Listening to the Earth's deepest secrets

07 April 2009 by **Rachel Courtland**
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GARY ANDERSON was not around to see a backhoe tear up the buffalo grass at his ranch near Akron, Colorado. But he was watching a few weeks later when the technicians came to dump instruments and insulation into their 2-metre-deep hole.

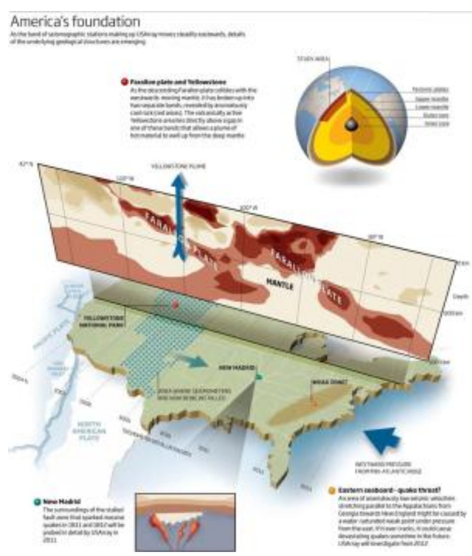
What they left behind didn't look like much: an anonymous mound of dirt and, a few paces away, a spindly metal framework supporting a solar panel. All Anderson knew was that he was helping to host some kind of science experiment. It wouldn't be any trouble, he'd been told, and it wouldn't disturb the cattle. After a couple of years the people who installed it would come and take it away again.

He had in fact become part of what is probably the most ambitious seismological project ever conducted. Its name is USArray and its aim is to run what amounts to an ultrasound scan over the 48 contiguous states of the US. Through the seismic shudders and murmurs that rack Earth's innards, it will build up an unprecedented 3D picture of what lies beneath North America.

It is a mammoth undertaking, during which USArray's scanner - a set of 400 transportable seismometers - will sweep all the way from the Pacific to the Atlantic. Having started off in California in 2004, it is now just east of the Rockies, covering a north-south swathe stretching from Montana's border with Canada down past El Paso on the Texas-Mexico border. By 2013, it should have reached the north-east coast, and its mission end.

Though not yet at the halfway stage, the project is already bringing the rocky underbelly of the US into unprecedented focus. Geologists are using this rich source of information to gain new understanding of the continent's tumultuous past - and what its future holds.

For something so fundamental, our idea of what lies beneath our feet is



As the USArray moves east, details of America's rocky underbelly are emerging

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sketchy at best. It is only half a century since geologists firmed up the now standard theory of plate tectonics. This is the notion that Earth's uppermost layers are segmented like a jigsaw puzzle whose pieces - vast "plates" carrying whole continents or chunks of ocean - are constantly on the move. Where two plates collide, we now know, one often dives beneath the other. That process, known as subduction, can create forces strong enough to build up spectacular mountain ranges such as the still-growing Andes in South America or the Rocky mountains of the western US and Canada.

In the heat and pressure of the mantle beneath Earth's surface, the subducted rock deforms and slowly flows, circulating on timescales of millions of years. Eventually, it can force its way back to the surface, prising apart two plates at another tectonic weak point. The mid-Atlantic ridge, at the eastern edge of the North American plate, is a classic example of this process in action.

What we don't yet know is exactly what happens to the rock during its tour of Earth's interior. How does its path deep underground relate to features we can see on the surface? Is the diving of plates a smoothly flowing process or a messy, bitty, stop-start affair?

USArray will allow geologists to poke around under the hood, inspecting Earth's internal workings right down to where the mantle touches the iron-rich core 2900 kilometres below the surface - and perhaps even further down. "It is our version of the Hubble Space Telescope. With it, we'll be able to view Earth in a fundamentally different way," says Matthew Fouch, a geophysicist at Arizona State University in Tempe.

> It is our Hubble Space Telescope - with it we can view Earth in a fundamentally new way

The combined effect of USArray's 400 seismic stations is to measure vertical and horizontal vibrations in the ground more comprehensively than ever before. Each one is housed in a dome-capped steel cylinder, similar in size to a basketball, which is buried sitting atop a 10-centimetre layer of concrete to prevent it floating to the surface in waterlogged ground. Solar panels above ground provide power, and from most sites cellular phone modems relay the seismometer data, which ends up at a coordinating centre in Seattle, Washington.

The stations are spaced roughly 70 kilometres apart in a more or less square grid. Each one remains in place for two years while stations are added further to the east. When its time is up, technicians dig it up and transport it eastwards to a new location at the front of the array. College students on vacation scout out future sites and contact potential hosts like Anderson. A total of 1624 sites is planned, covering all 48 states, and if you have land you think is suitable, the project even has a website where you can propose it. Remoteness and seclusion are musts: the seismometers are sensitive enough to pick up the rumble of pumps, wells, passing trucks, hydroelectric turbines and even the wind whipping off hilltop ridges.

Installation work snakes up and down the map with the seasons as technicians follow the best of the weather, installing stations in the colder north in summer and in the south in winter. Where the main array reveals regions of particular interest it can be augmented by a fleeter, more flexible array of over 2000 smaller stations providing short-term, high-density observations.

Keeping USArray moving is no small operation. "There were quite a few people who said it couldn't be done," says Robert Busby, who manages the array for the operating consortium, Incorporated Research Institutions for Seismology (IRIS), from an office in Falmouth, Massachusetts. "A few years ago, I was one of them." There is still the odd hitch: earlier this year, the solar panels of two stations in Idaho had to be dug out of 6 metres of snow, and on four occasions wayward bulldozers have decapitated the dirt-capped seismometers. Despite these mishaps, the average station is up and transmitting data 99 per cent of the time, Busby says.

Each station generates plots of sound waves arriving from all directions - the acoustic calling cards of earthquakes, volcanic eruptions and even storms and ocean waves crashing on distant shores. That might not sound like much, but used in combination the plots are a mine of information on what lies beneath Earth's surface. The way in which sound waves weaken, refract and twist within the Earth varies according to the temperature, pressure and composition of the rocks they pass through. By assessing how long it takes vibrations to travel from an earthquake or another source to the array's various seismometers, geophysicists can deduce the properties of the intervening material. If rocks transmit sound at speeds that are unusual for their depth, they immediately become interesting: it suggests that they originated somewhere else.

The kind of insight that this information can bring is illustrated by what we now know of the fate of the Farallon plate. The Farallon once underpinned an ocean to the west of America, but around 150 million years ago basalt bubbling up from the mantle drove a wedge between it and the Pacific plate further west, pushing it eastwards into the North American plate. It did not fare well in this encounter. Caught between emerging rock and a hard plate, it was forced underneath North America, raising up the Rockies in the process. Off the north-west coast of the US, in an area known as the Cascadia subduction zone, a last remnant of the Farallon, the Juan de Fuca plate, is still descending into the maw.

> A mystery area on the US eastern seaboard could become a subduction zone, with frequent quakes

Smashing plates

Cool, dense rock transmits sound waves faster than hot material, and small seismic arrays have previously caught glimpses of subducted Farallon material that had yet to reach the temperature of the surrounding mantle.

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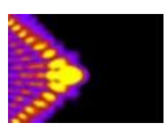

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These anomalous sightings appeared at various locations and depths - 400 kilometres below the surface in the western US, and deeper into the mantle near the eastern seaboard - but the connection between these fragments has till now been tenuous.

USArray has helped fill in the gaps. It has revealed new fragments of the Farallon that fit together like pieces of a puzzle (see diagram) and shown that its death was far from clean (*Nature Geoscience*, vol 1, p 460). As the plate subducted, it seems to have broken up repeatedly as it encountered a solid wall of old, stable material - the core of the North American continent being pushed in the opposite direction by material welling up far away to the east at the mid-Atlantic ridge. One fragmented slab of subducted rock slopes from the west coast to a depth of 1500 kilometres beneath the Great Plains of the Midwest. Another remnant descends independently further to the east.

Cracks thousands of kilometres long discernible in this rock are changing geophysicists' understanding of the entire seismic process. "The Farallon plate has been torn apart along these zones," says Guust Nolet, one of the authors of the *Nature Geoscience* paper, now at the University of Nice in France. "It's very much against the standard textbook image of beautiful oceanic plates going down into the mantle all continuous." The finding might also shed light on one of the biggest mysteries of North American geology - the intense geothermal and volcanic activity around the Yellowstone National Park (see "A new plume").

Another surprise is emerging from data being analysed by Fouch at Arizona State University. His number-crunching seems to indicate that a large drip of dense material from the underside of the North American plate is slowly sinking into the mantle beneath Nevada. "We think of subducting plates as the only things that go down," says Fouch, but the Nevada finding indicates it's not that simple. Drips of dense material affect how heat flows in the Earth's interior, and their presence could help to explain how the locations of seismic faults and volcanic activity have changed over time.

As USArray rolls on from the geologically active western states, it will enter the more stable territory of the North American craton, the ancient core of the continent that has been largely untouched by the convulsions of its peripheries. That could offer a look back further into the continent's past - as well as a glimpse into its future.

One area of focus will be the Reelfoot rift, a rent in Earth's fabric that extends some 200 kilometres south-west along the Mississippi valley, from New Madrid, Missouri, towards Memphis, Tennessee. More than 500 million years ago, rock began forcing its way up from the mantle beneath this area. Had it continued it might have created a new rift valley, and ultimately a new ocean.

It didn't. For reasons unknown, rifting failed, but that ancient drama still left its mark by creating the most seismically active area in the US east of the Rockies. Between December 1811 and February 1812, New Madrid was the scene of a succession of huge earthquakes, one of which was powerful enough to ring church bells in Boston, Massachusetts, more than 1500 kilometres away. The likelihood of a repeat event around New Madrid within the next 50 years has been estimated to be between 7 and 10 per cent; for a lesser, but still significant, quake the chances are between 25 and 40 per cent. As a result, the immediate region already boasts hundreds of seismometers, but further afield seismometer coverage is much sparser and knowledge of the risks correspondingly hazier.

USArray should change that - and not before time. By 2011, the array will be centred over the fault zone, and its northern end will be at the edge of the Great Lakes. "That should tell us something about how stresses could build up in a craton that looks otherwise stable," says geophysicist Suzan van der Lee of Northwestern University in Evanston, Illinois. We will then be

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able to say whether New Madrid is unique, or whether other parts of the central US look similar. "That scenario is a bit scarier," she says.

Nolet agrees that the data could be an eye-opener. "It may very well be possible there are other rift zones that are quiet right now but could come to life again," he says. USArray will provide only a snapshot in time, so will not predict when earthquakes will occur, but by telling us how the ground beneath us is structured, it might tell us which areas could be under stress, and which areas would be particularly vulnerable to shaking if an earthquake were to occur.

Over the far longer timescales on which geologists are accustomed to thinking, data from USArray may give us a hint of North America's long-term fate. According to van der Lee, an important clue may lie in a 300-kilometre-wide channel of anomalous material that runs to a depth of at least 660 kilometres along the US eastern seaboard. "Right now we have a fuzzy picture of this thing," says van der Lee. "We need USArray to get a sharper image."

She and her colleagues have raised the intriguing possibility that the mystery area is water-saturated rock that has risen from water-rich minerals held in the leading edge of the Farallon plate (*Earth and Planetary Science Letters*, vol 273, p 15). If so, it would represent a weak point in the otherwise firm undercarriage of the eastern US. As new material formed in the Mid-Atlantic Ridge continues to exert pressure on the North American plate from the east, it would be a natural point for a break to occur. Rather than continue to push, material would begin to subduct down along this weak line.

That could be as dramatic an event as the Farallon's subduction was in the opposite direction, triggering the formation of lava plains and volcanoes, and frequent, violent earthquakes. Within a few tens of millions of years, the relative tranquillity of the eastern US could be history.

Van der Lee speculates that these bursts of tectonic activity might be part of a larger see-saw pattern in the dynamics of some continents. Material subducting on one side of the continent could push watery rock in front of it, creating weak spots that ultimately help to trigger subduction on the opposite side.

No one who takes a long view of Earth's history would bet against such apocalyptic scenarios. Whether our descendants will be around to witness them is another matter. USArray's director, Robert Woodward, has his sights set on more immediate concerns. He wants to build on the array's success in the contiguous US and take it to Alaska in 2014 for either a five-year sweep of the state or a more focused study of particular areas of interest. "I think everywhere we take the instruments we'll learn something," he says, "Even if we're not 100 per cent sure what that is."

(Illustration by Joseba Elorza)

A new plume
The Yellowstone National Park in the Rockies is one of the favourite US destinations for visitors attracted by its wildlife, majestic scenery - and above all its spectacular geothermal features, such as the Old Faithful geyser. Two-thirds of the world's

geysers lie within the park.

Geologists have known for some time that this unusual activity is the subdued signature of a "supervolcano" underneath Yellowstone, whose last outburst 640,000 years ago produced a crater a kilometre deep and blanketed the surrounding area in more than 2 metres of ash. But the source of that volcano's heat has remained a mystery.

Now USArray has allowed us to pinpoint it, according to Richard Allen, a geophysicist at the University of California, Berkeley. His analysis of USArray data shows that Yellowstone lies directly above one of the gaps in the descending Farallon plate, allowing hot rock to well up unhindered from at least 1000 kilometres down. The plume probably punched this hole some 17 million years ago, when it lay beneath what is now Oregon. Since then, the plume has stayed anchored deep beneath the surface, while the overlying North American plate has tracked west, pulling Yellowstone into place above it.

Evidence of such plumes of mantle rock are most commonly seen at the ocean floor in places like the mid-Atlantic ridge, where deep material wells up to create rifts that separate plates and give rise to new crust. While hints of plumes have been found beneath Germany and elsewhere, "this is the first time a continuous plume has been shown coming up from great depth beneath Yellowstone", Allen says.

It is not clear exactly how great that depth might be. But as USArray, which is currently passing over the region, moves on it should reveal more about the plume's roots and how heat is transported to the surface. That could help us to assess Yellowstone's past and what it might be capable of in the future - a mission given new impetus by a marked upsurge in seismic activity in Yellowstone in December 2008.

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