# Appendix A4

***"Deep Science – A Deep Underground Science and Engineering Initiative"*, 12 October 2006 (48 pages)**

**http://www.dusel.org/DUSEL_101706.pdf**

# DEEP SCIENCE

## A DEEP UNDERGROUND SCIENCE AND ENGINEERING INITIATIVE

# DEEP SCIENCE

As the miner's headlamp casts light on subterranean darkness, research in deep underground laboratories illuminates many of the most compelling questions in 21st century science. Sheltered by the earth's crust from the background commotion of cosmic rays and human activity, exquisitely sensitive particle physics and astrophysics experiments search for the subtle but unmistakable signatures of a revolutionary new physics of the universe. Biologists probe the secrets of microbial life at extreme depths, in hot, harsh environments sequestered for millennia from the earth's surface. Geoscientists and engineers research the behavior of subsurface rock, minerals, water and energy sources.

A national Deep Science Initiative, structured around a new Deep Underground Science and Engineering Laboratory, would extend the frontiers of particle physics and astrophysics, biology, geoscience and engineering—and foster the synergies among them. This Deep Science Initiative would yield discoveries about the fundamental nature of our own planet, about the life that it harbors and about the universe that is its home. It would contribute strongly to the basic science that is the foundation of the nation's prosperity. It would provide unique opportunities for innovation in underground technology, with immediate and long-term applications for the nation's security and economic well-being. A Deep Science Initiative would address the nation's need to sustain world leadership in fundamental and applied science and to educate, train and inspire the next generation of scientists and engineers.

## PRINCIPAL INVESTIGATORS

**Astrophysics**
Bernard Sadoulet
*University of California at Berkeley*

**Physics**
Eugene Beier
*University of Pennsylvania*

**Civil Engineering/Rock Mechanics**
Charles Fairhurst
*University of Minnesota*

**Geomicrobiology**
T.C. Onstott
*Princeton University*

**Physics**
R.G. Hamish Robertson
*University of Washington*

**Microbiology**
James Tiedje
*Michigan State University*

## PRODUCTION EDITOR

Judith Jackson
*Fermilab*

## CONTRIBUTING EDITORS

Elizabeth Arscott
*University of California at Berkeley*

Hitoshi Murayama
*University of California at Berkeley*

**The National**
**Science Foundation**

## WORKING GROUP LEADERS

**Dark Matter**
Dan Akerib, *Case Western Reserve University*
Elena Aprile, *Columbia University*

**Low-Energy Neutrinos**
Tom Bowles, *LANL*
Bruce Vogelaar, *Virginia Tech*

**Long Baseline Neutrino Experiments**
Milind Diwan, *BNL*
Gina Rameika, *Fermilab*

**Neutrinoless Double-Beta Decay**
Steve Elliott, *LANL*
Charles Prescott, *SLAC*

**Nuclear Astrophysics and Underground Accelerators**
Joachim Goerres, *University of Notre Dame*
Michael Wiescher, *University of Notre Dame*

**Nucleon Decay/Atmospheric Neutrinos**
Chang Kee Jung, *SUNY Stony Brook*
Hank Sobel, *University of California at Irvine*

**Low-Background Counting Facilities and Prototyping**
Harry Miley, *PNNL*
Prisca Cushman, *University of Minnesota*

**Coupled Processes**
Brian McPherson, *University of Utah*
Eric Sonnenthal, *LBNL*

**Rock Mechanics/Seismology**
Larry Costin, *SNL*
Paul Young, *University of Toronto*

**Applications**
Francois Heuzé, *LLNL*
Jean-Claude Roegiers, *University of Oklahoma*

**Geomicrobiology**
Tommy Phelps, *ORNL*
Tom Kieft, *New Mexico Tech*

**Microbial Biology and Evolution**
Jim Fredrickson, *PNNL*
Nancy Moran, *University of Arizona*

**Infrastructure Requirements and Management**
Lee Petersen, *CNA Engineers*
Derek Ellsworth, *Penn State University*
David Berley, *University of Maryland*

**Education & Outreach**
Willi Chinowski, *LBNL*
Susan Pfiffner, *University of Tennessee*

DEEP SCIENCE

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Introduction

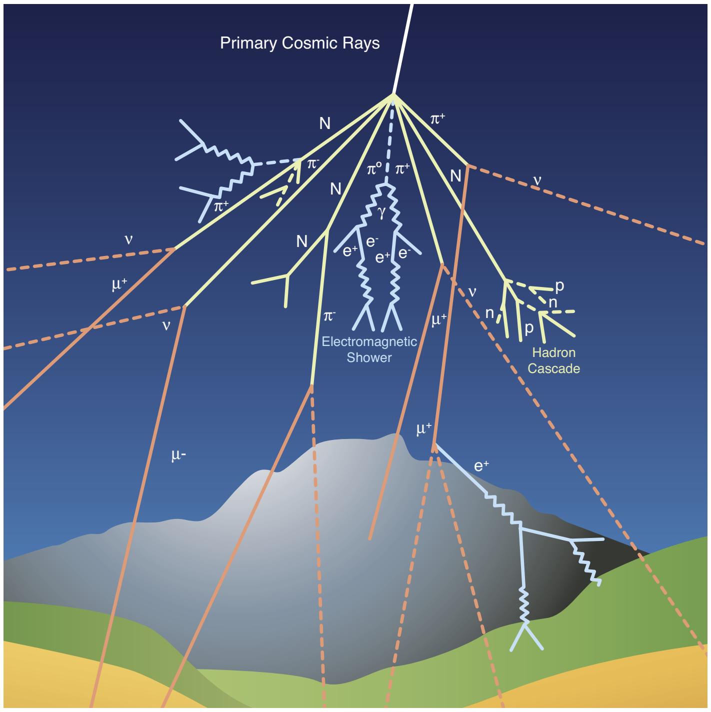
# DEEP SCIENCE

**AS ANY SUBWAY RIDER CAN ATTEST,** the world is different underground. It's dark, conditions are often extreme, and unusual forms of life emerge. Even deeper beneath the earth's surface, closer to the level of Jules Verne than of the F train, the world turns very different indeed.

Deep down, at the depth of a few kilometers, the chatter of invisible cosmic rays entering the earth's atmosphere fades to a hush. Temperatures rise, pressures increase, and the environment becomes salty and alkaline. Novel life forms, cut off for millennia from the earth's surface, eke out their existence in the darkness. And everywhere there is the rock, with its fractures and faults, its water networks, its stresses and strains, its slow movement and sudden cataclysms. Like a voyage to Mars, going underground is a trip to a different world. It's a world that scientists from a variety of fields would like to make their own.

To discover the mysteries of the universe takes some digging—literally. It might seem counterintuitive, but answers to some of the most compelling questions about what's going on in the farthest reaches of space and time are likely to come not just from Out There, via telescopes and space probes, but from Down There, in experiments planted in the rocky depths of planet Earth. As a result, growing numbers of scientists in the U.S. and worldwide are going underground.

Cosmic rays, mostly energetic protons, strike the upper atmosphere and create showers of subatomic debris. Among the particles produced are muons, which can penetrate as deep as 4000 m into the earth's crust. Still more penetrating are neutrinos, which can pass through the earth.
*Source: CERN*



Twenty-first-century particle and nuclear physicists and cosmologists define their science by a set of questions about the universe, some as old as humanity's quest to understand nature's laws, some prompted by recent discoveries. What happened to the antimatter that was almost certainly present at the Big Bang? What story do neutrinos, the slipperiest characters of the particle world, bring us from that ancient time when physical laws we no longer see ruled the universe? What are the invisible dark matter and dark energy that comprise more than 95 percent of everything that exists in the universe? Do all of nature's forces ultimately combine? These questions have excited physicists not only because of their compelling nature, but because, for the first time, the technological means appear to be at hand to discover the answers. The combination of observations in space, experiments at particle accelerators, and experiments underground promise, over the next few years, to change the picture of the universe beyond our wildest imaginings. Underground research will play a key role.

Why underground? Because it's quiet down there. We can't hear the commotion, but to the particle detectors that are the eyes and ears of physics experiments, the noise on the earth's surface is like a boiler factory. Detectors are immersed in the constant bombardment of cosmic rays. For a critical set of physics experiments, the surface noise drowns out the pin-drop signals that are physicists' clues that they're onto something. To hear the whisper of discovery, physicists need shelter from the cosmic racket. Which is why they are ready to start digging.

Below the surface, the noise fades as rock absorbs the particles from space. The quiet deepens as the depth increases, the cosmic-ray rate decreasing tenfold for every 300 meters of rock. Cosmic rays do not penetrate much more than 4000 meters. Even at 2000 meters, much of the cosmic chatter is stilled so that experimenters can pick out the subtle signals of neutrinos. They can look for the rare, solitary flash that would signal a proton's decay—and a whole new vision of nature's particles and forces. Sheltered by the earth's crust, scientists can tune in to the tiny but unmistakable signatures of a revolutionary new physics of the universe.

Physicists and astrophysicists have a strong tradition of underground research. Biologists, geoscientists and engineers also have their own compelling questions that they can only address by performing experiments deep beneath the surface.

Although half of the earth's biomass lives below the earth's surface, some of it in the hot, dark, rock-bound environment at depths of five kilometers or more, we know little about it. How do these microbes live in conditions that, from our surface perspective, would seem to make life improbable? How have they evolved, isolated for millennia from surface organisms? How do they alter the geology and chemistry of the subsurface? What can they tell us not only about life at the extremes here at home, but about life as it might exist on other planets? Deep underground, is there life as we don't know it? Biologists need sustained access to deep "pristine" environments, uncontaminated by mining operations and with the best possible control of drilling operations, to discover the nature of life at the underground extreme.

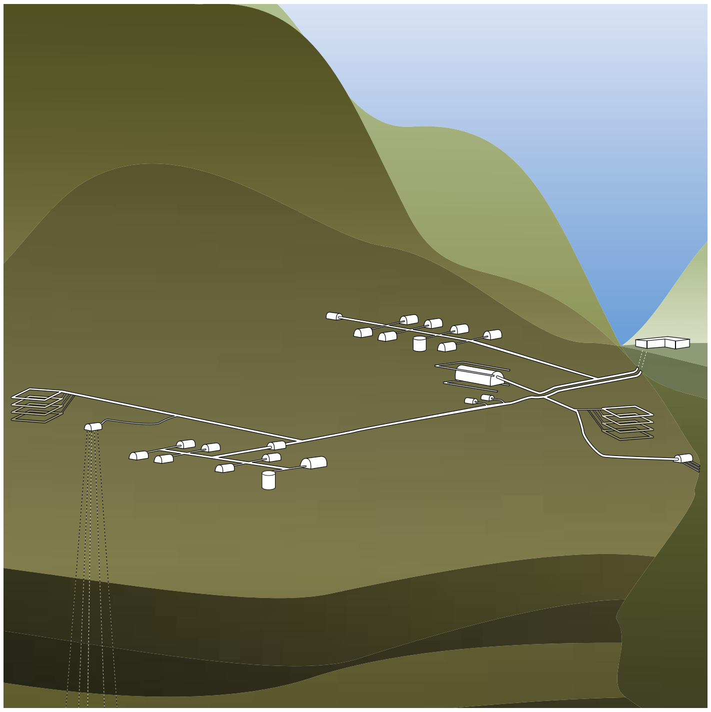
Geoscientists, in turn, see sustained access to large volumes of deep subterranean rock as an opportunity to address central questions in modern earth science. Can we understand and predict catastrophic natural events, especially earthquakes? How do material properties control processes in the earth's crust? Although geoscientists make use of opportunities afforded by mining operations, they dream of underground research facilities wholly devoted to science. Similarly, underground engineers anticipate that building and working in a dedicated underground laboratory will take them far in their quest to develop a "transparent earth," whose now-opaque mass might one day become transparent to observers either on the surface or gazing at a rock face underground. The increasing strategic value of underground space to meet the needs of our shrinking planet gives urgency to their efforts.

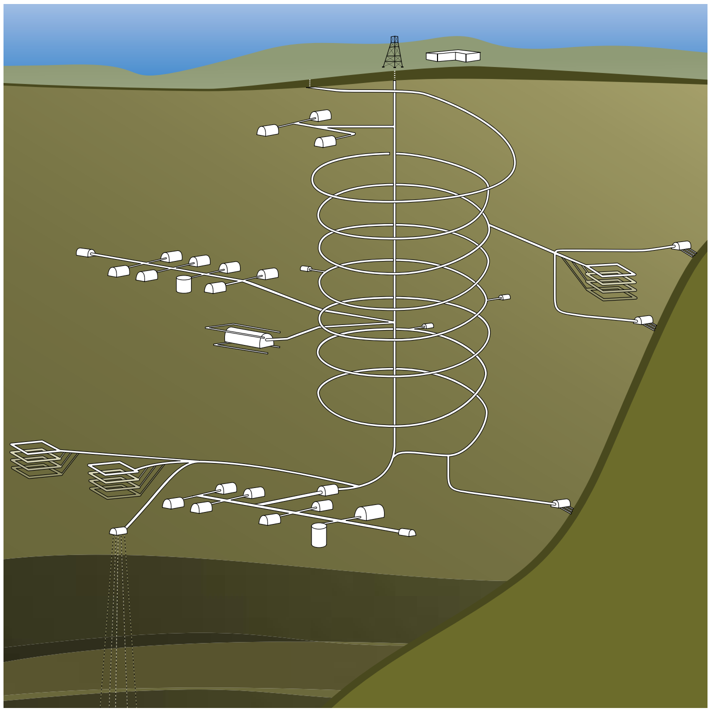
Physicists, astrophysicists, biologists, geoscientists and engineers all have their own scientific reasons for heading beneath the surface. They also anticipate a unique scientific synergy when scientists from diverse disciplines, whose surface paths don't often cross, join forces underground. Can we use the techniques of particle detection to probe the earth's core? What will we learn about rock mechanics and underground construction from building underground spaces for gigantic particle detectors? Who knows what cross-disciplinary insights will spring from lunch-table discussions underground?

**RECENTLY,** a nationwide cross section of researchers have examined the scientific potential of deep underground science and engineering. In a two-year study, they developed requirements for a strong U.S. program in underground research. "Deep Science" presents their findings and recommends a cross-agency Deep Science Initiative to expand and coordinate current programs, make use of existing U.S. underground facilities, and continue strong international collaboration. Although certain experiments can be performed at intermediate depth, they conclude, the scientific frontier is deep down at a depth of approximately two kilometers.

While most developed nations have carved out space for underground laboratories, in mines or under mountains, underground research space is severely limited in the U.S. There is no U.S. site below one kilometer deep. In response, "Deep Science," proposes the development of a Deep Underground Science and Engineering Laboratory to complement existing domestic and foreign laboratories and promote international collaboration. DUSEL would provide the U.S. with powerful underground scientific capabilities. At a time of growing concern about the erosion of U.S. scientific and technical leadership and its effect on future prosperity, the Deep Science Initiative would lead to scientific discovery and encourage technological innovation. It would provide a unique research environment to inspire and educate the nation's next generation of scientists and engineers.

Dig we must, for a greater understanding of the universe and our place within it.





Two possible arrangements that achieve the scientific objectives of a Deep Underground Science and Engineering Laboratory. One gives horizontal access into steeply rising terrain, the other gives vertical access into less mountainous terrain. Each configuration would also have escape routes, not shown here.
*Source: DUSEL S1 Study*

# Findings and Recommendations

## FINDINGS

Analysis of the current opportunities and challenges for deep underground science leads to three scientific findings and two programmatic.

- **Deep underground science is an essential component of research at the frontier.** Underground experiments are critical to addressing some of the most compelling problems of modern science and engineering; and long-term access to dedicated deep underground facilities is essential.

- **Disciplines in transformation.** Deep underground experiments have for some time constituted an important component of physics and astrophysics. Biologists, earth scientists and engineers have long made observations underground and have in recent years also recognized the extraordinary potential of deep underground experiments.

- **Benefits to Society.** Investment in deep underground experiments can yield important societal benefits. Underground construction, resource extraction, management of water resources, environmental stewardship, mine safety and national security are prominent examples. By creating a unique multidisciplinary environment for scientific discovery and technological development, a deep underground laboratory will inspire and educate the nation's next generation of scientists and engineers.

- **Worldwide need for underground space.** The rising interest in deep underground science; the diversification of underground disciplines; the increase in the number of underground researchers; and the increased size, complexity and duration of experiments all point to a rapidly rising demand for underground laboratory space worldwide. The opening of numerous facilities outside the U.S. attests to the gap between supply and demand, especially at very large depth.

- **Need for a U.S. world-class deep multidisciplinary facility.** The U.S. is among the very few developed countries without a deep underground facility (≥ 3000 m.w.e). In an international environment where deep underground space is at a premium, a U.S. Deep Underground Science and Engineering Laboratory would provide critical discovery opportunities to U.S. and foreign scientists, put the U.S. in a stronger strategic position in deep underground science, and maximize the benefits of underground research to the nation.

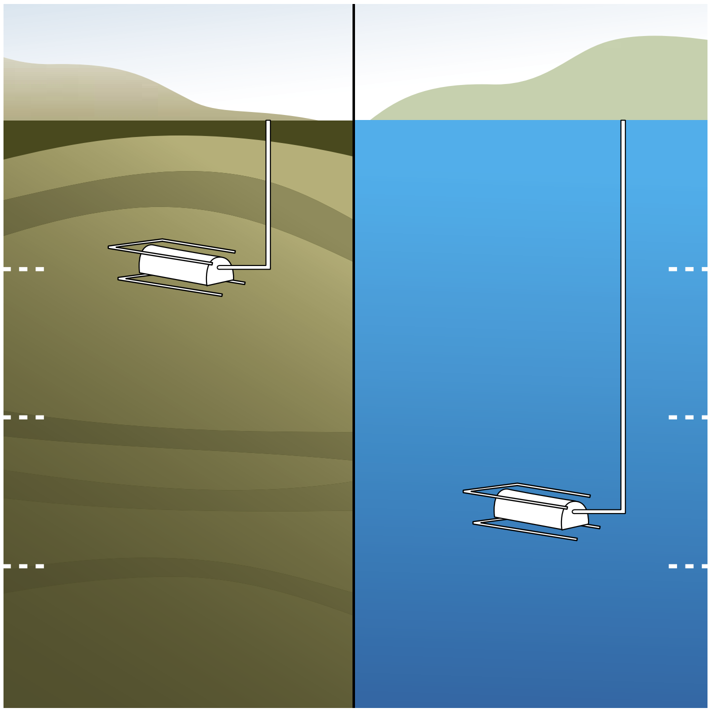
## RECOMMENDATIONS

- **Strong support for deep underground science.** The past decade has witnessed dramatic scientific returns from investments in physics and microbiology at great depths. Underground research is emerging as a unique and irreplaceable component of science, not only in physics and astrophysics, but also in biology, earth sciences and many disciplines of engineering. We recommend that the U.S. strengthen its research programs in subsurface sciences to become a world leader in the multidisciplinary exploration of this important new frontier.

- **A cross-agency Deep Science Initiative.** In order to broaden underground research and maximize its scientific impact, we recommend that the U.S. science agencies collaborate to launch a multidisciplinary Deep Science Initiative. This initiative would allow the nation to focus the whole range of underground expertise on the most important scientific problems. It would aim at optimizing the use of existing or new underground facilities and at exploiting the complementary aspects of a variety of rock formations. The Deep Science Initiative should be coordinated with other national initiatives and take full advantage of international collaboration opportunities.

- **A Deep Underground Science and Engineering Laboratory.** The U.S. should complement the nation's existing assets with a flagship world-class underground laboratory providing access to very great depth (approximately 2200 meters, or 6000 meters water equivalent) and ample facilities at intermediate depths (approximately 1100 meters or 3000 meters water equivalent) currently not available in the U.S.. Such a Deep Underground Science and Engineering Laboratory (DUSEL) should be designed to allow evolution and expansion over the next 30 to 50 years. Because of this long lifetime, the initial investment must be balanced with the operating costs. For maximum impact, the construction of DUSEL should begin as soon as possible.

Physicists have a scheme for comparing the depths of underground labs in terms of the cosmic-ray flux that penetrates to that depth. By expressing the depth in terms of the depth of water that would reduce the cosmic-ray flux by the same amount, one can readily compare one location with another. The water depth is known as the depth in "meters water equivalent (m.w.e.)" and it is 2.650 times larger than the amount of "standard" rock that would produce the same attenuation. Rock in fact varies significantly from standard density, and terrain can be flat or mountainous. By reference to water, one avoids these details. *Source: DUSEL S1 Study*



# SYNERGY

The benefits of a proposed Deep Science Initiative would add up to more than the sum of its component disciplines: physics and astrophysics, geomicrobiology, evolutionary biology, geoscience and engineering. When scientists pursue their research interests in company with others from different backgrounds, new ideas emerge. Each field of science has its own vocabulary, technology and way of seeing. Insights from the intersections of the separate disciplines are often the source of scientific and technological breakthroughs. Think, for example, of the profound implications for particle physics of the astrophysical observations of dark matter and dark energy, or the advances in the characterization of protein structure in biology provided by particle-accelerating light sources from physics. What might the synergies of underground research bring forth? We can anticipate a few possibilities.

- Physicists use giant underground detectors in order to discover rare and subtle signatures of particular phenomena of the universe. Geoengineers lead the way in developing safe and cost-effective methods of excavation and underground construction. Geoscientists are gaining an ever-more-sophisticated understanding of rock structure and behavior under varying conditions. An underground laboratory would provide the opportunity to develop new techniques of underground engineering to enable physicists to deploy massive detectors, and, with the help of their geo-colleagues, to observe rare processes such as the conversion of antimatter to matter.

- The interdisciplinary link between biological science, hydrogeology and geochemistry is another key synergy. Each depends on carefully controlled access to uncontaminated environments, and microbial populations are strongly influenced by the flow paths of water and solutions. Similarly, studies in rock mechanics, fracture propagation, fracture permeability, fluid flow, rock failure, and geophysical imaging of fractures are all closely intertwined.

- An early example of scientific synergy between physics and geoscience has already begun. Geoscientists are turning the normally outward-looking “eyes” of physicists’ massive and intricate neutrino detectors inward to search for geoneutrinos from the earth’s interior. Some theories predict that much of the earth’s heat, and hence its geomagnetic field, comes not only from the decay of radioactive materials within the earth, but perhaps also from a uranium-rich core that may once have functioned or may still function as a nuclear reactor. If the theory is correct, these nuclear reactions would produce detectable neutrinos. Using a neutrino detector, the search for geoneutrinos from earth’s core has begun. The detection of neutrinos typical of a nuclear reactor, but coming from the earth’s core, would confirm the existence of a georeactor and radically alter concepts of planetary evolution.

- Microorganisms in the deep subsurface degrade petroleum to carbon dioxide at rates that are at least a million times slower than the rates of surface microbes. Such a glacial pace of life suggests that an individual microbe may be anywhere from 100 to 100,000 years old. Using the low-level counting facilities constructed underground by physicists, biologists may be able to determine whether underground microbes are “as old as Methusela.” By coupling physicists’ photon detector technologies with the bioluminescence molecules used by biologists, underground researchers could develop the next generation of life-sensing technologies to examine subsurface microbial processes at natural rates and in their natural habitats.

Besides the depth and accessibility of its premier laboratory facility, DUSEL, a Deep Science Initiative would offer a rare opportunity to support scientific synergy among disciplines that have traditionally had little interaction. In a time when the trend is toward increasingly narrow scientific specialization, such an underground “melting pot” of disciplines would provide a unique environment for innovation leading to as-yet-unimagined discoveries and undreamed-of applications.

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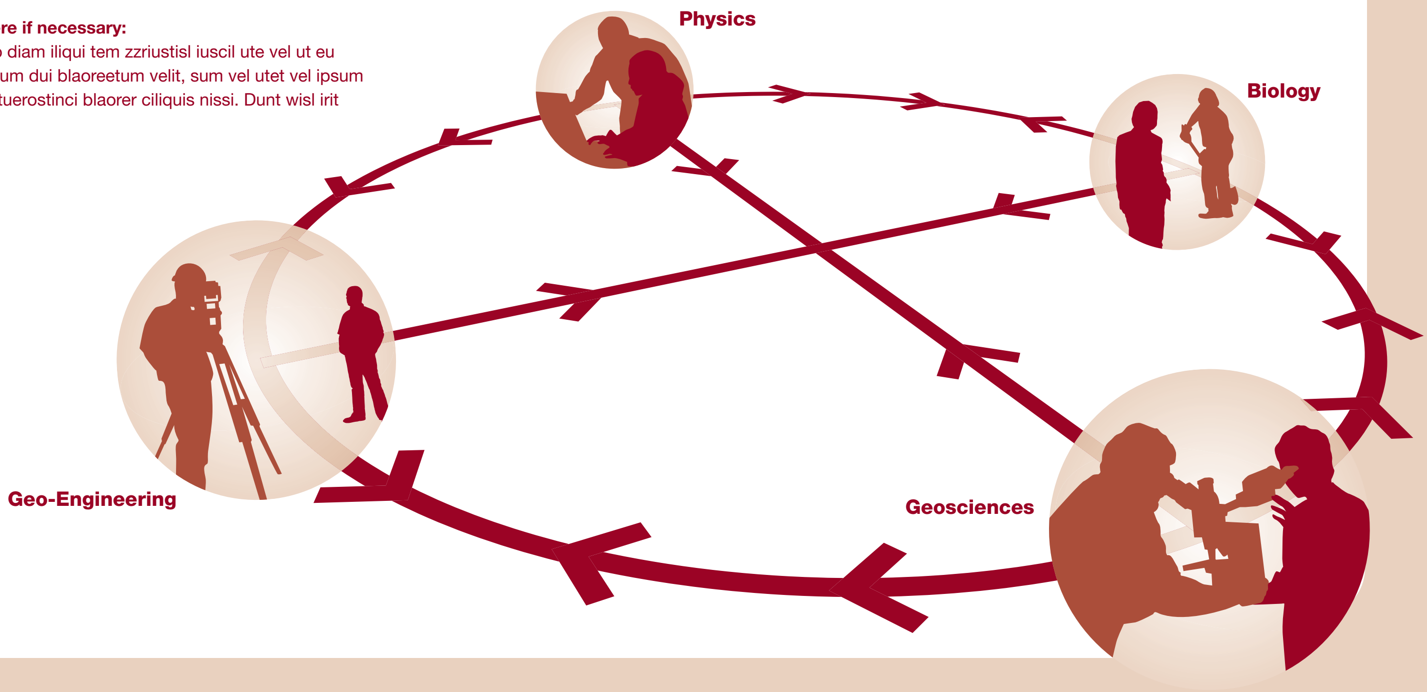


CHAPTER ONE

# UNDERGROUND UNIVERSE

## What is the universe made of?

## What is dark matter?

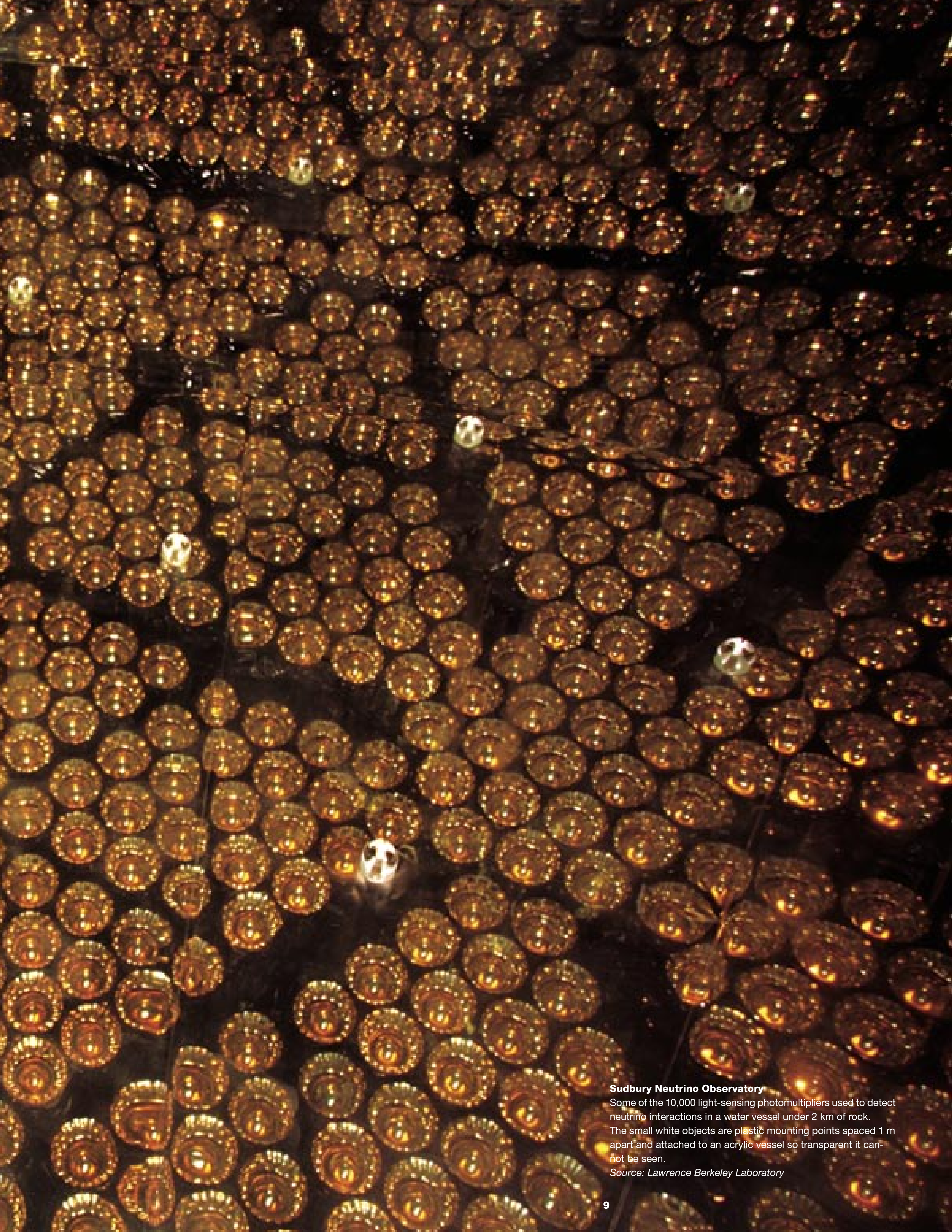
## What are neutrinos telling us?

## What happened to the antimatter?

## Are protons unstable?

## How did the universe evolve?

**The last decade in physics and astrophysics has defined fundamental questions about the universe, with its elementary particles and forces and its mysteries of neutrinos, dark matter and dark energy. Underground experiments will play a unique part in addressing these questions. The answers will revolutionize the human understanding of the cosmos. Why go below the surface to probe the universe? Some signals of the revolutionary new physics will only reveal themselves in experiments in the shelter of the deep underground.**



**Sudbury Neutrino Observatory**
Some of the 10,000 light-sensing photomultipliers used to detect neutrino interactions in a water vessel under 2 km of rock. The small white objects are plastic mounting points spaced 1 m apart and attached to an acrylic vessel so transparent it cannot be seen.
*Source: Lawrence Berkeley Laboratory*

PHYSICS AND ASTROPHYSICS

# UNDERGROUND UNIVERSE

Two clusters of galaxies in collision. The ordinary matter, gas and stars from both clusters, shown in red, is slowed down in the collision. The DARK matter, shown in blue, sails through and keeps on going because it does not interact. Both colors are false colors—the red is an image of x-ray emission, and the blue is an image of the gravitational effect on the light from more distant galaxies.
*Source: NASA*

## WHAT IS THE UNIVERSE MADE OF? (IT'S NOT WHAT WE THOUGHT.)

In recent years, astronomical observations have revealed that most of the universe is not made from ordinary matter. Scientists have made the startling discovery that the atoms that make up the stars, the planets and people are in the minority in the universe. Photons (particles of light) and ghost-like neutrinos outnumber everyday atoms by a factor of about a billion to one. In terms of mass, the mystery substance called dark matter outweighs ordinary matter five to one. If that were not bizarre enough, the empty space of the universe is filled by a strange force, termed "dark energy," that pushes the universe apart at ever-accelerating speed. Even the existence of matter itself is a puzzle. Strictly speaking, in the inferno of the Big Bang antimatter should have annihilated the matter, leaving only energy in the form of photons and neutrinos. In fact, the world of ordinary matter makes up only 4 percent of a universe so mysterious that it will take a revolution in physics to explain it. Underground experiments, together with observations in space and experiments at particle accelerators, will play a key role in this revolutionary physics.

## WHAT IS DARK MATTER?

Astrophysical observations, including the behavior of stars and galaxies, have over the past decade established that 73 percent of the mass and energy of the universe is dark energy, and 23 percent is dark matter, called "dark" because it is invisible. Without it, galaxies would not have formed, the stars would not shine, and life would not exist.

What is this dark matter that binds the galaxies? Although physicists have studied ordinary matter—atoms—in detail, nothing they have seen so far has the right qualities for dark matter. Discovering what dark matter really is stands as one of the major challenges in science today. Intriguing new theories of elementary particles suggest that dark matter might consist of undiscovered neutral particles, either much heavier than the proton or much lighter even than neutrinos. Discovering such particles would not only shed light on dark matter but solve other longstanding problems in elementary particle physics.

If the dark matter all around us is indeed an unknown heavy particle, scientists believe that all it should take is an ultrasensitive device to see the signal produced when a dark matter particle hits an atom in a detector—in a place that is quiet enough for the tiny signal to be picked up. The challenge with direct detection of dark matter is that environmental noise from cosmic rays can mimic its feeble signal. To avoid the noise, experiments must go deep underground. The deeper the experiment, the more protected it is from cosmic noise. Physicists can only claim that they have detected dark matter when they are completely certain that the signal is real, not merely noise. Large detectors at great depth have the best chance of yielding an unmistakable signal of dark matter particles.

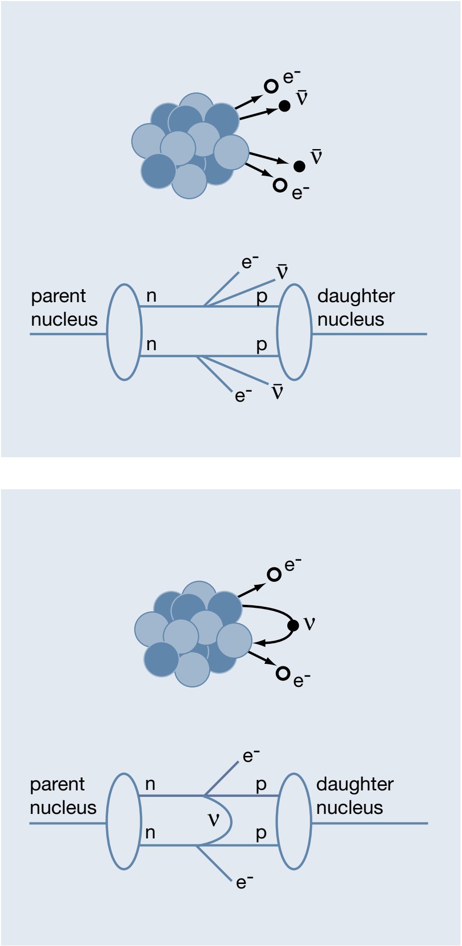
Scientists also plan to produce dark matter particles in the laboratory, using high-energy particle colliders to recreate the conditions of the early universe when today's dark matter particles were born. Collider experiments will attempt to produce dark matter particles and measure their properties in detail. Although these experiments are also expected to shed considerable light on dark matter, one key element will be missing. Accelerator experiments will not tell us if the collider-produced particles are the same as those that make up the actual dark matter of the universe. For that, direct detection of cosmological dark matter particles is required.

Should dark matter particles both be detected directly in deep underground experiments, and produced at an accelerator such as the Large Hadron Collider, it will be an extraordinary achievement for physics. The properties of the particles will be known, and their place in the universe understood. It will mark a giant step towards the "theory of everything."

## WHAT ARE NEUTRINOS TELLING US?

Although physicists first detected neutrinos in 1956, these elusive particles remain almost as enigmatic as dark matter. For many years, physicists believed that neutrinos had zero mass and always moved at the speed of light. Underground experiments of the past decade, though, have shown that in fact neutrinos do have a mass, and that they will eventually come to rest as the universe expands and cools. The mass is at least 200,000 times smaller than that of any other matter particle. Moreover, physicists learned that neutrinos have mixed identities; one type of neutrino morphs into another and back. These discoveries represent great advances in solving the mysteries of neutrinos. Yet physicists know the masses of the neutrinos only within a broad range. Collectively, the neutrinos made in the Big Bang assuredly outweigh the luminous stars. And exactly when they slow down and come to rest has critical implications for the formation of superclusters of galaxies, the largest structures in the universe.

Underground experiments would allow physicists to zero in on the exact mass of neutrinos by looking for an extremely rare nuclear transformation called neutrinoless double beta decay. A quiet environment underground, sheltered from the noise of cosmic rays, is crucial to detecting this extraordinarily rare event, if it occurs. Another underground neutrino experiment would use beams of neutrinos from distant particle accelerators aimed at an underground detector to decode which of the masses of the three different types of neutrino is the heaviest and which the lightest. Combining these two techniques would reveal the ghostly hand of neutrinos in shaping the universe.



The process of double beta decay. (top panel) A nucleus transforms itself spontaneously to another nucleus, emitting two electrons and two antineutrinos. This process is slow, but is known to happen. (bottom panel) Neutrinoless double beta decay. If the neutrino and antineutrino are the same particle, an emitted antineutrino can be re-absorbed as a neutrino. Only the electrons emerge, creating two new matter particles but no antimatter particles in the universe. Whether this happens is not known, but the search is a principal component of the DUSEL physics program.

## WHAT HAPPENED TO THE ANTIMATTER?

It's a good thing antimatter does not exist in today's universe. When matter particles meet antimatter particles, they annihilate into pure energy. Conversely, Einstein's $E=mc^2$ shows that with a high enough energy, pairs of matter and antimatter particles are created. At the super-high energy of the Big Bang, antimatter particles must have been created, presumably in equal amounts with matter particles. And yet no detectable signs of antimatter particles survive in the universe today. Where did the antimatter go? If the amounts of matter and antimatter were the same at the Big Bang, they should have annihilated each other, leaving the universe empty of matter—an outcome that clearly did not happen. A yet-to-be-found process must have reshuffled the matter-antimatter balance, transforming one part in a billion of antimatter to matter, with the result that the universe—and we—survived. So far, although scientists have caught glimpses of matter-antimatter asymmetry, they have not seen anything that could account for the dominance of matter over antimatter.

What exactly do scientists look for? The goal is to find evidence that antimatter is not just some sort of mirror image of the matter in the universe. They look for differences in the behaviors of matter and antimatter. Neutrinos produced by an accelerator can morph, or oscillate, into a different type of neutrino on their way to a detector many hundreds of kilometers away. Scientists measure the oscillation rate for these neutrinos and compare it to the oscillation rate for antineutrinos produced at the same accelerator. A difference in these rates shows that there are neutrino processes in nature that distinguish antimatter from matter. A second key ingredient is to show that nature actually permits changes in the relative amounts of matter and antimatter. A direct way to find that out would be the discovery of neutrinoless double beta decay, in which two new matter particles, electrons, were created from the energy available in a nucleus. Discovering the asymmetry in the accelerator test along with the observation of neutrinoless double beta decay, would provide the data to show how the universe survived the Big Bang.

## ARE PROTONS UNSTABLE?

Another possibility to explain the existence of matter is the decay of a proton (matter) into a positron (antimatter). Indeed, unified field theories, the kind of theories Einstein dreamed of, predict that such a process does happen. However, current data have shown that it happens extremely seldom—less than once in $10^{34}$ years for a given proton. To have a chance of spotting proton decay, researchers need to collect more than $10^{36}$ protons (for example in a million tons of water) and watch them carefully over many years in a quiet underground location. The huge detector needed in this quest is also one that can detect neutrinos beamed toward it from an accelerator thousands of kilometers away. The discovery of proton decay would shed light not only on how matter prevailed over antimatter, but also on the nature of matter and forces at the most fundamental level.

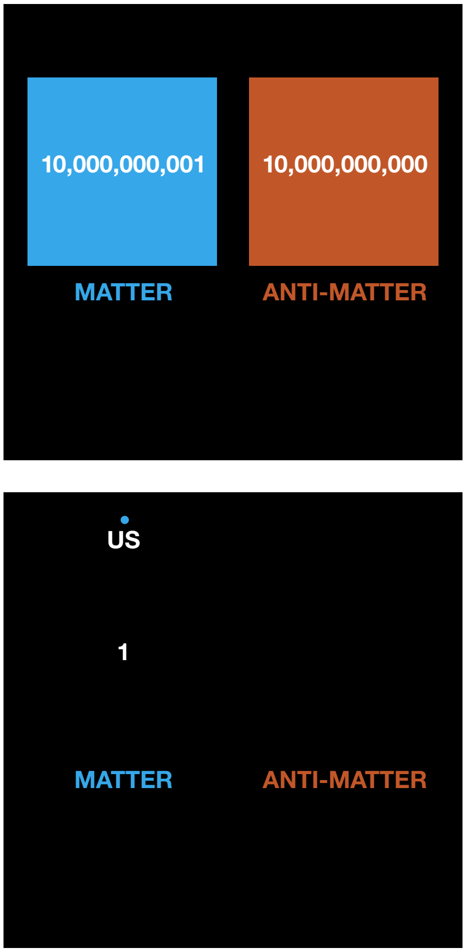
## HOW DID THE UNIVERSE EVOLVE?

Since stars are made of conventional atoms, perhaps they present no scientific mysteries? Not quite. Using light, astrophysicists see only the bright surfaces of stars, but neutrinos offer a view directly to their cores. Observations of a tiny fraction of the neutrinos from the sun have revealed the temperature at its center, 15 million degrees, to the amazing precision of only two percent. But the sun's true nature remains imperfectly understood. Precisely how does the sun generate life-giving energy? Does its energy output vary slightly over thousands of years? To address these questions, scientists need to take a direct look into the center of the sun, impossible with light but possible with neutrinos. Neutrinos are very difficult to detect, and only the most energetic neutrinos from the sun have been studied extensively. To see the majority of neutrinos from the sun, again scientists need a very quiet underground location to discover how much energy the sun is generating now.

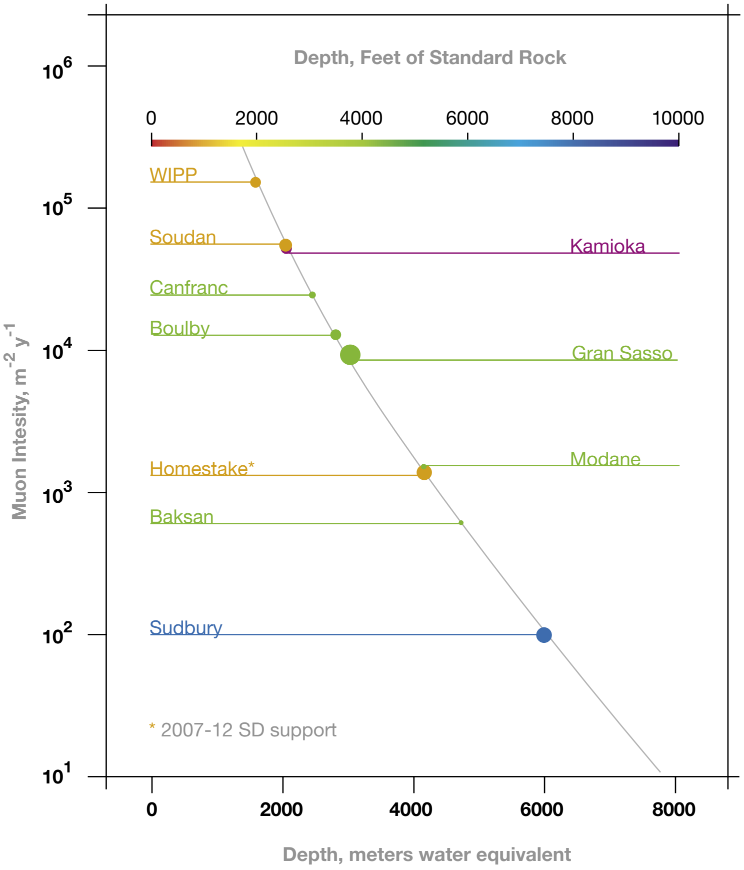
The universe sometimes experiences cataclysmic events, for example the merging of two black holes. Such events may be impossible to see with telescopes, but they have such a huge impact on space and time that ripples of bending spacetime spread out from the massive event. Gravitational wave detectors located underground can see the resulting small bends in spacetime protected from disturbance from human and seismic noise.

"We are made of star stuff," as the late astrophysicist Carl Sagan once put it. Each atom of our bodies was processed through many generations of stars before condensing to make our solar system and earth—and to make us. Understanding the birth and death of stars is an important part of our quest to understand the origin of life in the universe. To address the questions of how the atomic nuclei that form us were made, scientists use small underground particle-accelerator laboratories well shielded from cosmic rays.

Particle astrophysicists have detected a handful of neutrinos from a supernova, a dying massive star in a nearby galaxy. Neutrinos must also exist from past supernovae in galaxies near and far. If scientists can detect them, they will learn how many supernova explosions have happened in the past and hence how galaxies have evolved over billions of years. By detecting neutrinos from past supernovae, underground experiments may even shed light on the expansion history of the universe and hence on the nature of dark energy. ■



When matter and antimatter annihilated following the big bang, some tiny asymmetry in the early universe (top) produced our universe, made entirely of matter (bottom).



The intensity of muons created by cosmic rays as a function of the depth in feet of standard rock (density 2.65) or in meters of water (density 1.00). The world's underground laboratories are shown as dots, and the area of the dot is proportional to the area available for science at each lab.

# “YOU COULD HEAR A PIN DROP.”

The well-worn phrase describes the quintessential quiet place, so silent that a listener can hear the tiny “toc” of a pin dropping. It’s a good metaphor for the conditions required for certain physics experiments that are searching for the subtle indicators that would signal the discovery of radical new phenomena at work in the universe.

Physicists and astrophysicists are listening for the equivalent of a pin drop in the universe, the faint “toc” of a dark-matter particle hitting a detector. Dark matter is ubiquitous, streaming around—and indeed through—us all the time. Taken together, the combined mass of dark-matter particles provides the gravitational glue to keep our solar system from wandering off into intergalactic space. But trying to detect the feeble signals of dark-matter particles on the earth’s surface is like listening for a pin drop after a home run in the bottom of the ninth with the bases loaded. The background noise caused by billions of cosmic rays coming in to earth from outer space drowns out the pin drop of a rare dark-matter signal. To detect dark matter, physicists need the equivalent of Proust’s cork-lined room, an experimental environment so free of background noise that they can discern its whispered signal.

The solution for dark matter experiments—and for searches for other rare processes with key implications for shaping the universe—is to go deep underground, where thousands of feet of rock provide shielding from the cosmic ray background. Thus sheltered, experiments can detect the signals of dark matter or the evidence that fundamental forces may ultimately combine. Deep underground, the pin drops that will change the way we see the universe will come through loud and clear.

CHAPTER TWO

# DARK LIFE

## How do biology and geology interact to shape the world underground?

## How does subsurface microbial life evolve in isolation?

## Did life on earth originate beneath the surface?

## Is there life underground as we don't know it?

**The surprising discovery of deep subsurface microbial communities in the mid 1980s launched a new and rapidly expanding subdiscipline within biology, known as geomicrobiology. In geomicrobiology, the fields of geology, geophysics, hydrology, geochemistry, biochemistry, and microbiology have merged to study how life on this planet interacts with the earth's geology, how life may have originated and how life evolved over billions of years. Dark life, those organisms that thrive underground in the absence of sunlight, comprise 50 percent of the earth's biomass, are responsible for many geological phenomena, degrade our waste, and produce some of our energy. Yet many questions remain regarding dark life–questions that can only be answered by going underground.**

**BioFilm**
*Shewanella putrifaciens* exhibiting filamentous connections known as “nanowires.” The nanowires are a recently discovered physiological behavior common to most microorganism and represent a response to adverse environmental stress. The nanowires provide conduits for energy sharing and communication between individual cells.
*Source: Uri Gorby-Pacific Northwest National Laboratory*

# DARK LIFE

Biofilm: Black fluid emanating from a heavily corroded borehole at 3.1 km depth in the Mponeng gold mine in South Africa. The black fluid is due to “nanoparticles” of iron sulfide precipitated by thermophilic anaerobic sulfate-reducing bacteria and the corrosion is due to thermophilic aerobic sulfide and iron-oxidizing bacteria.
*Source: Duane Moser-Pacific Northwest National Laboratory*

Biologists filtering water samples from a borehole at 2.7 km depth in the Driefontein gold mine in South Africa. The borehole extends to a depth of 3.5 km and contains a novel thermophilic microorganism that had not been previously encountered.
*Source: Duane Moser-Pacific Northwest National Laboratory*

## HOW DEEP DOES LIFE GO?

Since the 1980s scientists have gained insight into the diversity and limits of life underground based on information from boreholes and from piggybacking on mining operations. They have discovered microbial life at depths of four to five kilometers and at temperatures of 60ºC. Microbes recovered from hot springs and deep-sea hydrothermal vents can live at temperatures of about 120ºC. Studies of petroleum reserves indicate that above 80ºC these reserves are not degraded by biological action. Does subsurface life reach down to depths where the temperatures are 100ºC or 120ºC or even more? Such a search would require drilling under aseptic conditions that are far more stringent than previous drilling programs have attempted. Drilling from an underground facility where the ambient rock temperature is 50ºC brings scientists more than one-third of the way toward their goal, and they can control air circulation and water filtration to reduce the contamination associated with surface drilling.

## HOW DO BIOLOGY AND GEOLOGY INTERACT TO SHAPE THE WORLD UNDERGROUND?

Earth’s deep, hot subsurface habitats differ from other high-temperature environments such as deep-sea hydrothermal vents and hot springs, because they are completely isolated from biological communities that rely on photosynthesis, earth’s atmosphere, or the oceans. Far below the earth’s surface, dark life relies instead on nonphotosynthetic biogeochemical processes that allow microbes to survive under extreme conditions and force them to interact with the environment. They do this by dissolving minerals, degrading petroleum and consuming gases for energy and nutrients. They may have the ability to detect chemically the presence of a nearby energy source and swim toward it. They precipitate minerals and produce gases, thereby changing the rock’s porosity and permeability, but normally at rates a million times slower than those of surface life. Given enough time, however, microorganisms secreting sulfuric acid can carve enormous chambers in limestone, like those of the Carlsbad Caverns. The extent to which microbes can alter the subsurface environment in general is not well understood and undoubtedly depends on many variables, including time. The only way to unravel these secrets is to perform microbial experiments in an underground laboratory with access to a large rock volume for a long time. By understanding how microorganisms can alter the subsurface under natural conditions, we learn how we can manipulate them for practical applications.

## HOW DOES SUBSURFACE MICROBIAL LIFE EVOLVE IN ISOLATION?

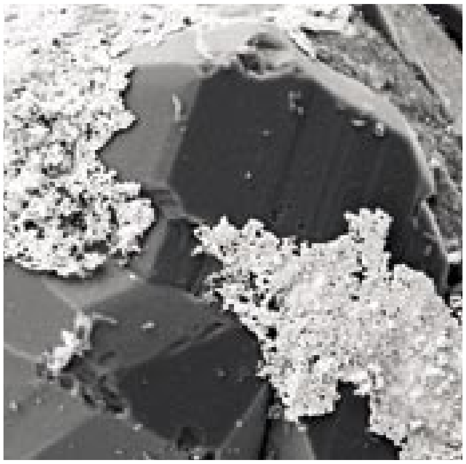
Surface life evolves by a variety of processes including random mutations and exchange of genetic information between organisms in response to environmental change. The sequences for entire genomes for many common bacteria and certain extremophilic organisms have revealed that they have acquired functional capabilities from other microorganisms and that pieces of genetic code are derived from viruses. Complete genome sequences have become powerful tools in unraveling the evolutionary construction of a microorganism. A recent comparison of all available microbial genomic sequences has shown that the bacterial lineages common to the deep subsurface communities represent the most “ancient” in the bacterial kingdom. Is this because they have evolved very little over billions of years? In the deep subsurface, microorganisms may live isolated existences, and their environment changes very little on time scales typical for surface life. In an underground laboratory, experiments designed to alter the subsurface environment by changing the temperature, salinity, or pH, for example, and supplying exogenous DNA in the form of viruses or bacteria, can decipher the evolutionary steps that led to the construction of a bacterial genome. Discovering how this dark life has adapted to thrive in heat, pressure, and high salinity at depth in our own planet can inform our understanding of how surface life evolves here as well as of the potential for life on other planets.

## DID LIFE ON EARTH ORIGINATE BENEATH THE SURFACE?

Deep subsurface environments mimic in many respects the surface environment of the ancient earth before the evolutionary development of photosynthesis pumped oxygen into earth's atmosphere. Thus, deep subsurface microbial processes are the closest living record of life as it existed on the ancient earth. Because current theories for the origin of life do not require the intervention of sunlight, and because the surface environment of the early earth was constantly subjected to the sterilizing effects of meteorite bombardment, life could conceivably have begun in the subsurface. Currently bench-top experiments have explored various aspects of life's origins, but performing such experiments underground could provide critical new clues to how life made the transition from a cluster of prebiotic molecules into a single cellular entity with nucleic acid.

## IS THERE LIFE UNDERGROUND AS WE DON'T KNOW IT?

Recent investigations of the microbial communities inhabiting hot springs have uncovered microorganisms with surprising attributes. Known as "nanobacteria," they represent a new limb on the tree of life. Such surprises may also exist in the deep subsurface where the world of DNA-based life forms is less abundant or even absent, but all the conditions required for life exist. As in the case of searching for earth's deepest life forms, the search for exotic forms of life will require careful aseptic procedures and highly sensitive detection methods, best provided by an underground laboratory. The search for new forms of dark life may also offer insights into how to search for life beneath the surface of Mars and could have significant implications for NASA's Mars exploration program over the next 15 years.



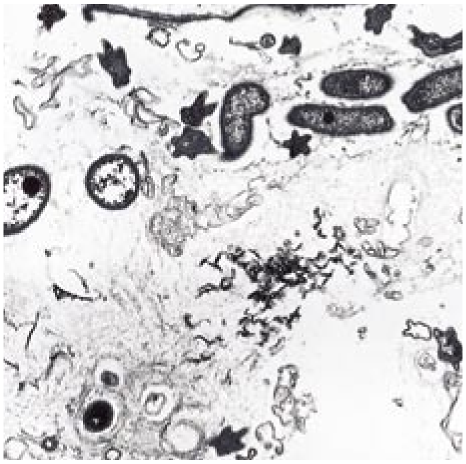
Microbial biofilm forming on gold crystals found in rock specimens collected from a South African mine. Experiments utilizing bacteria instead of toxic chemicals to chelate and precipitate gold from mining water represent a "hot" area of research in South Africa.
*Source: Gordon Southam-University of Western Ontario*

## FOUR DIMENSIONS OF LIFE UNDERGROUND

To address these questions, biologists need a dedicated program and facility for large-scale, long-term subsurface sampling and experiments. So far, nearly all microbiological studies of the terrestrial subsurface have relied either on shallow (less than 30 meters deep) arrays of boreholes or on deeper drilling and coring studies that piggy-backed on petroleum and natural-gas exploration. Others have relied on excavations and drilling within active mines, making them secondary to the exigencies of mine operations.

The few deeper boreholes drilled exclusively for biology are still relatively shallow (less than 500 meters) due to cost constraints. Moreover, boreholes yield relatively limited data, because borehole sampling is inherently one-dimensional. An array of boreholes provides three-dimensional data, but to be useful for microbial experiments they would need a spacing of 1 meter, which, at a depth of 2 kilometers, is difficult to achieve by surface drilling. Perhaps most problematic is the unavoidable contamination of samples by surface microbes resulting from the drilling mud used when drilling from the surface. Drilling from underground tunnels with filtered water in a controlled environment greatly reduces this problem. While underground laboratories for biological studies do exist outside the U.S., they are for the most part shallow and primarily devoted to other purposes such as waste storage and mining and provide only short term access. A dedicated, deep-underground laboratory in the U.S. would allow the four-dimensional access (three space directions plus time) that biologists need for discoveries of the nature of life under the unique conditions of the deep subsurface.

A key requirement for the investigation of indigenous microbial processes at a deep underground laboratory will be long-term access to rock environments free from contamination by prior or ongoing mining activities. Rock strata targeted for indigenous microbial experiments must be free from exposure to mine air or water, which alter the microbiology and chemistry of the native environment in ways that compromise the validity of scientific results. Mining environments carry with them considerable microbial and chemical "noise," background materials introduced during mining. By tunneling into "pristine" rock strata and aseptically drilling and sealing boreholes, biologists can install experimental facilities for detecting clean, clear signals from underground life. ■



Microbial biofilm collected from 2 km depth in a platinum mine in South Africa. This biofilm contains "star" shaped bacteria that have never before been seen. The phylogenetic relationship of these bacteria to known organisms and their function are currently under intense study.
*Source: Gordon Southam-University of Western Ontario*

CHAPTER THREE

# THE RESTLESS EARTH

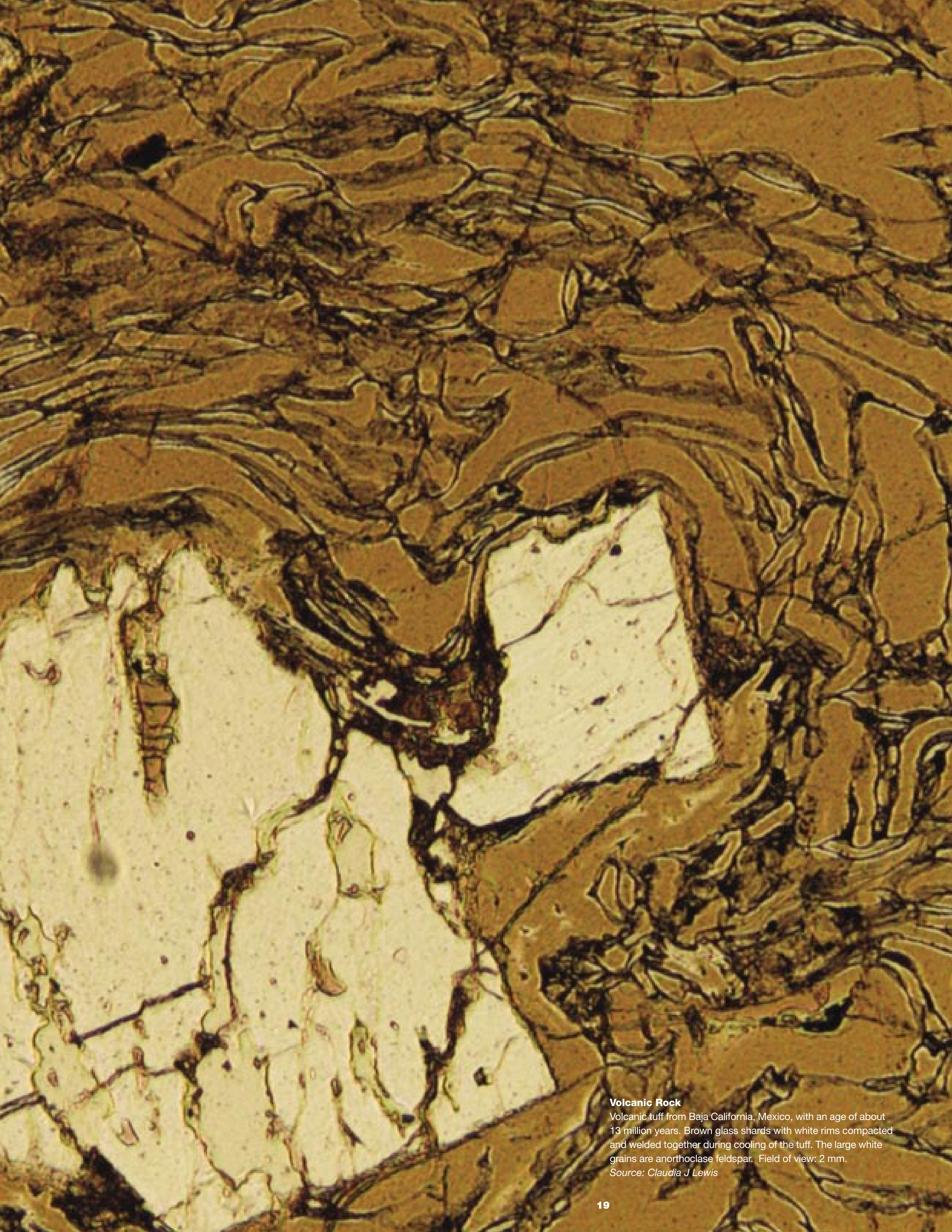
## What are the interactions between the various processes controlling the subsurface environment?

## Are underground resources of drinking water safe and secure?

## Can we reliably predict and control earthquakes?

## Can we make the Earth “Transparent” and observe underground processes in action?

**Rock, the emblem of strength in popular imagery, is no match for the relentless tectonic forces, driven by heat from the earth’s interior, that have operated continuously since the birth of the planet 4.6 billion years ago. The rock bends, buckles and breaks, raising mountains and producing underground folds and faults. Usually so slow as to be imperceptible, these processes occasionally turn violent, producing earthquakes and volcanic eruptions. Underground, the rock is hot, with temperatures increasing between 10°C and 30°C for each kilometer of depth. Rock becomes more deformable with heat and the underground environment becomes progressively more challenging to engineers.**



**Volcanic Rock**

Volcanic tuff from Baja California, Mexico, with an age of about 13 million years. Brown glass shards with white rims compacted and welded together during cooling of the tuff. The large white grains are anorthoclase feldspar.  Field of view: 2 mm.

*Source: Claudia J Lewis*

## CHAPTER THREE

# THE RESTLESS EARTH

Deformation-band faults in the Rio Grande rift, New Mexico. The Peralta Tuff is a sequence of volcanic deposits reworked by wind and water. Deformation-band faults are characterized by grain crushing, grain-boundary sliding, and pore collapse. *Source: Claudia J. Lewis*

### MORE QUESTIONS THAN ANSWERS

Fluids flowing under pressure through porous rock and along fractures transport natural resources and form minerals; earthquakes rend the earth; microbial organisms live and migrate in the deep subsurface. Understanding these processes, whose mechanisms remain largely unknown, is key to the wise and effective use of the underground world.

Society is critically dependent on the subsurface. Clean drinking water from underground is fundamental to civilization. Every society on earth extracts minerals from its depths. Hot subsurface rock is a potential source of enormous geothermal energy. Major structures—dams, foundations, slopes, tunnels—rely on the strength of the rock. The subsurface finds growing use as a storehouse for energy reserves or as a disposal site for toxic and hazardous waste and for $CO_2$ sequestration. Can we be confident that such applications will have no adverse consequences? The limited subsurface research to date has produced more questions than answers.

### WHAT ARE THE INTERACTIONS BETWEEN THE VARIOUS PROCESSES CONTROLLING THE SUBSURFACE ENVIRONMENT?

Most underground earth processes interact with and depend on each other. Tectonic forces cause rocks to bend and fracture, in turn altering the permeability and porosity of the rock, and therefore the pressures, directions and rates of fluid movement. Changes in fluid pressures cause changes in the rock's elastic response to deforming forces, which control movement along faults and, finally, earthquake frequency and magnitude. Chemical dissolution and precipitation as fluids move through different thermal environments can produce mineral deposits; they can change the mechanical strength and flow properties of rock. These *'coupled processes'* need to be understood if we are to assess their consequences reliably. Long-term cross-cutting experiments at great depth would lead to development of more reliable models of the earth's crust, models that would fully couple thermal, hydrologic, mechanical, chemical, biological-mass and energy-transport phenomena, an achievement currently not possible from surface-based field studies. The two *examples* below illustrate the broad significance of coupled effects.

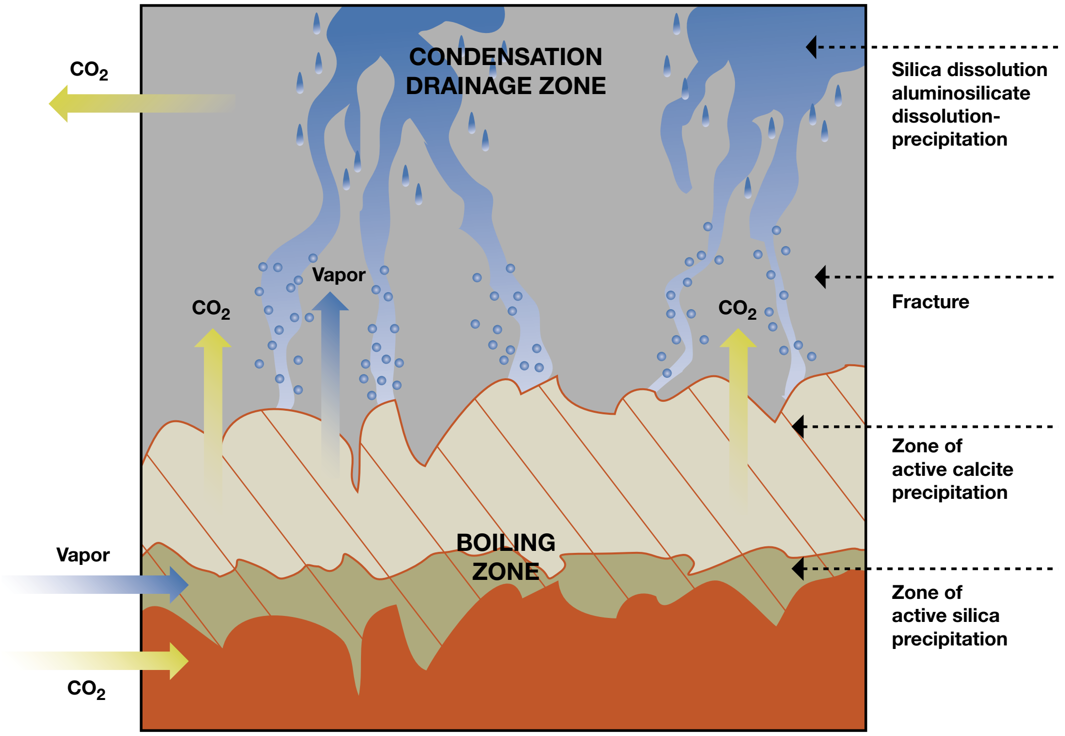
### ARE UNDERGROUND RESOURCES OF DRINKING SAFE AND SECURE?

Groundwater flow is estimated currently by point calibration of mathematical models using borehole data. This is inherently inadequate, since the rock volume between the boreholes is heterogeneous with scale-dependent properties that are unknown and hence not incorporated into the models. Samples of deep rock from drill holes are small and are disturbed by the drilling process, making them of limited value for testing the factors that control fluid flow. Operating mines provide direct access to the underground but do not usually allow for long-term basic research. Our ability to understand fluid flow and associated chemical and physical processes is consequently very limited. Direct testing on underground blocks of rock could overcome many of these limitations and would be a significant aid in groundwater research.

### CAN WE RELIABLY PREDICT AND CONTROL EARTHQUAKES?

Earthquakes occur when a fault or fault region can no longer accommodate the forces applied to it and dynamic slip takes place. This may result from an increase in tectonic forces, a decrease in the fault resistance due to thermal, hydrological, chemical and other changes along the fault surfaces, or to some combination of both. 'Precursor' events indicate that an earthquake is a progressive phenomenon, but the detailed processes are far from clear. The spatial distribution of rock deformation deep in the subsurface is also unknown. Are the forces on faults in a state of critical equilibrium, as some scientists suggest?

A deep underground laboratory would permit continuous, direct measurements of rock strain as a function of position and sampled volume at depth, both in the immediate vicinity of active faults and in the rock mass. These data would elucidate the influence of geology and human activity on tectonic strain and stress distribution in rock, allow direct observation of how energy accumulates near faults and fractures, and provide insights into how fault slip processes can be scaled to larger events. The understanding gained from this research would be a vital step toward reliable prediction of earthquakes.

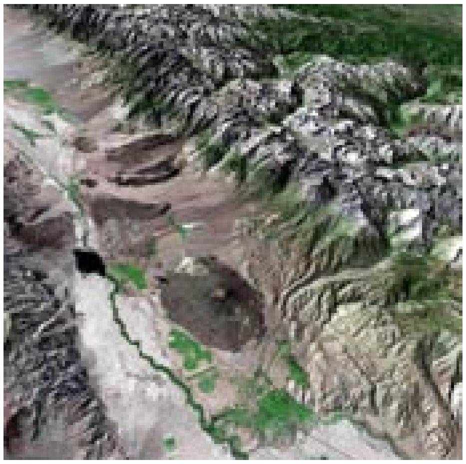


In a geothermal system, potentially a result of rock heated by intrusion of magma, or rock heated by storing nuclear waste, the heat induces a wide range of coupled mechanical, hydrological, chemical, and even biological processes. Open fractures act as conduits for water and steam, which accelerates chemical reactions leading to mineralization in the fractures. In addition to mineralization that can seal fractures, heating of the rock causes thermal expansion closing fractures. All of these changes act to modify the flow of fluids and the pressure distribution, transporting mass and energy through the rock. Under some environments, biofilms may develop and further modify the chemical environment and the flow of fluids in the rock.

Coupled thermal, hydrological, chemical processes, mass and energy within a single fracture heated from below (vertical scale approximately 1-10 meters, horizontal thickness 1 mm to a few cm). In a partially water-filled rock, boiling and transport of steam and $CO_2$ takes place, with resulting drainage of condensed water and chemical reactions induced by decreasing pH.

The example shown is based on observations during the 8-year duration Heated Drift Experiment in unsaturated high permeability volcanic tuff at Yucca Mountain. Rock temperatures exceeded 200C (?) Together with smaller scale experiments in various low permeability saturated rocks, this provides a valuable basis for studies of coupled processes in DUSEL.

*Source: Eric Sonnenthal, LBNL*



Landsat image superimposed on a digital elevation model (DEM) with a view to the southeast within Owens Valley of California. The Sierra Nevada mountains are to the right, and the White Mountains on the left. The trace of the 1872 Owens Valley earthquake scarp is evident in several places, most obviously on the left-front flank of the small shield volcano in the foreground.
*Source: William Bowen*

## CAN WE MAKE THE EARTH "TRANSPARENT" AND OBSERVE UNDERGROUND PROCESSES IN ACTION?

Rock is opaque; scientists can't "see" into the system they are exploring. Just as medical imaging techniques have revolutionized the practice of medicine, so would accurate subsurface imaging benefit the entire spectrum of basic and applied geoscience. Computer modeling advances now allow scientists to postulate how subsurface processes unfold, but until researchers can delve into the opaque rock, they cannot verify computer predictions. Advances in geophysical techniques are gradually revealing more details of the structure of the crust and the process operating within it, but a concerted effort could provide needed levels of precision on a variety of scales.

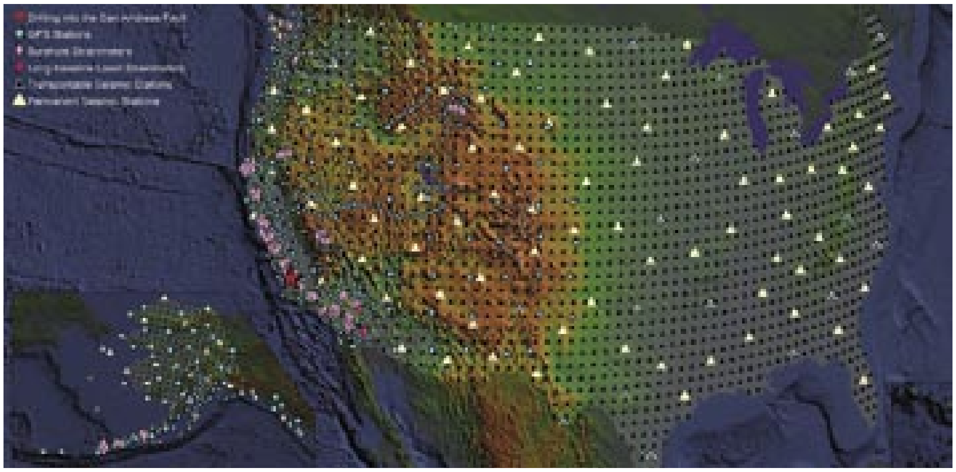
Seismic surveying from the surface is currently the main approach for imaging the deep earth and some impressive advances offer promise that more can be achieved. Subsurface geology is typically only inferred from the study of surface outcrops and samples from boreholes and mines. A deep underground laboratory would allow direct verification or "ground-truthing" of seismic imaging. Researchers could verify surface-based predictions of underground structures directly from a deep, three-dimensional volume of rock. Directly accessible underground, this rock volume would also serve as a test bed for imaging research and the development of new imaging techniques. Detailed views just 10~20 meters or so into the rock can illuminate coupled processes, follow slip development on faults, and help prevent catastrophic collapse in tunnel borings.

Surveying in a paleoseismic trench. The trench was excavated across a part of the Pajarito fault system in the Rio Grande rift, New Mexico. Trenching on this and other nearby faults revealed that three magnitude 6-7 earthquakes have occurred here in Holocene time.
*Source: Claudia J. Lewis*

## GEOSCIENCE AT A DEEP UNDERGROUND LABORATORY

A Deep Underground Science and Engineering Laboratory dedicated to long-term basic and applied research would provide a unique window on the unseen subterranean processes that so profoundly affect humanity's life on the planet's surface. Geoscientists, working with scientists from biology, physics and other disciplines would conduct fundamental experiments on research themes including transparent earth, groundwater, rock deformation, coupled processes, and dark life.

DUSEL would also provide an opportunity for very deep drilling into the upper crust. Depending on the site chosen, deep holes drilled from the lowest levels could provide valuable information on geophysics of the earth's crust, thermal structure at depth, tectonic stresses, and formation of ore deposits. Sites now under consideration for DUSEL are mines so research on the genesis of ore deposits is a logical component of studies in the underground laboratory. Drilling of deep boreholes involves high temperatures [(200-300)°C] and would provide valuable opportunities for technological innovation of particular interest to the petroleum industry. In summary, a deep underground laboratory would allow geoscientists to peel back the earth's surface and discover the mysteries of the deep underground. ■



EarthScope is a bold undertaking to apply modern observational, analytical and telecommunications technologies to investigate the structure and evolution of the North American continent and the physical processes controlling earthquakes and volcanic eruptions. Thousands of stations are being installed across the country and a 3.2km borehole has been drilled into the San Andreas Fault. The borehole will be instrumented to observe the deformation behavior of the Fault. In addition, EarthScope will purchase 2,500 campaign GPS and seismic instruments, which will be available for temporary deployments and individual research experiments. Most of the stations will transmit data in real-time to data collection centers for an additional 15 years. All of the data from EarthScope will be freely and openly available to the scientific community, the educational community, and the public.
*EarthScope is funded by the National Science Foundation and conducted in partnership with the US Geological Survey and NASA.*
*Source: EarthScope*

# GRAND RESEARCH QUESTIONS IN EARTH SCIENCE

A National Academy of Sciences study of Geoscience is in progress. It has identified 11 central questions of the field. Deep underground research directly addresses six of them.

**How did life begin on earth?**
The withering radiation and intense meteorite bombardment at the surface of the early earth presented a challenge for the origins of life. Although the subsurface represents a possible haven for early life, does it possess the necessary attributes for life to develop? If so, then life could be present within planets in our solar system that could never have supported life on their surfaces. In a deep underground laboratory biochemists and biophysicists could perform experiments in situ, within the confines of a high-pressure fracture zone to explore the influence of mineral surface properties and electrolyte interactions on origin-of-life processes.

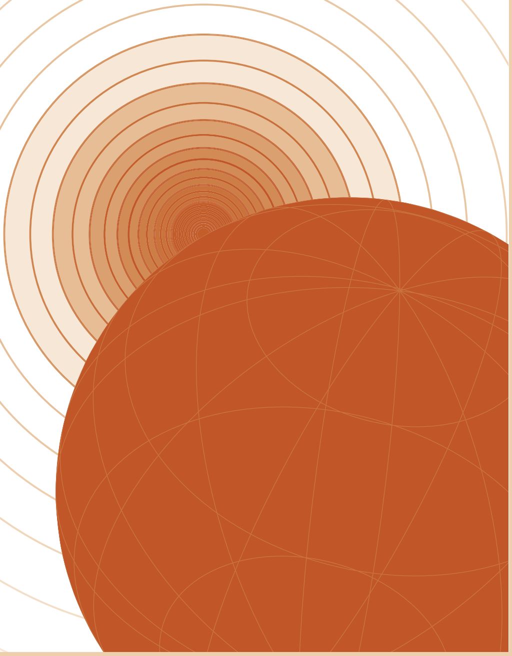
**Why does earth have a magnetic field?**
The origin and evolution of earth's geomagnetic dynamo is tied to its energy sources, and this in turn depends on the composition of the core. Does earth's core contain a natural "georeactor"? By observing the number of neutrinos emanating from the core, scientists at a deep underground laboratory, along with other neutrino observers, could detect the amount of radioactive decay in the earth's core to determine whether a georeactor sustains the earth's magnetic field.

**Can we understand and predict catastrophic natural events?**
Earthquakes result from unstable slip along faults in the earth's crust. A deep underground laboratory would offer the opportunity to measure directly and confirm the seismic properties of rock in place at depth, including the important effects of fluid flow. Scientists could examine slip processes on small faults to calibrate and refine theoretical models in order to see how slip processes can be scaled in size and time. Detailed knowledge of seismic properties and fluid flow are key to the understanding of what causes earthquakes, an important step toward predicting future earthquakes.

**How do material properties control planetary processes?**
The subsurface of our planet is teeming with active—albeit very slow—processes. Geoscientists would use a deep underground laboratory to study these interactions over a substantial volume of rock as part of a major program to develop geophysical and other imaging techniques to make the rock "transparent." These "Transparent Earth" experiments would provide for high-resolution mapping of three-dimensional rock properties, leading to a fundamental understanding of how they control the active processes in the subsurface.

**How do air, water, land, and life processes interact to shape our environment?**
The interactions among subsurface microbial communities, the chemical constituents of ground water, and the minerals and organic materials present in rock control the quality of drinking water, the formation of natural gas and carbon dioxide, and the potential for long-term storage of nuclear waste. A deep underground laboratory would provide a field site for studying these interactions over multiple decades, leading to models that couple the interactions of biology, chemistry, hydrology, heat and rock deformation.

**How has earth's interior evolved, and how has it affected the surface?**
The rock exposed in DUSEL is likely to be of several types, all subjected to hundreds of millions of years of tectonic stresses. Detailed analysis of the current state of stress in the rock, using stiffnesses measured on laboratory specimens, could provide valuable insights into the long-term viscous processes associated with the tectonic phenomena. The underground environment would provide a low seismic background opportunity to study the earth's interior by analysis of the behavior of seismic waves that have been propagated from natural events globally. Experimental study of the coupled processes of slip on (small) faults can also provide insights into the mechanics of earthquakes. Although the depth of DUSEL is a minute fraction of the 6500 kilometers of the earth's interior, it contains the depth that holds all of the accessible mineral resources, including groundwater, upon which civilization is critically dependent.



## CHAPTER FOUR

# GROUND TRUTH

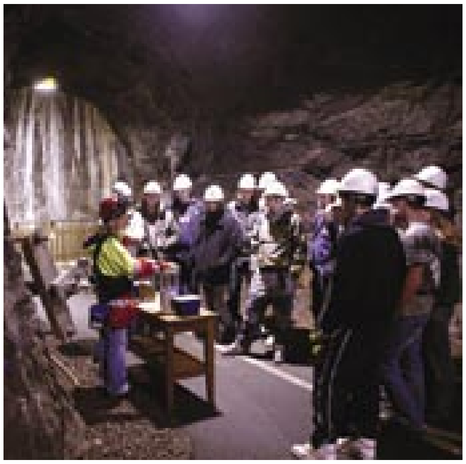
What are the mechanical properties of rock?
What lies between the boreholes?
How does rock respond to human activity?
How does water flow deep underground?
How can technology lead to a safer underground?

**The 21st-century exerts increasing demands to go underground. Expanding and developing populations put growing pressure on surface space, driving mass transit systems, hydroelectric plants, energy storage and waste disposal facilities and a host of other systems underground. The depletion of shallow mineral and energy resources sends prospectors ever deeper in search of essential raw materials and new sources of energy. Yet despite the demand for subsurface space and resources, major engineering obstacles to underground use remain.**

**Light at the End of the Tunnel**
A Tunnel Boring Machine (TBM) in the process of excavating a circular tunnel, 8m in diameter. The well-lighted trailing gear of the TBM provides work space for the miners as well as the scientists performing experiments as tunneling progresses. Lighting emphasizes the TBM to the right of the trailing gear. *Photograph by David Wehner, provided by the U.S. Department of Energy*

# GROUND TRUTH

Road Header machines, though slower, are capable of excavating more complex geometries than the TBM and are used, as an alternative to blasting, to develop auxiliary openings leading from the main TBM tunnels. The cutter head swings up and down and across the face of the heading, cutting into the rock and dropping fragments onto the steel apron. Gathering arms move the 'muck' onto the conveyor and out of the tunnel. The large circular ventilation duct provides fresh air to the heading.
*Photograph by David Wehner, provided by the U.S. Department of Energy.*



Students visiting the Äspö Underground Research Laboratory in Sweden listen to an explanation of an experiment to test the effectiveness of a full-scale seal, consisting of an expansive clay, sand and cement mixture. The seal is intended to isolate nuclear waste underground from the living environment. The sealed section of the tunnel can be seen (illuminated) on the left of the photograph.
*Source: SKB, Sweden*

## SERVING SOCIETY

The stability of deep underground structures depends critically on the strength and mechanical properties of rock, the environment in which rock exists, and the consequences of engineered changes. Unlike the properties of engineered materials such as concrete and steel, properties of rock vary markedly in space and time and often defy accurate prediction. All too often, the nature of rock as revealed by excavation and underground construction differs dramatically from the expected.

The resulting uncertainties in the underground engineering process drive up construction costs and increase both the human and economic risks of underground activities. Underground engineering has necessarily followed a conservative path based on empirical rules derived from experience in previous projects—rules that cannot reliably be extrapolated to new underground environments. It will take a systematic and sustained program of underground research to yield the new technologies for the accurate prediction of rock conditions and behavior if we are to take full and wise advantage of the underground dimension. Engineering research at a deep underground laboratory would support advances in underground construction practices, making them more cost-effective and less risk-prone. Key engineering elements of an engineering research program would include rock characterization, design and construction, rock engineering, underground technology and safety.

## WHAT LIES BETWEEN THE BOREHOLES?

The ability to recognize and characterize rock's complexity is important for design and construction both on the surface and underground. The consequences of inaccurate or incomplete characterization can be catastrophic.

As noted earlier, borehole-based investigations provide little direct evidence of rock's inherent complexity. Developing better remote sensing techniques to image the rock mass at depth would be a core component of an underground engineering research program, a superb opportunity for geoscientists and engineers to work together to develop technologies to characterize rock in all its natural complexity. The characterization of rock variables, such as intact strength, fracture, fluid flow and forces, poorly captured by current technologies, could be revolutionized by the development of emerging remote-imaging technologies.

## HOW DOES ROCK RESPOND TO HUMAN ACTIVITY?

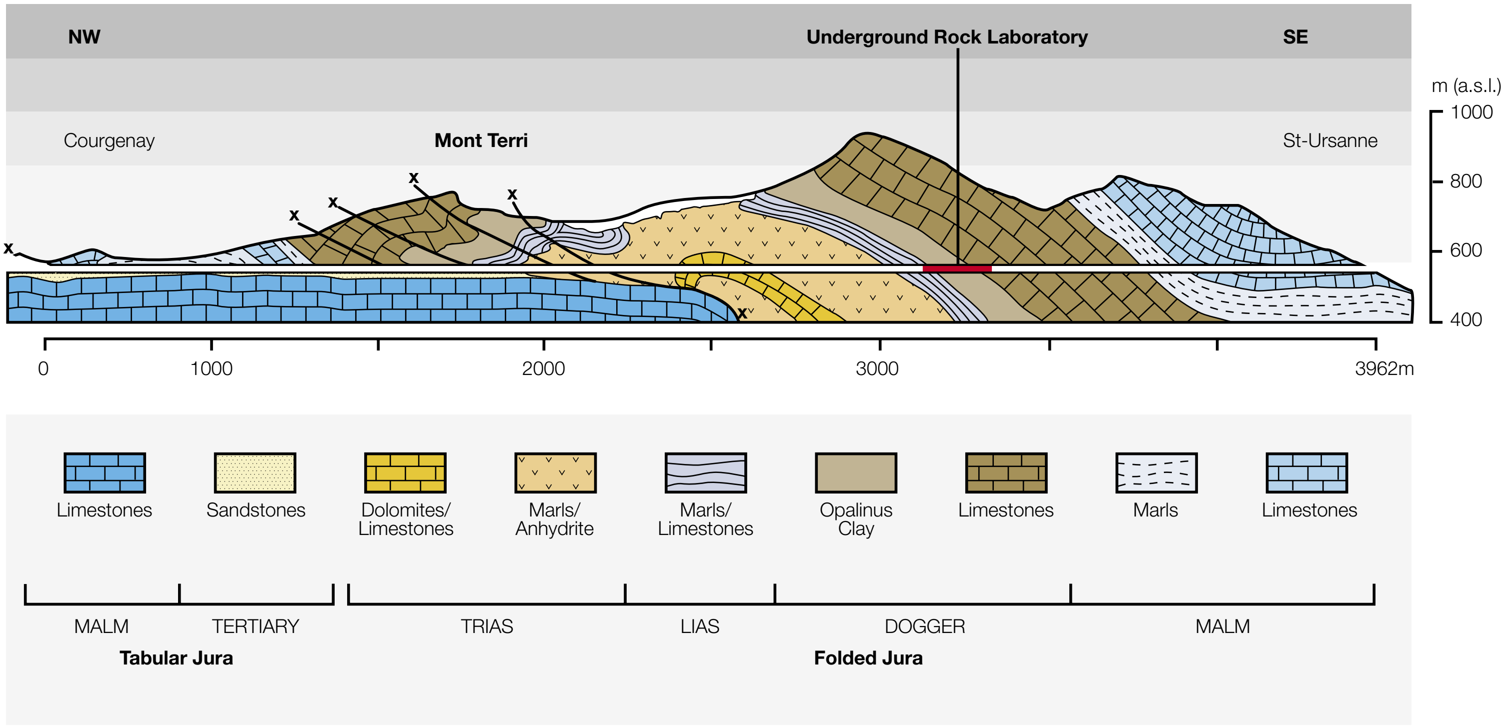
The stability of both surface and subsurface structures excavated in rock relies on rock's strength and mechanical properties. Yet systematic knowledge of how rock reacts to such human impositions is inadequate and often indirect, inferred from surface-based studies and borehole data alone. In the absence of direct basic knowledge of the rock, engineers continue to rely on rock-mass classifications developed using the small-scale data sets afforded by surface observation, coring and observation of the behavior of full-scale engineered structures. Building a deep underground laboratory would involve creating a substantial number of tunnels and large caverns at depth. The combination of depth and span for some of the caverns, and the requirement for stability over decades goes beyond current experience. Thus, the construction period itself represents a special opportunity for innovative excavation designs and experiments. Excavating large caverns for physics experiments, for example, would redirect and intensify the gravitational and tectonic forces in the rock around the cavity.

Advances in computing permit geoscientists to incorporate many of the complex and coupled influences on rock mass behavior into predictive models. As yet, however, no laboratory exists where such models can be tested on a useful scale. An underground laboratory would overcome this barrier by allowing engineers to “ground truth” their theoretical models and advance toward more rational and reliable underground design. Design-predicted values could be calibrated against excavation realities, yielding real-time model improvements. The data from an underground laboratory would support an accurate three-dimensional representation of the rock system *in situ,* which would, in turn, provide accurate input to the sophisticated software packages now available to model and analyze rock and fluid behavior. Instrumentation and long-term monitoring of the rock would further enhance model reliability.

Building a deep underground laboratory would involve creating a substantial number of tunnels and large caverns at depth. Excavating large caverns for physics experiments, for example, would redirect and intensify the gravitational and tectonic forces in the rock around the cavity. From small advance tunnels, engineers could monitor these changes and their effects on the rock as cavity excavation proceeds. The use of explosives to excavate the caverns provides opportunities for research on wave transmission in rock. The stability of supports in auxiliary tunnels close to the large caverns can be evaluated under conditions of dynamic stress, a topic of potential interest to the Department of Homeland Security. The development of precise electronic detonators also opens exciting opportunities for the use of explosives-driven waves in “conditioning” rock to prepare it for excavation by low-cost bulk methods.

## SAFETY UNDERGROUND

Safety and health would have the highest priority in the engineering of a deep underground laboratory and would be fully integrated into the design of laboratory activities at every stage of planning, design and construction. An underground laboratory would also provide an ideal laboratory for research and development leading to advances in underground safety systems and technology. Scientists and engineers could carry out safety and health research within a deep, controlled underground setting. Particular attention would go to advances in key areas such as underground communication, ventilation, access, emergency egress and refuge design. Because the temperature of rock increases with depth, typically 10ºC-30ºC per km, engineers would also undertake mechanical-systems research in the areas of air conditioning and filtration to support human activity and research at depth.



Mont Terri is an underground research laboratory (URL) in Switzerland. The laboratory is located in tunnels excavated from a safety (emergency) tunnel that runs parallel to a highway tunnel through a section of the Swiss Alps. The Opalinus Clay, in which the URL is placed, occurs in several locations in Switzerland, and is considered to be well-suited for isolation of radioactive waste. No waste will be placed in the Mont Terri site. The picture illustrates the geological complexity that one can encounter underground.
*Source: Dr. Peter Blümling, NAGRA (Swiss RadioAactive Waste Agency)*

## ROCK ENGINEERING—A DEEPER UNDERSTANDING

A major opportunity of a deep underground laboratory would be the availability of a large block of rock in situ exclusively for long-term scientific and engineering research. A broad suite of rock engineering studies would address a wide range of fundamental questions in rock behavior and fluid flow in rocks. Under moderate stress, excavation stability is largely determined by rock fracture. Under conditions of high stress, hazardous ground behaviors increase. Not only does the fall-out of fracture-bound blocks create hazards for underground construction, but underground operations may also encounter "rockburst" conditions. Rockbursts, earthquakes triggered in intact rock by underground operations, are a deadly and costly hazard for mining and underground construction operations. Research on the stability of fracture-bound blocks and the safe and nonviolent release of rockburst energy would have significant benefits for mine safety and efficiency.

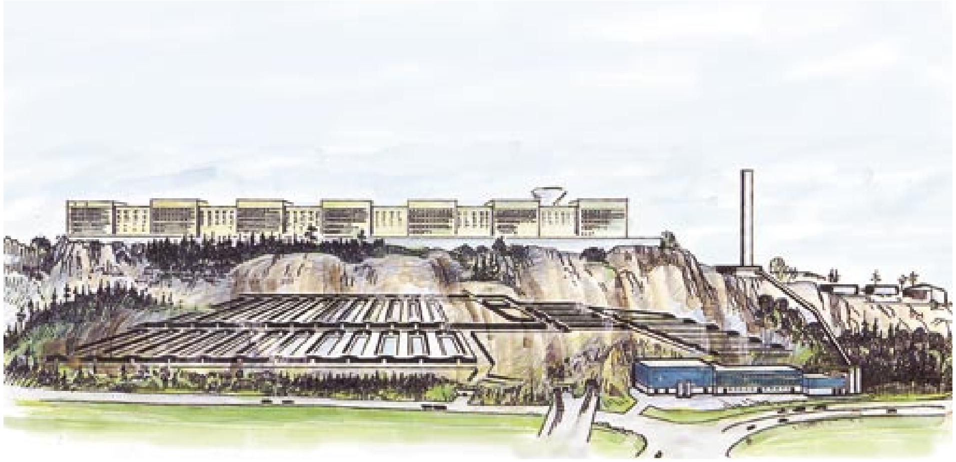
A deep underground laboratory would provide an ideal site for the study of groundwater system behaviors at depth. An improved understanding of fracture flow would aid reservoir engineers in protecting drinking water supplies, facilitate the bioremediation of contaminated aquifers and enhance energy recovery from geothermal systems. An improved understanding of fluid flow in rock could enable bioengineering advances for the in-place extraction of mineral resources.

## TOWARD A BETTER-ENGINEERED UNDERGROUND

An underground laboratory would provide both the academic and industrial communities with low-cost, long-term access to underground research sites. In a large, dedicated facility, new equipment and material trials could take place under a wide range of *in situ* conditions, and field tests could go forward without the production constraints imposed by mining operations.

A deep underground laboratory represents a unique opportunity for engineers to conduct both fundamental and applied research that would directly address societal needs. It would catalyze major advances in underground engineering and contribute strongly to a fundamental understanding of the rock mass. It would also provide an extraordinary opportunity for innovation in underground technology with immediate and long-term benefits for the economic well-being of the nation, for the protection and remediation of the environment, and for human life and safety. ■

Stockholm's waste-water treatment plant, the largest in northern Europe, is housed in 10 km of tunnel inside a hill. A residential area has been built on top of the facility. The Scandinavian countries have been very innovative in the use of underground space in urban areas, stimulated by the high quality granite that underlies the region. If we had reliable cost effective technologies in less competent rock types, then other urban areas around the world could be planned far more effectively adding the third dimension (down!) to reduce surface congestion.
*Source:* Going Underground, *Royal Swedish Academy of Engineering Sciences*



The concept of placing sewage plants underground was discussed in a meeting in the1980's between the Stockholm City Council and some Minnesota State legislators. "Why do you put the sewage treatment plants underground?" asked one of the Minnesota group. Replied a Council member, "That's where the sewers are!"
*Source:* Going Underground, *Royal Swedish Academy of Engineering Sciences*

# POSTCARD FROM PERSEPHONE

**In Greek myth, Hades, the god of the underworld, abducted the young Persephone, daughter of Demeter, the goddess of the earth. Hades carried Persephone off to the underworld and held her captive. In Demeter's grief at the loss of her daughter, she condemned the earth to eternal winter. The world would have starved if Zeus had not intervened to obtain Persephone's release. Before she left, though, Persephone ate six pomegranate seeds, which meant that she had to return to the underworld for six months of every year. Each year, according to the myth, when Persphone returns to her mother, winter ends and spring arrives. Until one day…**

*Dear Mom,*

*I don't know how to say this, but I won't be coming topside for a visit this year. Of course I'll miss you, and it will be a drag to skip spring and summer. But there's so much happening down here that I can't tear myself away.*

*True, the underworld was dreary at first. It was dark, there was nothing to do, and Hades totally got on my nerves. I couldn't wait for my annual leave. Now though, things have changed—I'm having the time of my life. The underworld is full of scientists, and there is never a dull moment!!!! I have joined a neutrinoless double-beta decay experiment, and if we find what we think we're going to find, it will absolutely change the way we see the universe. We'll know what happened to the antimatter after the Big Bang! Finally!!! I was tempted to sign on to a geoscience study of what causes earthquakes —trust me, it's not Atlas shrugging— or an astrophysics search for dark matter, but ultimately the neutrinos won out. (After a few eons down here, dark matter gets old…) Anyway, I will be taking shifts on my experiment, POMEGRANATE, over the next six months, so I won't be visiting you this year.*

*Another plus: Hades and I are actually getting along. He has become spokesperson for a geomicrobiology experiment looking at how life even survives in the underground without light, at incredible temperatures and pressures. (Tell me about it!) Between carbon 14 analysis and writing grant proposals, he's so busy I hardly see him, but he's truly a different person. He says it's possible life on earth actually started out down here. (No offense, Mom.) I must run—collaboration meeting.*

*Your loving daughter,*
*Persephone*

*Dear Persephone,*

*Got your note. Any room on the dark matter search for an Earth Goddess? I'm putting the seasons on "auto" and coming on down.*

*Your mother,*
*Demeter*

Modern day Persephone.
*Illustration: Modified by Sandbox Studio*
*Based on Triptolemus and Kore, tondo of a red-figure Attic cup by the Aberdeen Painter, ca. 470 BC–460 BC, found in Vulci*

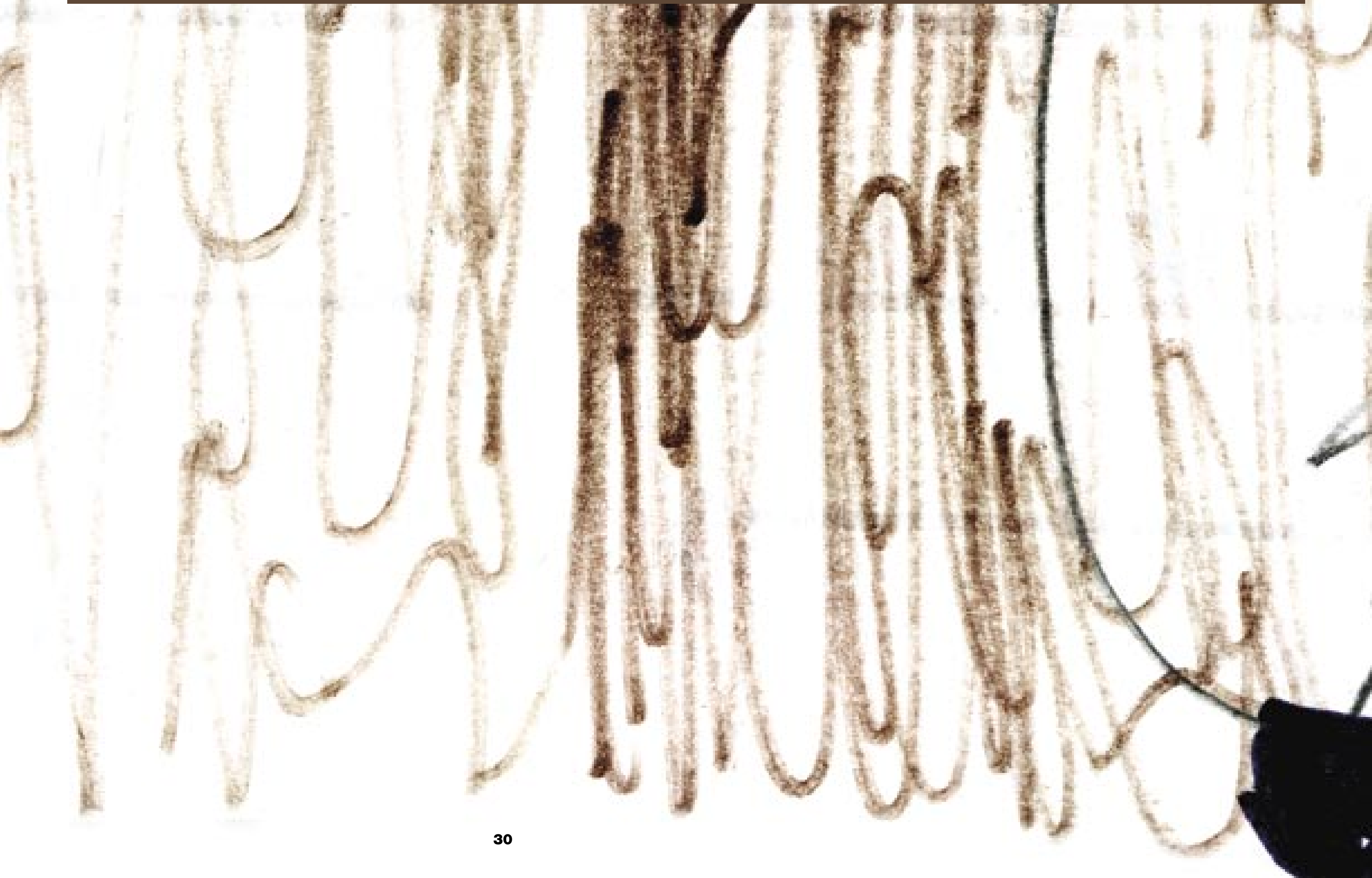
CHAPTER FIVE

# GONA DIG A HOLE

**“It is easy to be complacent about U.S. competitiveness and preeminence in science and technology. We have led the world for decades, and we continue to do so in many research fields today. But the world is changing rapidly, and our advantages are no longer unique. Without a renewed effort to bolster the foundations of our competitiveness, we might lose our privileged position. For the first time in generations, the nation’s children could face poorer prospects than their parents and grandparents did. We owe our current prosperity, security and good health to the investments of past generations, and we are obliged to renew those commitments in education, research, and innovation policies to ensure that the American people continue to benefit from the remarkable opportunities provided by the rapid development of the global economy.”**

(*Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future, 2005,*
Committee on Science, Engineering, and Public Policy [COSEPUP], The National Academies.)

**A strong multidisciplinary program of deep science research is an important element of a renewed national commitment to scientific education and leadership in basic science. It promises to advance fundamental science, produce direct benefits for important sectors of the nation’s economy, and contribute to educating the next generation of scientists and engineers.**



**Thank you letter**
Letter received received from a 4th-grader after a class visit by Chris Laughton to talk about underground research.
*Source: Chris Laughton*

# GONA DIG A HOLE

May 3 2000

Dear Mc Laughton,

Thank you for coming
I thougt it was great! After
the presentation I felt like
that I was gona dig a
hole Thank you for leting
us see all of the different
kinds of Rocks Thank you
again!

Sincerely,
McCoy

Letter received received from a 4th-grader after a class visit by Chris Laughton to talk about underground research.
*Source: Chris Laughton*

## EDUCATING THE NEXT GENERATION OF SCIENTISTS AND ENGINEERS

Higher education is based on research, and deep underground science and engineering provide essential opportunities for undergraduate and graduate students. They also bring a unique sense of adventure. The cross-disciplinary synergy that is starting to appear promises to foster a new breed of scientists and engineers skilled in multiple-science techniques and cross-cutting applications.

The growing demand for underground facilities has spawned a critical need for experts in all aspects of subsurface engineering, including safety. The increasing cost of and worldwide demand for mineral resources is inducing a renewal of the American mining industry. Combined with elimination of mining engineering from the curriculum of many universities over the past several decades, this has produced a critical shortage. Reflecting the supply-demand imbalance, mining engineers are now among the highest-paid engineers. Moreover, the never-ending quests for new water resources, waste management facilities and energy storage have created an urgent need for underground environmental engineers to help the nation make good use of the earth's natural reserves. The U.S. is training diminishing numbers of scientists and engineers in these specific areas and yet the need for them grows. Intensifying our effort in deep underground science and engineering would certainly help reverse this trend.

Underground laboratories, such as Soudan, have active outreach programs, which stimulate young minds and create excitement about science. They also integrate postsecondary training with K-12 education through interaction with local schools and internships for nationally recruited K-12 teachers. A national underground initiative would strengthen these programs. The combination of physics, astrophysics, biology, earth sciences and engineering would offer new opportunities to acquaint students with the scientific method applied to a variety of problems and inspire them to ask fundamental questions, cutting across traditional disciplines. A strengthened Deep Science program would contribute to the revitalization of science education both at the K-12 and informal levels, enabling a broader diffusion of standards-based curriculum materials, and close collaboration with science centers across the country.

A particularly important aspect of a national initiative in Deep Science would be to enhance the diversity of the scientific and engineering workforce. Building on existing successful strategies, it would develop innovative programs that create research-experience opportunities for underserved students, involve teachers from minority-serving schools, and engage women and minority scientists as role models.

## UNDERGROUND FRONTIERS

The exploration of the underground frontier directly addresses the fundamental yearning of humanity to understand its place in the cosmos, the nature of the dark universe, the mechanisms of the ever-changing earth, and the existence of unexplored new forms of life. The public's fascination with the universe, the lure of the subsurface world, and the eagerness to find answers to big questions of 21st-century science offer an exceptional opportunity for public engagement.

The creation of a Deep Underground Science and Engineering Laboratory would provide additional opportunities, with infrastructure for education and public involvement incorporated in the laboratory's design from the start, with facilities both on the surface and underground. Tours, interactions between scientists and the local community, a compelling presence on the Web, collaboration with science museums and centers across the nation, and active media involvement would form the core of the laboratory's public-communication plan. An underground laboratory would also provide significant opportunities to work with local residents, community officials and legislators, to help fulfill the community vision of the laboratory as a local employer, an instrument in regional economic growth, an educational resource, and a valued contributor to meeting critical national and international needs.

## DEEP BENEFITS

Deep science and engineering contribute to U.S. economic competitiveness through research central to effective stewardship of the environment and the mitigation of natural disasters. Investigations of deep subsurface microbial interactions hold the promise of significant practical benefits. Organisms from deep subsurface environments have already yielded biotechnological treasures in the form of highly reactive, thermally stable enzymes and microbially precipitated nanoparticles that can be used in industrial and environmental applications. Subsurface microorganisms probably play key roles in the formation and dissolution of minerals, especially ore minerals, and in the alteration of petroleum. A South African mining company has harnessed heat-tolerant microbes to extract zinc, copper and strategic metals from sulfide ore. Discovering how industry might use subsurface microbes to enhance the recovery of underground reserves may have critical implications for a world of diminishing resources. DUSEL would also contribute to the development of technologies that inhibit biocorrosion of underground infrastructure, the costliest aspect of mining and maintenance of underground structures.

Finally, a fundamental knowledge of subsurface biogeochemical processes and elemental cycling is critical for predicting the long-term stability of underground radioactive waste and carbon dioxide sequestration. The secrets of dark life may prove extremely important to our nation's health, as well as its energy and environmental security and well-being.

Analysis of the behavior of large rock masses at depth is critical to the understanding and predicting of earthquakes. A better understanding of underground water-flow systems may contribute to solutions to the growing shortage of fresh water resources. The development of waste storage is already a central component of underground science and engineering.

By providing long-term experimental access to greater scales of rock mass, a deep underground laboratory would generate fundamental advances in subsurface modeling technologies, advancing the dream of a "transparent earth." The engineering studies for the construction of such a facility and the monitoring of cavities during many decades will certainly yield better and more cost-effective methods of underground construction, benefiting the mining industry and improving design and development of underground facilities for countless purposes. The construction and operation of the laboratory with safe, general access as a major priority offers opportunities to hasten the development of better safety measures for the protection of human life in mining operations and underground construction. ■

Young people have an innate interest in science and welcome the excitement of hearing about research in novel environments such as outer space and deep underground. *Source: Elizabeth Arscott*

Graduate student Laura Stonehill guiding a readout cable for neutron counters into the Sudbury Neutrino Observatory detector 2 km below ground. The detectors are used to measure the neutrino flux from the sun and from cosmic rays. *Source: Jaret Heise*

CONCLUSION

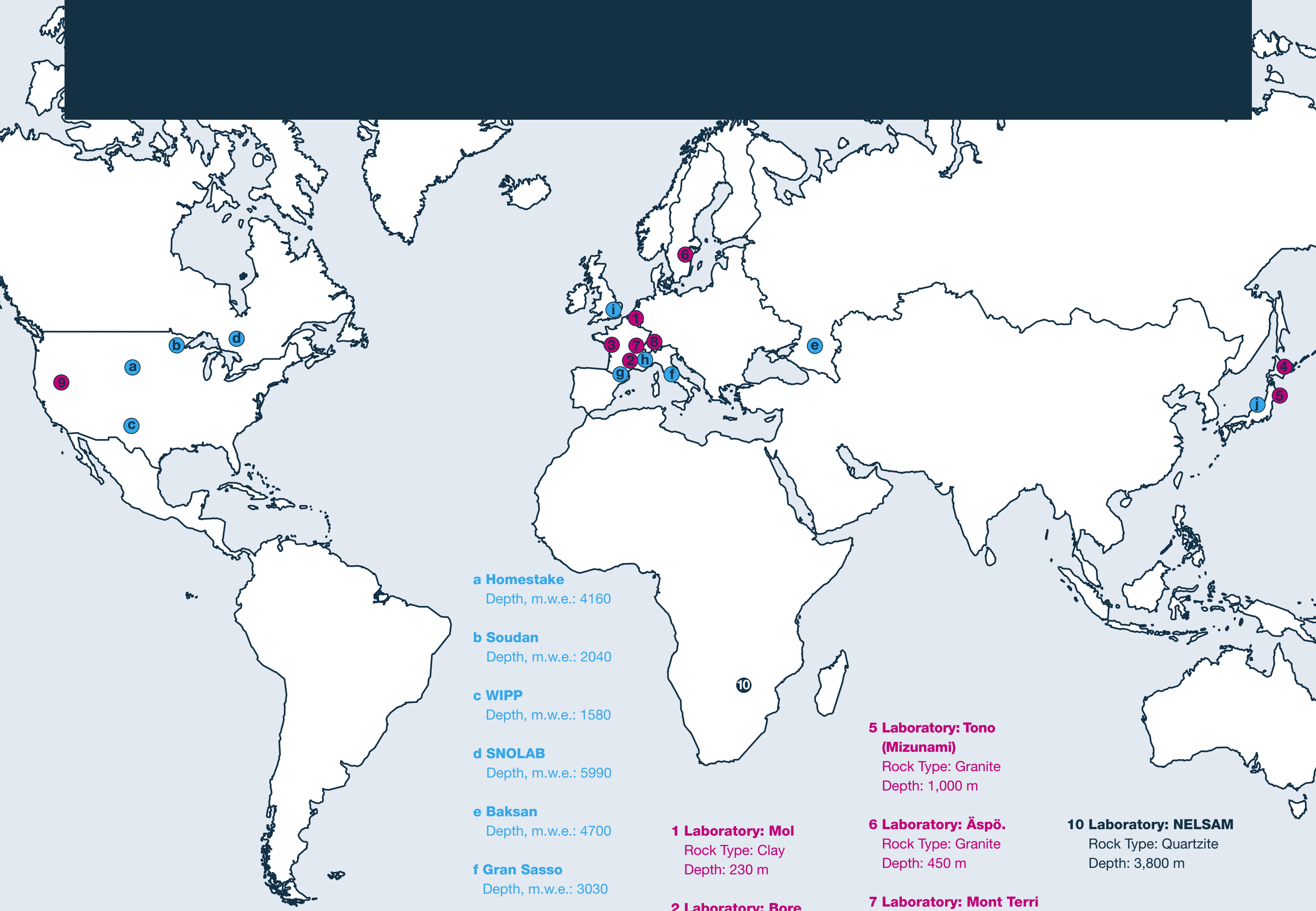
# THE DEEP FRONTIER

When Frederick Reines, a physicist, and Raymond Davis, Jr., a nuclear chemist went underground 40 years ago to search for elusive neutrinos, very few people expected them to find results that would revolutionize modern physics, and yet their Nobel-prize winning experiments gave birth to modern neutrino science. In 1989, underground detectors built to search for proton decay detected for the first time neutrinos emitted by a supernova and confirmed the understanding of the way stars explode. A subsequent generation of underground physics experiments in Europe, Japan and Canada established that neutrinos have a finite mass, thereby resolving the puzzles created by earlier results and opening a totally new field of study for particle and nuclear physics. Together, underground physics and astrophysics have led to three Nobel Prizes and broadened human understanding of the universe.

It is not a wild extrapolation of history to assert that deep underground research will similarly contribute to answering critical questions of 21st century science and engineering. Discoveries will come not only in physics and astrophysics, where scientists will explore the properties of neutrinos the nature of dark matter, for example, but also in biology, where research will include the investigation of the genome and evolution of subsurface microbes. Earth scientists will map the mechanisms responsible for the deformation of the earth crust,) and engineers will characterize the strength of large rock mass and the transport of fluids. Moreover, as in the serendipitous discovery of supernova neutrinos by proton-decay experiments, investigations with powerful underground instruments can expect to encounter totally novel phenomena.

It is clear that an important frontier of modern science is underground. A systematic and coordinated approach to underground science will lead to significant scientific progress. There is also much to be gained by bringing together scientists from different fields whose paths might otherwise rarely cross. Underground research has the potential to have a large positive impact on our economy, environment, education and well-being. Deep underground science and engineering represents a remarkable opportunity for the U.S., best pursued through a Deep Science Initiative. Such an initiative would focus expertise of multiple fields of science to solve key problems. It would maximize the use of existing facilities and international collaborative opportunities and complement the existing infrastructure with a very deep underground laboratory that will attract the best experiments from across the world.

# FACILITIES, FINDINGS AND RECOMMENDATIONS



**a Homestake**
Depth, m.w.e.: 4160

**b Soudan**
Depth, m.w.e.: 2040

**c WIPP**
Depth, m.w.e.: 1580

**d SNOLAB**
Depth, m.w.e.: 5990

**e Baksan**
Depth, m.w.e.: 4700

**f Gran Sasso**
Depth, m.w.e.: 3030

**g Canfranc**
Depth, m.w.e.: 2450

**h Fréjus/Modane**
Depth, m.w.e.: 4150

**i Boulby**
Depth, m.w.e.: 2805

**j Kamioka**
Depth, m.w.e.: 2050

**1 Laboratory: Mol**
Rock Type: Clay
Depth: 230 m

**2 Laboratory: Bore**
Rock Type: Clay
Depth: 450 m

**3 Laboratory: Tournemire**
Rock Type: Clay
Depth: 300 m

**4 Laboratory: Horonobe**
Rock Type: Sedimentary
Depth: 1,000 m

**5 Laboratory: Tono (Mizunami)**
Rock Type: Granite
Depth: 1,000 m

**6 Laboratory: Äspö.**
Rock Type: Granite
Depth: 450 m

**7 Laboratory: Mont Terri**
Rock Type: Clay
Depth: 300 m

**8 Laboratory: Grimsel**
Rock Type: Granite
Depth: 450 m

**9 Laboratory: Yucca Mountian**
Rock Type: Volcanic tuff
Depth: 300 m

**10 Laboratory: NELSAM**
Rock Type: Quartzite
Depth: 3,800 m

Figure 1: Underground laboratories worldwide. Physics laboratories (cyan) are listed with their depths in meters of water equivalent. Laboratories for research into the long-term (~million-year) isolation of high-level nuclear waste, shown in magenta, are listed with actual depth. The NELSAM laboratory (navy) is for earthquake research.

# Facilities for Deep Science

**What facilities will it take to carry out the compelling science of the underground? Briefly, it will require more underground facilities at greater depth, taking full advantage of international collaborative opportunities, and at least one deep underground laboratory in the U.S.**

## THE NEED FOR UNDERGROUND FACILITIES AT DEPTH

Although some investigations can be carried out at intermediate depth, it is clear that the frontier of underground science is at great depth. For physicists and astrophysicists, this is simply the quietest environment, with the lowest background noise from cosmic muons that limit the sensitivity of searches for neutrinoless double beta decay and dark matter, as well as for certain solar neutrino interactions (see sidebar). Depth is also the frontier for geomicrobiologists, who require pristine environments to study underground microbes *in situ,* with minimum disturbance of the underground environment. Starting from the lowest possible depth, biologists could drill down to measure to what temperature and pressure life continues to exist. Geoscientists also need to understand rock under the constant influence of biology, water, chemicals, heat and stress. Experiments in boreholes extending several kilometers below the lower levels of a deep underground laboratory would also be very valuable to them. Moreover, they require an opportunity to vary these parameters on a large volume of rock for long intervals of time. They must also go underground in order to verify, or ground-truth, the new computational and remote-sensing techniques that are being developed to make the earth "transparent." Such studies are complementary to those currently done in relatively shallow underground laboratories devoted to waste storage research Figure 3). The challenges of large depth for engineering will push the envelope of underground design and construction methods.

Because of its success and compelling nature, interest in deep underground science is growing. The trend is particularly strong in physics and astrophysics, with the recognition that discovering the nature of the quantum universe requires a coordinated program for discovery based on underground experiments combined with observations in space and experiments at particle accelerators. Similar trends exist in geomicrobiology, which emerged as a field some 20 years ago, and in the geosciences and engineering, where dependence on the subsurface as a multi-faceted resource is growing.

Figure 2 shows as an example the increase in the number of physicists involved in the search for weakly interacting massive particles that may form the dark matter in the universe following a seminal paper by Goodman and Witten 20 years ago. The recent discovery at underground experiments that the neutrino has mass has intensified interest in the search for neutrinoless double beta decay.

The importance of the scientific questions argues for carrying out several experiments with similar scientific goals using different technologies, as a protection against unexpected technical difficulties, such as unanticipated backgrounds in physics experiments. Besides providing an important cross check on results, comparisons between experiments often provide significant additional information. Because experiments are increasing in scale and complexity, their life cycles become longer and longer (10-15 years for large physics experiments). To maintain reasonable progress, it is necessary to start installing the next generation experiments while existing ones are still in active operation.

It is difficult to make an exact prescription of the need for underground space: a simple scientific wish list is unrealistic, and the need depends on scientific priority, on funds allocated to underground experiments in each of the fields, and on the scientific policy pursued by the agencies (e.g. with respect to the number of experiments pursuing parallel objectives). But the long-term trend is clear: in the next decades the demand for dedicated long-term research space underground will increase.

## GLOBAL CONTEXT

Like most modern scientists, underground researchers are deeply involved in international collaboration. This global cooperation applies not only in physics—as at the Sudbury Neutrino Observatory in Canada or in Japan's KamLAND and Super-Kamiokande experiments—but increasingly in geosciences and biology, as at the Natural Earthquake Laboratory in South African Mines. The trend toward internationalization accelerates with the increasing size and complexity of experiments. The costs of some projects—large detectors for neutrino physics and proton decay experiments, for example—mandate regional or interregional coordination. Worldwide, strong scientific interest has prompted universities and institutes in several countries to build and operate underground facilities. Figure 3 compares the volume (width of bars) and the depth (height of bars) of the major dedicated underground scientific laboratories in the world (page 35).

**Three observations can be readily made:**

a) In terms of volume available underground, the field is dominated by Gran Sasso in Italy at 3000 m.w.e. (~1400 meters deep). Smaller facilities exist at the Japanese Kamioka laboratories, at the U.K.'s Boulby mine, and at Canfranc, in Spain. In spite of its large size, Gran Sasso is fully subscribed, and major expansion is underway at Canfranc to meet the demands of new experiments. In the U. S., physicists have mostly relied on Soudan. All these facilities are primarily devoted to physics experiments.

b) With the exception of the Natural Earthquake Laboratory in South African Mines (NELSAM), all the earth sciences and microbiology underground research laboratory facilities are limited to shallow depth (<480 m). Limited facilities for hydrological and microbial studies in fractured granite are available at Aspö, Sweden, to a depth of 1200 m.w.e, (480 meters in rock). Several countries (Belgium, Canada, France, Sweden, Switzerland) have developed underground research laboratories (typically about 500 meters deep) for research related to long-term isolation of radioactive waste and are considering the use of these facilities for more general research in the geosciences and in microbiology.

c) There is a relative dearth of deep facilities: SNOLAB (6010 meter water equivalent [m.w.e.] ~2 km of rock), whose scientific facilities are currently being expanded, is the only very deep facility, and it is devoted only to physics experiments. Small facilities are available in the Fréjus/Modane tunnel connecting Italy and France, and at Baksan in Russia, both around 4800 m.w.e. (~1780 meters of rock). The state of South Dakota has recently announced interim funding

Figure 2: Evolution with time of the number of physicists involved in the search for Weakly Interacting Massive Particles (WIMPs), which may constitute dark matter.

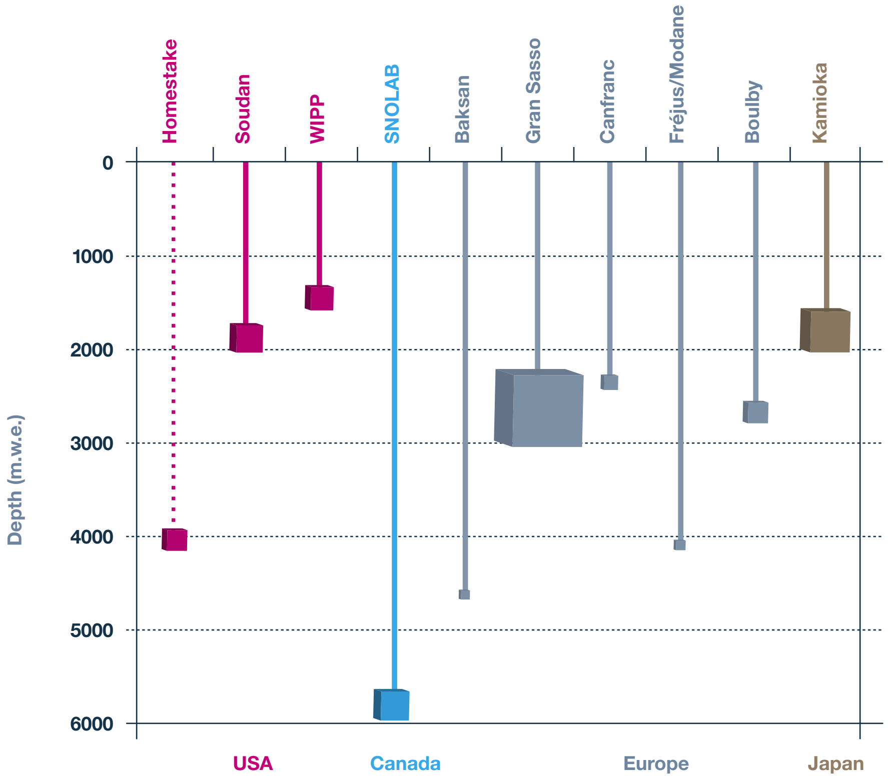


Figure 3: Major underground physics laboratories in the world. The width of each block is proportional to the usable volume of the laboratories underground. The color indicates the country/region (Gray=Europe, Brown=Japan, Blue=Canada, Magenta=U.S.A.).

(The Homestake facility is an interim facility being constructed at a depth of 4850 feet in the former Homestake mine with funding from the State of South Dakota) for the re-opening for science of the 4850-foot level (4050 m.w.e.) of the abandoned Homestake Mine. The National Science Foundation, in its DUSEL solicitation process, has provided funding for the preparation of conceptual designs for a laboratory at Homestake and at the Henderson Mine, an active molybdenum mine in Colorado.

The last decade has seen a severe space crunch for dedicated subsurface science facilities, particularly at large depth. While SNOLAB may serve North American needs in the short term from 2007 to about 2012, in the longer term a serious shortage of space threatens the generation of physics and astrophysics experiments slated for 2012-2015, and for the decade that will follow. Moreover, SNOLAB will not provide significant opportunities for research in other fields. The same lack of space applies to geosciences, biology and engineering, where there are essentially no dedicated deep facilities offering long-term research access. Europe, already home to the largest underground laboratory, is aggressively expanding at Canfranc and considering an expansion at Fréjus/Modane to meet the demand.

### The need for optimal use of existing facilities and for a deep national facility

Existing facilities internationally will not provide a long-term solution to the space problem of the rapidly expanding field of deep underground science. To support this emerging field, the U.S. must optimally use its existing facilities (WIPP and Soudan); take full advantage of international opportunities, in particular at SNOLAB, Kamioka and Gran Sasso; and consider building facilities deep beneath its own soil

Looking at the list of underground facilities worldwide given in Figure 3, it is striking that, at the moment, the U.S. is close to being the only developed country (specifically, in the G8 group) without an underground science laboratory deeper than 2000 m.w.e.. Clearly, this puts the nation at a distinct disadvantage in underground research. Although the results of science and engineering experiments performed in other countries' facilities are shared worldwide, and U.S. scientists have been very successful in international collaboration, important benefits accrue to any country supporting world-class facilities in its own territory. These benefits include leadership in experiment and technology development; rapid follow-up of novel ideas; optimal coordination with other national assets, such as accelerators, seismographic arrays and biological facilities; and impact on the national economy through science and technology transfer and education. There is no adequate substitute for a national facility.

A deep national science and engineering laboratory would therefore fulfill three goals: provide increased deep underground access to U.S. and foreign scientists in a space-limited international environment, put the U.S. in a stronger strategic position in deep underground science, and maximize the benefits of underground research for national well-being.

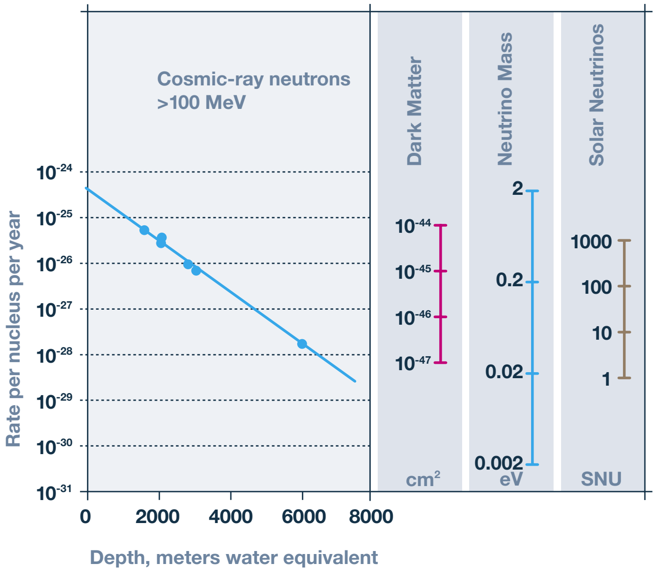
# A Question of Depth

### HOW DEEP MUST PHYSICISTS GO?

For physics, experimenters can quantify the background for any given experiment. The signal rates for events caused by processes at the frontier of physics may be only a handful per year. But at the earth's surface, twenty thousand cosmic-ray muons per minute pass through each square meter. Several techniques exist for mitigating this background, and depth is only one of them. For certain experiments, depth may be the only available strategy; for others it may be one of several options.

The graph in Figure 4 shows the rate per nucleus of interactions of cosmic-ray secondary neutrons with energies above 100 MeV as a function of depth. Those neutrons are the most difficult component of the cosmic rays to shield. The adjacent panels show the signal rates for "WIMP" dark-matter particle interactions, for neutrinoless double beta decay, and for solar neutrinos. For many experiments, scientists have developed strategies to reject backgrounds, and not every cosmic-ray neutron will mimic a signal, but the comparison shows that it is easier to carry out such searches at great depths. Where signals from the new physics will appear is unknown, but the ranges on the scales to the right cover what is expected for three major physics campaigns. As experiments become bigger and more sensitive (moving down on the graph), the need for depth becomes more acute.

If the expected signal rate falls below the cosmic neutron background rate, an experiment may still be practical. Among the



strategies that can be used are a) shielding, b) energy selection, c) association of an event in time with another event, d) topology of events. Even when those techniques are available, depth is still an advantage. Experimenters can dispense with costly shields required for each experiment at shallower depth in favor of the overburden in a shared deep facility. Deep experiments lessen the concern that an observed signal might actually be background. Depths in the range 4000-6000 m.w.e. are sufficient to meet the needs of this kind of physics. There is a depth limit beyond which experiments obtain no further gains, set by the rate of neutrino interactions. Even the whole earth provides no shielding against them. That depth limit is about 10000 m.w.e.

The search for proton decay is a case in which current experimental limits from 2000 m.w.e., are already a million times lower than the neutron rates shown. The high energy release and specific event topology help make this possible. Neutrinos are the main background for many proposed decay modes for the proton, even at that modest depth. The next generation of proton decay detectors will be very large, and at depths determined by a careful balance of engineering capability, cost, and physics requirements.

Not all physics experiments are sensitive to cosmic rays – gravitational wave detectors are not, but they face their own backgrounds from phenomena such as seismic surface waves, traffic noise, wind, waves, tides, temperature changes. A quiet location a few hundred meters underground meets their needs.

## WHAT DO THE BIOLOGISTS NEED?

The frontier in subsurface biological research is the depth where the temperature exceeds 80 to 125ºC. This boundary may lie thousands of meters below the surface, and can be reached by drilling. To study subsurface microbial processes also requires borehole arrays with close spacing. Drilling from an already deep location has three advantages: reduced drilling costs, high spatial control, and improved control over contamination from surface organisms. In Figure 5, cost estimates for drilling to various depths up to 10000 m from the surface and from a laboratory 2500 m deep are compared. The deep stance gives a great advantage in cost.

## HOW ABOUT GEOSCIENTISTS AND ENGINEERS?

The interests of geoscientists in fact extend to the center of the earth, and seismic and electromagnetic methods have been used to “see” through rock. How accurate these methods are can be tested and improved in an underground laboratory. At depths of a few thousand meters the rock pressure and temperature are high enough to modify the way rock responds to such probes. Thus direct access to rock at great depth is of interest to geoscientists and petroleum engineers. The rock pressure at depth also becomes the major challenge to engineers who must design large cavities not only for science but also for a wide range of technical, mining, and societal applications. But shallower depths are also important in these disciplines.

Figure 4: *Left panel:* rate per nucleus of events caused by cosmic-ray muons, plotted against the depth underground in meters water equivalent (m.w.e.). Left center panel: rate per nucleus of dark-matter particle interactions for cross sections from $10^{-44}$ to $10^{-47}$ cm$^2$. *Right center panel:* rate of neutrinoless double beta decays for effective (Majorana) neutrino masses from 2 to 0.002 eV. *Right panel:* rate of solar neutrino interactions for typical nuclear cross sections (the “SNU,” or solar neutrino unit, is the rate per $10^{36}$ target atoms.) All rates, both signals and background, are on the same common scale of rate per nucleus. The goal for each of these experiments argues for a laboratory at a depth near 6000 m.w.e. or 2200 meters.

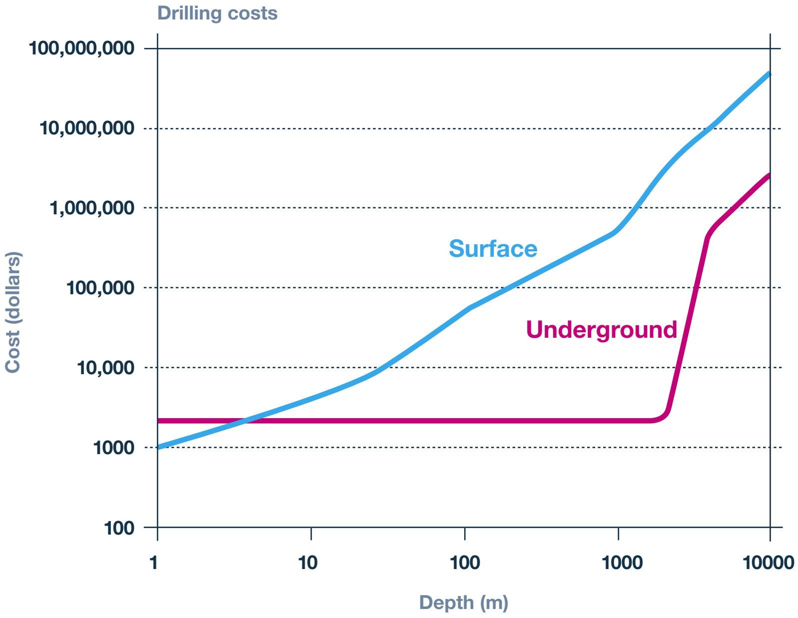


Figure 5: Comparison of costs for coring from the surface and from a stance 2.5 km underground.
*Source: Tommy Phelps*

# Findings and Recommendations

## SCIENTIFIC FINDINGS

The analysis of the current opportunities and challenges for deep underground science leads to three scientific findings.

**1. Deep underground science is an essential component of research at the frontier.** Underground experiments are critical to addressing some of the most compelling problems of modern science and engineering; and long-term access to dedicated deep underground facilities is essential.

- The nature of the dark universe, the stability of matter and the properties of neutrinos are urgent questions of physics and astrophysics, to which deep underground experiments will make contributions that cannot be obtained by other means.
- Research on subsurface microbial ecosystems offers unique opportunities for the study of novel microbes, their genomics and evolutionary biology in isolated, slowly changing environments. Such studies may offer insight into the origins of life on earth and the search for life on other planets.
- Deep underground studies will address central questions in earth science, including the origin of the earth's magnetic field, the role of material properties in planetary processes, and the understanding and prediction of catastrophic natural events such as earthquakes.
- A fundamental understanding of the complex mechanisms operative in a large rock mass is important for modern engineering and requires large-scale underground facilities.

Underground research has already led to unexpected discoveries and has generated fundamental shifts in our understanding of nature. Cross-disciplinary synergies among these disciplines add new research avenues.

**2. Disciplines in transformation.** Deep underground experiments have for some time constituted an important component of physics and astrophysics. Biologists, earth scientists and engineers have long made observations underground and have in recent years also recognized the extraordinary potential of deep underground experiments.

**3. Benefits to Society.** Investment in deep underground experiments can yield important societal benefits. Underground construction, resource extraction, management of water resources, environmental stewardship, mine safety and national security are prominent examples. By creating a unique multidisciplinary environment for scientific discovery and technological development, a deep underground laboratory will inspire and educate the nation's next generation of scientists and engineers.

## PROGRAMMATIC FINDINGS

Our previous analysis of facilities for deep underground science can be summarized in two programmatic findings

**1. Worldwide need for underground space.** The rising interest in deep underground science; the diversification of underground disciplines; the increase in the number of underground researchers; and the increased size, complexity and duration of experiments all point to a rapidly rising demand for underground laboratory space worldwide. The opening of numerous facilities outside the U.S. attests to the gap between supply and demand, especially at very large depth.

**2. Need for a U.S. world-class deep multidisciplinary facility.** The U.S. is among the very few developed countries without a deep underground facility (≥ 3000 m.w.e). In an international environment where deep underground space is at a premium, a U.S. Deep Underground Science and Engineering Laboratory would provide critical discovery opportunities to U.S. and foreign scientists, put the U.S. in a stronger strategic position in deep underground science, and maximize the benefits of underground research to the nation.

## RECOMMENDATIONS

**1. Strong support for Deep Underground Science.** The past decade has witnessed dramatic scientific returns from investments in physics and microbiology at great depths. Underground research is emerging as a unique and irreplaceable component of science, not only in physics and astrophysics, but also in biology, earth sciences and many disciplines of engineering. We recommend that the U.S. strengthen its research program in Deep Science to become a world leader in the multidisciplinary exploration of this important new frontier.

The discovery of neutrino mass and oscillations, the first observation of the neutrino burst from a core-collapse supernova, the recognition of the existence of life under conditions little different from those that may be present on other worlds—all have underscored the advances made possible by access to deep sites. As explained in the findings, there is a broad and compelling suite of underground experiments that address some of the most fundamental questions in physics, astrophysics, cosmology, microbiology, geosciences, and engineering There can be little doubt that increased effort in this area will yield tremendous scientific dividends, including totally unexpected results. Many fields and programs seek funding, but only in a few cases is the evidence for successful return on that investment as clear as it is in underground science.

**2. A cross-agency Deep Science Initiative.** In order to broaden underground research and maximize its scientific impact, we recommend that the U.S. science agencies collaborate to launch a multidisciplinary Deep Science Initiative. This initiative would allow the nation to focus the whole range of underground expertise on the most important scientific problems. It would aim at optimizing the use of existing or new underground facilities and at exploiting the complementary aspects of a variety of rock formations. The Deep Science Initiative should be coordinated with other national initiatives and take full advantage of international collaboration opportunities.

The premise of this recommendation is that the U.S. has access either on its territory or through international collaboration to a large reservoir of expertise and a number of assets (underground facilities, accelerators, seismic networks, sequencing and protein synthesis facilities). A cross-agency initiative would allow optimal use of these capabilities, and of additional resources recommended above. It is the best way to maximize the profoundly transformative effect of a unified program on all of the fields involved, both because of the phenomena it will undoubtedly discover and by virtue of the changes in the way of doing research that it will engender within and across disciplines. Historically, synergies like the ones that are emerging have provided a strong foundation for discovery.

Some of the facilities needed for this exciting program already exist in the U.S. and in other nations. Specific experiments should use the facilities (or combinations of facilities) most adapted to their purposes. The special features of, for example, WIPP, in a salt formation with very low natural radioactivity, are unique in the US. For biology, earth sciences and engineering, much can be learned from the diversity of rock types available world-wide. The program should support experiments in sedimentary rock, for instance, even if no dedicated facilities exist. In each case the science must drive the choice of facility or experiment, and not the other way around.

On the organizational side, such an initiative should ally all agencies and disciplines with a stake in underground science. In addition to the National Science Foundation (particularly the four directorates Mathematical and Physical Sciences, Geosciences, Biological Sciences and Engineering), natural partners include DOE (High Energy Physics, Nuclear Physics, Basic Energy Sciences, and Biological and Environmental Research), USGS, NASA (for astrobiology) and potentially NIH (for some genome studies and potential medical applications). Although NSF has been designated by the Office of Science and Technology Policy as the lead agency for such a program, the other agencies should be involved from the start in the development of common goals, funding structures and advising and review mechanisms.

In order to go beyond a mere relabeling of activities, such a Deep Science Initiative will require strong scientific coordination mechanisms that assure:

- Development of a coherent long-term scientific strategy and the support of an R&D program.
- Optimal use of all U.S. and international assets, and coordination with other national initiatives (e.g. neutrino beams at accelerators, Earth Scope, Secure Earth)
- Cross-disciplinary prioritization of projects within underground science, taking into account discipline-specific prioritization.
- Maximization of benefits to society, through the involvement of industry and other sectors, and a coordinated education and outreach program.

Such coordination tasks represent formidable challenges that would require both novel solutions and application of the best current practices of cross-agency and cross-disciplinary collaboration.

### 3. A Deep Underground Science and Engineering Laboratory.

The U.S. should complement the nation's existing assets with a flagship world-class underground laboratory providing access to very great depth (approximately 2200 meters or 6000 meters water equivalent) and ample facilities at intermediate depths (approximately 1100 meters or 3000 meters water equivalent) currently not available in the U.S. Such a Deep Underground Science and Engineering Laboratory (DUSEL) should be designed to allow evolution and expansion over the next 30 to 50 years. Because of this long lifetime, the initial investment must be balanced with the operating costs. For maximum impact, the construction of DUSEL should begin as soon as possible.

### WORLD-CLASS CHARACTERISTICS

Although the proposed initiative is larger than DUSEL, DUSEL will be the focus of the initiative and therefore should offer world-class characteristics in terms of depth, access, environmental control, safety, evolutionary capabilities and operation costs.

- **Depth.** The scientific frontier is at large depth. Although Canada's SNOLAB can accommodate the immediate needs of U.S. physicists in the coming few years (i.e. for experiments currently approved for construction), no long-term dedicated facilities at large depth are available to other sciences. The need for deep space for the physical sciences increases as experiments become larger and more sensitive. Consideration of the expected range for experimental searches and the cosmic-ray backgrounds indicate that a "deep campus" at approximately 6000 m.w.e. with a future capability for still deeper sites will meet the needs of the participating sciences for the foreseeable future. Not all experiments require or can be placed at such depths, and their needs can be met at an "intermediate campus" at approximately 3000 m.w.e. These new facilities would complement existing U.S. facilities at shallower depths.

- **Access.** The quality of access is also an important characteristic. The research community has engaged in lively debate about the relative merits of vertical access, ramps and horizontal access. Whatever the final technical solution, size matters. Ideally, the access should allow researchers to bring to significant depth small trailers (roughly 6 m long, space 2.5 m wide and 2.5 tall- approximately the standard ISO size for a "20 foot") of 5 tons (much smaller than the ISO standard). This capability is particularly important for small experiments: if they can fit in a few trailers of that size, the trailers can be assembled and made operational at investigators' institutions and brought underground with minimum disassembly. In addition, scientists should have as close as possible to round-the-clock access to their experiments, 365 days per year. It is also essential to have assured long-term access for at least 30 years.

- **Environmental control.** Environmental control is another essential characteristic. The control of dust (class ≤ 10000, and as low as class 100 for specific experiments) and humidity are important for a number of experiments. Access to absolutely pristine rock volume is essential for biology experiments that focus on indigenous life as we do not know it. Great precautions must be taken to prevent contamination by site exploration and construction or by prior mining activities.

- **Safety.** Safety considerations are essential, and DUSEL will need to develop policies and practices that meet or exceed the relevant codes. Such stringent safety policies may lead to restrictions on certain types of materials (e.g. low-flash-point flammable liquids or high-toxicity materials), to specific safety measures for large volumes of cryogens or to restrictions on the induction of fracture motion. If scientific arguments point to the need for a potentially dangerous activity, the laboratory must work actively with the experimenters and experts in underground safety to determine whether methods can be devised to carry out the experiment while guaranteeing the complete protection of the personnel involved, the rest of the laboratory and the environment. Such measures will yield advances in underground safety that may find application in the commercial and mining sector.

- **Expansion capability.** An important attribute of the laboratory is expansion capability. Although an initial set of cavities would be built to house the first suite of experiments, a successful laboratory will be able to accommodate the experiments that will be needed in 20 years. This requires a separation between “clean” and “dirty” accesses in the layout of the facility, and minimization of construction disturbance to running experiments.

- **Cost.** The operation and upgrade costs over the long lifetime of the laboratory (30-50 years) must be balanced with the initial investment for optimization of the program. A laboratory that is inexpensive to build but expensive to operate may not be viable.

## THE INITIAL SCIENTIFIC PROGRAM

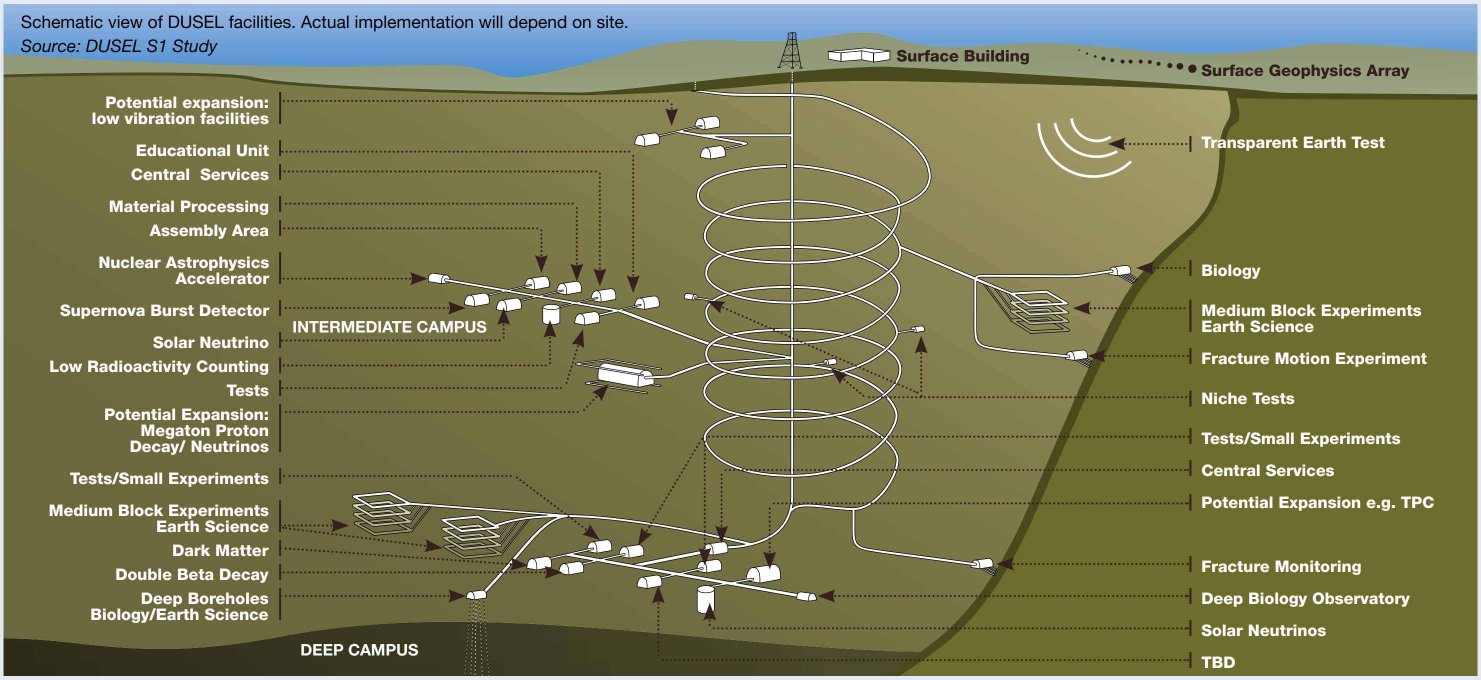
An interesting characteristic of a deep underground laboratory is that science starts on the day of the decision to explore a particular site. Four phases can be identified:

- **Before excavation.** As physicists conduct R&D and use low-radioactive-background counting facilities to select the purest materials for their equipment, earth scientists, hydrologists and rock engineers fully characterize the site with instrumented boreholes and imaging. Biologists and geochemists use the boreholes for aseptically sampling the water in the rock and constructing a large-scale fluid flow model for the site.

- **During excavation.** Earth scientists and engineers test imaging methods and carefully monitor rock motion and modification of stress during construction. Biologists sample rocks and fluid-filled fractures ahead of the excavation front.

- **The first suite of experiments proper.** (see below) A deep campus could include an ultradeep underground observatory for biological and bioengineering research; two medium-block experiments where geologists and rock engineers conduct tests on the rock; four cavities for the next generation of dark matter, neutrinoless double beta decay and solar neutrino experiments and a new experiment to be determined. Although experimentalists would prefer separate cavities, a larger cavity able to accept the four experiments may be cheaper to build and more flexible in the long run. In addition, space for test facilities and small experiments should be provided, together with offices and conference rooms. Intermediate-depth levels would house facilities and experiments that do not need great depth. Low-radioactive-background counting areas, assembly areas, and underground fabrication facilities including germanium and copper refining would be located on this intermediate campus. Experiments under consideration include an underground accelerator, a supernova burst experiment, solar neutrino experiments with high background-rejection capability, intermediate-depth block studies and biology observatories. Low-vibration facilities for atomic, molecular and optics experiments or gravitational research would also be at a relatively shallow level and isolated from the rest of the laboratory, to minimize disturbance from ongoing construction or rock mechanics experimentation. Far from the rest of the laboratory, geoscientists could perform fracture-propagation and earthquake-nucleation experiments. The educational outreach module should be underground but with relatively easy access, preferably with observation space for ongoing scientific activities.

- **Extensions in the first ten years.** The initial design should permit extensions in the first 10 years of the laboratory: an obvious case is a large cavity or cavities for proton-decay and neutrino-oscillation experiments, with a total volume of order 500,000 to 1 million $m^3$. A neutrino beam would be pointed to DUSEL. In the scenarios most studied so far (neutrino beam of approximately 3 GeV energy, produced at Fermilab), a broad optimum occurs around 2500 km and distances between 1000 km and 5000 km are adequate. The depth of this detector would be chosen after a careful analysis of its multiple physics objectives, costs, and the competence of the rock. A depth in the vicinity of 3000 m.w.e. is envisaged. Other possibilities for extension include a large low-pressure gaseous tracking chamber for dark matter and/or double beta decay experiments.


Schematic view of DUSEL facilities. Actual implementation will depend on site.
*Source: DUSEL S1 Study*

# Appendices

## APPENDIX 1

### Background and Organization of the Project

Scientists have argued for years that development of facilities deep underground is essential to answer compelling scientific questions in a broad cross section of science, ranging from particle and nuclear physics and astrophysics to subsurface geosciences, engineering and biology.

In March 2004 the National Science Foundation (NSF) put a new process in place for the development of a Deep Underground Science and Engineering Laboratory (DUSEL). The Solicitation 1 (S1)—the first step in the NSF-guided process—called for a community-wide, site-independent study to establish a cross-disciplinary scientific roadmap for such a facility and to identify the generic infrastructure requirements against which the capabilities of potential sites (see Appendix 3) would be measured.

The initial driver for such initiative had come from the physics community (nuclear physics, particle physics, and astrophysics), but it was quickly recognized that a facility deep underground could be equally beneficial to other sciences, as well as the engineering community. At the initiative of Bernard Sadoulet, director of INPAC[1], community-wide support was discovered for writing a single, site-independent document that would represent a spectrum of viewpoints, map the scientific and engineering program, and provide broadly accepted criteria for site and experiment selection. A proposal for the study was submitted to NSF in September 2004 and was approved in January 2005.

### Organization

The DUSEL process has been multidisciplinary from the start and involves four directorates at NSF (Mathematical and Physical Sciences, Geosciences, Biological Sciences, and Engineering). The key challenge for the S1 project, therefore, had been to present a fair and unbiased science case acceptable to all the competing sites and scientific fields but not watered down to the lowest common denominator. In view of that challenge an organizational framework was developed and a rigorous procedure was established (outlined below).

1. The six principal investigators, scientists with widely recognized science credentials across the relevant disciplines and from a broad institutional and geographical background, were responsible for the study, in particular its scientific quality. To preserve the objectivity and fairness of the study, none of the six investigators was in any way involved in or connected with the competing sites (see Appendix 2).

2. Four workshops were organized—Berkeley, CA, in August 2004; Blacksburg, VA, in November 2004 (earth sciences and biology–oriented); Boulder, CO, January 2005; and Minneapolis, MN, in July 2005. The workshops built on the considerable work done at the NUSEL[2] and NeSS[3] meetings and the recommendations that came after them.

3. Fourteen working groups were formed led by scientists or engineers, recognized specialists in their field (see Appendix 2). Twelve of the groups focused on scientific areas and were in charge of distilling the "big questions," drawing a roadmap of high priority generic experiments, identifying the corresponding infrastructure requirements, and attempting to map out the likely evolution of the demand for underground space in their fields and subfields. The two other groups were in charge of general aspects: the infrastructure and management needs, and education and outreach.

4. In addition, two consulting groups were established: (1) the Site Consultation Group, which provided an official channel for the eight candidate sites to comment on the final S1 study, without unduly influencing any of the writings; and (2) the Initiative Coordination Group, representing national labs and other major stakeholders, to help align the proposed DUSEL project with existing national initiatives and point out possible biases in the study.

5. Proceedings of all deliberations were systematically compiled on DUSEL website (www.dusel.org).

It was agreed at the outset that the end product should come in two parts:

- a publication of a "high level" document, directed at generalists (government, funding agencies, and the public), that would identify the big science questions, define the scientific activities at the underground frontier, synthesize the fundamental infrastructure requirements, and evaluate the arguments for a U.S. DUSEL in the context of growing international demand; and
- web-based technical reports[4], aimed at experts in the corresponding subfields, which would provide detailed infrastructure matrices and lab management requirements, define modules for the initial high-priority experiments, and elaborate on the key scientific issues discussed in the main publication.

The present document and the Working Group Reports have been reviewed by the following distinguished scientists and engineers, to whom our gratitude is extended.

Giovanni Barla, *Politecnico di Torino, Italy*
Pierre Berest, *Ecole Polytechnique, France*
Carlo Broggini, *Istituto Nazionale di Fisica Nucleare, Italy*
Gabriel Chardin, *Commisariat a l'Energie Atomique, France*
Yves Declais, *Institut National de Physique Nucléaire et de Physique des Particules, France*
Donald DePaolo, *University of California, Berkeley*
Stuart J. Freedman, *University of California, Berkeley*
Katherine Freese, *University of Michigan*
Vladimir Gavrin, *Institute for Nuclear Research, Russia*
William Ghiorse, *Cornell University*
George M. Hornberger, *University of Virginia*
John Hudson, *Imperial College, UK*
Takaaki Kajita, *University of Tokyo, Japan*
Boris Kayser, *Fermilab*
Hans Kraus, *University of Oxford*
Karlheinz Langanke, *Gesellschaft fur Schwerionenforschung, Germany*
Arthur B. McDonald, *Queen's University, Canada*
Susan Millar, *University of Wisconsin*
John Peoples, *Fermilab*
Andreas Piepke, *University of Alabama*
Alexei Smirnov, *International Center for Theoretical Physics, Trieste*
Andreas Teske, *University of North Carolina*
Petr Vogel, *California Institute of Technology*
Kai Zuber, *University of Sussex, UK*

# Appendices (continued)

## APPENDIX 2: LEADERSHIP

### Principal Investigators

**Astrophysics**
Bernard Sadoulet
*University of California at Berkeley*

**Physics**
Eugene Beier
*University of Pennsylvania*

**Civil Engineering/Rock Mechanics**
Charles Fairhurst
*University of Minnesota*

**Geomicrobiology**
T.C. Onstott
*Princeton University*

**Physics**
R.G. Hamish Robertson
*University of Washington*

**Microbiology**
James Tiedje
*Michigan State University*

## PRODUCTION EDITOR

Judith Jackson
*Fermilab*

## CONTRIBUTING EDITORS

Elizabeth Arscott
*University of California at Berkeley*

Hitoshi Murayama
*University of California at Berkeley*

### Working Group Leaders

**Dark Matter**
Dan Akerib, *Case Western Reserve University*
Elena Aprile, *Columbia University*

**Low-Energy Neutrinos**
Tom Bowles, *LANL*
Bruce Vogelaar, *Virginia Tech*

**Long Baseline Neutrino Experiments**
Milind Diwan, *BNL*
Gina Rameika, *Fermilab*

**Neutrinoless Double-Beta Decay**
Steve Elliott, *LANL*
Charles Prescott, *SLAC*

**Nuclear Astrophysics and Underground Accelerators**
Joachim Goerres, *University of Notre Dame*
Michael Wiescher, *University of Notre Dame*

**Nucleon Decay/Atmospheric Neutrinos**
Chang Kee Jung, *SUNY Stony Brook*
Hank Sobel, *University of California at Irvine*

**Low-Background Counting Facilities and Prototyping**
Harry Miley, *PNNL*
Prisca Cushman, *University of Minnesota*

**Coupled Processes**
Brian McPherson, *University of Utah*
Eric Sonnenthal, *LBNL*

**Rock Mechanics/Seismology**
Larry Costin, *SNL*
Paul Young, *University of Toronto*

**Applications**
Francois Heuzé, *LLNL*
Jean-Claude Roegiers, *University of Oklahoma*

**Geomicrobiology**
Tommy Phelps, *ORNL*
Tom Kieft, *New Mexico Tech*

**Microbial Biology and Evolution**
Jim Fredrickson, *PNNL*
Nancy Moran, *University of Arizona*

**Infrastructure Requirements and Management**
Lee Petersen, *CNA Engineers*
Derek Ellsworth, *Penn State University*
David Berley, *University of Maryland*

**Education & Outreach**
Willi Chinowski, *LBNL*
Susan Pfiffner, *University of Tennessee*

# APPENDIX 3: CANDIDATE SITES AND ONLINE REFERENCES

## Candidate Sites

Cascades, WA
*http://www.int.washington.edu/DUSEL/cascades.html*

Henderson Mine, CO
*http://nngroup.physics.sunysb.edu/husep/*

Homestake Mine Project, SD
*http://neutrino.lbl.gov/Homestake/*

Kimballton Mine, VA
*http://www.kimballton.org/*

Mt. San Jacinto, CA
*http://www.ps.uci.edu/~SJNUSL/*

Soudan Mine, MN
*http://www.soudan.umn.edu/*

SNOLab, Creighton Mine, Ontario
http://www.snolab.ca

WIPP (Waste Isolation Pilot Plant), NM
*http://euclid.temple.edu/~DuselWIPP/*

## Related Science Reports

Underground Science, 2001, John Bahcall et al.,
*www.sns.ias.edu/~jnb/Laboratory/science.pdf*

NeSS 2002: Final Report, 2002, International Workshop on Neutrino and Subterranean Science,
*www.physics.umd.edu/events/spevents/NeSS02/Final_Report.pdf*

EarthLab Plan, 2003,
*www.earthlab.org*

“Microbes deep inside the Earth,” 1996, Fredrickson, J.K. and Onstott, T.C., Scientific American, 275 (4), 68-73.

Technical Evaluation of Underground Laboratory Sites,
F.P. Calaprice et al., 2001,
*www.sns.ias.edu/~jnb/Laboratory/evaluation.html*

The Neutrino Matrix, 2004, DNP/DPF/DAP/DPB Joint Study on the Future of Neutrino Physics,
*www.intractions.org/neutrinostudy*

## National Research Council Reports

Neutrinos and Beyond: New Window on Nature, 2003, Nat’l Academies Press, Washington, D.C.

Connecting Quarks with the Cosmos, 2003, Nat’l Academies Press, Washington, D.C.

Department of Energy Reports on Underground Science
*http://www.sc.doe.gov/henp/np/nsac/nsac.html*
*http://www.sc.doe.gov/Sub/Facilities_for_future/facilities_future.htm*
*http://www.science.doe.gov/hep/hepap_reports.shtm*

## FOOTNOTES

1. Institute for Nuclear and Particle Astrophysics and Cosmology, a University of California multicampus research unit headquartered at Berkeley.

2. National Underground Science and Engineering Laboratory, an earlier initiative

3. International Workshop on Neutrino Subterranean Science (NeSS02), September 2002, Washington, D.C.

4. The technical reports are available at www.dusel.org/….

**DUSEL** Deep Underground Science and Engineering Laboratory

The National
Science Foundation