Windows into Yellowstone

An Interview with Geologist and Geophysicist Robert B. Smith

Dr. Robert B. "Bob" Smith has been associated with Yellowstone geology for four decades. Bob is a professor of geology and geophysics at the University of Utah. He has conducted research in the park since 1959 and has operated the Yellowstone seismic and GPS networks since 1982. He is a former president of the Seismology Section and a fellow of both the American Geophysical Union and the Geological Society of America. A lively speaker who talks about the many connections of features and resources in what he calls a greater Yellowstone "geoecosystem," Bob graciously spoke with senior editor Sue Consolo Murphy in 1999 during one of his many trips to the park. Windows into the Earth: The Geologic Story of Yellowstone and Grand Teton National Parks *is his new book with co-author Lee J. Siegel (Oxford University Press 2000; 240 pages, 69 illustrations).*

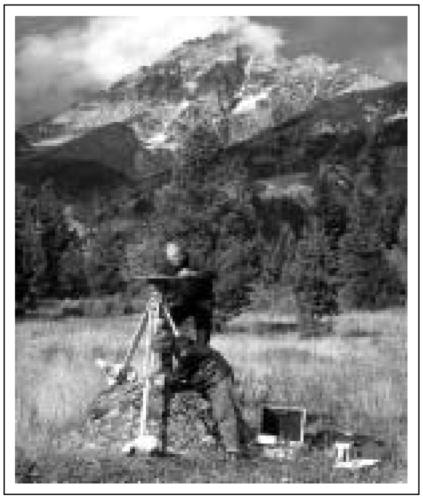
Yellowstone Science (YS): How did you get interested in geology?

Robert Smith (RS): I actually got started here in Yellowstone; I worked in 1956 as a GS-0. I think that's the truth—maybe it was a 1.

YS: No pay?

RS: Very little. It was a great year because my job was the lowest GS level they had. I was stationed at Lake working for the U.S. Fish and Wildlife Service. They brought us on in late February; we drove "weasels" across Hayden Valley. These were the first snowmobiles, these little army weasels, horrid things.

There used to be a grayling fish hatchery at Grebe Lake, west of Canyon. My first job was to ski in and open up this building and get the water flowing and then install fish traps and wait for the fish to spawn and be captured for study. When we were taking graylings, grizzlies would come to our cabin because they could smell fish eggs inside the building. I was sitting in my bed one night, and I heard this roar and pounding on the cabin. After that I slept with a two-bitted ax across my bed the rest of the time. I figured they were going to come right through the door.


Bob Smith

I then helped map the tributaries of Yellowstone Lake that could support fish spawn. I did surveys of water chemistry, salinity, and sediment conditions. I think I walked every mile of the drainage that summer. Monday they put a pack on my back and said, "See you Friday." There were no radios, no GPS (Global Positioning Systems), old maps, nothing, you just went. I would go up every stream, every tributary. I lived that summer at Fern Lake, upper Pelican, and we had cabins at Clear Creek, down at Trail Creek, and at Peale Island. We worked our way around Yellowstone Lake. That was really a fantastic experience.

They also had me assist with surveying lake bathymetry and limnology. We had an old surplus navy boat with a depth bottom sounder on it from which we did seismic profiling of the lake. We also lowered water and bottom sampling devices down the water column. All the way along, the sounder recorded data from beneath the lake bed with echoes of rock sediments beneath it. "Hey," I'd look at my boss, "what is all this?" He said, "Mind your own business. You're supposed to worry about fish, not about rocks." But I thought it was pretty neat. That was 1956.

I didn't finish high school, actually. I was admitted to college early, but I left that year after the opportunity came for me to work in Yellowstone. I ended up at Madison Junction that fall doing stream chemistry and creel censuses, all these things about fishing. Then the Hebgen Lake earthquake ripped off in 1959, and I switched into geology. That really got me interested. We students went up to the Hebgen Lake area and saw the aftermath of this major earthquake, including fault mapping and scarp measurements.

YS: You weren't here at the time? You didn't experience the quake?

RS: No. I was just finishing a summer geology field course in southern Idaho. At around midnight the ground started shaking as we said, "It's a big earthquake." It's what really got me interested in this mixture of geophysics—a combination of physics and geology. I also like the biological side of things because I started out doing that in Yellowstone. I went on and got degrees in geology, a Ph.D. in geophysics, and I started doing lots of other things; I went to pilot training in the Air Force, I put seismographs all over Europe to snoop on Russian nuclear testing, and

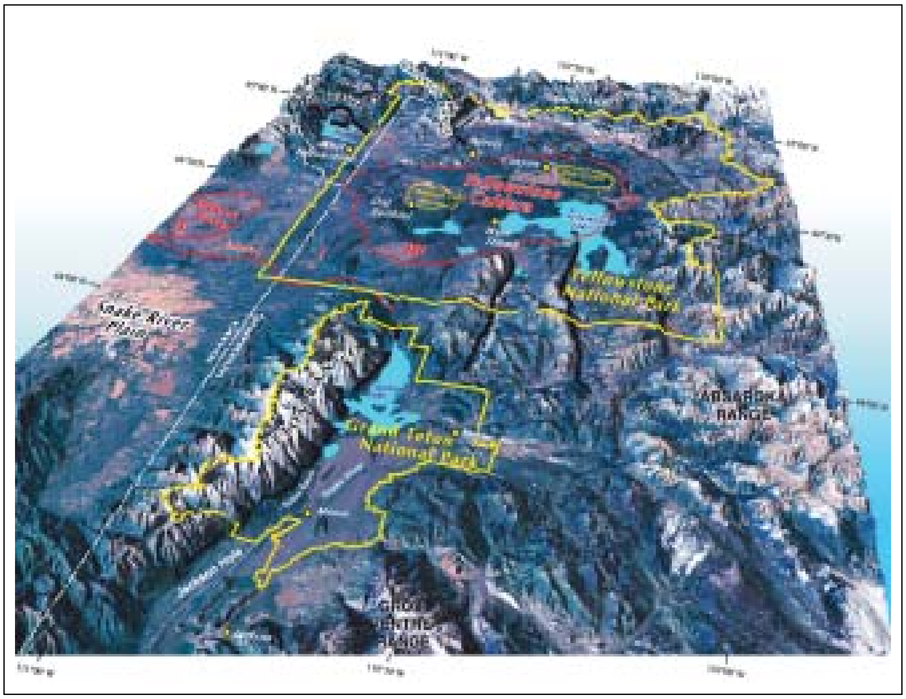


Figure 1. Space view of Grand Teton and Yellowstone national parks from satellite images overlaid on digital elevation maps. The 8,000-foot-high Yellowstone caldera was produced by a giant volcanic eruption 630,000 years ago. The caldera occupies a 45-by-30-mile-wide area of central Yellowstone. The Teton fault bounds the east side of the Teton Range and raised the mountains high above Jackson Hole's valley floor. (Image by E. V. Wingert.)

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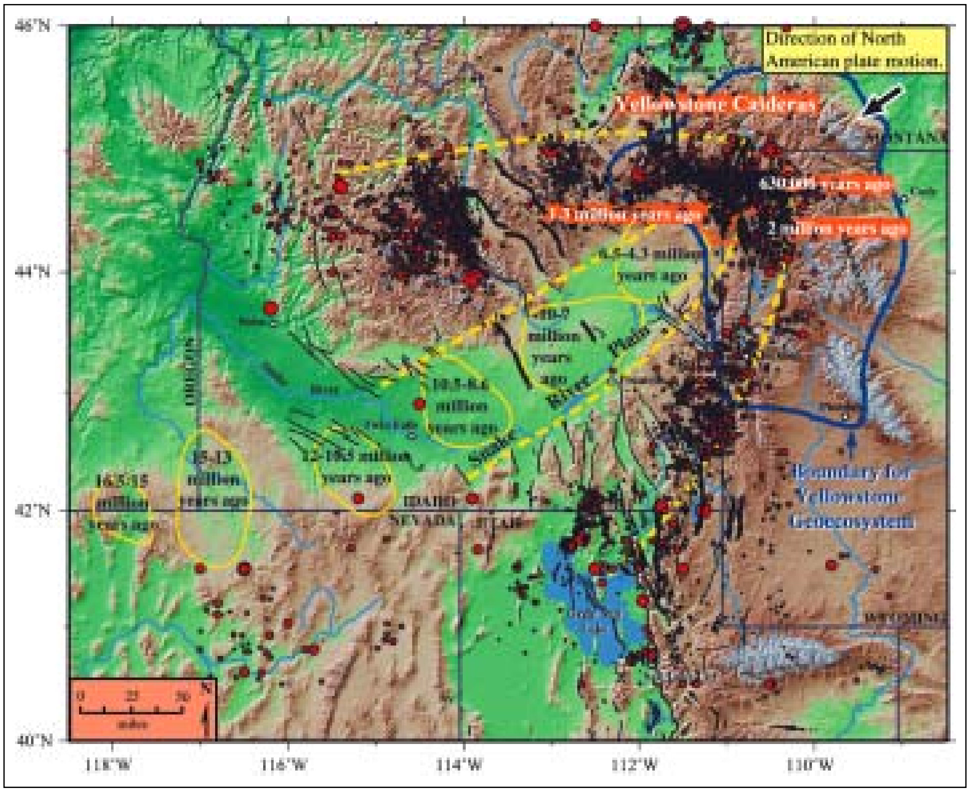

Figure 2. Path of the Yellowstone hotspot. Yellow ovals show volcanic centers where the hotspot produced one or more caldera eruptions—essentially "ancient Yellowstones"—during the time periods indicated. As North America drifted southwest over the hotspot, the volcanism progressed northeast, beginning in northern Nevada and southeast Oregon 16.5 million years ago and reaching Yellowstone National Park two million years ago. A bow-wave or parabola-shaped zone of mountains (browns and tans) and earthquakes (red dots) surrounds the low elevations (greens) of the seismically quiet Snake River Plain. The greater Yellowstone "geoecosystem" is outlined in blue.

was chosen as the American exchange scientist to the British Antarctic Survey and went to the Antarctic—lots of really kind of wild things.

YS: You spent a large portion of your career working with other folks to expand the state of the knowledge from what was just vaguely recognized as a volcano, a volcanic caldera, in Yellowstone, to what is now recognized as nearly the largest one in the world.

RS: The largest active hotspot on the continents and maybe in the oceans. We geophysically mapped the third dimension, that is, the subsurface geology with depth, and we studied "extinct" volcanic centers all the way from Boise, Idaho, to Yellowstone.

YS: When you first came to work on Yellowstone geology, what was the level of knowledge?

RS: It was somewhat limited, especially in terms of understanding the volcanic and tectonic processes in a plate tectonic framework. I finished my Ph.D. in 1967 and went to Columbia University to do post-doctorate research. There I went back through all of their old seismic records for western U.S. earthquakes, but focused on learning more about the Hebgen Lake earthquake. I also went to the University of California at Berkeley, because that was a famous seismological institute, and said, "I want all your data on this great earthquake at Hebgen Lake." We went down in the basement and this guy said, "They used to be here in boxes." Didn't find *one*…

About a month later a technician called me up and he said, "Dr. Smith, there's a pile of stuff here under dust and garbage, is this what you want?" It was like finding a gold mine! I now had all the world's records for the Hebgen Lake earthquake and its aftershocks. I started working with those. This really heightened my interest. I started coming up to the Hebgen Lake area, putting out seismographs and studying Yellowstone's fault and volcanic features in the 1960s.

Mapping of geology in Yellowstone was initiated in the 1870s by Ferdinand V. Hayden, the famous naturalist-geologist whose pioneering work helped get Yellowstone named as the first national park. Hayden made a prophetic statement from on top of Mount Washburn looking out across the Yellowstone Plateau saying, "This basin has been called by some travelers the vast crater of an ancient volcano…" But not many paid attention to his writings in the sense of the extent of the system or the youthfulness of Yellowstone's volcanism.

In 1922, Professor Jagger at Massachusetts Institute of Technology rode through Yellowstone on horseback on his way to Hawaii, where he founded the Hawaiian Volcano Observatory. He observed Yellowstone's geology and topography and made a famous statement, "Anyone who has spent summers with pack-train in a place like Yellowstone comes to know the land to be leaping…The mountains are falling all the time and by millions of tons. Something underground is shoving them up." He recognized that Yellowstone was a dynamic geologic system. Then after another long hiatus, a Ph.D. student named Joe Boyd of Harvard in the late 1950s mapped and outlined the detail of the Yellowstone caldera.

But it was in the mid-1960s that a modern and major effort to study Yellowstone's volcanic system was initiated by the USGS and funded by NASA, which was training astronauts to go to the moon. They were searching for places that had moonish, volcanic rocks—Craters of the Moon, deserts. They funded the USGS research on geology of Yellowstone because it was a big volcanic center. In the mid '60s, they were doing mapping here and we were starting our first installations of portable seismographs for earthquake studies. That's when I met up with Bob Christiansen of the USGS Volcano Hazards Branch. He and I became friends and close colleagues because our research really dovetailed together. I would develop some new information that would fit his ideas and vice versa. The integration really paid off. The sum of the two of us was much greater than individuals working alone. Also, Dave Love of the USGS, who had mapped in and around Yellowstone, collaborated with me, starting on fault and earthquake studies in the late '60s (Figure 1).

YS: You were at the University of Utah by then?

RS: Yes. I had started doing earthquake installations and detailed fault mapping in Yellowstone about 1967. The USGS installed the first permanent seismographs in 1973. It was also then that we got our first research grants. We put portable seismographs all over Yellowstone and the Tetons. We started our first survey at Norris, then studied the Hebgen Lake fault zone near West Yellowstone, Yellowstone Lake, and the Beartooth Plateau; then we went down and did the Teton fault. These were part of a long-term plan to analyze the Quaternary fault and volcanic history of the region.

We also built a boat to do seismic profiling, bottom-sediment coring, and heat flow measurements. From this vessel we ran seismic profiles of Yellowstone Lake and Jackson Lake. The piston cores allowed us to determine the composition and ages of the lake sediments from which we subsequently determined the first estimates of the past 7,000-year history of Yellowstone Lake. Bob Christiansen and his colleagues were also putting together the volcanic framework of Yellowstone at the same time, and Bob Fournier, also of the USGS, was doing his hydrothermal work along with Don White. Our data and ideas all came together roughly at the same time in the early '70s.

I wrote a couple of papers in 1974 that described the properties of Yellowstone as a "hotspot." Remember, plate tectonics didn't come into vogue until the late '60s, so there was no framework to even think about a hotspot until 1972 when a Princeton geologist plotted all the Earth's volcanic centers and recognized their pattern relating to plate motions.

YS: Is the hotspot considered to be contiguous with the caldera?

RS: "Caldera" is a Spanish word for a cooking pot called a caldron. When a large volume of magma is removed from beneath a volcano, the ground subsides or collapses into the emptied space, to form a depression called a caldera. They can range in size from a kilometer to tens of kilometers long, like Yellowstone's. "Hotspot" is a term used to denote an area of concentrated volcanism on the earth's surface with a deep mantle source of magma and heat. As the ascending molten rock migrates through the earth's mantle, some of the magma gets entrained on the base of the overlying plate, while part of the magma leaks upward into the crust, melting surrounding rocks and creating a shallow heat source. That magma feeds Yellowstone's magma chambers whose tops are located at depths of about 8 to 10 km and extend to depths of about 16 km.

This magma in turn provides Yellowstone's immense heat flow. It is not so much that Yellowstone's ground temperatures are high, but it is the flow of heat coming out the earth's surface that is 30 to 40 times higher than the heat flowing anywhere else in North America. Yellowstone is like an immense heat radiator.

There aren't a lot of big calderas around. Toba in the southwest Pacific is an example of a large caldera about the size of Yellowstone's. However, it's poorly known because it's so remote. As related to the giant eruptions and the calderas that occur elsewhere in the world, the Yellowstone caldera is a giant—50 km long by nearly 40 km across. This is the dimension of the roof that collapsed into the magma system.

YS: Tell me about mapping the young Yellowstone caldera and pursuing the bigger picture of how it relates to older volcanic activity across the western U.S.

RS: You can't just study Yellowstone in the context of nothing else. You have to do it in terms of how it fits into the world. I have prepared a map of the locations of the Yellowstone and the Snake River Plain calderas, the older calderas along the track of the hotspot (*e.g.*, the shift in the relative position of the hotspot as a result of continental drift). The map also shows how the topography, earthquakes, and faults were related to the Yellowstone hotspot track. That's when we first began thinking about the overall pattern of the effects of the hotspot on the surrounding area and its evolution, but more importantly, how it created the volcanism, earthquakes, and how it tied to the faulting—the energetics of a hotspot (Figure 2).

The USGS had mapped most of the pieces of Yellowstone by 1970. And a paper on a global hotspot and plume was published by a professor at Princeton in 1973. I published two papers in 1974 in which I described the effects of the Yellowstone hotspot and its volcanism. A professor at Yale, Dick Armstrong, first noted "old Yellowstone" volcanic centers along the Snake River Plain. He dated volcanic rocks, rhyolites, scattered along the floor of the Snake River Canyon; the rocks get older and older down the Snake River Plain from Yellowstone. But they were buried beneath the young basalts. Now, the Snake River Plain is a broad topographic depression, and we reasoned that there had to be mountains there before. You just don't blow away Rocky Mountains. Something destroyed them. Destruction is a product of explosion plus foundering of the mountain roots back into the magma system. Armstrong showed the progressive age of the volcanic rocks, oldest in southwestern Idaho and northwestern Nevada, and youngest in Yellowstone.

Plate tectonics had just hit. So in 1972 I calculated the North American plate's interaction with the Pacific plate. I said, "Let's assume that the source of Hawaii volcanism is fixed deep in the Earth and compare how Yellowstone relates to Hawaii." The model predicted the southwest motion of the North American plate at Yellowstone. Its trace, the 800-km track of the progressively younger volcanic centers of the Snake River Plain towards Yellowstone, fit this model of a plate overriding a magma source anchored deep in the earth, sometimes called a plume. Hawaii is over a hotspot beneath the Pacific plate, and we are over a hotspot beneath the North American plate.

Armstrong dated the rocks by potassium argon methods and showed that the oldest were to the southwest and the youngest to the northeast. That gave a plate velocity of 4 1/2 centimeters per year of movement to the southwest. I calculated the motion of the North American plate, using Hawaii as a reference frame, and I added in some extension, and it fit Armstrong's data within the margin of error. The light went on: the volcanic activity at Yellowstone is from a fixed Earth's mantle, and the progressive volcanic ages are just the record of the plate motion across this source. You can't see old Yellowstone calderas too well in the Snake River Plain because they got covered by younger basalts. But you can infer roughly where they are because of the ages of the rhyolites that are mapped. For the same reason, most of the Yellowstone caldera has all been covered up. Lisa Morgan and Ken Pierce of the USGS and Mike Perkins of the University of Utah have detailed the volcanic history of the Snake River Plain and delineated the details of many of its volcanic centers.

Thus we determined the track of the plate over the hotspot, and from seismic data we determined the size and location of its deep magma system. The magma that makes up the spread-out hotspot on the base of the plate is only 3 to 6 percent melt; the rest is solid rock. By integrating all available data from geophysics, geology, mapping, and dating, it all started to fall together.

YS: And the plate—where Yellowstone currently is—moves relative to this hotspot of liquid rock under the Earth's surface.

RS: You have to think about the framework. The mantle is fixed. The magma comes up and interacts with the overlying Earth's plates that are moving. It's like moving your hand across a burning candle. The flame leaves a line of burns on your hand and, if you leave it there long enough, the candle flame burns a hole through your hand.

Beneath southern Idaho, we've had a candle flame made up of magma burning upwards into the plate moving over it, starting down in the Boise area 16 million years ago. And the plate has moved from northeast to southwest since then. The youngest rocks are at Yellowstone (Figure 3).

YS: And so what is cold now, the rock that you map, was once a hot piece of rock.

RS: There were old Yellowstones all the way from Boise up here, but they are now inactive, cold and buried beneath basalt. Of course, the surface rocks in Yellowstone cool rapidly after exposure to the Earth's atmosphere.

YS: And it all became rhyolite, the rock we often see on the surface of the park?

RS: At the Idaho National Engineering Laboratory near Idaho Falls, 15 or so years ago, they wanted to learn about the subsurface geology beneath the site. They drilled a deep borehole, and low and behold, they drilled through surface basalts into rocks that we call rhyodacites. These are similar in composition to

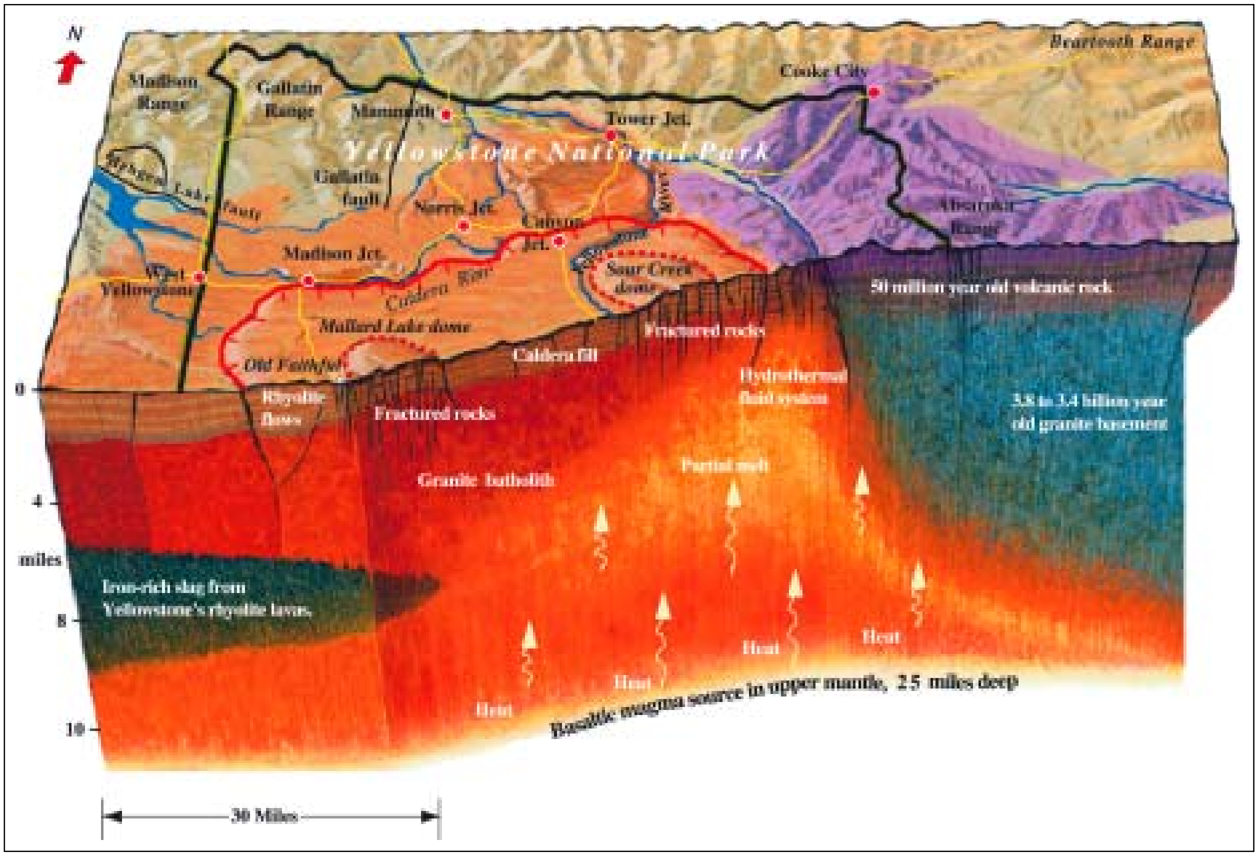

Figure 3. A cross section of Yellowstone reveals molten rock under the caldera at depths of about three to eight miles. Heat emitted by the molten rock powers Yellowstone's geysers and hot springs.

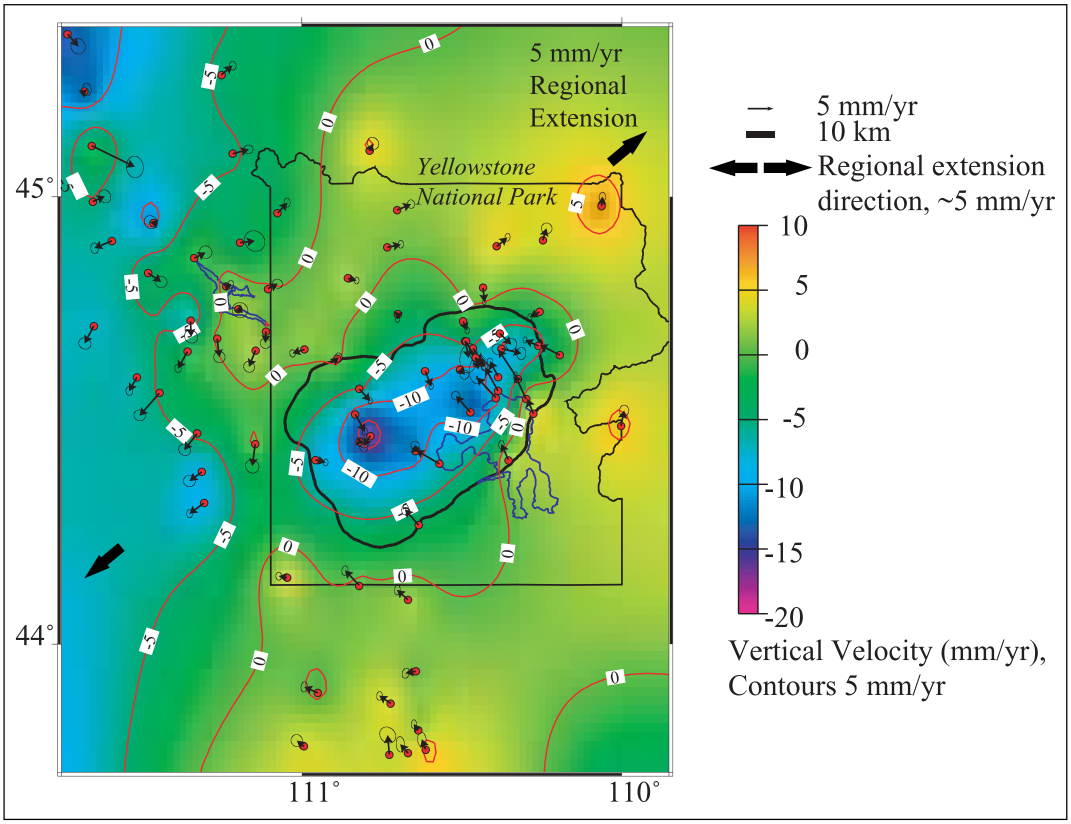

Figure 4. Crustal deformation of Yellowstone from GPS measurements. Three-dimensional GPS station velocities for Yellowstone from 1987–95. Arrows show horizontal velocity vectors at stations; color contours represent vertical velocities. Large arrows indicate direction of regional extension across the Yellowstone volcanic field. Courtesy Bob Smith, University of Utah, Yellowstone Hotspot Project.

Yellowstone's rhyolites. The rhyolites have been covered by younger basalts that you see when you drive south from Ashton to Idaho Falls to Pocatello. They are ragged black rocks that make up the surface. The inference then, from these and our geophysical data, is that the rhyolites actually make up a much thicker component of the Snake River Plain but they are buried by the basalts, which are just a thin layer at the top.

YS: You moved on, to monitoring the movement of Yellowstone—the breathing of the caldera, so to speak.

RS: We got into crustal deformation. I recognized from a return visit to the south end of Yellowstone Lake in the early '70s that there was something strange going on here; things didn't look right. The trees at the shoreline appeared to be inundated by rising lake water, and parts of Peale Island, where I had worked in 1956, were under water. I reasoned that the lake was tilting to the south, inundating its southern reaches and uplifting its northern parts. This effect would also increase the height of land at the north end of the lake, rising and expanding the beach behind the Fishing Bridge Visitor Center. We were witnessing the effect of a tilting toward the south of a bathtub ring, its shoreline, around Yellowstone Lake.

It was then that I realized that if we did precise measurements of the elevation of benchmarks originally established when roads were built in Yellowstone in 1923 and 1934, and we went back and re-observed those marks, we could see if they had moved vertically or not. We were contracted by the USGS and, with one of their crews, we surveyed and compared the data for three summers. Our first year we went across the caldera from Canyon to Lake. Our surveyor had the original surveyors' notes from 1923, and he said to me, "There's something really wrong here—we're way off from their elevations, I mean, we're like a foot and a half off."

I thought, boy, we've done something wrong; we've got to go back and redo our survey. No, we were doing even more precise surveying than the 1923 surveys. Excluding the errors that could have been in the 1923 survey, we showed that this whole portion of the Hayden Valley was going up. We ran a survey line from West Thumb to Old Faithful to Madison Junction, and we also went across the old road, from Nez Perce Creek over the top of Mary Mountain to Hayden Valley. That is how we connected the two profiles together. Altogether these measurements revealed that the Yellowstone caldera was rising, like a giant bulging stomach of a breathing creature.

This unprecedented discovery revealed what I called a *living* caldera. It had risen 75 cm—3/4 of a meter over a caldera that's 50 kilometers long. It really was unprecedented, seeing deformation this big, greater than most anywhere within a continent that we knew of with the exception of active volcanoes such as Rabual in the southwest Pacific and the Phlegrean volcanic field near Mt. Vesuvius volcano, Italy. Continued leveling of the points by Dan Dzurisin of the USGS and our new GPS measurements, however, showed a cessation of the caldera uplift, returning to subsidence about 1985 (Figure 4).

It was at the same time that we received an NSF grant to employ the new technology of Global Positioning Systems (GPS) to study Yellowstone. With this new method we didn't have to be on roads and were able to go all over the backcountry, essentially putting a grid of GPS benchmarks across Yellowstone. And we re-observed them every other year, from '87 to '95. These measurements revealed that the caldera had indeed reversed motion and began moving down at about 1.5 cm per year, at nearly the same rate as the uplift and over the same uplifted area. What, is this thing breathing? We were all excited about that. In looking at our '95 survey data, we noticed things were starting to bottom out. A couple of GPS stations around Old Faithful and LeHardy had come back up a little bit. But we didn't have any more money to continue our study. Starting in the mid '90s, Wayne Thatcher and Charles Wicks of the USGS used Interferometric Synthetic Aperture Radar (InSAR) that suggested the caldera began rising in 1994—another major change in the caldera dynamics, although our new continuous GPS data up to summer 2000 do not corroborate this uplift (Figure 5).

Nonetheless, we were lucky to have seen a giant caldera change from a period of uplift to subsidence, and perhaps another uplift in our lifetime. In a parallel effort, we studied the most intense earthquake swarm in Yellowstone's recorded history and found that the earthquakes occurred at the greatest rate during the change from caldera uplift to subsidence in late 1985 and continued into 1986. So we have this great correlation of earthquakes and changes in crustal deformation. I then coined the phrase a "living, *breathing* caldera."

YS: Do you have any idea, from your work done here or elsewhere, whether deformation has anything to do with the predictability of volcanic eruptions?

RS: We'd like to think it does…in Hawaii, where they have predicted eruptions on the basis of earthquakes, they can see the correlation of earthquakes related to migrating magmas which eventually erupt to the surface. But those are basaltic magmas—they flow much faster, they're not as explosive as Yellowstone's much more viscous rhyolitic magma and there's no precedent, no historic example to understand this behavior.

Eruptions in Rabaul, New Guinea, were preceded by uplift and subsidence and unusual periods of seismicity. On the other hand, there was no eruption in or near the Bay of Naples, Italy, during the period that land rose and subsided several feet, so that at one time some beautiful Italian buildings were buried under the water. Now they're back out of the water. They came up in the 1950s and '60s, when the ground did a lot of huffing and puffing—you know, it's also a caldera. It's erupted before. And of course, Vesuvius is nearby with three million people living in the area.

We've had to envision analog models from the basaltic cases as a working model for Yellowstone's rhyolitic eruptions. The rhyolitic magma would be more viscous and retain fluids and gases, causing uplift and subsidence with changes in pressure. Another reasonable model is one with large volumes of hydrothermal fluids underlying the caldera—the ones that feed its geysers, hot springs, fumeroles. These more easily running fluids pressurize their chambers, uplifting the ground then draining out its sides, and dropping the ground—a mechanism that also explains mechanics and numbers of earthquakes that we observed in the 1985 northwest caldera swarm. Above all we are dealing with a large rhyolitic volcanic system fed by a hotspot. Nowhere else does such a feature exist on a continent.

YS: So right now we're in a period of uplift again?

RS: Perhaps we are back into uplift. That does not necessarily mean a pending volcanic eruption. But remember, we've had 30 or so smaller but still explosive eruptions since the last giant eruption 630,000 years ago, the youngest only 70,000 years ago that occurred on the Pitchstone Plateau. It was however a giant, catastrophic eruption that created the Yellowstone caldera and blew ash all over much of the West. These post-caldera eruptions were smaller, but were tens to hundreds of times bigger than the Mt. St. Helens eruptions. And, based on Bob Christiansen's USGS work, they increased in frequency around 125,000 years ago. But there have been no volcanic eruptions for 70,000 years.

We've also looked carefully at the alignment of Yellowstone's post-caldera volcanic vents that line up northwest-southeast. These are smaller volcanoes, along with our new earthquake epicenters in the caldera, and they both line up; they're sitting there parallel one to another. We think the vents are along vertical dikes, if you wish. These are active magma systems just below the surface, and they create earthquakes, and they create volcanoes.

At the time of the big earthquake swarm in 1985, we called the situation to the attention of the Park Service. The earthquakes were coming at a very high rate. This was on the northwest side of the park, just beyond the caldera. It began in October, peaked about the first week of December, and continued through March 1986. We studied the sequence very carefully. The earthquakes progressed from the caldera outward to the northwest and going deeper as the sequence progressed. We interpreted the earthquakes as related to motion of fluid along a vertical dike, propagating fluid to the northwest.

It doesn't have to be magma to cause this effect; hydrothermal fluids may have been the responsible mechanism. My impression is that it could have been water moving outward from the caldera, leaving it to subside as supporting fluids were removed. As the caldera is subsiding it's got to get rid of the volume at about 0.02 cubic km per year. That means you're taking a volume roughly the size of Mammoth—the hot springs terraces, or the entire Mammoth developed area, wide and high. Interestingly, that is about the rate that magma would need to be injected into the crust to create the caldera uplift from 1923 to 1985 and to sustain its high heat flow.

And then the earth's surface started going down. The earth doesn't let you push fluid back down in it, so we surmise that it is being squeezed out the sides. We've hypothesized that caldera fluids, either hydrothermal or magma, could be migrating radially outwards from the caldera along dikes or vertical sheets of fluid. But Yellowstone's a big place. The stuff could leak out, especially if there is a lot of gas in it, and you may never see them if they are hydrothermal fluids. That mechanism is something reverse to uplift.

One of the nice things about our observations is the synchronicity of the uplift and subsidence between Hayden Valley and Old Faithful. They're 20 miles apart, yet they go up and down together. That implies you have a connected plumbing system. A "pipe" from Hayden Valley must be connected to the Old Faithful area at depth. That's probably the top of the magma system. So where we mapped the magma, which is actually a partial melt, that's the magma chamber. This body gives off heat that's coming up and creating the high heat flux, and it is what's heating the groundwater that makes the geysers. This system must extend under most of the caldera. But it shallows under the southeastern corner and the northeastern caldera. And one place where it seems to come shallowest, northeast of Sour Creek, is north of the Hot Springs Basin country, where it looks like there's a connection of these low-velocity magma bodies above the surface and a shallow hydrothermal system (Figure 6).

YS: Does the shallowness of the magma necessarily relate to where a next eruption might be?

RS: Oh, I think it would. You've got the two main pods in the middle, the southeast and northeast beneath the domes; if I'd be laying bets, I'd be thinking it probably wants to come up in the northeast. On the other hand, the geologic mapping shows the oldest post-caldera flows in the northeast, and they get progressively younger toward the Madison Plateau. So if you count on the past 150,000 years of volcanic history, you'd say the biggest potential is in the southwest plateau, along the caldera's southwest rim.

But I would look to the geophysical evidence, such as seismic images of magma and of where the earth's surface is moving from GPS measurements, and see if magma or hydrothermal fluids may be coming up on the northeast side. We just don't know the physics of these fluids well enough to predict that.

YS: You're talking about the shallow magma under the Mirror Plateau, the northeast edge of the caldera, and yet the hottest spot is under Norris Geyser Basin.

RS: Norris Geyser Basin has the hottest *water reservoir* temperature, but it is only probably 1 to 3 km deep. You have to differentiate between temperature and heat. You can have a concentrated blob of hot, hot water that's 450° to 600° Fahrenheit in a geyser reservoir, but it's an isolated body with a high temperature. Whereas the area of the caldera, on average, has a higher release of heat per unit area—that's heat flux.

YS: Now, describe how you map this magma. How long does it take to do that? And theoretically, can you retake a snapshot over time?

RS: We use the methodology used in medicine called CAT or MRI scans to do the same for the Earth, but using earthquake recordings of seismic waves passing through the earth. CAT scans are just a way of sending x-rays into the body, and they get reflected back from different parts of the body to produce an image of the body. X-rays transmit easily through soft tissues, but harder material like bones more easily reflect the rays. You've had CAT scans, right? A radiologist takes his little device and puts the gel on your belly and moves it around. He's sending rays in so he gets coverage. Lots of rays go through the whole volume and you get good coverage, then they are brought together in a computer to create a picture of your internal organs.

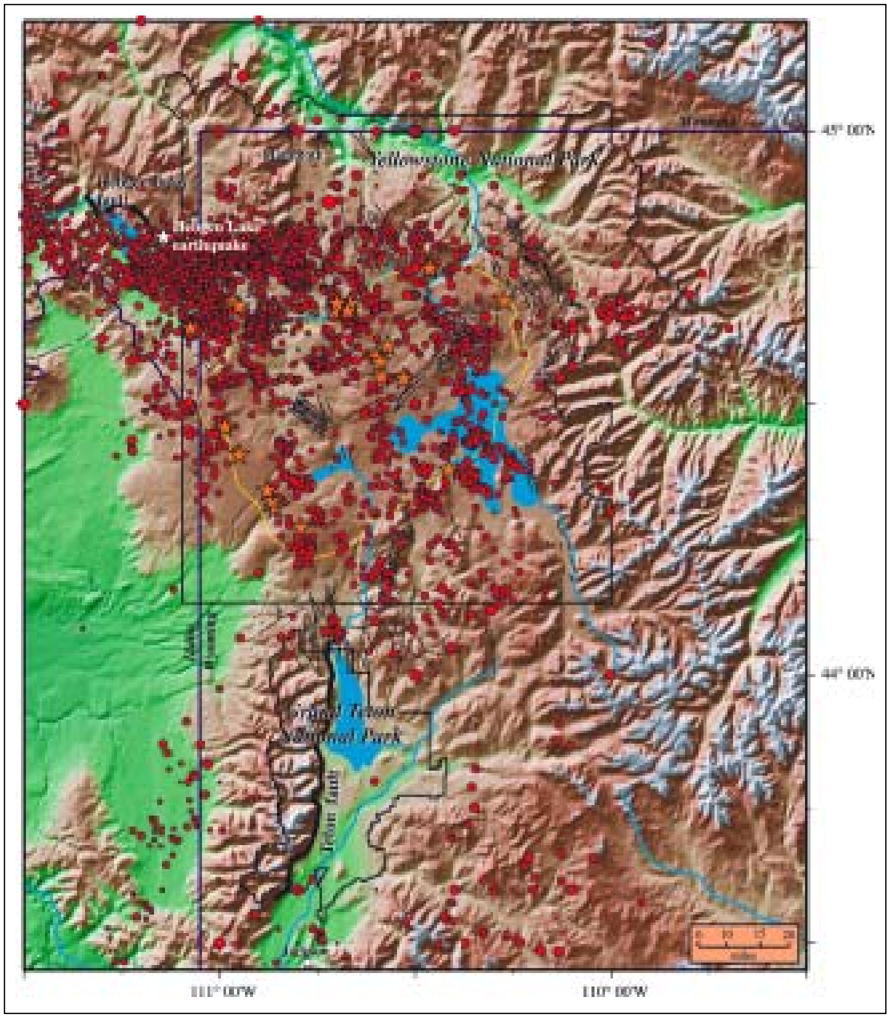

Figure 5. Earthquakes of the Yellowstone-Teton region. Epicenters of earthquakes from 1973 to 1996 are shown by red dots. Most of the quakes were under magnitude 5. The most intense earthquake activity is in the northwest corner of Yellowstone between Norris Geyser Basin and the Hebgen Lake fault. The Teton fault now is seismically quiet. Active faults are shown as black lines and post-caldera volcanic vents as orange stars.

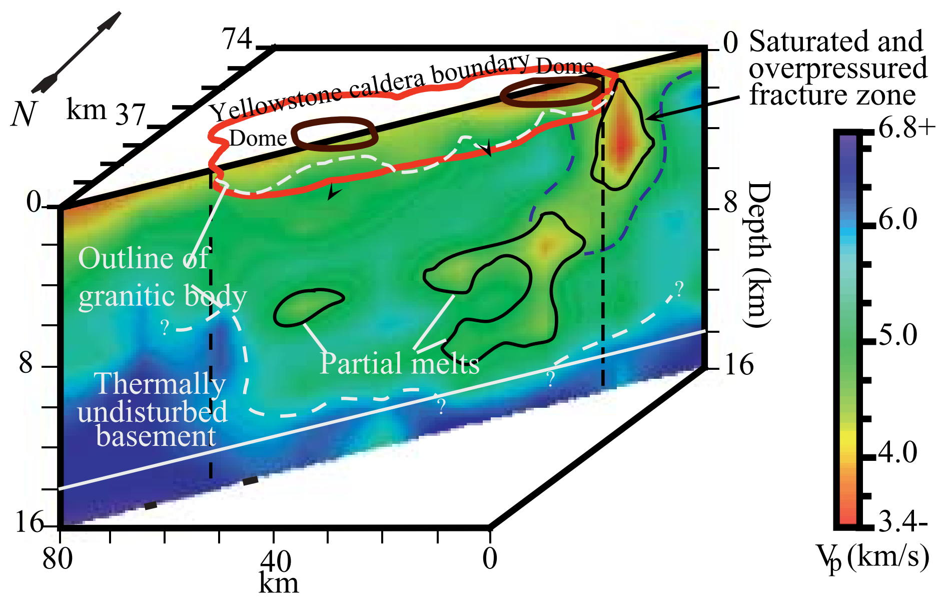

Figure 6. The Yellowstone magma chamber. Cross-section of the Yellowstone caldera from seismic images of the P-wave velocity using local earthquake tomography. It reveals the location of magma chambers beneath Yellowstone. The magma chambers are composed of partially molten rock containing 10–30 percent melted rocks. Warm color at depths of 8 to 16 km are hot rocks, blue colors are cold rock (from Miller and Smith, 1999).

Geologists apply the same method that we call tomography—seismologists developed it before the medical profession did. We use seismic rays that go into the earth. When the seismic wave encounters a hot rock, its speed of propagation slows down; when it encounters a cold rock, it speeds up. So if you have enough earthquakes in a region, recorded on enough seismographs, then you can reconstruct the ray paths of where they're fast and where they're slow. That's what we've done for Yellowstone's upper 15 km. We made a three-dimensional image of its structure. This is the method that we used to prepare the figure of Yellowstone's magma system.

We found magma, here 10 to 30 percent of melted rock, in a porous space of solid rock at depths as shallow as 8 to 10 km beneath the Earth's surface. It extends the length of the caldera with a conduit aimed toward the surface at the northeast side of the caldera. We do not have data that will provide the same kind of images deeper into the lower crust. But with our new NSF project focused on the dynamics and detailed mapping of the Yellowstone hotspot, we hope to probe as deep as 1,000 km beneath the surface and map the magma conduit all the way from the hotspot to the surface.

YS: And you do this taking advantage of the natural seismicity?

RS: We use the naturally occurring earthquakes. In 1978–1980, we recorded seismic waves generated by explosives in drill holes along the Snake River Plain to study the track of the hotspot all the way from Twin Falls to the Beartooth Plateau. We used our own earthquakes (we made them very small magnitude). And we also relied upon natural earthquakes. Natural earthquakes pose the problem that you don't know exactly where they are. So we have to calculate the location of the earthquake plus the velocity field. It's a more difficult mathematical problem. But if you have a few places where you've got a controlled source, like an explosion, and you know exactly where it is, that helps us calibrate it. We just put slices through the velocity model, and the low velocities map out the hydrothermal and magma systems compared to colder, higher velocity earth.

YS: So your mapping can show not only the spread of the magma horizontally, but the depth. Does it vary a lot?

RS: Not within the chamber, now, that's the very-near surface. It seems to be normal down to about 50 miles (80 km). That is where magma associated with the real hotspot begins. We do not know if the hotspot magma originates at the core-mantle boundary (at 2,700 km deep) or is the result of decompression melting or rock at much shallower depths of 100 to 200 km deep. Our new experiment should discern that model.

Regardless, magma is generated in the earth's mantle. Part of it leaks through the overlying lithosphere into the crust, melting surrounding rocks and producing a melt that resides in upper crustal magma chambers. This is what feeds Yellowstone's volcanism and enormous heat flow. However, most of the hotspot magma is sheared off on the bottom of the moving plate spreading out to the southwest beneath the Snake River Plain. We imaged that just recently, all the way from southern Idaho to Yellowstone, and it's about 100 km deep.

You asked an important question before: do things change with time? Well, geologists say that they do. I proposed an idea to the USGS volcano hazards group. If you went to an active volcano and magma was moving, as the magma came up it would heat the rocks around it and slow down the velocities of the seismic waves traveling through them, so you could do the tomography in real-time, like a doctor does. As magma ascends it slows down the seismic velocity and creates earthquakes. After the magma passes, the seismicity ceases and the velocity increases as the rock cools. I couldn't do it on hourly scales, but I could do it on daily to monthly intervals and see how the rocks are affected by heat creating different types of earthquakes and changing the rock velocity. I'm talking about an active volcano like Hawaii or some of the Alaskan or the Aleutian ones. Yellowstone would not be so practical because it is just so big and does not have the higher extent of rapidly moving magma. Remember, this technology is brand new. The ideas are brand new. It takes a lot of computing power. It takes modern and reliable real-time data.

YS: Up until now you just mapped it once?

RS: Once. We took one snapshot in time.

YS: But with this new work you hope to do it on repeat intervals?

RS: Right. That's why adding corroborating data from such methods as GPS is so important. GPS tells you how fast the ground is going up and down or sideways, due to magma or hydrothermal fluid migration. This motion must be differentiated from the overall global plate motions to ascertain how fast the ground might be moving as it builds up energy on faults or in its magma chambers. Seismic data also tells you the geometry of the magma body, so you can actually work out the dynamics. Because we map pressures and we can infer from pressures of the magma, we can say how fast it's actually deforming.

We run the Yellowstone seismic and GPS network. It contains 22 seismic stations—18 in Yellowstone and four outside the park along the Hebgen Lake fault, because they are integral to the interaction between the caldera and the fault mechanism. The seismic stations continuously transmit data by radio links via Mt. Washburn, to Sawtelle Peak, and from there on an FAA line to our Salt Lake City recording laboratory. We also employ satellite telemetry from our cooperative university-USGS Lake station that is sent to Golden, Colorado, then on to Salt Lake City via the Internet.

YS: So when you're down there in Utah, and something is happening here in Yellowstone, it instantaneously gives you a picture of what's going on.

RS: Yes. If there's an earthquake, it takes about 10 seconds to calculate the magnitude and location. That is broadcast to me and others via automatic telephone paging systems and sent to our online web site.

YS: I felt the Borah Peak, Idaho, earthquake when I was at Old Faithful in 1983. Why do I recall it took geologists a while to figure out exactly where the epicenter was?

RS: Because we didn't have the fast computers then, nor did we expect such a large quake in central Idaho and did not have an array of seismographs there. We didn't have the data coming in real time. We have no excuse not to do it now.

YS: Is it a triangulation process?

RS: Exactly. It's just surveying with seismic waves. But it's a much tougher problem, because the land surveyor transmits his signals through the air electronically. We have to transmit through this crummy earth. There are fast rocks and slow rocks. The surveyor points his eye at something and he assumes it's along a straight line. In the earth, it bends. We have to calculate all the bends. This new method of tomography allows us to calculate the earthquakes in this very heterogeneous earth.

YS: So, you're down there in Salt Lake City, and there's been an earthquake in Yellowstone, and it is "x" magnitude, and here's the epicenter. What does the GPS network add?

RS: The Yellowstone GPS network is made up of receivers over benchmarks on the ground. They continuously record transit times of radio waves from GPS satellites. It transmits these data back to our lab in the same way as the seismic data. Every thousandth of a second the seismographs are all transmitting data. We sample the GPS every 15 seconds. This type of recording provides an accuracy at the centimeter level.

All these data are dumped into fully dedicated computers that calculate the coordinate of that benchmark on the surface. We compare the coordinates of the point with time to see how fast it is moving. Now, the majority of the earth's motion isn't associated with earthquakes; only about 1 percent or less of the earth's motion is released as the energy in earthquakes. Earthquakes are just the creaking and groaning. But the earth is moving across the hotspot continuously. The rest of the motion, we call *aseismic* motion. It reflects the slowly deforming earth that moves more like silly putty, it is plastic. Plastically it's not going to create earthquakes, but it is what records the slow motions of earth's processes—such as magma movement, bending the rock before an earthquake, or uplifting the ground over magma. We subtract out the amount of movement related to earthquakes and get the total amount of deformation that's due purely to the plasticity, the volcanic mechanism. We can measure both uplift and horizontal movement with GPS to accuracies of millimeters now.

NSF just awarded us a multiple-year collaborative research grant, "Geodynamics of the Yellowstone Hotspot," between the University of Utah and the University of Oregon. The objective is to understand how the Yellowstone hotspot works, how magma gets from hotspot to the surface, and how this effects the topography as well as how it changes the pressure on its faults. To do this, we will conduct a GPS and seismic survey of the whole Yellowstone system. We're going to look at the effects of the hotspot across a broad region from Casper to Boise to Helena to Salt Lake. We're putting in permanent and portable GPS stations. There's a permanent GPS station right over here at the baseball field in Mammoth. They are also at Lake Junction and Old Faithful. And we've installed two in the backcountry in cooperation with the USGS, one in the lower Hayden Valley and one on the Sour Creek Dome. We're going to have about a dozen eventually, just like the seismic network. We will operate this network in continuous recording, just like our seismograph network.

Also in 2000, we're going to bring in about 80 portable seismographs and place them around the Yellowstone hotspot from as far away as 200 miles on a 30-mile grid. Then we will do tomography of the much deeper earth, just like we did it for the crust of Yellowstone, and we will be able to resolve the source and depth of the Yellowstone hotspot.

I feel like I'm just an earth internist doctor who's running his CAT scan—I just do it a little bit slower. We're going to record all the earthquakes, record all the GPS, find out what the structure is to depths of about 1,000 miles. Then we will add in the data on fault movements and information on Yellowstone's magma systems and determine from computer models what to expect on the Earth's surface, and perhaps what to expect in the future. So we'll really be able to define the form of the hotspot. We will use the GPS to measure the ground motion, how fast it's moving over a big region, not just Yellowstone park. Then we will put all these new observations together with Yellowstone volcanic history in a mathematical model and create a mathematical image of the hotspot.

We're going to put in all the faults and let the them rupture at the rate they want to. We're going to let this thing step through time. Probably in an hour of computing we can simulate 10,000 years and let things move according to the rates we see today. We can then try and predict what's happening, where the magma is, how big it is. We're going to try to calculate the magma reservoir sizes, the temperatures. We'll get all the physical characteristics we want out of this body. We're just doing internal medicine. Same thing. That tells us how active it is. The Yellowstone hotspot is a global community—remember it's the biggest one on the continents. It's affected 20 percent of the northwestern U.S. in its 16-million-year history. It's a big feature. It's much bigger than the National Park Service.

YS: Tell your story about Peale Island.

RS: In the summer of 1956, we had fish-research stations at Chipmunk and Grouse creeks. I lived at the cabin on that island in the South Arm of Yellowstone Lake. One incident I remember is that as we ran out of food—we had a few pounds of cheddar cheese and nothing else; we were eating fish and cheese. We were catching about 1,000 fish a day in the fish traps. We were so sick of eating fish. I never wanted to see another one.

I said to my partner, "This is enough. I'm through with this." So we took our little boat over to the shore, then walked west in the melting snow and muddy ground. It must have been in early June. We hiked about 14 miles to Heart Lake. We were really post-holing in the snow. We thought a grizzly bear would chew us up. And we finally worked our way to the road over by Shoshone Lake. Someone picked us up and took us back to Lake. There our boss said, "Here, take some food and get back to work."

I've been back at Peale Island several times since. I went back with Ken Diem [*of the University of Wyoming*] in about 1974, and he said, "Hey, we can't park our boat at the dock." Well, the boat dock was partly under water. And many of the trees around the south shore looked like they were being inundated. I reasoned that the only way to do that is to "tilt the bathtub back." That's why at Fishing Bridge you have this emergent beach all the way over to Storm Point; it's an

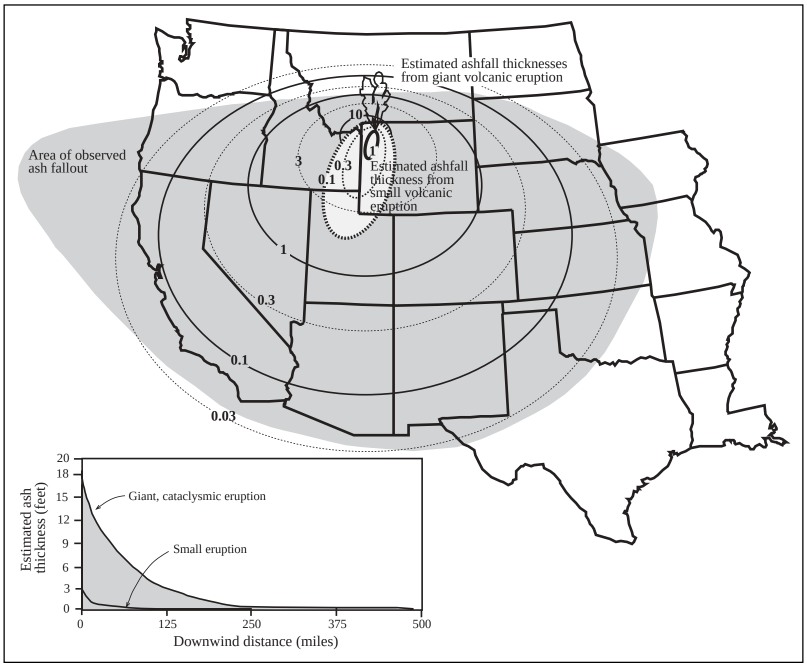

Figure 7. Depths of volcanic ash that could be deposited by future caldera eruptions (gray) and by smaller eruptions (white oval) at Yellowstone. Prevailing winds would determine actual ashfall patterns. Contour lines show ash depths in feet. (Michael Perkins.)

emergent beach in oceanographic terms. It's a beach that's rising because the uplift of the Yellowstone caldera is centered to the north, and that process of uplift and subsidence has no doubt been going on for thousands of years. The net effect is uplift of the Sour Creek Dome and the surrounding area, producing the damming of Lake Yellowstone at Le Hardy rapids.

YS: In the short-term, you don't expect to see the beach disappear and the dock come back up?

RS: No, I do not. That's the other thing about Yellowstone—the caldera is a pimple on the overall deformation of the entire Yellowstone Plateau. The caldera itself is moving up and down, but the whole region up to 300 miles wide has been uplifted 500 meters. The Yellowstone Plateau goes well beyond the boundary of Yellowstone Park—it goes out for 200 kilometers or more; it encompasses the greater Yellowstone ecosystem. That's a whole region of uplifted topography that probably wouldn't be there if the hotspot wasn't there. So you have the broad uplift of the hotspot that's very slow, and it's different from this little pimple that goes up and down.

YS: What is the relative rate of seismicity compared to other places in the country?

RS: Very high. Yellowstone seismicity, including the Hebgen Lake earthquake, is certainly the highest in the Rocky Mountains in historic time. If you calculate the amount of energy per square kilometer, it's higher than anywhere else in the lower 48 states except the San Andreas fault and related faults in California. Certainly within the interior of the continent it has the highest rate of energy use.

YS: And yet, the rate of "felt" earthquakes varies quite a bit from year to year?

RS: It varies, but when it's active there are a lot of felt earthquakes.

YS: How many did we have in 1998, for example?

RS: I think there were 11 or so. But back in 1985, there were 30 or more earthquakes over magnitude 3.5. In 1995, they were being felt pretty routinely. When we had the swarm on July 3rd, I thought, "Wow, July 4th is going to be real fireworks."

YS: In your book you get into questions of emergency preparedness.

RS: We point out the need for preparedness planning in the sense of the awareness of its potential volcanic and earthquake hazards. I have suggested people prepare emergency response plans accordingly.

YS: Is that based on projected trends of an increasing rate of seismicity?

RS: No. We're saying that all the agencies, the Park Service, Forest Service, the surrounding communities, should be aware of potential geologic disasters that can happen in time frames that they're responsible for and should be planning for. Most people in emergency management deal with a 24-hour clock or, at best, about a year ahead, as far as budgets are estimated. But remember, we have had the largest historic earthquake in the Intermountain West, the magnitude 7.5 Hebgen Lake earthquake that killed 28 in 1959. This gives us an idea of what to expect in the future.

FEMA (the Federal Emergency Management Agency) considers both short and long-term effects. The volcanic or the earthquake threat for Yellowstone is very low, in a human time frame. The public has got more important things to worry about, like getting creamed on the road or having the stock market fall. But the agencies ought to take, I think, a much longer-term view, that says we realize there's a much lower probability, but when it does happen it can be catastrophic, beyond things you've even thought about.

YS: This long-term uplift wouldn't necessarily be associated with a greater likelihood of a more serious event?

RS: We just don't know. The Yellowstone deformation field is a situation like that of a blind man coming up to the elephant. He's never seen an elephant before. He touches this thing and he feels it breathing and he says, "What is this? Is it an organism? Is it a tree that's moving?" We (the scientific community) have never seen an eruption or a major earthquake inside of a caldera in historic time. So we cannot say what to expect, but we can wisely estimate its effect by extrapolating observations from other volcanoes and earthquakes and using the geologic record to estimate the rates of occurrence. These data, along with real-time seismic and GPS observations, will provide us with a good working model and ideas of the expectations about precursory earth activity.

When we first discovered the uplift, people said, "Oh, boy, Yellowstone's in uplift and if it keeps uplifting it's gonna blow away." I'm very careful, and I thought, well, we don't know. We saw a 10-year period of uplift, subsidence, and uplift. We've seen a complete cycle of *something*. We don't know what the something is yet.

YS: You've said there was a 0.01 percent chance on an annual basis of either a volcanic eruption or a 7.5 earthquake.

RS: The actual probability is even lower than that. I was calculating the ground motion. People want us to predict things. Well, we can't predict things, we can predict the *effects* of things. And the effect of things that is most easy to predict is how the ground is going to move. So I predict the ground motion by predicting the acceleration of the ground. I can't predict when the fault's going to go off. But I can predict that *if* the fault goes off it's going to shake the ground over here a certain amount. Volcano prediction here is so far in its infancy no one knows what to predict. If you look at Hawaii, you can see that preceding so many eruptions the ground was slowly moving. There they have nice, runny basalts. And they have a lot of seismographs. They can actually see the earthquakes coming up with the magma and the ground rising. When the seismologists see anything unusual or starting to change, they radio the scientists working in the field to get them out. And they get people out. You can't do that in a rhyolite system because the motion is far too slow.

YS: In terms of emergency preparedness, then, you can't really tell us what's going to happen.

RS: We can tell you what will probably happen in a time frame of, at best, days, but mostly in months to years. We can give you a deterministic view—a scenario of the worst thing to expect.

YS: And how soon in advance of an event do you think you could do that?

RS: Oh, I could give you a scenario today—here's what could happen with a big eruption, a little eruption, and a tiny eruption. And I could say, "Give these ideas to the emergency management folks and plan around these scenarios." I ask the questions such as: Do you have built-in road escape? What about when something happens in the middle of Yellowstone and all the roads/canyons are closed? How likely are accompanying landslides? How vulnerable are medical facilities? Are outside groups prepared to assist? What are you going to do with 30,000 people on Sunday night during a busy summer season?

YS: When you say a "tiny" eruption, you're not really talking little, are you?

RS: I'm talking the size of a Mt. St. Helens eruption at the smallest, to maybe an eruption 1,000 times bigger. Or perhaps it may be a phreatic or a pure steam eruption. These do not have magma; phreatic eruptions are hot water and steam eruptions that, for example, blew out Mary Bay and Indian Pond on the north side of Yellowstone Lake.

YS: If we were to have even one of those little eruptions, would we have notice in terms of hours? Weeks? Years?

RS: I think we'd have notice in terms of weeks, if they're rhyolite. Perhaps shorter for basalt or phreatic eruptions, with a context of a modern seismic array, modern GPS, and bringing in the geochemists who can study the chemistry of the fluids. The USGS was doing chemical monitoring here, and they stopped it because of budget cuts. But a combination of monitoring would probably give you reasonable lead-time, on the order of days, weeks, months, because these things are slow. They're big; they're catastrophic in the sense that they're this gooey stuff. They build up so much pressure that when they finally go they're really explosive.

YS: If it were one of the big ones, wouldn't the scale of it be so large that one could argue that you couldn't be prepared anyway? You'd have to evacuate the entire western U.S. It's the end of the world as we know it (Figure 7).

RS: You're right. If it was a catastrophic caldera-forming eruption, yeah, like, who cares? Well, it would certainly create a globally significant change. You'd have pyroclastic flows from the volcanic vents destroying and cooking everything in their way for tens of miles from the volcano. In the surrounding area, you'd have 10 to 20 feet of ashfall that could decrease in thickness but could extend for hundreds of miles. What do you do with 10 feet of snow? Imagine turning it into ash—it ain't going to melt!

YS: Even in Salt Lake you'd get a foot of ash.

RS: A foot. Imagine a foot down in those clogged freeways.

YS: Why won't any of you even speculate on the next giant earthquake or volcanic eruption?

RS: Because we don't have a basis for their understanding yet. This whole science is so new, remember I'm the blind man coming up to the elephant. I finally figured out that the elephant is alive. I've kind of got its dimensions. I walked from one side to the other. And I've probably figured out it's an elephant. But I don't know if it's standing up ready to fall on me, or if it's laying down breathing, or if it's a rogue or what. I don't know if it's trained or if it's wild. So, we're just learning. Yellowstone and rhyolitic volcanism and the relationship to big earthquakes are so unique that we don't have a basis of experience to build on.

YS: Someday, when the hotspot is under Billings or wherever, Red Lodge, what's Yellowstone going to look like then?

RS: I would guess first it'll look like Island Park: lower elevation, much less hydrothermal activity, no geysers. It'll die away. Then it'll look like Ashton, Idaho. Then you'll start growing potatoes on it! See how the topography of the Snake River Plain falls away to the southwest? The hotspot has raised the ground up here; it's moving north, but behind it the land is collapsing in, creating a lower elevation and a depression. That fills in with basalts. And the basalts then produce the soils and the soils produce potatoes.

YS: Where do the basalts come from?

RS: The basalts are derived from the hotspot. They are the last thing that comes out of it. They're going to be more like Hawaii eruptions. They'll be exciting and they'll be on television, but they're not going to kill a lot of people.

YS: We don't have to quite worry about moving the Old Faithful Visitor Center yet.

RS: No, it'll move itself eventually. You've got to get a new one anyway.