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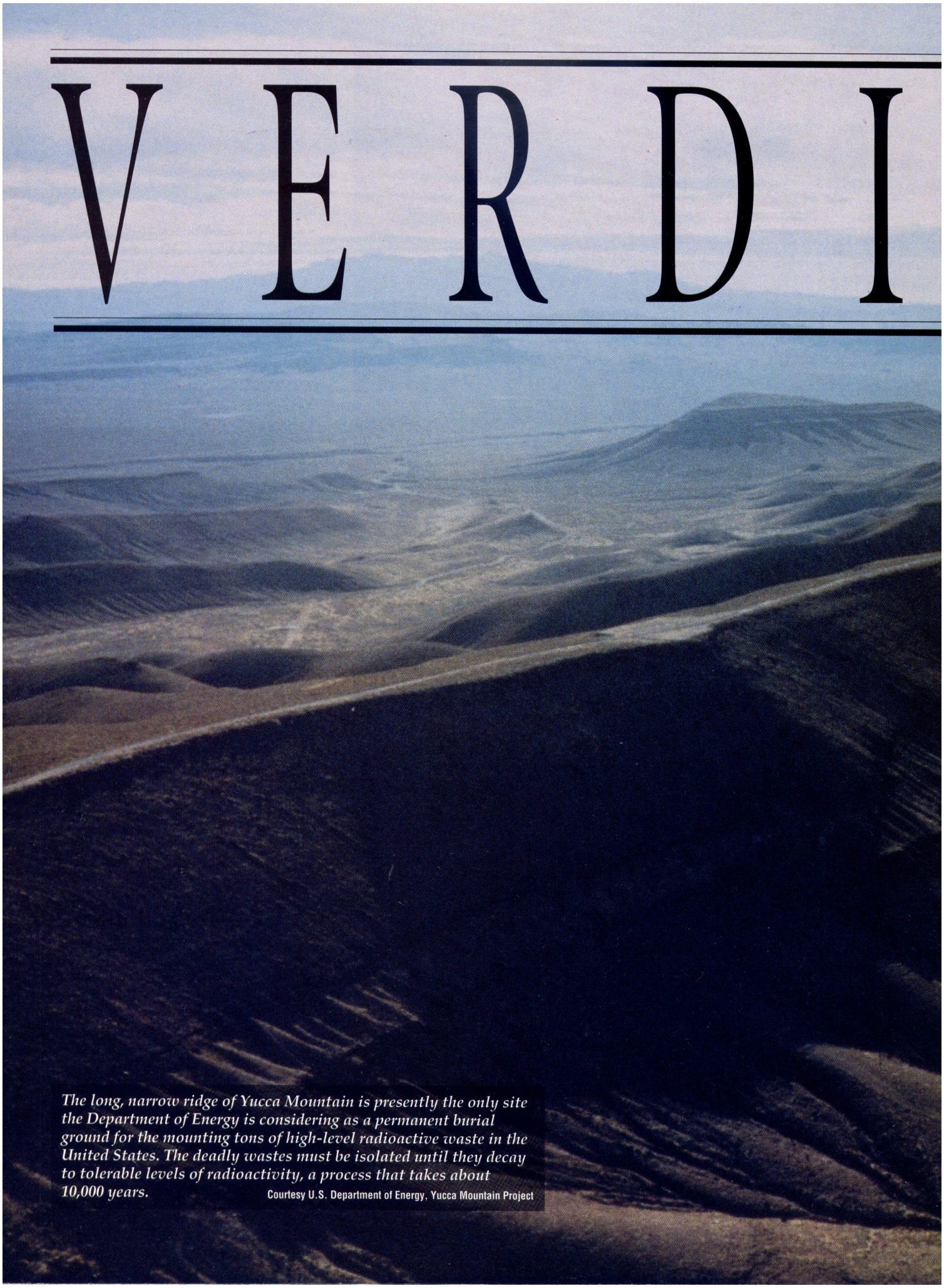
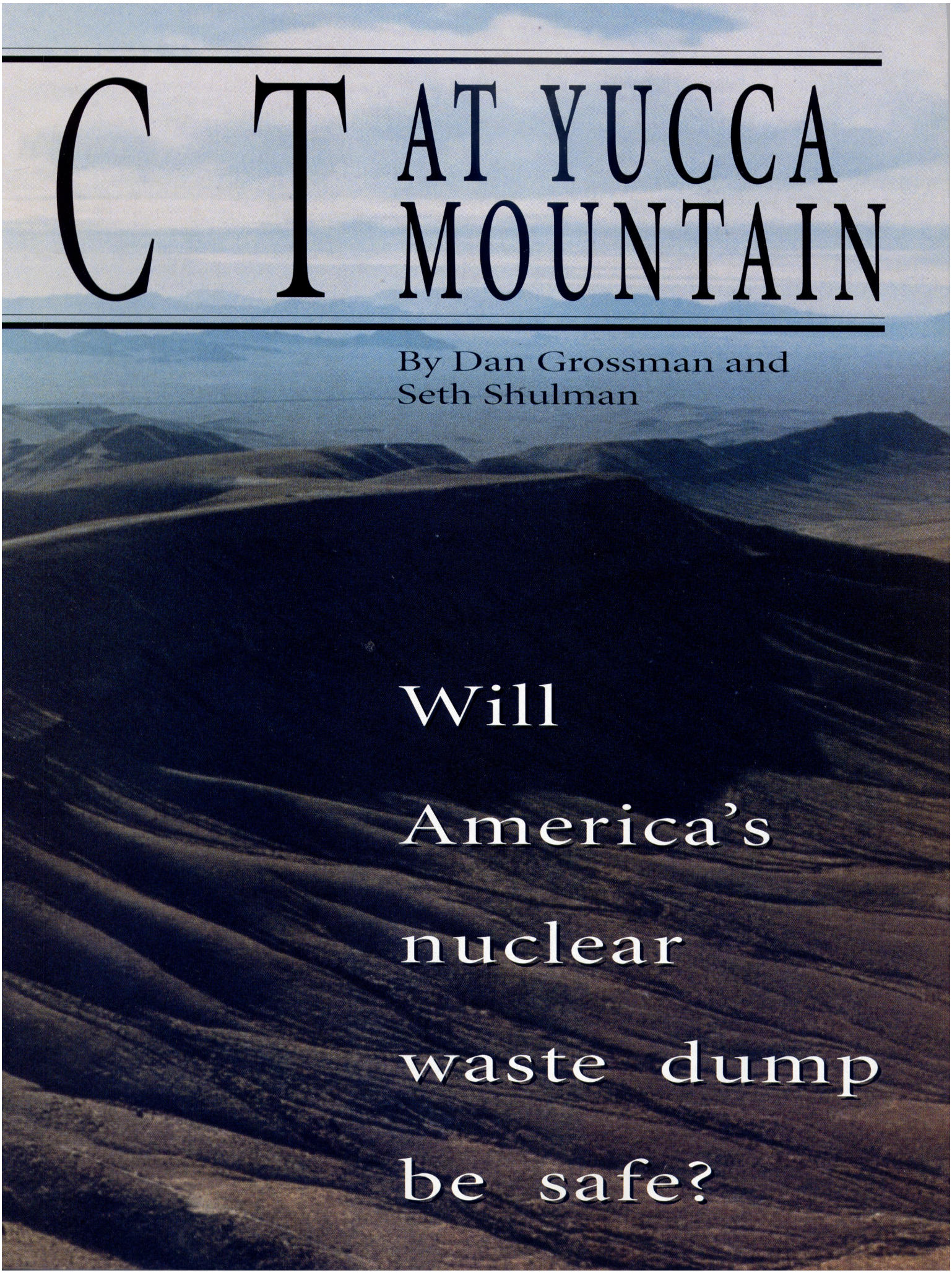


The long, narrow ridge of Yucca Mountain is presently the only site the Department of Energy is considering as a permanent burial ground for the mounting tons of high-level radioactive waste in the United States. The deadly wastes must be isolated until they decay to tolerable levels of radioactivity, a process that takes about 10,000 years.

Courtesy U.S. Department of Energy, Yucca Mountain Project


C T AT YUCCA MOUNTAIN
By Dan Grossman and Seth Shulman
Will America's nuclear waste dump be safe?

David Merritt squints in the desert sun at a remote site 100 miles north of Las Vegas. Before him is a windowless, corrugated steel building that houses one of the nation's most unusual lending libraries. Merritt, who oversees the collection, says demand is heavy — so heavy that researchers "fight for access" to the holdings contained here. The library, also known as the Sample Management Facility, is home to the U.S. Department of Energy's vast collection of rock core samples taken from a nearby mountain. It is also among the world's largest assemblages of rock specimens from a single geographic area.

More than 40,000 feet of carefully catalogued rock cores have been deposited here so far, shelved in boxes stacked 14 feet high from floor to ceiling. Roughly a decade from now, the Energy Department plans to use these samples, and thousands more, to prove that the high-level radioactive waste from the nation's civilian nuclear reactors can be safely stored in a repository carved into the bowels of Yucca Mountain, a barren ridge 8.5 miles to the south. As Merritt explains, the rock samples hold the proof of the repository's viability. It is imperative, he says, "that everything here be documented" and that these core samples be handled "in accordance with the rules of legal evidence."

Finding a site for the nation's only high-level radioactive waste repository is no simple task. Before the department can begin to fill Yucca Mountain with nuclear waste, it must prove that the deadly residues will stay put in the mountain's volcanic rock — and not somehow leak out into the environment — for at least 10,000 years. To establish this, the agency has assembled one of the largest teams of geologists in history to perform the most complete study ever conducted of any rock body.

The Energy Department has spent $1.3 billion on the project since 1986, when Congress chose Yucca Mountain as the single candidate to hold the mounting tons of civilian nuclear waste. More than 1,400 employees, including 700 scientists and engineers, currently contribute to the effort. Many of these researchers perform experiments on specimens they "check out" of Merritt's core sample library. By the time the study phase is done, sometime after the year 2001, the total cost of determining the mountain's suitability is expected to top $6 billion — just a fraction of the amount that will be required to actually build the repository.

But despite the massive investment in dollars and scientific brain power, critics say the Energy Department is not studying Yucca Mountain's suitability at all dispassionately. Rather, they argue, it is building a legal case to ensure that the repository is located here, no matter how severe the site's defects. "It's not a scientific research program," charges Steve Frishman, a geologist working for the state of Nevada, "but a political disposal program."

The department's approach reflects the tortuous history of the nuclear waste disposal program. Congress originally instructed the agency to scour the entire nation for possible disposal sites. The most likely candidates were to be thoroughly studied, or "characterized," and the best two chosen. But when activists in dozens of states rose up in opposition to the search in 1986, Congress issued new instructions: The department should characterize only a single site — Yucca Mountain. Nevadans still routinely refer to this decision as the "Screw Nevada Bill," calling it a political choice that is being shoved down the throats of people in a state with one of the smallest congressional delegations in Washington. (According to the latest poll, 71 percent of the state's residents oppose the construction of the Yucca Mountain repository.)

Senator Richard Bryan (D-Nev.) spoke for the majority when he declared that "a feeding frenzy," of 49 states "ganged up" on Nevada to put all the nation's "nuclear eggs in one basket." Although the bill passed, many members of Congress realized that they had placed the Energy Department's repository program in a precarious position. If Yucca Mountain is found defective, the agency will be forced to start from scratch to find a home for the nuclear waste. Representative Edward Markey

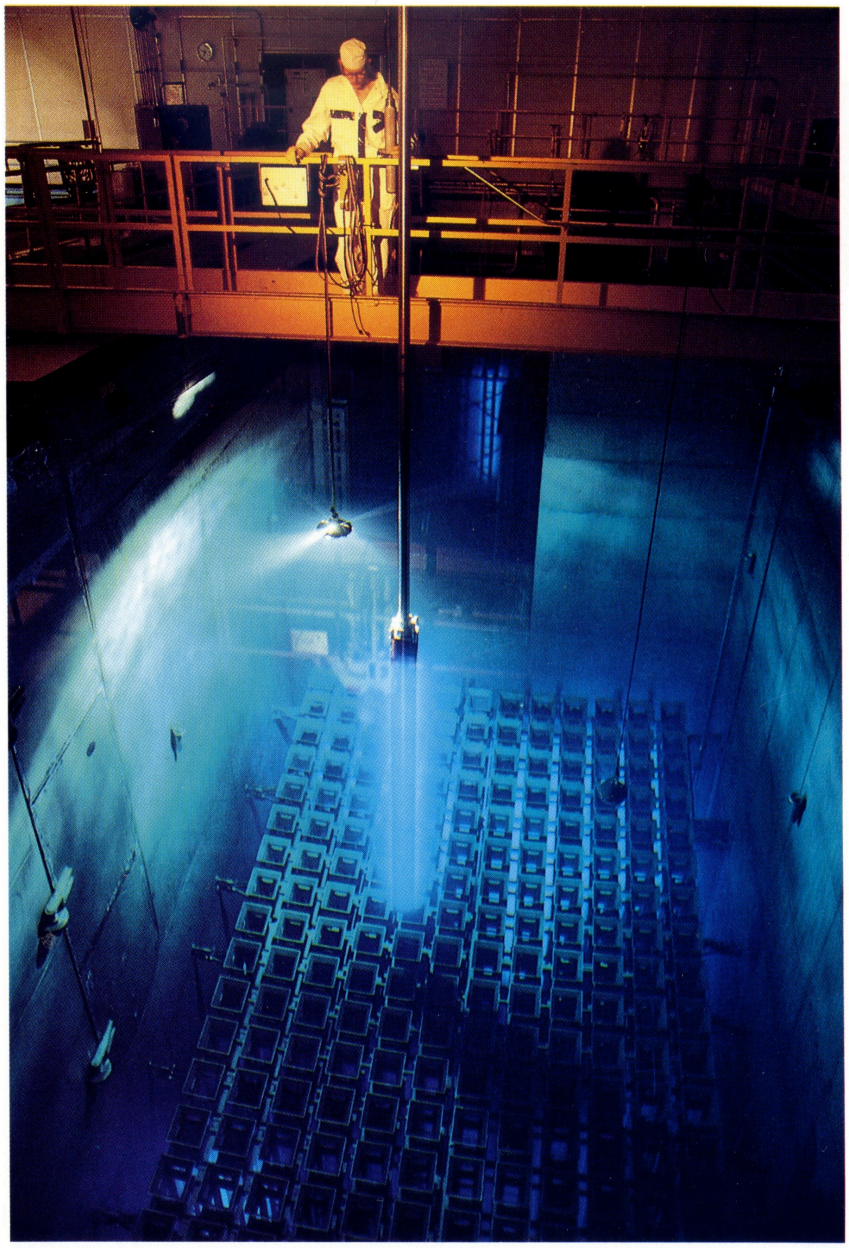
Courtesy U.S. Department of Energy, Yucca Mountain Project

This warehouse, called the Sample Management Facility, contains more than 40,000 feet of rock cores removed from Yucca Mountain — a number that is ultimately expected to double. The Department of Energy handles the samples with meticulous care, expecting to use them in court to prove the waste dump's safety.

(D-Mass.) warned his colleagues of this threat during the House debate over the plan: "As Nevada goes, so goes our nation's nuclear waste policy."

The state government, incensed about Nevada's being singled out for the repository, has already confronted the Energy Department twice in federal court, stalling environmental permits required to conduct research for three years so far. No matter what the results of the agency's research, the state is certain to challenge the plan again. Ultimately, Yucca Mountain's fate will be decided in court. Anticipating the bitter legal struggle sure to follow the characterization study, the department is taking procedural precautions that make its research appear more like briefings for the defense than data for a scientific paper.

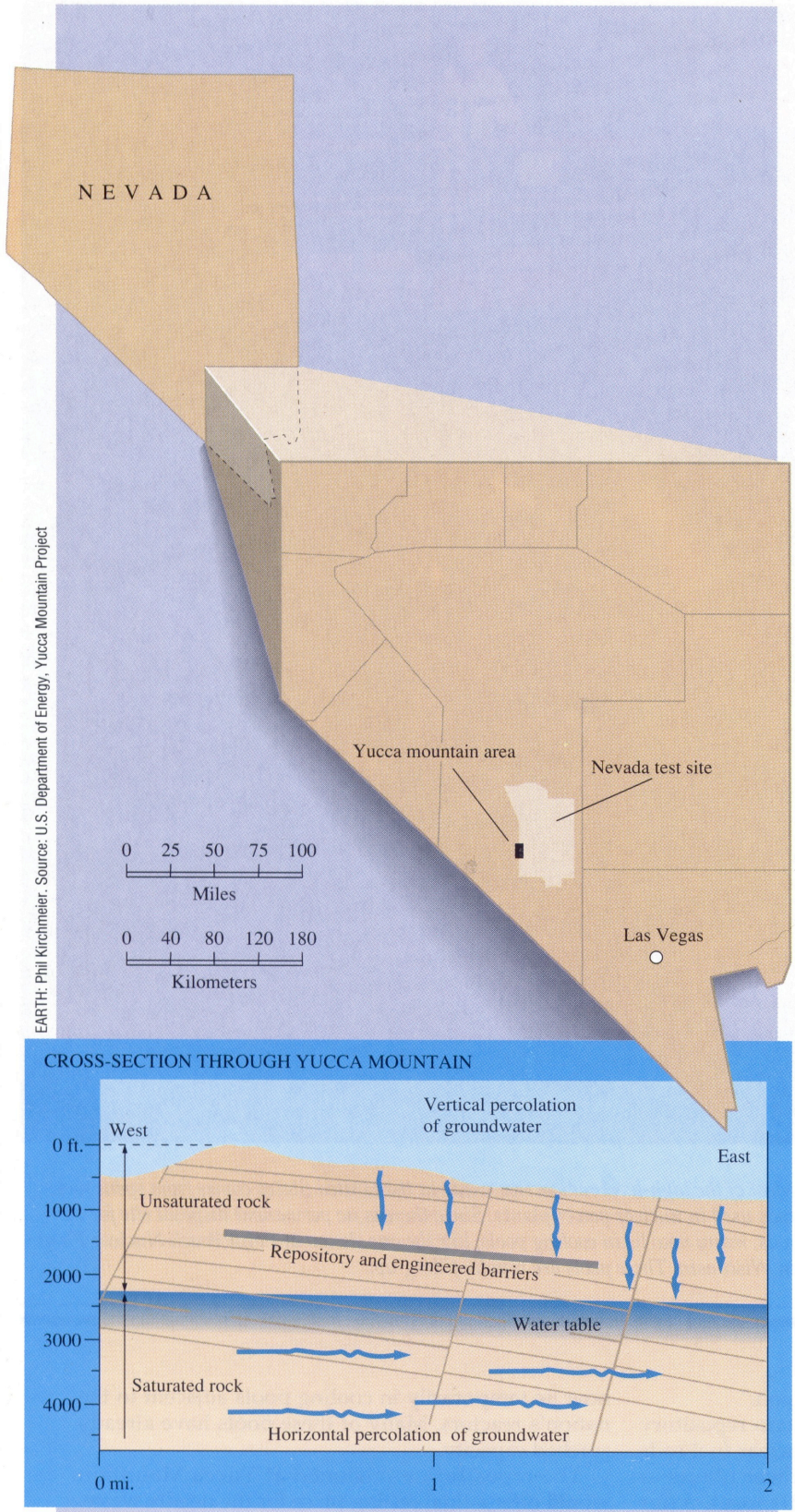
Legal language abounds among the staff of the Energy Department's Office of Civilian Radioactive Waste, which is in charge of the repository program. "We don't have to prove [that the repository is safe] 'without a shadow of a doubt,'" says staff geologist Thomas Bjerstedt. "We need only prove with 'reasonable assurance.'" Nowhere, however, is the agency's preparation for litigation more obvious than at the Sample Management Facility. The core samples here are stored in cardboard boxes, each holding three yard-long sections. Each section is labeled with a bar-code tag and marked with blue and red stripes to prevent the original alignment from being mixed up, and many are packed in plastic bags to prevent any moisture from evaporating. The department treats the rocks with the same care the police might give to sensitive evidence in a criminal case. Each is handled, Bjerstedt says, "just like a murder weapon."



Most of the high-level radioactive waste in the United States comes from spent fuel rods used in nuclear power plants. Since there is no permanent disposal site for the rods, many now lie in cooling pools, like the one shown at Point Beach Nuclear Plant in Wisconsin. These pools are rapidly filling up.

The demand for the Yucca Mountain repository stems from the highly radioactive nuclear fuel rods used in the nation's 109 nuclear power plants — some 22,500 tons of which await disposal. After three to four years in a reactor, the rods can no longer sustain a strong nuclear reaction. Yet by that time, they've become among the most radioactive objects on Earth. Since the United States has never built a permanent disposal repository, spent rods from the 40-year history of civilian nuclear power now lie temporarily in cooling pools adjacent to the nation's reactors. Many of these pools have already reached capacity.

The repository envisioned at Yucca Mountain would offer a final resting place for the deadly waste. The plan calls for a 1,500-acre honeycomb hollowed from the mountain, with more than a hundred miles of tunnels — a network that rivals in size the world's largest subway systems. Altogether, the tunnels would accommodate as much as 70,000 tons of high-level nuclear waste. The waste would enter the



EARTH: Phil Kirchmeier. Source: U.S. Department of Energy, Yucca Mountain Project

The proposed repository for nuclear wastes would be a maze of tunnels deep underground, but above the water table, in the volcanic tuff that makes up Yucca Mountain. The repository must be kept as dry as possible to prevent leakage and contamination of groundwater.

facility sheathed in specially built steel containers that are expected to corrode in a century or so. After that, the volcanic rock called tuff that makes up Yucca Mountain would be responsible for containing the radioactive material. The tuff would have to seal the waste off from the environment for the many millenia during which it could pose a serious hazard to human health and the environment.

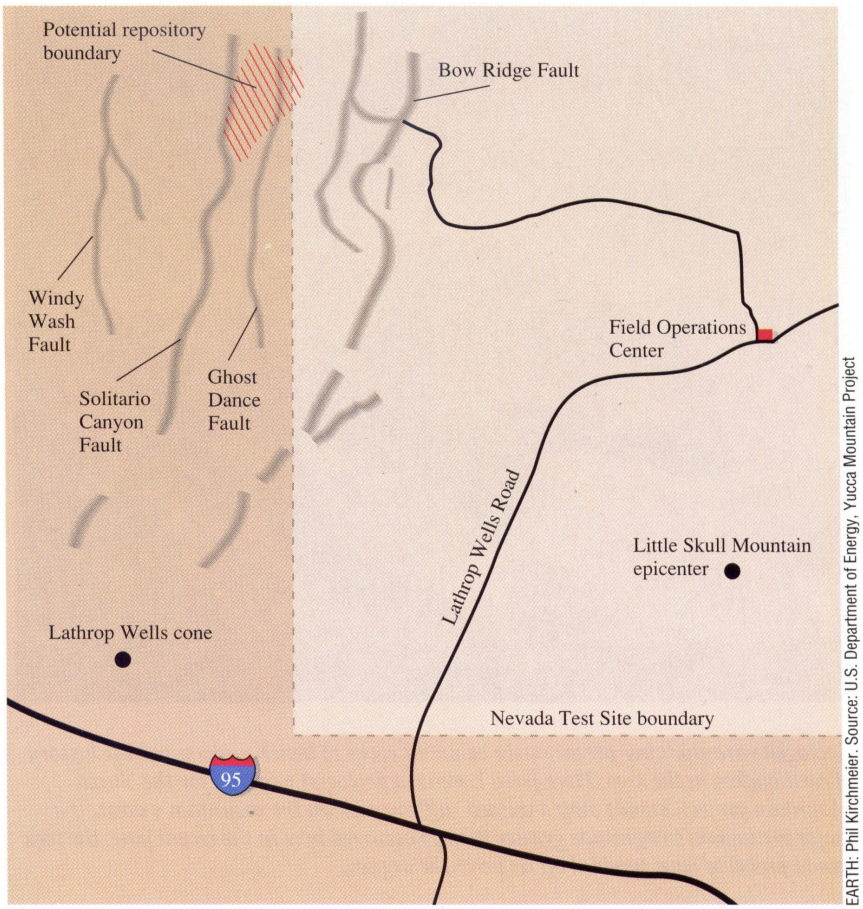
Assuring geological stability for 10,000 years is a staggering task — if it is possible at all. Researchers must resolve questions like the following: Will the waste seep into the water table or escape into the atmosphere? What are the odds of a disastrous earthquake or volcanic eruption? How might the weather change over the next 100 years? None of these questions have yet been answered conclusively. And some may never be.

Before the Department of Energy applies for a license from the Nuclear Regulatory Commission to construct a repository, the Radioactive Waste Office will conduct at least seven more years of study at a cost of approximately $5 billion, Bjerstedt explains. The research plan alone, called the Site Characterization Plan, fills nine volumes crammed on a shelf three feet long. Much of the research concerns three major hazards, each of which could conceivably release waste into the environment: volcanoes, earthquakes and groundwater.

At first glance, it seems almost laughable even to consider storing deadly material in Yucca Mountain. After all, the area is riddled with earthquake faults and has seen volcanic activity in recent history. Nevertheless, Bjerstedt and other agency officials emphasize that research has already shown Yucca Mountain to be at least a good candidate for the nuclear dump. He ticks off the location's positive features with practiced alacrity: The area is remote, it receives little rainfall, and the water table is very deep. No less important, the land is already owned by the government. "The site," he concludes, "is not a dog."

To underscore the point, Bjerstedt leads us on a marathon tour of the Energy Department's research efforts, from the base to the summit of Yucca Mountain. The Nevada sun is relentless, but Bjerstedt has come prepared, wearing a white baseball cap and a knit short-sleeved shirt. As the government van makes its way, coating the hardy roadside creosote and sage bushes with a fine layer of dust, he rebuts one possible objection to the site after another.

Earthquakes are an obvious source of concern, Bjerstedt explains, flipping through a half dozen maps of seismic activity in the region. As his charts show, the area is quite active seismically. Between 1852 and 1991, there have been 27 quakes with a magnitude greater than three within 25 miles of Yucca Mountain. And one large enough to damage office buildings occurred in 1992. According to James Brune, director of the Seismological Laboratory at the University of Nevada, more than a dozen faults or fractures capable of triggering a moderate quake lie within 30 miles of Yucca Mountain. The Solitario Canyon Fault skirts the base of Yucca Mountain, while the Ghost Dance Fault actually passes through the mountain — right through the site envisioned for the repository, in fact. But according to Bjerstedt, earthquakes pose little threat to the underground repository itself, only to the surface buildings used to prepare waste for burial.



Geologists must determine whether earthquakes, which are common in the Yucca Mountain region, pose a serious threat to the safety of the repository. Shown here are seismic faults located closest to the mountain. The Ghost Dance Fault runs right through the repository site. The most recent quake, marked on the map with a star, occurred in 1992 at Little Skull Mountain, 12 miles from the proposed dump site.

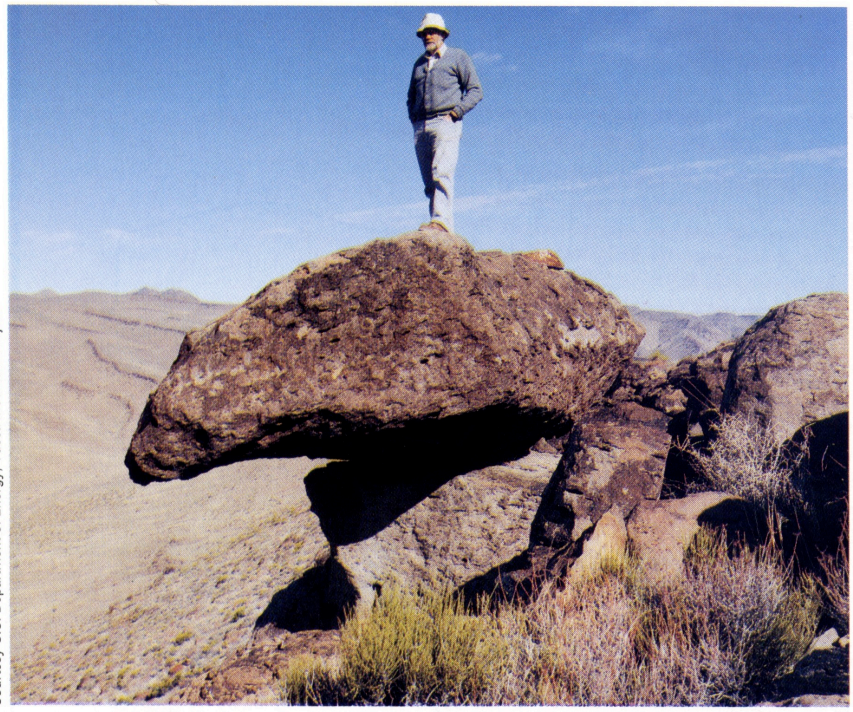
As he explains it, the disruptive movement of an earthquake confines itself to the surface; its "pitching and rolling" does not extend underground. Unless a fault slips within the repository itself, disrupting waste canisters and creating passageways for water to percolate down from the surface, he says, the only concern is that surface buildings will be damaged during the 100 or so years they will be used for handling waste. After that, when the repository is full, all surface structures will be dismantled.

The Ghost Dance Fault, which bisects the repository, has not been active for 2 million years and so is unlikely to slip in the next 10,000, Bjerstedt says. For safety's sake, though, the Energy Department now plans to locate the repository's waste canisters away from the fault line itself.

But geologists at the U.S. Geological Survey recently concluded that the Ghost Dance Fault is actually a much more complicated geological feature than originally thought, requiring elaborate and time-consuming research. The USGS team found that there was, in fact, no single fault, but a wide fault *zone*. Over millions of years, the ground has slipped in numerous places within this zone. In a report released last May, the General Accounting Office (an independent watchdog organization created by Congress) said this discovery could threaten the "suitability of the site."

Since the Energy Department now considers earthquake damage to the repository itself to be unlikely, seismological research at Yucca Mountain is focusing on events in the next 100 years that could disrupt the surface buildings in which waste shipments will be unloaded and packaged. These buildings, Bjerstedt says, will be designed to withstand whatever degree of seismic activity researchers discover.

Brune is conducting one such study. He has made an inventory of boulders on the peak's slopes that appear "precariously balanced" or just about ready to topple over. Brune contends that he can determine how long a precarious rock has been in its unstable position by sampling rock varnish, a dark coating that



Courtesy U.S. Department of Energy, Yucca Mountain Project

Geologists are studying precariously balanced rocks to better understand the history of earthquakes in the area. Here Jerry Lorenz, a geologist working for the Yucca Mountain project, stands atop a welded tuff cap rock on the mountain's crest. If a major earthquake (magnitude greater than 7) occurred here in the recent past, the rock would probably have tumbled off its perch, he argues.

collects on rock surfaces exposed to air. Then he estimates how much motion would topple the boulder. Sometimes he actually knocks rocks over to test his calculations. Brune says that his measurements prove that "there hasn't been a large earthquake in the area for thousands of years." But according to state geologist Frishman, Brune's methods have not been validated, calling into question the accuracy of his results. "I'd call it a precarious dating method," he says.

The tour's first stop is the headquarters for field work. This unprepossessing two-story office building takes some of the shine off Bjerstedt's cheerful enthusiasm. In June 1992, the largest earthquake to strike the region in over 100 years occurred at Little Skull Mountain, just 12 miles from Yucca Mountain. The tremor, measuring magnitude 5.6, shattered glass, cracked plaster and dislodged concrete blocks, causing more than $250,000 in damage to this building. A team of USGS seismologists concluded last summer that the Skull Mountain quake was actually triggered by another earthquake that occurred the day before in Landers, Calif., 144 miles away. According to Paul Reasenberg, one of the USGS researchers, the Landers quake affected the timing of the Skull Mountain quake but not the size. Movements along earthquake faults are bound to happen sometime, but distant events may suddenly trigger them. "Nothing happened that wasn't going to happen anyway," he says.

Frishman, however, is troubled by the possible consequences if a large earthquake damages the surface complex. Because earthquake survival can't be tested in advance, there's no guarantee that highly toxic material won't escape into the environment, he argues. "They can't demonstrate that disruption will not happen," he says.

Yucca Mountain is a long, narrow ridge buttressed by several perpendicular spurs. In spring, the slope is faintly green, but the summit betrays hints of purple rock varnish. Our van begins a long, slow ascent. "If you were here 1.4 million years ago, it would have looked the same," Bjerstedt says. When we reach the summit, however, a startlingly youthful geological feature comes into view: the Lathrop Wells Volcano, a perfectly symmetrical, diminutive cone rising alongside Crater Flat, the plain beyond the mountain's base. Lathrop Wells, located just 11 miles south of the Yucca Mountain crest, is one of seven small cones that have erupted in recent times. In fact, this particular volcano may have erupted three times in the last 100,000 years, most recently just 10,000 years ago.

Such cones, known as a Strombolian volcanos or cinder cones, do not erupt explosively as Mount St. Helens did. Instead, a fountain of lava cools to cinders that build up to form a cone. Because of their relatively peaceful birth and small size (Lathrop Wells is less than 300 feet high and a half-mile across), cinder cones do not threaten the Yucca Mountain repository, even if they erupt nearby, Bjerstedt argues. "Little eruptions," he says, "are very benign."

Yucca Mountain itself was actually formed by a much more violent series of eruptions from four giant calderas 12 million to 15 million years ago. These explosive events released hundreds of cubic miles of ash, leaving a 6,000-foot-thick deposit at Yucca Mountain. In time, as fallen ash was crushed under the weight of successive layers, the deposits were packed into hard volcanic tuff. Bruce Crowe, the Radioactive Waste Office's chief volcanologist, says that the chance of another explosive eruption — like those that created Yucca Mountain — is exceedingly small. The most recent such event in the vicinity occurred 8.5 million years ago, and Black Mountain Caldera, the volcano that caused it, is long extinct.

Of more concern to Crowe is whether a new Strombolian volcano will erupt within Yucca Mountain itself. His geological team is trying determine

how and why such volcanoes form. Crowe's research so far indicates that Strombolian volcanoes do not erupt in a single location only once — but actually erupt many times. This, he says, suggests that the next eruption in the region is more likely to be a reactivation of the existing Lathrop Wells cone than an eruption from a new volcano elsewhere in the region. In a recent study he estimated the probability that a new Strombolian cone would erupt right in Yucca Mountain, threatening to melt and eject the deadly waste from its underground crypt. Even making the assumption (which he terms "conservative") that the probability of an eruption is evenly distributed throughout the region, Crowe calculates that there is a one in 500 million chance per year that such an event will occur. "We feel very comfortable with that," Bjerstedt says of the figure.

Frishman, however, scoffs at these estimates. And he argues that there are many ways that a volcano could disrupt a repository without erupting right in the mountain. A nearby eruption could alter the water table, for instance. Such possibilities will ultimately be investigated by the Energy Department's Waste Office, but Frishman accuses researchers there of calculating the least likely events first for the purposes of public relations.

At midday, we finally arrive at Trench 14, perhaps the single most controversial source of samples in the entire site. A rectangular ditch hollowed into Yucca Mountain's eastern slope, Trench 14 is 120 yards long and just wide enough to accommodate a large bulldozer. As Bjerstedt explains, the excavation that began here across the Bow Ridge Fault nearly eight years ago uncovered mineral deposits that have been a source of acrimony ever since. The cream-colored deposits — filling thick, deep-running veins that stand out against the sandy, brown tuff — are made up primarily of a fine, grainy material called calcium carbonate, or calcite.

When the deposits were first discovered, one member of the USGS described them as travertine. Formed when calcium carbonate precipitates out of

The small, symmetrical Lathrop Wells Volcano, located just 11 miles from the proposed nuclear waste repository at Yucca Mountain, is one of several volcanoes in the area that have erupted in the geologically recent past — most recently 10,000 years ago.

Courtesy U.S. Department of Energy, Yucca Mountain Project

groundwater, travertine is the type of limestone that makes up stalactites and stalagmites in caves. Upon hearing about the deposits in 1984, Jerry Szymanski, then a geologist employed by the Energy Department, grew concerned that they might be a sign that groundwater had once risen up to the mountain's surface. After viewing the deposits himself, Szymanski says, he became convinced: The calcite veins represented the residue of large amounts of groundwater that had risen dramatically hundreds of feet to the surface, right through the proposed repository site.

Szymanski's theory, detailed in a 900-page report, postulates that Yucca Mountain's deep water table (at least 1,500 feet below the summit surface) is far less stable than most researchers presume. Cyclical changes in geological activity, he believes, have altered the size of tiny pores in the rock, forcing the aquifer up as much as 1,000 feet. He also fears that the water table could surge again. The "upwelling" theory, as it has come to be known, poses a mortal threat to the entire project. If Szymanski is right, a repository located in Yucca Mountain could experience a cataclysmic failure.

Water is a serious concern in any nuclear waste repository. Significant amounts of rainwater percolating down or groundwater rising up through the rock could hasten the corrosion of the canisters designed to contain the waste initially. Furthermore, over the centuries, water could dissolve the waste itself, and the resulting toxic brew could seep into the water table. One of Yucca Mountain's most attractive features, in fact, is the notable depth of its water table. The repository is designed to sit hundreds of feet above the aquifer, but still deep underground. Yucca Mountain is also very dry: It is located just 40 miles from Death Valley, the driest place in North America, and receives only three to six inches of rain each year.

So far, the evidence to support Szymanski's upwelling hypothesis appears equivocal at best. Although fluctuating water tables have been documented elsewhere, nowhere in the world has the dramatic shift postulated by Szymanski been proven. Nevertheless, due in part to his tenacity and in part to the explosive consequences if he is right, the upwelling theory has sparked many years of intense debate.

Most recently, a team from the National Academy of Sciences was called upon to assess Szymanski's theory. Their lengthy report ultimately dismisses it as a red herring. The team concluded that the Trench 14 deposits were formed by rain falling from above, not by groundwater rising from below. Nevertheless, many puzzles remain unexplained.

The academy panel, for example, cites the tapering V-shape of the deep veins as evidence that they were filled over millenia by dust borne from the surface by rainwater — in quantities too minute to endanger the repository. When we enter Trench 14, the observation appeared at first to be accurate: A vein on the right side tapers visibly as it approaches the bottom. Just a few feet away on the opposite side, however, the deposits are thicker (as much as three feet across) and show no signs of tapering at all. Faced with conflicting evidence such as this, it is hard to discount Szymanski.

To support their assertion that the formation was caused by water that was falling, not rising, academy scientists point out that the calcite deposits are fine-grained, similar to formations elsewhere created by falling rain. Sediments deposited by upwelling water, the report states, usually exhibit a notably coarser texture. Szymanski does not deny the panel's observation, but notes instead that the calcite deposits have a granular, "uncemented" quality consistent with formations caused elsewhere by upwelling.

Szymanski remains unshaken in his belief that Yucca Mountain is an unsuitable location for the repository. And he is not alone. The state of Nevada has now hired both Szymanski and a former colleague from the Radioactive Waste Office, Donald Livingston, to continue reviewing the data, bolstering the state's case against the site. Livingston, a veteran geochemist, resigned from the Energy Department in 1992 — not long after Szymanski resigned — when he became convinced that the upwelling

Courtesy Department of Energy, Yucca Mountain Project

The cream-colored veins of calcite at Trench 14 have long been a source of bitter controversy. At issue is whether the veins were deposited by rainwater or by the upwelling of groundwater. Upwelling groundwater could spell disaster, possibly causing the wastes to leak out into the environment.

Courtesy U.S. Department of Energy, Yucca Mountain Project

An opening cut into the mountain will lead to the Exploratory Studies Facility, an underground laboratory where geologists will conduct experiments to determine the mountain's stability. If the site is deemed safe, this tunnel will serve as the entrance to the repository.

theory was being brushed off by the agency.

As far as Bjerstedt is concerned, Szymanski's theory has already been "reviewed to death." And to be sure, Yucca Mountain's critics seem at times to be grasping at straws. But as Livingston points out, the deposits in Trench 14 are hard to explain by rainwater: "To say that veins of calcium carbonate [that run] a half kilometer deep are formed by rain is just about the wildest thing I've ever heard." He argues that the upwelling theory must be given "equal footing."

The van pulls up to a large clearing at the end of the twisting gravel road at the base of Yucca mountain. We see construction workers clad in heavy boots and colorful hard hats clustered around a huge semicircular gouge cut into the shoulder of the mountain. When complete, this opening will be the entrance to 14 miles of tunnels — the Exploratory Studies Facility — where the agency will conduct dozens of tests over the course of the next decade. Scientists will use these deep caverns as an underground laboratory where they can scrutinize the various deposits that make up the mountain. They will experiment with mining techniques, measure the flow of water, and observe how the rock behaves when loaded with hot canisters (heated electrically to mimic the characteristic warmth of containers of nuclear waste). Numerous samples of rock, cut from the underground chambers, will be deposited in the vast, meticulously curated lending library of the Sample Management Facility. Once these studies are complete, should the Energy Department's research pan out, this same tunnel will serve as the entrance to the actual repository.

Is the department really examining the suitability of the Yucca Mountain with an open mind? Bjerstedt and his colleagues insist that they are determining whether the bowels of Yucca Mountain can safely sequester the most hazardous materials ever produced by an industrial society. But Livingston and other skeptics believe that the agency has already made up its mind that Yucca Mountain is safe and is now simply trying to build an unassailable legal case, stone by stone, to shield them from the opposition. "People in the program know what answer they're looking for," he says. "Given what is at stake — that's unacceptable." ⊕

Dan Grossman and Seth Shulman write about science, technology and the environment for a variety of national magazines.