Z -- is the 1857 earthquake. Event X is an 1812 earthquake that we can identify using tree rings along the fault zone. Event V occurred about the time of Columbus. Event T occurred at the time of the Black Death in Europe. Event R occurred when King John was being petitioned by his subjects about human rights. Event N was the Battle of Hastings. Event I was -- I can't remember what happened in 1000 A.D. Event F happened about the time that Charlemagne was trying to put together the Holy Roman Empire and so on, all the way down through Mohammed.

This is an interesting pattern of earthquakes. If we had this sort of a pattern -- a record of a pattern like this for many, many places along the fault, we could put together a record of earthquake occurrence in space and in time along the San Andreas and other faults over many, many earthquake cycles. And we'd learn a lot more about where to expect the next one if we could do this.

For example, in this particular diagram, if you take just the average interval between events, it's 132 years. We've now come 133 years since the last great earthquake. So one might say, well, we're overdue. But in fact, most of the intervals -- five of the intervals -- are less than a hundred years and the remainder are mostly more than two hundred years. It looks as if there's a clustering of great earthquakes. It may well be that we are now in a dormant period and the Mojave Segment will not break for the next hundred years. These are the sort of questions that additional research could conceivably answer. I would like within ten years to be able to say whether the Mojave Segment could generate a magnitude 8 earthquake or whether, in fact, it will lie in repose like the Carrizo Segment for the next hundred years.

Summarizing, again, we have made a crude estimate of where, along the San Andreas Fault, and then in the lower figure, where along the Hayward Fault and other faults in southern California -- where we think the earthquakes are most likely to occur next. These are target areas, as Tom McEvilly is hoping to take advantage of up north. There are target areas there and there are target segments of faults elsewhere in the state that would benefit greatly from greater instrumentation, greater effort to understand what happens before the next earthquakes and then to capture and to trap that big earthquake when it happens. We will learn a tremendous amount about future earthquakes if we trapped the next future earthquakes.

Let me turn briefly to L.A. There are other sorts of maps we've produced and these are crude maps, and they're going to get better. But this map, for example, would be very useful to insurance companies. I don't know why, but they haven't picked up on it yet. We can now say which parts of this state are more likely to produce earthquakes than others. There's a great opportunity here for red-lining. (laughs)

Notice the number of faults capable of producing heavy shaking -- that is one tenth of gravity -- are concentrated in the metropolitan L.A. area and in the southern Bay Area. We can turn data like this and combine it with other data to produce maps like this that tell us what the return time for heavy shaking ought to be for any one place in the state. The areas shown in bright red have return times of less than fifty years. You might note that all the recent earthquakes -- all the damaging recent earthquakes -- have occurred within these red areas. The Santa Cruz Earthquake, the Whittier Earthquake and the Superstition Hills Earthquake down in 1987 in the Imperial Valley. We're getting pretty good at this, but we need to continue to collect data. We need to continue to be able to respond to being surprised by events like the Coalinga Earthquake.

Going now to the L.A. basin just for about a minute or so, most of the topography that you see on that plastic relief map is due to folding and faulting. The Santa Monica Mountains, which you can see where the coast goes east-west -- west to Los Angeles -- and the Hollywood Hills going off to the east, are a mountain range that is just as impressive as the San Gabriel Mountain Range, except that where it goes through the L.A. basin, it's buried by sediment. If you drive from downtown L.A. -- south a couple of miles -- you've driven over a range -- a crest -- a mountain range, that is six kilometers high. It's just that it's filled up with sediment. Well, that mountain range is still growing, just like the San Gabriel Mountains is, and it will probably produce big earthquakes.

Dr. Haukkson was very reserved in his comments about the potential for a large magnitude earthquake in the L.A. basin. I think that it's fair to say that, given the geodetic information we have about the rate at which Palos Verdes Peninsula is shortening relative to the San Gabriel Mountains, given the geological data, which I'll show in this slide here -- here's a cross-section that I'll explain a little bit later. I feel that it's -- the best -- the most likely scenario is that there will be a magnitude 7.5 or so under the downtown area. We don't know when. We don't know how fast the fault -- these faults that are shown with the black lines underneath the colored sediments -- we don't know how fast those faults are moving. We think they're probably moving about a centimeter a year, based upon the evidence we have. If that's correct, the question is are these structures moving? Are they deep enough that they can move in gooey rocks and not break in a big earthquake? Or are they shallow enough that the rocks are stiff and they're going to eventually yield in a great earthquake?

I think the potential for a great earthquake under the downtown is there and we geologists, we geodesists, we seismologists could contribute a lot to understanding just what that potential is. Will this fault system fail in one monstrous earthquake of magnitude 8? Will it fail in a series of magnitudes 6.5's? Will it fail aseismically? It's important to know this if we're going to design big structures in L.A. and keep the infrastructure operating over the next fifty years.

The last points I would like to make are partly reiterations of what's been said already. Bill Iwan mentioned in the first presentation that we already know an awful lot about the hazards. So the inference is we might not have to worry about that so much anymore. It's true we've had a lot of success in characterizing the hazard. But if you consider yourself to be a man in a jungle and you've discovered lions and you've discovered baboons and you've discovered monkeys, you can pretty much prepare for the lion and you can prepare for the baboon and you can prepare for the monkey if they happen to want to attack you. But if you hear some crashing around in the jungle and you don't see the animal but it sounds too big to be a lion -- it's too big to be a baboon -- it doesn't sound right for a monkey. It's got these strange shrill, long sounds. You've never heard of an elephant before. But you hear something out there. Well, it's best if you start probing. It's best if you start exploring and trying to figure out what that beast is. There are a lot of elephants out there. There are some lemurs and lorisses and there are some things we don't know about yet. The Whittier Earthquake showed that. The Coalinga Earthquake showed that. We really need to have an active, viable research program in addition to the very important business of keeping the infrastructure going during an earthquake.

Most of what you just heard from me and most of what you just heard from the rest of the witnesses today, you would not have been able to hear if twelve years ago, Alan Cranston hadn't gotten the NEHRP through Congress. The funding under NEHRP right now is a half of what it was in the mid '70s when it was first started, or something on that order because of inflation. We are starving. We are doing a pretty good job considering that we are starving. We're pretty proud of what we've been able to do. But we could sure use some help. Thanks.

CHAIRMAN GARAMENDI: Thank you very much. I have an observation and I would like to share this with all of you that are here. I want to do this before you begin to drift off, which I suspect will be any moment.

We've heard much testimony and a great many pleas for funding. There are several different types of programs that are envisioned. I am not sufficiently aware, knowledgeable and probably not even capable of picking and choosing where the priorities lie among these various programs. I do, however, have some experience and some capabilities in state-political matters. And the projects that I've heard have the great potential of pitting one area against -- of one area of the state against another area of the state. They also pit one type of science -- one branch of seismology against another branch, or one type of project against another type of project. That kind of competition will likely lead to the result that we have seen thus far in the state of California as it pertains to earthquake research or seismology research. That is no money -- to speak of.

My observation is that if there's going to be progress, there must be political union of north and south, project to project, region to region. And I need your help to do that. We need -- I need, the Legislature and the Governor will need a method of prioritizing, a method of rationalizing the differences between these projects and assistance in determining what should be done immediately versus what can wait a half a year or longer. What will give us the best opportunity to deal with the most pressing problem.

This Committee will be pursuing these questions over the next six months or so. We will be processing legislation. But we're not going to get very far without your assistance. I don't know when, if ever, all of you get together to sit down and to talk about and to arm wrestle these questions through. But I would suggest that if you expect to have funding from the State, you should arrange to have at least one or two sessions soon and if you have an organization, let that organization speak for all of you. If you don't, perhaps the Seismic Safety Commission might help prioritize. But in some way we need to have one voice from this community of scientists, geologists, seismologists and so forth. One voice saying here's a program for California that makes sense.

I frankly do not like the political feel of a Hayward Earthquake Study versus a Southern California Earthquake Center. It has the feel of defeat before you even get started. I know north-south politics. I know regional politics. And I know the competition. So that's my observation to you.

It would be very helpful if there was a program for California and if it came from all of you -- the scientists. If you need a forum, let me know. I think I have a small budget for half an airplane ticket or at least a bus ticket to some place, maybe Bakersfield.

Let's move along with our next witness, Duncan Agnew, from the Scripps Institute of Oceanography in San Diego.

DUNCAN AGNEW, PH.D.: Well, after that admonition, I will try to keep the grinding of ax noise to a minimum in my talk.

What I want to do is to talk very briefly about an observatory called Pinion Flat Observatory that we operate -- it's in southern California. It monitors crustal motion. It's the only major concentration of this kind of measurement outside of Parkfield in the United States. There are a few other installations operated by the Geological Survey, but basically Parkfield and Pinion are the two main places where crustal motion monitoring currently goes on in the U.S.

If I can have the first slide. This is just a cartoon of a fault. Since it's California, it's a strike-slip fault. To give the flavor of what goes on. The fault is slipping a depth. It's maybe slipping a little bit near the surface. In between, it's locked except when it gives way in an earthquake. And as the two sides of the fault move past each other, material away from the fault deforms, changes shape. And if you measure that deformation, you're measuring what is going into eventually causing an earthquake, or at least the build-up of energy that's eventually released in an earthquake. And if some patch on the fault were to slip in an earthquake, you'd know it with a seismometer. If it slips too slowly to be detected with a seismometer, then this kind of deformation monitoring is the only way you have of finding out about it.

So that's the general principle of what we're trying to do, where we're trying to do it. I'm hampered by the lack of a pointer. This is southern California with faults and the dots are major earthquakes since 1900 and if you can find Palm Springs, which is labeled -- it is the square with the PS in it and there's a little star just below that. That's Pinion Flat Observatory. We're about ten miles from the San Ysidro Fault which has been quite active in this century and about 15 to 20 miles from the section of the San Andreas fault that's currently given up a fairly high probability of producing a great earthquake.

The work at Pinion Flat began in 1971. At that time, I think people were very optimistic that it was very easy to do this kind of measurement. It's turned out it hasn't been very easy and we've had to spend many years -- it's a slow process because we're measuring slow things. Improving the instrumentation -- we've gotten, I'd say, a factor of a hundred to a thousand in the sort of ten to fifteen years since the Observatory started and more recently having gotten the instrumentation to that level, have been focusing more, though we've been doing it all along, on monitoring possible slow deformations, whether precursory to earthquakes or whatever. Just trying to understand what leads up to earthquakes in this area.

We have a lot of equipment. I won't try and list it all. Some of it's very large. This is a quarter section of land that the Observatory is on and some of the instruments, called laser strain meters, stretch almost the full length of the quarter section there. They're 2400 feet long. We have tilt meters that are about 1500 feet long. We have instruments in boreholes. So this is a much tighter concentration of equipment than at Parkfield, but also a much more varied set of equipment.

One big part of what we do is to try and compare different kinds of instruments that we hope measure the same thing to understand how different instruments perform.

And, again, I won't go through the list. This is a list of all the people who have been running experiments of one kind or another at Pinion Flat. We have groups from the USGS, from universities in California and, in fact, from institutions all over the world who've come to Pinion as part of this kind of instrument comparison exercise, and we've learned a lot by comparing instruments about what works, what doesn't work, what you can do.

I think we've developed this instrumentation and other people have developed their instrumentation to the point where this kind of measurement could be made elsewhere. You've heard about GPS. I'm personally very interested in having the kind of permanent GPS network that was described earlier. In fact, one of the things I handed you was a photograph of a permanent GPS antenna that we've installed at Pinion Flat. But I should point out that for monitoring possible precursors with periods of hours to weeks, the kind of strain measurement that we do at Pinion Flat and that other people can do is, in fact, more sensitive than GPS. So GPS does not answer all your questions.

Just to illustrate that. This is a sort of a "what if?" The shaded area on the bottom is where, if there had been an instrument, it would have detected at ten to one signal to noise strain from the Whittier-Narrows Earthquake, using this kind of strain meter or tilt meter operated at Pinion Flat. We were out at the one to one level. We did detect this earthquake, but if we'd been in the shaded area, we would have had a ten to one signal to noise.

The top shows the same thing for displacement, which is what GPS measures, and for this kind of rapid change or -- which -- and it would hold equally true for a precursor with periods of hours to days to perhaps weeks. A few strain observatories of this kind can cover a lot more ground than a network of GPS. It's not to say you shouldn't do the GPS. That gives you other equally and perhaps more valuable information, but they're -- I'm grinding the ax a little bit here -- they are competing, but to a large extent, complementary techniques.

So I guess I will make one point on funding, not directed to any area or any technique, but to the way in which this is done, and that is that I think there is a temptation, particularly following something like Loma Prieta and it -- it's made stronger by the way that government financing works, to invest in a fairly large capital equipment component and put out a large array of equipment. That is a really bad idea unless you are somehow prepared to continue to pay the operating costs, which amortized over time, will dwarf the capital costs over periods of decades because this is a decades kind of problem.

We've had a lot of problems keeping our Observatory running because money to do the same thing you did last year, which is to pay the power bills, to keep the instruments going, is something that's very hard to defend to research agencies like NSF and the USGS who have been our main support so far. Though we're part of the University of California, we don't get any funding from them and so I want to stress that the up-front costs are only a small part of the real cost of doing this kind of research and that has to be kept in mind when planning something or else you can often bite off more than you can support in the end. Thank you.

CHAIRMAN GARAMENDI: Thank you very much. I think you just confirmed what I had been fearful of and made comment to in my remarks just before you came up. Namely that we have competing proposals and probably far less money than necessary to fund -- well, all of them and perhaps even a few of them. We're going to need your help, all of you, in pulling together some sort of a reasonable proposal that includes those things that are critical to California's future here.

Let's move along. The next person is James Brune, Director of Seismological Laboratory and Professor, Department of Geological Studies, University of Nevada, Rent and Research Geophysicist at U.C. San Diego. Professor?

JAMES BRUNE, PH.D.: Thank you, Senator. I'm going to discuss a little bit a complimentary field of research that hasn't been brought up so much this afternoon, and that is, the fundamental studies of earthquake mechanics, and you might say earthquake physics, in the hope that we can understand the actual physical processes that are happening in earthquakes and this might help us limit the damage from earthquakes.

As a result of the development of plate tectonics models of the motions of the earth's crust, we have a general idea of the physical principles that govern earthquakes. And you've heard quite a bit about the idea of using the long term slip rate and slip motion to calculate the slip deficit and therefore the potential for an earthquake. I think that this kind of calculation is probabilistic. Calculation is going to get better as time goes on. It's pretty easy to imagine that we could reduce the errors by a factor of two in the next few decades.

I think one of the things that may change is that rather than using indirect methods to calculate or estimate the strain on a given section of the fault as we do now, say from seismic gap theory and from historic earthquakes, we probably will be able to add in more direct measurement of strain information, which we can then correlate with rock strength and perhaps estimate better the time at which the strain is high enough to actually start an earthquake.

There, however, are critical aspects of the mechanics of earthquakes which we don't understand. And this lack of understanding will have to be overcome before we can greatly reduce the uncertainties in our estimation of the earthquake probabilities. And I'll just mention a couple of these uncertainties.

First of all, we do not know the absolute shear or driving forces for earthquakes and the associated coefficients of friction, which must be overcome to cause the fault slip. A lot of indirect evidence suggests that these stresses are much lower than we would expect from laboratory experiments on rocks. And we don't really understand this. A mechanism to explain the discrepancy has not been established, although there have been many suggestions. There are indications that the stresses operating perpendicular to a fault may play a larger role than we had previously expected. And in this regard, I'd like to mention the Cajon Pass drilling experiment, which is an attempt to get down deep enough in the earth's crust to actually determine the stresses, to determine the frictional heat generation on the fault, and to determine the kinds of rocks and minerals, including water, that exist on the fault. And I think eventually this kind of experiment is going to have to be carried out if we're going to really understand the physics of what's going on.

CHAIRMAN GARAMENDI: That's going on now, isn't it?

DR. BRUNE: The hole is down a few kilometers now and is expected to go down to five kilometers and has already provided a lot of interesting information and, unfortunately, with just one hole, there's going to be some question about interpreting it, but I think, eventually, that hole, when it gets down deep, is going to really provide some important constraint on the physics of earthquakes.

There's another related drilling experiment which I don't know exactly how much priority to put on, but Dan McKenzie and I suggested it quite many years ago and that is, after a major earthquake to actually drill down in the fault plain after the earthquake to get the frictional heat generation on the fault, which might help us understand the physics a little bit better.

But one of the most exciting things that I've heard about recently and it's so new that I don't know how much faith to put in it. I've heard from Steve Kirby at the USGS that he's finally been able to find some rock -- some dunnite under certain conditions which will slip at a hundred bars of stress, which is the very lowest stress that we expect from other arguments, that exists down there. And if this is true, then we finally have a rock or a mineral or a mechanism, actually, is probably more appropriate. It's a solution and ex-solution process which allows rocks to move at about a hundred bars stress, even though there's tremendous compressional stress on the fault. And so with that, I'd like to say that I think we do have to have a complementary program in understanding rock physics before we really get to the bottom of this.

And the second important thing we don't understand, is we don't understand the various mechanisms which actually trigger earthquakes. This was mentioned briefly before. There's a lot of evidence that major earthquakes can be triggered by very feeble changes in the initial conditions. This is one of the hardest things that we have to deal with with earthquake prediction. If a large earthquake can be triggered by an arbitrarily small change in conditions, then it's going to be very hard to predict it.

And it seems, unfortunately, that a lot of recent California earthquakes, including this most recent one, seem to have had essentially no precursory phenomena occurring before them. Or put another way, you could say that if there really weren't any such things, that they in fact started as just tiny little cracks, which grew into gigantic earthquakes and therefore you might say were triggered by arbitrarily small precursory events. And that's very discouraging.

So a lot of earthquakes apparently in California are going to continue to occur without warning. However, I think we know also that there's a good chance that there will be some of them that have a lot of warning. That is there are going to be cases when there are lots of foreshocks, funny tilting of the ground, changes in water level in wells, and a host of things which are going to throw up a lot of flags and warnings about an imminent earthquake. Now, most earthquakes are going to fall somewhere between those two ranges, with no warning at all and there are lots of precursory things that tell us something's about to happen. And we're going to have to learn to deal sociologically with that kind of range of uncertainty.

As I said before, I think in the future our research, I hope, is going to gradually move more in the direction of actually measuring physical parameters in the earth's crust in order to estimate the probability of a future earthquake. As a strategy, I think that we should continue sophisticated arrays covering the region of California, but I think we also need to focus in a few specific areas like Parkfield and like the Anza Seismic Experiment, where we, rather than trying to cover everything or to cover all -- all possible earthquakes, we focus in on determining the physics.

And in this regard, I would emphasize something that Egill mentioned, that is, we need to cooperate with foreign countries. There are many earthquakes that are going to occur in foreign countries before a complete sequence of earthquakes has occurred in California to tell us exactly how things repeat. And if we can take advantage of earthquakes in these other areas to understand the physics of the faulting better, then I think we'll get to our goal a lot faster.

I just want to mention -- show one slide and mention one -- one particular type of earthquake prediction, you might say, that we're involved in. We've been working in cooperation with the Mexican seismologists for quite some time and in a sense, the type of probabilistic earthquake prediction that a lot of people have been talking about was successful in the case of the 1985 Mexico City Earthquake because, based on gap theory and the probabilistic arguments similar to those that you've seen today about the San Andreas Fault, at least five different investigators pointed out this area in Mexico, which is a seismic gap that's likely to have a big earthquake. And as a consequence of that, we submitted a proposal to the National Science Foundation to put a strong motion array in this area and capture the next earthquake. We had about half of the array in when the 1985, September 19th earthquake occurred, and killed more than 10,000 people in Mexico City.

The actual gap that we were thinking was more likely, however, is the Guerrero Gap, which is just a little bit to the southeast of that in the area between the dash circles labeled 1979 and 1957. This is called the Guerrero Gap and is a long section of the fault which, we think, has even a higher probability of a major earthquake than the 1985 earthquake. It's somewhat closer to Mexico City -- parts of it -- and therefore, we're faced -- the Mexicans are faced with the possibility of a major earthquake at any time which is comparable to the 1985 earthquake, with comparable consequences.

So there's a lot of social problems dealing with this possibility, as you might guess. We now have all of our array in -- so our motion array, we've literally recorded dozens and dozens of intermediate size earthquakes now and we have a tremendous range of the spectral characteristics of earthquakes. These are all done on modern digital instruments and we actually captured a 6.75 earthquake at one end of the array.

The last figure I want to show is a figure that Dr. John Anderson, one of my colleagues at the University of Nevada is going to show at the AGU Meeting in a few weeks about the seismicity in this region. Having this array, now, we've been able to locate the earthquakes a lot more accurately than we have in the past and you'll notice that in that section, there's a gap of seismicity and this gap of seismicity has been used in the past as indicator of imminent earthquake -- imminent earthquake. In fact, the characteristics of this gap, as you see, there's a high seismicity to the northwest and a high seismicity to the southeast and this gap in between, which is right in the center of the Guerrero Gap, is as convincing, we think, as the gap and seismicity that was used to forecast the 1978 Oaxaca Earthquake. So this is, I think, a very serious concern that this section of the fault may be about ready to go. And with that, that's all I have to say. Thank you.

CHAIRMAN GARAMENDI: Before you leave, a question and a request to all of those witnesses who are still here. Most of you have presented either slides or diagrams on the view machine there. We will need that information to complete the transcript for this hearing. I had forgotten to ask for that early on. So if you can get your handy, dandy little copy machine to copy data such as this -- the pretty pictures would be nice to have, but we could probably do without those. But the charts and diagrams that we've seen thus far, we really need that and we'll include that as appendices or where appropriate in the testimony itself.

Now, as I said earlier, this has been quite a day for me. To start off with space this morning and we're into inner space at the moment. Or maybe not inner space -- I suspect Assemblyman Vasconcellos might challenge that. Geophysical space. There's a definite connection between the two and one of the things that we were exploring this morning is the commercialization of space and space projects -- space industry in California, which has basically been a government operation thus far. There's a lot of instrumentation. There's a lot of knowledge. There's a lot of hardware that is used in various space exploration. And the question for those of you that like to play around in the dirt: Does it make sense for us to combine our space knowledge -- space program, if we're going to develop one for California -- and the goal of this morning's hearing was to develop a space policy for the state. Can we combine these two concerns? The concern of earthquakes, seismology and the like with our interest in space as an industry and as a science in California.

For example, if we choose to spend some money on space products or space technology, could that same money be used beneficially on the earthquake research programs?

DR. SIEH: I'll be brief.

CHAIRMAN GARAMENDI: And our next witness, he may as well start coming up. Michael Reichle. So Michael if you could come -- go ahead.

DR. SIEH: The GPS system that you've been...

CHAIRMAN GARAMENDI: Introduce yourself, please.

DR. SIEH: Kerry Sieh, Cal Tech. The GPS system that you've been hearing about utilizes military satellites -- the NAF Star Satellite. That is one area that we absolutely depend upon space technology. So the GPS system is one of the areas where we absolutely have to cooperate with people running the satellites. There are military restrictions, however, on our using those.

CHAIRMAN GARAMENDI: Okay. You might develop and pass onto the Committee, if you would, a little bit of information on the nature of that satellite system so that we can get a better resolution of it.

Just very quickly, the information from this morning: floods, fires, climate, air quality and this afternoon, earthquakes -- all satellite technologies of one sort or another. Combination satellites, maybe.

Let's move along. Michael Reichle. Michael, how do I pronounce your name?

MICHAEL REICHLE, PH.D.: It's Michael Reichle.

CHAIRMAN GARAMENDI: Thank you. Go ahead, Michael. Senior Seismologist, California Department of Conservation, Division of Mines and Geology. Incidentally, your report on the Bay Area earthquake hazards was a rave at the Special Session of the Legislature.

DR. REICHLE: Thank you, Senator. I've been asked to review a study that was conducted on the technical and economic feasibility of an earthquake warning system for southern California. The report's specifically for southern California.

Earthquake warning system is not earthquake prediction, but is a part of the continuum of information provided by scientists before the earthquake, during the earthquake and following the earthquake. This particular system would rely on seismic sensors spread along faults or in urban areas in the vicinity of an earthquake epicenter to sense the initiation of an earthquake. The shaking data from one or more sensors can be used to estimate the final size and to decide whether or not to issue a warning. If it's done rapidly enough, the signal -- the warning could out race the seismic waves and arrive in -- to potential users, providing some seconds to perhaps several tens of seconds of warning before shaking occurs -- before the strongest shaking occurs.

CHAIRMAN GARAMENDI: Incidentally, I know from personal experiences that that happened in San Francisco. I know two people that were on the phone to various members of their family or office workers, one from San Jose to Sacramento and one from San Jose to Berkeley, and they said, "My God, we're having an earthquake." Seconds or milliseconds tick by and then the other end of the line, "Yeah, me, too."

DR. REICHLE: The technical feasibility of this system is clearly not a problem. It has been alluded to several times already during the day. The problem remains of how much warning populated areas would or could receive before the onset of shaking and the uses to which they could put the warning.

We'll consider the time first. To help, I've supplied you with a couple of figures. The one labeled Figure 4.2 from our report shows as a solid straight line a fault rupture from say, a magnitude 7 earthquake along the Newport-Inglewood Fault. Let's assume that the epicenter is beneath the Baldwin Hills and the fault ruptured down toward Newport Beach. The area that would suffer significant damage -- the kinds of damage that occurred in Whittier or Coalinga from their recent earthquakes -- is outlined by the heavy oval line. The circles radiating from the epicenter show the amount of warning that could be received given certain assumptions. Given the assumptions we used here, basically Los Angeles and West L.A. would already know they're having an earthquake well before they received a warning. However, parts of Santa Ana, Newport Beach could receive between ten and fifteen seconds before the strongest shaking occurs.

The second example is shown on the second figure which is labeled Figure 4.4A. It assumes a rupture of the Mojave Segment of the San Andreas Fault north of Los Angeles. The epicenter or the initiation of the rupture is near Fort Tejon, and the fault ruptures to San Bernardino. The broad oval which encompasses the Fort Tahone (?), Riverside, San Bernardino and northern parts of the San Fernando and San Gabriel Valleys, again, are the areas that would be expected to have significant damage based upon the kinds of damage that has occurred in historical earthquakes in California.

For this particular earthquake, the northern San Fernando and San Gabriel Valleys could receive between twenty and forty seconds of warning before the strongest shaking arrived. And San Bernardino and Riverside could receive between fifty and sixty seconds of warning.

A second part of our study, after an analysis of the technical feasibility and the kind of warning that could be received, was a look at the economic feasibility of a distributed warning system and the kinds of uses to which the warning systems could be put.

To accomplish these objectives, we conducted two surveys of potential users of an earthquake warning system. One survey concentrated on large organizations -- corporations, principally in southern California, and government agencies. We chose large organizations because they would be more likely to have in-house expertise to evaluate the uses of such a system and we received eighty responses from a hundred and sixty contacts. A second survey concentrated on smaller businesses located within ten miles of the epicenter of the 1987 Whittier-Narrows Earthquake. Even though these two different groups are very different, the results of the two surveys were, in fact, quite similar, and, in some cases, surprising.

First, there is definitely interest in the commercial community about an earthquake warning system, in fact, about earthquake information at -- at nearly every level. Respondents do view an earthquake warning system as useful for mitigating damage and personal safety.

Four general areas of application were indicated. Computer system shutdown, applications to safety in the facility, personnel safety applications and production applications. The surprise to us in both surveys was that the respondents desired relatively long warning times for the kinds of applications they came up with. Eighty-four percent of those responding said that the minimum warning time was thirty seconds or greater. This is surprising because we had indicated that really, in most cases, they would only receive a few seconds of warning before the shaking really started.

The long warning times result from three main factors. First, there is a strong desire on the part of the people we contacted to keep human operators within the decision or the response process. Automatic response to a warning was really overwhelmingly rejected by the respondents. Without automatic response, the timing required to react to a warning is lengthened considerably.

The second reason is that the principal personnel response would be to evacuate a building. Even under the best of circumstances, this could take several minutes or more for a small building. Other potential personnel safety measures seem to be ignored in favor of complete evacuation.

A third reason was that many manufacturing processes simply require time to slow down and stop and that stopping the process could be begun with a short warning -- might not be slowed enough to mitigate damage with only a few seconds of warning.

If we accept at face value the need for a long warning time, we are limited to a system operating in the vicinity of faults capable of magnitude 7.5 or greater earthquakes. This pretty much limits the system to the San Andreas Fault north of Los Angeles and a system that would only operate once in the lifetime of the system and that would be for the earthquake with a thirty percent chance of occurring in the next thirty years. This system would have to work and it would have to generate tens to hundreds of million dollars of savings in order to be cost beneficial.

So the basic conclusion of our report is that from the uses given to us, there is not evidence that those benefits can occur and that the system can't be justified on a cost benefit analysis. This is pretty damning and I'd like to rephrase it a little bit. Just turn it around to the users or the people that we contacted and say that as long as they insist on non-automatic response and on long warning times -- basically as long as they don't trust the system and the information that they get, that the system cannot operate on a cost beneficial basis.

I might add that during the rescue efforts on Interstate 880, the Geological Survey set up a quick warning system using data from the vicinity of the epicenter. Sent messages to the rescuers allowing them at least the opportunity to start getting out from the damaged section before the shaking arrived in that area. Thank you very much.

CHAIRMAN GARAMENDI: Isn't there an old story about a pilot that didn't trust his instruments? I think he was one of those young, bold pilots that never became an old pilot.

Alan Flig. Thank you very much, Professor. I appreciate that information. Alan Flig is the Chief Executive Officer and Vice President for Engineering of Earthquake Safety Systems, an entrepreneurial company that has decided that there's something more here than just science. Thank you very much.

Alan, please summarize, if you would be so kind.

MR. ALAN FLIG: Honorable Chairman, Members of this Committee, Ladies and Gentlemen. Earthquake prediction is certainly an important part of earthquake hazard mitigation. Among the other vital parts are numerous occupant-preparedness measures, improved design codes, strengthening of older buildings and a well-developed group of non-structural earthquake hazard mitigation systems, such as those which I wish to describe to you today.

One of the concepts for earthquake hazard mitigation which has received increasing attention recently, is that of an early warning system which would consist of a dense network of sensors throughout the state, which would be tied into a computer-based decision matrix which would, in turn, transmit its conclusion as to the expected severity distribution of the earthquake waves to subscribers to use as they see fit for hazard mitigation purposes at their individual sites.

Although a recent study which we just heard about by the California Department of Conservation, Division of Mines and Geology, entitled "Technical and Economic Feasibility of an Earthquake Warning System in California" has concluded that quote, "It would not be justifiable on a cost-benefit basis to construct an early warning system at this time," unquote. It did not rule out the basic concept of early warning and it seems likely that such system will ultimately be implemented, perhaps even on a nationwide basis. The study pointed out, however, that such systems inevitably leave a large circular or oval area in the central region which will be subjected to severe shaking well in advance of a transmitted warning signal being received.

The same study has also concluded that quote, "If very short warning times -- ten seconds or less -- become desirable, existing local P-wave warning system technology could provide the necessary information. A local P-wave system could supply longer average warning times in the significantly damaged areas than an EWS system for earthquakes or for approximately magnitude 6.5 on Richter Scale. Thus we believe...

CHAIRMAN GARAMENDI: Mr. Flig, could you excuse me for just a moment? I'm going to have to interrupt you. I realized just a moment ago that I am supposed to meet with the President of this institution in a moment. I'm going to ask Karen to continue to run this meeting through its conclusion and take your testimony. We do have it in writing. And if you could summarize it, that would be the best way to handle it for the record. We'll put your written testimony into the record. In the meantime, I am going to depart. Karen will finish the hearing and if those of you that are here could provide us with your graphs and the like that I asked for earlier and any thoughts that have been generated as a result of testimony that you've heard during the meeting, you can write to us and we will include those after thoughts in the testimony.

I want to thank each and every one of you for your participation. It's been a very enlightening afternoon and one thing you can be certain of is that your testimony will result in specific legislation in the coming legislative year. You will help us draft that, both through the information you have given us thus far today and further comments that I hope to receive from all of you, keeping in mind my earlier request that you try to develop together one program that would address these multitude of issues that you've presented to us.

Mr. Flig, my apologies to you. Karen will complete the rest of your testimony. Thank you all very, very much.

MS. KAREN THIEL: Mr. Flig, I wanted to ask you what has been your experience --

you're actually marketing your system now?

MR. FLIG: Yes, we do.

MS. THIEL: And given the survey results that Dr. Reichle mentioned that went into his feasibility study where corporations and institutions were saying they required a thirty second warning and they wanted a human system. Are you having that same experience when you actually go to sell this to institutions?

MR. FLIG: It's part of my address. There are certain applications which definitely require thirty seconds and more and furthermore, there are applications which will require hours and even hours may not be sufficient to properly address non-structural mitigation. Yet there are a great number of situations where we would be facing life safety situations which would require just several seconds. And I would further define several seconds as two or three, four or five seconds. And such particular example could be well-drawn based on California school campuses. Well-conducted drills.

MS. THIEL: My children go to a school that has 700 Kindergarten through sixth graders. The school evacuates in sixty seconds in fire drills. Can you do that? That's the quickest they can get out.

MR. FLIG: First of all. Yes. First of all, every attempt should be made to provide children with the utmost safe position. After shaking has stopped, then normal procedures, which have been widely exercised in California school systems, would be to evacuate children typically onto a school field. So first, immediate reaction should be to perform a conditioned response, which is exercised in earthquake drills according to the Field Act from 1933.

But as Whittier experience has shown, children as well as teachers remain frozen in their seats and remain frozen for over fifteen seconds and everybody was confused, didn't know what to do and furthermore, some teachers even ran away from auditoriums and left children inside. Therefore we could easily point out an obvious need, an obvious application where automated response which would require just several seconds, indeed would find itself extremely useful and definitely would minimize potential for life, loss, and injuries.

MS. THIEL: Can you talk about some typical institutions which are purchasing this early warning system?

MR. FLIG: Certainly. At the present time we have two installations in California which are on twenty-four hour monitoring and protection. One is Ulysses Grant High School in Van Nuys, Los Angeles Unified School District. The second school we just finished is Pear Blossom Elementary School in Kepple School District. We will be unveiling another installation at the end of November at one of high schools in Hayward Unified School District in northern California.

MS. THIEL: Now are these regarded as demonstration sites for your system?

MR. FLIG: No, we certainly would like to use them as demonstration sites, but these are actually working systems which are properly installed in accordance with building codes and regulations and properly maintained.

MS. THIEL: So you feel that there is a market for an early warning system?

MR. FLIG: We certainly feel so. Again, and I hope very much that we will avoid marketing issues, I wanted to focus more on technical aspects. What is possible, what is impossible, how the system works and what potential benefits can be drawn out of it? I must admit that as far as marketing goes, it is not an easy issue and there is a substantial resistance from certain officials for various reasons, objective and subjective. Sometimes it's out of total ignorance because people would not understand technology. In some instances, it's a lack of funds. In some instances, it's a lack of initiative from local and state government to stimulate such systems.

MS. THIEL: I see. Can you describe where you are right now with what's possible?

MR. FLIG: Sure. That is exactly what my objective is for today. To testify on a subject of one of such local P-wave systems which have been developed and implemented by Earthquake Safety Systems jointly with Kinemetrics Systems of Pasadena, California.

While it appears the subject of earthquake prediction will continue to occupy the most challenging scientific minds in this country and abroad for at least another ten to twenty years, prudent and reliable seismically activated earthquake hazard mitigation instrumentation already exists and have been available for almost fifteen years. The basic technology was developed by California engineers from Kinemetrics Systems, Pasadena several years ago. And it had an excellent opportunity to mature and prove itself in over ten thousand installations worldwide. These installations include instruments that measure strong ground motion and structural response. They're used by virtually every scientific institution related to seismic studies and are installed at 150 nuclear power plants, numerous dams and bridges, elevator control systems in high-rise buildings and other one of a kind applications in the United States and eighty countries around the world.

Earthquake Safety Systems, the company which I represent, has joined forces together with Kinemetrics in establishing a vitally important new field of seismic engineering -- development of various matters and equipment to mitigate non-structural seismic earthquake hazards. Needless to say that this development clearly reflects a rapidly growing governmental and public concern for seismic safety in large industrial and commercial centers throughout California and the United States which have been adequately expressed in various recommendations issued by the Building Seismic Safety Council under auspices of FEMA, the Federal Emergency Management Agency, the United States and California Senate bills, including SB 2585, studies by the U.S. Geological

Survey, the California Division of Mines and Geology, the insurance industry and local governments. Our main goal is to provide a rapid transition of well-proven technology from scientific research and development fields in the wide-range of practical, industrial, commercial and institutional applications.

The core of ES Systems which include a low-cost, on-site, P-wave warning system, is an intelligent seismic trigger. The trigger detects seismic energy waves and when the level of acceleration exceeds a predetermined set point, an output signal is produced in less than 1/20 of a second. The seismic event is identified by measuring acceleration over an appropriate frequency band, thus making measurement immune to most cultural noises and industrial vibrations. The seismic trigger's ability to detect a compressional P-wave which travels through the earth's crust approximately twice as fast as usually more damaging S-waves provide a window of opportunity to perform various hazard mitigation functions such as protection of lifelines, such as natural gas, water, electricity, oxygen, rail lines; emergency sequential shut-down of vulnerable industrial processes and computer centers; containment of hazardous materials, especially Class I and Class II toxic gases widely used by the semiconductor industry; and finally, automatic early warning systems utilizing vocal enunciation, along with conventional siren and visual alarms.

Any system defined as an early warning system inevitably invites a logical question. How much time of advanced warning can the system provide? And obviously, depends, of course, on the distance from the earthquake's epicenter, type of geology, and response time of the technology utilized to detect, identify and transmit signals.

In any event, such early warning can be anywhere from two to three seconds up to thirty seconds for a strong seismic event. A few studies have acknowledged that in some applications, even several seconds of warning prior to an earthquake's arrival, can significantly minimize potential loss of life and injuries.

As I've already mentioned, an excellent example of the benefits available from even two or three seconds of prior warning can be found on any California school campus. Studies have clearly demonstrated that students require no more than one or two seconds to respond in a preconditioned manner to a command: drop, cover and hold -- the standard procedure exercised in every California school to get students to safety under their desks.

Until now, it has been widely assumed that teachers themselves will remain calm and unaffected by the dramatic experience of a major earthquake and will be able to provide such a command. Recall that an expectation that every school teacher is a walking seismic detector. Indeed, evidence from the Whittier Earthquake experience indicates that students and teachers remain frozen in their seats for as long as fifteen seconds waiting for a command to take cover.

Well, automatic early warning systems remove responsibility from teachers and personnel to alert students. ESS has met this challenge to engineer and implement such an automatic early warning system for schools and for general public safety. Early warning systems or a local P-wave warning system developed by ESS consist of a tri-vertical, triple-redundant-seismic trigger supplied by Kinemetrics Systems, uninterruptable power source, signal processing logic, state of the art voice synthesizing system, universal public address interface, monitoring pilot lights and external controls for periodic tests and drill procedures.

Systems are housed within industrial enclosures and permanently attached to a concrete slab, usually at the floor level. It is furnished with its own speakers or interfaces with any existing public address system already in place within the building. It is exactly the kind of technique which we have exercised at our school installations up until now.

And again, I will repeat that such systems have already been installed and currently provide twenty-four hour a day protection at U.S. Grant High School in Van Nuys, Los Angeles Unified School District and Pear Blossom Elementary School at Kepple School District and further installation is planned for a site at the Hayward Unified School District in northern California.

These systems are extremely cost-effective and thus would need only modest amounts of government financing. They also minimize liability risks for the State of California, school board members and private owners.

The potential for false alarms is significantly minimized due to the fact that seismic intensity is measured as a foundation of each individual building and due to a triple redundant design feature of the seismic trigger itself. Such systems have extremely low maintenance requirements. The value of this technology was clearly demonstrated during the recent Loma Prieta Earthquake when the Bay Area Rapid Transit District's earthquake warning system activated and engineers were able to bring passengers safely to the nearest stations.

As United States Senator Alan Cranston said, "We have been fortunate that the damaging earthquakes of the past decade have not cast doubt on our wisdom of our original decision to build knowledge and capability before we focus on application."

The hazard in many parts of United States is no less certain than it was in Armenia and the challenge that faces us now is to take the actions necessary to use our new capability and capacity for earthquake hazard reduction before we have to face the public and explain our inaction as the Soviets now do.

Earthquake Safety Systems and Kinemetrics Systems are committed to further development of reliable, prudent technology to provide maximum public safety and protection from seismic hazards. And we believe that these matters can and should be applied while the research that we have heard about here today proceeds. Thank you.

MS. THIEL: Thank you very much, Mr. Flig. On behalf of Senator Garamendi and the Joint Committee on Science and Technology, I'd like to thank all of our witnesses. We've heard today very timely and very interesting testimony from all of you. I know many of you came on short notice and had to rearrange very busy teaching and research schedules and I personally thank you for that.

Senator Garamendi has SB 22X, which would provide $5 million of State General Fund money for earthquake research and we may be reconsidering that amount in light of the testimony we've heard today. The bill was introduced during the Earthquake Special Session and is now in the Senate Appropriations Committee awaiting the resumption of the Special Session.

We'd appreciate your reaction to the hearing and continued contact with you and look forward to working with you as we try to move the legislation of Senator Garamendi and the Committee. Thank you.

A P P E N D I C E S

Additions to Testimony Given to the
Joint Committee on Science and Technology

California Institute of Technology
Pasadena, California
November 16, 1989

APPENDIX A

National Seismic System Science Plan
Dr. Thomas Heaton, Dr. Don Anderson, et al

CIRC. 1031

U.S. GEOLOGICAL SURVEY CIRCULAR 1031

National Seismic System Science Plan

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National Seismic System Science Plan

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CONTENTS

FIGURES

TABLES

National Seismic System Science Plan

By Thomas H. Heaton, Don L. Anderson, Walter J. Arabasz, Ray Buland, William L. Ellsworth, Stephen H. Hartzell, Thorne Lay, *and* Paul Spudich

EXECUTIVE SUMMARY

Recent developments in digital communication and seismometry are allowing seismologists to propose revolutionary new ways to reduce vulnerability from earthquakes, volcanoes, and tsunamis, and to better understand these phenomena as well as the basic structure and dynamics of the Earth. This document provides a brief description of some of the critical new problems that can be addressed using modern digital seismic networks. It also provides an overview of existing seismic networks and suggests ways to integrate these together into a National Seismic System.

A National Seismic System will consist of a number of interconnected regional networks (such as southern California, central and northern California, northeastern United States, northwestern United States, and so on) that are jointly operated by Federal, State, and private seismological research institutions. Regional networks will provide vital information concerning the hazards of specific regions. Parts of these networks will be linked to provide uniform rapid response on a national level (the National Seismic Network).

A National Seismic System promises to significantly reduce societal risk to earthquake losses and to open new areas of fundamental basic research. The following is a list of some of the uses of a National Seismic System.

Emergency Information Management:

- Near real-time estimation of damage patterns after significant earthquakes.
- Very short term (less than several minutes) warning of imminent strong shaking during significant earthquakes.
- Real-time probabilistic estimation of seismic risk by monitoring of potential foreshock sequences.
- Short-term warning of imminent danger from tsunamis.
- Monitoring of volcanic activity.

Estimation of Long-Term Risk:

- Accurate prediction of ground motions during future earthquakes.
- Seismicity maps of active fault systems.
- Recognition of seismic gaps.

Basic Research:

- Uniform catalog of earthquake activity.
- Systematic mapping of crustal stress.
- Better understanding of U.S. earthquakes.
- Better understanding of worldwide earthquakes.
- Systematic mapping of crustal and upper mantle structure beneath the United States.
- Mapping of whole-Earth velocity structure.
- Recognition of magma bodies.
- Nuclear-test treaty verification research.

Manuscript approved for publication, February 23, 1989.

INTRODUCTION

In this document we describe ways that seismic information can be used to significantly reduce the hazards from earthquakes, tsunamis, and volcanoes. We also describe some of the fundamental problems about the structure and dynamics of the Earth that can be addressed.

Elastic waves in the Earth are generated by a number of sources that range from earthquakes to weather, machinery, and explosions. The nature of seismic waves varies tremendously with time and space. Ground motions may have accelerations of about 10^{-8} g during relatively quiet times and they may exceed 2 g at distances close to large earthquakes. Similarly, the frequency of these waves varies from less than one cycle per hour to hundreds of cycles per second. Seismometer systems have been constructed to record these motions, but because of practical mechanical limitations, the range of amplitudes (dynamic range) and frequencies (bandwidth) that can be recorded by traditional systems is severely limited. Dynamic range and bandwidth have generally been less than three orders of magnitude and two orders of magnitude, respectively. Furthermore, the analysis of data from these systems has been time consuming.

These instrumental limitations have profoundly affected the nature of problems that seismologists could address. The application of modern digital technology to seismic recording systems has dramatically expanded their capabilities. It is now practical to build systems that have dynamic ranges of ten orders of magnitude and bandwidths that range from one cycle per hundreds of seconds to one cycle per hundredth of a second (four orders of magnitude). Furthermore, data can be rapidly collected and analyzed using computer systems. These new systems dramatically expand the types of problems that can solved.

We now describe some of the events that led to the writing of this document. The development of regional seismic networks and of modern digital seismometry both have long and complex histories that will not be covered. This document is an immediate result of a plan for a United States National Seismic Network developed by the National Earthquake Information Center (NEIC) of the U.S. Geological Survey (Massé and Buland, 1987). The network is to consist of approximately 150 modern digital stations that are distributed throughout the United States. Data from these stations are to be transmitted via satellite telemetry to a central recording site in Golden, Colorado, and the network will provide uniform (but rather sparse) national coverage. Funding from the U.S. Nuclear Regulatory Commission will permit installation of approximately 60 stations in the Eastern and central United States. The U.S. Department of the Interior has yet to make funding commitments to install stations in other parts of the country.

Many seismologists who have reviewed the NEIC plan have been very excited about capabilities of stations in this network. These stations appear to be able to record and rapidly telemeter ground motions that range from the largest motions expected during destructive earthquakes to ambient ground noise at quiet sites. They also record ground motion over a very large frequency band (approximately 30 Hz to 0.01 Hz). Thus stations in the National Seismic Network will provide data that can be used to study a very broad range of seismic problems.

At present, there are currently about 1,600 seismic stations in locally operated regional networks that are distributed throughout the United States, and this new National Seismic Network cannot (and is not intended to) perform the many functions of existing regional networks. Unfortunately, instrumentation in the existing regional seismic networks has very limited dynamic range and bandwidth. This has severely limited the applications and types of basic research problems that can be addressed with existing regional networks.

Many seismologists recognized that applying the technology planned for the National Seismic Network to the problem of regional seismic networks will greatly expand our abilities to reduce our risks from natural phenomena and to better understand the structure and dynamics of the Earth. A small group of seismologists (listed in table 1) from universities and the Federal government convened to discuss these issues in July 1987 at Alta Lodge in Utah. There was a strong consensus that we need to develop an integrated, nationwide approach to the recording, reporting, and exchange of seismological data in the United States. In this document we present a common vision that arose in the Alta meeting of what a National Seismic System might look like.

Table 1. Attendees of meeting at Alta Lodge, Utah, to discuss a National Seismic System July 8–10, 1987

Prof. Walter Arabasz University of Utah Salt Lake City, Utah	Dr. Thomas Heaton Scientist in Charge of the Pasadena Field Office U.S. Geological Survey Pasadena, California
Dr. William Bakun Chief Scientist for the Parkfield Prediction Project U.S. Geological Survey Menlo Park, California	Prof. Robert Herrmann St. Louis University St. Louis, Missouri
Prof. James Brune University of Nevada Reno, Nevada	Prof. Arch Johnston Memphis State University Memphis, Tennessee
Prof. Robert Clayton California Institute of Technology Pasadena, California	Prof. Hiroo Kanamori California Institute of Technology Pasadena, California
Prof. Robert Crosson University of Washington Seattle, Washington	Dr. Robert Massé Chief of Branch of Global Seismology U.S. Geological Survey Denver, Colorado
Dr. William Ellsworth Chief of Branch of Seismology U.S. Geological Survey Menlo Park, California	Dr. Elaine Padovani Manager, External Research Program U.S. Geological Survey Reston, Virginia
Dr. John Filson Chief of Office of Earthquakes Volcanoes, and Engineering U.S. Geological Survey Reston Virginia	Dr. David Simpson Lamont Doherty Geological Observatory Columbia University Palisades, New York
Dr. Thomas Hanks Chief of Branch of Seismology and Geology U.S. Geological Survey Menlo Park, California	Prof. Robert Smith University of Utah Salt Lake City, Utah
	Dr. Wayne Thatcher Chief of Branch of Tectonophysics U.S. Geological Survey Menlo Park, California

CONFIGURATION AND USES OF EXISTING SEISMIC NETWORKS

Current Regional Networks

From maps of earthquake activity in the contiguous United States (fig. 1), it is clear that seismic activity is distributed throughout the Nation. Alaska, Hawaii, and Puerto Rico also have high rates of seismic activity (the magnitude 9.2 1964 Alaskan earthquake is the largest known U.S. earthquake and the second largest in the world in this century). In order to understand this widespread earthquake activity, approximately 1,600 permanent seismographic stations are maintained throughout the United States by regional networks. Table 2 and figure 2 summarize the geographic loca-

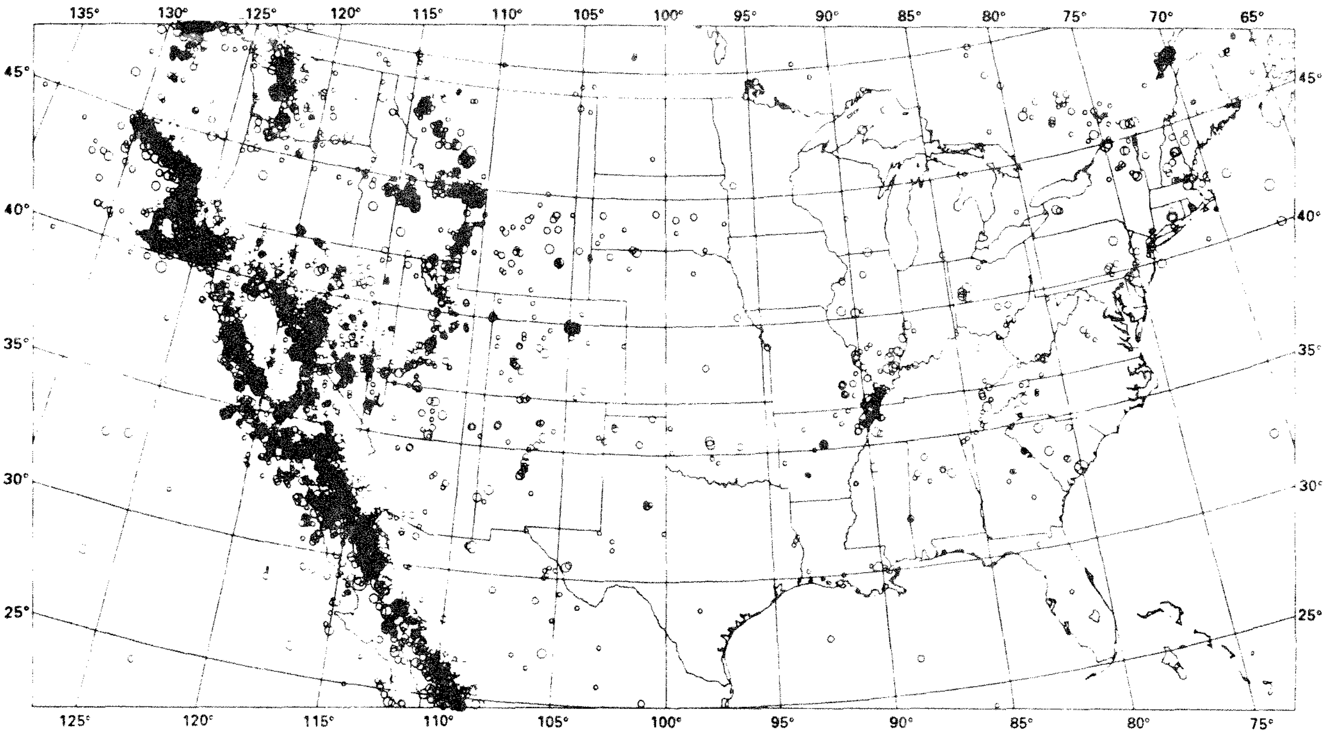


Figure 1. Seismicity within contiguous United States. All historical earthquakes with shaking intensity of at least VII (*M* approx 5.5), all earthquakes of magnitude of at least 5.0 since 1925, all earthquakes of at least magnitude 4.0 since 1962, and all earthquakes of at least magnitude 3.5 since 1975 are plotted (largest to smallest circles, respectively) (courtesy of E.R. Engdahl).

tion and operating organization for the largest of these regional networks (compiled from Simpson and Ellsworth, 1985). There is great diversity in the size of these networks, in the volume of data that is processed, in the nature of the operating facility, and in the funding sources. Although there are some notable exceptions, most of the stations consist of short-period vertical seismometers whose analog signals are continuously telemetered via voice-grade frequency-modulated (FM) telephone or radio links to a central recording site. In most instances, the incoming signals are digitized (typically at 100 samples per second) and processed on minicomputers. Although processing hardware and software varies considerably, all of the processing systems are designed to record only when several stations simultaneously detect signals above a threshold. Detected events are then analyzed to pick the times of seismic arrivals, locate the source of the seismic energy, and then catalog and archive the data on magnetic tape. The number of earthquakes recorded by these networks varies from less than 100 per year in much of the Eastern United States to more than 15,000 per year for the large California networks. Since the primary mission of regional networks is to monitor regional earthquake activity, many regional networks do not attempt to consistently record signals from distant earthquakes (teleseisms), although *P*-waves from larger teleseisms often trigger event detectors and are hence well recorded. Stations in the regional networks of California are shown in figure 3, and a compilation of earthquakes located with these networks for the period 1980 through 1986 is shown in figure 4 (D.P. Hill, written commun., 1987).

Uses of Current Regional Networks

Regional seismic networks are a fundamental multipurpose tool of observational seismology. Although commonly perceived as simply a tool for earthquake "surveillance" or "monitoring," existing seismic networks provide data and information for a host of uses:

–Public safety and emergency management
–Quantification of hazards and risk associated with both natural and human-triggered earthquakes
–Surveillance of underground nuclear explosion
–Investigation of earthquake mechanics and dynamics
–Investigation of seismic wave propagation
–Investigation of seismotectonic processes
–Earthquake forecasting and prediction research
–Probing the internal structure of the Earth

Importantly, seismic networks are also key facilities for the graduate education and training of this country's professional seismologists, and they provide direct outlets for public information and for expert assistance to public policy makers, planners, designers, and safety officials.

Table 2. Existing U.S. regional seismic networks

Network		Number of Stations
Northeastern U.S. seismic networks		
Lamont Doherty (Columbia University)		27
Weston Observatory (Boston College)		29
Woodward Clyde Consultants		42
Others		25
	Total	123
Southeastern U.S. seismic networks		
Center for Earthquake Research (Memphis State University)		30
Georgia Institute of Technology		17
University of South Carolina (also USGS)		22
Virginia Tech		17
Tennessee Valley Authority		18
Others		40
	Total	144
Central U.S. seismic networks		
St. Louis University		37
Oklahoma Geophysical Observatory		12
University of Michigan		15
Others		14
	Total	78
Great Basin, Intermountain, and Rocky Mountain networks		
University of Utah		75
University of Nevada, Reno		65
U.S. Geological Survey Southern Nevada (Denver, CO)		55
Others		65
	Total	260
California seismic networks		
USGS Central and Northern Calif.		360
USGS - California Institute of Tech. Southern Calif.		240
University of California, Berkeley		20
University of Southern California		30
Others		75
	Total	725
Northwestern U.S. seismic networks		
University of Washington—USGS Network		110
North American Rockwell		30
	Total	140
Alaskan seismic networks		
U.S. Geological Survey (Menlo Park, CA)		64
University of Alaska		36
Lamont Doherty (Columbia University)		20
Alaska Tsunami Warning Center		16
CIRIES (Boulder, CO)		11
	Total	147
Hawaii seismic networks		
Hawaiian Volcano Observatory (USGS)		60
Pacific Tsunami Warning Center (NOAA)		10
	Total	70
Approximate total number of stations in U.S. regional networks		1,600

Hanks (1985, 1987) published two informative summaries that reflect, in considerable part, the broad scope of current network seismology (see also Simpson and Ellsworth, 1985). They deal respectively with (1) the current scientific status of earthquake-related studies under the National Earthquake Hazards Reduction Program, and (2) seismology in the period 1983–1986. We elaborate on some of the uses of current seismic networks in the following two subsections, broadly labeled "Earthquake physics and hazard analysis" and "Structure of the Earth."

Earthquake Physics and Hazard Analysis

The majority of existing seismic networks in the United States relate fundamentally to understanding and mitigating the danger of damaging earthquakes. This involves anything and everything amenable to seismological observation—from the mechanics and dynamics of an earthquake source to the ground motions produced at any site from transmitted seismic waves. Describing the "anything and everything" that network seismologists investigate is beyond our scope. However, one way to outline much of that body of effort is to consider the aspects of a modern earthquake hazard analysis. Numerous interrelated pieces of information from network seismology become involved in the process.

To begin with, an earthquake hazard is a physical phenomenon with potentially adverse effects associated with an earthquake—for example, ground shaking, ground failure, surface faulting, tectonic deformation, inundation. In a rigorous seismic hazard analysis (for example, Electric Power Research Institute, 1987; Savy and others, 1986), quantitative models of earthquake behavior and effects are specified so that the level of hazard, such as the likely non-exceedance value of ground motion, can be computed for one or more sites for some exposure time, usually using a probabilistic approach.

The flowchart shown in figure 5 outlines the basic elements of a seismic hazard analysis for the hazard of ground motion. The sequence of necessary procedures is shown by steps 1 through 5 in the left-hand column; interrelated aspects of observational seismology are shown in the right-hand column.

Earthquake catalogs (step 1, fig. 5) are a basic starting point of earthquake seismology. Although the historical earthquake record is approximately 400 and 150 years in the Eastern and Western United States, respectively, good instrumental monitoring in many regions dates from only the 1970's (Simpson and Ellsworth, 1985). At a time when studies of prehistoric earthquakes attract attention (for example Allen, 1986), it seems worth emphasizing that earthquake catalogs are essential for estimating seismic hazard for earthquakes below the threshold of surface faulting (for example, the 2 May 1983 M 6.5 Coalinga earthquake or the 1 October 1987 M 5.9 Whittier Narrows earthquake). Along the Wasatch Front, Utah, such earthquakes (M 6.0–6.5) are the largest contributor to probabilistic ground shaking hazard for exposure periods of 50 years or less (Arabasz and others, 1987). In the central and Eastern United States, historical surface ruptures are virtually absent and information on prehis-

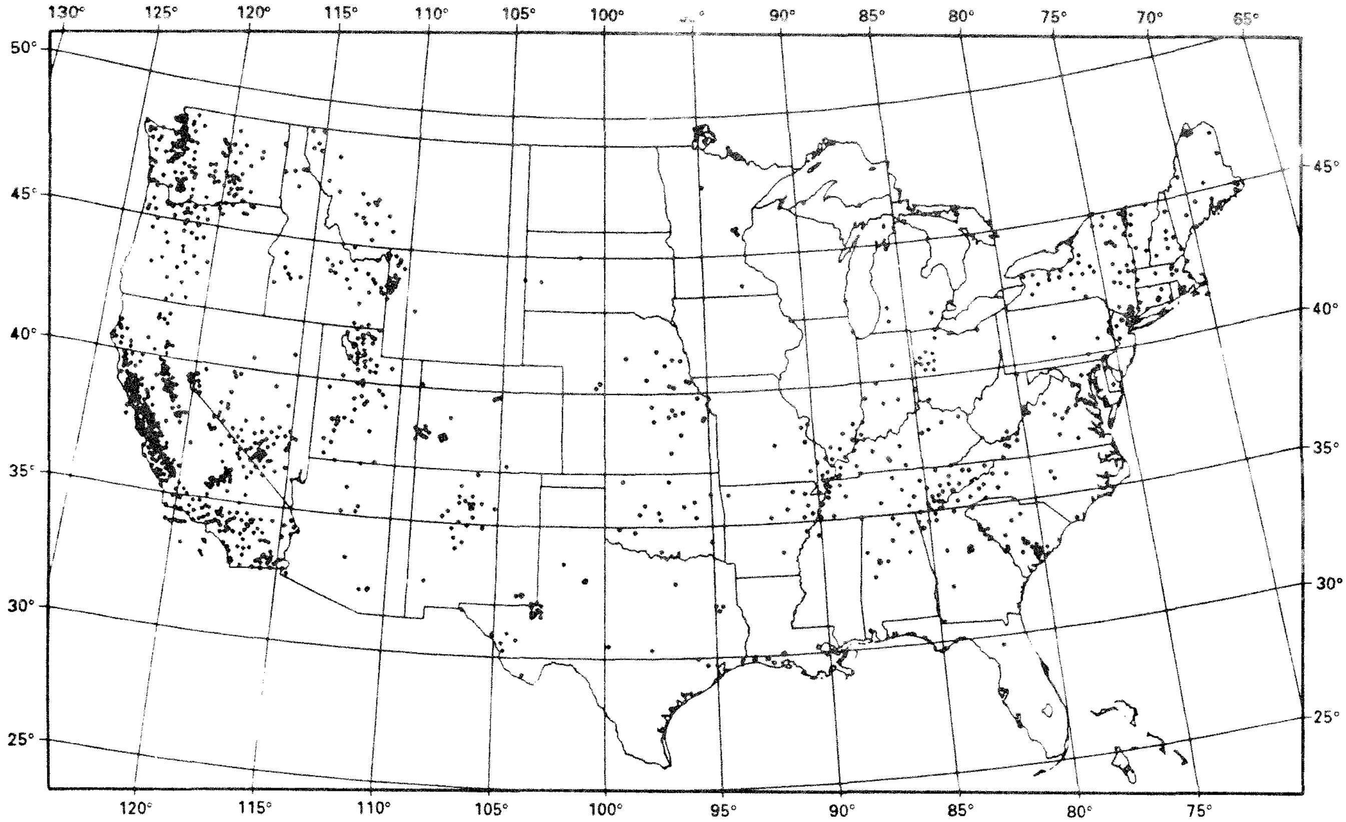


Figure 2. Seismograph stations operated by regional networks in the contiguous United States (map prepared by the National Earthquake Information Center). This compilation reflects station locations in the early 1980's, and although the current configuration of regional networks is similar, there are discrepancies between this map and the configuration of regional networks in 1988. A listing of the operators of regional networks is given in table 2.

toric earthquakes is sparse. Therefore, the historical and instrumental earthquake record is of great importance in assessing the potential sources of future earthquakes. In regions away from the active plate boundaries of western North America, the numbers of total earthquakes for any time period are significantly fewer than near the boundary. In the seismic regions interior to the plate, modern instrumental data become particularly important in the statistical processing of earthquake catalogs to estimate reliable seismicity parameters (step 4, fig. 5; see Veneziano and Van Dyck, 1986).

The characterization of seismotectonic framework (step 2, fig. 5) encompasses extensive efforts of network seismologists and gets to the heart of understanding earthquake behavior in diverse tectonic regions. The definition and geometric depiction of seismic source zones (step 3, fig. 5) is intimately related. Precise mechanisms and associated source parameters, stress state and strain rate, models for crustal structure, the location and geometry of active faults, and the fault mechanics and operative tectonic processes within a given region must all be investigated. We refer the reader to Allen (1986) and Hill (1987) for more comprehensive review papers.

Increasingly elegant techniques have become available to network seismologists for seismotectonic studies. Four examples (and representative citations) are: (1) cross-spectral analysis of waveforms for high-resolution earthquake locations (Pechmann and Kanamori, 1982; Ito, 1985); (2) inversion of focal mechanisms to obtain the stress field (Angelier, 1987; Michael, 1987); (3) determination of rupture characteristics of earthquakes from ground-motion data using the waveforms of adjacent small earthquakes as empirical Green's functions (O'Neill, 1984; Frankel and others, 1986), and (4) the mapping of seismic slip distributions on a single fault plane to investigate details of the earthquake generation process (Bakun and others, 1986). Despite such advances, there emphatically remain first-order problems throughout much of the United States in associating observed seismicity with specific geologic structures—and in confidently identifying the sources of future moderate-to-large earthquakes. Examples in the Pacific Northwest, the intermountain west, and eastern North America (including the problematic source of the 1886 Charleston, South Carolina, earthquake) were reviewed by Hill (1987).

Earthquake physics, based on network observations, becomes an important part of the modeling of ground-shaking hazard (step 5, fig. 5) in the specification of the source spectrum, its scaling with earthquake size, and effects on wave propagation and attenuation. Earthquake physics also governs

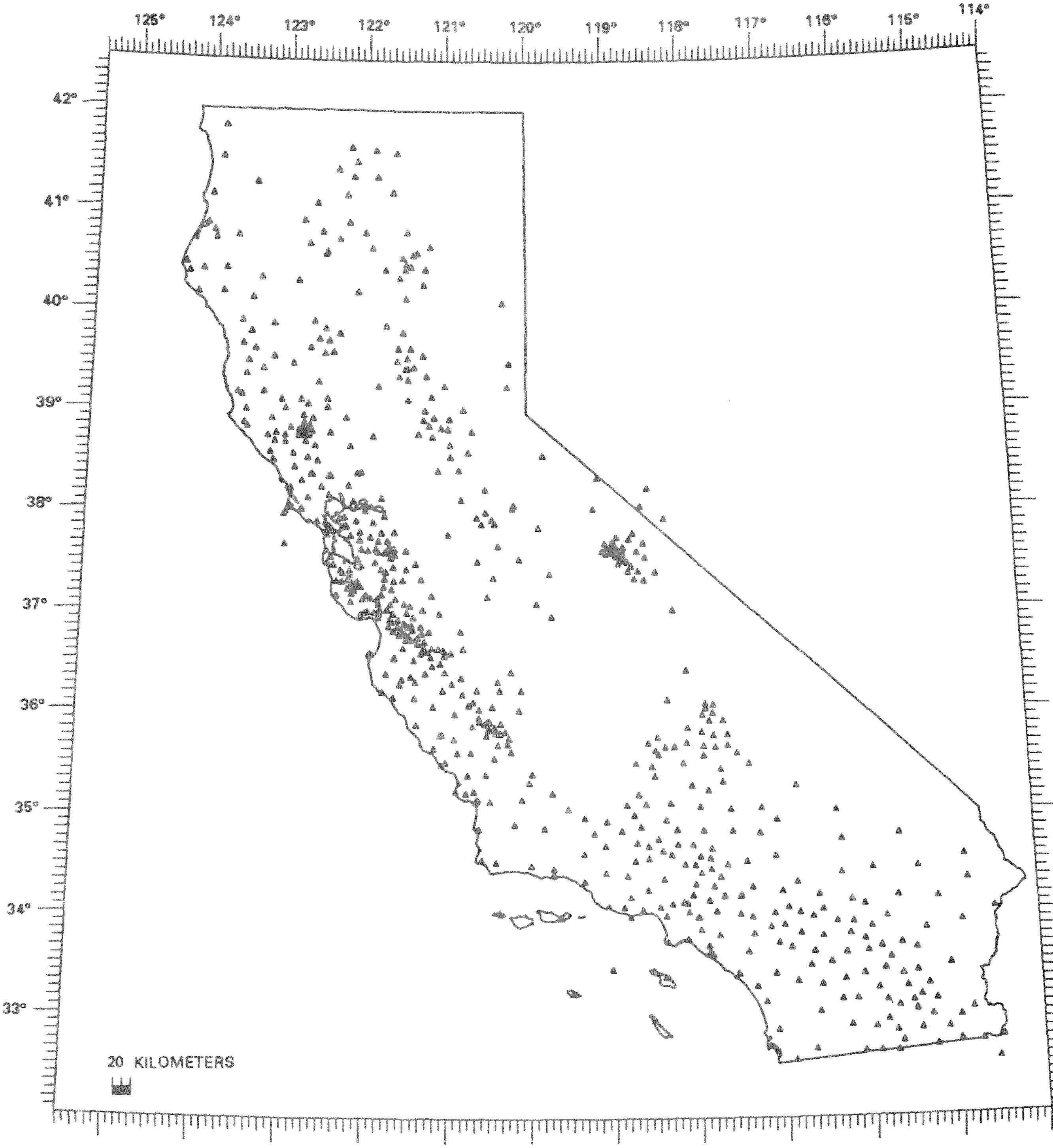


Figure 3. Major California regional network stations.

the assessment of maximum magnitude (step 4, fig. 5), although empirical approaches are more generally adopted. An important part of the hazard analysis is the recurrence modeling (step 4, fig. 5), which involves specifying time and size distributions of earthquakes for the identified seismic source zones. The so-called Poisson-exponential model is commonly assumed in which earthquake occurrences are postulated to follow a memoryless Poisson process in time and a truncated exponential distribution in size. The associated parameters depend fundamentally upon earthquake catalogs. If the place and time of an earthquake can be predicted, however, probabilistic estimates of hazard become drastically altered.

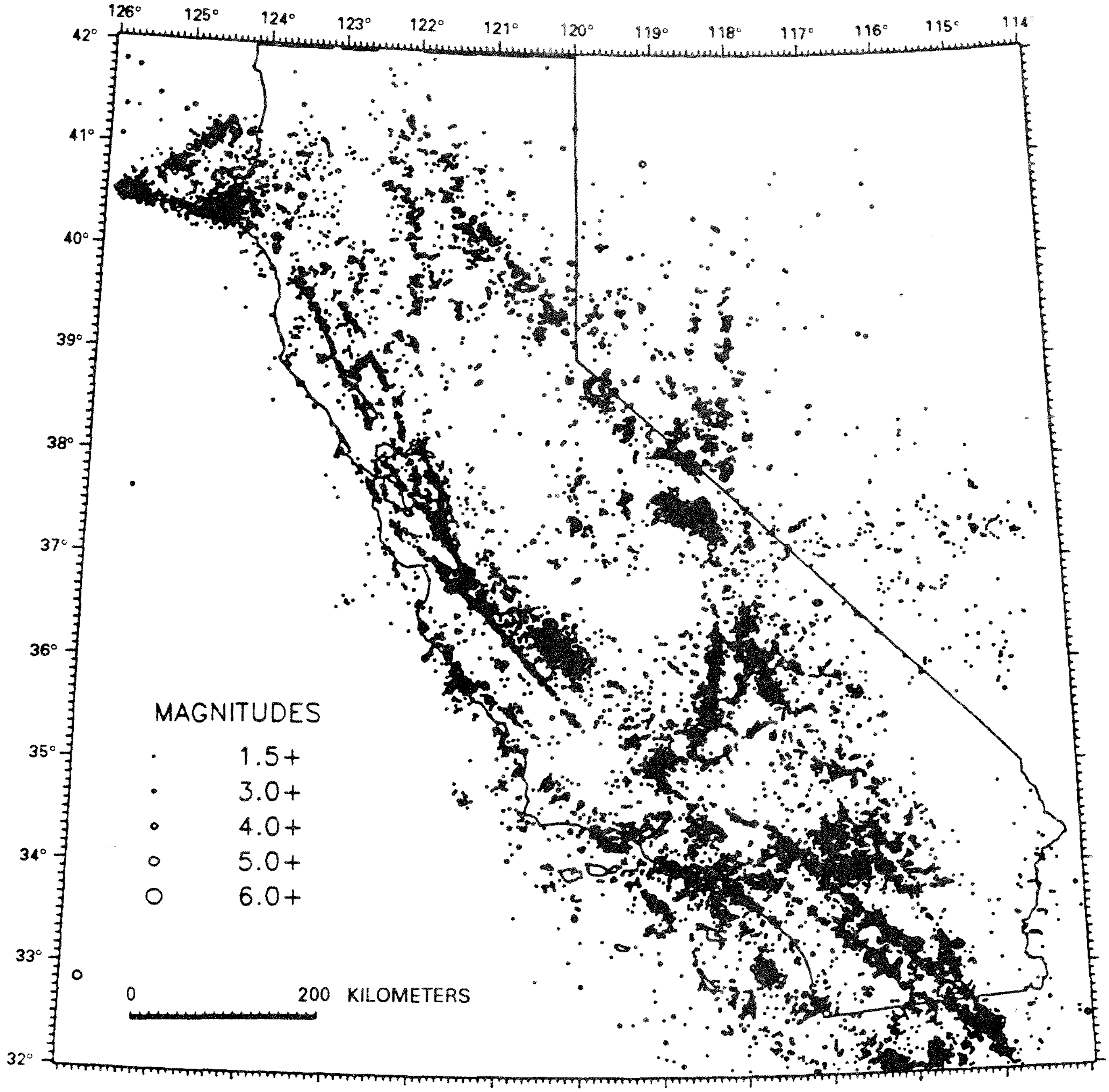


Figure 4. Seismicity throughout California and western Nevada for the period 1980–1986 (D.P. Hill, written commun., 1987).

Bakun (1987) provided a perspective on the current status of progress toward earthquake prediction, including description of a specific prediction by the U.S. Geological Survey (USGS) for the occurrence of a characteristic magnitude 6 earthquake on the Parkfield section of the San Andreas fault in 1988±5 years. Patterns of earthquake occurrence documented from global, regional, and local earthquake monitoring provide viable approaches (with different degrees of general acceptance) for a probabilistic approach to earthquake prediction on different time scales. These include (1) recognition of seismic gaps along plate boundaries, (2) the seismic quiescence hypothesis that proposes a decrease in seismicity before some larger earthquakes, (3) repetition of similar or characteristic earthquakes along definable fault segments, and (4) recognizable slip deficits along parts of well-monitored, seismically active faults.

Recently, an integrated assessment of the probability of occurrence of major earthquakes along the San Andreas fault during the next 30 years (fig. 6) was released by the USGS-sponsored Working Group on California Earthquake Probabilities (1988). The potential for future damaging earthquakes on each segment of the fault was derived through

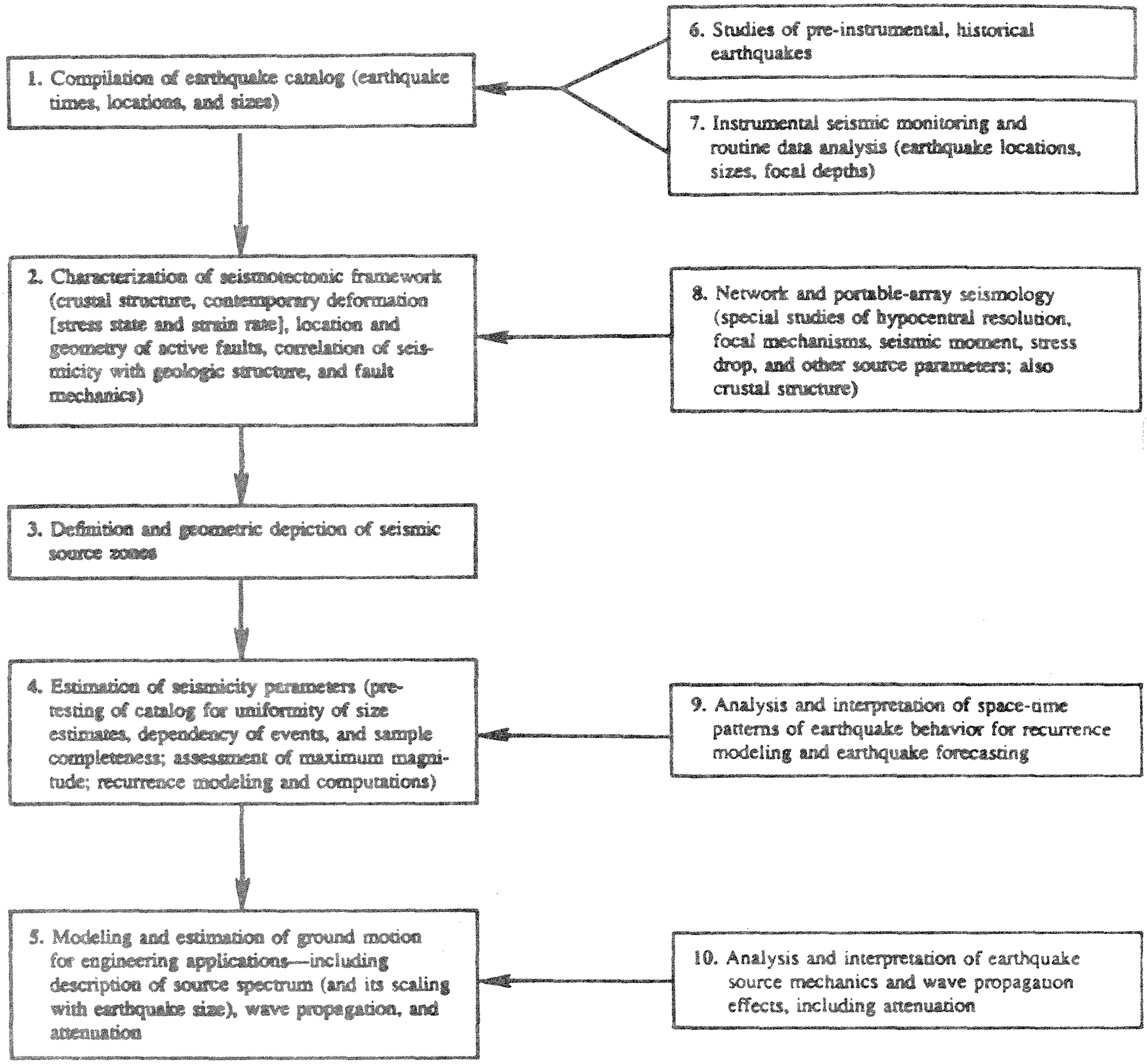


Figure 5. Steps in a formalized hazard analysis (left column) and interrelated aspects of observational seismology (right column). This example (from Arabasz and others, 1987) is for the Wasatch Front, Utah, region; a similar flowchart for California would involve more elaborate elements in the right column.

the synthesis of instrumental and historical seismic records, geologic studies of prehistoric events, and geodesy through the application of the same probabilistic approach employed at Parkfield and supported by worldwide observations (Nishenko and Buland, 1987). The report identifies the southern third of the San Andreas fault, including segments posing the highest risk to the major metropolitan regions of southern California, as having an aggregate probability of 60 percent for a M 7.5 to 8 earthquake by the year 2018. Just as the regional seismic data base has already played a critical role in defining the hazard, it has the potential to significantly reduce the risk posed by the anticipated earthquakes (see later discussion on applications of seismic networks).

Structure of the Earth

Since the 1960's there have been many applications of seismic arrays for analysis of detailed Earth structure. The principal advantages offered by an array are (1) that dense station distribution allows for direct measurement of the azimuths of approaching wavefronts and slopes of travel time curves, $dt/d\Delta$, which are directly used in earthquake locations

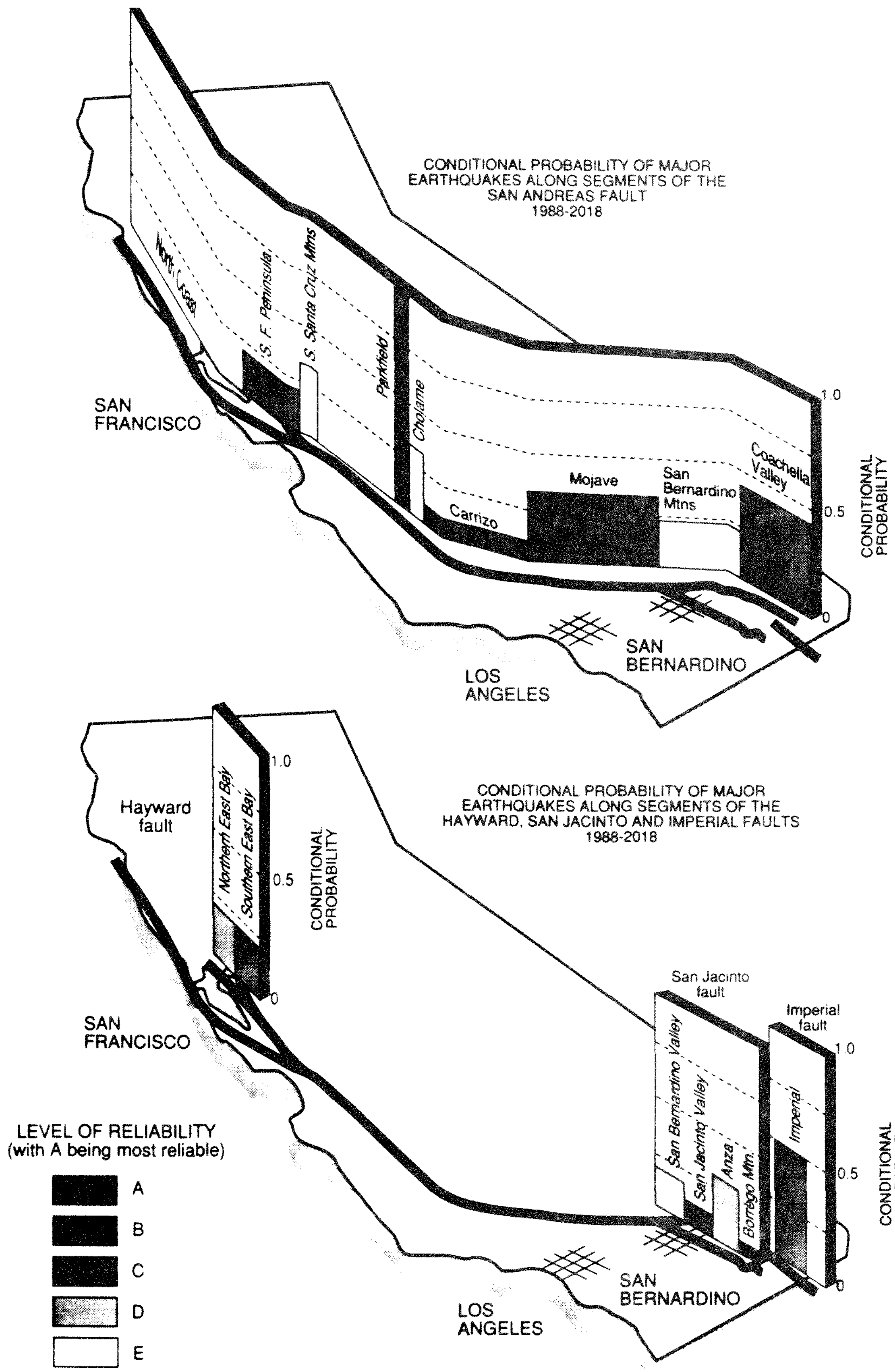


Figure 6. Conditional probabilities of the occurrence of major earthquakes on the San Andreas, Imperial, San Jacinto, and Hayward fault systems for the 30-year period from 1988 to 2018 (Working Group on California Earthquake Probabilities, 1988)

and earth structure inversions, and (2) that signal-to-noise enhancement can be achieved by stacking closely spaced observations. Many specialized arrays such as LASA and NORSAR have been deployed with regular geometries and standardized instrumentation; however, regional networks have proved equally useful as large "arrays" despite their irregular geometries and variable instrumentation.

Array diagrams for regional networks and arrays (fig. 7) are a way to indicate earthquake location capabilities of each array relative to a global network of stations (Powell, 1976). The CIT regional network (Southern California Seismic Network) shows remarkably small mislocation vectors, which is a consequence of its large aperture and high station density. Systematic analysis of the regional mislocation vectors has been adapted to a variety of studies, including analysis of mantle velocity heterogeneity near the earthquake source, deep in the mantle, and in the upper mantle and crust beneath the regional network. The data are acquired in a passive mode as the regional networks are operating to accomplish their regional monitoring functions, but many additional array processing capabilities can potentially be implemented for regional networks. Examples would include routine beam forming for enhanced detection of seismicity in global seismic gaps, aftershock zones, or nuclear test sites. Such applications have been sparse largely due to limitations imposed by cumbersome data management systems and by the limited frequency bandwidth and dynamic range of existing regional networks.

The dense spatial coverage provided by regional networks has been directly exploited in many studies of crustal velocity structure to map the crust at geologically meaningful scales. In one example of detailed imaging of lateral variations in shallow crustal velocity structure (Hearn and Clayton, 1986a), obtained by use of stations and local seismicity in southern California (fig. 8), the crustal velocity variations are strongly associated with surface tectonic features such as the San Andreas fault. Similar analysis of lateral variations in uppermost mantle structure based on the P_n phase also reveals striking spatial heterogeneity, as shown in figure 9 (Hearn and Clayton, 1986b). Given that regional seismic networks are intrinsically located in interesting tectonic environments (for example, similar models have been obtained using regional networks near New Madrid, Missouri, and Puget Sound, Washington), it is always of interest to obtain such detailed crustal models in order to understand the underlying physical processes causing the seismic activity. The data for such analysis are a direct by-product of the seismic monitoring function of networks.

In addition to using local earthquakes to investigate shallow crustal structure, regional networks accumulate teleseismic travel times and waveforms that allow deeper mantle structure to be studied. A spectacular example is seen in figure 10 (Humphreys and others, 1984), showing a high-velocity tabular root that extends several hundred kilometers into the mantle beneath the Transverse Ranges of southern California. New sophisticated tomographic inversion techniques have been developed to reliably resolve such structure from regional network data, and practical experience has shown that upper mantle heterogeneity is ubiquitous. This has many implications for the dynamics and chemical evolution of the crust and upper mantle. Regional network data have been used to produce three-dimensional images of velocity structure beneath southern California, northern California, New England, Washington, and the New Madrid seismic zone.

Accurate measurements of travel times and wave slowness by regional networks have played a major role in improving our detailed knowledge of upper and lower mantle radial and lateral variations. Figure 11 (Walck, 1984) shows the high resolution of travel time and ray-parameter measurements that can be attained using regional network data (in this case from the Southern California Seismic Network). The critical identification of secondary arrivals is abetted by the dense station distribution, as shown in figure 12, where data from several events are combined to develop a profile for the ray paths beneath the Gulf of California (Walck, 1984).

Current Strong-Motion Instrumentation

The term "strong motion" is used in the engineering and seismological communities to mean ground motions that are sufficiently large to be capable of causing damage, and "strong-motion instruments" are seismographs (usually accelerometers) that can record these large motions without overdriving the seismograph. Presently, a large number of Federal, State, and local governmental agencies, corporations, public utilities, and universities operate and maintain about 3,000 strong-motion instruments in the United States (National Research Council, 1987; table 3, figures 13 and 14). Each organization installs instruments to satisfy its own particular needs, and about 40 percent of the instruments are private and yield data not available for research. In general, the primary goal of the instrumentation is to gather data for engineering purposes. The majority of these instruments are installed within or on structures ranging in size from one-story fire stations, schools, and post offices to high-rise buildings, dams, bridges, storage tanks, and power plants. Few of these instruments are installed in free-field or ground sites, which typically consist of an accelerograph housed within a small fiberglass hut resting upon a concrete pad 1 meter square.

Although some digital accelerographs have been installed within the last few years, the vast majority of strong-motion instruments are analog and record their signals on moving photographic film. For a large structure in which many acceleration sensors are deployed throughout the structure, the signals from all sensors are conveyed to a central multichannel recorder that records all channels simultaneously on photographic film. For smaller structures and for free-field sites, the most commonly used accelerograph is a self-contained unit that records three orthogonal components of ac-

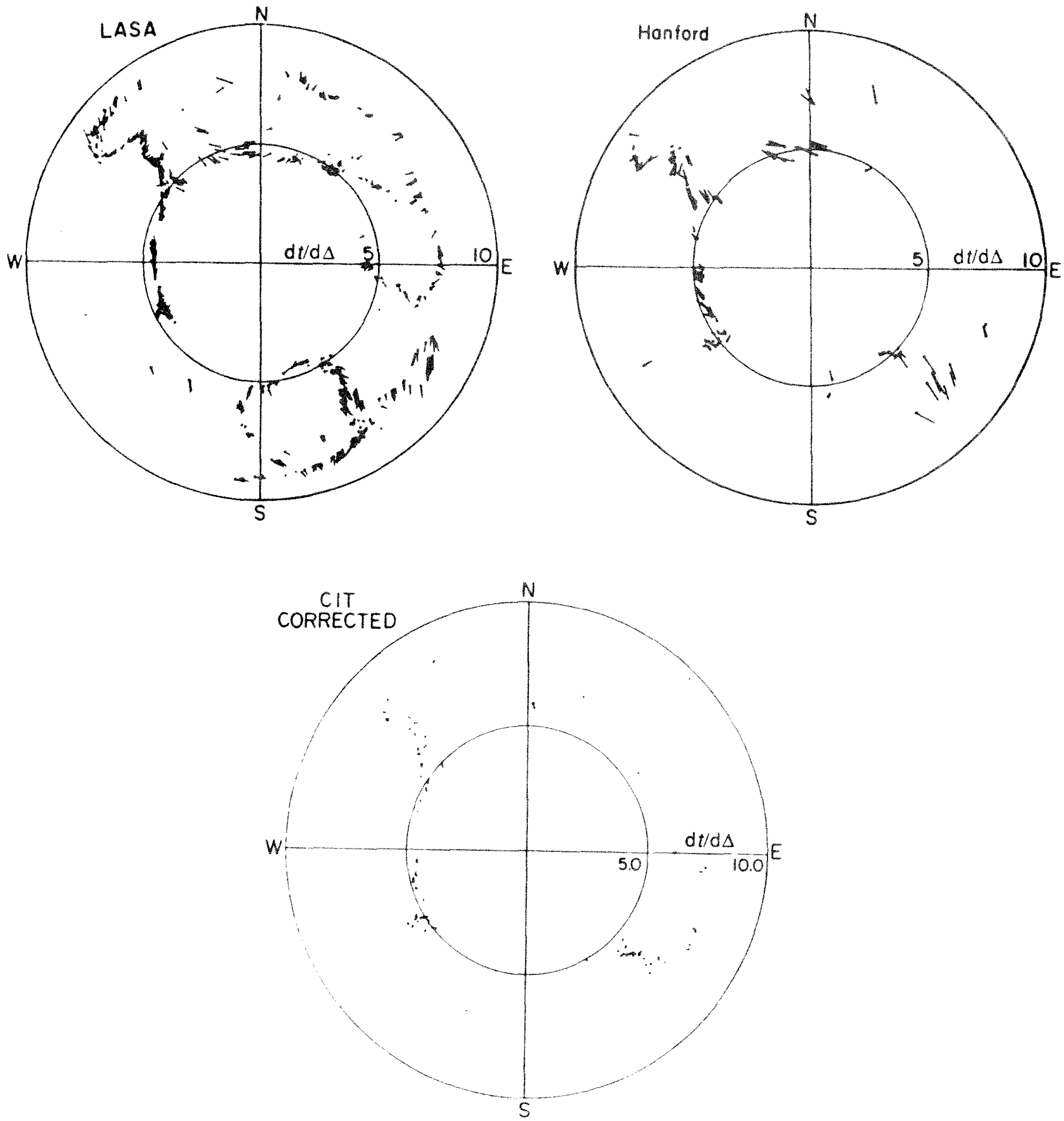


Figure 7. Mislocation vectors from Large Aperture Seismic Array (LASA) in Montana (discontinued in the 1970's), regional network in eastern Washington (Hanford), and southern California (CIT) regional network. Tail of each vector represents azimuth and incidence angle of a planar *P* wave from a teleseismic earthquake as observed at these networks, and the head represents azimuth and incidence angles expected from known locations of earthquakes and standard earth model (Powell, 1976). Apparent velocity, d*t*/dΔ, in seconds per degree.

celeration on a 70-mm photographic film strip. All of these accelerograph systems are "triggered" units, which sit dormant until detecting a ground acceleration that exceeds a preset threshold (usually 0.01 *g* on the vertical component). Once the threshold is exceeded, there is a short interval (about 0.1 s) during which the instrument's film transport accelerates to its desired operating speed. Because of the triggering and the delay of the film transport, these accelerographs cannot record the initial *P*-wave motions of the earthquake or any pre-event ground noise. In addition, many of these instruments have no external time reference, so that absolute wave arrival times cannot be determined, and in cases of multiple

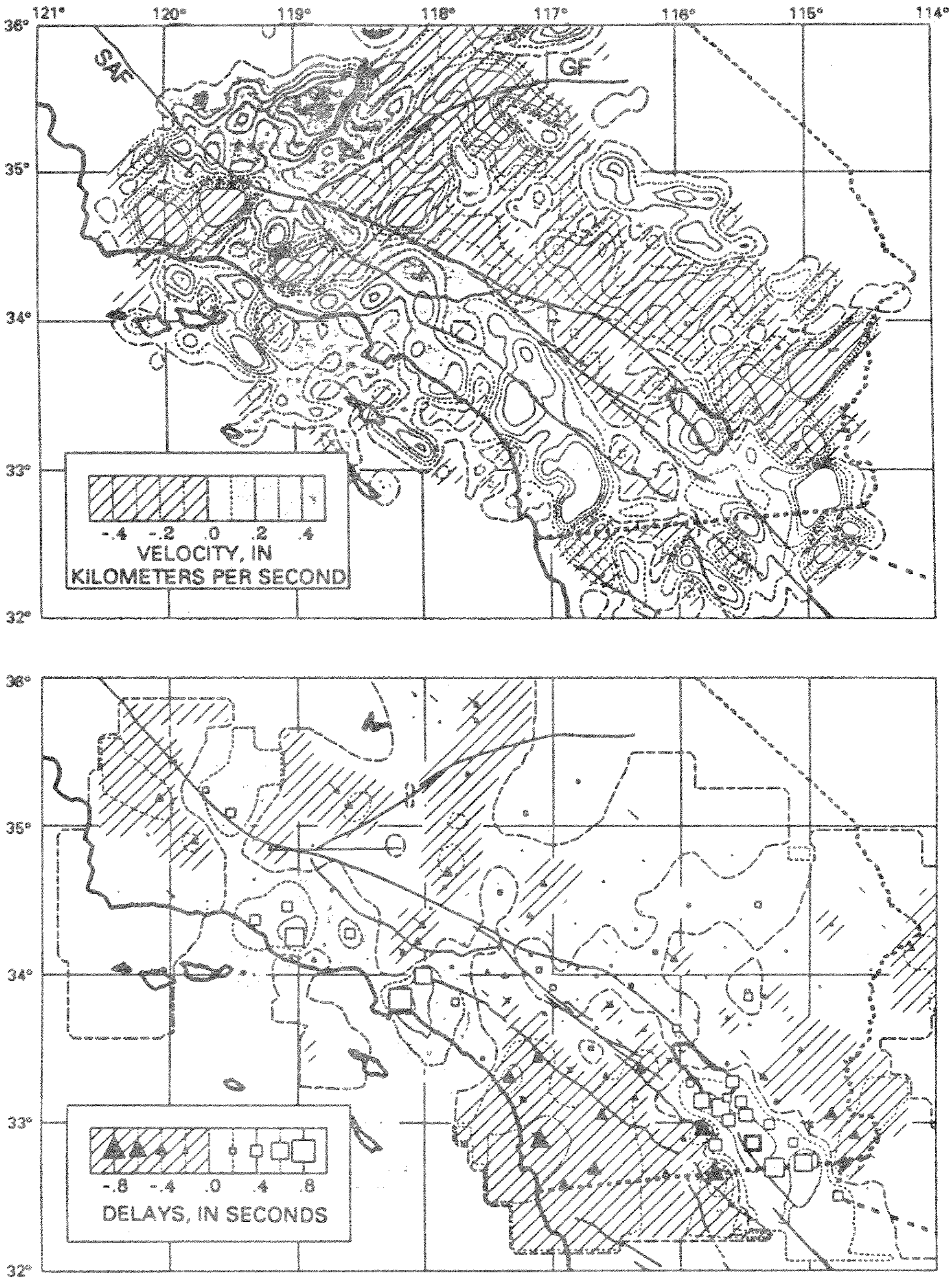


Figure 8. P_g velocity variation (top map) in southern California as inferred from tomographic inversion of P_g-wave travel times from local earthquakes recorded on the Southern California Seismic Network. P_g velocities are representative of the average crustal *P*-wave velocity. Hachured region indicates relatively low velocities and shaded regions are relatively fast. A strong correlation between P_g velocities and major geologic discontinuities such as the San Andreas fault (SAF) and Garlock fault (GF) can be seen. Station delays (bottom map) for corresponding study. Hachured areas show regions of early arrivals. Late arrivals (shaded areas) are associated with Los Angeles and Ventura basins and Salton trough (Hearn and Clayton, 1986a).

earthquakes (such as aftershocks) the lack of an external time reference prevents unambiguous identification of a recorded event. Because a rather strong signal (0.01 *g*) is required to trigger these accelerographs, these instruments detect relatively few events; they are usually only triggered by very local events of about *M* 4.5 or larger, or by larger more distant events. In many cases a strong-motion instrument will trigger on only the main event of a sequence.

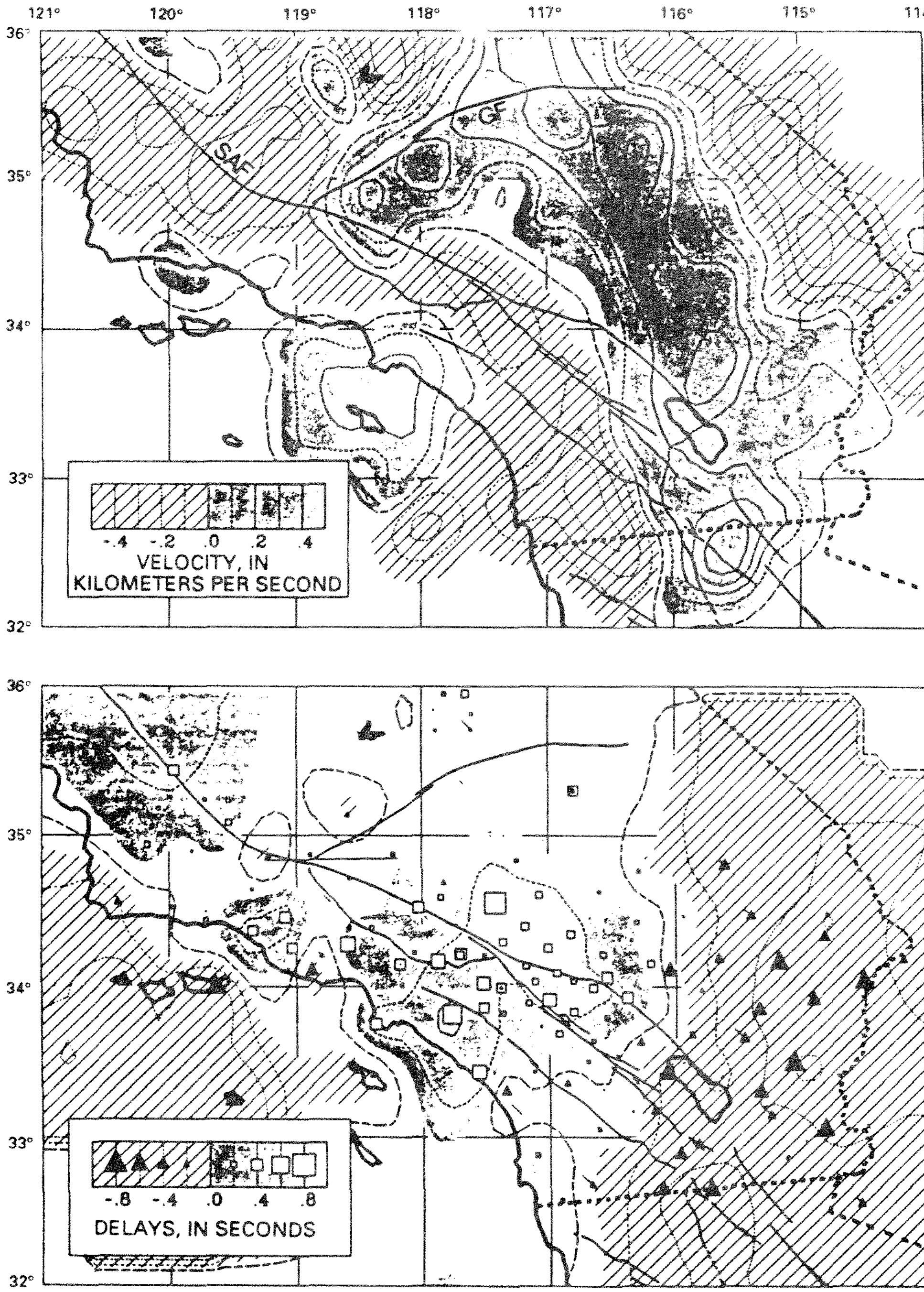


Figure 9. P_n velocity variation (top map) in southern California as inferred from tomographic inversion of P_n-wave travel times from earthquakes recorded on Southern California Seismic Network. P_n velocities representative of uppermost mantle beneath southern California. Hachured regions indicate relatively low velocities; shaded regions are relatively fast. P_n velocities are generally higher on North American plate, east of San Andreas fault (SAF), than on Pacific plate, west of San Andreas fault. Contour plot (bottom map) shows station delays. Hachured areas indicate regions of relatively early arrivals. Largest delays (shaded areas) are associated with sedimentary basins, and early arrivals are associated with thin crust (Hearn and Clayton, 1986b). GF, Garlock fault.

Most accelerograms recorded on photographic film are processed using a fairly standard procedure. The first step is the decision of which recordings are sufficiently interesting from an engineering standpoint to merit digitization; generally only those recordings having accelerations larger than 0.05 *g* are digitized. Thus, the detection threshold for digitized data is around *M* 5. The digitization is performed by an automated trace-following system supplemented by hand digitization of

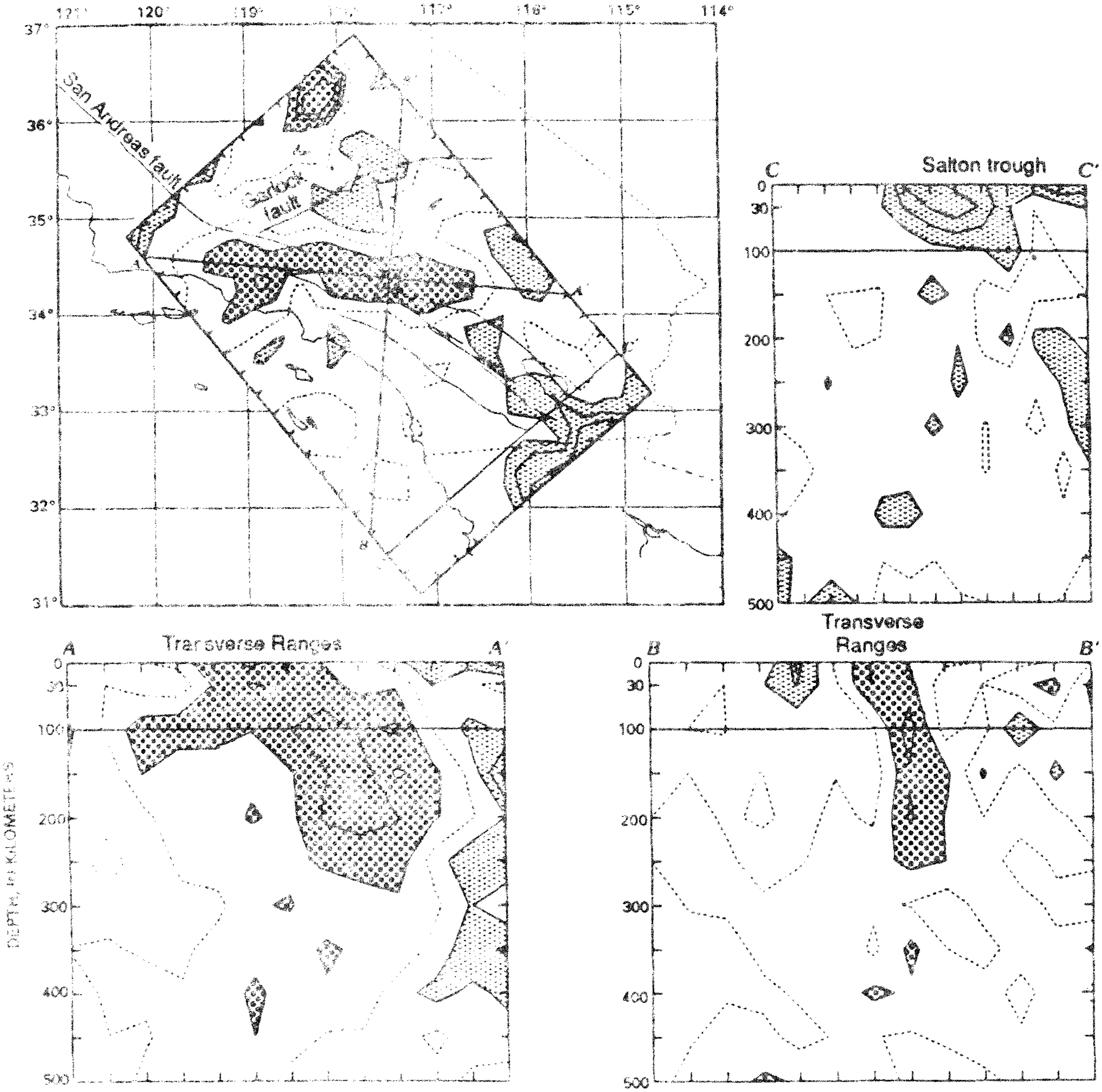


Figure 10. Three-dimensional upper-mantle P-wave velocity structure beneath southern California as inferred from tomographic inversion of teleseismic P delays derived from Southern California Seismic Network. In upper left panel, horizontal section at depth of 100 km is superimposed on location map of southern California. Locations are shown for three cross sections (A-A', B-B', C-C') displayed in other panels. Vertical and horizontal scales are identical. Contour interval is 1.5 percent velocity variations, with high-velocity regions indicated by dotted areas, and low-velocity regions indicated by chevron pattern. Zero contour is dashed. East-west-trending, tabular, high-velocity region beneath Transverse Ranges can be seen in cross sections A-A' and B-B'. This slab of high-velocty material may represent downwelling in mantle beneath Transverse Ranges. Cross section C-C' perpendicular to Salton trough, reveals region of velocities that are 2 to 4 percent slow at depths extending to 100 km beneath this region of crustal extension (Humphreys and others, 1984).

portions of the record where accelerations are large and the automated system cannot follow the traces properly. The digital acceleration data are then corrected for the instrument response and integrated to yield ground velocity and ground displacement records. The effective bandwidth of the data is from about 0.1 or 0.2 Hz at low frequencies to about 25 to 50 Hz at high frequencies. The bandwidth is much less broad for small events due to the large amount of noise introduced into the data during digitization. The effective dynamic range of these systems is about 60 dB.

Limitations of Existing Networks

The development of the current generation of regional networks within the United States began in the 1960's in response to the need to learn more about the distribution of seismicity within regions of recognized earthquake hazards. The most basic questions (such as, "Do earthquakes occur along recognizable fault planes?") had no answers at that time. Consequently, observational seismology was in a position to make rapid progress by adapting well-established seismological techniques of earthquake location and magnitude determination to local and regional scale problems. By the early 1970's the design characteristics of the network systems were largely established. These now-antiquated technologies have continued to operate into the 1980's with only modest upgrading of their data analysis capabilities and without any improvements in the resulting data.

The characteristics of existing regional seismic and strong-motion networks have been very strongly influenced by the objectives attainable with then available technology. In the case of regional seismic networks, the primary objective has been the construction of a high spatial resolution catalog of earthquake activity within each network. It has thus been imperative to obtain numerous *P*-wave arrival times for as many earthquakes as can practically be observed. Economic considerations dictated the recording of high-frequency, vertical-component ground motions from many sites.

The actual ground motion history has largely been sacrificed in this mission. Because of the need for high sample rates, the only practical solution in the past has been to continuously telemeter analog data streams. Furthermore, the required high sample rates have made it difficult to store digital records from long-duration records such as those expected from teleseisms. The use of analog FM data telemetry has severely restricted the dynamic range (typically 40 dB) of the seismic systems. Because the mission calls for the monitoring of small earthquake activity, gains are typically set high enough to resolve earth noise. Consequently, the signals are off scale for most of the significant earthquakes. Furthermore, small earthquakes are best detected and timed using high-frequency ground motions. Since there is typically high ground noise at periods near 6 seconds, there has been a conscious effort to record only frequencies higher than about 1 Hz. The effective dynamic range of typical existing networks compared with expected seismic signals is shown in figure 15. Clearly, much important ground-motion information is not currently recorded by the existing regional networks.

The need for continuous telemetry has also made the cost of telemetry a major consideration for the design of networks. In the present situation, the cost of telemetry increases linearly with the number of channels that are sent. The cost of telemetry, together with the limited dynamic range of the system, have largely contributed to the decision not to record horizontal components of ground motion at most sites. Unfortunately, this has led to very uncertain interpretation of shear-wave arrivals.

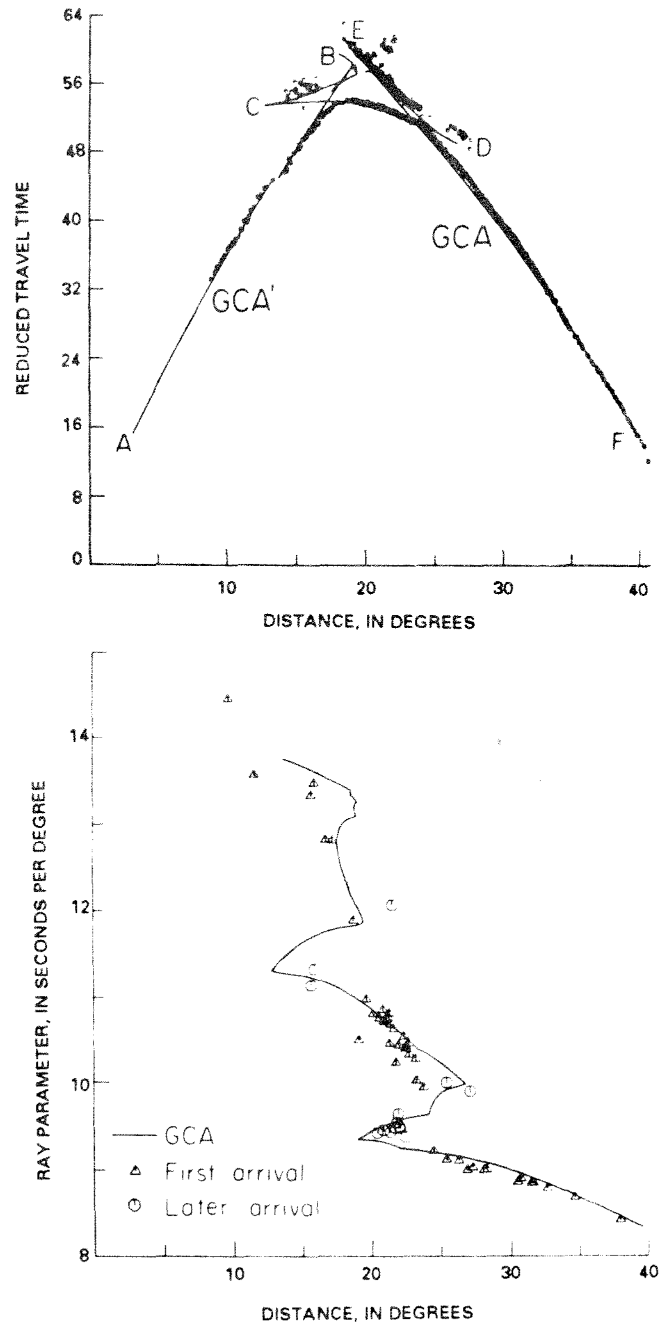


Figure 11. Reduced travel times (top plot) of *P* waves traveling in upper mantle from earthquakes located at regional distances and recorded on Southern California Seismic Network. Triplications caused by velocity discontinuities in upper mantle are easily identified (travel-time branches AB, CD, EF). Ray parameters (bottom) measured from corresponding data together with those expected for a model of upper-mantle *P*-wave velocities. See Walck (1984) for further discussion of Gulf of California region models GCA and GCA'.

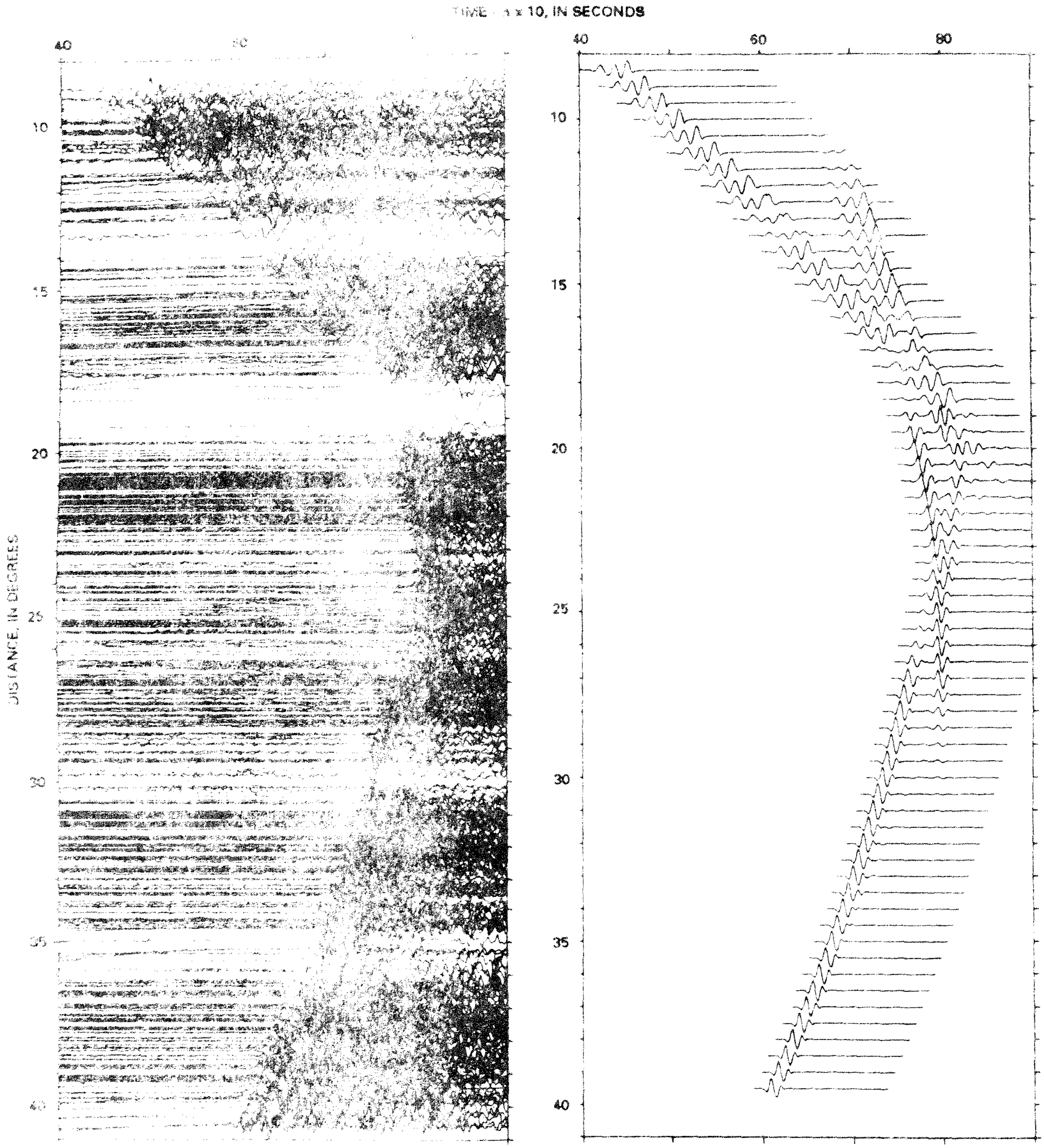


Figure 12. Data record section (left) [illegible] the P-waves from 10 earthquakes spanning the distance from 9° to 40° and recorded on the southern California Seismic Network. Mantle triplication phases are clearly visible. Synthetic record section (right) on the same scale (Walck, 1984).

Serious noise problems, including [illegible] "glitches" in telephone and radio systems [illegible] in analog FM telemetry. Furthermore, [illegible] analog signals from many stations are transmitted [illegible] pairs of wires to a single analog to digital converter (ADC). Inductive crossfeed between stations can sometimes be a serious problem that is difficult to recognize and which can lead to very serious errors in interpretation. These noise problems are

Table 3. Summary of strong-motion instrumentation efforts in the United States

Organization	*Number of instruments*
California Division of Mines and Geology	500
U.S. Army Corps of Engineers	350
U.S. Geological Survey	275
Pacific Gas and Electric Company	91
State of Washington	90
University of Southern California	81
U.S. Department of Energy	80
U.S. Bureau of Reclamation	70
U.S. Veterans Administration	65
Nuclear power plants	62
California Department of Water Resources	70
University of California, Los Angeles	36
Los Angeles Department of Water and Power	35
U.S. Navy	35
Federal Highway Administration	30
Metropolitan Water District of Southern California	30
Southern California Edison Company	26
Los Angeles Flood Control District	25
University of California, San Diego	21
International Business Machines Company	20
Columbia University	18
Stanford University	15
California Institute of Technology	15
Washington Department of Transportation	15
Idaho National Engineering Laboratory	15
Lawrence Livermore National Laboratory	15
Buildings instrumented in cities using Uniform Building Code	321
Instruments installed by various organizations	325
The City of Los Angeles requires owners of large buildings to install and maintain strong-motion instruments. This is the largest uncoordinated collection of instruments	500

not present in systems in which data are digitized at the station and then transmitted via error-detecting telemetry.

The large volume of data that must be managed in order to record many events at many stations and at high sample rates has necessitated the development of specialized computer hardware and software. Actual seismograms are stored on magnetic tapes, and it is usually an arduous task to retrieve subsets of the data for research. These high-rate data streams also make it difficult to stay current with data analysis during seismic crises, just when such analysis is most needed.

Although the monitoring of local seismic activity is a crucial one, the attainment of that goal has severely limited the usefulness of the data for many other areas of seismology. This has caused the study of regional network seismology to become intellectually isolated from other fields of seismology.

Strong-motion networks also have a relatively narrow, but very different, mission. Their primary function is to record three-component earthquake ground motions that could cause damage to facilities. They must operate on scale for shaking from relatively rare earthquakes that are large or close enough to cause damage. Continuous telemetry of these signals has been a very low priority since there are rarely any data to telemeter. Hence, it usually requires many days for strong-motion records to become available. Furthermore, since the knowledge of absolute time is of little interest to the response of an engineered structure, there is usually little information about the absolute time of seismic arrivals during strong shaking. This often considerably complicates any fundamental physical interpretation of the cause of the ground shaking.

Because of the difference in their primary missions, high-gain seismometers and strong-motion seismometers are very rarely collocated. As will be discussed later, this has several important implications: (1) Ground motions from small earthquakes are dominated by the effects of propagation through complex geologic structure. If these effects are understood from the study of recording of weak motions from small earthquakes, then they can be removed from the strong motions that occur during large earthquakes and the detailed nature of the seismic source can be ascertained. Therefore, it is difficult to separate the effects of rupture and wave propagation. (2) High-gain seismometers are rarely located in regions of intrinsically high noise, such as cities, or even basins. However, these are the areas having most inhabited structures. Important propagation effects (such as that which happened on 15 October 1985 in Mexico City) are usually not recognized until after a tragedy has occurred. (3) Perhaps the largest disadvantage of the configuration of present networks is the lack of interaction between earthquake engineers and earthquake seismologists.

CONFIGURATION OF PROPOSED DIGITAL NATIONAL SEISMIC SYSTEM

The U.S. National Seismic Network

The U.S. National Seismic Network (USNSN) is a new program being undertaken by the National Earthquake Information Center (NEIC) of the U.S. Geological Survey. Although a tentative plan has been developed to instrument the entire United States (see figure 16 for a preliminary distribution of stations), funding has only been obtained for the portion of the continental United States that is east of the Rocky Mountains as part of a joint project with the U.S. Nuclear Regulatory Commission (USNRC). The USNSN program is large and complex. The major elements are (1) the field system, (2) the telemetry system, (3) the central processing system, and (4) a data archival and distribution center.

The USNSN design goals reflect an attempt to satisfy a number of diverse requirements including national and global monitoring and research on a regional scale within the United States. However, the design goals have also been strongly influenced by known and suspected financial constraints in an attempt to ensure that the network can be completed and operated over the coming decades. Further, the design has been affected by the conscious management strategy of attempting to maximize functionality and minimize cost by the use of state-of-the-art technology without taking undue risks with emerging technologies.

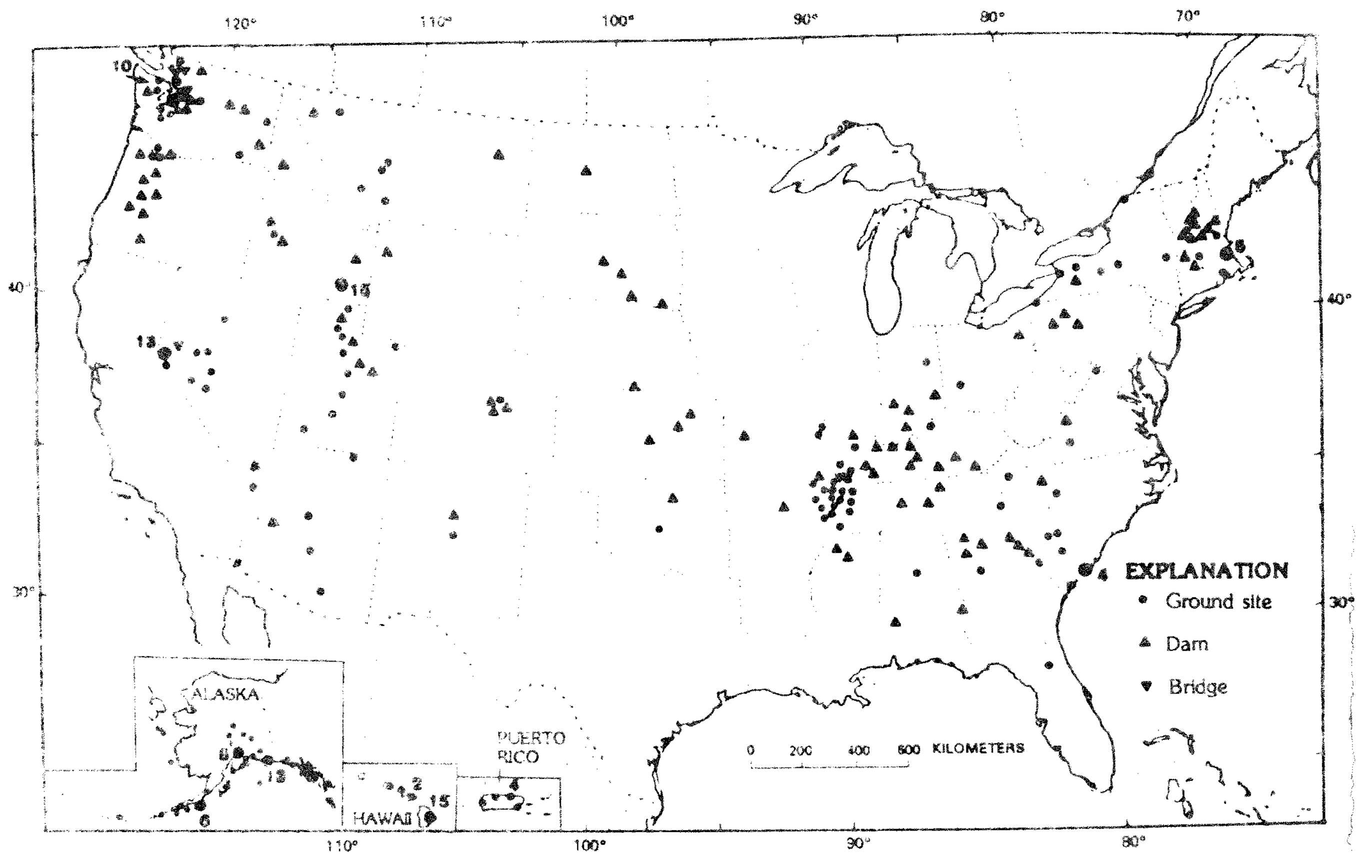


Figure 13. Known accelerographs in the United States outside of California as of April 30, 1981. Excludes commercial nuclear-powered electrical generating plants. Numbers indicate where more than one station is located.

The seismic monitoring design goals of the USNSN arise from the requirements of the National Earthquake Information Service (NEIS) Earthquake Early Alerting Service. These design goals tend to complement the capabilities of existing USGS and USNRC funded regional seismic networks that were described in previous sections. In fact, the NEIS currently depends on real-time data telemetered from a small subset of regional seismic networks for their Alert Service. The monitoring goals of the USNSN are (1) uniform coverage of the United States and (2) on-scale recording of all seismic phases of interest from all earthquakes of interest. Uniform coverage is defined as the ability to record any event of magnitude 2.5 or larger by at least five stations anywhere in the continental United States and any event of magnitude 3.5 or larger anywhere in Alaska, Hawaii, and Puerto Rico. Phases of interest for seismic monitoring are various compressional and shear wave groups within the frequency band 0.5 to 15.0 Hz and surface waves of 15 to 30 s. To be of use in Alert Service monitoring, all data must be available within several minutes of real time.

The research design goals for the USNSN can be summarized as a requirement for three-component, broad-band, high-dynamic-range data. The network should record both body waves and surface waves from local, regional, and teleseismic sources. Although data streams that are triggered and record only during the arrival of significant phases are considered to provide a practical solution to data management problems, it is important to develop sophisticated triggers to allow flexibility in the types of research problems that can be investigated with this network.

In order to meet these monitoring and research design goals with available technology, the USNSN will consist of the following components (shown diagrammatically in figure 17). The required dynamic range, linearity, and bandwidth of the seismometers dictates the use of force balance sensors. Even using state-of-the-art seismometry, the desired dynamic range will require the use of two sets of seismometers (a high-gain and a low-gain sensor for each component). In order to preserve this dynamic range, the seismometer outputs must be digitized onsite. This will be accomplished by means of state-of-the-art 24-bit (144 dB) analog to digital converters.

A station processor is required to perform the following functions: (1) acquire six channels of seismic data and up to eight channels of state-of-health data, (2) low-pass filter and decimate the six high-frequency (HF) channels to derive six broad-band (BB) channels, six long-period (LP) channels, and one short-period (SP) channel, (3) manage rotating buffers of pre-event data, (4) perform signal detection on the BB high-

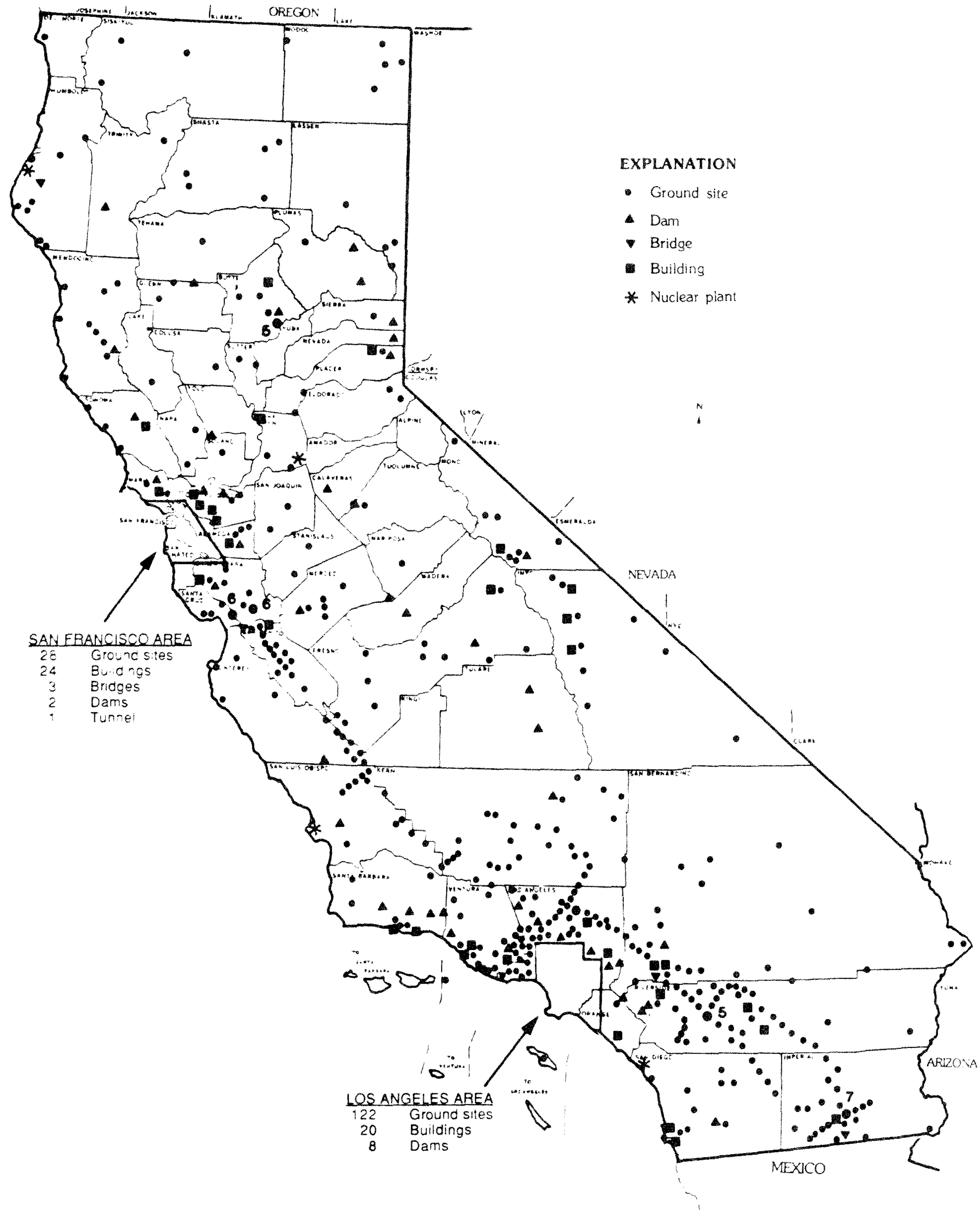


Figure 14. Known accelerographs in California as of April 30, 1981. Excludes instruments required by building codes. Numbers indicate where more than one station is located.

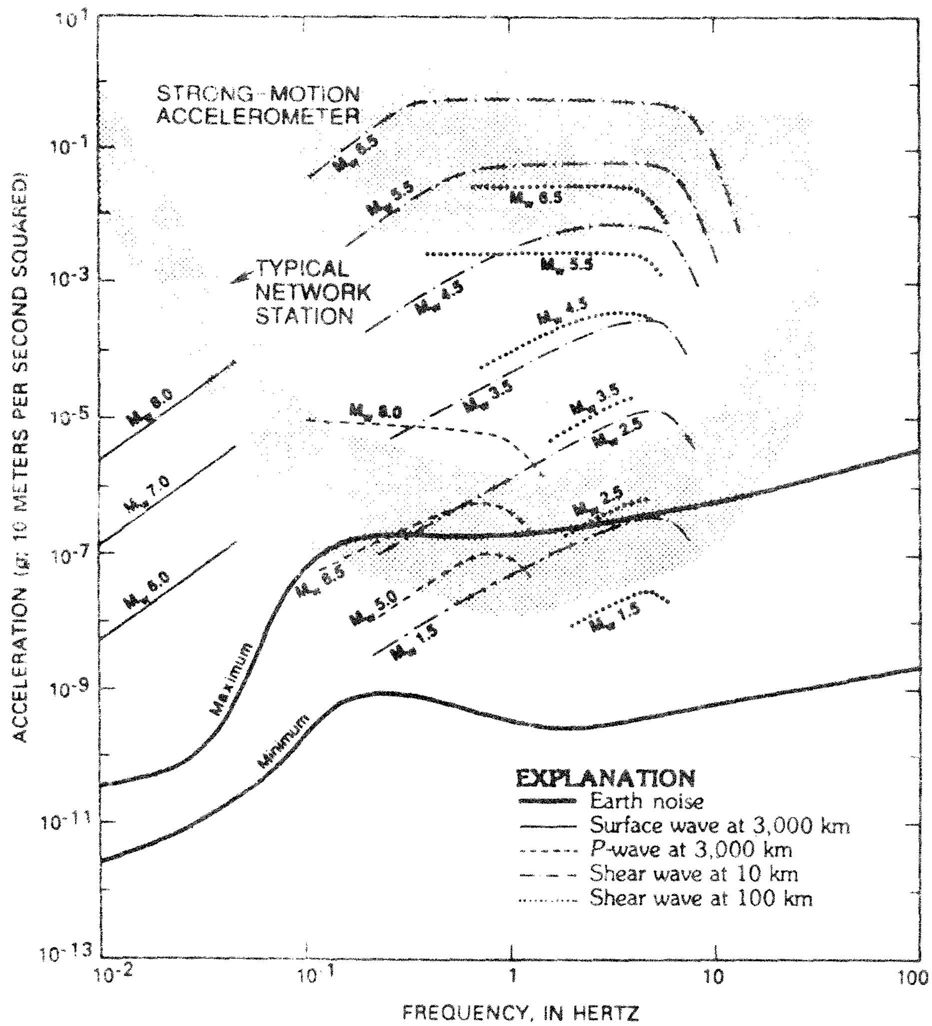


Figure 15. Dynamic range plotted against frequency for typical regional network station and typical strong-motion station as well as expected levels of ground motion for different seismic arrivals from earthquakes of different sizes and recorded at different distances.

gain vertical channel based on an integer fast-Fourier transform, (5) format and manage prioritized output queues of continuous and event data, (6) communicate with the satellite telemetry system, (7) acquire and maintain absolute time, (8) interpret and execute remote commands, and (9) provide calibration and control signals initiated by remote command.

Ku band (14–16 GHz), time division multiple access (TDMA), very small aperture telecommunications (VSAT) satellite telemetry technology has been chosen since no other system has been found to be nearly as cost effective. This approach requires a master station with a 4.5–7.0 m antenna at the NEIC to control the multiplexing of 56–96 kilobyte-per-second satellite channels and VSAT's with 1.2–3 m antennas and associated electronics at each field site. The system will have sufficient capacity to telemeter all data simultaneously in the event of a great earthquake in North America. Furthermore, the system will be capable of two-way communications, thereby greatly increasing the flexibility of future trigger algorithms and station maintenance. A modified VSAT X.25 protocol will provide error detection and correction, thereby providing a very low bit error rate. This will greatly simplify the processing at the station and the central recording site. In addition, the VSAT system will provide absolute time (broadcast periodically by the master station).

Two different scenarios are being considered for the physical installation of the sites. In either case, the seismometers will be mounted on a concrete pad in a shallow pit and covered by a partially buried fiberglass dome. The seismometers will be adequately coupled to the pad and adequately thermally insulated. In the first scenario, commercial electric power will be available at the field site. This power will be filtered through an uninterruptable power supply (UPS) and distributed by a custom DC regulation system to the seismometer filter and control electronics, the station

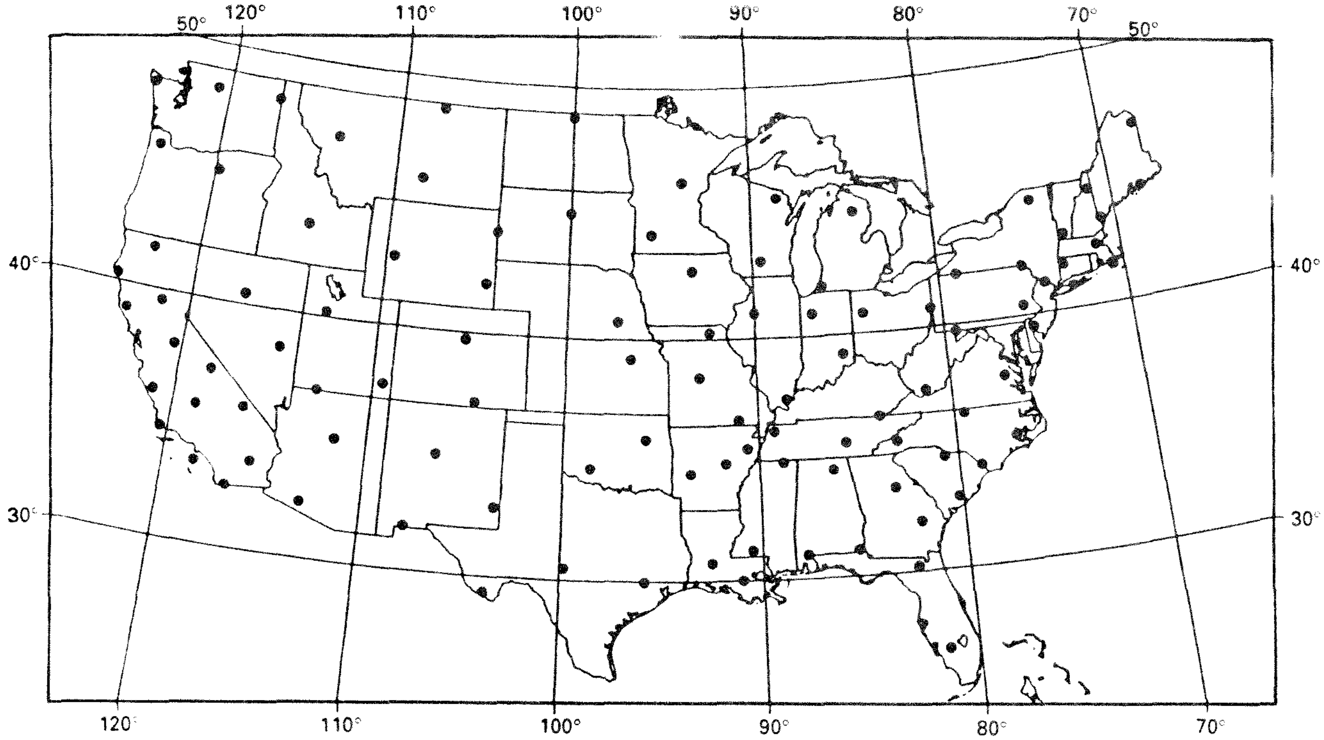


Figure 16. Proposed National Seismic Network stations in the contiguous United States. Additional stations are proposed for Alaska, Hawaii, and Puerto Rico. Only stations east of the Rocky Mountains in the contiguous United States are currently funded (from Massé and Buland, 1987).

processor, and the VSAT electronics which will all be housed in a separate, partially buried, vented enclosure. The VSAT antenna will be mounted on a standard kingpost set into a concrete pad. In order to minimize noise from cooling fans and wind coupled through the antenna, the seismometer will be removed from the VSAT hardware (using a hardwire cable) by as great a distance as is practical.

The second installation scenario is considered to be more desirable, but also more costly. In this case, commercial electric power will be available within a few kilometers of the field site, but not at the field site itself. The seismometer, seismometer electronics, and the station processor will be located at the field site and operated by batteries recharged by solar panels. As no fans will be required for the electronics, all equipment could be housed in a single vented enclosure. The VSAT electronics and antenna will be placed where commercial electric power and reasonable security are available. A 2,400-baud telemetry link will connect the seismometer and the VSAT sites. Although the latter scenario is somewhat more expensive, it provides the possibility of lower seismic noise, greater physical security, and greater lightning protection. If the VSAT electronics become available in a low-power configuration, it may be possible to eliminate the fans and commercial power at all sites. At sites where an adequate pre-existing borehole is available, provision is being made to mount the seismometer package in the borehole.

Relationship Between Regional and National Seismic Networks

Although the proposed 150-station National Seismic Network will provide exciting new waveform data on a national scale (only 60 stations are currently funded), it cannot perform the functions of the 1,600 stations currently in regional networks. In particular, the primary function of detecting and locating earthquakes cannot be accomplished at an acceptable level with only 150 stations nationwide. As an example, we show earthquakes located by the 75-station regional network operated by the University of Utah together with proposed sites for the National Seismic Network in figure 18. It is clear that the relatively low station density for the National Seismic Network would be inadequate to resolve the detailed patterns of seismicity seen with the existing regional network. As we discuss later, study of these seismicity patterns is vital for a better understanding of a wide variety of basic problems.

The relatively high station densities of existing regional networks are also vital for a wide range of other important seismological problems. These problems, listed in table 4, are discussed in detail in the sections on applications and research possibilities for a National Seismic System.

Even if sufficient station density were available in the National Seismic Network, regional networks would remain a focal point for research on important, but localized,

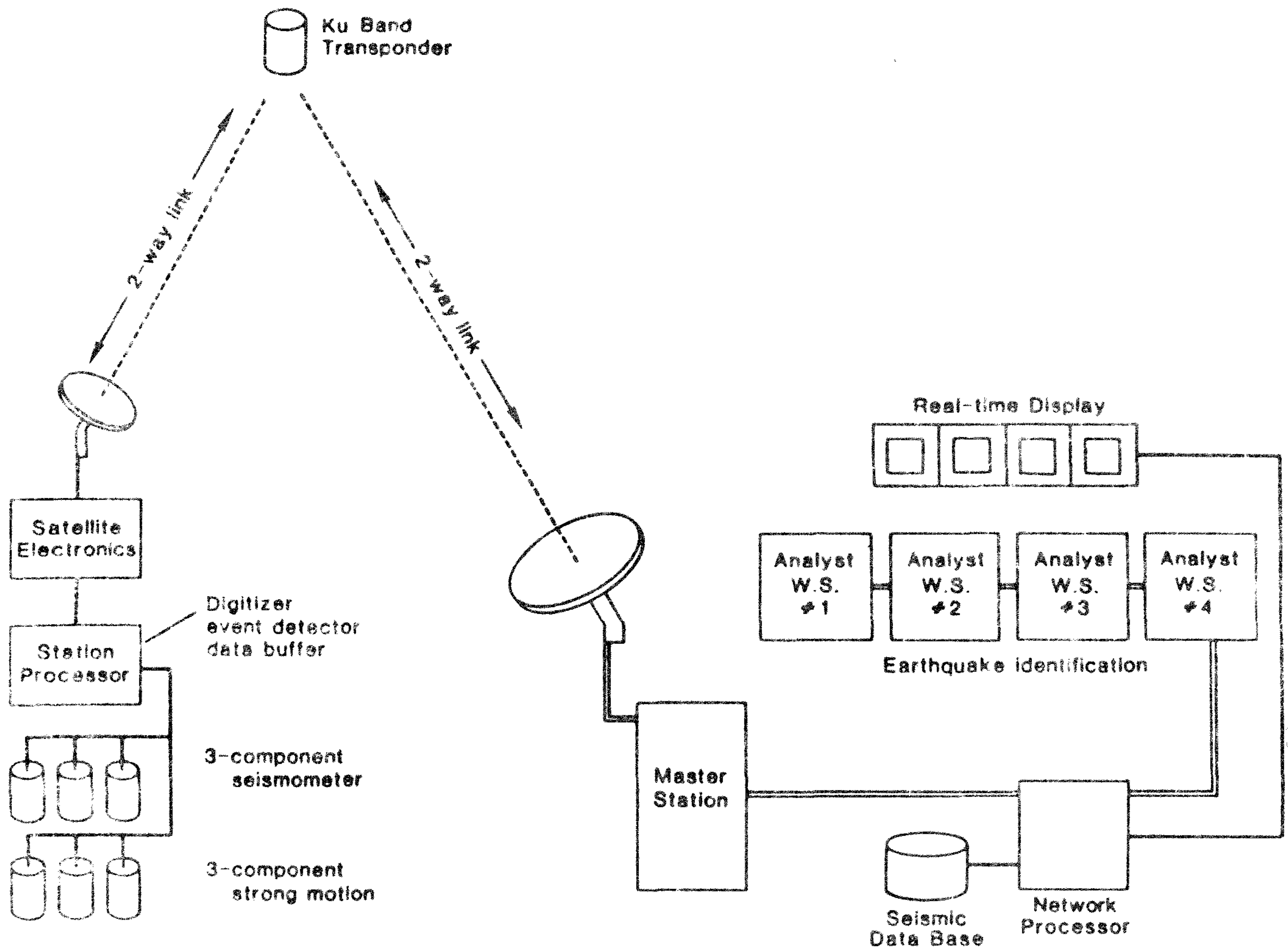


Figure 17. Schematic representation of National Seismic Network. Three-component, force-balance, broad-band seismometers (both high and low sensitivity) are digitally recorded at the station for a total dynamic range of approximately 10 decades (200 dB). Significant seismic signals detected at the station processor are telemetered via satellite to the Master Station in Golden, Colorado, for analysis and archival.

earthquake and tectonic problems. Although the National Seismic Network is not designed to replace regional seismic networks, it provides an opportunity to dramatically improve the capabilities of regional networks. That is, the National Seismic Network provides regional networks with the technology for recording broad-band, high-dynamic-range, three-component seismic data in real time and with low telemetry costs. Furthermore, the National Seismic Network provides a communications network that will interconnect regional networks. Standardized data manipulation procedures will allow better access to these important data sets by all researchers.

Need to Develop Digital Regional Networks

We have demonstrated that the existing regional networks provide a vital function in the observation of seismic waves, and their continuing operation should have a high national priority. We have also demonstrated that the existing regional networks are severely limited by the outdated technology on which they are based. Therefore, the upgrading of existing networks to digitally telemeter high-dynamic-range, broad-band seismic data is a long-range goal of high priority. Unfortunately, a coordinated plan to ensure that such a goal is met has not yet been formulated.

In the beginning of this decade, the seismological community recognized similar shortcomings in global seismic networks (principally the World-Wide Standardized Seismic Network, WWSSN) and in the field of dense portable networks. As a result, approximately 57 research institutions formed a nonprofit corporation, the Incorporated Research Institutes for Seismology (IRIS). IRIS has three principal goals: (1) develop a Global Seismic Network (GSN) of approximately 100 high-quality digital stations, (2) develop a portable network of approximately 1,000 portable digital seismic stations (Program for Array Seismic Studies of the Continental Lithosphere, PASSCAL), and (3) develop a Data Management Cen-

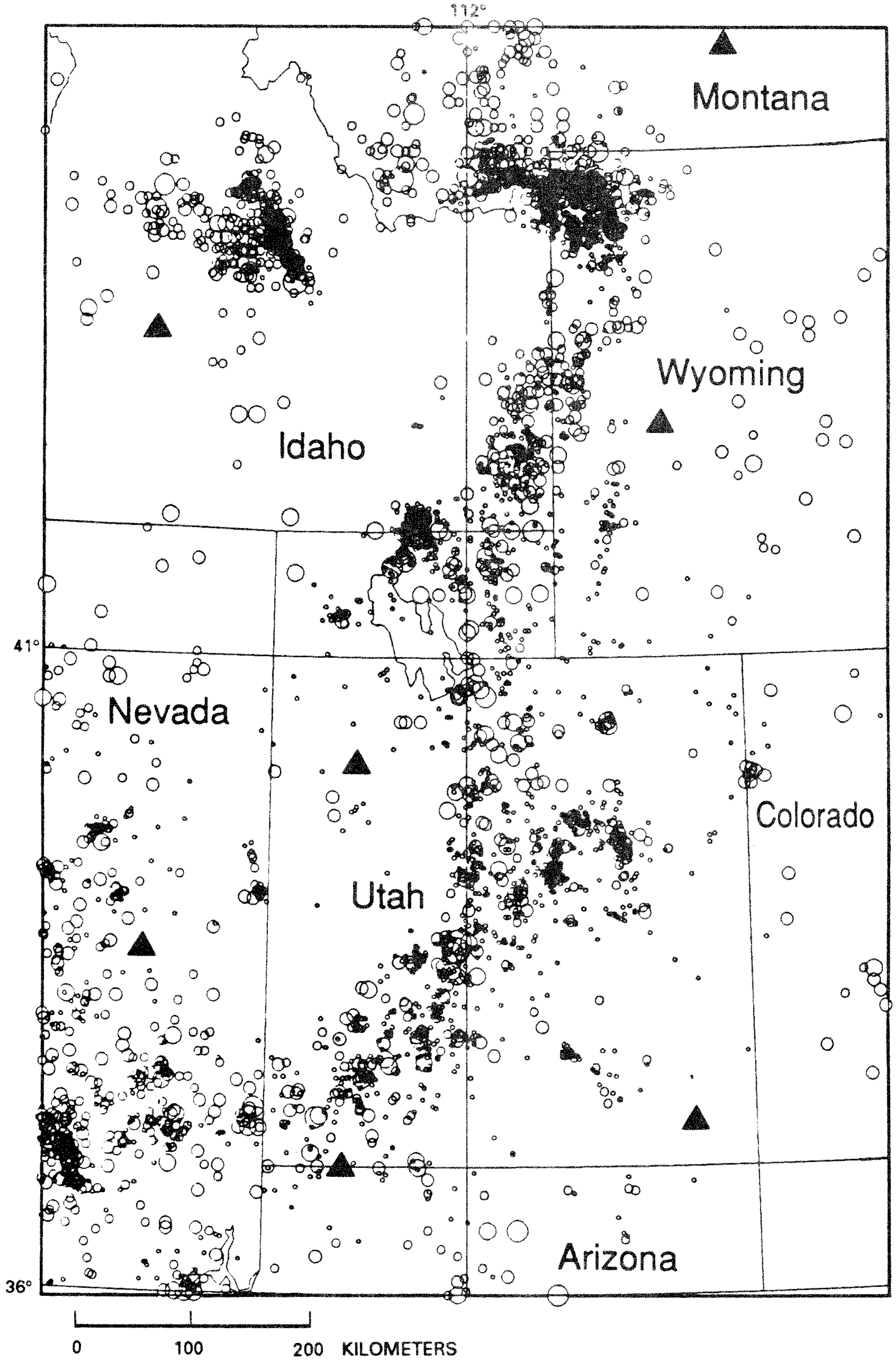


Figure 18. Seismicity of the intermountain region located using the 75-station regional network operated by the University of Utah. Earthquakes since 1962 and larger than magnitude 2.0 are plotted. Proposed station locations for the National Seismic Network (triangles) illustrate that the National Seismic Network is far too sparse to study detailed features of regional seismic activity (courtesy of R. Smith, R. Engdahl, and J. Dewey).

Table 4. Problems requiring high station densities

- Detection of microearthquakes (magnitudes less than 2.5)
- Accurate determination of hypocentral locations.
- Accurate determination of earthquake rupture characteristics.
- Rapid determination of shaking distribution for significant earthquakes.
- Short-term warning of imminent strong shaking during significant earthquakes.
- Real-time tsunami warning.
- Volcano monitoring.
- Determination of path effects to better predict strong-motion characteristics at individual sites.
- Determination of velocity distributions of the crust and the Earth's interior

ter (DMC) to store and disseminate the data from these networks. IRIS helps to coordinate activities within the United States to see that these important goals are met. However, it is important to recognize that these programs do not address the vital problems of developing regional networks. A national plan to deal with the issues of regional networks should be developed. It is not within the scope of this document to specify the way in which such a plan should be developed. However, it is clear that the formulation of such a plan should be a high priority of the U.S. seismological community.

APPLICATIONS OF A NATIONAL SEISMIC SYSTEM

Estimation of Current Earthquake Risk

When an earthquake occurs, the risk of a major earthquake occurring within a short period of time increases significantly because of the possibility that the first event is a foreshock. Seismologists have always become more wary in the first few days after an earthquake, but have not usually issued public statements because the chance of a false alarm in this situation is also high. In the last few years, however, more accurate estimates have been made of how the probability of a major earthquake increases following other seismic activity. In addition, both seismologists and emergency management personnel have recognized that an earthquake prediction should include not only time, place, and magnitude of the event but also the probability that the prediction is correct. These developments have allowed predictions of earthquake risk that are well above background but well below 50 percent probability to be issued and used. This has also increased the need for accurate information immediately after an earthquake. An example of the way that seismic risk increases dramatically after a potential foreshock is shown in figure 19. In this example, Jones (1985) shows that the probability per

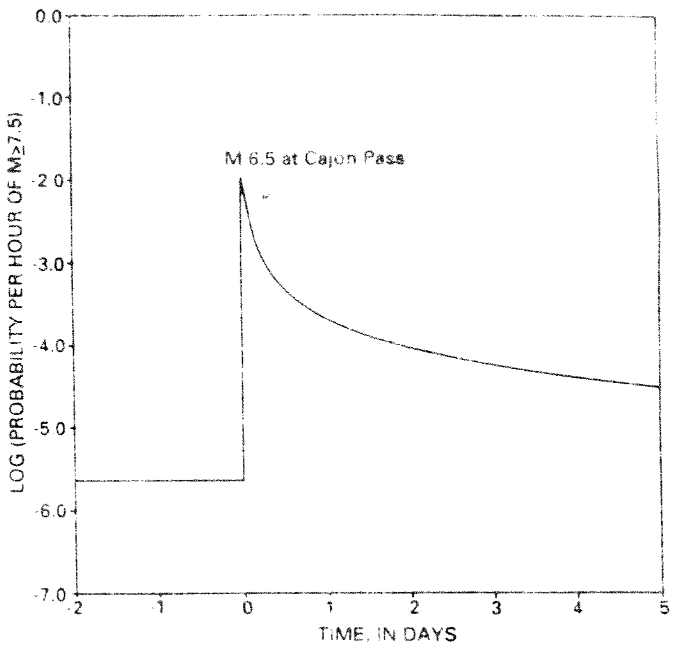


Figure 19. Probability per hour of a large ($M \geq 7.5$) earthquake occurring on the Palmdale section of the southern San Andreas fault as a function of time when a M 6.5 earthquake occurs at Cajon Pass (Jones, 1985).

hour of a large ($M \geq 7.5$) earthquake occurring on the Palmdale section of the San Andreas fault is a function of time when a M 6.5 earthquake occurs on the segment.

On May 27, 1980, the Director of the U.S. Geological Survey issued a Hazards Watch for potentially damaging earthquake activity in the Long Valley region of eastern California in the wake of the occurrence of three magnitude 6 earthquakes two days earlier. This first public statement in the United States was followed by a fourth magnitude 6 event (Hill and others, 1985).

The next statement from the U.S. Geological Survey about an increase in the probability of a damaging earthquake was made in June 1985 (Golz, 1985). Three M 4 earthquakes in San Diego increased the probability of a damaging earthquake to 5 percent within five days. Limitations of the old regional network in southern California led to delays in determining the location and magnitudes of these smaller earthquakes. However, because of the location of these earthquakes directly under a city of 1 million people, the California State Office of Emergency Services was notified of the increased probability as soon as it was recognized, four hours after the start of the sequence. San Diego responded by putting disaster management personnel on alert, checking water supplies and moving fire engines outdoors, appropriate for a 5 percent chance of having an earthquake.

Plans are being made to issue a similar short-term warning if foreshocks precede the Parkfield earthquake (Bakun and others, 1986). Parkfield is a site on the San Andreas fault where moderate earthquakes (M approx 6) have occurred on the average once every 22 years. Because of this apparent repeatability, an intermediate-term prediction has been issued for another M 6 event by 1993. In preparing for this earthquake, the U.S. Geological Survey is working with the California Office of Emergency Services to develop response scenarios for possible changes in the Earth that might precede the Parkfield earthquake. In particular, USGS seismologists have determined the probabilities of the Parkfield earthquake occurring within three days after earthquake activity on the San Andreas fault (figure 20). These probabilities range from 1 to 2 percent for a M 2 earthquake to over 35 percent for a M 4.5 event. These probabilities have been assigned to alert levels, such that during a level A alert, the chance of the Parkfield earthquake occurring is greater than 35 percent; during a level B alert, the chance is 10 percent to 35 percent, and so forth. The Office of Emergency Services has developed appropriate response plans for each alert level (State of California, 1988). Thus when an alert is actually called, information can be quickly and efficiently exchanged and plans activated because all of the decisions for that alert level have already been made.

A crucial element of the Parkfield plans is real-time location of earthquakes. Studies have shown that the increase in probability after a potential foreshock is concentrated in the first few hours after the event; one quarter of all foreshocks occur within one hour of their mainshock. The foreshock to the last Parkfield earthquake occurred only 17 minutes before the mainshock. Thus an extensive network has been installed in the Parkfield area and new computer systems developed to produce locations and magnitude estimates for earthquakes in real time.

New computer systems would allow real-time assessments similar to those at Parkfield to be made in other regions as well. For instance, a moderate earthquake on the southern San Andreas fault, like the North Palm Springs earthquake of July 1986, has been estimated to have a 10 percent chance of being followed by a M 8 great earthquake. However, six hours after such a moderate earthquake, the probability of a M 8 earthquake occurring is down to 5 percent; thus, quick response is essential. Although the chance of a false alarm—that the earthquake will not occur—is 90 percent, disaster planners have stated that a warning issued on this basis would be useful to them. Responses to such a warning could involve canceling vacations for emergency response personnel, moving fire engines outdoors, delaying toxic waste disposal operations, and many other steps.

Seismicity patterns on longer time scales than immediate foreshocks may also reflect changes in the earthquake hazard. As these are better understood, it will be possible to have earthquake risk maps that change with time, reflecting the probability of earthquakes over time scales of weeks and months. Significant seismic sequences that are potential foreshocks to hazardous earthquakes will continue to occur, and seismologists must be prepared to provide useful, timely information to mitigate potential hazards.

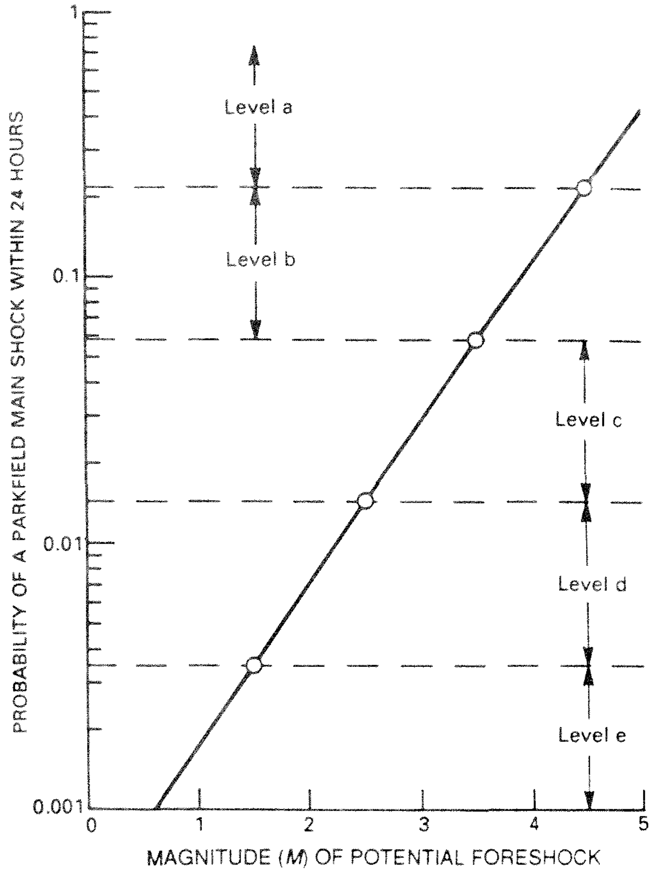


Figure 20. Probability of a characteristic Parkfield, California, earthquake in 24 hours following occurrence of potential foreshock of magnitude M. Levels a through e refer to alert levels as defined in Bakun and others (1986).

Short-Term Warning of Imminent Ground Shaking

In earthquakes of great fault length, substantial damage often occurs at great distances from the earthquake's epicenter. Because of the relatively slow speed of seismic waves, it is possible to electronically warn a region of imminent strong shaking as much as several tens of seconds before the onset of very strong shaking. Automated safety responses could be triggered by users after receiving estimates of the arrival time and strength of shaking expected at an individual site.

The great earthquake of 1857 that ruptured a 300-km-long segment of the San Andreas fault in southern California is an example of how a Seismic Computerized Alert Network (SCAN) could provide more than a minute of warning time before the occurrence of strong shaking in a heavily populated area. There is evidence that the rupture initiated in the vicinity of Parkfield, a small town 275 km northwest of metropolitan Los Angeles. It seems likely that the rupture propagated south toward the Los Angeles region at a velocity of about 3 km/s or less, and the strongest shaking in the Los Angeles region probably occurred at least 100 seconds after the ground began to shake at Parkfield.

In similar earthquakes, a SCAN could provide users with information during this time so that they could initiate certain safety precautions. The most suitable applications are those operations that come under computer control and can be safeguarded quickly. For example, a SCAN could initiate electrical isolation and protection of delicate computer systems, isolation of electric power grids to avoid widespread blackouts, protection of hazardous chemical systems and offshore oil facilities, closing of natural gas valves to minimize fire hazards, warning of nuclear power plants and national defense facilities, protection of emergency facilities such as hospitals and fire stations, and protection of fixed rail transportation systems. It may even be possible to provide protection to individuals in hazardous structures. For instance, structurally strong areas could be built in schoolrooms (such as a heavily reinforced table) to which students could rapidly evacuate.

Heaton (1985) discussed the basic principles and expected performance of a SCAN of the type shown schematically in figure 21. Ground motions recorded by a dense array of broad-band, high dynamic range seismometers are digitally telemetered to a central processing site. The occurrence of a large earthquake is detected and the location, time of origin, amplitude, and reliability estimates are transmitted instantly to microcomputers operated by individual users. The user's computer then combines this information with that about the user's site (for example location and geologic conditions of the site) to estimate the arrival time and nature of motions expected at the site. Decisions already programmed into the user's computer are then made on the basis of this information and the appropriate action is taken.

The problem of false alarms is minimized by continuous updates regarding the size of the ground motions at differing stations in the seismometer array. If the user is close to the epicenter of a developing earthquake, then the user's processor will recognize that little time is available to receive further information and immediate action may be appropriate. However, if the user is far from the epicenter, then considerable time is available before shaking begins. This time may be used to receive further information about the size of the earthquake. In this way, users at large epicentral distances take action for only the large earthquakes that present a real hazard, and each user adjusts the decision-making process to the needs of the site. The use of the seismometer array for the routine research study of numerous small local earthquakes will help to ensure that the system is maintained in good working order.

The circumstances surrounding the great 1857 earthquake, a damaging earthquake in Los Angeles with a very distant epicenter, are optimal for the operation of a SCAN system. However, there are a number of examples where damage is more localized to the epicentral regions such as was the case for the 1971 San Fernando earthquake or the 1933 Long Beach earthquake. In these cases only several seconds of warning could be expected in heavily damaged areas. Heaton (1985) provided estimates of the probability distribution that a site which experiences a specified strength of shaking will also receive a given warning time. The distribution of warning time as a function of peak acceleration is shown in figure 22. The contours give the probability that a user will receive at least a certain warning time in the event of at least a certain value of acceleration. The total area of southern California to receive a given peak acceleration or greater in a 100-year period is shown to the right. This number may exceed the total area of southern California (about 3×10^5 km^2) because many areas will experience low values of acceleration several times in a 100-year period.

The expected warning time is long at both low (<0.1 *g*) and high (>0.3 *g*) values of acceleration, but the expected warning time is short for moderate (0.1 to 0.3 *g*) values. Because small accelerations occur at large distances between site and fault, the warning time is large for small accelerations. In this model, accelerations of 0.2 *g* are most likely to occur close to the numerous moderate-size earthquakes, and hence the expected warning time is short. However, large accelerations result from large earthquakes of long rupture length. Thus areas that receive large accelerations can also expect to receive large warning times.

The 27 March 1964 Alaskan earthquake (M_w 9.2) is the largest earthquake documented in U.S. history and it is the second largest earthquake of this century. The fault rupture extended more than 600 km in length and had a width of more than 200 km. Very strong shaking of unusually long duration (several minutes) occurred over a very large region, and devastating local tsunamis were generated (National Academy of Sciences, 1972). The strong shaking and giant tsunamis extensively damaged cities and transportation links within the regions of Prince William Sound, Kenai Peninsula, Kodiak Islands, and Cook Inlet. Because of the very large rupture dimensions, most of the region that was strongly shaken would hypothetically have received many tens of seconds of warning if a SCAN system had been operational. This giant earthquake was the result of thrusting of the North American continental plate over the Pacific Ocean plate, a process known as subduction. Similar subduction processes are known to occur along most of Alaska's southern coast and also along the entire length of the Aleutian Island chain.

The Cascadia subduction zone is a 1,200-km-long plate boundary in the Pacific Northwest along which the North American plate overthrusts the Gorda, Juan de Fuca, and Explorer oceanic plates. This plate boundary extends from northern California to Vancouver Island, British Columbia. Although there have not been large historic subduction earthquakes on this zone, recent studies indicate that very large subduction earthquakes (perhaps as large as M_w 9.5) may occur there (Heaton and Hartzell, 1987; Atwater, 1987). If subduction earthquakes occur on this zone, then relatively strong shaking can be expected over a large area of the Pacific Northwest, including the Puget Sound and Willamette Valley regions (Seattle and Portland). Because of the potential for

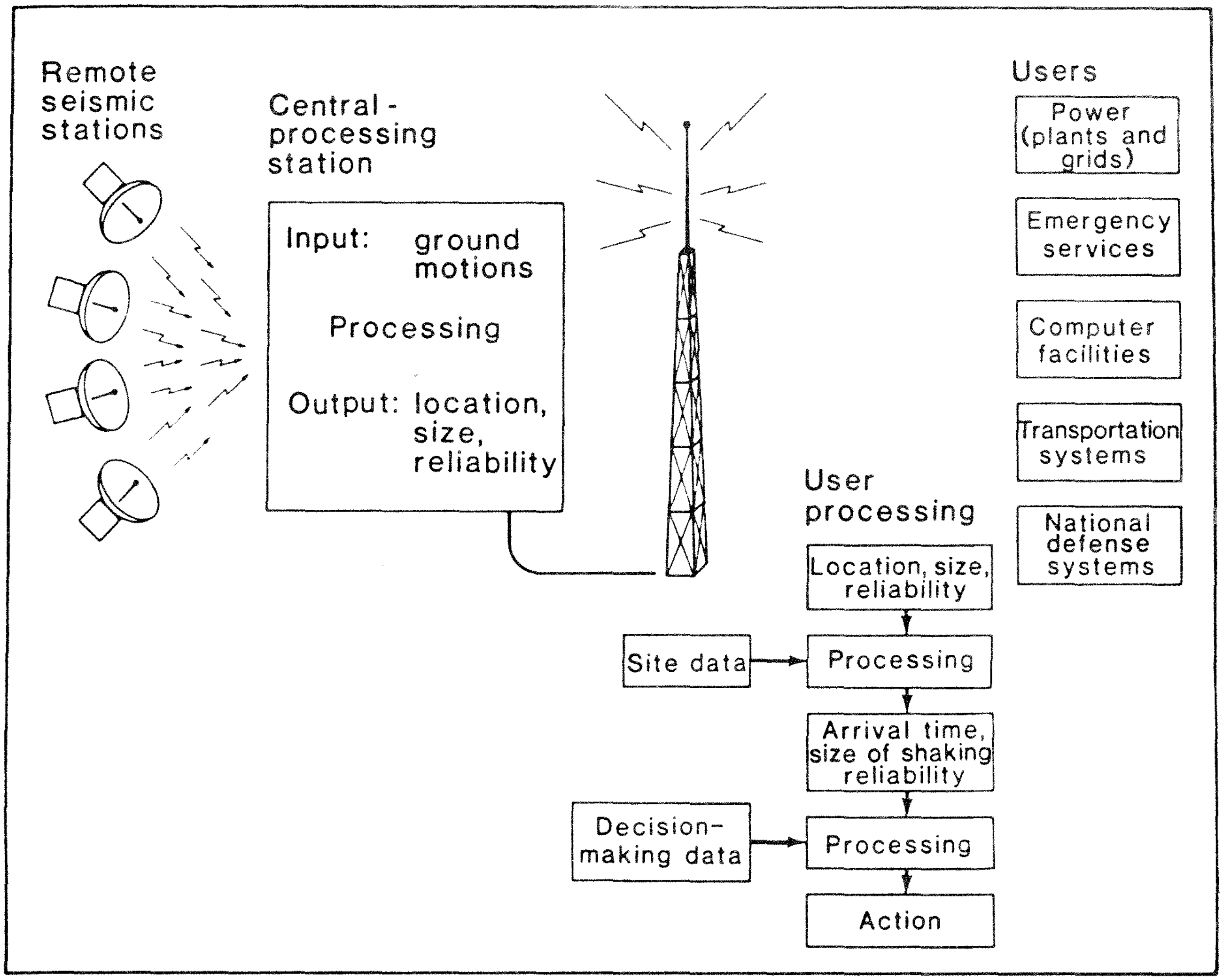


Figure 21. Conceptual design of a Seismic Computerized Alert Network (SCAN). The purpose of this system is to provide very short-term prediction of the arrival time and size of imminent strong shaking to areas at some distance from an earthquake's epicenter. The system relies on the relatively slow speed of seismic waves (approximately 3 km/s) compared with electronic communications. The system would also provide important emergency information immediately after a damaging earthquake (Heaton, 1985).

earthquakes of very large rupture dimensions, a SCAN system may provide many tens of seconds of warning in advance of very strong shaking for great subduction earthquakes in the Pacific Northwest.

Large historic earthquakes have also occurred in the United States that are far from known plate boundaries. Specifically, large earthquakes occurred in the central United States (New Madrid) in 1811 and 1812 and also in the southeastern United States (Charleston) in 1886. Although the mechanisms of these events are poorly understood, these events probably do not involve large rupture dimensions. Nevertheless, the felt areas of these earthquakes were larger than those for the largest California earthquakes (Nuttli and Zollweg, 1974). It is generally felt that the principal reason for this phenomenon is a lesser degree of attenuation of seismic waves east of the Rocky Mountains. Because rupture lengths of great earthquakes in the central and Eastern United States may be less than 50 km, the regions of strongest shaking that lie adjacent to the rupture zone are not likely to receive large warning times. However, Rossi-Forel intensities of IX and VIII may have extended to distances of 100 and 200 km, respectively, for the 1811 and 1812 New Madrid earthquakes. This means that a SCAN system could still provide a significant warning time for areas shaken strongly enough to cause great damage during great earthquakes in the central and Eastern United States.

Rapid Estimation of Shaking Intensity

Past experience has proved that there is always great confusion immediately following damaging earthquakes. Very heavy loads are put on communication lines at a time that they

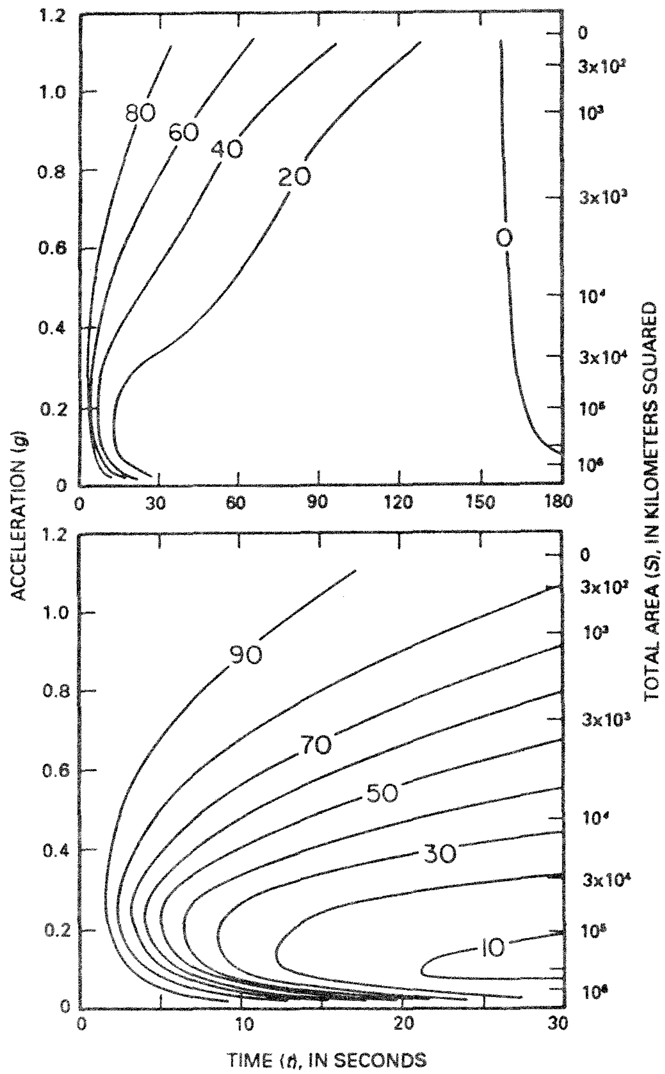


Figure 22. Theoretical calculation of distribution of warning times for SCAN system in southern California as a function of expected peak ground acceleration. Contours denote percent of area having peak acceleration of *g* or greater that receives a warning time of *t* or greater. *S* is total area to receive a peak acceleration of *g* or greater in a 100-year period in southern California. Warning time is given relative to arrival time of maximum shaking. Bottom part of figure is same as top, but with an expanded time scale (Heaton, 1985).

may already be damaged during the earthquake. It is very difficult for emergency management professionals to rapidly assess the nature of the crisis. Unfortunately, seismologists have not always provided much assistance because most of their available records are completely off scale. However with a high dynamic range, digitally telemetered seismic network of the type that is necessary for a SCAN system, it would be possible for seismologists to provide a very rapid assessment of the severity of ground shaking for different regions.

The California State Office of Emergency Services is currently developing plans for a southern California emergency response center that will be responsible for coordinating emergency services after a damaging earthquake. Recent earthquake disasters, such as those in Mexico City, have emphasized the importance of rapid rescue and relief activities. The cost of inadequate response can be many lives. In an area as extensive as southern California, it may be very time consuming for officials to assess the true nature of an earthquake disaster. Estimates of the strong shaking could be relayed directly to the State's emergency response center. These estimates will allow rapid assessment of the overall extent of the disaster. It may even be possible to automatically project earthquake damage based on this incoming data. For example, the Southern California Association of Governments is currently developing a geographic relational data base using census statistics. They plan to use this data base to model hypothetical earthquake disasters assuming several different earthquake scenarios. Included in the data base are such items as hospitals, lifelines, transportation links, hazardous facilities, and current distribution of population (how many people are away from their homes?). Once such a system is developed, it should be possible to input estimates of the actual shaking immediately after an earthquake in order to anticipate the most immediate emergencies.

Rapid estimation of earthquake damage is also of vital interest to many other organizations. For instance, our national defense system may receive severe damage during a large earthquake. Proper and timely reallocation of resources will depend on accurate estimates of the extent of the earthquake. This post-earthquake damage information is also of obvious value to the repair and protection of lifeline systems (aqueducts, electrical power grids, telecommunications, natural gas, and so on).

Tsunami Warning

Tsunamis are long-period (usually tens of minutes) ocean waves that are commonly generated by large earthquakes beneath the ocean. In general, the largest earthquakes are responsible for the largest tsunamis. Tsunamis are also sometimes generated by underwater volcanoes and perhaps by underwater landslides. Several devastating tsunamis that occurred in Hawaii (1946, 1960, 1964) were actually generated by earthquakes several thousands of kilometers distant from Hawaii. In these instances, the tsunami waves, which travel less than 1,000 km/hr, took many hours to traverse the Pacific Ocean to Hawaii. Much of our present tsunami warning system is based on the premise that warning will be given for populated coastlines for tsunamis that are generated in remote and distant regions of the Pacific. However, very large tsunamis with runup heights in excess of 20 m have struck U.S. coastlines from nearby earthquakes in 1868 (Hawaii), 1946 (Aleutian Islands), 1958 (Alaska), and 1964 (Alaska). Tsunamis that occur in the region of the generating earthquake are referred to as local tsunamis. Local tsunamis can be particularly dangerous because they can be exceedingly large and because they may strike within 15 minutes of the causative earthquake. Although most of the coastal areas of the contiguous United States have not experienced historic devastating tsunamis, there is evidence that large tsunamis from great subduction earthquakes may present a severe problem in the Pacific Northwest (Heaton and Hartzell, 1987; Atwater, 1987). Furthermore, it is difficult to preclude the possibility of damaging tsunamis along any U.S. coastal region.

Kanamori (1985) presented a methodology for determining tsunami sizes from near-field ground motions that occur within the first several minutes of large coastal earthquakes. Furthermore, reasonably precise predictions of local tsunami runup heights are now feasible using complex models of sea waves in detailed models of seafloor bathymetry (Satake, 1987). However, on-scale measurements of long-period ground motions in the near-source region of large earthquakes must be available in real time in order to provide a working local tsunami warning system (Bernard and others, 1988). Clearly, regional networks with seismic instrumentation, communication, and real-time analysis systems of the type proposed for the National Seismic Network would be able to meet these needs.

Volcano Monitoring

On 20 March 1980 the regional seismic network operated by the University of Washington detected small earthquakes beneath usually quiet Mount St. Helens. Over the next two months, seismic activity increased dramatically as the volcano experienced several small phreatic (steam-blast) eruptions and the flank of the volcano bulged dramatically. Because of this precursory activity, thousands of lives were saved from the catastrophic eruption of 18 May 1980. Careful monitoring of seismicity in the Mount St. Helens region was a key tool for the prediction of numerous other eruptions over the next several years (Swanson and others, 1983). Seismic monitoring has also been a key tool in the prediction of numerous eruptions in Hawaii (Klein, 1984; Klein and others, 1987). Smith and Luedke (1984) estimate that there are approximately 75 volcanoes distributed in 11 Western States of the conterminous United States that have potential for future eruptions. In addition, there are 33 Holocene volcanoes on the Alaskan peninsula, 40 in the Aleutian Island chain, and six in the Hawaiian Islands (Simkin and Siebert, 1984). Regions of the United States that have a potential for future volcanic activity are shown on figure 23 and summarized in table 5.

Not all large explosive eruptions are preceded by significant periods of precursory eruptive activity. Simkin and Siebert (1984) reported that of 205 of the largest documented eruptions, 92 occurred within a day of the onset of eruptive activity. No precursory eruptions were reported for the largest volcanic eruption this century, which occurred in 1912 at Alaska's Katmai volcano. However, earthquake activity was noted for several days before the main eruption (Bullard, 1962) and most (if not all) great volcanic eruptions are preceded by a significant seismicity precursor. "Harmonic tremor" or "volcanic tremor," which is characterized by a nearly continuous oscillation of the ground, seems to be a phenomenon that is particularly diagnostic of magmatic activity. As is the case with earthquake ground motions, the range of amplitudes of ground motion during harmonic tremor is very large. Because of the unusual nature of the seismic source for harmonic tremor, this phenomenon is best studied with three-component, broad-band instrumentation.

Because there are so many potentially active U.S. volcanoes that may have little in the way of precursory eruptions, the monitoring of seismic activity is of vital importance for U.S. volcano prediction. This monitoring requires relatively dense seismic networks throughout the Western United States, Alaska, and Hawaii. Furthermore, it is important to monitor seismicity from volcanic regions in near-real time. When visibility is limited (as it often is on large volcanoes), seismic monitoring can also be important for the recognition of significant eruptions that may trigger dangerous lahars (mudflows often triggered by the rapid melting of snow and ice) as occurred with tragic results in 1985 at Colombia's Ruiz volcano, killing over 20,000 people. In addition, even moderate-sized eruptions can send ash into the atmosphere that can be a serious hazard for aircraft.

Volcano monitoring is already an important task of existing regional seismic networks. The upgrading of these networks to include three-component, high-dynamic-range seismometers, and the development of systems to analyze seismicity in real time will greatly enhance the ability to recognize, understand, and respond to U.S. volcanic hazards.

Prediction of Site Effects in Strong Ground Motions

One of the most critical factors in the engineering of structures is anticipating the nature of the ground motions that may be experienced by the structure. Earthquake ground motions are determined by the nature of the seismic energy radiated by the source and also by the way in which the seismic energy propagates through the medium to the site. A complete physical description of this process is exceedingly complex, and the current practice in earthquake engineering is to simplify this problem by parameterizing the earthquake source by magnitude and the effects of propagation by distance between the earthquake and the site. Unfortunately, this parameterization can be tragically inadequate, as was the case for the 1985 Michoacan earthquake in which thousands lost their lives in Mexico City. Although Mexico City was over 350 km from this earthquake (the distance between Los Angeles and Las Vegas), there was heavy damage to earthquake-engineered structures caused by ground motions that were strongly amplified by the sedimentary structures beneath the city. Significant amplification of longer period ground motions of the

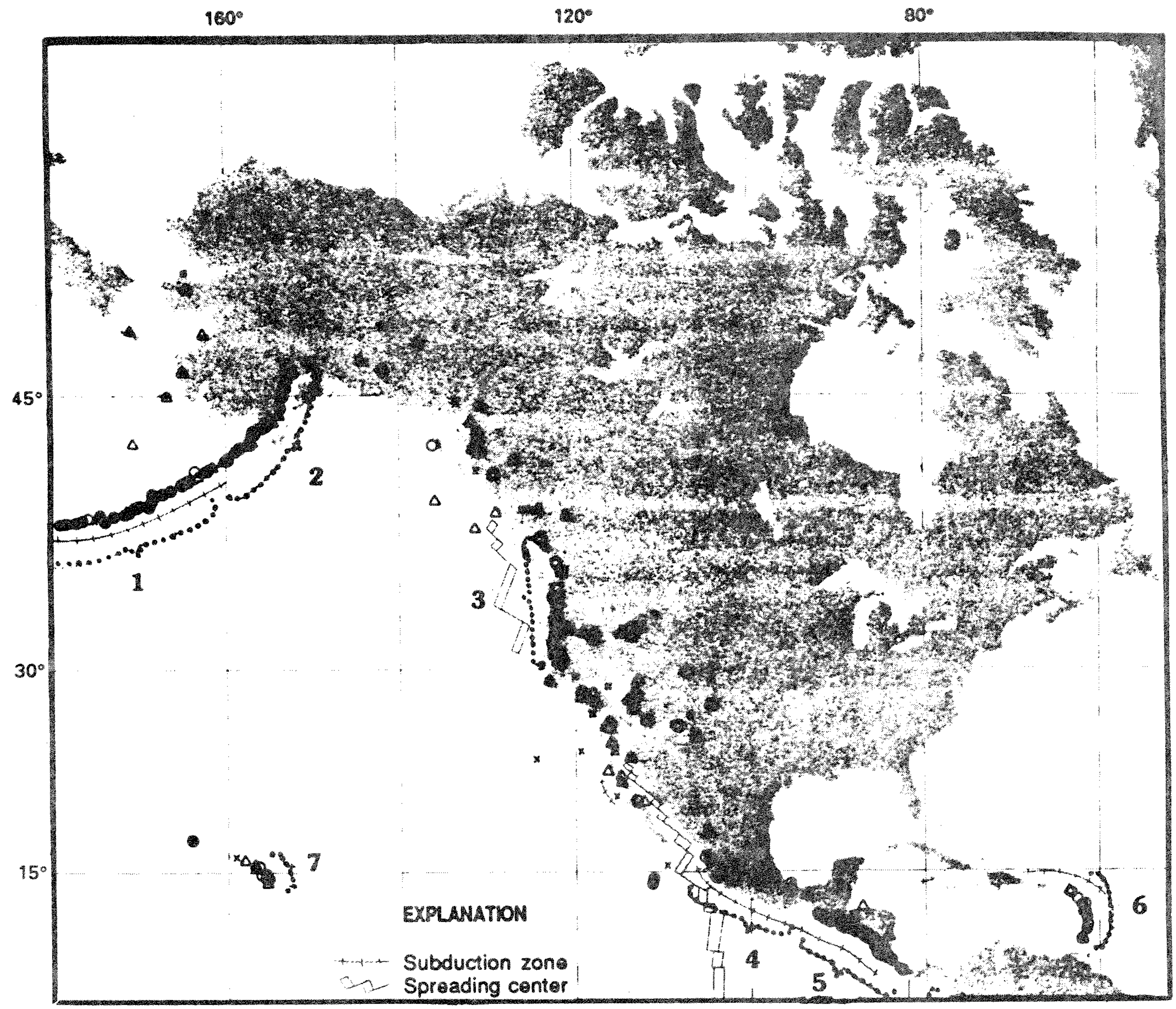


Figure 23. Locations of probable Holocene volcanism (last 10,000 years). Volcanoes with known eruptions since 1880 are shown by filled circles. Volcanoes with dated eruptions, but none since 1880, are shown by open circles, and those with undated but probable Holocene eruptions are shown by triangles. Volcanoes with uncertain or only solfataric activity are shown by a small x. Volcanic belts that are numbered correspond to table 5 (modified from Simkin and Siebert, 1984)

type that threaten high-rise buildings was also observed in the Los Angeles and San Fernando basins in the 1971 San Fernando earthquake. Figure 24 shows a profile of ground velocity records across these basins (Liu and Heaton, 1984). Individual sets of surface waves are developed within these basins, and these surface waves control the duration and peak amplitude of the longer period parts of the ground motion.

The effects of propagation of strong ground motions in complex geologic structures, such as basins, are usually included in earthquake design studies as a simple scalar site amplification factor whose value is determined by the local site condition (hard rock, intermediate, soil). Such a procedure cannot adequately characterize the phenomena that make

Table 5. Holocene volcanism of North America and Hawaii

[from Simkin and Siebert (1984)]

Belt name	Length (km)	Number of Holocene volcanoes	Eruptions since 1880
1. Aleutians	1,457	40	203
2. Alaska Peninsula	944	33	120
3. Cascades	1,152	38	141
4. Mexico	1,043	22	64
5. Central America	1,254	79	35
6. West Indies	632	17	59
7. Hawaii	174	6	114

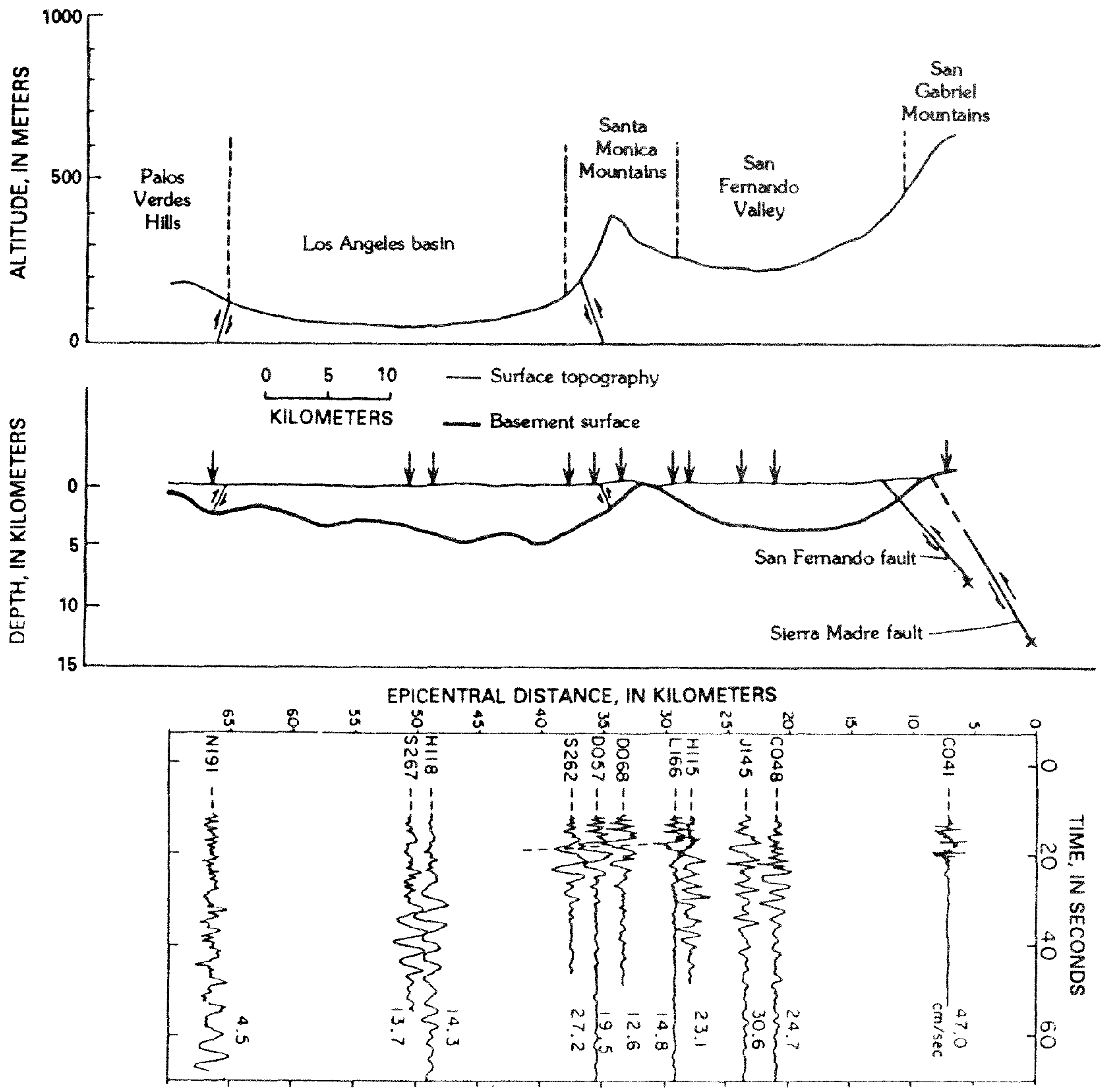


Figure 24. Transverse component of ground velocities recorded during the 9 February 1971 San Fernando, California, earthquake. Records are plotted as a function of epicentral distance along a profile (top) running south across the San Fernando Valley and the Los Angeles basin. Corresponding free-surface and basement-surface profiles are shown in the center. Dashed lines in records (bottom) indicate probable phase arrival of surface waves. Note that the apparent surface waves seen within the basins do not appear to propagate across the Santa Monica Mountains (from Liu and Heaton, 1984).

sites at equal distance from the same earthquake experience very different ground motions. Response spectra from M 6.5 strike-slip earthquakes that were observed at a distance of 50 km are shown in figure 25. It is clear that simply knowing distance, magnitude, and soil condition still leaves an order of magnitude uncertainty in the estimation of ground motions.

Fortunately, we needn't wait to record destructive ground motions at a site before we can anticipate dangerous amplification effects. Since wave propagation in earthquakes is by and large a linear process, we can infer the effects of propagation by the study of weak ground motions from numerous smaller earthquakes. By studying these smaller motions from a variety of sources, we can understand which effects are stable with respect to the geometry of the source and the site. Ground motions recorded by a digital telemetered network will be ideally suited for these types of studies. In order to increase station coverage to get an even more detailed understanding of the variations of ground motion with site location, the array would be temporarily supplemented with portable stations that will be occupied only long enough to record data from several sources which could even be artificial sources (quarry blasts, Nevada test site, and so forth).

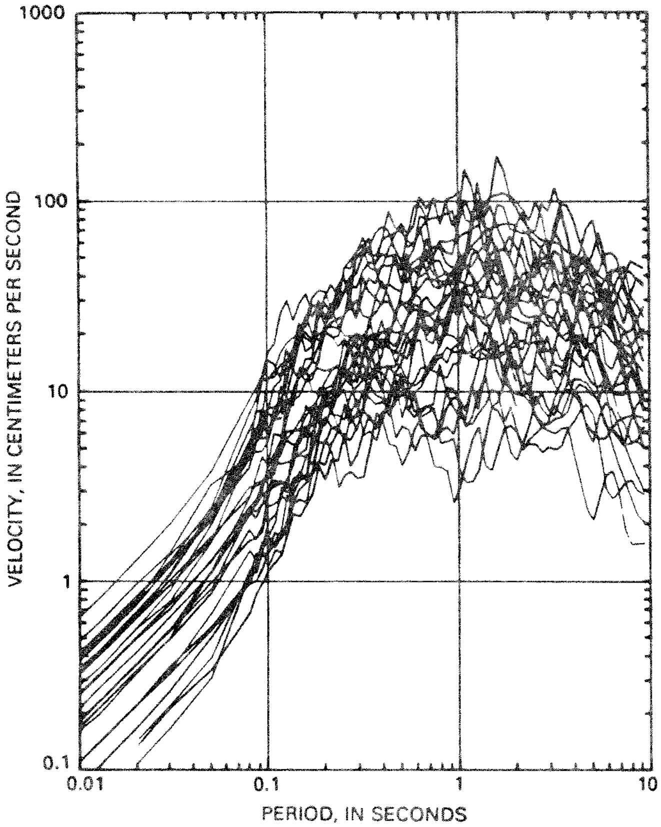


Figure 25. Response spectra (3 percent damped) for horizontal components of 15 records from strike-slip earthquakes, scaled to a distance of 50 km and a magnitude of 6.5 (from Heaton and others, 1986). Such scatter is typical of ground motions recorded at a given distance and magnitude.

RESEARCH POSSIBILITIES OF THREE-COMPONENT DIGITAL REGIONAL NETWORKS

The approximately 1,600 seismic stations in existing U.S. regional networks have the potential to form the world's largest and densest seismic array. This array could be used for highly innovative studies of earthquakes, the structure of our continent, and the structure and dynamics of the Earth. Unfortunately, the limited capabilities of the instrumentation in these arrays and the lack of standardization have severely limited the scope of research problems that have utilized regional array data. We now briefly summarize some of the research problems that will be analyzed using data from regional networks of modern three-component digital instruments.

Earthquake Studies

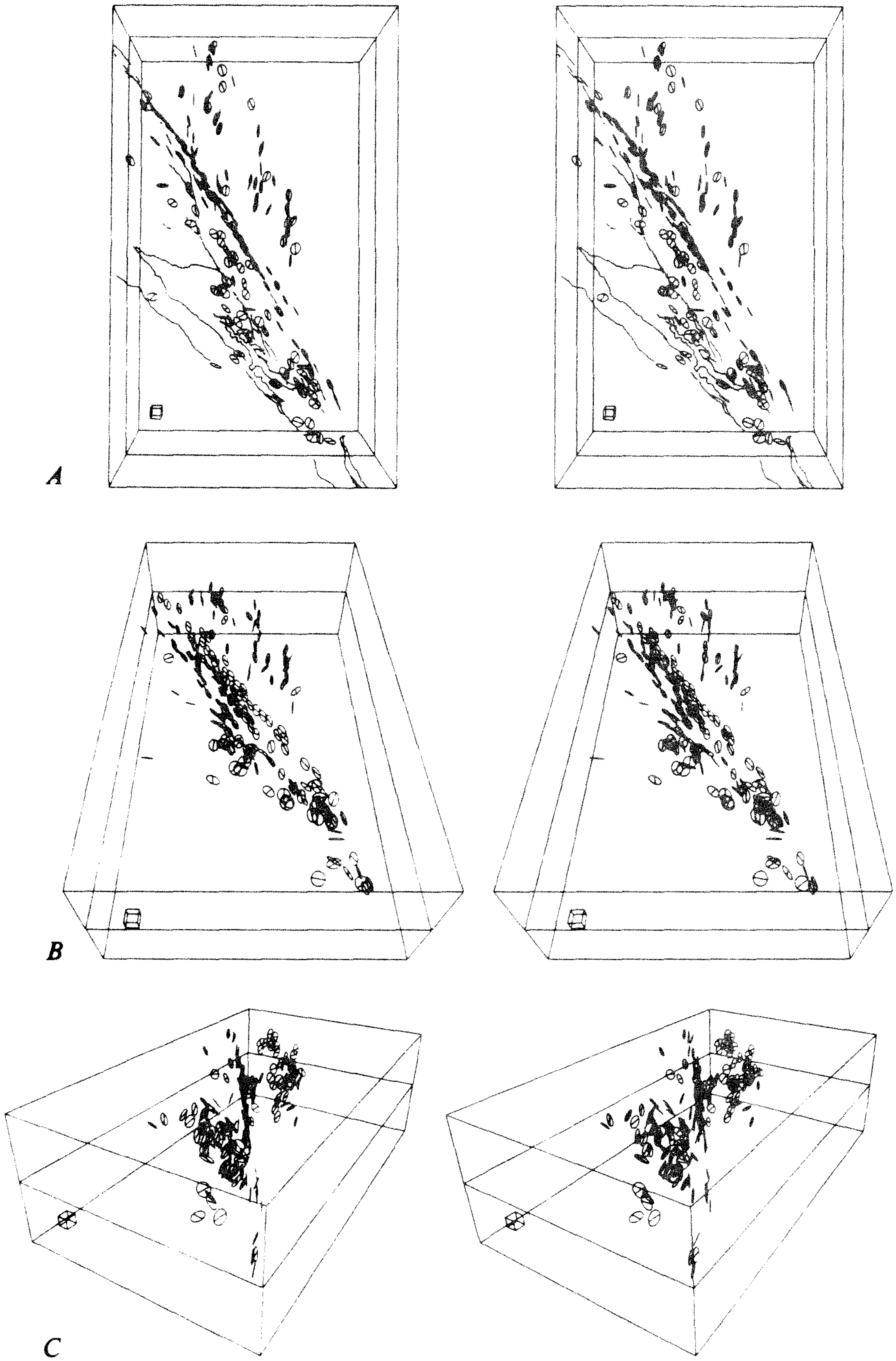
Earthquakes are the result of sudden changes in elastic strain within the Earth. Elastic strains within the Earth may be caused by several mechanisms that include the overall shifting of the Earth's plates (by far the most important), the migration of magma to the Earth's surface, readjustments to load on the Earth's surface (rebound of mountains due to erosion or glaciers), and injection or withdrawal of fluids. We can infer that some of these processes are occurring throughout the Earth. The Earth is constantly deforming, and sometimes this deformation is accompanied by earthquakes. However, most of the deformation within the Earth occurs slowly and steadily without earthquakes. When and where does deformation occur through unstable slip (earthquakes)? We wish to be able to better predict how large earthquakes will be and how often they will occur. We seek a better understanding of the fundamental physics of deformation in the Earth.

Seismicity Patterns

Perhaps the key motivation for constructing the existing regional seismic networks is the study of patterns of small earthquake occurrence. This is a very large subject with many volumes of literature, and only a few points can be made here. Seismic activity in California for 1980 through 1986 is shown in figure 4 (D.P. Hill, written commun., 1987). Data from more than 600 stations in three regional networks were combined to construct this figure. A number of major seismic lineations can be seen, and the majority of these coincide with recognized active faults. Some seismicity lineations occur in broad zones for which there is not an identifiable surface expression. One of the most striking features of this seismicity is the paucity of small earthquakes along the stretches of the San Andreas fault that experienced great earthquakes in 1857 and 1906. Stretches of the fault that are slipping steadily (creep) experienced the highest rate of small earthquake activity. Study of spatial patterns of small earthquakes helps to delineate changes in the physical properties of faults. These physical properties determine the size and frequency with which large earthquakes will occur. Bakun (1980) studied spatial seismicity patterns on the Calaveras fault of central California and identified a segment of the fault that was ultimately the source of the M_L 6.2, 24 April 1984, Morgan Hill earthquake. An example of the nature of the detailed seismicity patterns that can be seen in the vicinity of the Morgan Hill earthquake is shown in figure 26.

The study of distributions of seismicity is also very important in other parts of the United States. Seismicity defines the geometry of subduction zones in the Pacific Northwest, Alaska, Aleutian Islands, and the Commonwealth of Puerto

Figure 26. Stereoscopic views of locations and fault plane orientations for aftershocks of the *M* 6.2 1984 Morgan Hill earthquake (Oppenheimer and others, 1988). Each fault-plane solution is represented by a circle centered on a hypocenter and oriented in a preferred plane of slip. The line through the diameter is parallel to the slip vector. *A*, View from directly above showing surface fault traces. *B*, Oblique view from south. *C*, Oblique view from southeast along strike of Calaveras fault. Figure can be viewed with any standard stereoscope.


A
B
C

Rico. Seismicity patterns also help to define seismic gaps that may experience large earthquakes. Although there have been very large historic earthquakes in the Eastern United States, surface traces of the causative faults have not yet been identified. Nevertheless, the distribution of small earthquakes in the eastern United States allows the identification of lineations and zones of activity. Seismic activity in the central United States located with the regional network that is operated by St. Louis University is shown in figure 27. This was the source region of three very large earthquakes in 1811 and 1812 (Nuttli, 1973). Although very little has been known about the source of these earthquakes, modern seismicity in the region reveals a well-defined pattern of lineations that are thought to define the extent of the faults that were responsible for these important earthquakes. The distribution of seismicity is also the key tool for mapping the magma systems in active volcanoes. A cross section of seismicity beneath Hawaii's Kilauea Volcano (fig. 28; Klein and others, 1987) reveals a striking 40-km-deep pipe of seismicity that is believed to trace the magma supply system through the lithosphere.

Large earthquakes along subduction zones occur deep within the Earth and are almost never accompanied by recognizable surface rupture. Furthermore, many important shallow crustal earthquakes, such as those that occur in California, do not cause surface rupture. Recent examples are the *M* 6.5, 2 May 1983, Coalinga earthquake, the *M* 6.2, 24 April 1984, Morgan Hill earthquake, and the *M* 5.6, 8 July 1986, North Palm Springs earthquake. The spatial distribution of aftershocks from such earthquakes is the most important tool for defining the geometry and extent of the rupture surface for many earthquakes. Data from regional networks are essential for the study of aftershock distributions, and the absence of this information can result in fundamental misunderstandings of the nature of specific earthquakes.

Important patterns in the temporal distribution of earthquakes have also been observed. The occurrence of foreshocks and aftershocks are the most obvious examples of temporal patterns. The temporal distribution of foreshocks and aftershocks appears to vary regionally, and this variation seems to correlate with the tectonic environment. For example, swarms and multiple earthquakes (several mainshocks) often occur in extensional environments. In addition, Tajima and Kanamori (1985) reported that the temporal expansion of spatial distributions of aftershocks is small for subduction zones that are mostly locked, and the aftershock expansion is large for subduction zones that are slipping without large earthquakes. There are also indications that the average rate of seismicity may vary systematically with time for a given region. For instance, Ellsworth and others (1981) reported that seismic activity in central California was considerably higher in the half century preceding the great 1906 earthquake than in the half century following it. There are also several examples in which significant southern California earthquakes have been preceded by weeks to years of higher seismicity (Heaton, 1987). In addition, there is evidence that some earthquakes are preceded by months to years of seismic quiescence (Wyss and Habermann, 1988).

The existing U.S. regional seismic networks were designed primarily as a tool for the study of seismicity patterns, and in the last 10 years they have enabled a quantum leap in the knowledge of seismicity. However, even seismicity studies suffer from the limited capabilities of the existing networks. Limitations of the existing data have severely restricted the information available in these studies. Earthquake locations and magnitudes are generally well determined, particularly for the numerous small-magnitude events, as are focal mechanism solutions for most of the larger magnitude events. However, other essential physical measures of the earthquakes, such as moment tensor solutions, stress drop, and source dimension, are absent from virtually all catalogs and thus severely restrict the types of research that can be performed.

Most regional network stations record only the vertical component of ground motion, and therefore *S*-wave arrivals cannot be reliably recognized in many instances. These *S*-phases are of great value in the determination of hypocentral depth, a parameter of great significance to our understanding of earthquake physics. Furthermore, the limited dynamic range of the existing networks makes it very difficult to recognize significant events that may occur during crisis periods when the network is already off scale from events that have just occurred. Determination of earthquake size or magnitude is also an important problem that is limited by the capabilities of existing networks. Magnitudes are generally determined in a relative way with respect to a particular type and configuration of instruments. However, the configuration of any network changes in time, and it is difficult to know if an earthquake assigned a particular magnitude decades ago would still be given that same magnitude today or in the future. Problems of this type are eliminated by modern digital seismometers since they essentially record absolute levels of ground motion given in standard units. The use of three-component, high-dynamic-range seismometers in regional seismic networks promises to bring another quantum leap in our understanding of the spatial and temporal patterns of earthquake occurrence.

Source Characteristics

Ideally, the goal of seismic source studies is to achieve a sufficient knowledge of the physics of earthquake rupture so that the detailed rupture behavior of future earthquakes could be predicted in advance given knowledge of the Earth's mechanical properties and geological structure. To achieve this goal it is necessary to learn the state of stress within the Earth and the distribution of strong and weak zones within the Earth. In addition, we must be able to model the process of spontaneous rupture that occurs in heterogeneous regions.

While the gross kinematic aspects of earthquake sources are fairly well understood, their behavior is poorly known on

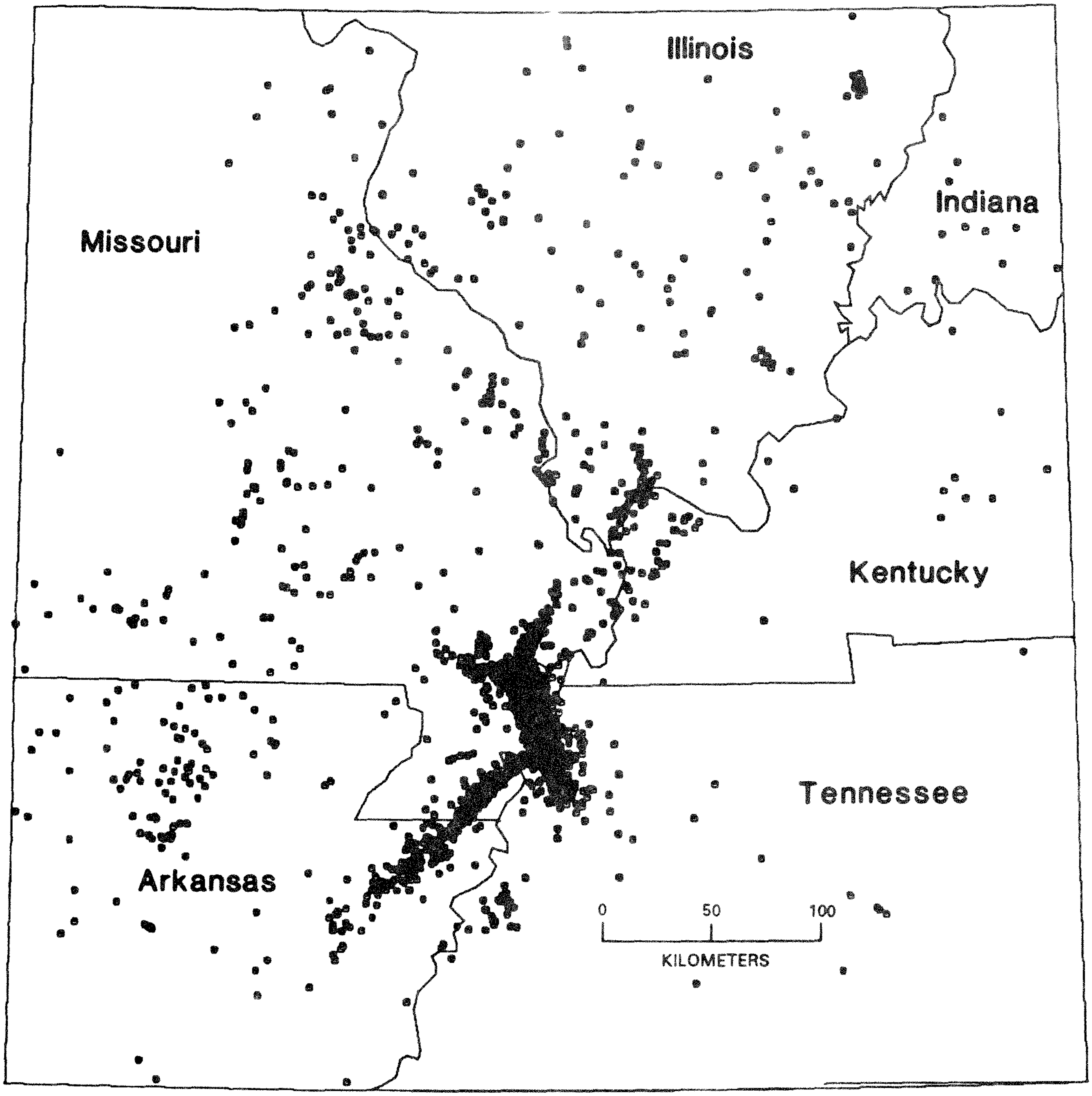


Figure 27. Seismicity in the central United States, 1974 through 1987 (2,900 events), located by seismic networks operated by St. Louis University, Memphis State University, the University of Kentucky, and the University of Michigan. A series of three very large earthquakes occurred in this region in 1811 and 1812 (Nuttli, 1973), and a repeat of similar events could result in catastrophic consequences (unpublished map courtesy of Robert Herrmann, St. Louis University).

time scales short compared to the total source duration and on distance scales short compared to the source extent. From an observational standpoint it is very important to analyze a large number of earthquakes in order to characterize the amount of nonuniformity in the distribution of slip on faults and the degree of irregularity with which rupture propagates along faults. Once these irregularities are observed, we must attempt to determine the irregular stress conditions and fault strength distributions that would result in the observed rupture behavior. In particular, recent advances have been made in the field of

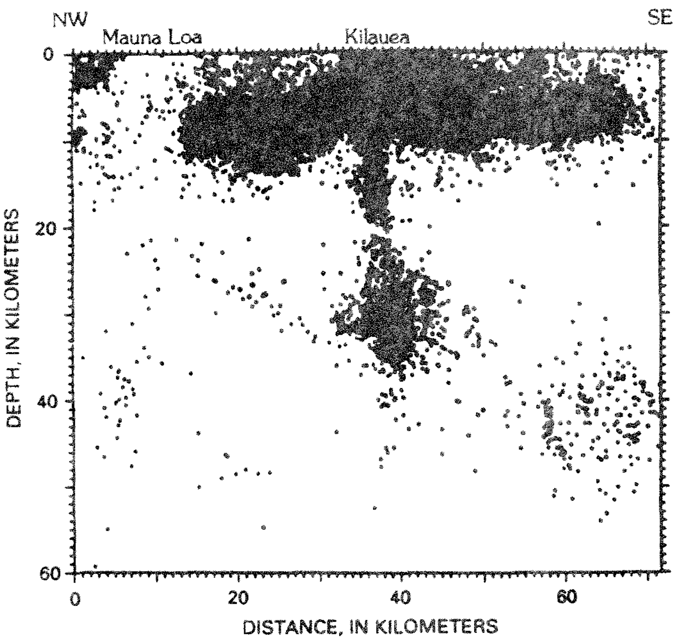


Figure 28. East-west cross section of seismicity through Kilauea Volcano, Hawaii, from the surface to the deepest seismicity at 60 km. Earthquakes, for the time period 1970 to 1983, appear to define the conduit through which magma ascends beneath Kilauea Volcano (Klein and others, 1987).

rock mechanics in the understanding of the mechanical properties of faults through state-variable friction laws. Using these laws, the material properties of faults can be characterized by two position-dependent material properties and a position- and time-dependent state variable. These parameters govern the quasistatic and dynamic behavior of faults, and are related to other properties such as end-zone length. By observing rupture behavior in earthquakes, it may be possible to infer the values of these parameters at depth on real faults.

A second poorly understood characteristic of earthquake sources is their geometry at depth and its relation to the dynamics of rupture and the resulting ground motions. Surface faulting is often observed to consist of a complex group of en echelon cracks, often with associated Riedel shears. Mapped faults are known to have bends and jogs, which have, in some cases, appeared to affect the process of rupture on the fault. It is very important to attempt to deduce the geometry of faulting at depth from the radiated motions, both to learn the geometry of the fault itself and to understand how rupture actually propagates when complicated zones of weakness are present and offer potential avenues for slip. Such information may ultimately be used to predict the characteristics of future earthquakes and their associated ground motions given a known fault geometry.

Numerical modeling of ground motion is the primary tool for studying seismic sources. Ground-motion data are inverted to discover the slip history as a function of time and space during earthquakes. Of course it is essential to understand and account for the effects of wave propagation on the recorded ground motions. These propagation effects are best studied using ground motions from small earthquakes that have relatively simple rupture histories. By studying the way that ground motions vary with source location and fault orientation, we can account for these effects when modeling ground motions from significant earthquakes. In order to accomplish this, we need three components of ground motion data that are spatially well distributed in regions that may produce significant earthquakes. High dynamic range is of very great importance since we require ground motions from very small and very large earthquakes that are recorded at the same site. Unfortunately, sensitive seismometers and strong-motion accelerometers have very rarely been collocated. Furthermore, the fact that current seismic networks record only the vertical component of motion over a very limited frequency band and amplitude range has severely limited their usefulness in seismic source studies.

An example of the way that ground motions recorded on dense regional networks can be used to study earthquake rupture is shown in figure 29 (Mendoza and Hartzell, 1988). The slip distribution on the Calaveras fault that best models strong ground motions observed during the 1984 Morgan Hill earthquake (Hartzell and Heaton, 1986) is shown together with the aftershock distribution (Cockerham and Eaton, 1987) determined using the USGS central California regional seismic network. It appears that the slip is highly heterogeneous and that the regions of high slip are characterized by a relative paucity of aftershocks. This same feature has been inferred in several other instances (Mendoza and Hartzell, 1988).

Strong-Motion Attenuation

Engineering design decisions are based partly on expected peak values of ground motion (acceleration, velocity, displacement) for the maximum expected earthquake at a given distance. The process used to estimate these values relies on strong-motion attenuation curves with distance. These curves are usually obtained from regression analysis of existing measurements of ground motion. Difficulties often arise, however, from the limited nature of the strong ground motion data set. It seems apparent that there are regional differences in these attenuation laws. For instance, strong ground motion in the Eastern and central United States seems to decay less rapidly with distance than in the southwestern United States. Although there is a fairly extensive strong-motion data set for the southwestern United States, there are few records for other parts of the country. However, ground-motion data from small earthquakes can be used to study the distance attenuation laws that would be expected during large earthquakes. Regional networks equipped to record broadband high-dynamic-range three-component ground motions could be used to obtain very reliable estimates of distance attenuation laws to predict strong shaking.

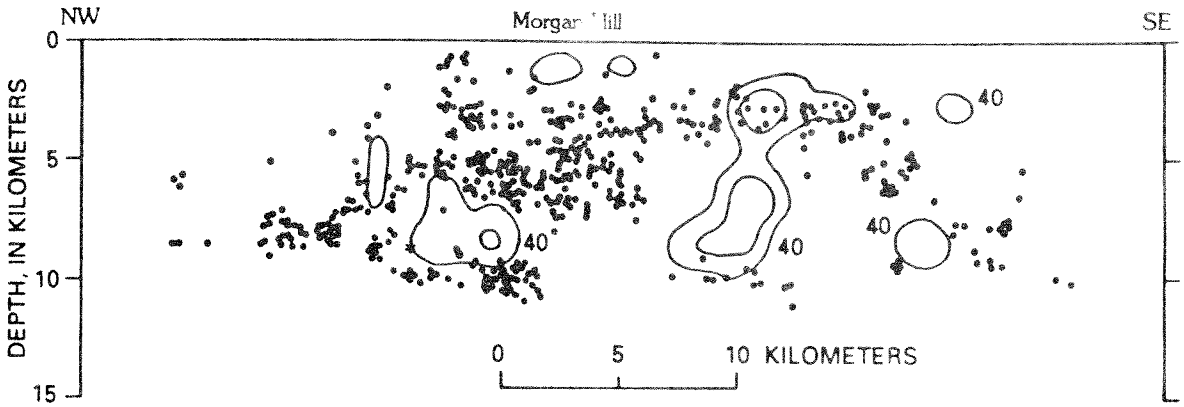


Figure 29. Aftershock distribution (dots) of 1984 Morgan Hill earthquake (from Cockerham and Eaton, 1987) coplotted with slip distribution that Hartzell and Heaton (1986) deduced from modeling strong ground motion (contours at 40-cm intervals). In this sequence (and several others) it appears that aftershock activity occurs mainly outside area of major coseismic slip (from Mendoza and Hartzell, 1988).

Strong-Motion Simulation

In the last section we discussed a commonly used method for estimating the ground motion of an earthquake at a given distance and magnitude. However, even if the distance and magnitude are known, there is large uncertainty in the determination of ground motions that will result. To illustrate, we show response spectra from horizontal ground motions recorded at distances near 50 km from shallow, crustal, strike-slip earthquakes of about magnitude 6.5 in figure 25. The largest ground motion is over 10 times larger than the smallest, and it is obvious that a wide variety of ground motions have occurred at a distance of about 50 km from M 6.5 strike-slip earthquakes. Wave propagation through geologically complex structures is one of the major reasons for the large observed scatter. In a previous section, we described how records from small earthquakes can be used to remove the effects of wave propagation from records of large earthquakes. In a similar manner, the records from small earthquakes can be used to simulate the nature of strong shaking to be expected when large earthquakes occur. That is, records from small earthquakes can be used as empirical Green's functions, and these Green's functions can be summed to simulate the shaking in the vicinity of the seismic station (Hartzell, 1978; Kanamori, 1979). If stations are located within metropolitan areas or near critical facilities, then important effects due to wave propagation can be anticipated.

Earth Structure and Wave Propagation

In our earlier discussion of the uses of existing networks, we pointed to numerous important studies of Earth structure that were made possible by the existence of regional networks. Most of these studies would have been impossible with sparse or temporary networks. In most instances and because of the nature of the data, these studies only use *P*-wave arrival times to infer large-scale variations in seismic velocities. However, the availability of broad-band three-component data from regional networks will greatly expand the nature of studies into the structure of the Earth and the manner in which waves travel through complex geologic structure. In particular, it will be possible to continuously observe the development in long-period waveforms as they sweep across entire regions. It will be possible to deterministically study the nature of and reasons for scatter in wave amplitudes that have been noted, but poorly understood. We now give some examples of the types of problems that will be studied with high-quality regional networks.

Shear Waves

The availability of three-component waveforms will dramatically improve the ability to study shear waves. Shear waves are typically very poorly recorded on vertical seismometers, and *S*-wave arrival times can be in serious error when only a vertical-component seismogram is used for analysis. Furthermore, interactions between *P* waves and vertically polarized *S* waves (*SV* waves) often complicates the interpretation of shear waves, and it is usually best to rotate motions into radial and tangential components so that tangential-component shear waves (*SH* waves) can be studied separately. This type of analysis is not possible with existing regional networks, but would be routine with high-quality three-component data.

Shear waves provide information about the Earth's interior that is independent from *P* waves. Since they do not propagate through fluids, the search for travel paths along which shear waves are missing (or attenuated) is an important tool for mapping the subsurface extent of magma bodies. Furthermore, low shear-wave velocities are often inferred for zones of high tectonic slip rates, the presence of petroleum deposits, and the presence of geothermal resources. The use of shear-wave information promises to open a new class of problems in the exploration of the Earth's interior.

Surface Waves

Surface waves are another class of seismic waves that are important for understanding the properties of the crust and uppermost mantle. They are also of interest because they may be an important factor in the seismic hazard of longer period structures (tall buildings, bridges, and so on). Although surface waves can have any period, they are generally important at periods of greater than 1 second. They are usually classified according to the polarization of the motions they produce, either transverse polarization (*SH*-type Love waves) or radial-vertical (*P-SV*-type Rayleigh waves). At large earthquake distances, these are usually the largest arrivals seen on a seismograph, and they contain important information about the average properties of the crust. Three-component data are essential for the identification and study of surface waves. Furthermore, the fact that these are relatively long-period waves means that they are usually not well recorded by existing short-period regional networks.

Understanding the Coda

The seismic coda has been the focus of considerable interest because it is thought that material properties of the Earth's lithosphere can be inferred from the coda, and because temporal variations in codas over periods of days to years may precede large earthquakes. The seismic coda, which is the part of the seismogram following the *S* wave, is generally thought to consist of body and surface waves scattered off material heterogeneities in the Earth's structure (Aki and Chouet, 1975). If the coda consists primarily of single scattered waves, then the energy in the coda samples a large volume of the lithosphere, and thus the characteristics of the coda may be sensitive to the large-scale properties of the crust. Many researchers have measured the temporal decay rate of the seismic coda in various frequency bands. These observations have been widely characterized using a measurement called coda-Q (Q_c), which has been observed to increase with frequency. Similarly, some researchers (for example, Jin and Aki, 1986; Novelo-Casanova and others, 1985) have observed temporal variations in coda-Q before large earthquakes. It has been hypothesized that variations in average crustal seismic velocity would be relevant to earthquake prediction (Poupinet and others, 1985). Also, the spectrum of the coda has been used to infer the earthquake source spectrum and the site response of the seismic station (Phillips and Aki, 1986).

Despite all these proposed uses of the seismic coda and Q_c, there is still no general agreement on what property of the crust is measured by Q_c, on the volume of the lithosphere sampled by the coda, on the relative proportion of single- and multiple-scattered energy in the coda, and on the relative importance of near-surface heterogeneity on the time domain and frequency domain characteristics of the coda. One common interpretation of the coda is that it consists of energy that is singly back scattered from the lithosphere (Aki and Chouet, 1975). However, there are alternative models, such as the multiple-scattering energy-flux model of Frankel and Wennerberg (1987). In the single-scattering model, Q_c represents the total transmission Q of the medium, including both the effects of scattering and anelastic attenuation, whereas in the multiple-scattering model, Q_c is at best a measure of only anelastic attenuation. Considerable disagreement exists on the portion of the lithosphere that is sampled by the coda. Levander and Hill (1985) have shown that a considerable portion of the coda energy may consist of surface waves, converted from body waves, that are trapped within the heterogeneous low-velocity region within a few kilometers of the Earth's surface. Spudich and Bostwick (1987) showed that the early part of the coda was dominated by multiply scattered waves reverberating within a few kilometers of the seismic station. If the coda is dominated by waves that sample only the near-surface zone, then Earth properties inferred from the coda will be biased toward their values near the surface of the Earth, and temporal changes in the coda may be related to near-surface fluctuations such as water table changes, rather than to temporal changes throughout the lithosphere. If the coda does not sample the entire lithosphere uniformly, then the widely observed frequency dependence of Q_c may not indicate a true frequency dependence of anelastic attenuation in the crust, but rather may result from different frequency components of the coda preferentially sampling different depth regions of a lithosphere in which anelastic attenuation is a function of depth.

Consequently, it is necessary to determine the type of waves composing the coda, the importance of multiple scattering, and the volume of the Earth that these waves sample. We need to learn the relative importance of scattering attenuation and anelastic attenuation. Moreover, we need to learn the frequency dependence and spatial variation of these Earth properties. Careful study of broad-band waveforms recorded at a large number of sites from a large variety of seismic sources will be the key to unraveling the physics of seismic coda.

Deep Structure of Basins and Mountains

Achieving better resolution of the structural makeup and physical properties of the deeper parts of the continental crust in the United States has become one of the major goals in the U.S. seismological community (Panel on Seismological Studies of the Continental Lithosphere, 1984; IRIS, 1984; Mooney, 1987). Regions of basins and mountains are key targets whose subsurface study is motivated by their typical association with earthquake processes, their economic potential (for instance, hydrocarbon and other mineral deposits), and the fundamental need for new, high-quality data to evaluate competing hypotheses about their origin and evolution.

As outlined in the 10-year program plan for seismic studies of the continental lithosphere (IRIS, 1984), outstanding research problems are both topical and geographical. Topical studies relating to crustal structure include, for example: the geometry and nature of intracrustal discontinuities and lateral heterogeneities in velocity structure; the subsurface geometry of structures such as faults, domes, batholiths, and volcanoes; and information relevant to understanding processes associated with basin formation and extension, continental terrane accretion, detachment tectonics, magmatic intrusion, and volcanism. Mooney (1987) summarized by geographical region both (1) the nature of important problems relating to crustal structure and (2) recent and current investigations.

Three-component digital seismic networks will significantly enhance imaging of tectonically important regions—even though controlled-source studies (near-vertical-incidence reflection and refraction/wide-angle reflection; see Mooney, 1987) will continue to be primary investigative tools. The analysis of seismic waves from local and distant earthquakes complements, and indeed provides well-known advantages over, the use of artificial seismic sources for probing crustal structure. Earthquake sources are impulsive, occur at depth, generate higher levels of energy over a broader frequency range, and radiate shear-wave energy. Compared to short-term experiments, seismic networks provide the advantage of continuous, long-term recording for sampling earthquake sources. The broader regional coverage of seismic networks may also be advantageous, although some tomographic applications require close spatial sampling that realistically will only be achieved with dense temporary arrays of digital seismographs.

The inversion of travel times of earthquake body waves is a well-established tool for imaging the three-dimensional velocity structure beneath a seismic array. For studying crustal-level structure, station spacing and the availability of horizontal-component recordings (for *S*-wave velocity structure) are important constraints. Some examples of the successful inversion of *P*-wave travel times for crustal structure using local earthquakes recorded by existing vertical-component seismic networks are given by Walk and Clayton (1987), Hearn and Clayton (1986a,b), and Kissling and others (1984). Networks of three-component seismographs would allow similar resolution of *S*-wave velocity structure.

Owens and others (1987) demonstrated the power of a single three-component digital station for resolving local crustal structure from earthquake sources. Using a teleseismic-waveform-inversion technique, they derived a detailed vertical shear-velocity structure for the crust beneath the receiver site using converted waves of the *P*-to-*S* type. Scherbaum (1987) described another single-station inversion method for subsurface impedance structure from locally recorded *SH* waves. Regional earthquake phases that propagate in the crust are known to be sensitive to lateral changes in crustal structure (Campillo, 1987) and offer yet another potential way of mapping crustal structure with three-component digital networks.

High-resolution three-dimensional inversion of local crustal structure will unquestionably be pursued with temporary dense arrays of IRIS/PASSCAL-type instruments, in the best cases combining the recording of both earthquakes and controlled sources (IRIS, 1984). Three-component digital seismic networks, with their temporal continuity and regional extent, will contribute to resolving subsurface crustal features through refined source definition of seismically active structures at depth, through inversion of both travel times and waveforms for *P*- and *S*-wave velocity structure, and through complementary interaction with controlled-source studies.

Structure of the Earth's Interior

Uniform, broad-band, high-dynamic-range instrumentation will enable far more complete resolution of deep Earth structure. In the future, the capabilities of regional networks will become even more important for the analysis of the structure of the Earth's mantle and core. These studies promise to provide the underpinnings for detailed models of the dynamics of plate tectonics, the evolution of the Earth, and origin of the Earth's magnetic field. In particular, density variations together with variations in the Earth's viscosity are the basic engine of plate tectonics. If these variations in the Earth's interior properties can be mapped, then we will have a much deeper understanding of plate tectonics. The use of data from regional networks will give an unprecedented look at the detailed structure not only beneath North America, but also along the travel path between North America and seismic sources located throughout the globe. Detailed studies of the nature of the Earth's interior discontinuities, such as the core-mantle boundary or discontinuities in the upper mantle, will be feasible. There are even suggestions that the currents of fluid iron within the Earth's core may be observable with seismological studies. If this is true, then very detailed observations will be necessary. Since these currents may also change over time scales of years, dense permanent seismic networks (such as those in regional networks) are desirable for such studies.

For simplicity, the Earth is usually considered to be elastically isotropic. Detailed studies, however, usually indicate the presence of anisotropy, often on the order of 5 percent. This effect is comparable to variations caused by changes in temperature and mineralogy. Anisotropy shows up as azimuthally dependent velocities, *S*-wave splitting (different time shift for different *S*-wave polarities), and discrepancies between Love and Rayleigh wave observations. Although anisotropy can be considered as an irritating complication, it contains important information about mineralogy, flow, and stress. Time-dependent anisotropy has even been proposed as a possible earthquake precursor. Since the most important diagnoses of anisotropy are *S*-wave splitting and Love-Rayleigh inversion, one requires broad-band, three-component seismic data. Since anisotropy may not be a second-order effect, the failure to recognize it may result in serious errors in our interpretation of the Earth's interior structure.

The anelastic properties of the Earth's interior are also of great importance for understanding its overall dynamics.

However, it is difficult to study anelastic attenuation of seismic waves because it is intertwined with geometric spreading, focusing, and defocusing. Because of this, studies of the Earth's elastic and anelastic properties go hand in hand. The study of anelasticity requires spectral studies which, in turn, require high dynamic range and broad-band data. High-quality modern three-component instruments are essential. Anelasticity sheds light on the physical properties of the crust, mantle and core, the temperature, and the state of stress (dislocation density). Anelasticity also causes the elastic properties, including the seismic velocities, to be frequency dependent. This information is required in detailed modeling of the Earth's structure.

Nuclear Discrimination

Artificial explosions are commonly observed on existing regional seismic networks. These explosions are commonly quarry blasts observed at distances less than several hundred kilometers, but many of these explosions are the result of testing of nuclear weapons. There has been considerable study of the problem of detecting and recognizing nuclear explosions throughout the world. Although earthquakes and explosions both generate *P*, *S*, and Rayleigh waves, explosive sources are fundamentally different from earthquake sources. One of the most important differences is the relatively short process time of an explosion compared with an earthquake. Furthermore, the spatial amplitude pattern (radiation pattern) is completely different for explosions and earthquakes. The high station density of regional networks makes them ideal for detecting both regional and teleseismic explosions. In particular, stacking of signals to detect waves coming from regions of particular interest (such as known test sites) can significantly improve signal-to-noise ratios. Because of their limited bandwidth, current regional networks are not particularly well suited for explosion discrimination problems. However, regional networks with enhanced instrumentation will be well suited for studying explosions.

CONCLUSIONS

There are approximately 1,600 permanent stations in existing U.S. regional seismic networks. These networks were constructed with the primary function of locating the earthquake activity of different regions of the United States, and they are well suited for this task. Because of the now-antiquated telemetry and data-logging technology that was available during their development 20 years ago, existing regional networks only record the vertical component of motion over a very restricted range of amplitudes and frequencies. This severely restricts the role of regional networks.

Modern seismic and telecommunications systems have the capability of measuring all three components of ground motion with amplitudes ranging from ambient ground noise to the strongest shaking experienced during earthquakes and over a very broad band of frequencies. This new generation of instrumentation has the potential to revolutionize the role of regional networks. Regional networks should play a vital role in emergency response activities during and after significant earthquakes. Furthermore, enhanced regional networks would vastly improve the national capability to study earthquake physics, strong ground motions, the structure of the crust, and the structure and dynamics of the Earth's interior. The formulation of a national plan to develop new digital high-dynamic-range, broad-band regional seismic networks should be given a high priority.

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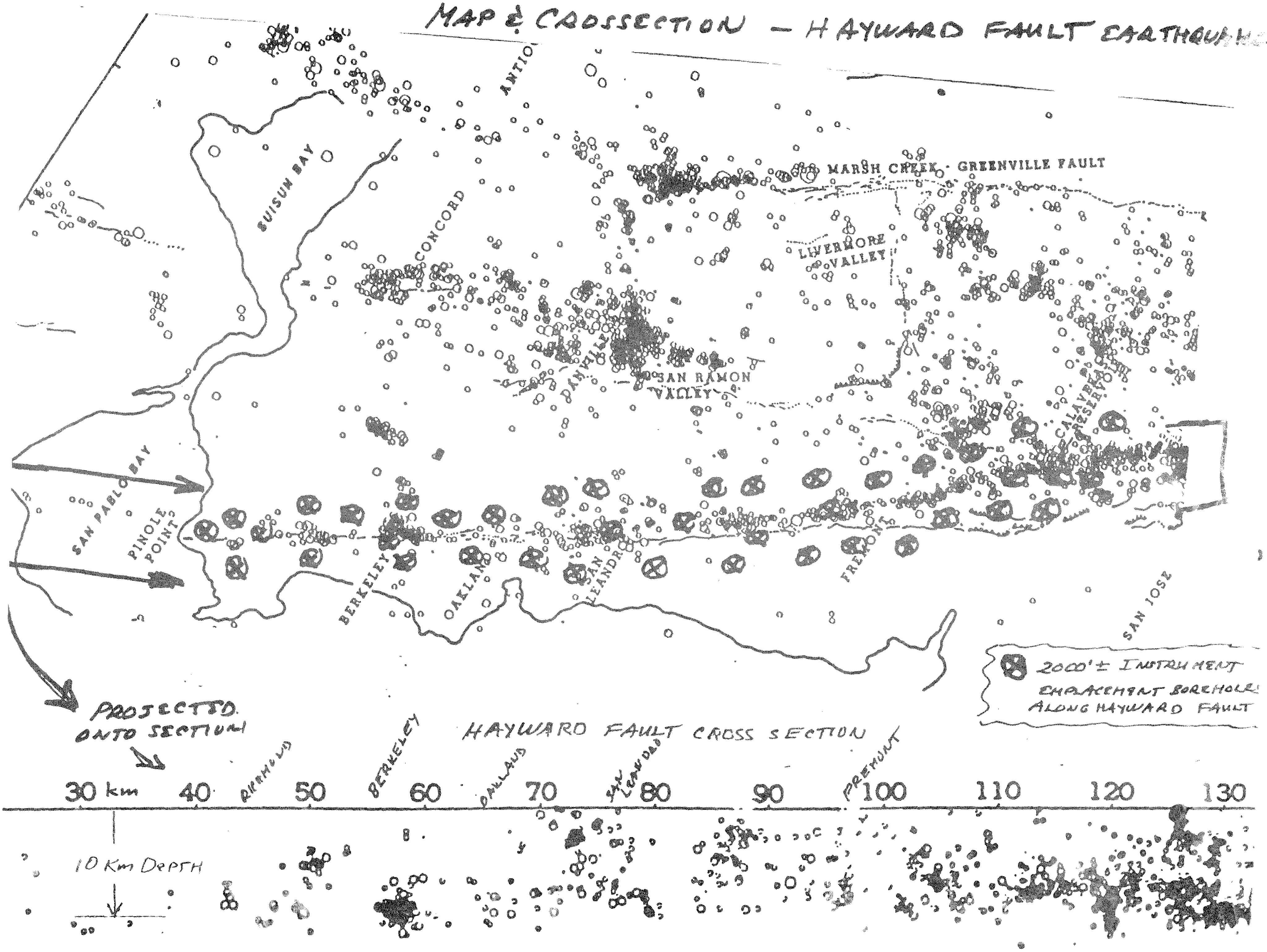
APPENDIX B

Hayward Fault Eathquakes/Map & Crossection
Dr. Allan Lindh

MAP & CROSSECTION – HAYWARD FAULT EARTHQUAKES



SAN FRANCISCO BAY AREA SEISMICITY
1981 - 1985

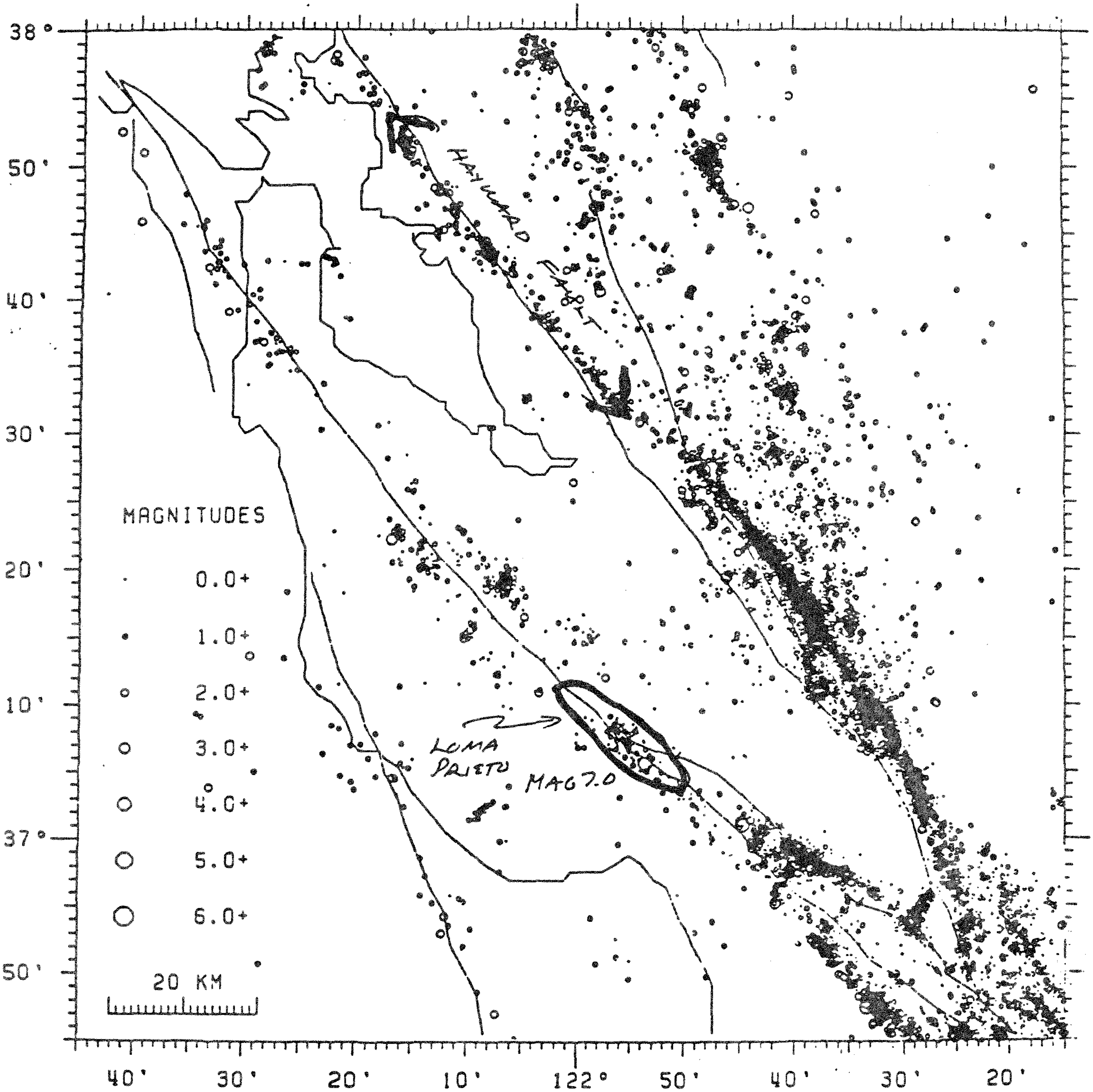


Figure 4b

APPENDIX C

Hayward Fault Surveillance Project
Dr. Thomas McEvilly

TESTIMONY 16 NOV 89
to the
JOINT COMMITTEE ON SCIENCE & TECHNOLOGY OF THE CALIFORNIA LEGISLATURE

by
Thomas V. McEvilly
Professor of Seismology
University of California, Berkeley, and
Director, Earth Sciences Division
Lawrence Berkeley Laboratory

MESSAGE:

IT IS APPROPRIATE AND URGENT AT THIS TIME TO APPLY THE TECHNOLOGY DEVELOPED AND DEMONSTRATED IN THE PARKFIELD PREDICTION EXPERIMENT TO THE HAYWARD FAULT

APPROPRIATE because the use of borehole-emplaced high-resolution seismic monitoring systems and accurate geodetic methods for observing crustal deformation have been demonstrated to be front-line technologies in earthquake prediction work, and

URGENT because the earthquake hazard of the Hayward fault is known to be great, but it is poorly understood in terms of both long-term slip behavior and the recurrence times of major earthquakes.

HAYWARD FAULT SURVEILLANCE PROJECT

A Proposed Real-Time On-Line Diagnostic Monitoring System for the Hayward Fault

A plan for Monitoring the Failure Process Underway on the Hayward Fault which will Lead to the Likely Next Magnitude 6.5-7 East Bay Earthquake

Put forward by seismologists of the University of California at Berkeley and the Lawrence Berkeley Laboratory for immediate consideration by the State of California

Anticipated collaborating scientific entities using the facility:

- U.S. Geological Survey
- Office of Emergency Services
- Southern California Earthquake Research Center
- California Division of Mines and Geology
- Other UC Campuses and Laboratories

SUMMARY

We propose the emplacement of a monitoring system, using the latest technologies and scientific methods developed over the past ten years in earthquake prediction research, for concentrated surveillance of the Hayward fault. Consisting of three elements - **a net of borehole-installed seismic sensors, a Global Positioning System receiver network for deformation monitoring, and a rapidly accessible data base and on-line computational system** - the proposed program requires $12.5M capitalization and $3M per year operational and analysis costs. Principal goals of the project are the timely detection of diagnostic changes in the tectonic environment and related response of the Hayward fault, better prediction of the expected large earthquakes in space and time, and more accurate estimates of the distribution of potentially damaging ground motions from these earthquakes.

BACKGROUND

The recent 10/17/89 magnitude 7 earthquake on the Santa Cruz Mountains section of the San Andreas fault (the Loma Prieta Earthquake) has highlighted the ever-present risk of earthquakes to the Bay Area. This event also serves to remind us that the Hayward fault which runs along the east side of San Francisco Bay presents an even greater threat to society. Because the Hayward fault is known to be capable of major earthquakes (such as in 1836 and 1868), because of the high level of cultural development along the fault, and because earthquakes on this fault are closer to dense population centers than are those in the Santa Cruz Mountains, the potential for death and property loss from a major earthquake on the Hayward fault is estimated to be substantially larger than that experienced in the earthquake of October 17. The 1868 earthquake on the Hayward fault, until 1906 known as *The Great Earthquake at San Francisco*, was preceded by an earthquake in 1865 in the Santa Cruz Mountains, very similar to the recent event. This apparent coincidence and that between the 1836 Hayward fault earthquake and the subsequent shocks on the peninsular San Andreas fault have heightened public awareness of the geographic extent of earthquake hazard in the East Bay.

We have learned much in the past 10 years through research under the National Earthquake Hazards Reduction Program, particularly in assessing probabilities for earthquakes on known active faults and in instrumental monitoring and data analysis for high-resolution studies of fault zone processes where a major earthquake is suspected to be nucleating, as in the Parkfield Prediction Experiment in central California. In addition, recent advances in computer networking and data-base management make it possible to place the critical data, virtually in real time, in the hands of those responsible for decision-making at the time of the emergency.

The University of California has recently committed substantial resources to the upgrade of instrumental facilities of the Berkeley Seismographic Stations. The upgrading program, developed over the past two years, will commence early in 1990. This proposal will take advantage of the new capabilities to be emplaced in the Berkeley center. It also will make good use of the advanced seismic computing systems and field logistics support in the Earth Sciences Division at Lawrence Berkeley Laboratory, where much of the Parkfield seismic system maintenance and data processing is done. These two institution will jointly install, operate and maintain the surveillance system.

PROPOSED HAYWARD FAULT MONITORING

In our considered view, several actions, given the present state of technology and knowledge, should be taken immediately to begin to monitor the activity on the dangerous Hayward fault:

1. Borehole-emplaced monitoring network.
   40 instrument emplacement holes should be drilled along the full East Bay length of the Hayward fault. Seismometers, acoustic sensors and dilatometers should be installed with operating specifications sufficient for high-resolution 3-dimensional imaging of the ongoing microearthquake and deformation processes. Methodologies developed at Parkfield are directly transferable to the Hayward fault. An auxiliary set of 15 portable instruments and supporting materials will be required to focus increased attention on areas showing anomalous behavior.

2. GPS Deformation Network
   The Global Positioning System (GPS) for absolute location of points on Earth's surface offers the capability for continuous monitoring of strain and its changes throughout the complex faulting system of the greater Bay Area. Some 20 GPS installations, about 15 fixed and 5 moveable, would provide the needed coverage for 'part in a million' or better strain resolution throughout the zone of interest.

3. The California 'SEISMONET' Data Facility
   Emergency services require on-line access to a state-of-activity data base which is redundant and robust. Modern computing and data storage/retrieving hardware and software can place the data acquired by the two monitoring systems recommended above directly into the hands of agencies, offices and scientists/engineers responsible for 'watching' the constant activity of the Hayward fault. Complementary systems in northern and southern California can assure that data will remain on line given a major earthquake in either area.

4. Hayward Fault Dynamics Project
   A continuing base funding level is required to provide for the analysis of the data stream, maintenance and operation of the system.

Estimated costs by element:

1.	Approximately$150K per borehole installation plus $2M for the hardened data acquisition system, and $0.5M for the portable recorders,	$8.5M
2.	Approximately $100K per system,	$2M
3.	Approximately $1M each redundant node (2 minimum),	$2M
4.	Approximately $3M annually	

This amounts to some $12.5M one-time capitalization costs, and a $3M per year operating budget commitment.

WHY NOW?

The technology exists for the first time to be able to measure the fault-zone process with a resolution that may allow prediction in a useful time of the next major Hayward fault earthquake.

The public is now aware of the major risk to the Bay Area of a large earthquake on the Hayward fault. This project offers enhanced peace of mind to a very large population.

Positive action by the state of California will provide the leverage for possible matching funds from federal agencies.

ANTICIPATED RESULTS OF THE HAYWARD FAULT SURVIELLANCE PROJECT

Definition of coherent segments of the Hayward fault and potential nucleation zones, to specify strong ground motion and hazard more accurately than possible with current source models.

Identification of the interrelation between microearthquake activity, fault creep and strain accumulation, in order to model the Hayward fault dynamics.

Pre-earthquake definition for emergency services of the probable extent of faulting and degree of damage expected from the coming earthquake

Real-time provision of estimated ground motion for specific sites such as critical facilities, available on-line to users needing automatic shut-down signals.

Possible short-term warning for process shut-down, critical alerts, evacuations, etc., depending upon the developing understanding of the fault zone behavior and predictive methodologies.

Proof-of-concept for a full-scale earthquake prediction monitoring system which can be duplicated elsewhere as needed.

PROJECT SCHEDULE

We anticipate full operation of the of the surveillance system can be achieved in three years.

SUMMARY

We can't afford not to do our best in mitigating the scope and extent of this serious earthquake hazard. The scientific and technical resources at the University of California, Berkeley and the Lawrence Berkeley Laboratory will ensure that the program is efficiently and successfully carried through.

Since 1887, and especially after the 1906 earthquake, the state has supported and relied on cutting-edge seismological studies at U.C. Berkeley. This plan has the same goals - only the price of the tools has increased.

There is a good chance that this project, if it can provide the expected greater understanding of the Hayward fault dynamics and an intermediate-to-short-term warning for major East Bay earthquakes, may save hundreds, if not thousands of lives.

TECHNICAL DETAILS

PROJECT MOTIVATION

Scientific and technical advances, made in the Parkfield Prediction Experiment of the National Earthquake Hazards Reduction Program, provide the basis for specific action in the Bay Area in response to the recent destructive Loma Prieta earthquake near Santa Cruz. Action is warranted because of the serious hazard present in the East Bay in the form of the Hayward fault, which is capable of producing magnitude 7 earthquakes, the most recent of which were experienced in 1836 and 1868. Public awareness of this threat has been heightened by the seriousness of the damage inflicted on areas in the East Bay and in San Francisco by the Loma Prieta earthquake, from a distance of some 70-80 km, whereas the Hayward fault traverses the entire length of the East Bay, cutting through nearly continuous major metropolitan centers.

The two technical elements of the proposed Hayward Fault Surveillance Project are based on promising results obtained at Parkfield. and in other investigations.

BOREHOLE SEISMIC NETWORK

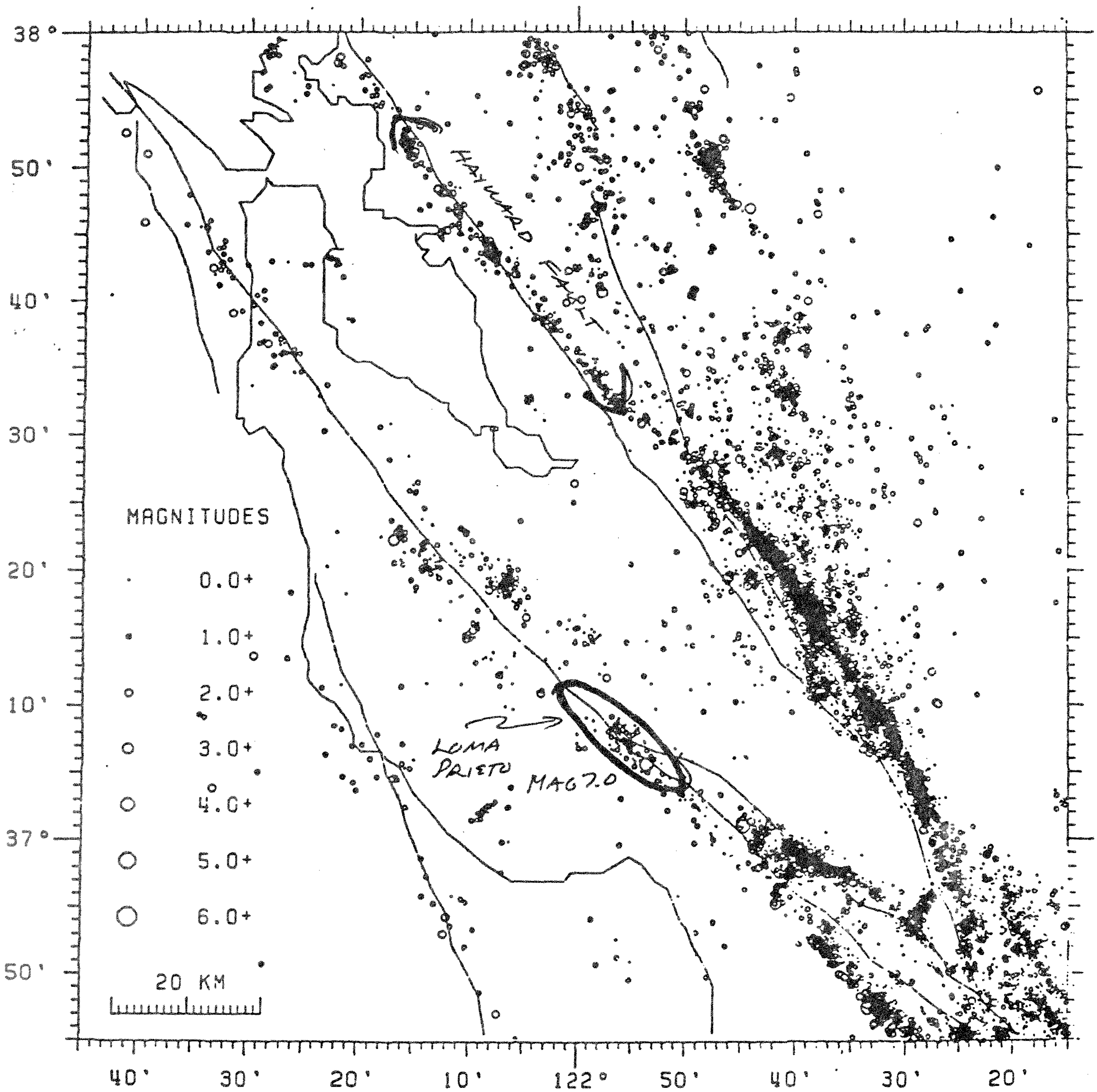
In the Parkfield experiment seismometers are cemented into boreholes at depths of 600-900 feet, resulting in a sensitivity to earthquakes some ten times smaller than those detectable at Earth's surface with conventional seismic installations. In addition, signals are recorded containing frequencies of 100 Hz and more, allowing timing precision to one millisecond or less. This timing resolution in turn yields hypocenter location precisions of a few tens of meters. The result is that, for probably the first time, we are able to view individual small 'patches' of high friction on the fault surface, and to watch them fail in the microseismic process of fault slip preparatory to a magniitude 6 earthquake on the San Andreas. If any observation of fine-scale seismicity is going to allow for eventual predictive capability, this indeed is it. Three is no reason <u>not</u> to put this system into operation on the Hayward fault now, in order to begin the monitoring of that fault at similar high resolution. In addition to conventional high sensitivity seismometers, the instrument packages to be installed in the deep boreholes will include sensors for acoustic emissions detection and borehole strainmeters, along with sensors of fluid pressure. Emplacement depths will have to be about 2000 feet, in order to avoid the continuous seismic noise created by the constant activity in the cities on the earth's surface above. Data from these instruments, at some 40 sites along the fault, will produce the required high-resolution picture of the Hayward fault behavior.

GPS NETWORK

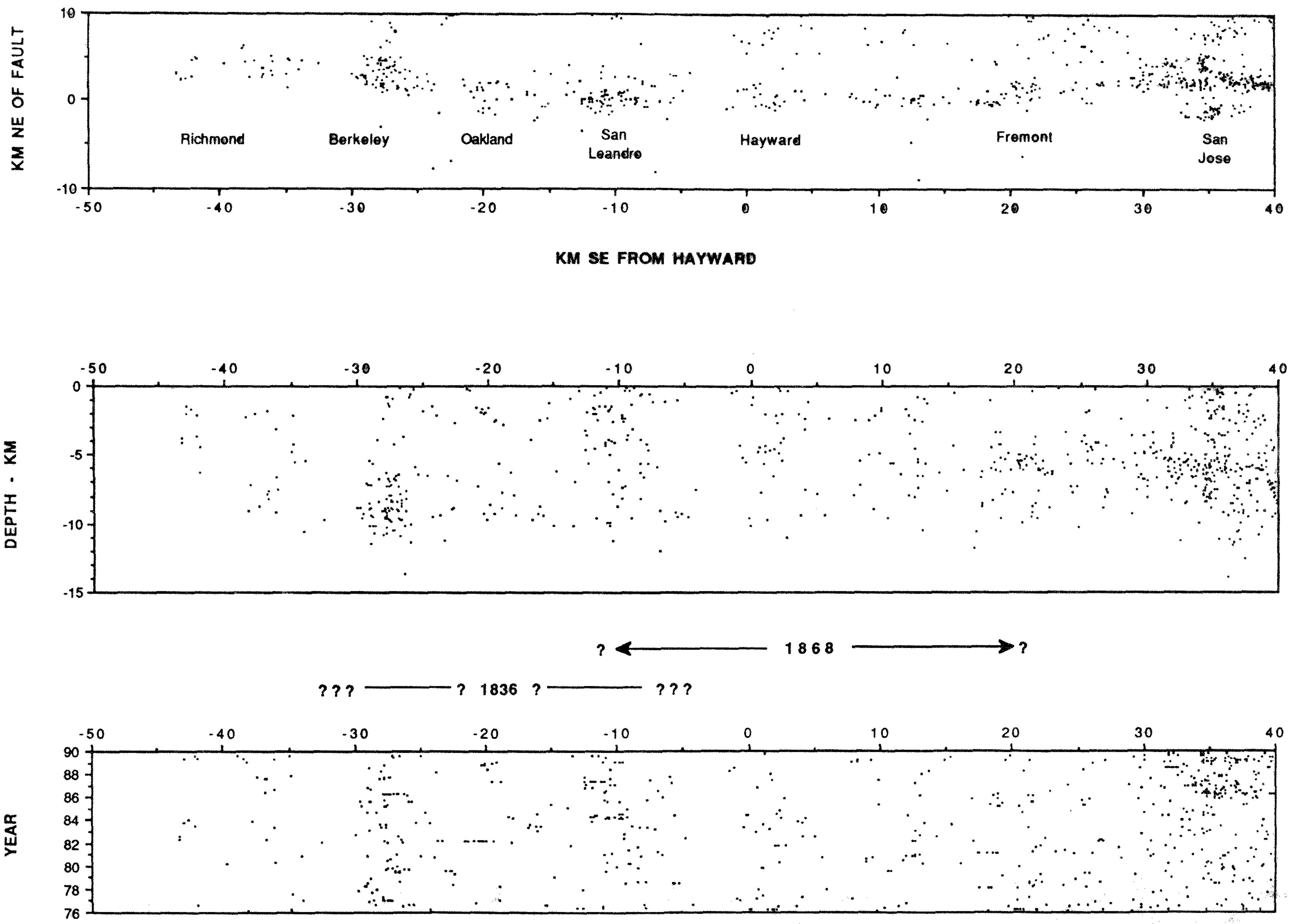
These remarkable instruments are just proving their value in continuous monitoring of crustal deformation. Sub-centimeter resolution of relative motion between two points many kilometers apart on Earth's surface provides a monitoring capability of better than part-per-million in strain. A GPS network of the type proposed here is already operational on-line in Japan. Experience at Parkfield with the two-color laser distance ranging system has demonstrated the great value of crustal deformation monitoring in understanding fault zone processes. Tectonic deformation on the scale affecting the Bay Area can be detected in several weeks' GPS observations. This capability, installed at sites from the coast to Mt. Diablo, will provide a continuous view of the pattern of relative deformation throughout the network of large faults in the Bay Area, at a resolution in space and time adequate to understand the partitioning of stress among the major seismogenic faults in the system. This information is critical to the development of realistic models for Hayward fault loading and ultimate slip in major earthquakes.

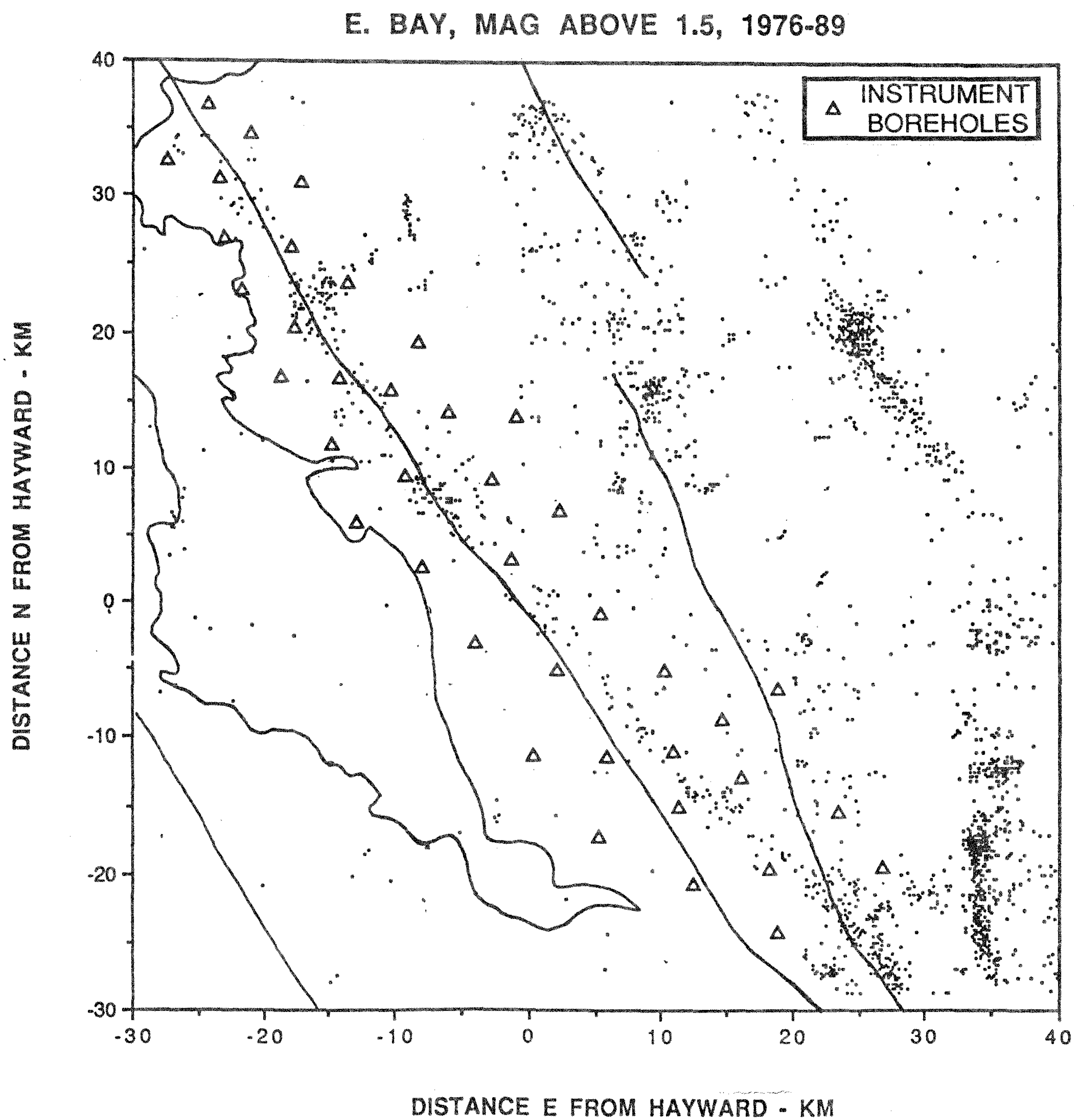
T.V. McEvilly
15 Nov 89

SAN FRANCISCO BAY AREA SEISMICITY
1981 - 1985



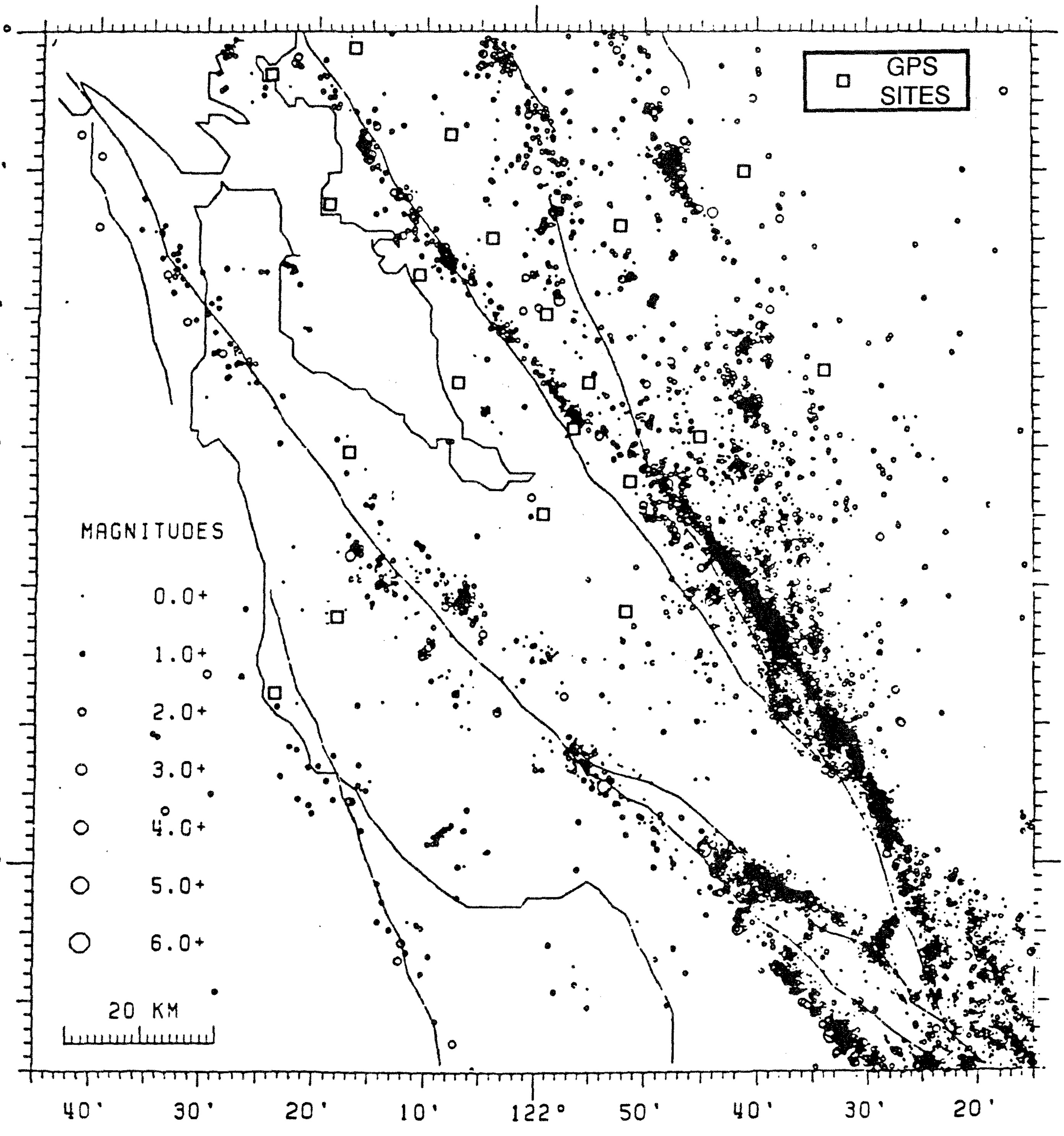
HAYWARD FAULT EARTHQUAKES, 1976-89
MAGNITUDE ABOVE 1.5





E. BAY, MAG ABOVE 1.5, 1976-89
INSTRUMENT BOREHOLES
DISTANCE N FROM HAYWARD - KM
DISTANCE E FROM HAYWARD - KM
40
30
20
10
0
-10
-20
-30
-30
-20
-10
0
10
20
30
40

SAN FRANCISCO BAY AREA SEISMICITY 1981 - 1985



Lawrence Berkeley Laboratory
1 Cyclotron Road Berkeley, California 94720
(415) 486-4000 • FTS 451-4000

November 27, 1989

Senator John Garamendi
Joint Committee on Science & Technology
State Capitol
Sacramento, CA 95814

Dear Senator Garamendi:

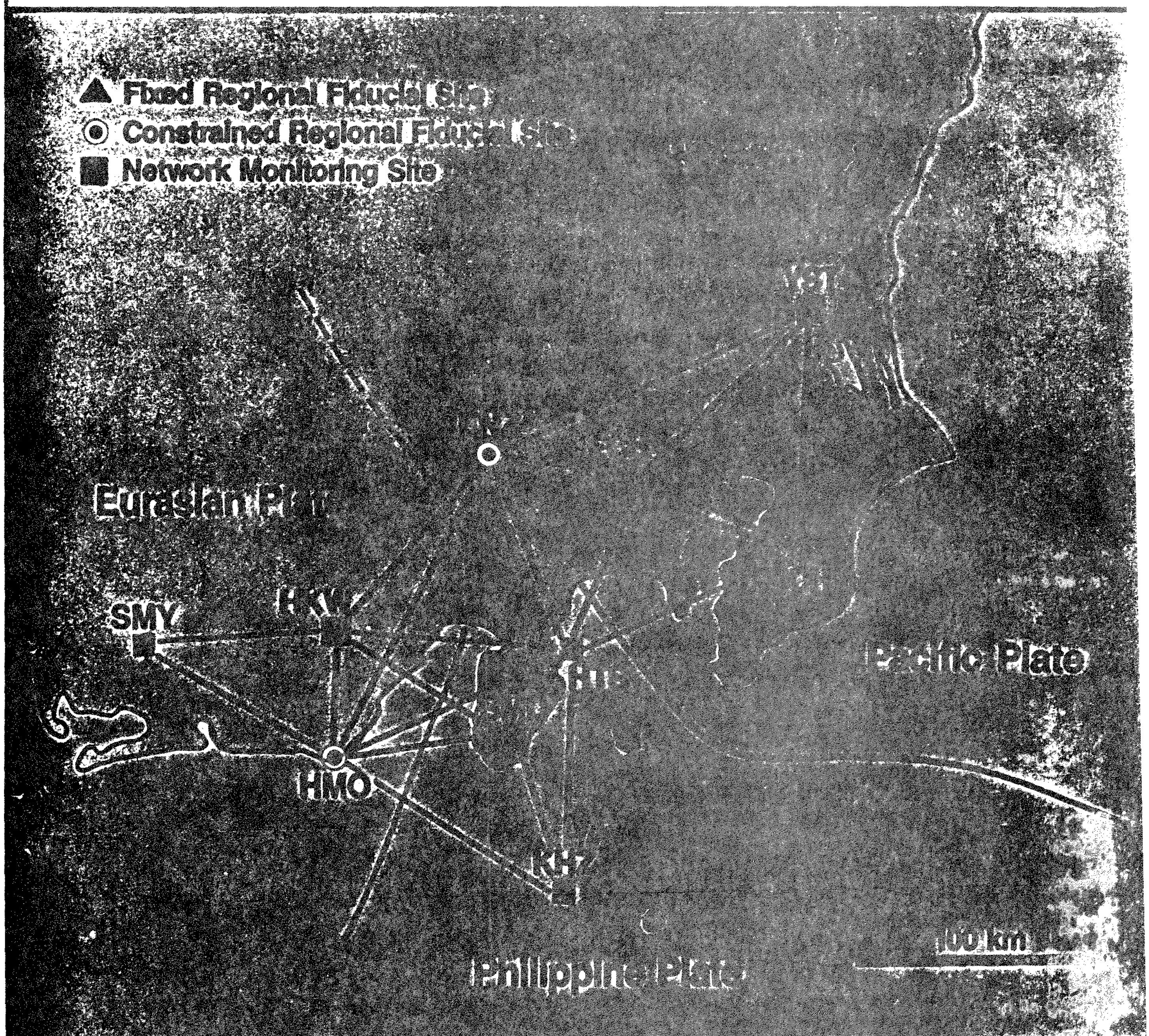
Per your request, I transmit the accompanying materials on the use of GPS (Global Positioning System) in Japan,which were presented, along with the hardcopy furnished at Pasadena, to your hearing on 16 November.

The three figures illustrate the recent deployment of a regional GPS network in Japan for seismic and volcanic hazard monitoring, and the successful detection of the deformation preceding the eruption in July this year of the Teishi Volcano off the Izu peninsula. These are important observations as they probably represent the first definitive results of a network of fixed GPS monitoring stations, similar to those proposed in the Hayward Fault Surveillance Project reviewed for your Joint Committee (I enclose another copy of this proposal). This surveillance system, if implemented initially on the Hayward fault, could gradually be extended to include the major hazardous fault systems in California by, say, the year 2000, at a cost of some $5M per year.

Sincerely,

Thomas V. McEvilly
Professor of Seismology and
Director, Earth Sciences Division

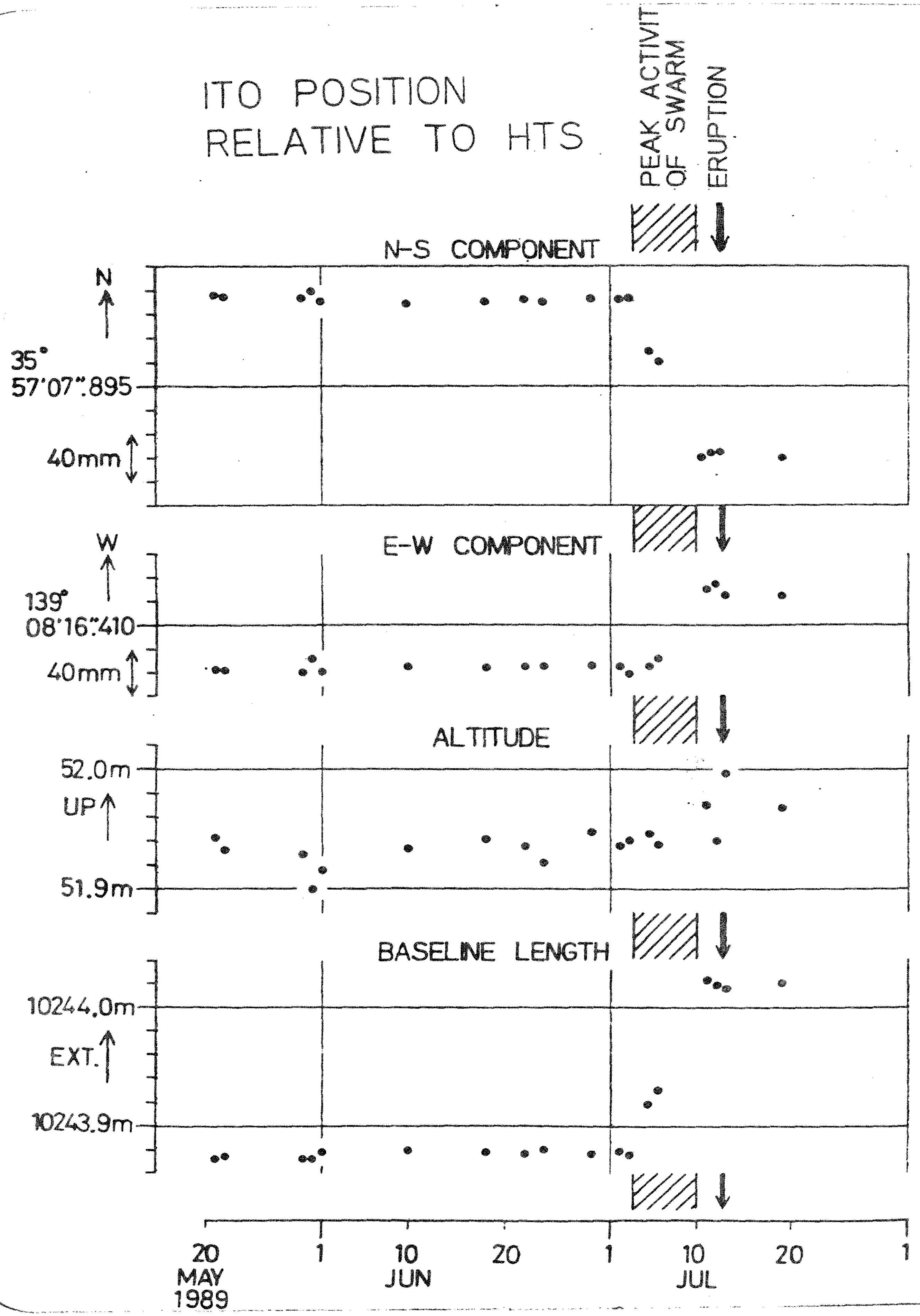
GPS Crustal Motion Monitoring System using Aero Service MINI-MAC™ GPS receivers and SONAP™ software

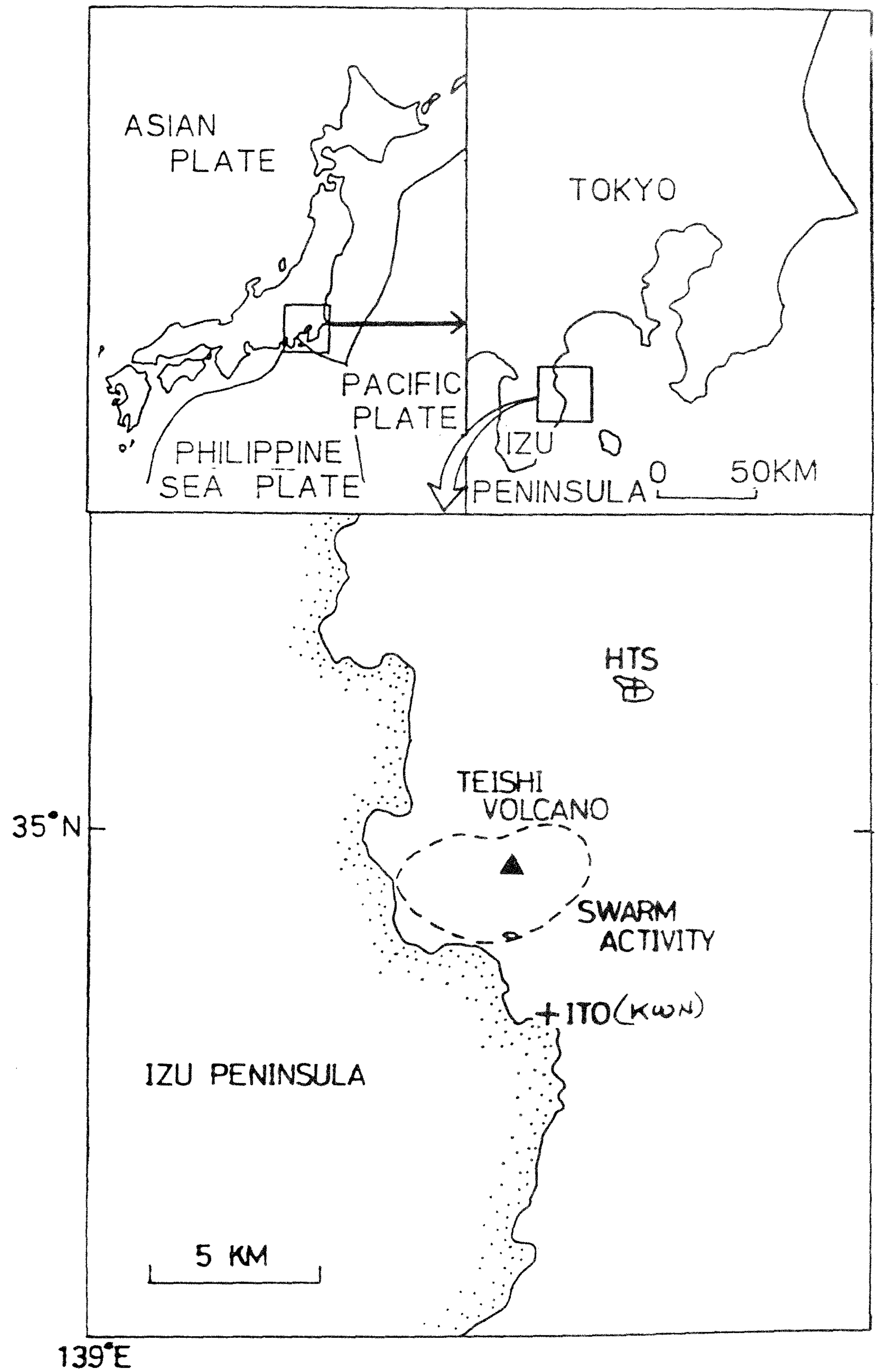


Western Atlas International

A Litton Dresser Company

AERO SERVICE


ITO POSITION
RELATIVE TO HTS
PEAK ACTIVIT
OF SWARM
ERUPTION
N-S COMPONENT
N
35°
57'07".895
40mm
E-W COMPONENT
W
139°
08'16".410
40mm
ALTITUDE
52.0m
UP
51.9m
BASELINE LENGTH
10244.0m
EXT.
10243.9m
20
MAY
1989
1
10
JUN
20
1
10
JUL
20
1


ASIAN
PLATE
PACIFIC
PLATE
PHILIPPINE
SEA PLATE
TOKYO
IZU
PENINSULA
0 50KM
HTS
TEISHI
VOLCANO
35°N
SWARM
ACTIVITY
+ITO(KWN)
IZU PENINSULA
5 KM
139°E

<u>APPENDIX D</u>

Earthquake Hazards From Buried Faults In
The Los Angeles Metropolitan Area
Dr. Egill Haukkson

EARTHQUAKE HAZARDS FROM BURIED FAULTS IN THE LOS ANGELES METROPOLITAN AREA

Presented to Senator Garamendi, at a hearing on earthquake hazards mitigation
held at Caltech, November, 16 1989, by Egill Hauksson,
Dept of Geological Sciences, Univ. of Southern California

The occurrence of the 1987 Whittier Narrows earthquake (M_L=5.9), which presented new and previously unrecognized earthquake hazards, has revised our understanding of earthquake hazards in the Los Angeles Metropolitan area. We have come to realize that:

* Moderate-sized earthquakes do not necessarily occur along well-mapped, universally recognized faults strands.

* These events are often located in the basement rocks beneath warps and uplifts in the overlying sedimentary section, which are common in the L.A. basin. This conclusion is reinforced by other California earthquakes in recent years, such as: Kern County, 1952, Coalinga, 1983, Santa Barbara, 1978, Pt. Mugu, 1973, and Malibu, 1979.

* The Whittier Narrows earthquake occurred beneath a zone of uplifts stretching from Whittier, through Downtown and the Wilshire Corridor, to Malibu; these faults are collectively called the Elysian Park fault system. A second such zone exists beneath the South Bay area of Los Angeles, called the Torrance-Wilmington fault system.

* These kinds of earthquakes and their causal fault structures have not been adequately incorporated into earthquake hazards assessments for the Los Angeles area. For example, "design" earthquakes typically deal only with events on the San Andreas and the Newport-Inglewood faults.

From these realizations rise questions that need to be addressed vis-a-vis these new recognized hazards. Some of the important questions are:

* Is the Elysian Park fault system a single continuous fault capable of a M$\geq$7.5 earthquakes, or alternatively, is it segmented and only capable of generating M=6.0 events? Are Loma Prieta size events possible?

* If the zone is segmented, what geologic structures control the segmentation, and how can they be recognized; where are the potential sites of future M=6 "Whittier Narrows Earthquakes"?

* What are the long-term geologic and short-term geodetic slip rates of the Elysian Park fault system?

* Is the Torrance-Wilmington fault system a single continuous fault or is it segmented? What are the geologic and geodetic slip rates?

APPENDIX E

Notes
Dr. Hiroo Kanamori

Prediction (Forecast)

	Present (range)	"Public"
Time	30 years	a few days
Size	0.5 unit	0.5 unit
Place	30 miles	10 miles
Probability	50 %	90 %

Uncertainties Arise from

- Variation in Strength of Crust
- Triggering
- Incomplete Knowledge of Earthquake Physics

Given These Uncertainties

To Minimize Seismic Hazards:	Research and Facilities needed
After	
"Realtime" Information (Location, Magnitude, Rupture Pattern) to allow effective emergency services. to forecast what will happen.	Realtime Network Robust Communication Development of Methodology for Realtime Seismology Global and Regional Network Human Resources Archiving Old Data
Before	
Planning based on long-term forecast. Estimation of ground motion Retrofitting weak structures	Broadband Seismic Source Study Evaluation of Path and Site Effect Regional Network Portable Instrument Human Resources (Seismology-Engineering)

Calls Received at PAS after the Loma Prieta Earthquake
(Origin Time 10/18/1989 00:04:15 GMT)

10/18/1989
00:15:09 brad cit
00:23:36 hiroo
00:23:36 hiroo
00:50:13 hiroo
01:43:53 Mark T., Woods, NU
02:21:19 U of W gopher project
02:56:50 hiroo
03:06:31 ?
03:34:26 ...
03:44:42 Seismo. Lab. Caltech
04:16;08 U of W gopher project
04:40:48 d. Wiens washington Univ
05:01:22 hiroo

05:17:26 Kenji Satake at Cambridge
05:29:57 Kenji Satake at Cambridge
05:40:42 Kenji Satake at Cambridge
05:47:30 K. Abe ERI, Tokyo
06:13:11 HEATON USGS
06:54:25 HEATON USGS
07:13:53 HEATON USGs
07:45:52 abe, k, eri, tokyo thanks for your service
08:40:33 a. morelli mednet-ing roma
09:23:05 salvatore mazza mednet group -ing roma
10:03:21 salvatore mazza mednet group -ing roma

12:17:55 E.A. Okal, NU
13:09:51 jms
13:55:15 D. W. Forsyth Brown U.
14:07:07 hiroo
14:20:37 Mark T. Woods, Northwestern Univ.

15:13:04 Galley - Harvard EPS
15:26:20 ---
15:59:30 day--sdsu
16:18:25 Carl R. Daudt, Purdue Univ., W Laf IN 47907
16:49:30 Carl R. Daudt, Purdue Univ
17:11:48 Carl R. Daudt
17:47:54 ejhaug, St. Louis U.
18:04:00 susan beck llnl
18:22:50 SUSAN BECK LLNL
18:59:00 brad cit
19:54:09 ---

21:19:14 brad cit
22:26:34 susan beck llnl
23:03:42 susan beck llnl
23:44:42 susan beck llnl

10/19/1989
00:03:23 susan beck llnl
00:26:23 susan beck llnl

01:31:58 cohee/wcc
05:12:36 cohee
05:49:45 HEATON USGS

07:05:34 brad cit

13:47:14 Galley - Harvard EPS
15:22:14 hiroo
15:42:09 hiroo
15:51:04 Hitoshi Kawakatsu Geological Survey of Japan

17:03:42 Keane - asl
18:50:35 susan beck
21:29:12 brad cit
13:47:40 rhett butler, iris gsn
16:10:46 Mark T. Woods, Northwestern UNIV

21:36:34 brad cit
22:05:16 logout
23:06:07 brad cit
00:47:25 mori
01:23:09 mori
02:05:46 MORI

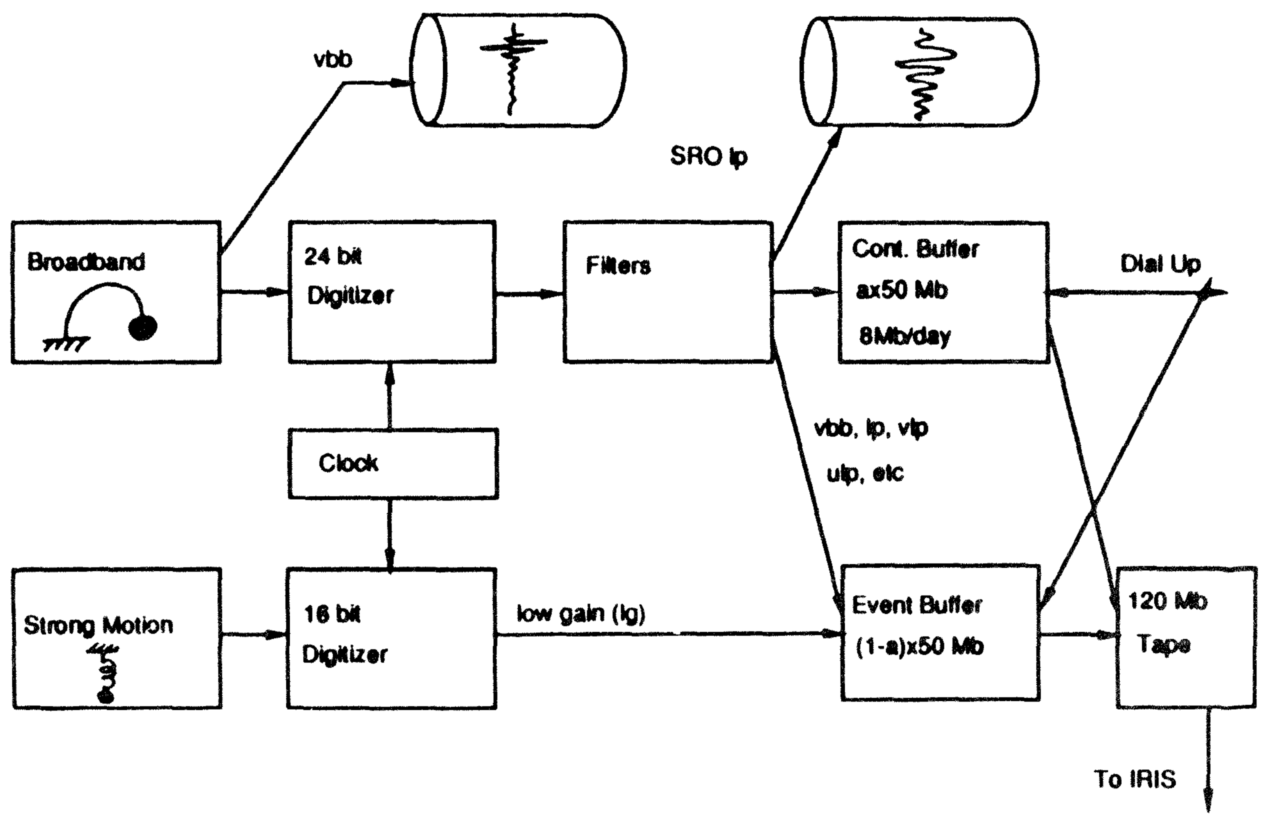
04:38:53 coheeheadism
04:47:09 cohee
05:03:32 HEATON USGS
05:42:40 HEATON USGS
06:12:30 HEATON USGS
06:34:18 HEATON USGS

09:21:21 Y. Yoshida ERI U. Tokyo
17:35:26 hiroo

APPENDIX F

Pasadena Very-Broad Band System (IRIS, TERRAscope)

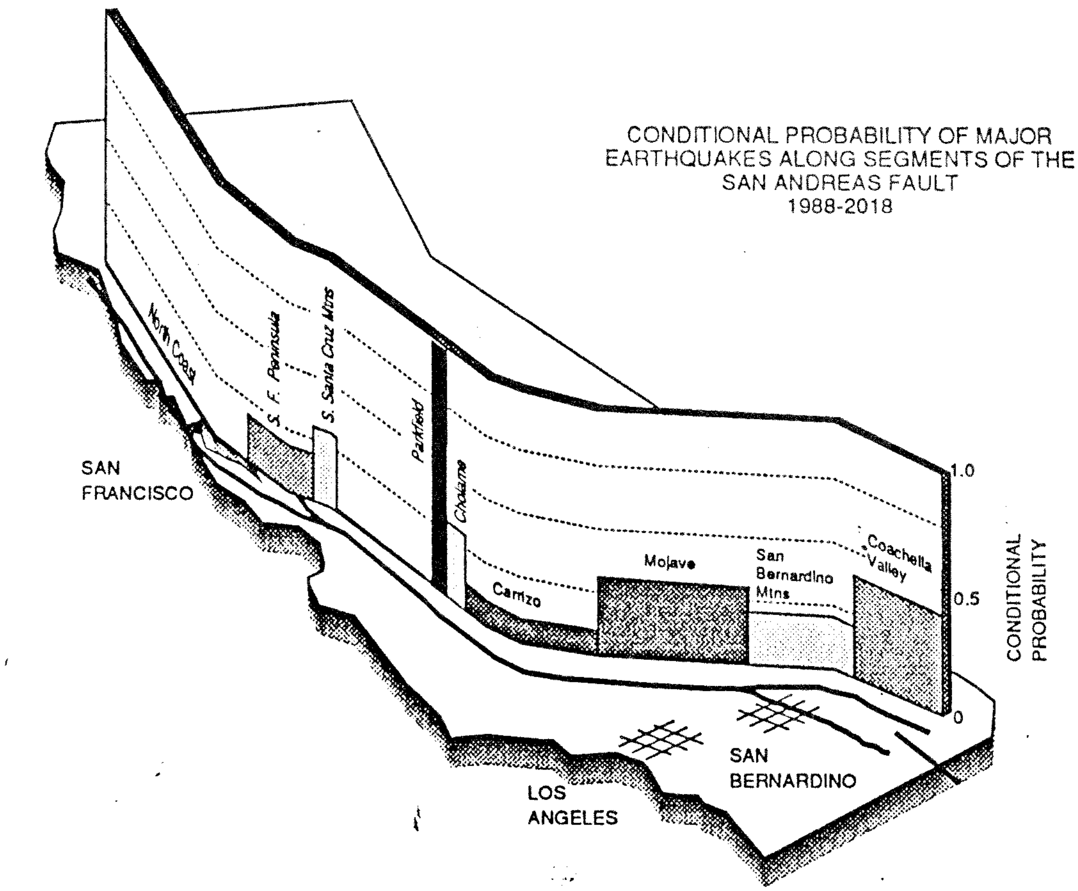
Dr. Don Anderson



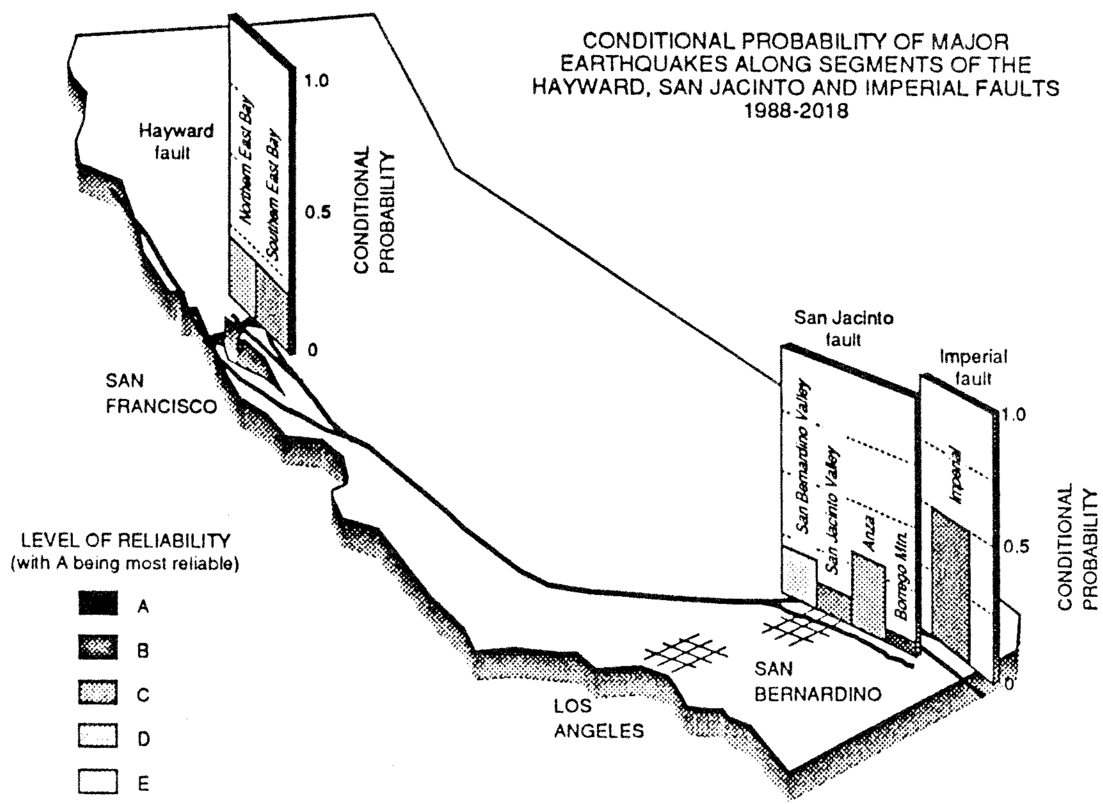
Pasadena Very-Broadband System (IRIS, TERRAscope)

APPENDIX G

Probability of Earthquakes
Dr. Kerry Sieh



CONDITIONAL PROBABILITY OF MAJOR EARTHQUAKES ALONG SEGMENTS OF THE SAN ANDREAS FAULT 1988-2018
North Coast
S. F. Peninsula
S. Santa Cruz Mtns
Parkfield
Cholame
Carrizo
Mojave
San Bernardino Mtns
Coachella Valley
1.0
0.5
0
CONDITIONAL PROBABILITY
SAN FRANCISCO
LOS ANGELES
SAN BERNARDINO



CONDITIONAL PROBABILITY OF MAJOR EARTHQUAKES ALONG SEGMENTS OF THE HAYWARD, SAN JACINTO AND IMPERIAL FAULTS 1988-2018
Hayward fault
Northern East Bay
Southern East Bay
1.0
0.5
0
CONDITIONAL PROBABILITY
SAN FRANCISCO
San Jacinto fault
Imperial fault
San Bernardino Valley
San Jacinto Valley
Anza
Borrego Mtn.
Imperial
LOS ANGELES
SAN BERNARDINO
LEVEL OF RELIABILITY
(with A being most reliable)
A
B
C
D
E

Figure 4.4a Postulated Magnitude 7.3 Earthquake on the Mojave Segment of the San Andreas Fault Epicenter near Lebec

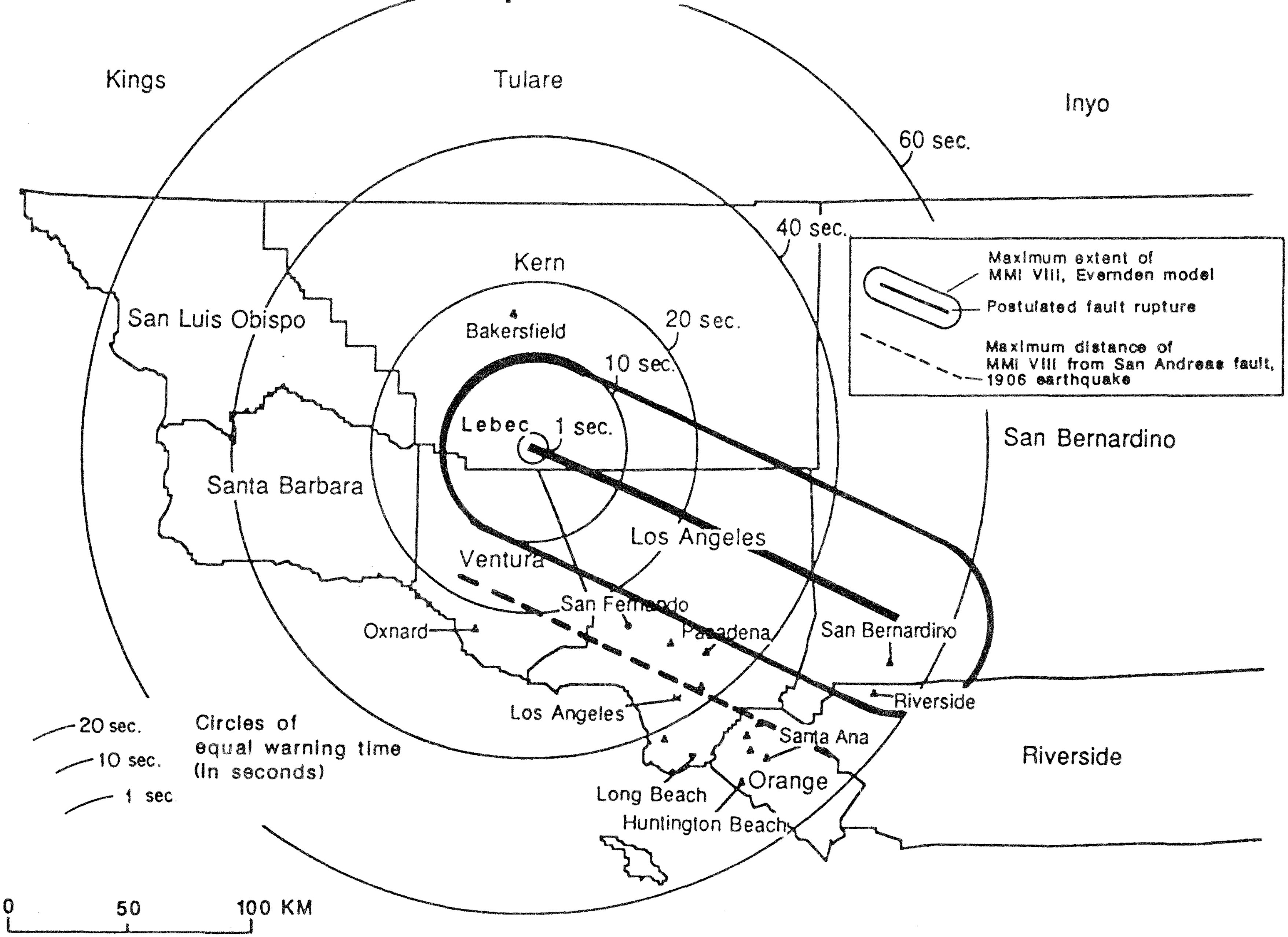
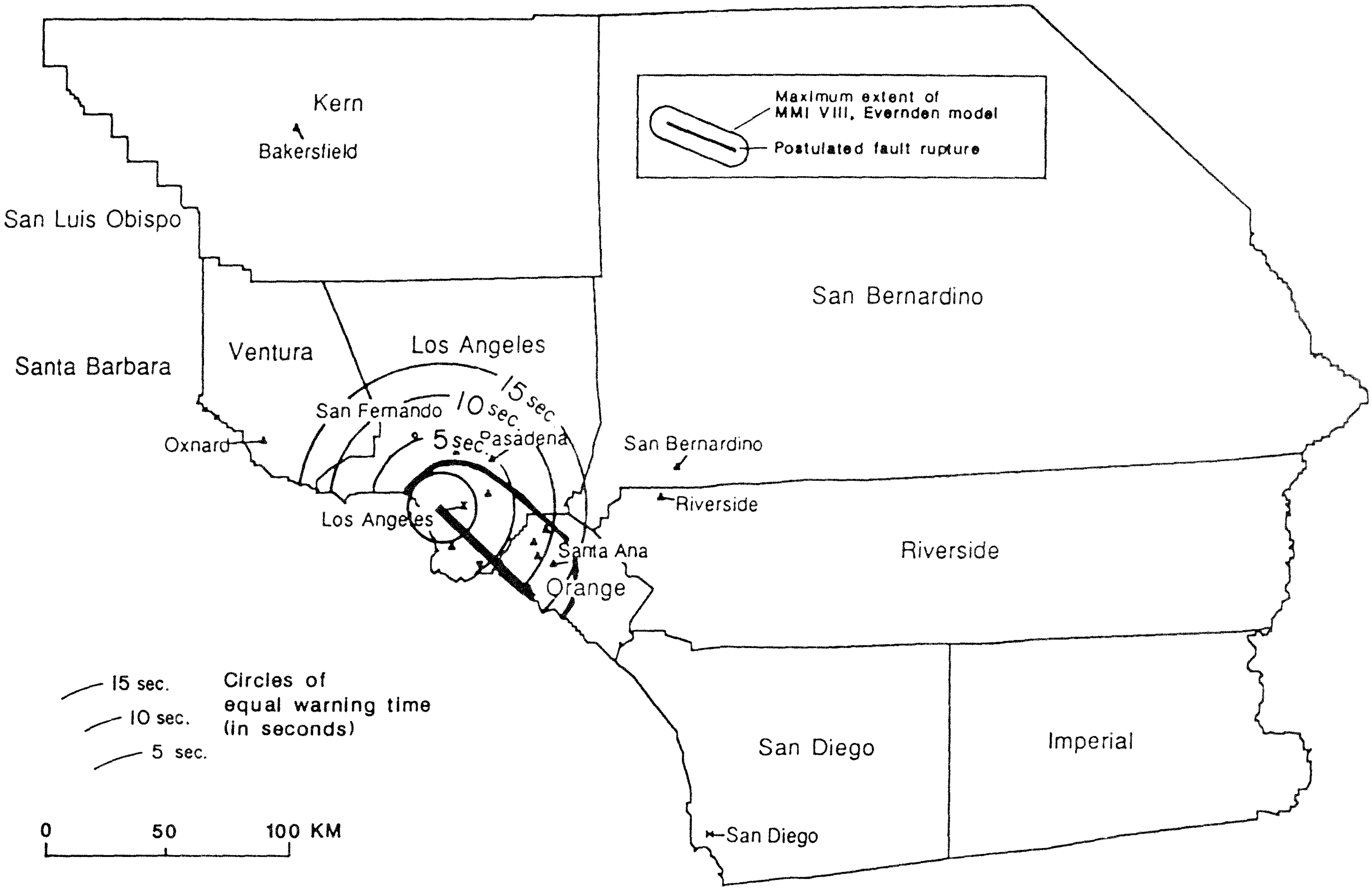


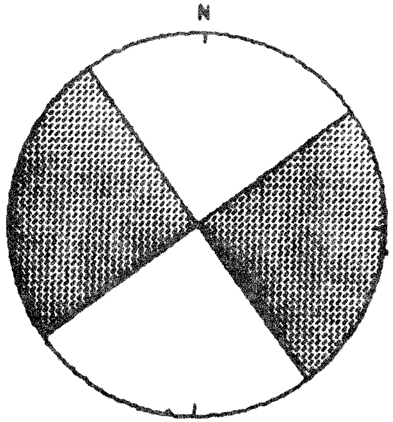
Figure 4.2 Postulated Magnitude 7.0 Earthquake on the Newport-Inglewood Fault



10/18/1989 Los Gatos

HRV(R1+G1) plus PAS
(PAS R1 node assumed)

M0=2.4x10**26 dyne-cm
Mw=6.9



P wave

max= 0.284E-02 min= 0.481E-05 range= 0.283E-02 length= 64.0

.00

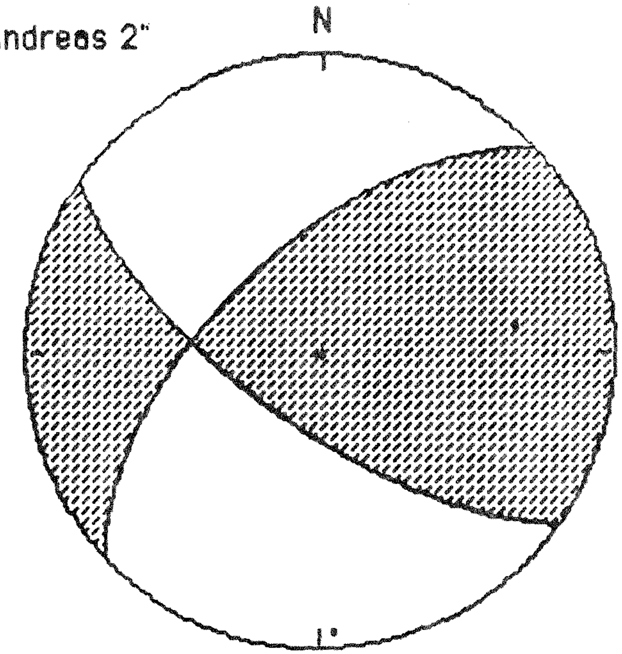
SH wave

max= 0.393E-01 min= 0.530E-03 range= 0.388E-01 length= 64.0

.0

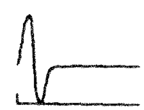
Modified "San Andreas 2"

dip=70
rake=150
strike=125



P wave

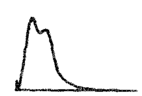
max= 0.170E-01 min=-0.127E-01 range= 0.298E-01 length= 64.0



.00

SH wave

max= 0.250E-01 min= 0.305E-03 range= 0.247E-01 length= 64.0



.00

APPENDIX H

Pinon Flat Observatory
Dr. Duncan Agnew

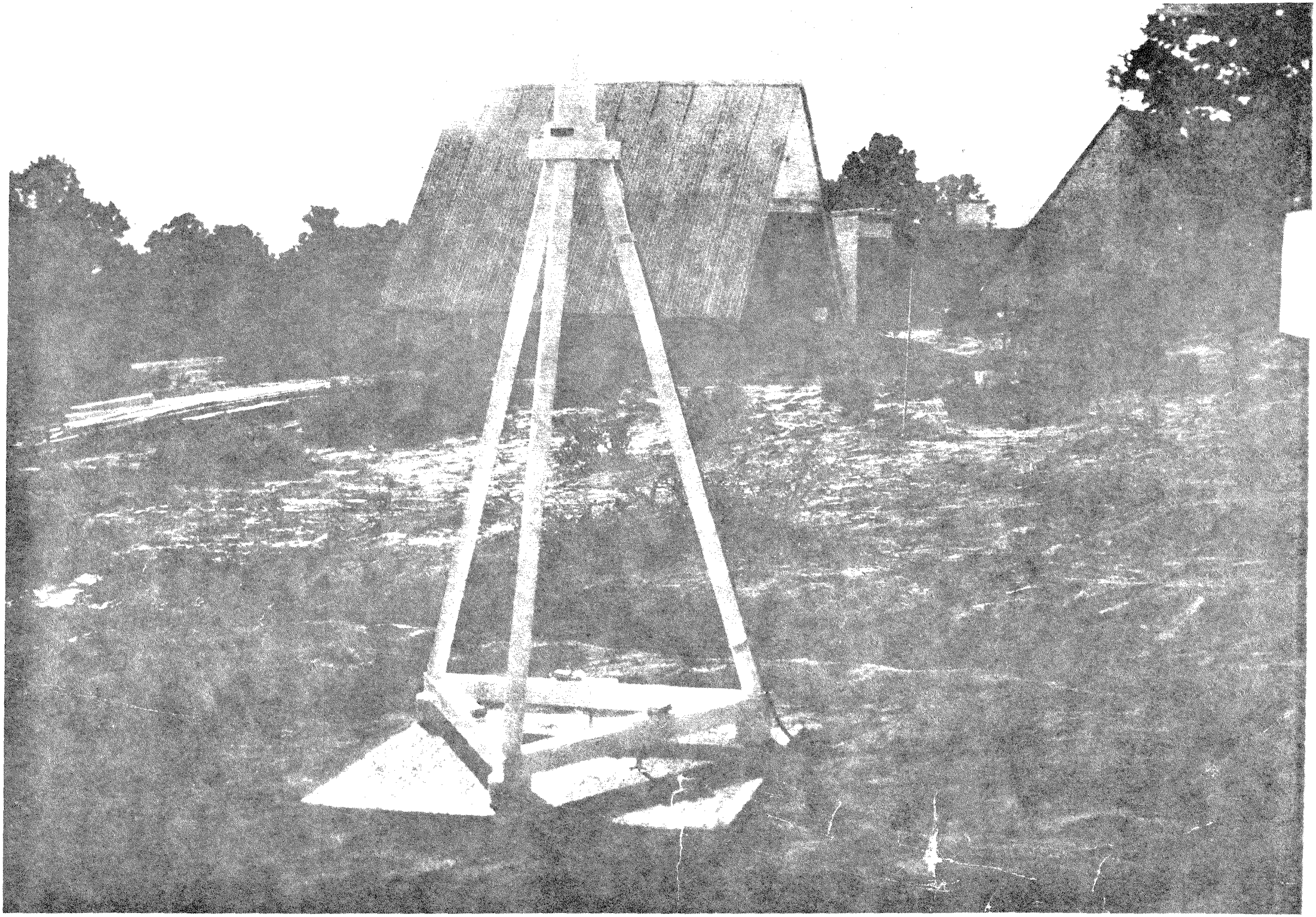
Piñon Flat Observatory

Purpose and Aims:

- To support the development, testing, and evaluation of instruments designed to detect crustal deformation in the period range from seconds to years.
- To operate, in support of this goal, the best possible instruments to serve as "reference standards" against which others may be compared.
- To monitor accurately the deformation of the earth's crust near the observatory, which is between seismic gaps on two active fault systems.

Research Program Objectives in Crustal Deformation:

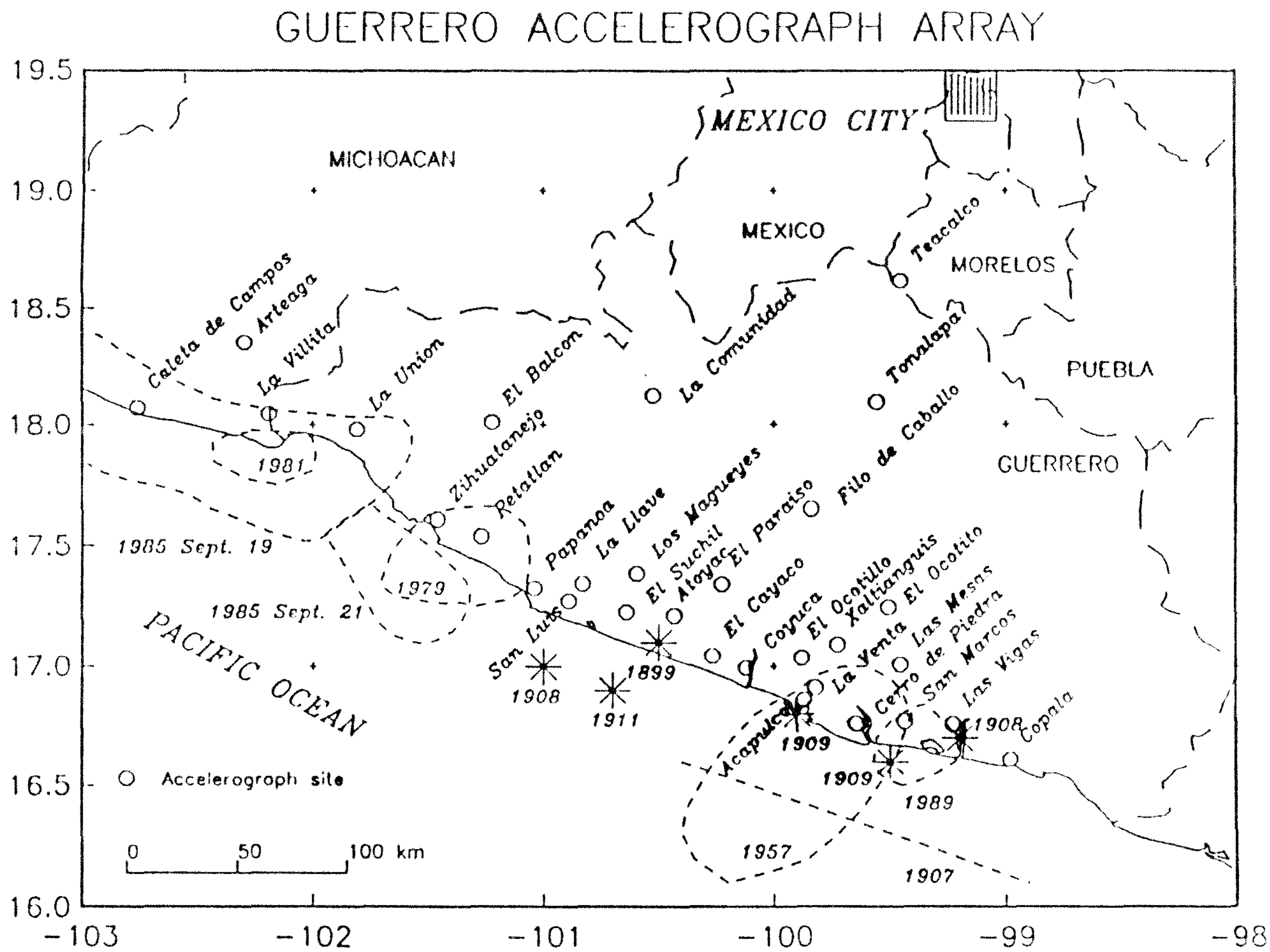
1. The development of better instrumentation for the continuous measurement of crustal deformation (better both in the sense of improved accuracy and of easier use).
2. The understanding of possible noise sources in measurements of this type, such as hydrological and thermal influences, and relating these to measurements made elsewhere.
3. The creation of improved methods to describe and understand the random processes which appear to characterize crustal motions and the errors in the methods used to study them, so as to devise better procedures for evaluating different techniques.



Permanent GPS System at Piñon Flat Observatory

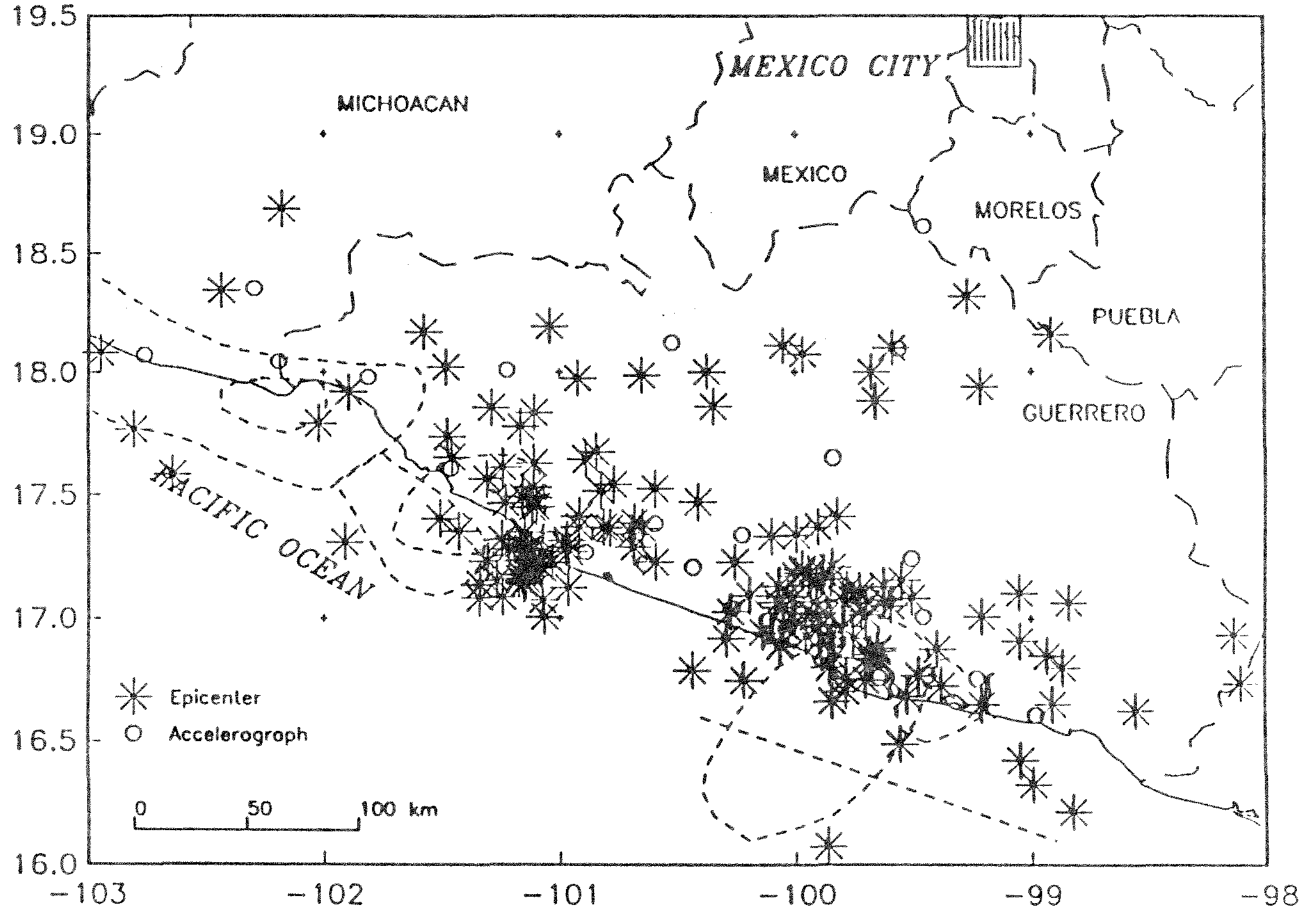
APPENDIX I

Guerrero Accelerograph Array
Dr. James Brune


GUERRERO ACCELEROGRAPH ARRAY
MEXICO CITY
MICHOACAN
MEXICO
MORELOS
PUEBLA
GUERRERO
PACIFIC OCEAN
Caleta de Campos
Arteaga
La Villita
La Union
El Balcon
La Comunidad
Teacalco
Tonalapa
Zihuatanejo
Retatlan
Filo de Caballo
Papanoa
La Llave
Los Magueyes
El Suchil
Atoyac
El Paraiso
El Cayaco
San Luis
Coyuca
El Ocotillo
Xaltianguis
El Ocotito
La Venta
Las Mesas
Cerro de Piedra
San Marcos
Las Vigas
Acapulco
Copala
1981
1979
1985 Sept. 19
1985 Sept. 21
1908
1911
1899
1909
1909
1908
1989
1957
1907
Accelerograph site
0 50 100 km
19.5
19.0
18.5
18.0
17.5
17.0
16.5
16.0
−103
−102
−101
−100
−99
−98

/oc

GUERRERO ACCELEROGRAPH ARRAY



APPENDIX J

An Earthquake Warning System
Dr. Michael Reichle

TECHNICAL AND ECONOMIC FEASIBILITY OF AN EARTHQUAKE WARNING SYSTEM IN CALIFORNIA

A Report to the California Legislature

February 28, 1989

CALIFORNIA DEPARTMENT OF CONSERVATION
DIVISION OF MINES AND GEOLOGY
1416 Ninth Street, Room 1341
Sacramento, California 95814

TECHNICAL AND ECONOMIC FEASIBILITY OF AN EARTHQUAKE WARNING SYSTEM IN CALIFORNIA

A Report to the California Legislature

By

Richard Holden, Richard Lee and Michael Reichle

February 28, 1989

CALIFORNIA DEPARTMENT OF CONSERVATION
DIVISION OF MINES AND GEOLOGY
1416 Ninth Street, Room 1341
Sacramento, California 95814

Background

The Department of Conservation was directed to prepare a feasibility study of an earthquake warning system (EWS) for California, pursuant to Chapter 1492, Statutes of 1986, and the 1987 Budget Act. The study was to include: (1) possible scenarios for seismic activity along the San Andreas fault north of the Los Angeles metropolitan area, (2) a description and evaluation of an EWS, (3) an assessment of the value of a warning and (4) a description of the funding, management, reliability and liability aspects of an EWS. The study is confined to those portions of central and southern California that are affected by earthquakes occurring along the San Andreas, San Jacinto and Imperial faults and the Silicon Valley (Alameda and Santa Clara Counties).

An EWS is not an earthquake prediction system. Rather, it would provide users with a warning that an earthquake has begun. Depending on the distance of the user from the earthquake epicenter, the warning could be received some seconds or tens of seconds prior to the onset of strong shaking.

Method

An assessment of the value of an EWS is inherently difficult. Potential users must be identified. The benefits to those users of a non-existent system must be estimated. These estimates must be based on uncertain assumptions about the probability of damaging earthquakes, the effects of geology on seismic motion, and the extent and nature of damage. Finally, the EWS must be designed and priced.

In our study, we attempted to overcome some of these difficulties by conducting three independent, but complementary, activities. First, we asked people in large, private and public California organizations to estimate the benefits that an EWS would provide them in the case of a future large earthquake. Next, we asked people in small, private California manufacturing companies who had recently experienced a damaging earthquake, to estimate the benefits that an EWS would have provided them had it been operating during that earthquake. Finally, we asked a technical expert to estimate the benefits of an EWS to industrial facilities using observations of earthquake damage to such facilities.

Findings

- For small and moderate earthquakes (those with magnitude of 7 or less), an EWS could provide warning of the onset of damage of only 10 seconds or less. For large earthquakes (magnitude 7.5 or greater), however, warnings of 30 seconds or more could be provided.

- Users prefer long (30 seconds or more) warning times because (1) they prefer to keep humans within the decision chain, perhaps reflecting a lack of confidence in the reliability of an EWS; (2) the primary personnel safety response was facility evacuation; and (3) some actions in response to a warning cannot be completed in a very short time.

- Given the current preference for long warning times, the only earthquakes for which an EWS could provide useful warnings are those of magnitude 7.5 or greater. The United States Geological Survey estimates that the annual probability of such earthquakes in southern California is about 2 percent.

- An EWS is technologically feasible today. It would cost, depending on the reliability, between \$3.3-5.8 million in capital costs and \$1.6-2.4 million in annual operating costs.

- The liability issues associated with operating an EWS in California appear to be addressable by the enactment of clarifying legislation.

- In order for an EWS to be cost-beneficial, it would have to provide benefits of tens to hundreds of millions of dollars upon the occurrence of the warnable earthquake. (This conclusion is based on the estimated cost of an EWS, the probability of an earthquake for which a useful warning could be provided, and the cost and probability of a false alarm.)

- Based on these findings, there is no compelling evidence that an EWS in California would produce such large benefits. It would not be, therefore, justifiable, on a cost-benefit basis, to construct an EWS at this time. It seems improbable that private or public funding would be available to build and operate an EWS given the uncertain financial benefit.

Technical and Economic Feasibility of an Earthquake Warning System in California

Introduction

Background

Chapter 1492, Statutes of 1986, directs the Department of Conservation to prepare a feasibility study of an earthquake warning system for California. The study is to include: (1) possible scenarios for seismic activity along the San Andreas fault north of the Los Angeles metropolitan area, (2) a description and evaluation of an EWS, (3) an assessment of the value of a warning, and (4) a description of the funding management, reliability, and liability aspects of an EWS. These topics are discussed in more detail in a comprehensive technical and scientific document prepared by the Department.

An EWS is not an earthquake prediction system. Rather, it would provide users with a warning that an earthquake has begun. Depending on the distance of the user from the earthquake epicenter, the warning could be received some seconds or tens of seconds prior to the onset of strong shaking. In principle, an EWS would take advantage of the difference between the velocity of seismic waves and that of radio waves. Instruments near an epicenter would sense the beginning of the earthquake and radio ahead that potentially damaging earthquake had begun. Japan Railways (JR) operates such a system. The JR system reduces the speed of or stops the "bullet train" and conventional trains whenever a predetermined level of ground motion is exceeded along a portion of the track. The present study concentrates on the design, uses, costs, benefits, and liability considerations if an EWS were to be operated in California.

The amount of available warning time would depend on the location of the earthquake epicenter relative to the users, and on the time lag between the initiation of the earthquake and receipt of the warning. The nature of the warning could be an electronic signal that could be interpreted by a user as a (1) simple "alert", (2) more detailed information on the nature of the seismic activity and anticipated damage, or (3) electronic instructions to perform some automatic function (e.g., close a pipeline or open a door).

An earthquake warning system could include the following components: (1) a number of ground motion sensors placed along the San Andreas and/or other fault(s), the signals of which are transmitted to a central receiving station; (2) a central computer facility to analyze the seismic data and, upon detection of significant earthquake, issue the warning signal; and, (3) user receivers for the warning signal and whatever accompanying data is transmitted. The receivers then issue a local alarm and allow a user to take action to mitigate damage or reduce injuries.

Earthquake Hazard

The feasibility of an earthquake warning system in California is dependent both on user-related and earthquake fault-related factors. Southern California has numerous faults capable of generating damaging earthquakes. Indeed, it is probable that many hazardous faults have yet to be discovered and mapped. One of the most hazardous, and currently one of the "quietest" faults in southern California is the San Andreas fault. Only one major earthquake has occurred along its entire length in southern California (from southern Monterey County in the north to the Salton Sea in the south) since the early 19th century. This was the great Fort Tejon earthquake of 1857, which had an estimated magnitude of 8.3. The United States Geological Survey estimates that there is a 30 percent probability of a magnitude 7.5 or greater earthquake along the San Andreas fault between Tejon Pass and Cajon Pass in the next 30 years. In addition, they estimate a 40 percent probability for a magnitude 7.5 or greater along the fault between the San Bernardino Mountains and the Salton Sea for the same 30 years.

Other faults in the Los Angeles metropolitan area have not been as well studied as the San Andreas fault. The 1933 Long Beach (magnitude 6.3, Newport-Inglewood fault), the 1971 San Fernando (magnitude 6.5, "San Fernando" fault) and the 1987 Whittier Narrows (magnitude 5.9, unidentified fault) are examples of earthquake that could occur along any of the area's faults at any time. Unfortunately, not enough is known of the earthquake history of these faults to estimate the probability of future activity. Most of these faults are thought to be capable of earthquakes in the magnitude 6.5 to 7 range.

In order to evaluate the potential advantages of an earthquake warning system we must be able to estimate, at least roughly, the extent of damage that may result from future earthquakes. The damage caused by an earthquake is a function of its magnitude, the proximity of the earthquake rupture to populated areas, the local geological substrata and the construction type and quality. For earthquakes in the magnitude 6 to 7 range, significant damage (Modified Mercalli Intensity VIII–damage slight in structures built especially to withstand earthquakes, considerable in ordinary substantial buildings, partial collapse, racked, tumbled down; fall of walls–similar to the damage that occurred in Coalinga in 1983) can be inflicted out to distances of about 30 miles from the causative fault. For larger earthquakes, there is little data in California, but historical M7.5 and greater earthquakes have inflicted significant damage from 50 to about 230 miles from the earthquakes' epicenters.

Decisions on the usefulness or feasibility of an EWS must include all aspects of a region's seismic exposure. In southern California, there are numerous known faults–and probably several yet unidentified–that contribute to the region's seismic hazard. As the needs of users of an EWS are identified, an EWS can be designed that will incorporate faults for which those needs can be met.

EWS Uses Data Collection

Method

The potential uses for an EWS were based on three independent, complementary data collection activities. These activities include:

- a survey of 164 large public and private organizations located in southern and central California likely to experience damage from earthquakes occurring along the San Andreas, San Jacinto, and Imperial faults and four large manufacturing firms in the Silicon Valley,

- a survey of 78 small- to medium-size manufacturing firms located within 10 miles of Whittier, the site of the October 1987 earthquake, and

- a review and analysis of a earthquake damage database comprised of records of damage to major facilities from recent worldwide earthquakes.

A survey of large organizations was conducted because such concerns are likely to (1) experience a large economic impact resulting from earthquake damage, and (2) have the expertise, equipment, and financial resources to understand and employ an EWS. The survey of small- and medium-size manufacturers was intended to ascertain whether firms recently subjected to a damaging earthquake would be able to better identify potential uses for an EWS. Finally, the review and analysis of earthquake damage data by earthquake engineering experts provided an independent opinion of how an EWS might mitigate damage in major facilities.

Results

Respondents from both surveys indicated a number of uses for an EWS. The large and small- and medium-size organizations surveyed signified a desire for warning times of 30 seconds or greater. In fact, many indicated warning times of more than 60 seconds. The earthquake experience data corroborated the result that there appear to be few uses for short warning times (less than 30 seconds). Respondents from both surveys indicated many personnel safety uses for an EWS. A number of respondents revealed an interest in post-shaking information. Many expressed concern over a system which generates false alarms. The data indicate that potential users appear to be reluctant to pay for an EWS.

The results of the data collection suggest that, while there is interest in an EWS, many uses require long warning times (60 to 120 seconds). In addition, some of the indicated uses are of dubious merit (e.g., personnel safety uses involving evacuation). Systems which address longer warning times are discussed below.

System Design

In order to evaluate the range of warning times that might be available from an EWS, one possible warning system, containing ground motion sensors spaced along a fault at about every 6 miles, was considered. Data from the sensors would be transmitted by satellite to a central data analysis center, where a decision to warn is made, based on the recorded levels of ground motion or other seismic parameters. The warning is transmitted to users by satellite, commercial radio frequencies or microwave. The users' equipment may include audible or visual alarms or an automatic programmed response to the received alarm.

Assume that a warning is issued and received by users one second after two adjacent ground motion sensors are triggered by significant motion. For an earthquake in the magnitude 6.0 range, an average of about 2 seconds warning will be available to areas of significant damage. (The warning will range from no warning–strong shaking arriving before the warning is issued–to about 5 seconds.) For an earthquake of about magnitude 7, an average of 10 seconds will be available; for magnitudes of 7.5 or so, 30 seconds. The strong preference of surveyed potential users for long warning times–30 seconds and greater–effectively limits the usefulness of an EWS to those faults capable of generating magnitude 7.5 and greater earthquakes. This would limit an EWS in southern California to the San Andreas fault. For an earthquake rupturing the fault between Tejon and Cajon Passes, warning times to the San Fernando and San Gabriel Valleys would be about 25 and 35 seconds. San Bernardino would receive between 0 seconds and about 50 seconds of warning, depending on the epicenter (point of initiation) of the earthquake. Longer warning times would be possible for facilities in southern Los Angeles and Orange Counties, but these would probably be useful only to facilities sensitive to long-period ground motions.

A system that could provide this warning for the San Andreas fault would cost approximately $3.3 million in capital and installation costs (excluding personnel) and approximately $1.6 million in annual operation and maintenance costs. This does not include the users' costs of purchasing and maintaining warning receivers and of integrating warning actuation into their systems.

Because the San Andreas fault in southern California is very quiet, a relatively simple warning decision process, with low system overhead time, could be implemented. Such a system would probably trigger on nearby large events such as the 1952 Tehachapi (M7.5), 1971 San Fernando (M6.5) and 1986 West Palm Springs (M5.6) earthquakes. The Japanese system for the bullet train has experienced approximately five earthquake-caused false alarms each year, and approximately one equipment-caused false alarm per year. Since the seismicity of California is about one-tenth that of Japan, we would expect one earthquake-caused false alarm every five years in California. Careful selection of equipment and trigger algorithm can reduce the equipment caused false alarms. Given the possibility of occasional system failures and of normal seismic activity on faults near the southern San Andreas, a more sophisticated system may be required to reduce the probability of false alarms.

Real-Time Earthquake Information

The system discussed in the previous section is based on the premise that very short warning times are, in fact, not particularly helpful. Several factors may contribute to the strong desire of the respondents of our surveys for long warning times. Respondents generally preferred to keep people within the decision chains, rather than trust an automatic response to a warning. When considering personnel safety issues, respondents frequently requested sufficient time for building evacuation (often much more than two minutes). An earthquake warning system could never guarantee enough warning time to allow a complete evacuation of a facility.

A number of respondents to the large corporation survey, particularly those involved in emergency response, indicated that, even if they might have no particular use for a warning as such, they could use more rapid information on the earthquake's magnitude, location and the resulting damage distribution. This service could be provided through a relatively economical augmentation of the existing California seismic networks, such as those operated by the U.S. Geological Survey, California Institute of Technology, California Department of Water Resources, the University of California and the University of Southern California.

Data from the existing high-gain seismic stations could provide the basic information for an initial estimate of the earthquake epicenter. But their communication lines are generally not hardened against earthquake effects. It would be necessary to augment the existing network with some hardened, high dynamic range, broad band seismic stations capable of providing magnitude and location data for the largest earthquakes. In addition to new seismic monitoring stations, the network operator(s) may require additional computing capacity to assure that the data are analyzed as accurately as possible in real time. Also, some form of communication system between the network computer and the emergency response agencies would have to be implemented.

This augmentation would require an additional commitment on the part of the network operators. Installation, operation and maintenance of this type of system may not fall under their current research or public information mandates. System costs would be about $1 million for equipment and $300,000 to $500,000 per year for maintenance and operation.

A secondary advantage of implementation of this real-time earthquake information system would be that the public would become more accustomed to receiving rapid and automatic information regarding earthquakes. In this way, the reliability of automatic earthquake information systems can be demonstrated. Should the public feel that they can, in fact, trust automatic warning system, they may be more willing to allow automatic response, leading to greater feasibility of a region-wide EWS.

Economic Evaluation

The originating legislation for this report specified that the study include an "assessment of the value of warning to various elements of society," including an "estimate of the value of the warning as a function of warning time and its reliability."

The data received from the survey efforts contained too much variance to be used in a rigorous cost-benefit analysis. In order to provide information on the possible economic aspects of an EWS, we have derived a set of decision rules. These rules are based on (1) the annual probability of a warnable earthquake on the southern San Andreas fault–2 percent, (2) the expected number of false alarms generated by an EWS each year–0.2 to 1.0, (3) annual system costs of $1.8 million to $2.8 million, and (4) false alarm costs ranging from $0 to $10 million.

The general decision rule for an EWS may be summarized as follows: *For an EWS to be cost-beneficial* *(benefits > costs), the total estimated savings as a result of receiving an earthquake warning must be at least 50 times the annual system costs plus 10 to 50 times the total false alarm costs.*

Based on this rule, an EWS would have to result in estimated savings of tens to hundreds of millions of dollars to be cost-beneficial. The results from the two surveys and the expert analysis of earthquake damage data, however, did not provide compelling evidence that these savings are likely.

Funding and Management

The organization of an EWS should be based on the following considerations: the purpose of an EWS, the appropriate role of government based on the expressed purpose, the anticipated beneficiaries of an EWS, funding availability, and exposure to liability. There is no preferred organizational arrangement for an EWS. A system could be operated by State or regional government or by a private enterprise.

Federal funding is not likely to be available to support the development and operation of an EWS under the auspices of the National Earthquake Hazards Reduction Program. Because of limited funding availability and competing needs, State and local governments may not be able to support the financing of an EWS. The viability of a privately operated EWS will probably depend on the (1) reliability and effectiveness of the EWS offered, and (2) development of an extensive market to justify the large capital and operating costs of an EWS.

Liability Issues

Legal analyses by the Attorney General and Legislative Counsel indicate that the State implementation and operation of an EWS is not likely to be a source of significant liability to the State. This conclusion is conditioned on the following: (1) the limitations of the system are made known to end users, and (2) EWS employees exercise reasonable care in operating the system. A specific statute may authorize the issuance of an earthquake warning and provide immunity for public entities and employees involved in issuing the warning. The State may also limit liability from damages to end users of an EWS by including indemnification clauses in contracts with the end users.

If the State contracts with a private operator for an EWS, the State should require that the operator contractually indemnify and defend the State in court proceedings so as to limit the State's exposure. In addition, the private operator should be required to demonstrate financial solvency or that it has obtained a suitable insurance policy naming the State as an additional insured. If the State wishes to contractually indemnify a private operator from liability for damages to end users (so as to encourage private development of an EWS), the contractual provision would require legislative approval because of the potential costs involved.

In summary, the liability considerations of an EWS do not appear to be insurmountable barriers to the implementation of an EWS under current law. Contractual provisions between the State and private operators of an EWS or end users would appear to be sufficient to limit the

State's exposure to liability. Exposure to the State could be further limited with the enactment of specific legislation authorizing warning and providing for specific immunities to the State and State employees.

CONCLUSIONS

Based on our review, there is no compelling evidence that an EWS in California would produce tens to hundreds of millions of dollars in estimated savings to potential users. On this basis, construction of an EWS would not be justified at this time.