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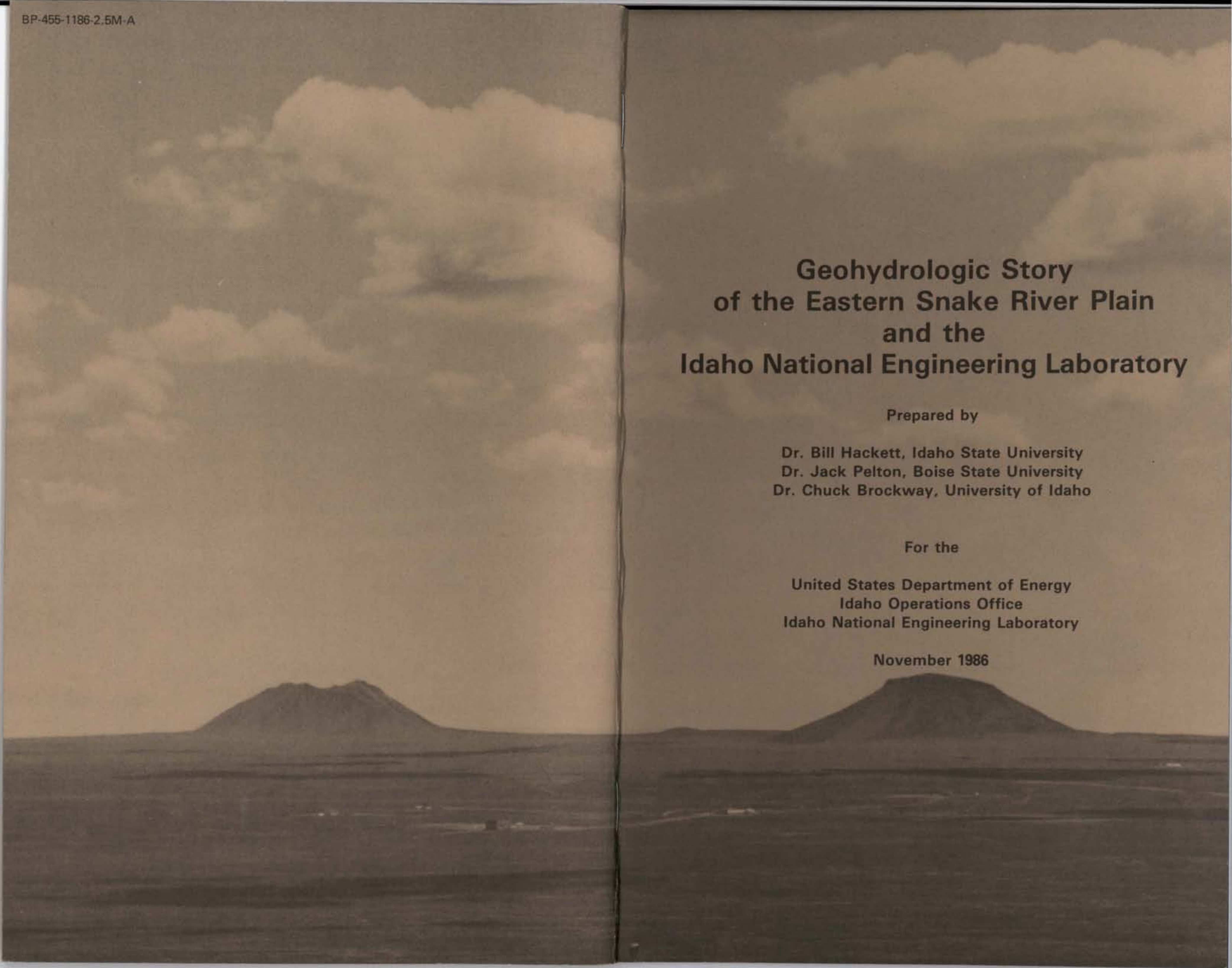

Geohydrologic Story of the Eastern Snake River Plain and the Idaho National Engineering Laboratory

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For the

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Idaho Operations Office
Idaho National Engineering Laboratory

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GEOHYDROLOGIC STORY OF THE EASTERN SNAKE RIVER PLAIN AND THE IDAHO NATIONAL ENGINEERING LABORATORY

After getting the necessary information from our leader,. . . I travelled according to his directions south until dark amid thousands of buffaloes. The route was very rocky and my horse's feet (he not being shod) were worn nearly to the quick, which caused him to limp very much. . . . The next morning I arose and proceeded on my journey down the stream. About nine o'clock, I came to where it formed a lake, where it sank in the dry and sandy plain. From this I took a southeasterly course. . . towards a high butte which stood in the almost barren plain. . . . On surveying the place I found I could go no further in a south or east direction, as there lay before me a range of broken, basaltic rock which appeared to extend for five or six miles on either hand and five or six miles wide, thrown together promiscuously in such a manner that is was impossible for a horse to cross them. . . . I had plenty of provisions, but could not eat. Water! Water was the object of my wishes. Travelling for two days in the hot burning sun without water is by no means a pleasant way of passing time. I soon fell asleep and dreamed again of bathing in the cool rivulets issuing from the snow-topped mountains.

Osborne Russell, *Journal of a Trapper*
September 30, 1835

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Foreword

Osborne Russell's impressions of the eastern Snake River Plain are similar to ours today: frustration with the forbidding lava plains, combined with curiosity about the origins of this arid, moon-like landscape, nestled within the northern Rockies. One hundred years later, Russell would be amazed to discover that much of this once-barren land has now been made productive by the use of ground water; water that disappeared into "lost rivers" and was inaccessible to early travelers.

Russell and other early explorers were familiar with the eastern Snake River Plain, and reluctantly crossed the area that is now the Idaho National Engineering Laboratory (INEL). Established in 1949 for the purpose of conducting energy-related research and development, the INEL is also a National Environmental Research Park, preserving habitat and fostering biological and geological research within this relatively undisturbed environment. The INEL Site includes a number of facilities within an 890 square mile area of the eastern Snake River Plain, a region with a long and fascinating geological history (Figure 1). The Site is situated on a relatively aseismic or earthquake-free plain, in a generally mountainous, geologically active region. Southwest of the INEL at Craters of the Moon National Monument, geologically young basalt lava flows graphically illustrate the process by which the eastern Snake River Plain and Yellowstone National Park were formed.

In areas of such recent volcanism and active mountain building, man must be particularly aware of natural hazards, and must design ways of minimizing the risks associated with those hazards. But living in an actively-building landscape also includes many benefits, the buried lava flows of the eastern Snake River Plain now act as a valuable formation, holding enough ground water to cover the entire state nearly four feet deep (USGS, 1986) and providing an abundant water resource for Idaho's agricultural economy. If eastern Idaho were geologically dead, there would be no mountains; who can imagine Idaho without its high peaks? Furthermore, these mountain ranges capture rain and snowfall, which percolates back into the earth and recharges the ground water supply.

In this booklet, the geologic story of the landscape within and around the INEL is briefly explained. The volcanic geology of the eastern Snake River Plain is emphasized, including its beneficial role in producing a world-class aquifer.

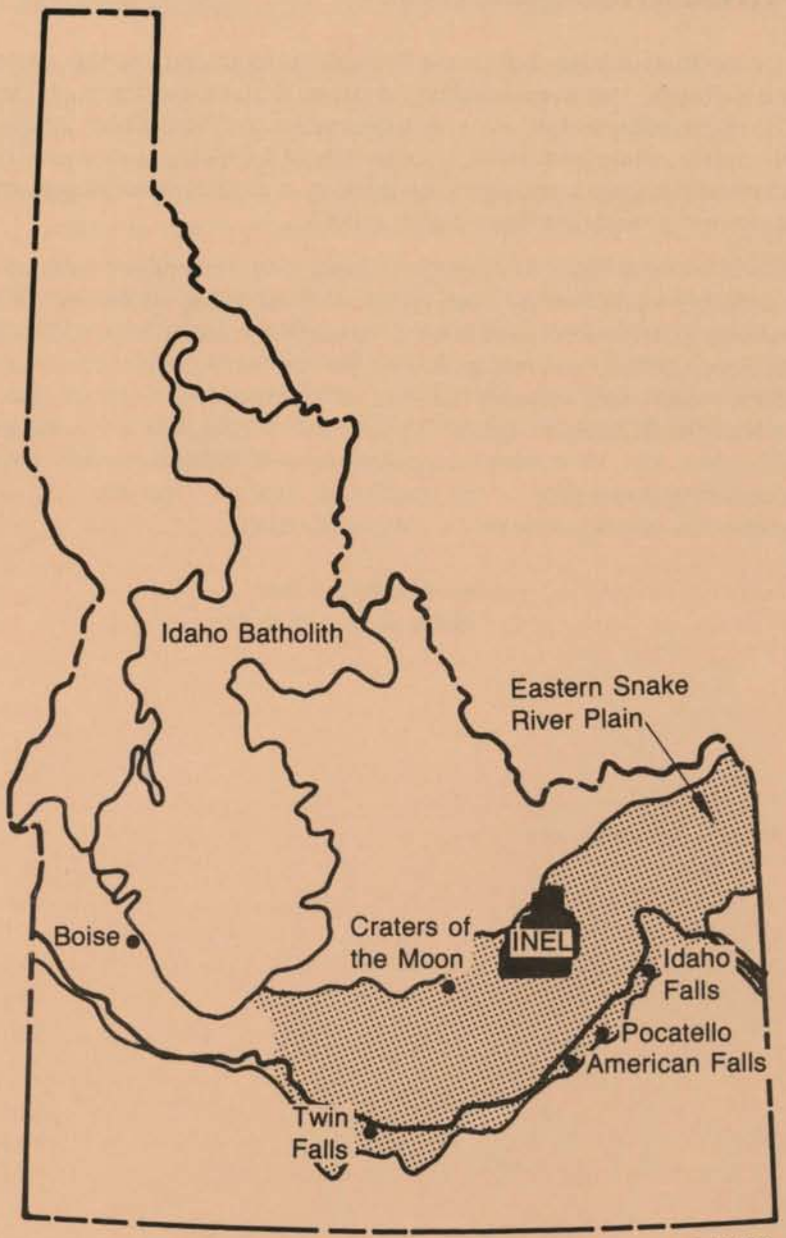


Figure 1. Location of the Idaho National Engineering Laboratory (INEL), showing the major cities and the Snake River Plain.

Acknowledgments

This booklet is intended to provide public information on the geology of the INEL Site, and was funded by the United States Department of Energy (DOE). Production of the booklet was contracted to EG&G Idaho, Inc., who in turn subcontracted the writing to geologists of the Idaho universities. Thus, the booklet reflects current geological thinking, as told by research geologists who are not directly affiliated with the INEL.

Sections on the regional geologic history and earthquake hazards of the INEL were prepared by Jack Pelton of Boise State University. Chuck Brockway of the University of Idaho prepared the material about the Snake River Plain Aquifer. I was responsible for the introduction, the sections about volcanic history and volcanic hazards, and final editing. I am grateful to Clay Nichols, DOE, Brent Russell, Karen Koslow, and Jack Barraclough of EG&G Idaho, Inc., for making this opportunity available to us, and for helpful advice during preparation of the booklet. In addition, I am appreciative of the technical editing provided by Deanna Carlson.

Bill Hackett, Editor
Idaho State University

Introduction

The earth's surface, as we know it today, has changed dramatically since its origin about 4,500 million years ago. Some of the changes that occurred include the rising and receding of oceans, the collision of continents, and the uplift and erosion of vast mountain ranges. The mountains and plains surrounding the INEL, despite their apparent timelessness, represent relatively young landforms that developed in the last 17 million years, less than one half of one percent of the total age of the earth. Today, the eastern Snake River Plain can be characterized by the abundant availability of ground water in the Snake River Plain Aquifer and a seismically quiet setting, although it lay in the prehistoric path of volcanic activity. These and other characteristics are further discussed in this booklet in terms appropriate for a lay person. A more detailed geologic account is provided in Appendix A for those who are interested.

The Snake River Plain Aquifer—Lifeblood of Southern Idaho

Streams and rivers characterize the earth as a planet with abundant water, yet there is a much greater source of fresh water that flows unseen beneath the ground, in permeable rock layers that are known as aquifers. The recent geologic history of southern Idaho has led to a unique and fortunate set of circumstances. Abundant rain and snowfall occur within a 35,000 square mile region of the actively-building mountains around the Snake River Plain. Much of this water eventually percolates into the ground to recharge one of the largest aquifers in the world—the Snake River Plain Aquifer. It is estimated that this aquifer contains a quantity of water that is approximately equal to the volume of water contained in Lake Erie. The aquifer provides fresh water for a variety of economic, municipal, and domestic uses.

Sources of Water

The Snake River Plain Aquifer underlies about 10,000 square miles of the eastern Snake River Plain. This remarkable water resource is estimated to have a potential storage capacity of approximately 200 million acre-feet, enough to cover the entire state of Idaho with 4 feet of fresh water. The yearly recharge and discharge is about 8 million acre feet. The primary source of recharge is deep percolation of irrigation water diverted from the Snake River and tributary streams. Other sources are underflow from tributary stream valleys, rain and snowfall on land overlying the aquifer, and seepage from the Snake River and other surface water sources such as the Big Lost River. Over a single season, changes in aquifer storage are generally small, and the discharge is nearly equal to the recharge. The primary sources of outflow are springs in the Thousand Springs and American Falls areas.

Table showing inflow to and outflow from the Snake River Plain Aquifer during a typical year. Numbers are in millions of acre-feet.

Source	Recharge	Outflow
Irrigation diversions	5.1	
Valley underflow	1.5	
Precipitation	0.8	
River seepage	1.3	
Total	8.7	
Pumping for irrigation		1.6
Springs and river gains		7.1
Total		8.7

Water flow into the Snake River either loses water or gains water from the aquifer, depending on location and time of year. During the summer, the entire flow of the Snake River is diverted for irrigation at Milner Dam, just downstream of the city of Burley. Between Milner and Haggerman, a distance of 90 miles, a new river is formed from 6,000 cubic feet per second of spring flow out of the aquifer, and from surface irrigation return flows.

The Movement of Underground Water

The Snake River Plain Aquifer consists of a series of basalt lava flows, with volcanic ash and highly fractured rock zones along the flow contacts, and sedimentary deposits of sand, gravels, and clays between the lava flows. These layers of basalt and sediment are well exposed in the Snake River Canyon, notably in the Twin Falls and Haggerman areas. In the American Falls area, ancient lake deposits border on the basalts and may exceed 1,000 feet in thickness. The total thickness of the lava flows and interbedded sediment, all included in the Snake River Group, ranges from about 2,000 to 10,000 feet (Figure 2).

The tops of many basalt lava flows are highly permeable, and water moves primarily along these layers. Occasional lava tubes may fill and convey water rapidly for short distances. Some of the sedimentary deposits are coarse grained and will store and transmit significant quantities of water. In any case, water flows easily through the Snake River Plain Aquifer one of the most permeable large aquifer systems in the world. It is thought that the amount of pore space decreases with depth, so that the effective depth of the aquifer is probably much less than the depth of the basalt lava flows.

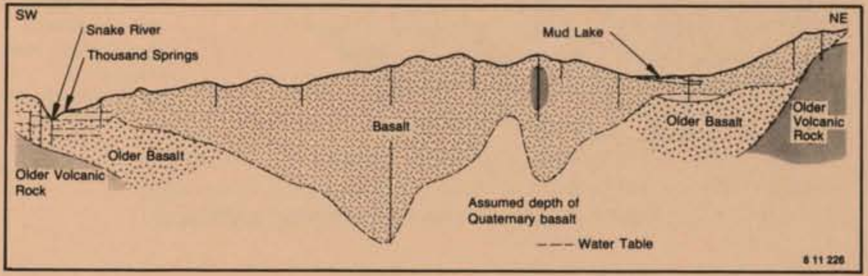


Figure 2. Geologic cross section of the Snake River Plain Aquifer, showing thickness of basalt and depth to water table.

The ground water follows the gently sloping regional topography of the eastern Snake River Plain, and generally flows from northeast to southwest (Figure 3). In the Mud Lake area and extending southeast is a region called the Mud Lake Barrier, which impedes ground-water flow. Beyond the Mud Lake Barrier, the water table is relatively flat as the ground water moves southwest into the American Falls area, where large springs upstream of the falls discharge over 1 million acre-feet per year into the Snake River. West of the American Falls area, another barrier at the Great Rift Zone causes the water table gradient to become steeper. West of the Great Rift Zone, the ground water proceeds toward the Snake River Canyon, where it issues from numerous springs in the canyon wall. These make up the famous Thousand Springs, with some springs producing as much as 300,000 acre-feet per year of water (Figure 4).

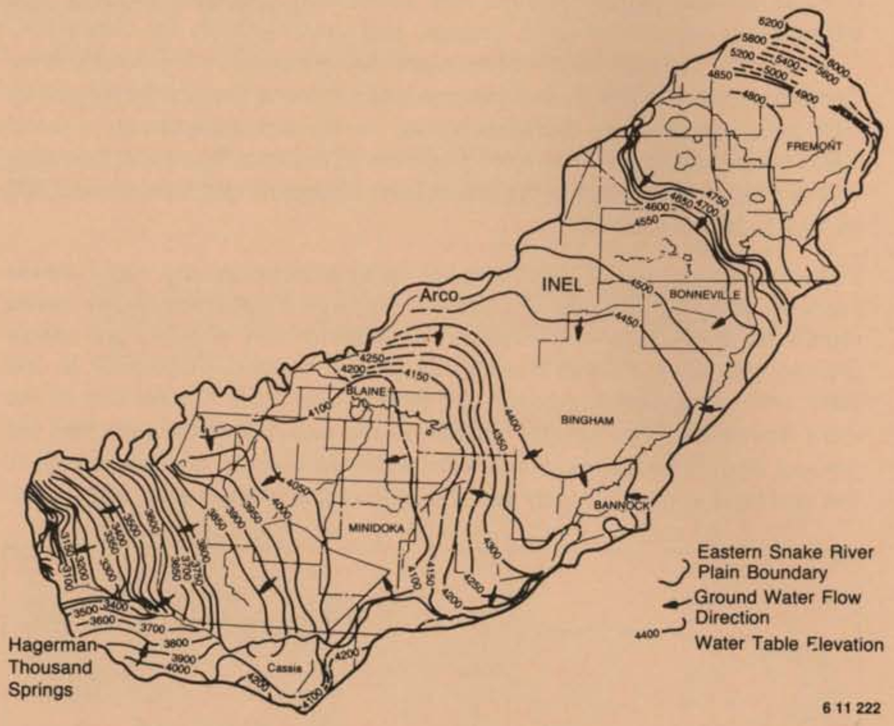


Figure 3. The Snake River Plain Aquifer.

Dynamics of Water Flow

Every year over 8 million acre-feet of water enters and is discharged from the aquifer system. Because deep percolation from surface irrigation accounts for over 50% of the total aquifer recharge, water tables and spring flows are responsive to trends in irrigation development and diversion. Prior to 1900, surface irrigation from the Snake River and its tributaries covered less than 500,000 acres and the annual flow of the Thousand Springs was slightly more than 4,000 cubic feet per second. Beginning about 1910, surface irrigation grew rapidly and diversions onto lands over the aquifer increased. From about 1910 until 1950, surface irrigation and diversions onto lands overlying the aquifer increased. In the early 1950s, new technology for deep well drilling became available and development of new lands for irrigation began to increase. As a result, the flows of the Thousand Springs increased from 1900 to 1955 and decreased from 1955 until the early 1960s (Figure 4). The drought of 1977, during which irrigation diversions onto lands over the aquifer were severely curtailed, was reflected by a sharp decrease in spring flows (Figure 4).

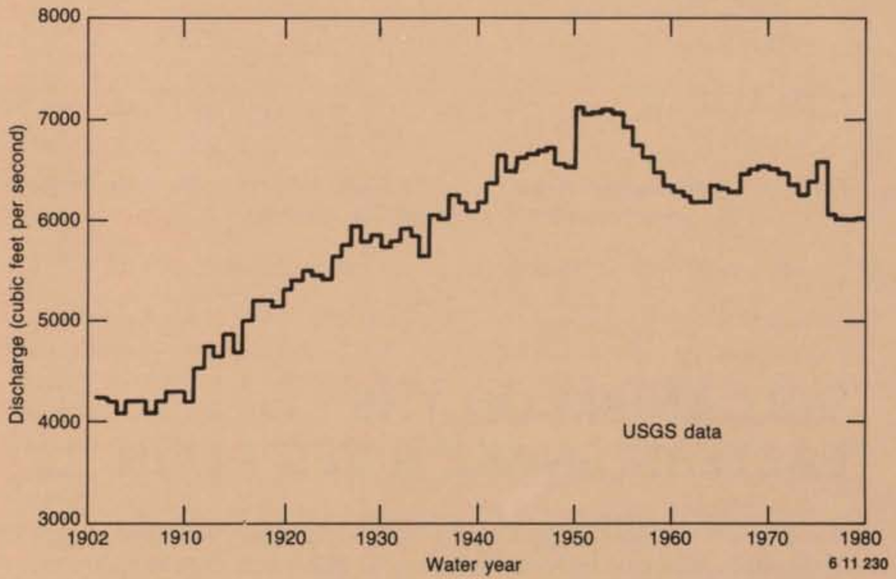


***Figure 4.** Discharge of springs from the Snake River Plain Aquifer at Thousand Springs, showing response of the springs to irrigation diversions during the past 80 years.*

Water table elevations in many observation wells have reached new lows since 1977 as a result of decreased recharge from irrigation and increased use of the ground water for irrigation. During the 24-year water level record for a Lincoln County observation well, the maximum fluctuation of the water table has been 12 feet and the seasonal fluctuation is less than 4 feet (Figure 5).

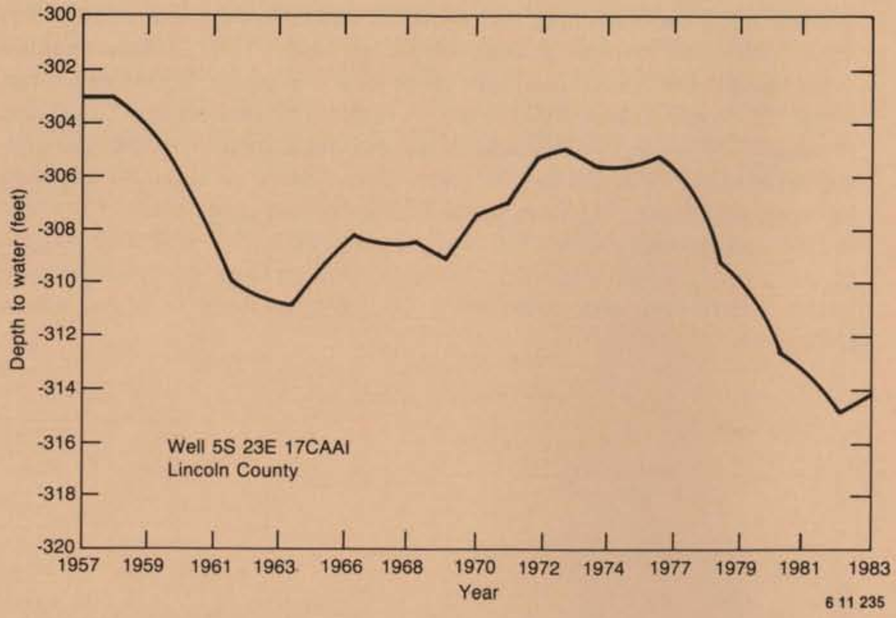


Figure 5. *Water table fluctuation in the Snake River Plain Aquifer, as shown by an observation well in Lincoln County.*

VOLCANISM ON THE EASTERN SNAKE RIVER PLAIN

The Snake River Plain dominates southern Idaho and covers nearly a quarter of the state. Volcanic rocks form a 40 to 62 mile wide, curved plain that extends about 400 miles—from the Idaho-Oregon border to Yellowstone National Park. A remarkable feature of the Snake River Plain is that the volcanism tends to become increasingly younger from southwest to northeast. Today the focal point for this volcanism (plume of magma) is situated underneath Yellowstone National Park, hence the geothermal activity in that area. Some residual volcanism has occurred since the passage of the plume as evidenced by Craters of the Moon National Monument.

In southwestern Idaho, the Idavada Volcanics consist mainly of welded ash flows that erupted about 13 to 9 million years ago. These deposits are considered to be the "basement" of the Snake River Plain (Figure 6). Two younger volcanic series complete the generalized stratigraphic column: the Glenns Ferry Group (about 3 to 9 million years old), which consists of volcanic ash beds, lake sediments, and some basalt in lava flows and the Snake River Group (0 to 3 million years old), which occupies the eastern Snake River Plain and is composed mainly of basalt lava flows that cover the underlying rhyolite deposits and has successively displaced the Snake River southward to its present course.

The INEL is located within the boundary of the eastern Snake River Plain, a broad, nearly flat plain underlain by approximately 1/2 mile of basalt lava flows interspersed with sediment that was deposited during the past 3 to 4 million years. Basalt magma was formed beneath the Snake River Plain by melting of the earth's upper mantle at depths of about 31 to 37 miles.

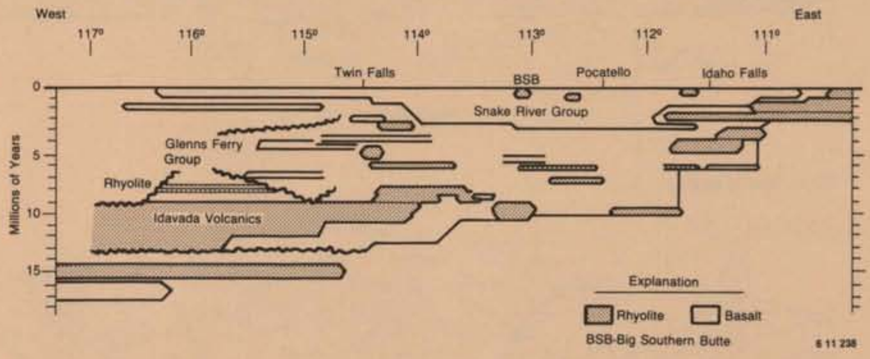


Figure 6. *Volcanic rock units of the eastern Snake River Plain.*

Basalt magma has a viscosity similar to honey, and contains little dissolved gas. Because of its fluidity and low gas content, basalt is usually mildly extruded onto the earth's surface in the form of thin lava flows that follow preexisting stream valleys and fill old river canyons. The outer portions of the lava flows solidify rather quickly, but the flow interiors remain hot and fluid, allowing the lava to travel long distances. When lava ceases discharging from the vent, drainage of these underground channels occurs, leaving lava tubes whose roofs often collapse, permitting access by animals.

Basalt lava flows issue from small shield volcanoes, so-called because they resemble the broad profile of a warrior's shield. The INEL region consists of innumerable lava mounds, each of which is a small shield volcano. As lava withdraws from the vents, small collapse depressions (pit craters) are formed at the summits of some shield volcanoes. Less commonly, small spatter or cinder cones are built at the vents; such cones characterize Craters of the Moon National Monument southwest of the INEL. Basalt volcanism is fundamentally mild and nonexplosive. Exceptions can occur when 2,000°F basalt lava encounters ground water or river water. In these situations, the water flashes explosively to steam and the basalt lava is fragmented into fine ash or gravel-sized pieces. The resulting landforms are maar volcanoes; broad, low cones that are composed of fine volcanic ejecta rather than lava flows (Figure 7). No features of this type are known within the INEL boundary.

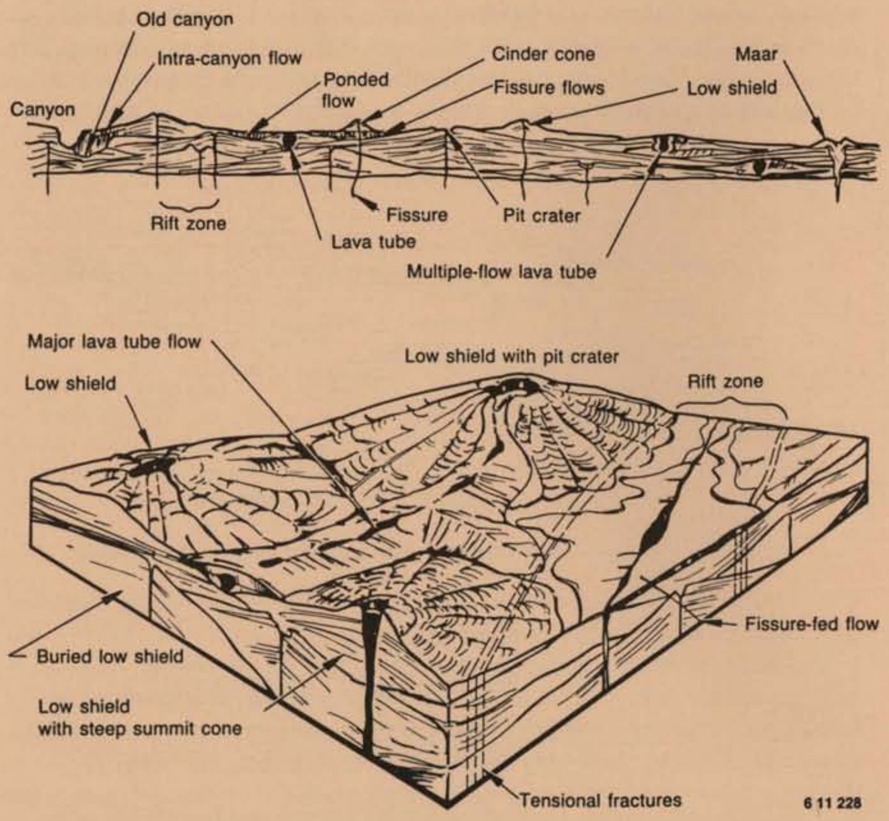


Figure 7. Features of basaltic volcanism on the eastern Snake River Plain.

Basalt vents of the eastern Snake River Plain are not randomly distributed, but form linear arrays of fissure flows, small shields, spatter and cinder cones, pit craters and open cracks. These features define volcanic rift zones where eruptive activity has been concentrated. Several postulated northwest-trending volcanic rift zones cross the southwest corner of the INEL and are located along the southeast projection of the Lost River and Lemhi Range frontal fault systems (Figure 8). The youngest volcanism in this set of rift

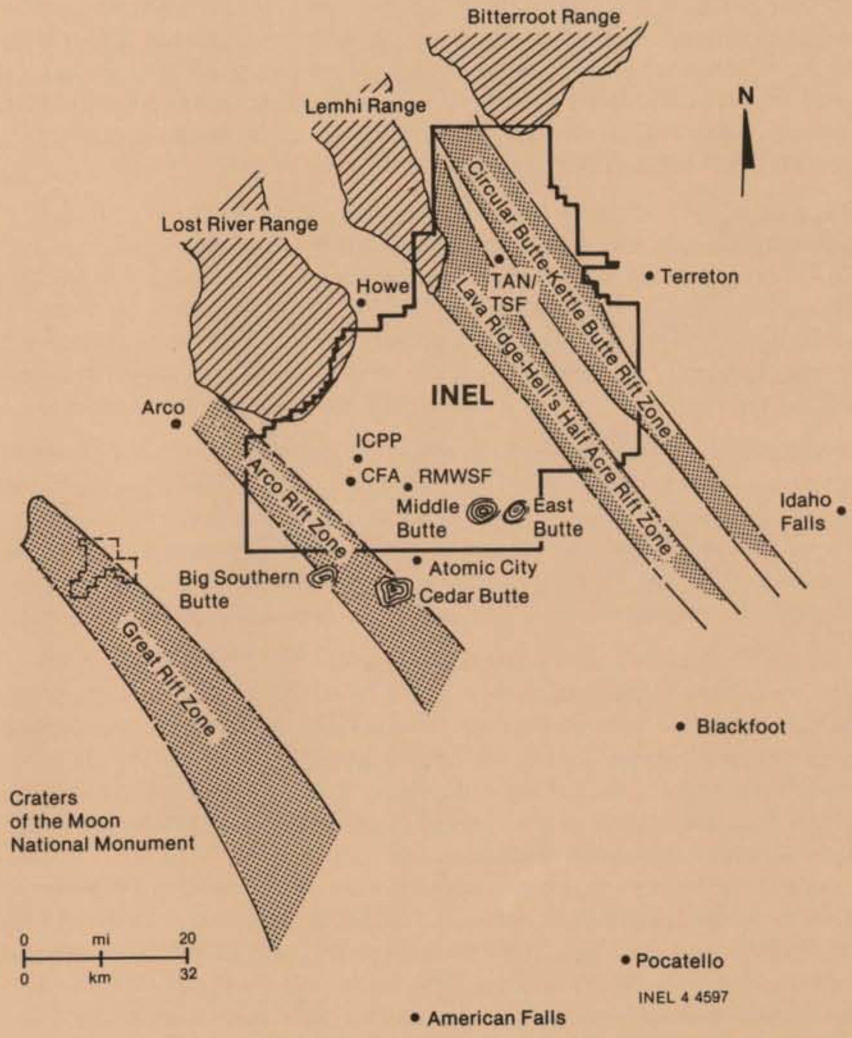


Figure 8. Postulated volcanic rift zones of the eastern Snake River Plain.

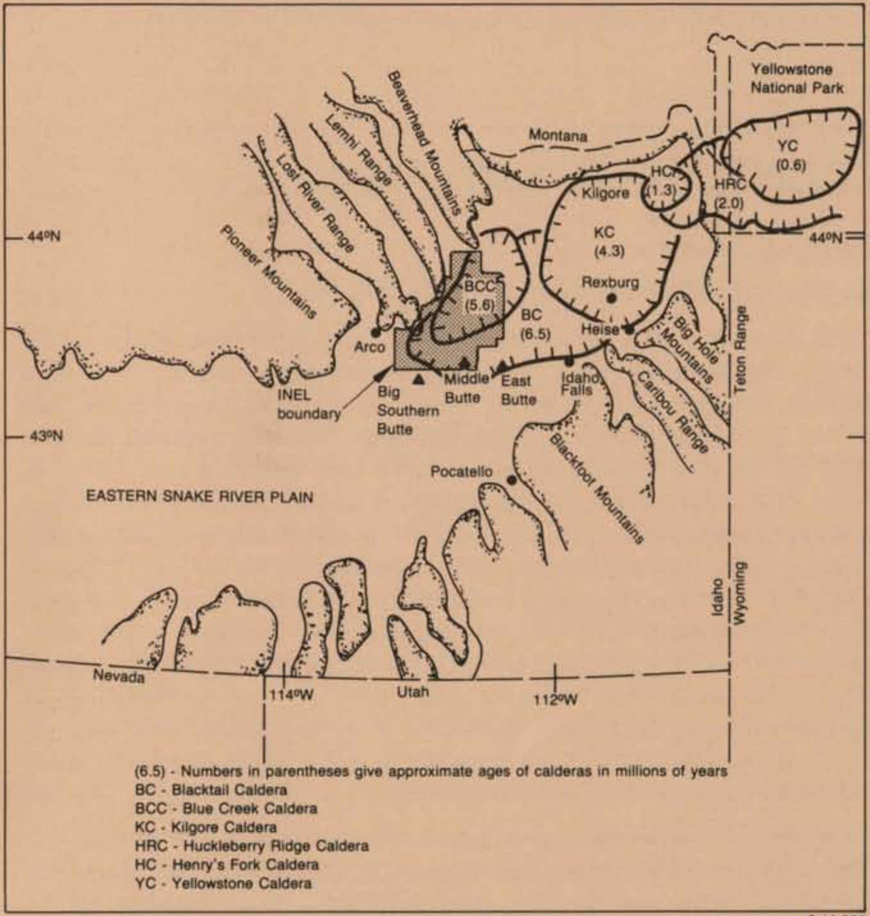
zones occurred about 11,000 years ago from vents south of the INEL, and lava flows reached four miles into the INEL. The Lava-Ridge-Hell's Half Acre volcanic rift zone crosses the central portion of the INEL and is located along the southeast projection of the Lemhi Range frontal fault system. The youngest volcanism in this rift zone occurred at Hell's Half Acre, south of the INEL, about 4,100 years ago. The poorly-defined Circular Butte-Kettle Butte volcanic rift zone crosses the northeast corner of the INEL; the volcanism of this rift zone is older than about 100,000 years. The Great Rift volcanic rift zone lies southwest of the INEL and includes the very young cinder cones and lava flows of Craters of the Moon National Monument, the most recent of which erupted only 2,100 years ago. The projection of most rift zones into fault systems of the surrounding ranges suggests that volcanic vents are located above deep-seated basin-range faults, which predated the volcanic activity that formed the Snake River Plain.

The northeast-trending zone of volcanism along the southern boundary of the INEL includes not only basalt vents, but also rhyolite volcanoes. Big Southern Butte and East Butte are domes of viscous rhyolite lava that erupted through the basalt lava flows about 500,000 years ago, forming the conspicuous landmarks that were used by pioneers as they traveled westward on the Oregon Trail. Middle Butte is a cap of basalt lava flows that was uplifted by yet another rhyolite dome that did not reach the surface.

The Snake River Plain is commonly thought of as a region of "young" basalt volcanism, but the basalt flows are only a thin veneer that covers a much greater volume of older rhyolite. This is shown by outcrops of rhyolite in the surrounding ranges that disappear under the younger basalt flows of the eastern Snake River Plain. A well drilled at the INEL penetrated through approximately one-half mile of basalt lava flows, but bottomed out in rhyolite.

It is believed that the melting of the crust beneath the Snake River Plain produced rhyolite magma, which then collected in large reservoirs 3 to 6 miles beneath the surface. Rhyolite is highly viscous with the consistency of asphalt or caulking compound and is rich in dissolved gases. These factors combined in the past to produce highly explosive eruptions that are the antithesis of mild basalt eruptions. Tens-to-hundreds of cubic miles of frothy rhyolite pumice violently erupted in periods of only hours or days. Incandescent mixtures of pumice, ash, and gas traveled hundreds of miles from their vents to form welded ash flows. Gas-poor rhyolite also erupted at times during the final stages of activity. These lavas were too pasty to travel far from the vents, and thick rhyolite lava flows or domes were formed. Concurrently with the ejection of voluminous pumice, the earth's surface often collapsed above the evacuated magma chambers to form elliptical depressions that are many miles across. These are known as volcanic calderas. On the basis of detailed geologic mapping, drill hole information, and geophysical data, several ancient rhyolite calderas are inferred to be present beneath the basalt lava flows of the eastern Snake River Plain (Figure 9).

The ages of the rhyolite calderas become progressively younger to the northeast. Beneath the INEL, they are 5.5 to 6.5 million years old and are covered by 0.6 to 1.2 miles of younger basalt flows. At Island Park, northeast of the INEL, the calderas are 1.3 to 2 million years old, and their floors are only partially covered by basalt. Yellowstone Caldera is the youngest, formed 600,000 years ago, after the eruption of voluminous rhyolite ash flows from the Yellowstone National Park area; no basalt has yet erupted in the Yellowstone Caldera. Thus it seems that a progression of ancient "Yellowstone Parks" has been successively covered by basalt lava flows, and if recent geologic trends continue, Yellowstone National Park will one day be a flat basalt lava plain, similar in appearance to the INEL region.



(6.5) - Numbers in parentheses give approximate ages of calderas in millions of years
BC - Blacktail Caldera
BCC - Blue Creek Caldera
KC - Kilgore Caldera
HRC - Huckleberry Ridge Caldera
HC - Henry's Fork Caldera
YC - Yellowstone Caldera

6 11 225

Figure 9. Rhyolite calderas of Yellowstone National Park and the eastern Snake River Plain.

The northeastward migration of volcanism invites explanation, and several hypotheses have been proposed by geologists. The simplest and perhaps the most reasonable explanation states that the eastern Snake River Plain is the volcanic trail from a plume of hot, upwelling rock in the earth's upper mantle. Like a candle flame held beneath a moving piece of paper, North America is envisioned as a plate of the earth's crust that has migrated westward, over a fixed heat source in the earth's upper mantle. Basalt magma formed within the plume, and then rose into the overlying crust. This heated the crust, leading to the production of rhyolite magma, explosive eruption of the rhyolite, and caldera formation. Large bodies of rhyolite magma within the crust are believed to have formed barriers to the rising basalt, and the basalt could only erupt later, after the rhyolite was solidified. Today, the plume seems to be beneath Yellowstone National Park, and millions of years in the future, new volcanic centers may appear northeast of the Park.

LIVING WITH NATURE

Earthquakes—Signs of Active Mountain Building

On October 28, 1983, a magnitude 7.3 earthquake occurred in south-central Idaho. The epicenter was approximately halfway between Challis and Mackay, and faulting broke the surface for 25 miles along the western base of the Lost River Range near Borah Peak. Damage was estimated at $12.5 million, and the lives of two children were lost in Challis. The 1983 Borah Peak earthquake is the most recent of several damaging earthquakes that have affected Idaho in historic times, and serves as a reminder that the faults bounding the ranges to the north of the eastern Snake River Plain pose a significant earthquake hazard that must be carefully evaluated. The goals of earthquake hazard evaluation are the prediction of realistic "worst-case" ground motion for a particular area in a given time interval, and the assessment of dangers related to the secondary effects of earthquakes, such as soil mass failure, rockfalls, and landslides. Building codes for seismically active areas require engineers and planners to safely locate structures and to design them to survive the expected ground motion without serious damage.

A complete and accurate record of an area's seismicity is an important part of the data needed for earthquake hazard evaluation (Figure 10). The record should include the size, location, and date of previous earthquakes, so that the average time interval between large events (the recurrence interval) can be calculated along major faults. Proper evaluation of recurrence intervals is difficult because earthquake observations extending far back into prehistoric times are required.

Geologists have found that one way of obtaining the necessary data is the construction of trenches across fault zones. Offsets of strata and other structures revealed in the trench walls provide valuable information on earthquakes that occurred thousands of years ago. Trench measurements carried out by the U.S. Geological Survey across the Lost River fault indicate that the surface rupture associated with the 1983 event was very similar to the surface rupture of the last large scarp-forming event, which occurred not more than 12,000 years ago. The data are still undergoing analysis, and it is possible that radiometric data techniques will provide a much better estimate of the age of the previous large earthquake. Similar measurements on other segments of the Lost River fault and the fault along the base of the Lemhi Range have been undertaken, and it is hoped that this work will result in a reliable description of prehistoric seismic activity along the major faults in south-central Idaho.

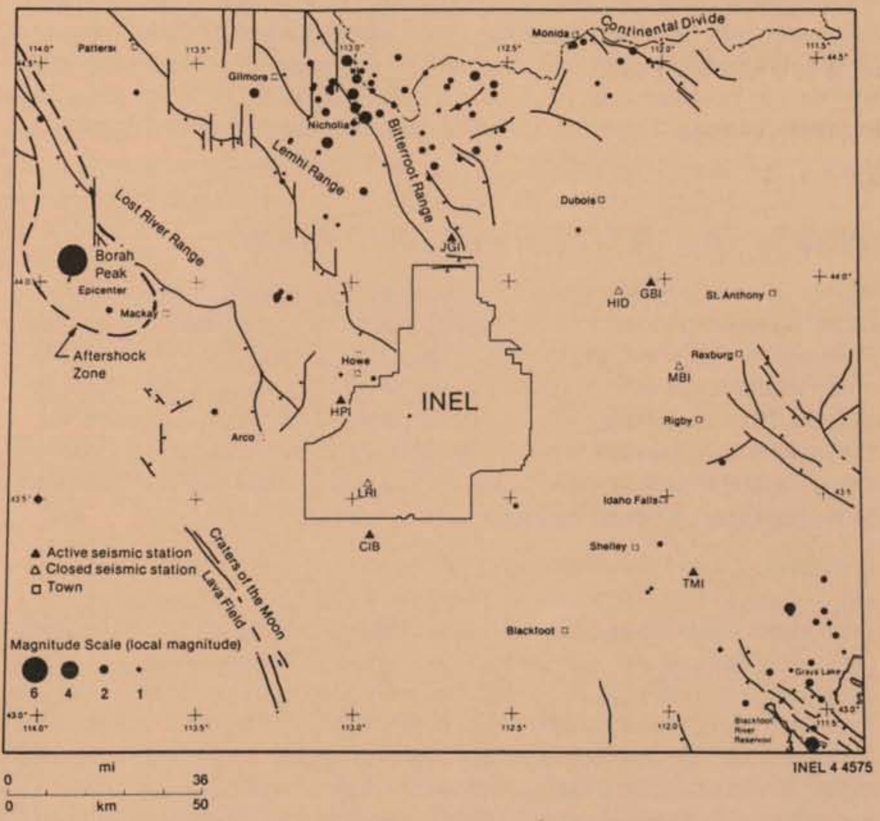


Figure 10. INEL earthquake catalog for October 1972 through December 1983, including approximate location of epicenter, fault scarp, and aftershock zone for the Borah Peak Earthquake.

Maps of earthquake epicenters are also used by geologists to assess earthquake hazard. In seismically active areas, small tremors occur frequently and their positions help to locate active faults. However, the most dangerous faults may be marked by the absence of earthquakes above a certain magnitude level. Such faults may be locked, storing energy that will ultimately be released in a large destructive earthquake. When this concept is applied to south-central Idaho, an interesting picture emerges. Figure 10 shows a preliminary epicenter map compiled by the INEL Seismic Group for earthquakes located in Idaho and southwestern Montana between 1972 and 1983. Each epicenter is surrounded by an ellipse that indicates the accuracy of the location. Notice the pronounced gap in earthquake activity for the Lost River, Lemhi, and Bitterroot Mountain faults. In 1983 this gap in seismicity was partially filled by the Borah Peak earthquake, which broke the Lost River fault. One implication is that tectonic strain might now be accumulating in the region of the Lemhi Range and Bitterroot Mountains, eventually resulting in a large earthquake. This possibility is reinforced by the existence of young surface ruptures mapped along the base of the Lemhi Range, making it clear that prehistoric earthquakes similar to the Borah Peak earthquake have occurred. Furthermore, the lack of seismicity preceding the 1983 Borah Peak earthquake indicates that we cannot expect a large shock to be preceded by smaller warning tremors that are detectable with existing seismic networks.

Why is the INEL Seismically Quiet?

Although several large shocks have occurred during historic time in the surrounding mountain ranges, earthquakes beneath the Eastern Snake River Plain are rare and have small magnitudes. Why is the Snake River Plain so quiet, in the midst of surrounding mountain ranges that are seismically active? Perhaps the passage of the Yellowstone plume has somehow "cured" the rocks deep beneath the plain, making them more resistant to fracturing. Or perhaps the rock at depth is still so hot that it flows like putty, instead of fracturing to produce earthquakes.

Earthquake hazard evaluation must also consider the effects of ground shaking on near-surface materials. For example, water-saturated sediments have been known to become unstable and spread laterally during an earthquake, producing fissures and slumping at the surface. This phenomenon, called liquefaction, can destroy even well-designed buildings by removing support from the foundations. During the Borah Peak earthquake, liquefaction damaged the highway between Mackay and Challis in Thousand Springs Valley. In mountainous areas, the stability of near-surface materials also determines landslide and rockfall hazards. Fortunately, the danger can be avoided by recognizing unstable slopes and cliffs. Rockfall caused by the Borah Peak earthquake was especially serious in Challis, where delicately balanced boulders were dislodged from steep cliffs above the town. The earthquake also caused a large landslide at Birch Creek at the base of the Lost River Range, in an area of water-saturated materials where previous landslides had occurred. The water-saturated materials were of low strength and the severe seismic shaking was sufficient to dislodge approximately 100,000 cubic yards of soil, mud, and rocks, which flowed downslope for several hundred yards. Another large landslide at Lupine Creek in the White Knob Mountains was discovered three days after the earthquake, also in water-saturated materials.

Although ground offsets, landslides, and other effects of the October 1983 Idaho earthquake were observed in the surrounding mountains, the INEL facilities sustained little or no damage. Seismometers operated by the INEL recorded the Idaho earthquake at approximately 8:06 a.m. on October 28, 1983. As a safety measure, the nuclear reactors and support facilities operating at the time were immediately shut down, until the extent of the damage could be assessed. It was discovered that the reactors suffered no damage and that other INEL buildings sustained only cosmetic damage, such as small cracks in cinderblock walls. The reactors were soon restarted without difficulty. Later analysis of the earthquake data showed that the ground beneath the INEL moved very little as the earthquake waves passed through the Site. It was shown that the acceleration of the ground was only about one-tenth of that which the INEL buildings were designed to withstand, even though the Idaho earthquake was of magnitude 7.3 and occurred only about 30 miles northwest of the INEL. Apparently, the fractured basalt lava flows of the eastern Snake River Plain do not transmit waves very well, and serve to muffle seismic shocks from earthquakes centered in the surrounding mountains.

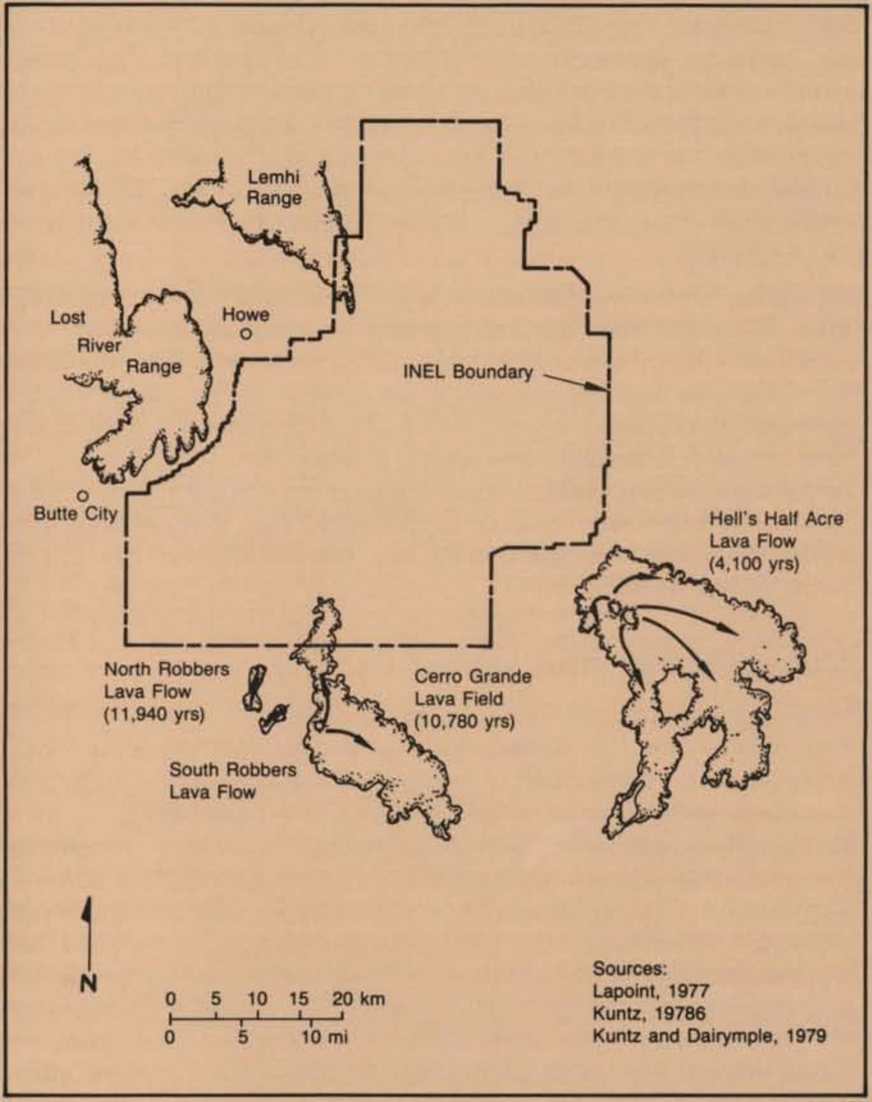
Recent research on earthquake prediction, although promising, has yet to provide a simple and accurate means for forecasting the time, location, and size of an impending earthquake. Research into the possibility of earthquake prevention has also made some progress, but there is not likely to be any serious attempt at prevention in the near future. It is therefore important to identify seismic hazards where they exist, evaluate the seriousness of those hazards, and then prepare for the expected earthquakes through careful siting and design of structures.

Implications of the INEL's Volcanic Past

Even in well-studied regions of active volcanism, such as Hawaii, predictions of volcanic eruptions are little better than nonspecific predictions of the weather: we can say that it will definitely rain at some place within a given time period, but the size of the cloudburst and its precise time of arrival are nearly impossible to predict until the event is upon us. The prediction of future volcanic hazards generally relies on knowledge gained from assessing past volcanic patterns. Geologic studies in the INEL region have led to the recognition of two types of past volcanic styles: explosive rhyolite volcanism and mild basalt volcanism. Five to six million years ago, explosive rhyolite volcanism occurred beneath the INEL, but the calderas are now dead and buried beneath basalt lava flows. The only rhyolite volcanism near the INEL that can be termed recent (hundreds of thousands of years ago) involved local dome extrusion that apparently was of low explosivity. The youngest rhyolite dome (Big Southern Butte) is about 300,000 years old, and East Butte is about 600,000 years old. These centers are believed to represent the waning stages of rhyolite caldera eruptions that occurred in the eastern Snake River Plain about 5 to 6 million years ago. Rhyolite volcanism has shifted to Yellowstone National Park, and the likelihood of a future rhyolite dome eruption near the INEL is considered to be remote.

In contrast to the past rhyolite volcanism, basalt volcanism has been the dominant form present in the vicinity of the INEL in the last two million years (Figure 11). Two of the volcanic rift zones have been active within the past 20,000 years. The Arco-Big Southern Butte volcanic rift zone erupted the North and South Robbers lava flows about 12,000 years ago, with neither of these reaching the INEL. The Cerro Grande lava field also erupted from this rift zone about 11,000 years ago. These flows traveled about 12 miles from the source and encroached onto what is now the southern INEL boundary. The youngest lava flows in the INEL area erupted 4,100 years ago from the Lava Ridge-Hell's Half Acre lava field. By comparison, the youngest dated vent within the INEL boundary is about 300,000 years old. These observations suggest that should future basalt eruptions occur from the Arco-Big Southern Butte and Lava Ridge-Hell's Half Acre volcanic rift zones, such eruptions would probably be lava flows that would travel generally to the south, since the land surface of the eastern Snake River Plain slopes gently southward. Based on geologic mapping and on dating of prehistoric lava flows, it is estimated that volcanism may recur every 3,000 years within the Arco-Big Southern Butte and Lava Ridge-Hell's Half Acre rift zones. The most recent dated eruptions of lava from these two rift zones occurred 10,780 and 4,100 years ago, respectively. Perhaps the most active threat is 20 miles to the southwest, at Craters of the Moon National Monument, since lava flows have erupted there as recently as 2,100 years ago. However, future lava flows from this area would probably travel mostly to the south and away from the INEL, as they have done in the past.

In addition to lava flows, future INEL facilities on these rift zones could be affected by earthquakes associated with volcanism, or by ground deformation in the vicinity of volcanic vents. Historic eruptions from Hawaiian shield volcanoes have had accompanying earthquakes as large as magnitude 7, but most volcanic earthquakes are of magnitude 5 or less. Studies of Hawaiian shield volcanoes also indicate that swelling of the ground surface by several feet, and opening of tensional fractures at the surface can accompany the upwelling of magma beneath volcanic vents. There are few streams within the INEL boundary, but rising basalt magma could encounter the ground water of the Snake River Plain Aquifer and erupt explosively to form maar volcanoes. No features of this type are known within the INEL boundary, but the Menan Buttes (500,000 years old?) near Rexburg are large tuff cones that formed when basalt erupted through the ancient river bed of the Snake River. The effects of future "Menan Buttes-type" eruptions would probably involve fallout of volcanic ash and emanation of acrid vapors, affecting an area of perhaps several square miles. It is anticipated that even the most explosive basalt eruptions of the eastern Snake River Plain would affect rather small areas, and would not compare with the more extensive damage that occurred at other volcanoes of the United States, such as Mt. St. Helens.



Sources:
Lapoint, 1977
Kuntz, 19786
Kuntz and Dairymple, 1979

Figure 11. Map of young (< 20,000 years) lava flows in the vicinity of the INEL.

In all areas of recent volcanism, there is some risk of damage to life and property, and comparison with similar regions of historical volcanism helps to define the amount of risk. It is interesting to note that the ancient landforms of the eastern Snake River Plain are remarkably similar to the non-violent eruptions associated with volcanoes in the Hawaiian Islands.

Water Use and Benefits

Irrigated agriculture provides the economic base for the people of southern Idaho, and the Snake River Plain Aquifer makes possible a significant percentage of that base. In addition to providing ground water for irrigation of over one third of the three million irrigated acres of the Snake River Plain, springs from the aquifer provide clean, safe water at just the right temperature for raising more than 25 million pounds of rainbow trout; this is about 75% of the entire annual production of the United States. It is estimated that over 127,000 people depend on the aquifer for domestic and municipal water needs; water from the aquifer is a constant 58 degrees all year, and requires no chlorination.

The storage capability of the aquifer is also an important benefit to southern Idaho. There are three major surface storage reservoirs and five smaller reservoirs in the eastern Snake River Basin, with a combined usable capacity of five million acre-feet. By comparison, the Snake River Plain Aquifer has an estimated usable storage capacity of over 200 million acre-feet. Furthermore, water stored in the aquifer is not subject to evaporation and is relatively protected from contaminants. Without the large storage capacity and subsequent delay in the return of water to the Snake River, seasonal fluctuations of river flows would be much greater, and this would impact hydroelectric plants as well as irrigators.

Water Rights and Water Quality

Water rights in Idaho are based on the appropriation doctrine of 'first-in-time, first-in-right.'' On surface streams, this doctrine works well; when natural flows decrease, junior water rights or diversions are cut off by priority of time, with the senior or earliest right on the stream being the last to be shut off. Ground water rights are also subject to the same doctrine, but the relationships between wells are difficult to define and interference is difficult to prove. The aquifer and the river system are interconnected, and administration of water rights becomes even more difficult. Since ground water pumping anywhere in the aquifer can ultimately affect river flows, the time and magnitude of impacts on the river and on other areas in the aquifer are difficult to determine without the aid of computer models. The State of Idaho is now defining water rights in and adjacent to the Snake River Plain Aquifer, and is developing a computer model to assist in management and understanding of the system.

Pollution of the aquifer is of prime concern since it provides drinking water to a large number of people. Water quality in the aquifer is excellent, primarily because the overlying soil filters chemicals and pollutants from irrigation and other water that passes through it. No general water quality problems exist in the aquifer, but pollution can occur from accidental spills of toxic materials such as pesticides and industrial chemicals, leaching of nitrates from fertilizer, direct injection of chemical or agricultural wastes, or failure of septic tanks and drainfields.

The topography of many irrigated areas above the Snake River Plain Aquifer is such that runoff from fields does not return to surface streams but accumulates in closed basins. Many irrigators have drilled drainage wells to allow runoff to flow into the aquifer, along with sediment, associated phosphorous, and accidental spills of agricultural chemicals. Between 1953 and 1984, the INEL used a deep well for injection of low-level liquid radioactive waste from a chemical processing plant. Tritium was first detected in monitoring wells located within the INEL near the southern boundary in 1983. It has since been detected in these wells but has never exceeded the National Interim Primary Drinking Water Standard. The injection of low-level waste as a routine disposal technique was replaced by the use of an evaporative and seepage lagoon in 1984, and further mitigative procedures are planned and funded.

The State of Idaho has developed a plan for management of the Snake River Plain Aquifer to include guidelines for waste management and protection from pollution by toxic substances. The aquifer certainly deserves our good stewardship, since the ground water is not only a vital resource, but is also the vehicle for impact on other users.

Suggestions for Further Reading

Barraclough, J.T., Teasdale, W. E., and Jensen, R.G., *Hydrology of the National Reactor Testing Station, Idaho, 1965*, U.S. Geological Survey Open-File Report IDO-22047, 1967.

Barraclough, J. T., Teasdale, W. E., Robertson, J. B., and Jensen, R. G., *Hydrology of the National Reactor Testing Station, Idaho, 1966*, U.S. Geological Survey Open-File Report IDO-22048, 1967.

Barraclough, J. T., and Jensen, R. G., *Hydrologic Data for the Idaho National Engineering Laboratory Site, Idaho, 1971 to 1973*, U.S. Geological Survey Open-File Report 75-318 (IDO-22055), 1976.

Barraclough, J. T., Robertson, J. B., and Janzer, V. J., *Hydrology of the Solid Waste Burial Ground, as Related to the Potential Migration of Radionuclides, Idaho National Engineering Laboratory*, with a section on Drilling and Sample Analyses, by L. G. Saindon, U.S. Geological Survey Open-File Report 76-471 (IDO-22056), 1976.

Barraclough, J. T., Lewis, B. D., and Jensen, R. G., *Hydrologic Conditions at the Idaho National Engineering Laboratory, Idaho - Emphasis 1974-1978*, U.S. Geological Survey Water-Supply 2191, 1982.

Bonnichsen, B. and Breckenridge, R. M. (eds), "Cenozoic Geology of Idaho", *Idaho Bureau of Mines and Geology Bulletin, 26*, 1982.

Lewis, B. D., and Goldstein, F. G., *Evaluation of a Predictive Ground-Water Solute-Transport Model at the Idaho National Engineering Laboratory, Idaho*, U.S. Geological Survey Water-Resources Investigation 82-25, 1982.

Lewis, B. D., and Jensen, R. J., *Hydrologic Conditions at the Idaho National Engineering Laboratory, Idaho: 1978-1981 Update*, U.S. Geological Survey Open-File Report 84-230, 1984.

Lindholm, G. F., *Plan of Study for the Regional Aquifer-System Analysis of the Snake River Plain, Idaho and Eastern Oregon*, U.S. Geological Survey Open-File Report 81-689, 1981.

Lindholm, G. F., Garabedian, S. P., Newton, G. D., and Whitehead, R. L., *Configuration of the Water Table, March 1980, in the Snake River Plain Regional Aquifer System, Idaho and Eastern Oregon*, U.S. Geological Survey Open-File Report 82-1022, 1:500,000, 1983.

Macdonald, G. A., *Volcanoes*, Englewood Cliffs, NJ: Prentice-Hall, Inc., 1972.

Morris, D. A., Barraclough, J. T., Chase, G. H., Teasdale, W. E., and Jensen, R. G., *Hydrology of Subsurface Waste Disposal, National Reactor Testing Station, Idaho, Annual Progress Report, 1964*, U.S. Atomic Energy Commission, Idaho Office Operations Office Publication, IDO-22047-USGS, 1965.

Mundorff, M. J., Crosthwaite, E. G., and Kilburn, C., *Ground Water for Irrigation in the Snake River Basin in Idaho*, U.S. Geological Survey Water-Supply Paper-1654, 1964.

Norvitch, R. F., Thomas, C. A., and Madison, R. J., "Artificial Recharge to the Snake Plain Aquifer, an Evaluation of Potential and Effect," *Idaho Department of Reclamation, Water Information Bulletin*, 12, 1969.

Robertson, J. B., *Digital Modeling of Radioactive and Chemical Waste Transport in the Snake River Plain Aquifer at the National Reactor Testing Station, Idaho*, U.S. Geological Survey Open-File Report IDO-22054, 1974.

Robertson, J. B., Schoen, R., and Barraclough, J. T., *The Influence of Liquid Waste Disposal on the Geochemistry of Water at the National Reactor Testing Station, Idaho: 1952-1970*, U.S. Geological Survey Open File report IDO-22053, 1974.

Russell, O., *Journal of a Trapper or Nine Years in the Rocky Mountains 1834-1843*, Boise, Idaho: Syms-York Company, 1921.

Seitz, H. R., La Sala, A. M., and Moreland, J. A., *Effects of Drain Wells on the Ground-Water Quality of the Western Snake Plain Aquifer, Idaho*, U.S. Geological Survey Open-File Report 76-673, 1977.

Stearns, H. T., Crandall, L., and Steward, W. G., *Geology and Ground-Water Resources of the Snake River Plain in Southeastern Idaho*, U.S. Geological Survey Water-Supply Paper-774, 1936.

Walker, E. H., "Subsurface Geology of the National Reactor Testing Station, Idaho, *U.S. Geological Survey Bulletin, 1133-E*, 1964.

Williams, H. and McBirney, A. R., *Volcanology*, San Francisco, California: Freeman, Cooper & Co., 1979.

Young, H. W., and Harenberg, W. A., "Ground-Water Pumpage from the Snake Plain Aquifer, Southeastern Idaho, *Idaho Department of Water Administration, Water Information Bulletin, 23*, 1971.

Young, H. W., and Jones, M. L., *Hydrologic, Demographic, and Land-Use Data for the Snake River Plain, Southeastern Idaho*, U.S. Geological Survey Water-Resources Investigation Report-84-4001, 1984.

Zohdy, A. A. R., and Stanley, W. D., *Preliminary Interpretation of Electrical Sounding Curves Obtained Across the Snake River Plain from Blackfoot to Arco, Idaho*, U.S. Geological Survey Open-File Report, 1973.

Appendix A

In the beginning...

It is now thought that the earth is 4,500 million years old, and in that lengthy interval, the surface has undergone amazing changes, including the rising and receding of oceans, the collision of continents, and the uplift and erosion of vast mountain ranges. The mountains and lava plains surrounding the INEL Site, despite their apparent timelessness, represent relatively young landforms that developed in the last 17 million years, less than one half of one percent of the total age of the earth. Before that, the area was alternately covered by shallow seas and dominated by ancient mountain ranges and volcanoes. This is an introduction to some of the geologic events that have affected the region of the INEL Site.

The Breakup of a Continent and the Early Continental Margin

In the 1970s geologists began to interpret sedimentary rocks in western North America, deposited between 650 and 350 million years ago, as laid down in a shallow sea at the margin of an ancient continent. The lower part of this rock sequence is exposed in a curved band approximately 2,400 miles long, trending roughly north to south from the Yukon territories in Canada through Idaho to southern Arizona (Figures 12 and 13). It is believed that this band marks the site of a continental breakup about 900 million years ago, when a major continent separated and a wedge of shallow-water sediments was deposited at the new continental shelf, which included much of Idaho. Farther offshore in Oregon, deep-water sediments were accumulating in a sea of unknown character. Exposures of the ancient shelf rocks are found in the mountains of the western United States, including the Lost River and Lemhi Ranges northwest of the INEL Site.

Ancient Mountain Building

The deposition of shelf sediments ceased about 350 million years ago, when a process termed subduction, developed offshore west of Idaho, probably in Oregon. The subduction process is marked by a deep-sea trench, and involves the destruction of oceanic crust, as it pushes against the margin of a continent and is forced down into the earth (Figure 14). Although marine sediments continued to be deposited and remained an important geologic process in south-central Idaho until at least 230 million years ago, the rock record indicates that sedimentary rocks were uplifted above sea level, and mountain building events periodically dominated the scene. In particular, a major upheaval of the land, between 140 to 65 million years ago, resulted in the emplacement of the many thrust sheets exposed in the mountains north of the eastern Snake River Plain and the INEL Site.

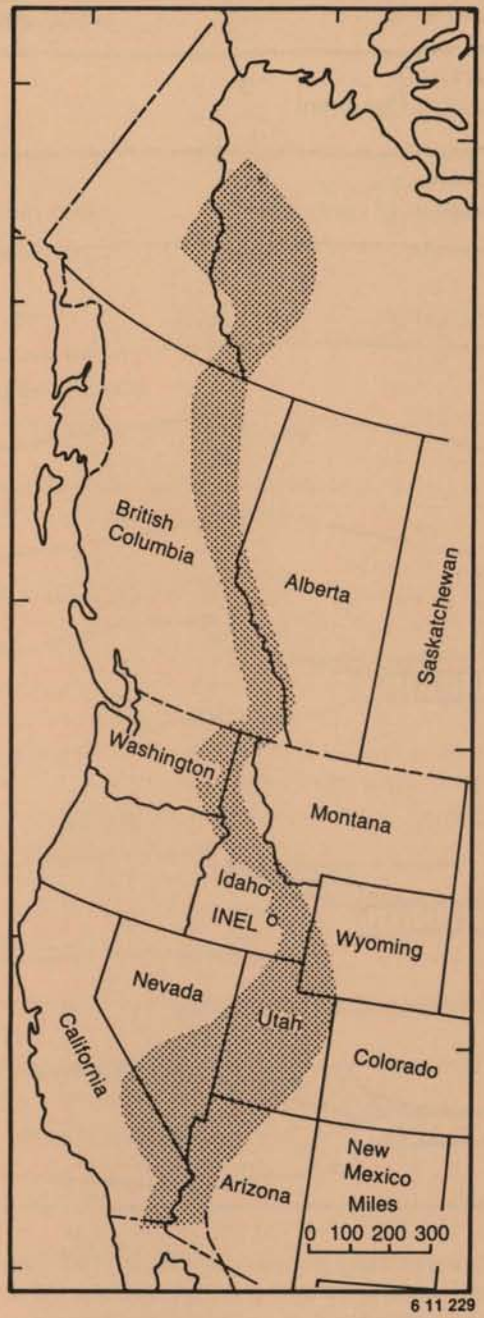


Figure 12. ***The shaded band shows the approximate position of sedimentary rocks interpreted as deposited at the edge of an ancient continent between about 650 and 550 million years ago.***

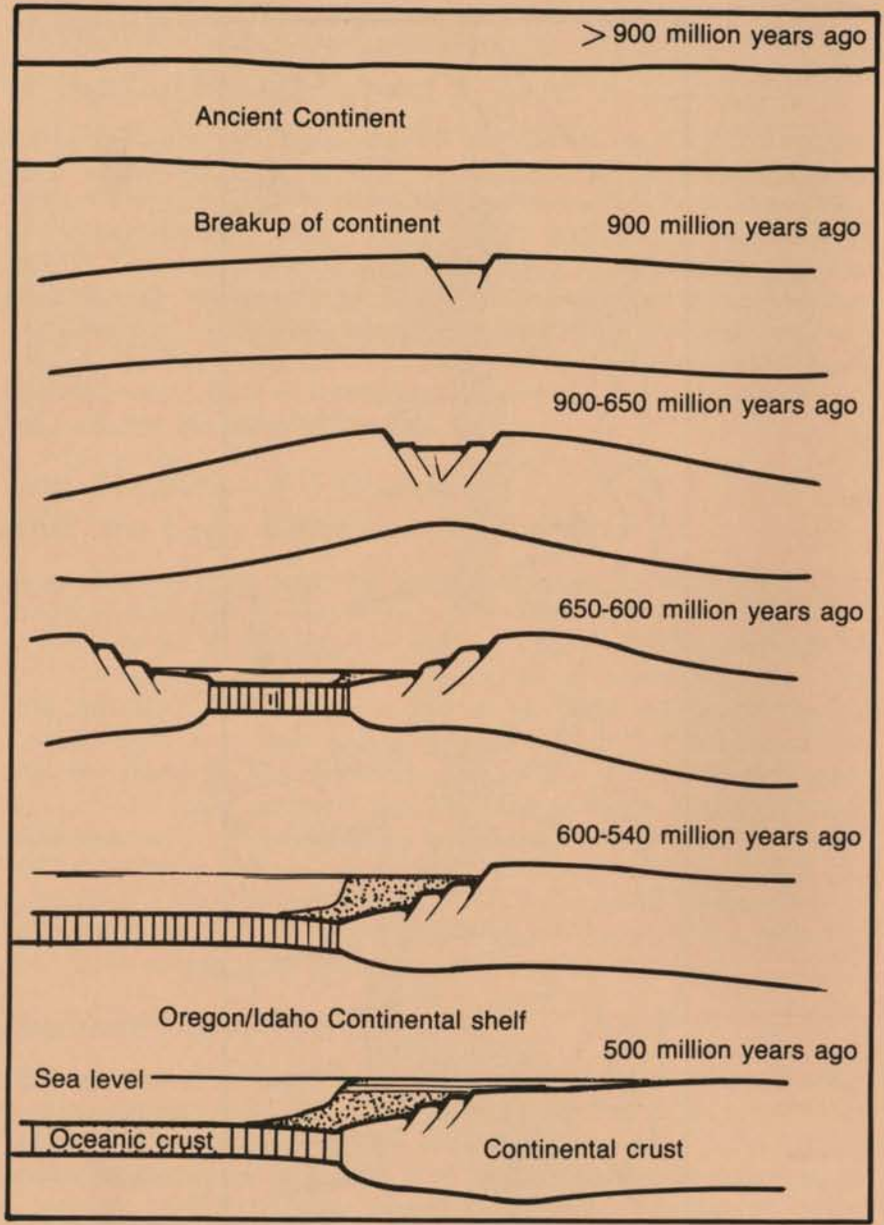


Figure 13. Sequence depicting breakup of the continent and development of a continental shelf along the ancestral edge of western North America.

Thrust sheets are large slivers of rock, thousands of feet thick, which are stacked one upon the other and are separated by curved fractures called thrust faults (Figure 15). Thrust faults are believed to develop when the earth's crust is compressed. In the upper crust, rock layers break and slip along many shallow parallel fractures, and crustal shortening takes place by telescoping huge slivers of rock. Deeper and hotter layers probably respond by flowage. Rocks can travel substantial distances by these mechanisms, as much as 90 miles or more. For example, a body of sedimentary rock called the Milligen Formation is believed to have been deposited about 380 million years ago in relatively deep water just off the edge of the ancestral continental shelf of western North America, near the present Idaho-Oregon boundary. Geologists now find the Milligen Formation exposed in the mountains north of the INEL Site, many miles to the east, and the structures exposed in the mountains indicate that the rocks were carried there by thrust faults.

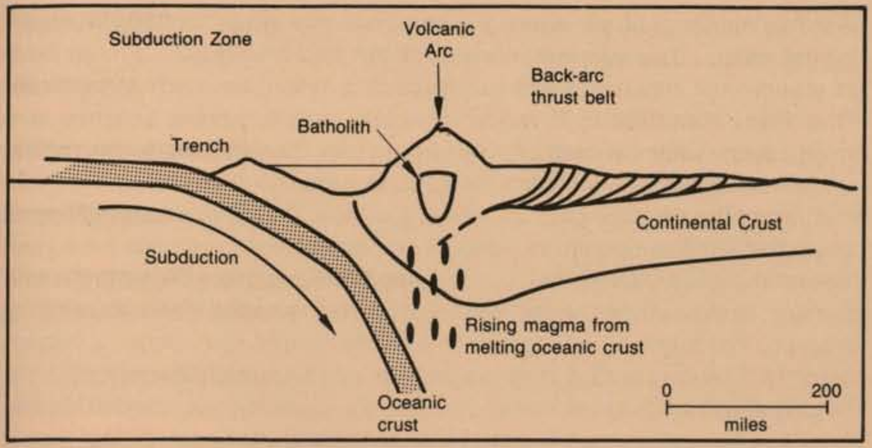


Figure 14. Schematic cross section showing important geologic features of a subduction zone.

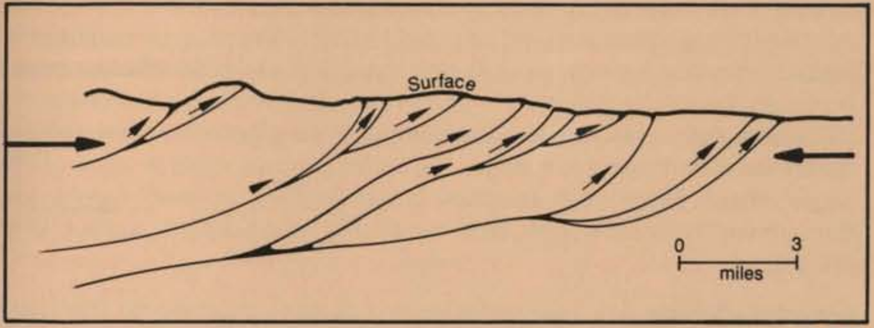


Figure 15. Thrust sheet development under the action of compressive forces. Motion of each thrust sheet relative to the underlying sheet is indicated by small arrows.

Another major geologic event accompanied the thrust faulting in south-central Idaho. This was the intrusion of the Idaho Batholith, a huge body of granitic rock that is exposed over much of central Idaho north of the Snake River Plain. About 100 to 75 million years ago, granitic forming magmas were buried deep within the crust; these magmas may have formed by the melting of the subducted oceanic plate beneath western North America, or by the melting of the continental crust above this plate. Deep mines and drill holes show that earth temperatures increase with depth, and geologists have good reason to believe that at depths of approximately 20 miles beneath the land surface, temperatures can be high enough to melt solid rock and produce magma. The high heat of large magma bodies might melt nearby continental rocks, thereby creating other magmas of granite composition. In any case, large batholiths consist of numerous smaller granitic forming magma bodies, forming a "sea of granite" that rises within the crust above subduction zones. Later, uplift and erosion exposes the once deep-seated granitic rock.

Approximately 55 to 40 million years ago, another wave of subduction- related magmas lay beneath south-central Idaho. Some of these magmas erupted to form a large volcanic field north of the eastern Snake River Plain—the Challis Volcanics. These volcanics are very common in central Idaho east of the Idaho Batholith, where they blanket exposures of much older sedimentary rock; they are especially well exposed in the Pioneer and White Knob Mountains. The rock compositions of the Challis Volcanics are quite unlike those of the eastern Snake River Plain, and they may have been produced by a partial melting of a subducted oceanic plate.

Development of the Basin-Range Structure

South-central Idaho was relatively quiet after the extrusion of the Challis Volcanics, until about 17 million years ago when a fundamental change in crustal forces occurred. Large blocks of crust became detached and moved vertically along faults, forming parallel mountain ranges and intervening valleys. This type of topography characterizes much of the present-day western United States, and is often called a basin-range structure. The total vertical movement along some basin-range faults is three miles or more. However, the topographic relief is always considerably less because the rising mountains are continually being eroded into the adjacent valleys and the thickness of sedimentary fill above the bedrock is two miles in some of the larger valleys. Basin-range structure is seen in the Lost River, Lemhi, and Beaverhead Mountains with their associated intermountain valleys (Figure 16).

Figure 16. The Lost River Range from Thousand Springs Valley. These mountains have been uplifted relative to the valley by at least 1½ miles.

Geologists believe that basin-range faulting occurs in response to stretching of the earth's crust. The results of many studies suggest that the western United States has undergone east-west extension of as much as 71 miles during the past 17 million years. At present, there is no agreement on the ultimate cause of this extension. One view is that the relative motion between the Pacific and North American crustal plates has resulted in stretching of the crust across a broad region of the western United States. Another view suggests that hot rock in the earth's mantle rises, spreads laterally at the base of the crust, and results in uplift and extension of the overlying crust. Although these theories differ, both relate the beginning of extension to the cessation of subduction (and compression)—about 20 million years ago.

In addition to uncertainty regarding the fundamental cause of basin-range structure in the western United States, there is also a lack of consensus regarding the geometry of the faults that separate the crustal blocks (Figure 17). According to one theory, steep faults form as a result of extension. Further extension enables some crustal blocks to sink and tilt relative to others, much like keystone blocks in a brick archway, when the archway is spread apart. A competing theory suggests that the faults are steep at the surface but flatten at depth, so that simple rotation of a block would tilt one end up to form mountains and the other end down to form valleys. Recently, seismic images of the earth's interior obtained by oil companies near basin-range faults indicate that some faults do indeed flatten several miles below the surface. Both styles of faulting probably occur, depending on the location.

Figure 17. Possible subsurface geometries of basin-range faults.

Downwarping and volcanism in the area that is now the eastern Snake River Plain accompanied the development of basin-range structure in south-central Idaho. Both basin-range mountain building and volcanism continue to occur, as shown by large earthquakes centered in the surrounding ranges, and by "geologically recent" volcanic activity on the eastern Snake River Plain.