UNITED STATES OF AMERICA

U.S. NUCLEAR REGULATORY COMMISSION

# SEISMIC INFORMATION WORKSHOP

DAY 1

SESSIONS 1 & 2

September 08, 2010

8:00 A.M.

TRANSCRIPT OF PROCEEDINGS

Public Meeting

San Luis Obispo, CA

# APPEARANCES

Panel:

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Professor of Geophysics
University of California, Berkeley

Ralph Archuleta
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Megan Williams
Reactor Inspector

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Staff Member

P R O C E E D I N G S

MR. MAIER: Good morning, everyone. Welcome to the Seismic Information Workshop. My name is Bill Maier. I am too low? You guys got it. My name is Bill Maier. I work at the Nuclear Regulatory Commission's Region IV Office in Arlington, Texas. And it's my pleasure to facilitate this two day workshop. Joining me in facilitation duties is Mr. Butch Burton. Butch is a branch chief at the Office of New Reactors in Rockville, Maryland. And we would like to introduce you to this workshop. And the purpose of this workshop, as you can see from your agenda, says it's to provide a forum for members of the public to gain a basic knowledge of seismic hazard and its applications for the safety and operation of commercial nuclear plants, including -- tomorrow specific discussions of the Diablo Canyon facility.

Before I introduce the welcoming remarks speaker, go over a few safety and logistics items for you. In event of fire, we've got doors right behind us and a door out here. Please exit through the doors to the rear, and go out into the parking lot and walk away from the building. Make room for as many people to get out so that everyone can have room to get away from the building in the event of a fire.

Can I have a show of hands please of anyone in the room who is certified in CPR? And keep your hands up, please. Okay, if you think you are going to need chest compressions, figure out who it is that you want to do chest compressions on you.

Restrooms were on the way in to your left. You should have seen them on the way in here from the front door. Refreshments; we have two water stations in the back. If you need any other type of refreshments there is a gift shop on the other side of the registration desk. As you came in it was to the left as you came in the front doors.

Today's session will be videotaped by AGP Productions. We're using their sound systems; for that reason we ask that everybody put their cell phones on vibrate or off. And that please do not -- refrain from any shout-outs from the floor. In order to be properly recorded, we want the person who's got the microphone, or who's talking into the microphone, to be the one who is speaking at any one time. Only one speaker at a time.

On your agenda, you'll see that we have four sessions scheduled for today. They are two in the morning followed by a hour and 15-minute lunch, which is on your own by the way -- they asked me to say that -- and then two sessions in the afternoon. Between each session there are half hour breaks. And I would invite you -- if any of the speakers have set up in there, we have got the Los Osos room and the Aetna room reserved for posters or any other visual aids that speakers may have brought to let people take a look at. We invite you to peruse those on the break. Or if you have any other personal walking around time, you can try to check those out. If you don't see any in the beginning, maybe some speakers haven't had the chance to set them up yet, you might want to try a little later.

With that I think it's time to introduce Roy Caniano, who will give the welcoming address. Roy is the director of the Division of Reactor Safety at the NRC's Region IV Office in Arlington, Texas. Roy's division is responsible for conducting inspections and reviews of engineering issues at nuclear power plants. And I'll turn it over to Roy.

MR. CANIANO: Not yet? Oh it's on now, I can hear it. Okay, good morning and welcome. I am Roy Caniano and has Bill Maier mentioned, I am the Director of the Division of Reactor Safety at the Nuclear Regulatory Commission's office in Region IV just in Arlington, Texas. Our core responsibility at the NRC is to ensure adequate protection of public health and safety, promote the common defense and the security, and protect the environment.

When you reflect on the workshop that we're having today, an important aspect for us meeting this responsibility is to have open dialogue -- maintain that open communication with the public and items of issues of interest. And of course, seismic we believe, is one that is extremely on the minds of everybody here.

We want to engage all interested parties today to have constructive discussion on seismic issues as they relate to safe operation of nuclear power plants in the United States. We hope that today's session is going to provide useful and informative information that are going to be presented by some of the leading experts in the field of seismology, as you can see from the agenda. And also when we go through from some introductions through the panel, I think you're going to see that we really were fortunate to have a high level of individuals with expertise.

A few administrative comments before we get started with the session. This is considered to be a Category 3 public meeting. This means that the public is invited to participate in the meeting by providing comments and asking questions throughout the meeting. The NRC is recording this workshop, as was mentioned by Bill Maier, and we're going to be making it available on our

NRC public website. My guess it will probably be seven to 10 days when that will be available.

You passed the registration desk in today, and hopefully everyone has signed in. We would like to have a record of attendees. I want to point out that today's sessions is not going to be a decision making session. And we're not here to sway or to influence everybody. It's intended to be informative, and address any questions or comments that you have. There are feedback forms that are available, and if you have any questions that you want to submit in that way, feel free to do that. We're always interested also in seeking suggestions on how we can improve on our public communications.

As you can see from the agenda, there are numerous panels that are scheduled over the next two days; four of them are scheduled for today. What we have done is scheduled, right after each panel, a question and answer period. So I would appreciate it if you could hold some of your questions until that Q and A session after each of the panels. In addition, the slides for today's presentation are available on the table, and we're also going to post them on our public website.

As we earlier mentioned, we have two facilitators to assist us during this workshop. If anyone in the audience has questions and comments, please allow time for the facilitators to get to you with a microphone. This is going to make it easier for all to hear the questions and the answers. We also have note cards that are available in case you would like to submit a question in writing. We're going to do our best here to address, fully, your questions if we can. If we don't have a complete answer, however, we're going to make a note and respond to the questioner at a later time.

We've known for a long time that there was great interest and many questions regarding seismic issues at Diablo Canyon. In an effort to adequately address these questions, the NRC planned for this workshop a long time ago; even before the license renewal process was implemented. We've brought together, again, an extraordinary group of experts and presenters, and we're excited that so many national recognized experts in the field have made their time available to provide the benefit of our knowledge and experience. The field of seismology has seen many changes and advancements over the years. It's the goal of this workshop to provide that information to you that should be of interest to all members that are in attendance today. We truly encourage you to ask as many questions as you can. Again, I think that will benefit all of us.

It's now my pleasure and honor to introduce Dr. John Stamatakos of the Rockville, Maryland Office of Southwest Research Institute. He's a geologist and geophysicist currently serving as the director of the Environmental Program, Geosciences, and Engineering Division of Southwest Research. He holds a bachelor's degree in Geology from Franklin and Marshal College; a Master's degree and Ph.D. in Geology from Lehigh University. He manages several sponsored investigations that evaluate earthquake and volcanic hazards at nuclear facilities. He has written or collaborated on more than 60 reports and papers on structural geology, tectonics, geophysics, and has made presentations at international conferences in the United States, Canada, and Europe. Prior to his work at Southwest Research Institute, he taught Geology and Geophysics at the University of Michigan. We are pleased to have Dr. Stamatakos here today to open our workshop. John?

Dr. STAMATAKOS: Let's see if we can do all the stuff we need to do to get a slide show.

[laughter]

Well. Right in the middle. Okay. Well, it's a real pleasure for me to be here. I know that in the original agenda, the president of GSA was going to give these remarks, and so I feel a little humble that because he couldn't make it that NRC asked me to come and make this presentation. I think the goal of my opening remarks is twofold: One, I'd like to try to set the stage and try to cover some of the topics at the highest level that you're going to hear about in the sessions. I'll start to introduce some of the terminology, but I'm really just hit some of the high points.

I think the more important goal of my presentation here is to really leave you with a number of questions, just to get you to start thinking about the types of questions that, you know, may be important in our discussions later on today and tomorrow. Now I came at geology and geophysics from the point of view of tectonics and became in love with geology because of tectonics. So I'm going to start this presentation with a slide of the West United States that shows the topography.

The West United States is dominated by the tectonics that's occurring along the western edge of North America, very close to us here in California. It's because of these interactions of these geologic plates that we're really talking about significant earthquakes and significant affects of earthquakes. Those effects extend, the tectonic effects extend well inboard into the United States. And it's really this interaction of these plates, the Juan de Fuca Plate, and the North American Plate, and Pacific Plate that ultimately drive what's going on in terms of earthquake hazards here in the Western United States.

And it's the understanding over the last five or six decades of plate tectonics that's, in a sense, guided us on earthquake studies for a long time. It's not the entire story. This is a map of the United States that shows about a hundred year record of earthquakes -- the larger the red circle, the larger the earthquake. And superimposed on that are yellow stars; and the yellow stars show nuclear facilities. So while the West United States is dominated by earthquakes, especially all the earthquakes that occur in response to the plate margin along the San Andreas Faults and all the associated faults, there are other parts of the United States that also have significant earthquake records -- the Wasatch Front that runs through the Rocky Mountains, especially in Utah.

The New Madrid Zone in Tennessee, and Kentucky, and Indiana, Illinois, Charleston earthquake, the earthquake in the 1880s, a pretty large earthquake, that are away from plate boundaries. So although tectonics does a good job of helping us explain a lot of earthquakes, doesn't explain them all.

And the other point is that earthquakes are of concern at lots of nuclear facilities across the United States. And so it's a very important and very serious topic that I think keeps us all very interested in understanding them. Now, earthquakes aren't all bad. From a geologist point of view, we're actually pretty glad that sometimes there are earthquakes.

There's a picture of the Teton Mountains, beautiful mountains in Wyoming. And the front of the Teton Mountains is essentially a large fault. The Teton Mountains were produced over the last several million years by the accumulation of many, many earthquakes. In a sense, I kind of think of earthquakes as this, you know, the individual steps of a marathon, if you will. So we can look at the final result, we have to study those individual steps, but from a geologist's point of view, it's what gives rise to a change earth and the dynamics of the earth.

We also know that earthquakes are dangerous and can cause serious damage. Here are just some images that I pull from a talk I have to admit I gave many, many years ago. This shows some of the damage of earthquakes in Taiwan and in Turkey. So we know that the potential for destruction, damage to property, and loss of life is significant. I think this year has been especially hard in terms of casualties in Haiti, Chile, property damage in Chile, New Zealand, elsewhere. So it's been a significant year for earthquake damages. So I think the point that we want to make is that, yeah, we need to take hazards and earthquakes extremely seriously. It's an important topic.

From NRC's point of view, NRC adopts a philosophy that in regulating facilities for safety, they'll use something that's -- you'll hear us talk about -- hear NRC talk about is risk-informed performance-based. What that really means is that they want an understanding of no undue risk to public healthy and safety.

And the questions you want to ask, the questions that I think that are right to ask when you take this kind of an approach, basically are the questions I think we all ask ourselves subconsciously or consciously every day, and the risk triplet, you know, what can go wrong, how likely is it, and what are the consequences? So as they're sitting down to breakfast this morning, and I decided to have that second piece of bacon, I subconsciously asked myself that same question. What can go wrong? How likely is it that it's going to go wrong? And what are the consequences? So at all levels of society, I think that this is a very important set of questions that we want to ask ourselves in evaluating all of safety.

So I thought I'd put together just some obvious earthquake basics as a starting point for our discussions. We know that earthquakes are destructive; no question about that. We know that earthquake and earthquake-related phenomenon, things like ground shaking, fault ruptures, soil liquefaction, other kinds of phenomena are very complex. And we have a whole host of leading experts who study all of those effects and will hopefully be able to walk you through a lot of those.

We know we can't yet predict precisely when and where the next earthquake will occur. I think most people who work in seismology, that's a question that gets asked most -- when's the next big one? And I think although that's an important question, I think the other question is even more important. And that is, are we prepared for it? So with sufficient information, can we actually predict or estimate the ground motion, the amount of shaking that an earthquake will produce at a particular site, and then can we be assured that structures can be designed to withstand those effects. And I think there's ample evidence that with careful planning and with good engineering, that the answer to that last part is, yes; structures can be designed to withstand the effects of ground motion. We just need to make sure we continually evaluate what the ground motion might be.

So in a simple sense, when we think about earthquake hazard or seismic hazard assessment, we really want to look at a number of factors that can influence. So and this is kind of a cheesy diagram. I apologize. It's not really to scale, but on a cross section I tried to illustrate that really when we're talking about the ground motion site, we want to know what's going on at the source. So what happened when the earthquake occurred on the fault? You know, what are the characteristics of that source? Did the energy spread out equally? Did it spread in one direction? We want to know what happens along the path. So how is that energy attenuated as it moves from the source towards our site?

And also we want to know, we know from many earthquakes, that the site effects are very important. So as the earthquake energy gets very near a facility, the soil or the rock that's beneath the site plays an important role in how much shaking, or how much vibration our facility will experience.

So what does it take? Well, it takes a lot. It takes a whole series of different kinds of expertise in order to really do a good job in producing a reliable seismic hazard assessment. So I've just tried to list a few of the topics that we're going to talk about. Plate tectonic setting, we want to know as much as we can about the historic and even the prehistoric earthquake records. We've been measuring earthquakes since probably accurately since around the 1960s. So we have a record, but is that long enough?

There have been tremendous strides made in paleoseismic studies; studies that look at information along faults to try to discern what was going on in prehistory in terms of earthquake records. We want to know about faults. We want to be able to identify the faults. Often, that involves looking in the subsurface. And I know that we'll have lots of discussion about geophysical methods to help identify faults.

We want to be able to characterize those faults in terms of their ability to produce earthquakes, what kind of magnitude, what's their rate of activity, are they active, what style? Is it a fault that moves side-by-side? Is it a fault that displaces in a normal sense? Is it a fault that displaces in a reverse sense of we call a thrust fault? We want to know about how the rupture propagates the rupture dynamics of that source. We want to know how the attenuated energy moves through the, or how the energy moves through the earth and is attenuated, and we want to know about the site effects, in particular, the geotechnical conditions of the soils and rock beneath our site that can so importantly influence the ground motion we ultimately see.

So seismic hazard really focuses on the two fundamental methodologies, and I know there's some -- we'll have a panel discussion about deterministic assessments and probabilistic assessments. So I thought I'd try to introduce those here.

A deterministic assessment is one in which we try to define what are likely shaking is at the site based on a single set of conditions. So a single earthquake on a fault, often in NRC history, has been termed "the maximum credible event." That would be the largest earthquake that could occur could on the fault closest to the source, perhaps with the least amount of attenuation from the source to the site. And so we can, in that sense, have a very simple assessment of the likelihood of ground shaking at our site.

But implicit in a deterministic assessment are a lot of assumptions -- you know, what's credible? How do you define credible? Is the maximum credible earthquake really the maximum credible earthquake? What about uncertainty and uncertainty in your assessments? So in more modern assessments we now rely on probabilistic assessments rather than deterministic assessments. And these are much, much more complex structures.

So in probabilistic assessments, we define the hazard in terms of --

not in terms of what a single event might do, but we might define it in terms of the probability of exceeding some level of ground motion. You could think of this in terms of the way that you drive. You know if -- I know that probably only about five percent of you in here ever speed. But those of you whoever speed on the highway, you might say, you know you have a five percent chance that you're going to get caught. There's a five percent chance that you're going to exceed the ability to evade a ticket. It's not really that different in terms of a probabilistic assessment. And the advantage of the probabilistic assessment that we explicitly try to include our uncertainty and evaluate that uncertainty in our knowledge.

The methodology that's most often used is to construct what we call logic trees, and I recognize this as a very complex. This is just a piece of a logic tree of one seismic hazard study. This is from Utah from a probabilistic assessment that was done in Central Utah. But I just wanted to show you that the way that this is implemented in terms of uncertainty is that for each question that we ask along the -- for a single fault. So for the Clover Sheeprock Fault, we ask a number of questions. Is it segmented? Well, 60 percent chance that it is; 40 percent chance that it's not. What's the state of activity? There's a 60 percent chance that it's active, and a 40 percent chance that it's not. What's the distribution of the likely magnitude? Well, the mostly likely magnitude in this model is that it would produce a 6.6, but there's a three percent chance that it could produce a seven. And so when you construct these logic trees and then you run simulations, thousands and thousands of simulations, through all of these, you get some sense of what the ultimate hazard might look like.

And so you're going to see examples of what we call probabilistic seismic hazard curves. And these are essentially what I was describing in terms of the speeding ticket. Basically, you can think of these as the probability of that some level of shaking at your site is going to be exceeded. So 10 to minus 3, that's a 1,000, chance. So in a given year, the annual frequency in a given year on this curve -- oops, if I can get the mouse here -- the likelihood that you might get .4 g exceeded in a 1,000 years.

Now, there's of course this is uncertainty around that. That uncertainty is that that number could be a small .2 g and perhaps as big as .5 or .6 g. So that's what these probabilistic assessments tell us. They give us some idea about what's the likelihood that you might get some ground shaking at your site.

So once you have that kind of assessment, of course, you're going to have to ask the question, the next one? When it is unlikely enough, right? You have to make a decision now about well, now that I know what the likelihood of exceeding ground motions are, what's important to me? How unlikely am I going to try? Because, you know, we can't go to infinity, right? We would live in a bubble if we were not willing to take any risks at all. And I know one of the issues that we're facing is as we try to do -- to go with lower and lower probabilities of ground shaking, that these ground motions can get extremely large.

I think the other question is that in terms of not only the hazard, but we want to understand -- tomorrow's discussion we'll focus a little bit on how will the system respond? So these are the famous train tracks that were displaced at Strike-Slip Fault in Turkey. They're -- if we can design a structure so that it can resist the impacts of earthquake, that's really the ultimate goal. So it's not just the hazard itself that's important, we want to also understand the ability of the facilities to be able to withstand the damage from earthquakes.  And we can look at that in a deterministic way, but we can look at how damage, how structures may be damaged in a probabilistic way too.  So we do that through something that's called fragility.

Fragility just describes the likelihood that my whatever will fail; whatever I'm looking at will fail in terms of the ground motion of the input ground motion.  So if I have .45 g acceleration, there's an 80percent chance that I'll lose off-site power.  It's at 100 percent chance and an 80 percent chance.  Some of these other, you know, diesel generator or piping, and this example of fragility, it just shows you that we, you know, it's not for certain that you'll get some kind of damage, but there's a likelihood you can get some damage.  And you can merge the information from the hazard with the information from the fragility to really understand a lot about how your system will behave under different kinds of earthquakes.

So in summary, I think that seismic hazard assessments are based on a broad spectrum of geology and geophysical data.  That's really the focus of a lot of what we're going to talk about in this morning's sessions.  The goal of seismic hazard assessments has developed reliable estimates of ground motion, especially the uncertainty.  It's very important that we talk about uncertainty.

Seismic hazard assessments are really only part of the evaluation.  And combining the seismic hazards and the estimates of fragility can really lead to better understanding the probability of something that important will either fail or last during an earthquake.  That's an important question.

I think the really fundamental question that drives us is what are we willing to do in terms of risk, huh? I always loved this picture because this is a friend of mine, Chuck Connor. We used to go camping a lot together when my kids were much smaller than they are now. And one time I wasn't there, and Chuck took them hiking. And he had gone to the top of this rock. And my youngest son, Johnny, said, "Hey, Chuck, this is great. My dad would never let me do this."

[laughter]

So I think at some point, you know, the most fundamental question we have is what's our ability to absorb some level of risk? Thank you, very much.

[applause]

MS. WILLIAMS: Go ahead? Good morning. My name is Megan Williams. I'm a reactor inspector with the Nuclear Regulatory Commission at the regional office in Texas. And this morning, I have the pleasure of introducing our Session 1 speakers. First, we'll have Ralph Archuleta, is a professor, as well as the chair of the Department of Earth Sciences at the University of California, Santa Barbara. His research interests include the dynamics of earthquake source and the ground motion it creates.

Doug Dreger is a professor of Geophysics in the Department of Earth and Planetary Science at the University of California, Berkeley. His research interests include seismic wave propagation and the development of automated systems for the rapid dissemination of earthquake information. And Robb Moss is an assistant professor at Cal Poly, San Luis Obispo. Areas of expertise include geotechnical earthquake engineering, engineering seismology, and risk and reliability with respect to earthquake engineering.

DR. ARCHULETA: Good morning. I'm going to introduce the topic of plate tectonics and sort of discuss a little bit about just how we got where we are today in California. And to give some idea, a small overview and introductory overview in seismology and some of the terms that you will hear with regard to earthquakes; you know the type of motion they cause. And also I want to talk a little bit about the ground motion that comes from earthquakes, some of their general properties, without going into specifics for any given earthquake.

So you know, when you look at the world, it wasn't always this way. We all know that but we're looking at a much longer time period. So if you go back even 225 million years -- that's a little bit old -- but, nonetheless, the earth has been in motion basically since about three and a half billion years. It's about four billion years old, and plates are in existence from about three and a half to three billion years. So the face of the earth has always been changing. So what we see today is something that has evolved over time and will continue to evolve. And, in fact, it's this motion between the plates, in fact, that stores the energy that gives us, you know, the rise to the earthquakes that we experience.

And so if you look at today's present configuration of the plates, what you will see then is that, you know, we've named all these plates. But these plates on the surface of the earth are always jostling and juggling and trying to get by each other. And what we find is that basically as they try to do this and different methods of doing it, this is the place where we find earthquakes. And so if you look at the plates -- and they're not always moving in the same way. They're not always in -- you know, it's not always balanced in the sense that, okay, this one has 3 millimeters per year, so the other one has 3 millimeters. No, different plates are moving at different rates. But averaged across the surface of the earth, they're in balance. And so they keep moving. And what you find then, not surprisingly, is that if you look at the seismicity of the world, you find that, you know, a nearly perfect outline of the plates.

Now as we saw earlier, not all of the earthquakes occur at plate boundaries; but by far, the vast majority do. And this is the place where at least we can start to understand, in part, why we're getting the earthquakes and at what rate we should expect to get earthquakes if we can understand how those boundaries are changing over time.

So if you look at global seismicity, you know, this is over a ten-year period, you look at the earthquakes around the world, you can see that they are -- they're associated with the -- they're associated with the boundaries of the plates. The recent earthquake over here in Chile that occurred at the end of February, a large magnitude, magnitude 8.8 earthquake; but then, you know, we've got earthquakes over here you can hardly find New Zealand, where the most recent earthquake occurred.

On the other hand, even if you take a snapshot of the earthquakes that are occurring in the world today -- this was taken on August 24th -- you find basically the same picture. So whether or not you're looking at something over long periods of time or of short periods of time, basically the activity is still going to be confined near the plate boundaries. And so what we're looking at then is the system of where we can understand, at least in part. And again, it's in part in the sense that we understand it on average. You don't always understand it on detail.

So the other aspect about these earthquakes when you compare long-term average, short-term average, there's always been the question whether or not because, you know, people say, “Wow, the earth --the number of earthquakes is increasing.” In fact, the long-term average of the earthquakes probably is not increasing at all. As far as we can tell, it’s not doing anything except staying about the average because, again, the plates which are driving the occurrence of the earthquakes, they’re basically in steady state. They’re generating earthquakes, they’re in balance, they’re getting by each other. And so over time, the number of large earthquakes, in fact, is staying just about constant. It may be slightly changing over shorter periods of time, but we don’t really -- we don’t really know why or if it really does happen.

But as you can see from here, when people start to worry about the occurrence of earthquakes, and they really worry about it because what we see are the casualties that are associated with earthquakes, what we’re really seeing is the influence of the fact that the population is moving into the hazardous zones. In other words, the population is growing in the world, and the population are in these hazardous regions. Part of which is because some of the most beautiful places in the world are, in fact, due to the active tectonics, as we saw in the previous slide with the Tetons, or as we all know of because those of us who live in California. But the thing about it is that this active tectonics, in fact, is what leads to the beautiful topography, which, in fact, attracts people to live, and, of course, you present people; now you put them into greater risk.

So if you look then, and we’ll first start to focus in now as we come in towards California, you know we’re looking then at the plate motion. The big plate motion for California is the relative motion between North America and the Pacific Plate. Okay. And so you can see from this slide here that we’ve got the motion then of the Pacific Plate is moving into the northwest, being subducted beneath the Aleutian Arc. And of course, this is reflected in the seismicity in California and in the Western United States. What you see is that, yes, there are earthquakes in the eastern part of the United States. But the large and the greater occurrence of earthquakes is occurring in the west. And that's because of this relative motion between the Pacific Plate and the North American Plate.

Now up here to the Northwest, we have a different plate. We have the Juan de Fuca Plate, which is being subducted beneath the Oregon and Washington coastline. And actually, it goes from Cape Mendocino all the way to Victoria, Canada.

But when we talk about the boundary, the major boundary, why we always talk about the San Andreas Fault, and admittedly, this is the primary fault in California. Okay, it takes up most of the motion between the Pacific Plate and the North American Plate. So the North American Plate relative to the Pacific Plate basically is trying to move at about something on the order of five centimeters per year. It's roughly the length at which your fingernails grow each year. Okay. So five centimeters, about two inches, okay, per year, the North American Plate is trying to slide by the Pacific Plate. And the major part of that is on the San Andreas Fault. But it's not the only fault that exists. In other words, when you look at the boundary, what you'll see is that the faults in California come about because of a past history. And before the San Andreas, we actually were the boundary of a subduction zone, very much like what we have right now at the Juan de Fuca Plate going under Oregon and Washington.

And so what we had was the Farallon Plate. We're going to start this at a 40 million years before present. This is an animation due to Tanya Atwater. And what we have then is that the Farallon Plate will go underneath

North America. You can see how squeezed up Nevada is, and California is really squeezed in here. And you'll see that basically it's only about 25 million years that we start to form the basis for the San Andreas, and then it really kicks off at about six million years, which I'll come back to.

So the Farallon Plate is being subducted beneath North America. And then what happens is right about here, we're starting to see the formation of the San Andreas. It's starting to form. We start seeing motion of the Pacific Plate relative to North America, and we see the extension as it's pulling out across California. Okay. At about six million years, we had the opening of the gulf.

This is showing a little bit more nicely in this animation also by Tanya Atwater at UCSB, in which case, we're going to see, basically, how also in Southern California what we have are the Transverse Ranges, how they rotate into place and why they sort of go perpendicular to the direction of the Pacific Plate.

So we have motion here at 16 million years, and, you know, the time is changing up with the upper 12. Santa Barbara is rotating into here. We have the Santa Maria Basin. We're going to start to form the large Los Angeles Basin. And so what'll happen is that we have then the current condition or the current orientation of the plates as we have the Pacific Plate relative to North America. And we've got other boundaries in here as well.

Well, as a result of this, we now see in California seismicity that is not only here on the --basically associated with what we would say is the boundary, but you know, the San Andreas Fault; we also have very complicated ground motion and earthquakes in Southern California and we have those that go up on the eastern side of the Sierra Nevada.

But when you look at the San Andreas, the San Andreas is not simply one fault. In other words, it really is the San Andreas Fault system. So this is taken from, if you're looking in the Bay Area, for example, and you're looking up here, you have the San Andreas Fault, okay. But you also have an important fault relative to where we are today, the San Gregorio Fault, which is a link to the Hosgri. But you also have in the Bay Area, you also have the Hayward Fault and you've also got the Calavares Fault. In other words, you have a system of faults. And this is, in fact, what we generally see when we look at the boundaries and the breakup. It's not like it breaks on just single plain. You have, in fact, many different faults that you have to account for. And each of these are taking up some of that plate motion that we're looking for.

Well, looking at a California geological survey activity map, you know, you look then and you say well, here's the San Andreas. But they're also active faults that are offshore, there are some here in Nacimiento, there are some that basically you find, you know, the White Wolf, and then you find those down in Southern California associated with the Transverse Ranges.

Then what we have then in those Transverse Ranges because the San Andreas is not perfectly aligned with the plate boundary and there is this -- I forgot to point it out -- it makes this bend here as you get near Bakersfield and comes through Gorman and then goes across the Mojave. And so what happens then is that you end up then with a compression across this region. And when you're compressing two things together, what you're going to do is that you pop up the mountains. And that's exactly what's happened in Southern California.

When you look at Southern California, what you see here are the

Transverse Ranges. And so what you have then are the San Gabriel's, you have the San Bernardino's, you have the Santa Inez Mountain range, you have the Hollywood Hills. These are all basically being popped up by this compression as we come across. And this is what's generating a different style of earthquake, which are the thrust earthquakes like Northridge and 1971 San Fernando. So we'll talk about this just briefly.

You know, in those earthquakes in San Fernando, Northridge, they're what's called a reverse fault. And a reverse fault, what happens is that you will find that one part, the hanging wall, moves up over the foot wall. Okay. And so you get this upward motion where you -- what we call a thrust or reverse, and the motion is reversed in the sense it's acting in the reverse sense of gravity.

A normal fault in which the motion of the block over here is going to act in the direction of gravity, you would see as such. Okay. And the normal fault is such that basically the motion of the hanging down. It's normal in the sense it acts in the direction of gravity.

Now for strike-slip, it's slightly different because now what we're going to have is the relative motion of two sides of the fault. This is what we would expect on the San Andreas. And on a strike-slip fault, what you get is motion that is basically tangential; it's parallel to the free surface, slipping one against the other. In fact, this is very -- this is very much the motion that we have in the recent New Zealand earthquake.

So what's happening over time? So over time what's happening is that these two plates are trying to get by each other on these boundaries, which we'll identify as faults. And what will happen is that over time what you're doing is that you're going to slowly build up the stresses on either side of the fault. But the fault is locked due to friction. But at some point it breaks. And when it breaks, we have this earthquake. And at that time is when we release the seismic energy.

So these forces, which are applied over time basically, are occurring constantly, in other words, because of the relative motion of the plates. And what will happen is that you keep the fault locked due to friction. At some point, it cannot stand at friction anymore and it will simply break. And we have then what is an earthquake and then we get then, one side moves relative to the other side, and we get the slip in the earthquake.

So when you look at California, Southern California, you look at all the earthquakes and you see all these dots, which everybody always plots in the newspaper; and they really don't give a sense of what's really happening in these earthquakes. Because what they're representing is the epicenter of the earthquake. They're representing a point directly above the hypocenter, the point where the earthquake first got started, but they're not really giving a sense of the full length of the size of that earthquake.

For example, the 1857 Earthquake, you would put the epicenter here, near Parkfield. But this rupture went about 350 kilometers, more than 200 miles. It didn't stop until it got to almost Interstate 15. Over that time, it's rupturing about four and a half meters a slip, you know, somewhere on the order of 15 feet, one side relative to the other. So these are the differences between when you look at an epicenter and when you actually say what is the fault doing. And we've had some big earthquakes in California. The 1906, the 1857, and we're still waiting on a repeat of this one down here, 1680, which is long overdue.

So I wanted to say that what does an earthquake actually look like if you were to look at one rupturing, okay? So these are snapshots in time, about one second a piece, showing on the fault Plain how the rupture proceeded from south to north, and you see it sort of moves up the fault. But a little movie sort of shows better how what happened in this earthquake. It jumps all over the place. Okay. It's moving very fast, greater than basically the speed of sound at about a factor of 10, so it's going mach 10. And it moves up the fault as the rupture proceeds. And all during that time, it's radiating elastic waves. So elastic waves are not just coming from the focus, they're coming from every point on the fault that slips. And when you do that, you generate these elastic waves. This is what, in fact, we feel.

So my voice here is generating compressional waves, okay. So these are like the P-waves that arrive first. Okay. Later on you get the S-waves. Now the thing to take note about the S-waves, and that you should know this for your own safety, if you feel an earthquake, you better hope that it's the S-wave, because then it's not too bad. But if it's the P-wave, it's simply a wakeup call that the next waves coming in are going to be a lot larger and a lot more severe. So when they're coming in, these S-waves are almost always basically larger. And then they're going to be followed by sort of the rolling motion that you get later on back in here.

And so when we look at this, what we've got then are the P-waves coming in. We're going to get this large shearing motion. And the shearing motion is, in fact, is what we know to be the most damaging motion to most structures. Because when you're compressing something, if you ever tried to break a pencil, nobody ever tried to break the pencil by squeezing it between their hands, okay. Not unless you want a hole in your hand. So what happens is that you break it, but you shear it. And so the shearing motion that's occurring during an earthquake, this is the type of thing that's coming in at the base of this building, it's going horizontally, and, in fact, what you're doing then is bending, you know, shaking the ground horizontally. You're not compressing it, you're moving the ground. The building's got to respond, or the structure, and all kinds of things go haywire. And, of course, the problem is, is that the closer you are to an earthquake, the more damaging the earthquake.

So this is Parkfield when you get in close. And the thing here, this is measured in time and seconds. So if you happened to be at this station right here, okay, the acceleration comes in, you have basically about two seconds of warning -- that's all. Imagine at 3:00 a.m. how much time -- what you could do in two seconds. You know, barely blink your eyes. Okay, so what happens is that right after that, though, when you're in close, you get the large amplitude ground motion over here that you can see right in here. So you get very large amplitude ground motion, and then it's over. Okay, this is a small earthquake, a magnitude six, but the strong shaking lasts for something on the order of four seconds.

A larger earthquake in Japan -- this is the purpose of this slide is not to tell you much more about this other than where the earthquake occurred -- but to point out that it's well recorded by many, many stations around Japan. And what you see is, again, the small amplitude P-waves are coming in, and the very large amplitude shear waves are coming in. The total duration in this case is of strong ground motion is more on the order of about 10 seconds in some cases, much shorter in other cases.

But again, the point I want to make here, though, is that as you move farther away from the fault, as you move away from the hypocenter in this case, you see this decay with distance. The amplitudes of the peak amplitudes are decaying with distance. So the closer you are, the larger the amplitudes, the stronger the shaking. This is generally what happens -- not always, but in general.

And we saw this with Northridge as well. If you look at the intensity as a function of distance, you basically see that the intensity -- the intensity of shaking is decreasing as you get away. But out to about 20 kilometers, you know, which is something on the order, you know, you multiply by .6, so you're about 12 miles out or something like this, you are still going to get basically about the same level of shaking. It's not like you say well, I moved a kilometer. You know, if you're in ground zero, you're in ground zero, okay, out until you get about the depth of the fault; you're going to have basically the same amplitude.

And so I want to conclude with just this final slide that's taken from a combination. It's from the California Geological Survey, and it is, in fact, a cooperation, of course, with the USGS and other agencies, but it shows the shaking in California, the anticipated shaking based on the occurrence of earthquakes, the expected size, and the like.

And what you find is that basically, yes, as you get close to the big faults, like the San Andreas, you expect a higher intensity of shaking. There are other places in Southern California you cannot always identify the -- I don't know what happened there -- the amplitude here in Southern California is more diffuse because, again, you've got faults almost everywhere in Southern California. And here we are on the coastline, you know, there's not as much amplitude as you see in other places, especially in Northern California.

And so when you're looking around and when you're understanding earthquakes, understand basically that those plates have been moving for 100, 200, 3 billion years. They're going to continue to move, okay. We have to just be prepared basically for the consequences. But it's not like we're going to stop the engine that, in fact, is driving the earthquakes. And so with that, I'll stop. Thanks.

[applause]

DR. DREGER: Let's go to Session 1. I used to be PC literate, but I switched to a Mac recently. I'm really happy to be able to join you here today, this morning, to share some of the work that we've done at the Berkeley Seismological Laboratory in terms of real-time earthquake reporting. And I'd also like to take the opportunity to describe some of the monitoring technologies that we have.

So beginning about almost two decades ago, Berkeley expanded its broadband network and started developing technologies for automatically analyzing signals from earthquakes, and to determine the characteristics of earthquakes and to report that information in as timely a manner as possible.

Recently, we've partnered with other institutions from the California Integrated Seismic Network, in which different organizations are pooling their resources to improve network coverage throughout the state and also to develop software capabilities to improve our monitoring capabilities.

So most of the talk is going to basically take you through a timeline that illustrates what we're able to do today. And I'd like to, I guess, provide a foundation for this through examples for recent central coast earthquakes. But before I move onto that, I'd just like to introduce this timeline. You're going to be seeing it on several different slides.

This is a 10-minute timeline. Okay. So the earthquake starts at zero. And there are different things that we need to do. We need to detect earthquakes, we need to locate them, we need to calculate the magnitude. For example, magnitude determination for this particular earthquake which occurred near San Jose was about four, four and a half, to five minutes. There are things -- I'll be describing shake map, which is a reporting of strong ground motions through the earthquakes so that's available within five minute's time. We compute things like moment tensors, which are updated, improved estimates of magnitude. They can be thought of that way. We also look at finite source models automatically. And the goal of all of this is to try to get as much information about earthquakes as possible in as short a time as possible because that might help affect the emergency response.

So the California Integrated Seismic Network, as I mentioned, is basically a pooling of resources. The public agencies, California Geologic Survey, the USGS, Cal EMA are participants. Cal Tech operates the broadband strong motion that work in Southern California, and UC Berkeley is contributing its broadband in strong motion stations in Northern California. So the plot on the left is showing broadband and short period stations throughout the state. Obviously, effort has been to concentrate the recording capabilities in the urbanized areas of the San Francisco Bay Area and Southern California. Oops, this is very sensitive.

On the right, is the strong motion instruments. And, you know, clearly it's even more pooling of resources in the urban areas where there's great concern. There's also improvements in recording capabilities in areas like the Central Coast ranges in the last several years.

Red is showing stations that have communication, and blue are strong motion stations that don't have communication. And the communication is really important because that's the vehicle by which we get the information back to processing centers where we can use the data to say something about the strength of shaking, for example.

Faults are not only on shore. There are offshore faults as well. This is really clear in the image here for the Monterey Bay, which shows offshore faults. All the recording stations are on land. That really biases our recording coverage. And so if we want to have a better understanding of earthquakes that are occurring offshore, we need instruments located on islands, we need instruments located on the sea floor. So Berkeley, in partnership with MBARI, the Monterey Bay Aquarium Research Institute, deployed a broadband-seismometer in one kilometer depth of water, and it successfully recorded teleseisms, global earthquakes, and also local regional earthquakes. We're very excited about this project.

I'm not going to go through all the nitty-gritty details here, but these are some of the specifications of what a modern recording network must have. It's broadband. Basically, what that means is that we're able today to record the entire spectrum of the earthquake source process, the wave propagation process. So it's a great improvement over earlier forms of instrumentation.

The other part of it is I've labeled here high dynamic range. But the way to think about this is that it's actually digitally recorded out at the field. So these recording instruments have sophisticated field computers at each site. And these sites, it's like a sound card in your laptop, it digitizes the analogue signal out at the site and it packages it in a way that allows for telemetry over a variety of different technologies, including continuous telemetry over telephone, microwave, radio and satellite networks. We use whatever technology we need for the particular application.

And because earthquakes have damaging motions, there's a great possibility that we would lose our AC power, and so all of our sites have secondary sources of power. Some are solar and some are battery-powered with a three-day capacity and onsite recording. So if we don't get the real-time data, we can get it eventually if -- when the site comes back online.

So the challenge here is we have all of this seismic wave form data streaming into our data center. We need to be able to identify an earthquake from just background noise. The way that that's done is there's computer algorithms that might scan a seismogram. Here's top seismogram, for example. It's just looking at the characteristics of the amplitude and period over time, maybe a moving average could be used, and so if that moving average, as the data streaming in, is moving across the seismogram like this, it's actually documenting what the noise level is, until finally there's some change that takes place.

This is the arrival of a P-wave that Ralph Archuleta spoke about. And that enables the first detection of an earthquake. If we have multiple detections at many different stations, then there are algorithms that try to bring these detections together into ways that basically tests the hypothesis that those arrivals are due to an earthquake and not some telemetry glitch or some other type of noise.

Given knowledge of earth velocity structure and P-wave and S-wave times, we can use that to determine the distance. And so this is that same diagram. And you can see clearly, these seismograms are aligned in absolute time. So this record is occurring first. That means it's closest to the earthquake source. And that station is located right here, Station C. Station E, for example, is located here. And its P-wave arrival is occurring much later.

Well we can get these automatic P-picks ,and sometimes S-picks, and we can use that to determine distance, and then we can plot the distance around that station as a circle. So if we only had this record, the earthquake occurred somewhere on this circle, if we're so lucky to have a station close to the source. But if we only had data from Station F, for example, arriving at 18 seconds, then the earthquake can occur anywhere on that circle. But since we have the overlapping of two circles, now there are two points where that earthquake could occur. Add a third station, we triangulate into a point and we can locate the earthquake. Add another station, we can start to improve our locations.

The important thing to note here is that even -- suppose we're not so lucky to have a station close into the source, even these more distant stations carry enough information to locate the earthquake. So this is something that's been done for -- since the beginning of observational seismology, but now it's something that's automated and it's done in several seconds time.

The other important information, as Ralph mentioned, is the amplitude of seismic waves, in particular, the amplitude of the S-waves, which carries the damaging ground motions. And one way to characterize differences in earthquake size is through earthquake magnitude. It's basically a measure of relative size. It can be confusing. There are many different types of magnitudes that can be based on shaking amplitude, duration, frequency, and wave type.

The one that's most common, everybody's likely heard of, is the Richter magnitude. And Charles Richter developed this first magnitude scale based on observations from a particular type of instrument, a Wood-Anderson seismograph. This is a Magic Marker here for scale. And this is really a robust instrument. It's the workhorse of seismology for many, many decades, only recently being retired.

The way this works is that -- or the way Charles Richter developed the magnitude scale is really in an ad hoc manner. What he said is okay, I have a station located 10 -- 100 kilometers from this earthquake. And on this particular type of instrument, the Wood-Anderson seismograph, it registered 1 millimeter amplitude. So that's what this line -- this blue line is showing. So this is the distance curve. So the stations at 100 -- very sensitive -- 100 kilometers, the amplitude is one millimeter. And then he just basically said I'm going to call this a magnitude three earthquake.

Suppose we have that magnitude three earthquake now located a distance of say seven kilometers. Well, what happens, you can see, is that the amplitude would be much larger. It would be 20 times larger according to the scale. So this is just another manifestation of the ground motion attenuation that Ralph Archuleta mentioned.

Now, if we have that same 23 millimeter amplitude, which is measured off the short period record here, we have the S-wave -- P -- S minus P time of 24 seconds, we can plot that 24 seconds point here, corresponding to a distance of 200 kilometers. The 23 millimeters amplitude on this instrument indicates that it's a magnitude five. So that's how earthquake magnitude works. The important point is that this is just a relative measure of size, and the actual numerical value of magnitude doesn't really have very much meaning beyond that.

[inaudible] down first motions. That information leads to a diagram, which I'm not going to go into great detail. In fact, I'm not going to go into any detail describing. But we affectionately call it the beach ball diagrams. And what you can get here from this slide is that there are three main types of earthquakes. There are strike-slip earthquakes, like those that occur on the San Andreas Fault, there are normal earthquakes that might occur in the horst graben structures of Nevada, reverse events like occurred in the 1994 Northridge earthquake. This diagram is showing the different block motions of these three classes of earthquakes. And these diagrams are just used by geologists and seismologists to plot in map view to be able to quickly identify the type of fault motion. I'll show you an image of why that this representation could be useful.

Well it's just two weeks ago, today, in fact, that there was a magnitude 3.7 earthquake 20 kilometers north of San Simeon, and occurred on August 25. And so this is a first-motion mechanism that the U.S. Geological survey produced. And the pluses are showing up first-motions, the circles are showing down first-motions. Not many observations in this quadrant. You can see this quadrant's predominantly up. This one's up, that one's down, and so we see that alternating pattern.

At Berkeley we utilize this continuous streaming wave form data. We process it by low-pass filtering. We can fit these wave forms very well. The computer-generated seismograms are the dotted traces in this diagram. The observations are solid. We fit three orthogonal components of motion, and we're mostly fitting surface waves, Love and Rayleigh waves. And by fitting these types of data, we can get this beach ball diagram, which is showing predominantly strike-slip faulting.

So the reason why this is useful is we can -- if we can do this quickly, then we can say what kind of fault slipped in an earthquake.  If we do this over many years, then we can plot these beach ball diagrams in map view and they start to reveal the underlying tectonics.  We learn more about the fault systems throughout California, surrounding areas.

Another very important data product that has been developed by the US Geological survey is the Did You Feel It? map.  And I have the webpage at the base of this -- at this slide, so if you’re not aware of it, I do encourage you to surf over to this website and take a look at it.  It basically provides the opportunity for the public to contribute in earthquake monitoring by reporting what an individual felt.  I actually find it as a very useful tool as I’m responding to an earthquake, because this map is updating minutes after the earthquake.  I could immediately see if many people felt the earthquake.  I can an idea of the intensity of ground shaking very quickly with this very important information that the public provides.

If we have instruments located around the source, then we can use those instruments to report ground motions, maybe accelerations or velocities, or in this case, cast in terms of seismic intensity.

For this earthquake on August 25th, the ground motions were not very severe, with a maximum of about Intensity 4 or so, which is potential damage, none, light-perceived shaking.  And this is just a map that’s showing the peak ground accelerations.  And these are very low, maybe one percent g maximum peak ground acceleration for this event, weak motion event.

So this is a cartoon that illustrates the automated processing timeline that we've developed, and we're continuing to develop, through the CISN partnership. We can determine a hypocenter and magnitude within 30 seconds to four minutes depending on the type of method that's used. We use multiple methods. It takes more time to get more robust solutions.

We can determine the seismic moment tensor now automatically five to seven minutes. And if the earthquake's large enough, one important question is which of these two possible planes actually slipped in the earthquake? And so if it's above a magnitude five, we perform automated finite source analysis to determine the orientation of that causative fault, and we determine the slip distribution, and we try to use that information to make an estimate of what the ground shaking is in the earthquake inside of a 30-minute time frame.

Okay. So what I'd like to do is just illustrate this for, you know, what transpired the day of the San Simeon earthquake, magnitude 6.5, located not too far from here. On the right is showing the community internet intensity map, the Did You Feel It? map for this earthquake. Intensity seven to eight over these fairly large zip code regions. It seems that the intensities are asymmetrical, with the largest intensity as being reported to the southeast, east, southeast of the event.

Okay. So I'm going to go through very quickly a series of maps here. This first map -- and each map is going to have a number at the bottom. This is the elapsed time since the earthquake. This is the actual time. This map is showing where the earthquake occurred. Now these are the recording stations that were available at the time of the earthquake occurrence.

So 24 seconds after the earthquake occurred, the first 20 stations registered P-wave detections, and a quick-look location was available. About four and a half minutes later, there is an updated hypocentral location and a duration magnitude of a 5.6 was determined. This was a 6.5, so the duration magnitude is already saturating and underestimating in this event. Give a few more seconds, 30 seconds or so, and the Richter magnitude was determined at 6.4 using more distance stations. You can see the location's not changing very much. Just another 40 seconds after that, we have the moment tensor solution that's indicating it's a moment magnitude 6.5 event, a reverse mechanism. Both reverse and strike-slip earthquakes can occur in this area, and they have different types of strong shaking patterns. So it's important to know this as quickly as possible.

This is an image that it just shows the moment tensor solution, the fit to the long period wave form data that's used. The first ShakeMap was available at eight minutes after the earthquake. And I point out where Paso Robles is here, if the arrow comes up again. There it is. It's this crossroads here. And the ShakeMap prediction doesn't really have -- at the time there weren't many recording stations in the area, so it's really an estimate of strong shaking. And it's coming in low at about intensity five. So its potential damage is very light, moderate perceived shaking. But there is actually some fairly significant damage, a collapse of unreinforced masonry buildings, and some damages to reinforced structures. The level of damage shown in this -- these images is greater than what the initial ShakeMap would lead us to believe.

The ShakeMap was updated 22 minutes later. They're automatically updated on a -- I guess on a schedule, and they incorporate all of the newest data each time the update is done. So this one, the moment magnitude 6.5 is available. It doesn't really change things very much. Well, we didn't have the finite source method automated at this time, so it took about two and a half hours after the earth -- within two and a half hours after the earthquake. We were able to determine the finite extent of the rupture. This is analogous to the movie that Ralph Archuleta showed. The earthquake hypocenter is located here at zero. He showed that movie of this very complicated rupture running down the fault. This is a static image that just shows that slip extended about 22 kilometers away from the hypocenter, and it extended 22 kilometers in the direction towards Paso Robles. So it ruptured at mach 10 directly towards Paso Robles.

If we incorporate this information in the ShakeMap, then the effect is that the intensities are increased in Paso Robles to Intensity seven to eight, and those levels of motion are more consistent with the types of damage and shaking that was observed or felt there.

Okay. So the last topic that I'm going to discuss is development by Professor Richard Allen in our department in developing earthquake early warning systems. The current effort is to develop a test system. This is being done in partnership with PG&E and BART and other organizations. Basically, what it works on is it triggers on a P-wave. I'm not going to go through the details of all of these plots, but it determines the characteristic of the P-wave, notably the period. Okay, so the longer the period of the P-wave, the bigger the earthquake is how it works.

And so -- and this is a four-second time frame. So Richard tries to do this analysis within four seconds. Each second, he updates the map. So at the trigger time, there is no information. After one second, there's the beginning of a ShakeMap. Two seconds, there's more information. Three seconds, if you have a nearby station, you might even be getting S-wave information that helps improve the ShakeMap. So this a -- or he calls it "AlertMaps."

This is a timeline that shows when the P-wave reaches -- first reaches the seismometers. This is the first ElarmS detection for the Alum Rock earthquake several years ago. One second later, AlertMap, two seconds, and the three-second AlertMap. So 20 seconds after the earthquake. This is the time when the damaging or the strong shaking S-waves reached Oakland and San Francisco. This earthquake was located near San Jose. So there is a 15-second telemetry delay built into this test system.

There's -- recently there's been updates to the monitoring technologies that are available. In fact, we're updating our data loggers that enable telemetry every two seconds, say several seconds' data transmission latency. And so that reduces the cellemetry delayed to maybe five seconds or so. You get these three AlertMaps within 10 seconds. And for an earthquake located in San Jose, that means you can have upwards of 10 seconds of early warning before the arrival of the S-waves at Oakland and San Francisco.

So this is a system that is being developed and tested against available data and improved, and it may, in the future, be and lead to an early-warning system in California. But that's really an area of current research. Okay, so to wrap up, each earthquake provides new experiences that we use to improve the realtime monitoring and reporting system. In 2003, as I showed for the San Simeon earthquake, the detection through finite source took two hours and 38 minutes. For the 2007 Alum Rock earthquake, that whole process took less than 10 seconds -- 10 minutes. I wish it was 10 seconds -- took 10 minutes. And so that's a great improvement. And if we're able to do this routinely on a 10-minute time basis, then we can provide information that could be very useful to emergency responders dealing with an earthquake emergency. Thank you.

[applause]

DR. MOSS: Okay. Good morning. I'm going to be taking this discussion towards the near surface and talk about how earthquakes can impact the foundation soils and structures. And there is really not a lot of rock left to build on, and so most of our structures are founded on soils. And so one of the primary concerns in earthquakes is how soils respond and how that foundation soil is going to react with the structure.

So I have a simple cartoon here showing a very simplistic earthquake at depth and the ground motion's propagating up to the surface. And what I want to focus on is this near surface area. And we get into the near surface, and again, as was mentioned before, we're primarily talking about the shear waves that are the issue. So as we get not the near surface, we have to deal with different geologic layering, soil stratigraphy, topography, and other effects. And my talk is divided up into site effects, soil failure, fault rupture, and then I'm going to talk generically about structural response and infrastructure.

Now, these shear waves that are propagating to the surface are of primary concern because most structures, they're built to resist gravity, but they're not built to resist lateral forces. And that's why we see most of the structures fail in earthquakes due to these lateral forces.

With site effects, we can group it into really three broad categories: Near surface soil response, topographic effects, and basin and basin edge effects. So how does the topography, any geologic structure, and the dynamics of the soil interaction with the ground motion? And these can result in changes in the amplitude of the ground motion.

And here, I'm showing a recording that was made after the 6.5 San Simeon earthquake in 2003 right here in San Luis Obispo. And so these site effects can result in changes in the amplitude. And what we're concerned about is amplification, or increasing of the amplitude, can alter the duration of the ground motion. So maybe we could have more significant cycles and can also change the frequency content.

Here's kind of a busy plot that I want to break down. But the study just came out. And it's looking at site effects from the 2003 San Simeon earthquake. And what I've boxed in there on the top plot is the high ground shaking -- high ground shaking intensity. So we're looking at measuring the earthquake in terms of peak ground acceleration, usually in terms of gs. And so we're looking at 30percent g or greater.

And what this study did is it looked at single-family homes. And we can see that on the left, the primarily the damage rate for hilltops was greater than it was for slopes. And this is what we would call a topographic effect. The ground motions come up, and for hilltops, they can get channeled into that hilltop, and so we see much stronger ground shaking at the top of the hill than we would see down at the bottom of the hill.

The bottom plot shows how the particular geology in the soil derived from those rocks can affect the ground shaking. And we've got three different rock types that have weathered into different soils, and you can see that they resulted in dramatically different damage rates, again for single-family homes. So site effects is something that we need to be concerned about -- how does the near surface geology, topography, and other features change the ground motions as they get to the ground surface?

I want to move into soil failure here. And one of the primary concerns when we talk about soil failure and earthquakes is liquefaction. This cartoon shows if I take a cup of dry sand, dry loose sand, and I shake it, it will get denser. Now, if I take that same cup of sand, but it's saturated, and I shake it really fast, what happens is that the water doesn't have time to get out of those pore spaces. It pushes out on these sand grains, making the sand grains essentially buoyant. It's counter-acting the gravity forces, pulling down the sand grains, and the soil becomes fluidized.

And what we see in the picture on the left is that when a soil is fluidized, what used to be solid now tends to flow. And if we have stuff pushing down on it, like here we have some soil pushing down on it from the top, well it wants to get out of the way. It wants to relieve that stress, and it will come out in what we call sand blows, or volcancitos, or sand boils. This is what we call surface manifestation of liquefaction.

Now, if we have a structure sitting on there and the structure's relying on the soil to support it, and the soil now liquefies, then we have a big structural problem. Here is some surface manifestation from liquefaction from the San Simeon earthquake, showing both the Salinas River, up near Paso Robles, and Santa Maria River, further south. And what happens when you have a structure sitting on it, well, it tends to tear the structure apart. This was in Oceano. In the bottom left picture, the soil liquefied and then started to flow downhill, creep downhill, and it essentially tore that single-family home apart.

And the picture on the right shows the ground pushing out on the curb.

So these are some fairly contained examples of liquefaction from a local earthquake. An earthquake that I visited this spring, the Chilean earthquake, much larger earthquake, much stronger ground shaking, longer duration. We see more exacerbated liquefaction effects. The lower left, you can see evidence of lateral spreading over that entire site. In the upper right is when we bury things in liquefiable soil and it liquefies, if it's less dense than that liquefied soil, then it becomes buoyant. And we see this with pipelines, we see this with tanks. Anything that's less dense than the liquefied soil pops out of the ground.

Another type of soil failure is seismic induced landslides. And here I have a cartoon showing a slope, and there's some mass that could potentially slide. And the earthquake kind of affected it in a couple of ways. One is, it provides a big kick, a lateral kick to it, and that can destabilize the slide mass. And the ground shaking can also result in strength the loss at the base of that slide mass. And the primary variables that we're dealing with is the resonance -- do we see the slide mass resonating with the particular frequency content of the ground motion, and how many cycles of that earthquake are going to kick the slide mass?

What does that look like? San Simeon, it was fairly contained. Again, that was a 6.5 earthquake, some good peak ground acceleration, but not a lot of duration. On the right, you see surficial sliding. And not really an engineering issue, you just scrape the dirt off the road and you keep going. On the lower left, a larger existing slide that reactivated. Lower left larger, deep-seated slide. You can see the ground cracking there in the foreground. And out on the coast, we see destabilized coastal bluffs due to the ground shaking there.

Again, bigger earthquakes, more effects. This was Chile this spring. A large land mass that moved -- no strength lost here, just the kick from the ground motion destabilizing that slide mass. What other near surface effects do we see from earthquakes? Well, we can see fault rupture propagating to the ground surface we call the “surface fault rupture.” And I don’t need to go through the different types of faults. We’ve been through that before. But the length of surface fault rupture is strongly correlated with the magnitude of the earthquake. And that’s what that busy plot on the lower left shows. Surface rupture length versus moment magnitude.

So again, an earthquake is a rupture at depth in some seismogenic rock and does that displacement propagating to the surface. [inaudible] frozen turf and the fault ruptured right here and essentially toward [unintelligible]. The same response we see with structures. It was a rupture to a structure that is not properly enforced did a lot of damage, essentially tears it apart. Okay. Let’s get to talking about generic structural response and infrastructure relating to earthquakes.

You’ve seen this picture before. San Simeon, we had this awful occurrence where the Acorn building collapsed and [unintelligible]. And if some of you have been following in the press, there’s been a lot of litigation, and it’s really effecting how building owners deal with retrofits. This was primarily the only structure that failed, and it was an unreinforced masonry structure, which meant that it was either brick or masonry that was stacked up, resisting gravity forces, but not shear forces, and it collapsed.

I want to juxtapose this with an earthquake that occurred essentially three days later in Iran. The entire city was built out of unreinforced masonry. It's a very old city. And you can see it looks like a bomb hit the place. San Simeon, two people died in unreinforced masonry collapse. Here, we're talking about tens of thousands of people that died in unreinforced masonry collapse. I'm not showing this to be catastrophic, I'm showing this to make a point that why didn't we have more deaths in San Simeon?

The mechanisms are a little bit different. The magnitudes are about the same. The ground shaking in Iran was a little bit stronger. The fault actually ruptured right through the town. But the primary difference is that we have seismic codes here; and there's no seismic codes there. And we can talk about the same effect with the Chilean earthquake and the Haiti earthquake.

The Chilean earthquake, much larger, longer duration, stronger amplitude ground motions. Haiti, hundreds of thousands of people died. Chile, we're talking about hundreds of people died, and that was primarily due to the Tsunami. So seismic codes work. If we design structures to resist these lateral forces, it shows that it works. We save lives. Here we show some structural failure in Chile. And again, unreinforced masonry. Typical residential adobe construction on the left, older, poorly reinforced construction on the right.

And this picture -- these pictures are particularly interesting. The single-family home there is a modern home. It was probably designed well. And let me preface this a bit by saying that Chile has very good seismic codes equivalent to our seismic codes in California. So this home was probably designed adequately for ground shaking but not for the liquefaction and lateral spreading that it experienced there. That's very hard to design against.

However, the apartment complex that's below it was on the same lateral spread and performed very well.  So it had a very beefy matte foundation. It went for a ride, but it survived.  I mean, it's essentially -- the people could move right back in.  The problem is that a lot of damage surrounding the structure, and you can see the sidewalks are collapsed and the fences fell down.  They might have a little trouble opening the doors.

The picture on the lower left is a very interesting picture.  You can see the building that fell down there.  That was recently completed.  And then there's the building on the upper left of that picture that's almost completed. Now, they had essentially the exact same ground motions, they have the exact same foundation conditions, and the only difference here is that the one on the lower right somehow did not follow the seismic codes as carefully as they should have.  This building is now in a lot of litigation.  When we flew over, you can see the cranes are tearing it apart.  The next day, the cranes were halted because they were doing some forensic analysis on it.  But basically, there was something that went on where the codes were not followed and that building fell down.  And the bigger building up behind it, and it's almost finished, no damage.  So, again, seismic codes work.

Let's talk about infrastructure because this is one of my primary interests and it has a wide region effect in terms of earthquakes.  The bridge you see in the upper picture, that should look -- the type of damage that look familiar to you from people that saw the '89 earthquake and the Bay Bridge dropping one of its decks.  Same type of issue here, that this bridge deck was not designed to handle those types of ground motions.  The Chilean government knew that.  This bridge was closed to traffic, and rightly so.  It performed poorly.  It dropped the bridge deck.

The pictures along the bottom of this slide show liquefaction. And particularly, the middle picture here, the ground liquefied and then flowed this direction and then sheared this column. And you can see that this older bridge sustained a significant amount of damage. Here, our colleague's standing in one of these sand boils where there was some liquefaction and ground loss.

This was an older bridge, was not designed very well, and the ground deformations due to liquefaction hammered it pretty good. Here was a bridge that was built in 2008. A very rigorous seismic codes. The bridge performed very well, even though you can see essentially the same effect -- liquefaction, lateral spreading, ground pushing on the foundation of the bridge. The bridge did well. The bridge was perfectly fine after the earthquake. They had to deal with the abutment a little bit. There was some abutment deformation, but no reconstruction needed on this bridge.

Here we have a soil failure along, essentially, the main highway in Chile, the Pan-American Highway. And most of the failures that we saw were in engineered fills, soils that had been compacted to support something, and there were some issues with either the soil underneath the compacted fill or that the fill settled. Here, we see large failures. Again, same type of stuff we saw in the Northridge earthquake, lots of fill settlement. We saw that in the San Simeon earthquake on the highway that goes from Paso Robles to Cambria. Lots of compacted earth fill did not perform very well. It's not catastrophic failure, but it costs a lot to go back and fix this. On the Pan-American Highway, every 10 kilometers, there was some type of ground failure like this.

Port facilities tend to take the brunt of earthquakes. In the '89 earthquake, Loma Prieta, Port of Oakland, Port of San Francisco, they got hit really hard. We were talking about poor soils -- we're talking about saturated, soft, weak soils -- amplified ground motions liquefy fail. And so here you can see evidence of that. Lots of ground damage, lots of damage to the piers and wharfs and the supporting foundations.

What other types of impacts do we see from earthquakes? This was an interesting one from the San Simeon earthquake is that Paso Robles used to be known, the turn of the last century, known for its warm springs. And essentially that fell out of favor and they capped a lot of these or diverted them. Well, they came back with a vengeance. The picture on the right shows city hall, and that's the parking lot of the city hall. And it used to be -- they used to have a bathhouse there. And this warm spring decided to re-emerge and essentially eroded out a huge hole, and they were throwing everything they had in there to plug the hole. And the lower left picture shows a new spring that came out of the, ironically, Spring Street exit in Paso Robles. [laughter] Coming right out of the embankment there. As an engineering issue, not a problem. Kind of a pain in the neck to deal with.

Again, other impacts, larger earthquakes, bigger stuff. The lower left shows what tsunami damage looks like. And, essentially, there used to be a town there, and the town's gone. Tsunami damages -- dealing with tsunamis is at the forefront of our engineering issues right now. It's a very big problem.

In the upper right, why are all those ships sitting on dry ground? Well, it used to be a port there, the town of Lebu. And the ground that that person is standing on used to be one to two meters below what it is now. That's wholesale tectonic shift. And so we had within the time frame that the earthquake occurred, that entire section of the crust rose up one to two meters, essentially, leaving the port facility high and dry.

So just to briefly summarize what I've run through. I'm talking about impacts of earthquakes on soils and structures. The hazards that we're dealing with -- ground shaking, soil failure, fault rupture, and structural failure. And I've been very broad with structural failure and just talking about hey, lateral forces we need to design for.

I think there's no argument about that seismic design codes work well. And that's why we have performance issues here in -- or in developed countries, we have performance issues. Well, we've got to deal with the highways, and we have to deal with, you know, minor issues, and people avoiding the code. In developing countries, we need to get the codes in place.

There is a lot of infrastructure issues that remain. Highways I showed, bridges, whatnot, but some of the other peripheral issues -- power continuity, water transmission, telecommunication. A lot of the hazard planners talk about being on your own for 72 hours, and that was true in Chile. Even the big city of Santiago that was far away from the epicenter, they were without electricity for a couple of days, without water for a couple of days, and telecommunication took about a week to get back online.

And critical -- the critical path forward is mitigating these hazards and then having a proper emergency response. So that's all I have for you today.

[applause]

MR. MAIER: If you notice the waves traveling across the screens and how could you not --

[laughter]

-- I apologize to the presenters and to you for their existence. We're going to see what we can do to try to get those -- get rid of those during the break.

This brings us to the first question and answer session. And I'd like to go over a little bit of the protocol or ground rules for conducting questions and answers. We finished up each session with a 15 minute question and answer session. As you heard me mention earlier, the entire proceedings are being videotaped by AGP for inclusion on the NRC's website. For that reason, once again, we ask that only one person speak at a time and wait for Butch or I to come around and hold the microphone for you while you speak. I hope you won't be insulted if we hold the microphone. That's the first -- that's the -- that's the prime directive of facilitating, right, Butch? You never surrender the mic.

Okay. We ask you to raise your hand, and Butch and I will alternate between opposite sides of the room. I invite you to stand and identify yourself if you want to. Direct the question to whichever panel member you want to direct it to. Please bear in mind that we -- in the interest of brevity, we would like folks to kind of keep their questions as focused as possible so that the maximum number of people who have questions can be included in the question-answer session. And I'd also like to ask the answerers to try to keep your answers as focused as possible, also in the interest of time.

If you don't have an opportunity to get your question asked during the question-answer session, Butch and I have 3x5 cards that we'll carry around. And if you've picked up any on the way in, there's some outside, I believe. Write your question down on the card, put some contact information for yourself on it, either an e-mail address or telephone, and please write legibly. And if we don't get a chance to your questions, then if you hand that question back to Butch or to me, we'll make sure that an answer gets back to you in some fashion.

Also, we would ask that you -- we only have the folks who just presented up here, so we would ask you to focus your questions on the topics that these gentlemen just presented. If you have a topic on another issue that's not related to what they just presented on, we ask you to look at your agenda, figure out which session would be the best one to ask that question in, and then hold your question for that session. Tomorrow will be all day Diablo, so what we're looking at today is the basics of the sciences.

If you won't be at a session that you think that your question should be asked in, put it on a card, get it to Butch or to me, and we'll make sure that an answer comes back to you somehow. Anything I forgot to mention, Butch?

MR. BURTON: No, I think you covered it.

MR. MAIER: Okay. And if anybody has any questions, please raise your hand.

MR. WARDELL: Ferman Wardell, Diablo Canyon Independent Safety Committee. My question's directed to Dr. Dreger of Berkeley. And on the handouts, I don't' think you showed this slide, but it's the -- looks like the last one. It says if a San Simeon earthquake was a strike-slip, the extent of damaging ground motions would have been larger. And I guess my question's twofold, is one, how well can we characterize the faults as to where they're strike-slip or what else? And in general, how much larger could it be or could -- in this particular earthquake if it were strike-slip as opposed to what we characterize it as?

DR. DREGER: To answer the first question, we can characterize the type of faulting very well. There's many different techniques that we employ to get that information. In regards to the second question, what that slide addresses is if you take the model that was determined for the actual San Simeon earthquake and change it from a dipping fault to a vertical fault, and changing it from one where it's a reverse fault where the hanging block moves -- is thrust up over the footwall block to one where the motion is side-by-side, all other perimeters being identical, the area of strong shaking is larger. It's about three times larger. In this model, and it's important for me to state that this is a model, the peak ground motion is about the same. It's just that the area of elevated motions is larger.

MR. MAIER: Other questions?

MR. BARD: My name is Geof Bard, Upland Research Science Action. My question is directed to Dr. Moss regarding the phenomenon of soil liquefaction. I would appreciate it if you could please expand a bit and tell us about the variables, topographic and soil composition variables, hilltop versus slope, the effect of pitch, and also the depth of the aquifer or proximity to bodies of waters, such as creeks, and streams, and lakes in the ocean. And also, how well-mapped is all of that type of data?

DR. MOSS: Liquefaction if a phenomena of loose granular soils that are saturated. So any time you have a -- is this working okay? Yeah? Okay. Any time you have a loose granular soil to it, a sand that's saturated, so below the water table, and you apply strong enough ground shaking, then you could have liquefaction.

Now, you mention a number of other things that aren't necessarily related to liquefaction. Usually, we find these loose sandy soils in some type of river deposit or some type of beach deposit. And are they mapped well? The CGS provides liquefaction hazard maps, but the coverage is usually restricted to the areas that have been studied. The state does require a liquefaction analysis for every, essentially, every development. Does that answer your question?

MR. MAIER: Other questions?

MS. COCHRAN: June Cochran, Shell Beach. The Japanese plant shut down -- and this is to mainly Professor Moss -- the Japanese plant shut down by an earthquake in 2007 was to designed to withstand short, intense tremors. The builders had studied and designed the plant based on these studies, not the broad, horizontal swaying that occurred with the 2007 earthquake. This caused water to slosh out of storage pools, with around 1200 liters, contaminated with radioactive material reaching the Sea of Japan. At least 63 other problems were reported, including burst pipes, water leaks, and radioactive waste spillage.

In five of the reactors, major exhaust pipes were knocked out of the place, as Professor Moss demonstrated in pictures from Chile. About 100 drums containing radioactive water fell over. I'm almost done. Some of them were found with their lids open, cobalt and chromium 51 leaked into the atmosphere. Given that the Japanese regulators were incorrect in their calculations about earthquake movement and the design of the plant, can the NRC rely totally on the seismic studies being performed for Diablo to be totally accurate, especially when there are strike-slip movements in California?

DR. MOSS: Wow --

[laughter]

-- I don't have any specific knowledge about the shutdown of that plant in Japan. What I presented was a generic description of the hazards that we're dealing with. Now, there has been a lot of study of that plant, and we can dig that up, but that's not my background is how earthquakes have affected particular power plants and why they've been shut down.

Now, generically, we do a very good job with seismic codes and seismic containment. Now, are we learning? Yeah, we're always learning. Every earthquake provides us with new information. Can we deal with every contingency? Well, we can do our best, but it doesn't necessarily have to do with nuclear power plants, it has to do with anything -- highways, tall buildings, sewer systems. And so we're always improving the seismic design.

MR. CANIANO: And I think in Session 4 later this afternoon, that session is titled "Nuclear Power Plants and Seismic Hazard." Maybe you might want to ask one of those folks.

MR. MAIER: Other questions? Anybody from Butch's side of the room?

MR. BURTON: Yeah, my side's kind of quiet.

[laughter]

Ah, we got one.

MS. HUNT: My name is Gail Hunt, and I would like to have you review just one more time how you determine moment magnitude.

DR. DREGER: There are actually many ways to do it. But the way that we do it is we process the data in a way that highlights the long periods. And as earthquakes get larger, they radiate more and more energy at longer periods. And the precise way that we actually determine moment magnitude at Berkeley, is to fit three component long-period seismograms with computer-generated seismograms that were computed for a specific velocity structure that's appropriate for the region. So it's a model fit.

You can kind of liken it to if you have a distribution of points and you fit a straight line through those points. You know, maybe you just take a ruler and fit a straight line through those points. We're doing the same thing, except instead of a straight line, we have these wiggly lines, which are the seismograms, the computer-generated seismograms.

DR. MOSS: Doug, can I add one thing to that? If we have a good measure of default area and how much displacement occurred on that fault area, that's directly proportional to the moment magnitude. So if we have, if we can -- and what Doug's talking about is defining that fault area. And that's not easy. Defining the fault area and then how much displacement occurred on that fault area at depth, and that's directly proportional to the moment magnitude. So it's a measure of, essentially, the moment, the moment alarm that occurred at depth and how much energy that took.

MR. MAIER: Okay. We have another question here.

MS. EVERED: I'm Judith Evered from Goleta, Santa Barbara County. And I'd like to ask a question of Mr. Doug Dreger. It's the relationship between the P and the S waves. For instance, I felt the Northridge earthquake in Santa Barbara. And I immediately identified it as an S-wave; it was a waiving kind of motion --and I thought -- it's not close and it's fairly distance. Is it north or south? I always think that when I feel an earthquake in Santa Barbara. And it turned out, when I phoned LA, no answer. I phoned San Diego, oh, yes, it happened in LA. But now you've mentioned that a P wave turns into an S wave, and I'm wondering if I didn't just feel the P wave that night or whether S waves can be by themselves. And usually I thought they were the end of an earthquake effect, the farthest from the epicenter, for instance.

DR. DREGER: Well, they're P and S waves, and there are actually many other waves. So for that swaying motion, you might have actually felt a surface wave. That's a possibility. And those arrive after the S waves. Sometimes you'll only feel the S wave, but that would be for small earthquakes because the P wave -- the P waves are much lower amplitude, so they're not perceived. A large earthquake like Northridge -- how far is Goleta from Northridge? A hundred miles? So you may have felt the P wave in that event. I felt the Landers earthquake when I was in Pasadena. That was 100 and -- about 100 miles away, and I felt the P wave, and responded to that and got in the door jamb before the S wave arrived. You're not supposed to do that now, but that's that's what I did back then. One thing that you can do next time if you feel a P wave, just start counting off, you know, 1/1000, 2/1000, until you feel the larger amplitude waves. And if you multiply that number, that number of seconds by eight -- I call it the "rule of eights," then you can get the distance of the earthquake.

MS. WILLIAMS: Can you take one more, Bill?

MR. MAIER: Anyone from the other side? Nope? I got another question here. I guess I'm going to get most of the exercise during this workshop, I think.

FEMALE SPEAKER: This is not a question. This is a statement to the NRC staff.

MR. MAIER: We really wanted to make sure that it was questions for the folks who were here. Maybe you could hold it for a better session if it's a better session tomorrow?

FEMALE SPEAKER: Unfortunately, the reason I'm -- I want to make this statement today is because tomorrow is Rosh Hashanah, a Jewish New Year, and I won't be able to be here, as will many of the people who would like to be here tomorrow. And that's the reason for my statement because the NRC staff chose today, September 8, and tomorrow, September 9, the eve of Rosh Hashanah and Rosh Hashanah day, the beginning of the holiest time of the year for the Jewish people to hold these workshops in San Luis Obispo. To me, it indicates a gross insensitivity, to say the least, and a lack of planning. And I'm just wondering how well we can trust the staff of the NRC to reassure us about the safety of an -- of a nuclear power plant with 2,000 metric tons of highly radioactive waste stored 11 miles from here if they can't even plan to make these meetings on a date when people can attend? Thank you.

MR. MAIER: Thank you for your statement. Questions from the other side?

FEMALE SPEAKER: [unintelligible]

MR. BURTON: We're running a little late, but we can take a little bit out of the break, I think. This lady over here. Stand?

FEMALE SPEAKER: I'm wondering if individual faults have characteristic geometry or if any -- am I in it? Do individual faults have characteristic geometry or is any type of movement possible on any fault?

MR. MAIER: Is that direct to any panel member in particular?

FEMALE SPEAKER: Dr. Dreger.

DR. DREGER: You can answer this question with different layers. I would say that, you know, for the most part, a fault, once it's identified as being reverse or normal or strike-slip, that's the predominant sense of motion. When we look at earthquake ruptures in detail, we can see some deviation from that. Sometimes there are earthquakes that have compound ruptures. The Denali earthquake in Alaska was one that started as a reverse event and then ended up as a big strike-slip earthquake.

FEMALE SPEAKER: Thank you.

MR. CANIANO: Megan, if it's all right, let's do one more. I see these two young ladies here who have raised their hand several times. And if anyone else isn't able to get their question in, again, we have index cards. You can leave your question and your contact information on the card and we'll make sure we get back to you. Hi Jane.

MS. SWANSON: Hi, my name is Jane Swanson. I have a two-part question about those S waves, and I think you'll know who wants to answer. One is very simple. The "S," I think that stands for the word "shear"? I'd like that clarified. Very simple. And the other one is I'd like one of you to expound on the effects of those S waves, the difference between their effects on a low-thick wall versus a very tall, skinny structure, a pipe or anything, a tower, or something tall and vertical and skinny -- the difference between the effects on those types of structures.

MR. MAIER: I think Dr. Moss is going to jump on that one.

DR. MOSS: "S" stands for "secondary" or "shear" wave. We use both. It's generally shear in nature by the time it reaches the ground surface, so it's this lateral movement. And it was primarily called the secondary wave because it was the second one that came in when people started recording earthquakes. Now your question about how the S waves affect -- I think you're talking about different structures, but you used the example of a short, thick wall and a tall, slender pipe. It's a little more complex than that. It has to do with the -- at what frequency that structure's going to resonate at with the frequency content of the motion. And you just think about a tuning fork. A tuning fork resonates at a particular frequency, and structures do the same thing. And if you hit that frequency, then you're going to get resonance and you're going to get a large displacement of the structure or large response of the structure. Now you take that response and you say well, how well built is it? So if we're talking about an unreinforced brick wall versus a steel pipe, well, it's kind of a no-brainer there. The unreinforced brick wall is probably going to fall apart due to the shear waves, and the steel pipe is not. It's a very simplistic answer. I hopefully -- that gets to what you were asking.

MR. MAIER: And Sherry, we have time for one more? Sherry, you want to ask a question?

MS. LEWIS: I'm Sherry Lewis. Do you have liquefaction under the sea?

DR. MOSS: Yes. We can have liquefaction under the sea. Any loose, saturated soil, whether it's below the ground surface and below the water table, or if it's below the ground surface beneath the ocean, you can get liquefaction.

MR. MAIER: All right. Well, that -- I want to thank our presenters, and thank you for the questions. We're going to take a break now until about 10:30. I urge you to check out the Los Osos in the Aetna rooms. I don't know if there are any posters or any displays up for those, but if there are, you might find them useful. And we'll be back here at 10:30 for Session No. 2.

[break]

MS. DENISSEN: My name is Christie Denissen. I'm with the NRC, and I'm here to introduce Session No. 2, which is Seismic Source Characterization. And we have brought three specialists from the U.S. Geological Survey and California Geological Survey to talk about how faults are characterized. So first we have Vicki Langenheim, who's a research geophysicist with the U.S. Geological Survey in Menlo Park, California, specializing in the application of gravity and magnetic methods to assessment of seismic hazards. And then Jeanne Hardebeck is also with the U.S. Geological Survey in Menlo Park. Her research interests include the strength of faults, earthquake stress triggering, and imaging fault structures using microseismicity. And finally, Tim Dawson is an engineering geologist at the California Geological Survey, also in Menlo Park, California. His research has focus on developing paleoseismic earthquake records along the Hayward and San Andreas Faults in California and the Denali Faults in Alaska. And with that, I'll let Vicki take it away.

MS. LANGENHEIM: Okay. Well, thank you for this opportunity for me to talk to you about how we use geophysics to characterize faults. And in particular, I'm going to be talking about the gravity, magnetic, and seismic reflection methods. Because this workshop is focused on the Central California Coast ranges, I thought I would introduce these methods with the geology and geophysics of this region in mind. But before we get on to geophysics, I thought I would just show you what an actual fault looks like at the surface, because this is what we're trying to characterize at depth, indirectly mapping them using these geophysical techniques. So here's a photo of a fault, which is a fracture or fracture zone, along which there has been displacement of the sides relative to one another. And the displacement could be really quite minor on the order of inches, or it could be really significant, like hundreds of miles like our friend, the San Andreas Fault. Note that this definition doesn't say anything about when the fault last moved. So a fault could have last moved seven years ago, like in San Simeon, or it might have moved thousands to hundreds of thousands to millions of years ago.

Okay. So looking at this photo, we see a zone of shearing, which separates rocks of different ages. And on the left side, we have the Monterey Formation and we have the Pancho Rico Formation on the right side. We can get information on how the fault moved, in that the Monterey Formation is older than the Pancho Rico, so it must have moved up. And looking in the sheared zone, we have indicators that indicate that the fault also moved such that the rocks on the left moved away from us relative to the rocks on the right. We can also look -- get some information on when this fault might have last moved, because, obviously, the fault must post-date the rocks that it displaces. And the youngest rocks that look like they may have been displaced are these river terrace deposits up here, which are between about 10 to 100,000 years ago. Sounds like a lot of time to us, but geologically, this is a fairly young fault. So what I'm going to be doing is trying to show you how we map these features and extend them into the subsurface where earthquakes actually occur, and this is using gravity, magnetic, and seismic reflection methods. So let me first show you something about the geology of the area because these geophysical methods are indirect ways of mapping these rock types through their physical properties.

Okay. So this is a topographic map of the area. For reference, here's Monterey, Paso Robles. Here we are in San Luis Obispo, the beautiful town of Lompoc, and Santa Barbara. And that photo in that last slide was taken here. The red lines on this map are quaternary faults. These are geologically young faults. And we see that that fault actually extends to the North, forming the eastern margin of the San Lucia Mountains, and then it extends oh, about 100 kilometers to the South. So this is a fairly significant fault. This is called the Rinconada-Reliz Fault. And it's now overlaid the geology on top of this topography. And I've simplified this geologic map to kind of reflect the physical properties that these geophysical methods we'll be looking at. And we're just going to go through this map from youngest to oldest. So the youngest deposits are those sands, gravels, clays that are deposited in the valley, sometimes mantle the hill slopes. Beneath them, we have older sedimentary rocks, such as the Monterey Formation, which is about 17 to 7 million years old. It's a widespread marine sedimentary unit. Locally, we have volcanic rocks that are inner-layered with these older tertiary rocks in places we have them intruding, such as this line of volcanic necks here, culminating with Morro rock.

The next package of rocks we have are cretaceous sedimentary rock, such as the Atascadero formation. This is along Highway 41. Again, it's very well bedded, but we'll see it's denser, more consolidated. So somewhat different properties. To a geophysicist, these sedimentary rocks, these younger rocks, we call them "cover." And what we're -- what that's covering are the basement rocks. And we have three basic basement types. We have the Mesozoic granitic and metamorphic rocks that are exposed in, for example, the Gabilan, Santa Lucia, and here in the La Panza range. Then we have a very characteristic basement rock, the Franciscan Complex. These are basically mostly oceanic sedimentary rocks that were scraped off the edge of North

America when we had a sub-duction zone here. And the result of this is that it's kind of a mélange, a mixture. It's very heterogeneous, very disrupted. It also incorporates things that geologists call "knockers," such as this. I don't know why they call that, but that's what they call it. And then the third basement type are bits of oceanic crust and mantle that are interleaved within these basement rocks. So, for example, we have here at Port San Luis, these are pillow basalts. These are basalt flows that extruded onto the ocean floor, forming these pillow-like structures that have then been tilted upward.

All right. Now that I've introduced the geology, let's talk about some geophysics. So the first method I'm going to talk about is gravity. And this exploits very small variations in the earth's gravitational field force to map subsurface density. And so you might thought -- you think that gravity is a constant. It is not on the surface of the earth. It varies. According to our famous equation describing gravity by Newton, it varies with your distance from the center of the earth, so are, and it also varies as the mass. So if you have denser rocks in there, you'll actually feel a little bit heavier -- well, maybe not you but some of our very sensitive instruments can sense this.

So here we can make these measurements at various locations on the earth's surface and be able to map and figure out where we have different density rocks. And this is kind of schematically shown in these cartoons. The slide -- the cartoon on the left shows what you might expect if you had a buried dense body. You would see that the satellite is more increasingly pulled towards that dense body. If you have a fault that juxtaposes rocks that are dense verses less dense, you would see that the satellite would become increasingly more pulled as you got over those dense rocks, forming this gradient in gravity. Well how do we measure these variations? These are very small variations. We're talking about one part in a million of the earth's gravitational field or less. And we do it, well mostly on land with something that we creatively called a gravity meter. It's basically a weight on the end of a spring, and that weight is pulled more strongly over dense rocks, less so over less dense rocks.

We can lower this kind of instrument onto the ocean bottom, level it like we would on land and measure the earth's density there, or we can also measure it from a ship, which is a bit more complicated. This is on a gyroscopic platform. And you also have to isolate the accelerations that the ship is experiencing. Well, in the Central California Coast ranges, we have all of these various kinds of measurements. And the blue dots are the measurements that we have. You can see we have tens of thousands of these measurements. We are very grateful to the Defense Mapping Agency, which is responsible for this grid of gravity data. They collected that data in order to better constrain the paths of missiles launched from Vandenberg Air Force Base, but we're using it to look at geology. So we take these measurements, we process them so that we remove kind of the gross earth mass so that we're really focusing on the mass or densities in the upper, let's say, 10 to 15 miles. We processing them, we grid them, and we produce a gravity map.

So for orientation, here's Monterey, Paso Robles, San Luis Obispo, Lompoc. And the warm colors on this map are gravity highs where we have higher density rocks exposed or voluminous in the crust. And the gravity lows are the cooler colors. This is where we have lower density rocks. So going back to the geologic map. The less dense rocks, we have a really good density contrast between the sedimentary rocks and the basement rocks. So we would expect gravity highs over the basement rocks. So where the pinks and dark greens are, we would expect gravity lows over the more beige and blue areas. And for the most part, that's what we see. We see a good gravity lows over the Salinas Valley, the Santa Maria Basin, San Joaquin Valley, Santa Barbara. But we can also see that there are these linear gravity gradients that coincide at least locally with our major faults, such as the San Andreas, the Rinconada-Reliz, and the Hosgri Fault.

Now I'm just going to give you an example of how we use gravity to extend faults into the subsurface. Let's focus in on this area. This is a gravity map. Here's Morro Bay. Here's the coastline. And here's the Hosgri Fault. Note that the Hosgri Fault lies near the base of this rather significant gravity gradient where we have a gravity high, and therefore, denser rocks on the east side of the fault. By looking at where the fault lies relative to that gradient, we can say something about how that fault dips into the subsurface. So if the fault lies in the middle of the gradient, it's going to be a vertical fault, typically a strike-slip fault. If the fault is located near the top, it will be more of a fault dipping off to the west. And if it's located at the base, it's dipping off to the east. So just by looking at where the Hosgri Fault lies relative to this gradient, we can tell that the fault dips to the east, it's not a vertical fault, and it's a rather steeply-dipping fault because this gradient is rather narrow.

Let's go on to our second method, the magnetic method. And it works a bit like the gravity method, except we're looking at very small variations in the earth's magnetic field to look at magnetic rock types beneath our feet. So here's an example of a magnetic anomaly or variation that would be produced by a fault offsetting these concealed magnetic rocks. And we can also -- oops --

measure these variations by either walking a magnetometer, which means that we take a really long time to map the Central California Coast ranges and I don't have that much time in my life I don't think. So what we often do is we mount it on an airplane, such as this, or on a helicopter, and you can cover a lot of ground that way. We can also tow it behind a boat so we get marine magnet. So let's see. We can get a feel for how deeply buried those magnetic rocks by looking at the wave length of the anomaly. So in general, the shallower that magnetic source is, the more high wave length -- short wave length we get. As it gets deeper, the variation becomes more broader and low amplitude. So you can think of this as another way.

If you collected the data from an airplane -- of course, you have to fly somewhat over the ground -- you'll get a broader anomaly than if you collected that over the same ground with a magnetometer on the back of your backpack. So this is a map collected from an airplane flown about 1,000 feet above terrain as safely as one could. And what I want you to do is focus on the offshore area and this area here. I'm going to merge in data collected from a boat and from a helicopter, and you'll see just the increased amount of resolution. Let me just do that again. You can see a lot of these anomalies are being cut off. This is the Hosgri Fault running down through here. All right. This is an aeromagnetic map of the whole region -- again, Monterey, Paso Robles, San Luis Obispo, Lompoc. And this is a map made of merging several different surveys all flown at about the same height. So this is a consistent data set in that the broader anomalies that we see over here really are more deeply buried magnetic rocks than the more high frequency short wavelength anomalies over here.

Going back to the geologic map. What are the magnetic rock types? Well, the most important rock type for producing magnetic anomalies is oceanic crust and mantle. In fact, it's a rock called Serpentinite. It's your state rock, at least for now. And it's a very prominent magnetic anomaly producer. We also can get magnetic anomalies from some of the granitic rock types and locally from some of those tertiary volcanic rocks. So going back to the magnetic map -- oh, let me go back here one sec [spelled phonetically]. For example, we can map faults here because if you have sedimentary rocks, which you'll notice are not magnetic, up against these magnetic rock types, you can look at the fault geometry that way. You can also map buried faults where they're concealed beneath the sedimentary cover. Because, again, the sedimentary cover is not very magnetic. So an example here at Point Sow [spelled phonetically], we have a little bit of oceanic crust and mantle exposed. If we look at the magnetic map, we can trace these magnetic rocks beneath the sedimentary cover of the Santa Maria Basin. And if that magnetic property contrast is a major fault, we might want to rethink where this poorly-known quaternary fault is located based on the magnetic data. We can also gain some insight into the total displacement on some of these faults. For example here, this is the La Panza Range. And we see that this prominent magnetic anomaly is truncated on its west side by the Rinconada-Reliz Fault. If we look along the fault, we can see an equivalent anomaly off to the Northwest. And so this is suggesting that the long term displacement of this fault is about 38 kilometers. Oops, it went back. We can tell that this was mostly right lateral strike-slip, but there's also some vertical component in that the granitic rocks are exposed here but are concealed beneath the sedimentary cover here.

Okay, the next thing I'm going to show you are a couple of profiles that we modeled to extend the geometry of the San Gregorio Fault, the Hosgri Fault and the Rinconada Fault. So this northern panel is across the San Gregorio Fault zone, which is offshore, and the black dots here are the observed magnetic and gravity variations. The red and blue lines are the predicted magnetic and gravity responses, given this geologic cross section and attributing densities and magnetic susceptibilities to it. The feature we're trying to fit is this magnetic gradient along here, which we do a very good job with having magnetic rocks off to the west, extending at a moderate dip to the east down to 10 kilometers. We can also fit that gradient if we extend it down to 15 kilometers, but we can't fit it if the fault is vertical. Along that southern profile, here is the Hosgri Fault. And we see that there is significant magnetic and gravity gradient associated with that. Modeling these data together tells us that in the upper two to three kilometers, which is constrained by the gravity, the Hosgri is dipping steeply off to the east. But we can extend that fault near vertically using the magnetic data down to depths of about 12 kilometers. For the Rinconada Fault, we can fit this gradient quite well with magnetic granitic rocks on the east side of the fault. If we introduce a dip to that fault of 60 degrees, we no longer fit the position of that gradient. We're significantly mismatching the location of that gradient. And I just wanted to show you a couple of these examples so you have an idea of how sensitive these methods are to sensing faults at depth.

Okay. So let's now go on to our third method. This is the seismic reflection method. This is used extensively in oil and gas exploration, and it uses sound waves induced by explosives, vibrating devices, or percussive equipment, such as hammers or shotguns. And the reflections of these sound waves, you can get at the subsurface structure by looking at how the energy bounces off rocks of different types. Reflection of transmitted energy will occur when there's a good contrast in acoustic impedance, which is a function of the density of the rocks, but also how fast that energy can travel through the rocks. So this is a really good method for mapping, especially bedded rock, such as sedimentary rocks. So let me just show you a couple of examples of how we've collected that data in the Central California Coast ranges. This is a fibrosis truck. And you'll see that its wheels are not on the ground. All the weight is on this platform, which then vibrates at a whole sequence of different frequencies. That energy is transmitted into the ground, and then it is picked up by these geophones. These are essentially microphones placed into the ground that record those vibrations and the time at which they occur. Offshore, we use something called a mini-sparker. It's basically sending out an electrical impulse in the water, sending out energy. And then in this cable here, we have hydrophones. These are listening devices to pick up that energy. We can also use an air gun, which releases a blast of compressed air in the water, sending out energy. The advantage of hang these two different sources, is that this is a higher frequency source than this. And I'm going to highlight that in the next slide.

So this is a profile, offshore Port San Luis here. The upper panel is the sparker, and this is the air gun. And one thing about the frequency of the energy, the higher frequency means you get higher resolution, but it doesn't always mean that it propagates very deeply. In fact, usually it doesn't. And this is a really good example. The sparker here, the time thing here, is about two -- about .45 seconds. We can actually see structure really only to about here. Two seconds, it's about 200 meters, dots. You can see that there's very folded sediments in here that are truncated here by the various strands of the Hosgri Fault. The bottom panel, this green line, corresponds to the depth of penetration of the sparker. So you can see that the air gun is seeing much deeper down to about three seconds or about 3 kilometers. It's also mapping the strands of the Hosgri Faults of where these well-bedded reflections are terminated. But you can't really see much close to the ocean floor. In fact, it's overwhelmed by these multiples here. So you can't really tell how close this fault comes to the surface. And this is important because, especially in bedded rocks, the closer that fault gets to the surface, that means the younger that fault must be.

Okay. So let me just show you another example of two para-lines [spelled phonetically] here, this time off of Morro Bay. And I just want you to see that these disruptions here, especially here, go all the way as close to the seafloor as you can. So this is a very young fault. Since this is an environment where you have kind of a steady rain of detritus falling down. I also want to point out that if you go to the northeast part of the profile, you see that it's fairly transparent. There aren't a whole lot of reflections, except for these things, which are multiples. These are echoes bouncing off the seafloor interface. This doesn't mean that we don't have bedded rocks in here, but in this technique, if the rocks dip more than 20 to 30 degrees; this has a real difficult time seeing those reflections. And the other thing is, the bedrock, the basement rocks, like the Franciscan, it's all disrupted. It does not lend itself to producing nice layered reflection. So this is a place where this technique doesn't work as well, but if you use it in conjunction with gravity, magnetic, and geology, you can get a hope of trying to characterize these faults in the subsurface. Just a couple of examples from online profiles, again, illustrating that, for example, along here, along SJ6, well-bedded reflections. These are from the young tertiary sedimentary rocks. But the granite beneath it is fairly transparent until you get down to depths of about 10 to 15 kilometers, which is seen on some adjacent profiles here. This package of reflections may be reflecting sediments that were under-thrust beneath California when the sub-duction zone was active before the San Andreas was born. And there's some question about whether -- this is a way to tie the faults that are active here in the Coast Ranges with the San Andreas. This is certainly an area that warrants future research.

So in conclusion, we can use these really small variations in the gravity and magnetic fields to provide horizontal and down-dip constraints on locations of density and magnetization contrasts, which, in turn, can reflect faults. Seismic reflection data are great because they can tell us about folding and faulting within the sedimentary rocks, and this information can tell us about the latest movement on a fault. But really, this is just one part of the puzzle of trying to characterize these faults. And so, in order to determine if a fault is seismically active or likely to be seismically active, or whether it's going to produce a magnitude 7 or 3 earthquake, other information is needed, such as dating the layers that are offset or not offset, measuring how the ground is deforming, and seismic monitoring -- seeing where these little earthquakes occur. And that's really what Jeanne and Tim are going to talk about next. So thank you.

[applause]

DR. HARDEBECK: That's not the beginning of the talk. Okay. Can I just slide this slider back? No, that's the size [chuckles].

FEMALE SPEAKER: [unintelligible] Go, go to here.

DR. HARDEBECK: Go to slide show?

FEMALE SPEAKER: Go to slide show.

DR. HARDEBECK: From the beginning. I'm glad somebody here is a PC person who knows how to do this. Okay, so as Vicki said, I'm going to sort of take it from here on how we find out about active faults, faults that are currently moving and currently having earthquakes.

So first I'm going to talk about how we use seismicity or how we use the locations of small earthquakes to image active faults in 3D. And I just want to start this off with a reminder that we tend to look at faults as a line on a map, and we tend to look at earthquakes as a dot on a map. And we have to remember that faults are actually 3D, that is, when an earthquake -- when a large earthquake occurs on a fault, two 3D chunks of rock move relative to each other in this earthquake along some surface that is the fault. And where this fault hits the surface, that you might refer to as a fault line, or the more technical term would be the surface trace of the fault, this is really just a small part of the fault where it happened to reach the earth's surface.

The faults can extend more than 10 miles down into the earth, and, in fact, it's this deeper part of the fault that's often where the large earthquake starts. So we need to be able to see, not just where faults are near the surface or at the surface, we need to be able to see where faults are deep below the surface of the earth. So one way we can do this is that some of these larger faults have small earthquakes or seismicity occurring on them all the time. And if we can get a good idea of where these small earthquakes are happening below the surface of the earth, we can use them to image where that fault is beneath the surface.

So sometimes the situation of a fault is very simple. And an example near here that's quite simple is the Parkfield segment of the San Andreas Fault. This is a vertical strike-slip fault, meaning that the two blocks of crust on either side of this fault are moving horizontally relative to each other.

And you can see in this little inset map here that the surface trace of the fault is in red, and the small earthquakes happening on this fault are in black. And the small earthquakes in map view look like they're basically happening right along the fault, because this is a nice, simple vertical fault. There are a lot of faults that are not nearly this simple. And an example from around here is the San Simeon earthquake.

So San Simeon earthquake, to remind you, is a thrust-type earthquake where the fault isn't vertical like the San Andreas. It has a dip. And one of the -- one of the blocks of rock is moving up and over the other block of rock. So this creates a much more complicated situation than the simple vertical strike-slip faults. So to give you an idea, this map here just has the surface traces of the map faults in the vicinity of where the San Simeon earthquake occurred.

And if you look in the Santa Lucia Range, you see, well, there's a map fault on one side of the range and there's a map fault in the other. But then if we see where the earthquakes happen, if we plot them in map view, this star is the hypocenter of the San Simeon earthquake, and all of these dots here are its aftershocks. And you can see that these faults aren't limited in map view to the places where the surface trace of the fault was, that they're occurring deep in the earth, down to 10 miles deep into the earth, and they're occurring, first of all, on dipping planes. Oh, this is very sensitive, isn't it? They're occurring on dipping planes. Therefore, the earthquake at depth aren't right under the surface trace of the fault. And there's also a very complicated fault geometry here at depth that isn't reflected in the surface.

So why is it important to see what's happening at depth for seismic hazard estimation? This is an example from the southern part of the San Francisco Bay area. And this is, this little blob here, is the southern end of the Bay, and north is this direction. So here are the surfaces traces of the Calavares Fault and the Hayward Fault. And like the San Andreas Fault, these are vertical strike-slip faults that the two sides, the crust on either side of these faults are moving horizontally relative to each other. And the faults are pretty much vertical for most of their length.

So looking at this map of the fault traces, you would say, okay, well these faults come close together in this area, but they don't actually connect, so if we're going to be doing some seismic hazard analysis here, we're not going to consider earthquakes that would connect these faults, we just consider some earthquakes in the Calavares Fault and some earthquakes on the Hayward Fault.

However, if we look at what's going on below the surface, if we plot in the earthquakes, we can see that these two faults are actually very clearly connected at four miles and deeper in the crust. And these are, of course, the depths where the major earthquakes are occurring. So the realization that these two faults are connected is actually changing the way that we're thinking about potential earthquakes that could occur on the Hayward and Calaveres Fault.

And it's interesting to note that this chain of seismicity here at four miles to eight miles depth in the crust isn't actually another fault that's connecting the Hayward and the Calavares, this actually appears to be a dip in the Hayward

Fault as it merges towards the Calavares. And we can see this dip in this seismic image here on the Hayward Fault, that the Hayward Fault is dipping toward the east. And if we can continue that dip down to the depth to where the seismicity is occurring, we see it matches up very nicely. So it actually appears that these earthquakes here are not following the surface trace of the Hayward Fault any more, are deviating from the Hayward Fault and are matching up with the earthquakes on the Calavares Fault. So as I said, this has changed the way that we've been thinking about the potential hazard of these two faults.

So clearly, it's very important to be using seismicity to map faults at depth. So let me walk you through a little bit what we do to locate these earthquakes to image them.

So Doug Dreger talked earlier this morning about how we locate earthquakes, that is, the basic idea is that if we have three or more stations and we have an idea of the distance from each of these stations to the earthquake, we can just draw a circle around each of these stations at the appropriate distance, and the location where these three circles intersect is the location of the earthquake.

So as Doug talked about, one of the ways that you figure out the distance from the station to the earthquake is that you look at how long it took seismic waves to arrive at the station. So how long it takes seismic waves to arrive at a station depends on how fast these seismic waves can move through the earth's crust. And how fast these seismic waves can move depends on the geology. So when we're locating earthquakes, if we want to locate these earthquakes very precisely, we either have to know something about the geology at depth where these seismic waves are propagating or we have to assume something about the geology.

And most of the time when we locate earthquakes, we just approximate the real geology in the earth with what we refer to as a one-dimensional velocity model, basically assuming that the geology in the earth is just these simple flat layers. So in some circumstances, this works pretty well, in some circumstances, this does not.

So just to give you an example of what earthquake locations look like using a 1D velocity model, this is this region. Here we are in San Luis Obispo. And these are the earthquakes of this region located using a simple 1D velocity model. And all these earthquakes up here, these are the aftershocks of the San Simeon earthquake. And if you look at the rest of the earthquakes, they look pretty scattered. They don't look like they're very precisely delineating any faults. Some of this could be because there is complex geology here that's not getting modeled in the simple 1D model.

So, for instance, if there was some block of rock here that didn't fit this layered 1D model and seismic waves could travel through this rock really fast, if we were recording this earthquake at that station under the trees, we might say oh, the waves from this earthquake reached the station under the trees pretty fast, so this earthquake must be close to the station under the trees. And we might move our earthquake location to be closer to that station. And now, unfortunately, we've moved that earthquake location from its true location and we've moved it off the fault, and we're not doing a good job of imaging that fault.

So one of the ways that we can improve the locations of small earthquakes is try to do a better job of modeling the 3D changes in geology and the 3D changes in seismic wave speed in the earth.

So this is something we’ve attempted to do for this region. And this is just a little slice through a 3D model that we’ve made of the seismic wave speed in this region. This is at four miles depth. Then you can see that these yellow patches are places where it appears that the seismic waves are moving relatively slowly and the darker patches are reasons where we think the waves are moving relatively quickly. And we can use this to relocate these earthquakes.

So just as a reminder, here’s what the earthquake locations look like when we use a simple 1D model, and here’s what they look like when we use a 3D model. And you can see, if you compare these, there’s a couple of differences.

First of all, a lot of the offshore earthquakes have shifted sort of nearer to the shore. And if you focus on some reasons -- regions, you can see that we can start seeing some fault structures more sharply. For instance, if you focus out here in the 1D model, this just looks like a big cloud of earthquakes. But when we use a 3D model, it starts looking like there might be a fault structure there. So this is moving us a little bit closer to imaging some of the faults.

So we want to image these faults even more sharply. And one of the things that we can do to image the faults more sharply is to get a better idea of the relative locations of two earthquakes relative to each other. So for instance, if we had these two earthquakes here, the blue one and the red one and they might be on the same fault, they might not be, and we want to see what their -- what the structures are that they might be defining, we’re really interested not so much in where these earthquakes are exactly in space, but we’re interested in how close together they are. And, in fact, how close together they are in space is directly related to how much time there is between when the seismic waves arrive at a station from one earthquake and the other. So this blue earthquake is a little farther away from the station, so the seismic waves arrive a little bit later.

And, actually, it doesn't really matter if there's some geology that we don't know about along the path of the waves from these earthquakes to the station, because it's going to speed up or slow down the waves from -- okay, I'm really getting ahead of myself -- it's going to speed up or slow down the waves from both of these earthquakes just about the same.

So looking back to this region around here again, these are the earthquake locations with the 3D model. And then on top of that, I apply this relative location technique to try to better constrain the relative locations between every pair of earthquakes in this -- in this region now. And you can see that this has definitely caused us to sharpen our view of some of the earthquake -- some of the fault structures.

For instance, if you look at the Hosgri Fault offshore here, in the 3D model, these earthquakes, again, look kind of scattered. But once we looked at their relative locations, you see that they sharpen up in a line following the strike at the Hosgri Fault. And you can see a number of other places along the Hosgri Fault off here in the bay. And, of course, the Shoreline Fault have really sharpened up in this analysis also.

So this is -- just going to quickly draw these -- there are all these faults on here. If you're interested in looking at the earthquakes in this region in a little bit more detail, I have a poster in the other room that you can kind of stare at for a while.

But the one thing I want to remind you of this slide is to go back to how I started, when I was talking about how faults are really three dimensional. So I'm drawing lines on a map here, and I'm looking at faults in terms of earthquakes that appear to line up in map view, and we're even calling one of these faults the Shoreline Fault. But we have to remember that these faults are really in 3D. And even when we look at what looks like a line of faults along this -- a line of earthquakes along the surface, we have to remember some of these earthquakes are occurring in shallows two miles depth -- whoa -- and some of these earthquakes are occurring as deep as almost 10 miles of depth. So this -- all of these faults, the Hosgri Fault, Shoreline, all of the faults, I show 3D faults separating 3D blocks of crust that move relative to one another.

So the sorts of ways that these blocks of crust can move relative to one another has been covered a couple of times already in this workshop. But just as a reminder, the two types of faults that are important in this area: One type is the strike-slip fault, where the two blocks of crust are moving horizontally relative to each other, and the other important type is the reverse or thrust fault, where one chunk of rock is moving up and over the other.

So I'm glad Doug Dreger took a stab at explaining these beach ball plots to you earlier. The basic idea here is just the beach ball, this slip -- the slip on the fault is in the direction of the filled part of the circle. So a strike-slip fault looks like these sort of quadrants and the slip is towards the filled quadrant. And if you have a thrust fault, which means that the slip -- that the fault motion is pushing something up, it's the symbol where we have the filled part of -- the filled part of the circle is up.

So to look now at -- we can get -- use that micro-seismicity to small earthquakes that are occurring all the time to get a sense of what the faulting style -- for the faults around here are.

And these beach balls are not now individual earthquakes, like Doug was showing you. These are average motion over a lot of small earthquakes. And you can see that there's a lot of strike-slip motion offshore on the Hosgri Fault. Let's see if I drew the faults on --yeah. Offshore, for instance, the Hosgri Fault, Shoreline Fault, and the bay here, there's strike-slip.

There's uplift in the region of this -- of the San Simeon earthquake, which makes a lot of sense because it's these earthquakes that are raising the Santa Lucia Mountains, and that's why they're such high mountains there. We also see some uplift just west of San Luis Obispo.

Okay, my talk really wants to move ahead, so let's move ahead. I'm also going to talk about how we use geodesy to watch faults move. And the word "geodesy" really just means "measuring the shape of the earth or measuring the shape of the surface of the earth." And for studying earthquakes, we're mostly interested in changes of the shape of the earth.

So this little benchmark here, that I'm showing a picture of, is a benchmark that was installed in 1932 by the U.S. Coast and Geodetic Survey. And the sort of geodesy they would have been doing back then would have been using very standard surveying techniques to look at the movements of these benchmarks relative to each other.

So I'm going to talk today more about modern techniques that we can use to watch the surface of the earth move, modern techniques based on satellite data.

So the first technique that we use is GPS, Global Positioning

System, which is exactly the same satellites and basically the same technology as is in navigation systems in cars and in cell phones and in other consumer electronics. The only difference on how we use GPS for scientific studies is that we need much higher precision to watch plates that are moving, you know, the rate that your fingernail grows. We need much higher precision than we need just for, you know, navigating your car on the street. And so the way we do that is by leaving a GPS receiver in its position for a longer period of time, like a day or so, so that it can talk to the satellites for a pretty long period of time and get a very precise measurement of the location of the receiver.

And the way the GPS location works is actually pretty much the same way as earthquake location works. If we know the distance between the stations and the earthquake and we draw these circles at the appropriate distance from the station, it gives you a location of the earthquake. Now we're just looking at your distance between your receiver and the satellites orbiting the earth. And so that's what the spheres are in this drawing -- is equal distance away from one of these satellites. And if you can see at least three or four satellites and you can draw these spheres around each satellite, the place where the spheres intersects is where you are.

So we can use GPS in sort of the same mode as standard surveying; that we can go to one of these benchmarks and set up a GPS receiver. And this is just a GPS on top of a tripod to keep it very stable for a long enough period of time to get a very precise measurement of where it is, and then we can come back a few months later, a year later as such. And that -- and, for instance, for this station, we can see, you know, if we've measured this over time, then we can see it's moving a little bit to the north and a little bit to the west.

And, so this is what we would call campaign or survey-mode GPS, where we just come out and visit these stations occasionally.

The other thing we can do is install these GPS stations permanently. And, so this is an example of a continuous GPS station near the San Andreas near Parkfield. And this station is permanently installed there and is constantly recording data. And you can see from this example here that you get very detailed -- very detailed information about the movement of this location, much more detailed than you would get if you just visited this every year or so. And these are some maps of continuous GPS stations installed in the western U.S., and you can see that there's been quite an investment in installing GPS stations.

So these are -- this is just sort of zooming into this area now. And the arrows here represent the velocity of each of these GPS stations relative to somewhere way out in the east coast that's considered to be the stable North American Plate.

So what GPS really tells us that's useful for seismic hazard assessment is it tells us what is the relative velocity of the blocks of rock on either side of a particular fault. And in this example, if you look at -- if you look at arrows on either side of the San Andreas Fault -- for instance, if you look at these arrows on either side of the San Andreas Fault, that can give you an idea of what the rate is of slip on the San Andreas Fault. And if you look at the arrows near the San Andreas Fault and compare those to the arrows near the coastline, you can see that those stations at the coastline are actually moving a bit faster than the stations near the San Andreas Fault.

And this difference -- [coughs] excuse me. And this difference in motion is reflecting the slip rates of all of the smaller faults that are west of the San Andreas here. So this has the potential to give us a lot of information about the slip rates on all of the various faults.

Although you can see in this picture one of the downsides of using GPS is that we can only install these stations on land or on islands. So we're not going to be able to use GPS, or at least land-base GPS, to get an idea of slip rates of faults offshore.

So the other technique that -- satellite based geodesy technique that I want to discuss is called Interferometric Synthetic Aperture Radar, or just simply InSAR. And what happens here is a satellite passes over some spot on the earth, and it sends a radar signal down, which bounces off the earth, and comes back to the satellite. The satellite then is going to come back later some time after there's been some ground deformation, such as an earthquake. It's going to send this radar signal, the radar's signal's going to bounce back again, but this time, it took the radar signal longer to bounce back. So that gives us a measurement of how much the earth moved. And the difference in the time it took is actually measured as a phase difference of a wave, so that's going to affect kind of how these -- how these patterns look But the basic idea is it's really just measuring the difference in time it took a wave to hit the surface and come back.

So over on the right there is an example of what we would see just if this little -- if just a little circular hill popped up. So you can see the advantage right away of this over GPS, which is that GPS gives you the movement at one point in space, whereas an InSAR image gives you the movement over a whole region so you can see the details of this hill popping up. And it looks like, because it's a very symmetrical little hill, you get these symmetrical little set of rings.

So in the real earth, it can be quite more complicated. This is an example from the San Simeon earthquake. This is some deformation continuing after the San Simeon earthquake. And you can see again that there are these rings of color outlining the region that's being uplifted. But because the San Simeon earthquake was such a complicated earthquake, this is actually a very complicated diagram. And we can draw some cross sections across it, and on the right here, just some cross sections across this image showing this very complicated pattern of continuing uplift following the San Simeon earthquake.

So both of these -- both of these space-based techniques -- GPS and InSAR -- are showing us the movement of the surface of the earth. And as I kind of keep coming back to, faults are 3D, faults are extending into the earth by 10 miles or more. So what we really need to do is translate these observations we see at the surface to tell us something about what's going on on these 3D fault structures at depth.

So we have to use models then. We have to move from the data at the surface and use that to come up with a model for what's going on on the fault that it can explain the data we see at the surface.So this is just an example of a few GPS stations near the San Andreas Fault near the Parkfield earthquake, and all the arrows just indicate the direction and the amount of movement during this fault.

And on the right, we've translated that to a model of the slip on the fault that best explains those set of GPS observations. And interestingly, we can see that although the earthquake started here where this red star is, most of the movement in the earth -- most of the motion in the earthquake that we can see using GPS actually happened to the north. And we can also see that motion in the fault continued for more than a couple of months after the earthquake.

So this is an example of using GPS just to look at one fault and over a short period of time. But what we'd really like to know for seismic hazard assessment is what are the long term slip rates on all of these faults. And if you can get -- if you can use geodesy to see the long term relative rate of motion of the two blocks on either side of a particular fault, that can give you long term slip rate of the fault, which then can give you the rate of earthquakes on that fault.

So this can also be done through modeling. On the left is GPS observations covering all of Southern California, and on the right is an attempt to fit that data with a model of the slip rate of all of the important faults.

And you can see, for instance, that the San Andreas fault has a very high slip rate, so it's there in red and it's very thick, but you can also get an idea of the slip rate of some of the other faults. For instance, the Hosgri Fault has a slip rate in this model, and it has some detail to it. For instance, this model says that the slip rate of the northern part of the Hosgri Fault is higher than the southern part of the Hosgri Fault. And there's also quite a bit of detail about the other faults in Southern California in this model as well.

So this is the sort of model where you would have the slip rates -- where you would have the slip rates on all of the -- the long term slip rates on all of the faults to give you an idea of the long term earthquake rate, that then it's the sort of thing that you would put into a seismic hazard assessment for the area. And Tim is going to talk to you a little bit more about how we do seismic hazard assessment. Thank you.

[applause]

MR. DAWSON: Okay. Let's get this. Okay. Good morning, everyone. Thanks for wading through all these talks -- wading through all these talks and all this information. There's a lot to be presented still.

My talk today is in two parts. First of all, I'm going to explain how we use geology to characterize active faults. I'm a geologist, and so that's sort of my area of expertise. And then the second part of this is going to provide a flavor of what some of the future sessions are going to be talking about in the site [spelled phonetically]. What do we do if all this geologic, seismic, and geodesy data, and geophysical data, and how do we use it to construct an earthquake rupture forecast or how do we use it to come up with the probabilities of future earthquakes on this fault system?

So we've seen this before a little bit, this geologic map of California. Simply, the geologic map just shows the distribution of rock types throughout the state, as well as geologic structures such as folds and the location of faults. And from this, a geologist can piece together the geologic history of the region. That's important because we want to know what happened in the past, how did the rocks get to be where they are? It provides context for what we're looking at today, and it also can help us look into the future and see what might happen.

For seismic hazards, geology can also be used to help predict potential shaking. On the lower or on the left side here is the geologic you just saw in the previous slide converted to a shear wave velocity map of the upper 30 meters. And what this map shows is that in the most red colors, those are the fastest shear wave velocity rocks in the state that's mostly, you will notice, it's in the mountains. It's where the bedrock is generally hard. The more yellow colors and, kind of getting down to the pinker colors, which are kind of hard to see on this figure, are the types of rocks and unconsolidated sediment where shear wave velocity is sort of low, and where it can be kind of used as approximately where shear wave velocity is, is a little bit slower, it tends to amplify the shaking.

So what we do if this kind of -- this type of geologic map, is when we -- oops, this is sensitive -- when we combine it with the fault locations, as shown here in the upper right, we can start making these shaking potential maps. And all it does is it shows -- it's a combination that shows the influence of geologic materials, as well as the location of faults on shaking potential. And in general, you can see that most of the expected shaking within the State of California, it's generally along the major faults that are in the upper right-hand corner or the upper right-hand part of the map. But there are some basins and areas of the state which will shake just because of the nature of their geologic materials that are underlying the surface.

So how do we find these faults? Well, what we're mostly concerned with are the active faults. Those are the faults that have moved in general within the quaternary [spelled phonetically] that last about two -- 1.8 to two million years. In this example here, this is a blocked diagram that shows some of the features that a geologist looks for when looking for an active fault, especially in this case, which is an active strike-slip fault. Typically, you'll see things like scarps, sag ponds, ridges, alignments, drainages. In this case, this is a right lateral fault. You can see this stream right here being offset down here. This is the idealized example.

Here's a more realistic example. This is taken -- it's a photo of the San Andreas Fault at Wallace Creek, California, which is just south of Highway

58, I believe, in the Carrizo Plain. You can actually go out here and visit this site. There's a nature's trail that the Southern California Earthquake Center and Caltech and the Bureau of Land Management have set up at this site.

But as in the previous figure, you can see things like alignments of drain -- of troughs along the faults, scarps. This creek here, Wallace Creek, has been offset along the faults. And you can even see evidence of past offsets. This feature right here, which we call beheaded channel, actually is the kind of ancestral Wallace Creek, and thousands of years ago it actually was connected to Wallace Creek, the upper parts of Wallace Creek, and it's been offset, it's been abandoned. This newer channel of Wallace Creek has formed and also been offset. If you look really closely, there's even smaller offsets, like this channel is offset from here and here. And all these offsets occur from multiple earthquakes. You know this -- and I'll talk about this in a little bit, but this one offset from here to here occurred over the past, about, 3,800 years. So that's hundreds of earthquakes.

In the past, geologists have typically mapped the active faults on the ground. We go out there, we look at the faults themselves, we map the rock types. We use aerial photographs as well. Within the last, you know, 10 or 15 years, we had one new technology, which is really exciting to us. It's called the LiDAR. It stands for Light Detection and Ranging. And essentially what this is, it's an airborne mountain laser system. This laser is mounted on the bottom of the aircraft. It shoots out tens of thousands of points per second. And each one of these points will hit the ground. A number of them will be reflected back up to the censors within the aircraft. That time difference is used to map the surface of the earth.

The advantage of this process is just the sheer number of points. There's, you know, probably multiple -- they call them returns -- for every square meter that these lasers hit on the surface of the earth.

The other advantage of this is because this system is tied to GPS satellites, as well as base stations on the ground, there's stunning accuracy, both horizontally and vertically. And so what we can do with that is make some very positionally accurate maps of the earth's surface.

And here's an example of some LiDAR data. Actually, before we get -- describe that, on the very far left here is just what you would see is in an aerial photograph of this region. Notice that there's a lot of vegetation. This site right here is actually from the north coast of Northern California on the San Andreas Fault. And even to an experienced geologist, we would have a hard time defining where all -- oops -- all the active faults are. We might map something like this right through here where you can see this gap in the trees. There's some other erliniments [spelled phonetically] that you might see up here on the screen, but it would be very difficult to get out there, use this photograph to map where the faults are. It's also, because the density of the vegetation, extremely difficult to get out there on the ground and locate yourself.

With LiDAR, we kind of call this our virtual lawnmower. What the LiDAR data does is when you process it, you can filter out the trees. It'll take only the very last laser returns from the very -- the bare earth of the ground. And what we've done here is processed all the trees away, and now you can see where the faults actually are on the ground. Here's some nice scarps right through here, right through here. And in general, some of this does line up with where we saw -- we thought we saw faults before on this aerial photograph, but there's a lot more detail, and it's a lot more accurate than anything we'd be able to do just off of an aerial photograph. On the far right here, is interpretation of the faulting for this image that you're seeing.

Why is the location of these faults important? Well, for us at CGS, one of the things we do is we're actively involved with mapping faults for the Alquist-Priolo Act. And what that is, is that the state requires us to map where there's a potential for earthquake surface rupture. That's where the earthquake fault, when it ruptures, as an earthquake, it actually reaches the ground and has the potential to destroy structures and roads and things that are located on the top of the fault or that cross the fault.

In the upper left here is -- you can see the fault crossing the figure right through about the middle of it. This is from the 1992 Landers earthquake. It actually nicked this home right here. It kind of goes through this trailer that's parked out back and continues on its way. If that home was located even closer on top of the fault, it would have been completely destroyed. I think, as it were, it had to be abandoned.

The right-hand side here is an example of the Chi-Chi Earthquake in Taiwan in 1999. This waterfall, actually, was not there before the earthquake. This is caused by a thrust fault that ruptured the ground surface. This waterfall is formed as a result of that fault movement. And this highway bridge was actually built across the fault, and that's why it eventually -- it collapsed during the earthquake.

The Alquist-Priolo Act is designed to address surface fault rupture through avoidance. And so in California, what we do is the CGS goes out, they map these faults using some of these techniques, mostly on aerial photographs, geologic mapping, and lately, even using some of the LiDAR data, and by law, we're required to create these setback zones.

So on this figure right here, the lines in black are the actual fault traces that we've mapped. And then the shaded area, buffered by this -- these red lines, are what we've defined as our earthquake fault zone. And under AP Law in the State of California, it requires if you want to build a structure within one of these earthquake fault zones, it requires certain geologic investigations to make sure that you're not going to build on top of one of these fault traces because there's fully fit -- there could be other fault traces that we're not able to see within this zone. And typically, this is done through geologic investigations such as trenching. If they happen to find a fault, any structures that are going to be built on that property need to be set back from that.

And just to clarify, the criteria for AP Law in the State of California is Holocene-active. That's about the last 11,000 years. And I just want to make the point that for other structures regulated by other government agencies such as dams, critical infrastructure, the term "active fault" may even be longer than that. It could be tens, hundreds of thousands of years that make it an active fault. That's movement within that time period.

In some cases, structures might require mitigation to survive earthquake surface rupture. For a thing, something like a pipeline, you can't avoid crossing a fault. This is an example of the Trans-Alaska Pipeline in Alaska. And back in the '70s, when they were designing this pipeline, they realized that this pipeline would be crossing the Denali Fault. They knew the Denali Fault was potentially active at the time. And so they sent a team of geologists up there. They did some careful geologic studies that mapped out the fault trace as best as they could at the time. And the one thing they did in this case is that the pipeline crossing -- here's the proposed pipeline through here -- crosses through this valley here where it was really difficult to see the fault. And so through this careful geologic mapping, the geologists defined this zone where they thought the fault would be that could impact the pipeline should there be an earthquake. And the geologists also provided some estimates of how much displacement to expect if there was a large earthquake on this fault.

They gave this information to the engineers, and the engineers were able to design a system to accommodate this fault movement. What they essentially did was they put the pipeline on these slider rails, and so when the fault moved in a right lateral sense, the pipeline was allowed to flex with that fault movement.

The one really interesting thing about this earthquake is they built this for -- they built this pipeline before an earthquake happened on the Denali, and in 2002, this design was actually tested and survived nearly 20 feet of right lateral displacement during a magnitude 7.9 earthquake on that fault. So a magnitude 7.9, that's about what we have in California on the San Andreas Fault. The 1906 earthquake, 1857, were both about that size.

Other things geologists do is paleoseismology. That's the study of ancient or prehistoric earthquakes. These are the questions we like to address when we're doing these paleoseismic studies. How often do the large earthquakes occur? When did they happen? How large were these earthquakes? And how fast is the fault moving?

So how often do the large earthquakes occur? How do we do this? Typically, we do this through subsurface investigations. The photo you see here is an example of a trenching investigation on the Hayward Fault across a golf course in El Cerrito, California. The reason why the geologists who were involved with the study picked this site is because through mapping and analysis of aerial photos before this golf course was built, they could see a nice fault scarp crossing through here where these dash lines are. There's -- you can see the inflection in the surface here. That's typical of what an active strike-slip fault looks like.

Also, through the aerial photos, there was a sag pond at this site, marshy area that was created by fault movement, kind of down-dropping the earth's surface at this location. These types of features, like a sag pond, are very conducive for preserving evidence of past earthquakes. So that's one of the reasons why the geologists picked this location.

In the subsurface, what are we looking for? Well, as I showed in some of the past -- previous slides, when an earthquake ruptures to the ground, it'll displace the earth's surface, it displaces the geologic strata below the earth's surface, and that's shown in this first diagram right here. This is -- we can call this Times -- Time One or Time Zero, when the earthquake just happened. It creates the faults, they reach the earth's surface, they displace the ground, they displace everything below that. Well, with time, especially in one of these sag pond environments, there will be subsequent deposition after the earthquake, and it'll cover up this evidence of past faulting. So you can see here, this was the first geologic unit to be deposited after that earthquake. There's some other units that are unbroken until the next earthquake.

And this is what the geologists are looking for, is independent evidence of different earthquakes occurring in the subsurface. So if I dug a trench right here and saw this in an exposure, I would identify an earthquake that one, reached the surface. That would be the most recent earthquake. And then somewhere down here, I would see that evidence for the first earthquake that had occurred.

Here’s an example of what we really see in the trenches. It’s actually -- this is a good example. Typically, it’s not quite as nice. In this figure, this is taken from the Tule Pond site, also on the Hayward Fault. And what the geologists who worked on this did was we excavated a trench across the fault, carefully logged both the features, such as the geologic units in the trench. We logged -- and the faulting relations. And each one of these blue dash lines represents an earthquake horizon. So when an earthquake occurred, we’ve identified evidence, such as upward terminations, and increasing amounts of deformation that indicate that an earthquake occurred at one of these horizons, sort of like in the previous figure.

In fact, you can see here that this orange unit and everything above it, about to this blue line, is a lot more disturbed than everything above it. And it’s interesting to note that this orange unit was originally deposited relatively flat, and it’s been deformed by about four earthquakes in this trench.

So what do we do with that information? Well, if we want to answer the question of how often these earthquakes occur and over what period of time, well, we’re going to need some dating for this. And typically, in one of these trenches what we have are radiocarbon samples. It can come in the form of charcoal preserved, plant matter, bone. That’s another example. Those things can be dated through radiometric dating techniques. And we can develop a model of the ages of each of those units that were deformed and when the earthquakes occurred.

This example, we actually have a lot of different types of information that helped us develop this earthquake record. We have historical records. The most recent earthquake we know on the Hayward Fault there was in 1868. And so we use that to pin our record. And that's represented by the spike right here.

And then we also used a combination of radiocarbon dating of plants and seeds, as well as pollen analysis, to develop this chronologic model of the earthquake -- the earthquake timing at this site. And so each one of these curves in the gray represents the radiocarbon age derived from a piece of charcoal or a plant fiber. Those are from the individual units in the trench, whereas these black probability density functions, such as this one, this one, and this one, represent the timing of an earthquake in calendar years.

So what we have here is we saw about four earthquakes in the last 400 years. That's three intervals between earthquakes. And what you might hear a lot about are average recurrence intervals for a fault. Well, there's three intervals, and you take the 400 years, you do some simple division, even a geologist can do it, you come up with an average recurrence interval of about 130 years.

The one thing to note is that each one of these probability density functions for an earthquake age, it's not just one single date, it's kind of a range. And so they don't always happen periodically. And within the uncertainties of the dating, the individual intervals between earthquakes should be less than 100 years or could be as much as 150 years.

The other thing geologists try to do is they try to measure how fast the fault is moving through geologic time. Jeanne here talked about GPS trying to measure how fast faults are moving. Well, GPS has only been around for the last, you know, 30 or 40 years. That's a very short interval of time to measure how fast the fault's moving, and it's not really averaged over a lot of earthquakes. And so what we're doing is getting how fast the faults are moving in geologic time. So hundreds, thousands, tens of thousands years, that's what we're looking for to average out the, you know, tens or hundreds of earthquakes that have occurred along a fault.

Here's an example in map view of a stream that's been progressively offset. I showed an example of this a little bit earlier, which we'll revisit in a second. Initially, the stream crossed the fault relatively perpendicular to the fault strike here. During one earthquake, or several earthquakes, it was offset along this fault. Sometimes these channels will be abandoned. We'll call this Offset 1 from where the stream, the upper part of the stream is to this abandoned channel. And then it's offset yet again. So what we want to measure is the cumulative offset through time. So that's all a slip rate is. You'll hear a lot about slip rates. But when we're talking about geologic slip rates, it's basically the total offset of a feature, such as a stream. It can be any feature that really -- that crosses a fault. It could be a marine terrace, it could be a stream terrace, it can even be a street curve -- curb. And so the total offset, take that, divide it by the time it took for that offset to accumulate, and it's usually expressed in millimeters per year.

Here is the real-life example from Wallace Creek. I think you've seen this figure already, but this is how the calculation goes. It's fairly simple. We know that we can measure this at the earth's surface. This channel has been offset to about here. That's about 130 meters or 130,000 millimeters.

And through careful dating that a person -- a professor at Caltech did back in the '80s, his name was Carrie Si [spelled phonetically], he was able to conclude that this offset took about 3,800 years to accumulate, so that's hundreds of earthquakes on the San Andreas Fault. So that's hundreds of earthquakes on the San Andreas Fault. So by doing the division here, 130 millimeters or 130,000 millimeters, divided by 3,800 years, comes up with 34 millimeters a year. So that's the slip rate for the San Andreas Fault. A good chunk of that 50 millimeters for the total plate rate that's been tossed out in a couple of talks this meeting.

I'm going to move onto the second part of my talk here. That's forecasting earthquakes. How do we come up with the probability of earthquakes? And the most recent study of this that's been done for this state was called UCERF, the Uniform California Earthquake Rupture Forecast. It's a joint project between the USGS, the Southern California Earthquake Center, the California Geological Survey. In part, it was sponsored by the California Earthquake Authority, which administers a good chunk of the earthquake insurance within the State of California.

So this process takes place under the umbrella of what's called the Working Group on California Earthquake Probabilities. And they've met periodically over the last 20 years to calculate the probabilities of earthquakes. And when they first started out, they were concerned mainly with the largest faults within California, San Andreas, the Hayward Fault back in 1988. [coughs] Excuse me.

MALE SPEAKER: Want to grab some water?

MR. DAWSON: They've shifted their focus through time to different regions of the state. In 1990, they focused mostly on the northern San Andreas Fault and Hayward Fault system. 1995 was when the first big regional studies focusing on Southern California. 2003 was the second of the big regional studies focusing on the Bay Area. And most recently, in 2007 was the first statewide earthquake probability forecast.

The process is really designed to develop a consensus model for the probability of earthquakes within California. It has participants from academia, industry, and government working on this, each tapping into their various strengths as to what they're experts in. And this is used as a model that finds its way into public policy. So the earthquake probabilities that are developed by these working groups are used to building codes, earthquake insurance rates, and hazard mitigation.

As I mentioned, 2007 was the first statewide application of the working group, and it was sponsored in part by the California Earthquake Authority, who is interested in a kind of -- a consistent treatment throughout the state.

So what is an earthquake rupture forecast? Well I think this figure really illustrates what we're getting at when we're trying to find the balance of what goes into the system and what's released in the system in earthquakes. And so the forecast seeks to use all the available data that we can get our hands on; the geology, the geophysics, the seismology, geodesy, to assess the number of earthquakes and the sizes of these earthquakes.

What we do know and have a good handle on is like what's going into the system. This plate rate of about 50 millimeters a year or two inches, it's about two inches a year that goes in across this system of faults throughout California. What we are trying to get at is how that energy that's going into the system is being released, and this scale kind of illustrates that. You can see that as you dump more of this plate motion on this side of the scale, your earthquake odds will start going up unless they're released by earthquakes, which are represented by these balls. And you can see here that if you took one of these big balls like a magnitude 7.8 earthquake, your earthquake odds will go down a lot more significantly than if you just dumped one or two of these little 6.5 earthquakes into the system.

Okay. Almost done. So here are some of the ingredients, going to try to bring all this together. Default models specifies the spatial geometry of the large active faults within the system. This is done through geology and mapping these fault systems at the surface, as well as some of the other things we touched on today like the geophysical data that specifies the geometry, and the seismicity data, which also gives us a handle on how these faults look in the subsurface, as well as the depth of seismicity.

The deformation models. It takes all these slip rates, the geologic slip rates, the geodesy and puts it onto these faults like I mentioned for the net tectonic movement that goes into the system that's defined by geodesy. And geodesy can also help constrain the fault slip rates as well.

Seismology, it's important both for the fault geometries, but it also helps us figure out the rate of earthquakes located off of the larger faults. Because not all of the earthquakes in the state happen on the largest known faults. There's a whole spectrum of earthquakes that either occur on faults we don't yet know about, or that just occur randomly throughout the state and we use the rate of seismicity to define that in our analysis here.

Earthquake rate models. There's different ways of looking at how the energy's released. This example just shows a magnitude -- two different magnitude area relationships. These are different models to explain what we observe in the data. And since we don't really know which model is right, we try to incorporate both of them into our analysis.

Same with the probability models. I think Ralph earlier in the first talk of the session; he talked about Reid's Elastic Rebound Theory. There's been some thinking in one model, one in-member model, is that earthquakes along a fault or maybe certain faults are more or less perfectly periodic. However, there's other people who think that maybe earthquakes aren't perfectly periodic and there's a range of different earthquake sizes that occur in fault. These are represented by the saw-tooth diagrams. The top one is more or less perfectly periodic; whereas, say a fault with a range of earthquakes and a variation in the time of the largest earthquakes is represented by this kind of noisy figure that you see down here at the bottom.

So all this is put together into the composite forecast. This is the 30 year earthquake probability for the State of California, magnitude 6.7 or larger. I'm sure you're curious about some of the actual numbers, so I'll get to them and wrap up the talk here.

But as you can see that for the smaller earthquakes are much more frequent throughout the State of California, and they can happen with some probability almost anywhere. This is for a magnitude greater than a magnitude five. As you get up to the highest magnitude earthquakes, most of those probabilities are located on the largest faults in the system. So here we have the

Southern San Andreas Fault, the Garlock Fault, the Northern San Andreas Faults, faults that we know are active, have been active in the past, and are the largest faults in the system and capable of producing some of the largest faults we expect to see.

Here's just a summary of the highlights of the study. Southern San Andreas Fault has the highest probability in the next 30 year of a magnitude 6.7 earthquake or larger at 59 percent, and it goes down from there. The Hayward-Rogers Creek, which is probably the most dangerous fault in the Bay Area, has a 31 percent probability of earthquake -- a large earthquake.

Just to wrap up here, we just started the UCERF3 study. It's the next generation of this earthquake rupture forecast. And what we're trying to do is we're trying to improve the deformation model, incorporate more of this new GPS data that's been coming in. We're going to include a wider arrange of fault behaviors not addressed in previous models. I think someone in the first session mentioned how the Denali earthquake actually started on a thrust fault before it turned into a strike-slip faulting earthquake. That really has been looked at in detail in past earthquake probability studies for California, and we're going to look at that.

And finally, something that I'm not really involved with, but will hopefully happen with this next generation of study, is real-time forecasting; and that if an earthquake happens somewhere in the state of significance, they'll be able to adjust the probability model as it happens to forecast areas where there's a higher likelihood of seismicity, large earthquakes occurring because of that adjustment and the stress from that earthquake that had just occurred.

And I think that's it. We go on to the question session. Thank you.

[applause]

MR. BURTON: Victoria, Jeanne, Tim, thank you. Great presentations. We are running a little bit behind schedule, but we do want to allow time for some questions related to the session. After that, we're going to be going to lunch, so I'll go on and open it up. Now, I will say just before we get started, Bill offered to switch places with me, but I told him I'm invested on this side of the room --

[laughter]

-- and I am very confident that my side will come roaring back with a lot of questions. So if you don't mind, we'll start on this side, and we do have a question. And give us your name. You can stand.

MR. PECK: My name is Michael Peck -- oh, you're not supposed to give up your microphone -- my name is Michael Peck. I have a question for Dr. Hardebeck. Thank you. You had put a picture up here of earthquakes in the San Luis Obispo area and superimposed both the Hosgri and the Shoreline Fault using the 3D velocity model. And in that slide, you show data points of -- on the northern part of the Shoreline Fault intersecting all the way up through the Hosgri. My question is, based on that data, would you say that the northern part of the Shoreline Fault as it integrates with the Hosgri is active?

DR. HARDEBECK: Okay that -- is my mic on? No, my mic's not on.

FEMALE SPEAKER: It's [unintelligible].

DR. HARDEBECK: Okay now, is it on now?

MALE SPEAKER: It's no -- here.

DR. HARDEBECK: Does this one -- here. Does this one work?

Oh, that one really works. What you've just asked is an incredibly important question, and I hope this is something that we will get into tomorrow when there's more discussion specifically of the Shoreline Fault and hazard in this area.

I first want to say that when I drew those lines on the map, that is interpretation from seismicity locations. So there is certainly seismicity going from sort of the central Shoreline Fault up all the way to the Hosgri Fault. There -- that suggests that there is some sort of active faulting going all the way to the Hosgri Fault. And we're currently in the process of trying to get even better locations for those earthquakes to better understand whether that's really a single active fault, whether that's a zone of deformation, or what exactly that is.

But there are certainly small earthquakes on that northern most part of the Shoreline Fault, but I think it's really too early to say what that says in terms of what could actually happen in a larger earthquake, whether a large earthquake could rupture through there, or whether that zone could actually connect an earthquake from the Hosgri Fault to the Shoreline Fault. I think that's something that's an incredibly important question, and I think that's something that's still kind of unanswered.

MR. MAIER: Question over here?

MS. EVERED: Yeah, I'm still from Santa Barbara. And we've been continually in the last, as I remember, 30 years, been warned we're in for "the big one" in Santa Barbara because in the last 700 years there's been on an average a big earthquake every 100 years until this period. And we're probably 85 years now overdue for "the big one." And I'd like to get anybody on the panel their opinion of this. Is it just an aberration of some kind, and how might it play out in San Luis Obispo?

MR. DAWSON: Of the last figures I showed, showed that basically anywhere in this state, you could have a large earthquake, a damaging earthquake. You know the probabilities for statewide are almost certain for one of those earthquakes to occur. Specific to region, it's a little bit harder to address without cutting up the study in even finer detail. But for the San Andreas -- you know when people talk about "the big one," they usually refer to the San Andreas, both the largest earthquakes within the state's history, have occurred on the San Andreas -- the 1906 in Northern California, 1857 in Southern California. Some of the figures that we showed in the first session looks like the southernmost part of the San Andreas from the Salton Sea up to San Bernardino is what people, you know, might hear them say is overdue. It's past its average recurrence is what they mean.

I think a few weeks ago there was a newspaper article in the LA Times saying that the earthquake recurrence on the San Andreas Fault, in the Carrizo Plain in some of the slides I just showed, was a lot more frequent than geologists thought in the past, perhaps every hundred years. And so I think if you -- if you're going to live in California, you just need to be prepared for one of these earthquakes no matter where you are. And in some areas, it's a lot more likely than others. And certainly, Santa Barbara has a number of active faults surround it. And the truth is, some of those faults, we don't really know that much about, but we know they're active. And so the best bet is to be prepared for these earthquakes and expect them at some time in the future.

MR. MAIER: Okay. Very good. I have one here. Take a stand. Give your name.

MS. BECKER: Okay, hold my mic. My name is Rochelle Becker, and I'm with -- is that on? The Alliance for Nuclear Responsibility. And you talked about the complexity of the San Simeon Fault. And I was just wondering -- we've also heard about a lot of the faults that are offshore are slip-strike faults, that a lot of the faults that are onshore are thrust faults -- and I was wondering what happens when your thrust fault onshore may meet an 1800 feet away offshore fault at the shoreline. And have you had incidents of onshore faults triggering offshore faults that are going in different directions?

MR. MAIER: Anybody want to take that one?

MR. DAWSON: I think -- the one thing I should clarify is that there probably is really no difference in behavior of onshore and offshore faults. We probably don't know as much about the offshore faults as we'd like to just because they are harder to get at. It's like the paleoseismic studies that I showed in my talk. They're really difficult, if not impossible, to do offshore with current technology.

As far as faults going together, you know, we have seen instances worldwide of different faults triggering other faults -- the Landers rupture is commonly cited as one of those examples of one fault jumping to another fault as it was mapped. The Denali Fault earthquake in Alaska started out on a thrust fault and then connected with a strike-slip fault. And, you know, it's a big question. And that's one of those things that we may not have such a good handle on, but we're working on trying to find the range of fault behaviors and how these things work together.

MR. BURTON: Question from Sherry.

MS. LEWIS: Yes. So in answer to the very first question about the Hosgri and the Shoreline Fault, would then it be a great help to have more 3D mapping in order to find all that stuff out? You need more research is what you're saying, and does the 3D mapping help with that?

DR. HARDEBECK: Can I just ask for a quick clarification of your question? Are you talking about the 3D seismic imaging?

MS. LEWIS: I was addressing primarily your answer to the very first question, which is whether the two faults can connect, as I recall. The Shoreline and the Hosgri can connect. Apparently, there's not quite enough research yet to know whether they really are connected, if they affect each other, and so to find that out, you need more research, is that true? And a sub little question, does 3D mapping come into that kind of research to understand that?

MALE SPEAKER: Is your question would the 3D seismic imaging get you that answer more or likely?

MS. LEWIS: That's part of the question. The first question is -- the first question is, apparently, you need more research, right? And the second is does 3D imaging, is that part of that research?

MS. LANGENHEIM: Okay. Well I'll take a stab at this. We don't really have any information on timing of events on the Hosgri versus the Shoreline for some of the reasons that Tim alluded to. So if we could come up with a way of doing that, that might help address that question.

I think also you can do some theoretical modeling of faults that intersect with each other; how likely they are to propagate one pathway versus another? But in terms of hard data, we don't have the answer to that question right now.

And 3D mapping would help maybe, but I think you really need to get some age control on it as to whether they really are linked. Yeah, more research, of course.

[laughter]

MR. BURTON: Anybody on this side? Don't fail me, guys. No? Nothing? Okay. Over there.

MS. COCHRAN: Cochran. I have a quick question for Timothy Dawson. Would you consider the land Diablo is on an earthquake fault zone since there's -- since there's like 13 faults there?

MR. DAWSON: Well in some ways, all of California is an earthquake fault zone. You know we're spreading this plate motion from one side -- the western part of the state all the way over to Nevada. And so there's really nowhere within California that you can go to which doesn't have some of this plate deformation distributed on it. I'm not sure if that really answers your question but [laughter] it's part of a fault system. There's faults, you know, that accommodate all this fault motion, and how that's partitioned is -- it's a good question. Most of it's partitioned on the large faults, and then there's a number of less active faults where some of that motion is as well.

MR. MAIER: June, we may also be able to get better information tomorrow during the session on Diablo. If you -- if you'd like to leave your question on a card, we can maybe get an answer back to you.

MS. COCHRAN: But that slide that you have --

MR. MAIER: Wait.

MS. COCHRAN: -- that slide that you have --

MR. BURTON: Wait, need your mic. Need your mic.

MS. COCHRAN: -- earthquake fault zone. Remember the slide that you had that had an earthquake fault zone?

MR. DAWSON: [assent]

MS. COCHRAN: Okay.

MR. DAWSON: The photo or the --

MS. COCHRAN: The photo. Okay.

MR. DAWSON: Okay, yes.

MS. COCHRAN: Okay. So would you consider then the Diablo site a fault zone similar to that one?

MR. DAWSON: I don't think I can really answer that question because I haven't looked at the Diablo Canyon site itself. That fault zone that's drawn on the AP maps, that's a regulatory fault zone and that's -- in some ways, it's rather arbitrary. It's done as kind of a safety buffer zone that when the geologists -- when they map defaults, depending on how distributed they think that fault zone is within that area, they'll draw wider regulatory zone around it where they thing that geologic investigations are required. And that -- the width of that zone, you know, it will vary depending on how complex the fault is at the earth's surface. And so without knowing what the faults around Diablo Canyon look like, it would be really hard for me to decide whether I think it's in a fault zone or not. And --

MR. BURTON: Uh --

MR. DAWSON: -- just because it's in that box doesn't -- at least the figure that you saw, just because it's in that box, doesn't actually mean it's a fault zone as much as that's what the state has mandated specific fault investigations need to occur in.

MR. BURTON: And let me just say, as you can see, some of the question specifically on Diablo Canyon, we don't really have the experts here up at the panel who can ask -- who could answer those specific questions. That's why we had asked folks to save those questions for tomorrow when we're going to be focusing on Diablo Canyon. If you're not going to be here tomorrow but you have those questions, please write them down with your contact information. We will raise them tomorrow, and we'll make sure that we get them answered and you get that answer.

It's almost 10 after 12. We're cutting into the lunchtime. So maybe we can take two more questions and then we can -- we can break for lunch. Any questions on this side?

MR. MAIER: I've got one here.

MR. BLECHA: Jim Blecha of Port San Luis Harbor District. Curiosity, there's been a seismic vessel off of Port San Luis, three, four miles out for the last two or three days. Out of curiosity, is that seismic or oil? Do we know?

DR. LANGENHEIM: I'm not aware of a USGS vessel offshore port in San Luis right now, so. They were doing surveying a year ago off of Port San Luis, but I don't think they're doing it right now.

MALE SPEAKER: [unintelligible] now.

DR. LANGENHEIM: Oh, okay. [laughs] Might not be our boat.

MR. BURTON: What? Time for one more? Anyone?

MR. MAIER: This lady wanted to ask a follow-up question.

MS. COCHRAN: Just one quick question for Jim Dawson? Tim. Has the ground underneath Diablo Canyon ever been seismically mapped? I mean, do you have a seismic map of that area? Does anybody?

MR. MAIER: I think we have people that will be able to answer that

--

MR. DAWSON: Yeah, that's -- that's --

MR. MAIER: -- later.

MR. DAWSON: -- that's something that I can't answer. I really don't know all the details of what's been studied at Diablo Canyon.

MR. BURTON: Barbara, would you like to ask a question?

MS. BYRON: [assent]

MALE SPEAKER: Oh, excuse me, sir.

MS. BYRON: I'm sorry, I just had a follow-up question for Dr. Langenheim. You mentioned that 3D mapping would be helpful but that you needed some age control along with that. I was just wondering if you could elaborate on what that would -- what that means.

MS. LANGENHEIM: Well, if we could get Tim in a scuba tank --

[laughter]

-- dig a, you know -- take a backhoe, and if we could first locate where the strand comes closest to the surface -- and I think they'll probably talk about that tomorrow because there's some bathymetric maps that have been done -- to go there and dig a trench across it and try and look at the layers like they do on land, try and do it under the water, which I don't think they've done a whole lot of that. But then try to get samples of carbon, or something to date, so that you could actually maybe get an earthquake history for those structures offshore. Does that answer your question?

MR. BURTON: I think that will probably do it for this Q & A. That still leaves us about an hour for lunch. We're going to meet back here about 1:15 for Session 3. And as Bill mentioned, you're kind of on your own for lunch.

There are a lot of good places to eat.  And we'll see you back at 1:15

[Whereupon, the proceedings were concluded]