Deep thoughts

North America is about to come under intense geophysical scrutiny. Rex Dalton explains how the four projects known as EarthScope will advance our understanding of volcanoes, fault systems and earthquakes.

Astronomy has its huge telescopes; high-energy physics its particle accelerators. Even biology, once the bastion of small science, has the Human Genome Project. But until now, scientists studying the interior of the Earth haven't had a flagship endeavour to propel them into the major league of big science.

In the United States, however, that's about to change, thanks to a bold initiative called EarthScope. The goal is to provide a three-dimensional view of the geophysical processes affecting North America, supplying data in real time. EarthScope's backers predict huge scientific dividends. To quote the initiative's website: "Integrated with new and existing geologic information, these data will provide unprecedented opportunities to unravel the structure, evolution and dynamics of the North American continent."

Our understanding of volcanoes, fault systems and earthquakes will be revolutionized, claim EarthScope enthusiasts. "There are huge implications for understanding seismic hazards," says Mark Simons, a geophysicist at the California Institute of Technology in Pasadena.

President Bill Clinton's farewell budget request to Congress, for the fiscal year 2001, includes US$19.4 million in start-up funding for the first two components of EarthScope. If the initiative is funded in its entirety, the total cost is likely to rise to more than US$500 million over the next decade. That should be achieved without squeezing the National Science Foundation's (NSF's) budget for research grants, as the money will be requested from the NSF's Major Research Equipment allocation, the US Geological Survey (USGS) and the space agency NASA.

Into the unknown

While most Earth scientists are excited by EarthScope's promise, many are aware that spending huge amounts of money on big science means tackling serious logistical problems — and taking big risks. Some are already worrying about the potential for cost overruns, and the damage to their field's image should any of the high-profile projects fail to achieve their goals. "We are all taking risks on EarthScope," agrees Mark Zoback of Stanford University in California, a principal investigator on one of its component projects. "All the projects are expensive, but they are taking us to where we have never been before."

ROGER RESSMEYER/CORBIS

Shock tactics: the San Andreas fault (seen here crossing the Mojave Desert) will be the focus of much of EarthScope's efforts as the project attempts to unravel the mysteries surrounding seismic activity.

Indeed, Zoback and others argue that Earth scientists must seize the moment. Advances in instrumentation have made EarthScope technically feasible, they say, while the current favourable budgetary climate has provided the chance of funding. They expect the initiative to foster collaborations between geologists, geophysicists and seismologists, strengthening Earth sciences as a whole. "Each of the projects emerged simultaneously from different communities," says Zoback. "The concept of combining them should give us some real breakthroughs."

EarthScope is made up of four projects. The San Andreas Fault Observatory at Depth (SAFOD) is an ambitious scheme to monitor an active region of the infamous fault.

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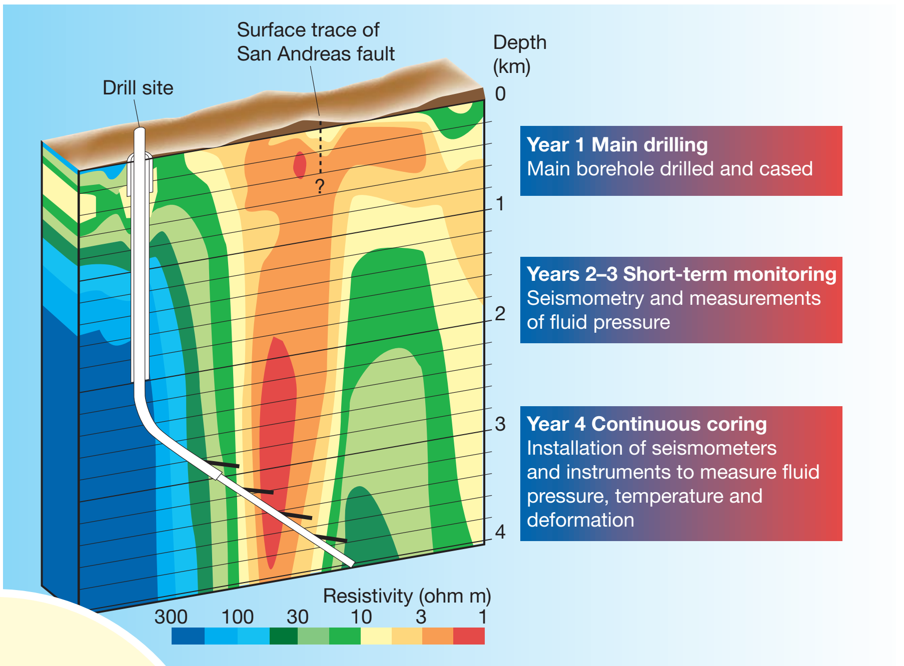
Researchers plan to drill a borehole to a depth of 4 kilometres in the mountains south of San Francisco. The USArray project will use an array of seismometers to provide three-dimensional images of the structures that lie deep beneath the entire United States.

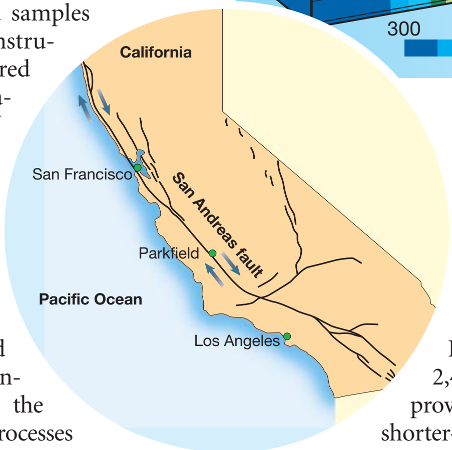
The Plate Boundary Observatory (PBO), meanwhile, will study the surface deformation caused as the Pacific and North American plates grind slowly past one another. The final element is a satellite fitted with interferometric synthetic aperture radar (InSAR). This will map tectonically active regions of the continent, allowing researchers to study displacements of the Earth's surface before, during and after earthquakes or volcanic eruptions.

SAFOD and the USArray already have the backing of the NSF's governing body, the National Science Board. The board wants to spend US$75 million on equipment for both projects during a four-year period from 2001. It also envisions a companion fund of US$62 million to pay for operations and research over the next decade.

With the SAFOD borehole, scientists will be able to place instruments in and around a zone of earthquake generation, giving them a three-dimensional view of seismological activity. The planned location is near Parkfield, where the San Andreas fault spawns



Going underground: the borehole to investigate seismic processes in the San Andreas will be the first shaft to be drilled so close to a major fault.



frequent quakes. The last significant Parkfield earthquake was a magnitude 6 event in 1966, and the USGS had predicted that a similar-sized quake would happen by the end of 1993. Since then, it has become clear that earthquake prediction is much more complicated than was once supposed, and seismologists are still waiting.

Shaking off uncertainty

Data from SAFOD should help narrow the uncertainties that make understanding the processes that drive earthquakes, and predicting their occurrence, so difficult. The main borehole will be drilled straight down for about 2 kilometres next to the San Andreas fault, before veering directly through the fault until it reaches a depth of 4 kilometres (see figure, right). From about 3 kilometres down, side holes will be bored into the fault, allowing scientists to extract rock and fluid samples for laboratory tests. Instruments will also be lowered into the shaft to measure the pressure of fluid within pores in the rocks, temperature, stresses within the fault zone, and near-field seismic waves from nearby earthquakes.

These data should address the many unknowns surrounding the physical and chemical processes that affect the San Andreas fault, and provide a firmer understanding of the stresses driving earthquake rupture. Many theoretical models have been put forward to explain the fault's behaviour. For instance, geophysicists have proposed that fluid within the pores of rocks deep within the fault is under high pressure, and that variations in this pressure influence the occurrence of earthquakes. But in the absence of the sort of information that SAFOD should yield, these theories remain untested.

William Ellsworth, a geophysicist with the USGS in Menlo Park, California, and one of the project's coordinators, predicts that the difference between SAFOD's results and those of surface-based projects should be as striking as that between conventional X-rays and the three-dimensional medical images obtained using computerized tomography scanners. “With SAFOD, we can get under the earthquake activity,” explains Ellsworth. “This should open up some exciting opportunities for imaging.”

Bigfoot steps in

The USArray is a seismic mapping project that will start in California, and will cover the entire nation over a period of 10 years. At its core will be a transportable array of 400 broadband seismometers — dubbed “bigfoot” by seismologists — that will be placed in a grid spaced at intervals of about 70 kilometres. In addition, some 2,400 instruments will provide high-density, shorter-term seismic recordings from interesting regions within the larger array. The project will also provide new instruments to upgrade and expand, to more than 100 permanent stations, the National Seismic Network run by the USGS, which monitors areas of high earthquake risk. The NSF is expected to fund the seismometers through the Incorporated Research Institutions for Seismology (IRIS), a consortium of universities which has its headquarters in Washington DC. IRIS already operates a pool of more than 500 seismometers for other geophysical projects.

Both natural seismic events and explosions will be used to draw up a comprehensive picture of the geological structures lying beneath the continental United States. This will include data on the depth of faults, the dimensions of magma chambers under active volcanoes, and the deep structure of sedimentary basins. Through collaborations with seismologists in Canada, and possibly Mexico, the survey could become truly pan-continental (see ‘Keeping up with the neighbours’, overleaf).

The USArray could image structures such as the deep roots of the North American craton, the ancient rocks that sit beneath the middle of the continent. It will also probe deeper still into the Earth's mantle and core. “A project like this will give us coherent and continuous images at high resolution — a more holistic view of what is going on in the deeper Earth,” says Anne Meltzer of Lehigh University in Bethlehem, Pennsylvania, who is coordinating planning for the USArray.

Defining the daily grind

The PBO has yet to be placed firmly on the NSF's wish-list, but geophysicists regard it as an integral component of EarthScope. The Pacific–North American Plate boundary zone covers a third of the North American continent. Its diverse features include the Rocky Mountains, the Sierra Nevada, the volcanic peaks in the Cascade Mountains and Alaska's Aleutian Islands, and the San Andreas fault system. The PBO will place this zone under unprecedented scrutiny using an interconnected network of global positioning system (GPS) receivers, strain meters, tiltmeters and seismometers.

A backbone of GPS receivers, roughly 100 kilometres apart, will stretch from Alaska to Mexico, and their relative motions will be used to draw up an overall picture of the surface deformation caused by the opposing drifts of the Pacific and North American plates. Higher concentrations of instruments will be placed along the San Andreas fault, and at sites where magma is known to be welling up from deep Earth. These include Yellowstone National Park; Long Valley east of the Sierra Nevada in California; two locations in the Cascades, one of which is likely to be Mount Rainier; and two places in Alaska.

The full PBO network would consist of 1,275 continuously recording GPS receivers and 245 strain meters — of which around 400 GPS receivers and 45 strain meters are already ▶

in place under existing projects. The strain meters will gauge short-term deformation on timescales from minutes to months, whereas GPS devices work best at charting movement over periods of months and years. Using these instruments, the PBO researchers hope to observe the full range of tectonic activity, including the build up of strain before a quake, and the relaxation that follows.

Paul Silver, a seismologist at the Carnegie Institution of Washington, who is chairing the steering committee for the PBO, says the project offers an unprecedented opportunity to study slow transient deformation — the gradual stop–start movement of the plates over periods of minutes to years. Seismometers miss these movements, Silver notes, recording only fast slips of the plates. "There are many reasons to believe that slow plate movement over a period of time is an important part of the cycle of an earthquake," he adds. "We pussyfoot around on earthquake prediction. This is an opportunity to explore transient deformation, which will bring us much closer to understanding the earthquake problem."

Screen shots from the sky

As a natural extension of their effort, Silver and his colleagues want to work with the team planning the InSAR satellite. NASA would be the prime funding agency for the satellite, which is the priciest EarthScope project — costing between US$200 million and US$400 million, depending on the type of instruments flown. Although NASA is not yet firmly committed to the project, officials are making encouraging noises. "We are extremely interested in cooperating with the NSF and the USGS," says Earnest Paylor, the agency's programme director for solid earth and natural hazards.

The European Space Agency already operates a satellite — ERS-2 — with InSAR technology. Synthetic aperture radar allows precise mapping of the Earth's topography. InSAR, which analyses sequential images of the same area, can measure deformation at the Earth's surface caused by seismic events (see right). But ERS-2 is used for a wide range of different projects. Obtaining its data is costly, and can take months. What's more, observations of North America aren't repeated frequently enough for the needs of US geophysicists.

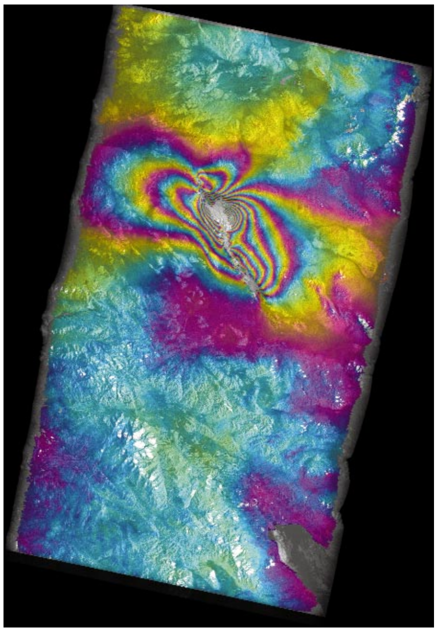
In contrast, the EarthScope InSAR proposal would provide data for free, almost in real time, over the Internet. "Imagine — you come into the lab in the morning, pull up the previous day's data and watch a volcano deform in Chile, or an earthquake in Taiwan," says Caltech's Simons, a member of the InSAR planning team. The satellite's orbit would be arranged so that it provided images of the region being studied by the PBO every eight days. This would allow scientists to stack radar images to create three-dimensional pictures of earth movement over time, complementing the PBO results.

Digging for victory

While few Earth scientists doubt EarthScope's scientific potential, some remain nervous about the risks posed by going down the 'big science' road. The blow suffered by their colleagues in planetary science, following NASA's loss of two consecutive Mars probes, is fresh in everyone's minds.

The biggest questions surround SAFOD, as no one has drilled this close to a major fault before. At the annual meeting of the Seismological Society of America in San Diego in April, the SAFOD team stressed that the precise location for the hole is critical: bore in the wrong place — say, in an old, inactive fault zone — and the budget for the project would be blown with no real scientific returns.

To place the borehole at the best site, the SAFOD team is using magnetotelluric techniques employed by Martyn Unsworth, a geophysicist at the University of Washington in Seattle. Unsworth sends electrical impulses into the Earth using a portable generator, and analyses high-frequency changes



JPL/CALTECH/ESR-2

The big picture: this interferometric image of the 1999 Hector Mine quake in the Mojave Desert, California, shows how the ground was displaced.

in electrical and magnetic waves to determine the resistivity of the rocks below. "It's like viewing a fetus with ultrasound," says Zoback, one of SAFOD's coordinators.

Unsworth's analyses have prompted the planned drilling site to be moved twice. But whatever the location, some scientists fear that shifting geological structures, high temperatures and pressures, or salt-water flows could disrupt the shaft or damage instruments. "This is something that has never been done before," says Christopher Scholz, a geophysicist at the Lamont-Doherty Earth Observatory of Columbia University in New York. "You can expect massive cost overruns."

But Zoback rejects such criticisms, pointing to the findings of an NSF review panel that examined the SAFOD plan in 1999 and concluded that it was well designed. However, the panel did question whether a US$1 million contingency fund set up to cover unexpected problems with the drill project was sufficient.

Viewed in the context of the scientific gains promised by EarthScope, the initiative's backers argue that the risks associated with SAFOD are entirely justified. Once EarthScope's results start coming in, they predict, the criticisms will soon be forgotten. "EarthScope will energize Earth science like nothing since plate tectonics," says Zoback. "We need to move ahead." ■

Rex Dalton is *Nature*'s West Coast US correspondent.

EarthScope ➧ **http://www.earthscope.org**

US Geological Survey Parkfield site ➧ **http://quake.wr.usgs.gov/QUAKES/Parkfield/**

Nature debate on earthquake prediction ➧ **http://helix.nature.com/debates/earthquake/equake_frameset.html**

Incorporated Research Institutions for Seismology ➧ **http://www.iris.edu**

Sample InSAR images ➧ **http://earth.esa.int/INSI/**

Keeping up with the neighbours

In a project that will dovetail neatly with the USArray of seismometers, a Canadian consortium of government, universities and businesses is planning a similar seismic mapping project.

Called POLARIS (Portable Observatories for Lithospheric Analysis and Research Investigating Seismicity), the project would include 90 seismometers and 30 further instruments to measure the resistivity of deep geological structures. It would cost almost Can$10 million (US$6.7 million). The proposal is now being considered by the Canada Foundation for Innovation, a federal government agency, which is expected to make a decision by July.

If the foundation approves its Can$3.8 million share, individual provinces are expected to contribute another Can$3 million. Diamond-mining companies should provide about Can$1.5 million, with the remainder coming from several universities. "This is Canada's biggest investment in equipment for Earth science," says John Cassidy, a seismologist with the Geological Survey of Canada in Sidney, British Columbia.

US National Science Foundation (NSF) officials had hoped Mexico would fund a similar programme, in effect extending its USArray survey to the south as well as the north. Unfortunately, it seems that the money isn't available. But some Mexican activity may still be possible, if scientists from the country put in compelling scientific proposals to use some of the seismometers currently operated for the NSF.