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FRONT COVER PHOTOGRAPH. *The eruption of Kilauea Volcano on the island of Hawaii, which began in 1983, continues (see first article in this issue). The photograph shows lava pouring from the episode-50 fissure on the side of a large cinder and spatter cone, called Pu'u ' O'o', that formed earlier in the eruption. The episode-50 vent is about 17 km from the volcano's summit. Small lava fountains delineate the fissure. Photograph by Jim Griggs, February 18, 1992.*

The Ten-Year Eruption of Kilauea Volcano

by David A. Clague and Christina Heliker
Hawaiian Volcano Observatory
U.S. Geological Survey

Hawaiian volcanoes are examples of a class of broad, gently sloped volcanoes called shield volcanoes. Characteristically, shield volcanoes erupt quietly with few catastrophic explosive eruptions. The molten rock or magma brought to the surface at Hawaiian shield volcanoes is basaltic and flows freely due to its low viscosity. Under these conditions, gasses within the molten rock escape gradually and do not build up to cause explosions.

The First Ten Years of Eruptive Activity

The Pu'u 'O'o-Kupaianaha eruption now ranks as the longest-lived historic eruption on the East Rift Zone and the most destructive in Kilauea's recent history. About 1 km^3 of lava erupted during the first 10 years of the eruption. Lava flows have destroyed 181 houses and severed the coastal highway along the volcano's south flank, severely restricting transportation on this part of the island of Hawaii. The eruption consisted of many distinct episodes characterized by activity at different vents and by different eruptive styles. The following summarizes the first 10 years of the eruption, starting with the initial outbreak in 1983.

Episodes 1-3: The Initial Fissure Eruption

The eruption began early on January 3, 1983, and, over the next 4 days, a discontinuous series of fissures opened along an 8-km-long section in the middle of Kilauea's East Rift Zone about 17 km from the volcano's summit. Lava fountains became localized along a 1-km-long section of the fissure system. This activity continued intermittently for several weeks. The next episode began on February 10 with low-level activity at a new vent, called the 1123-vent after the time of initial activity. The episode culminated on March 4 after a vigorous, 8-day-long eruption from the same vent. Episode 3 took place between March 21 and April 9. During this episode lava fountains occurred at the same vent and at a new vent. The new vent was initially called the O-vent because its location coincided with the letter "o" in the word "flow" on a topographic map of the area. This vent was later renamed Pu'u 'O'o.

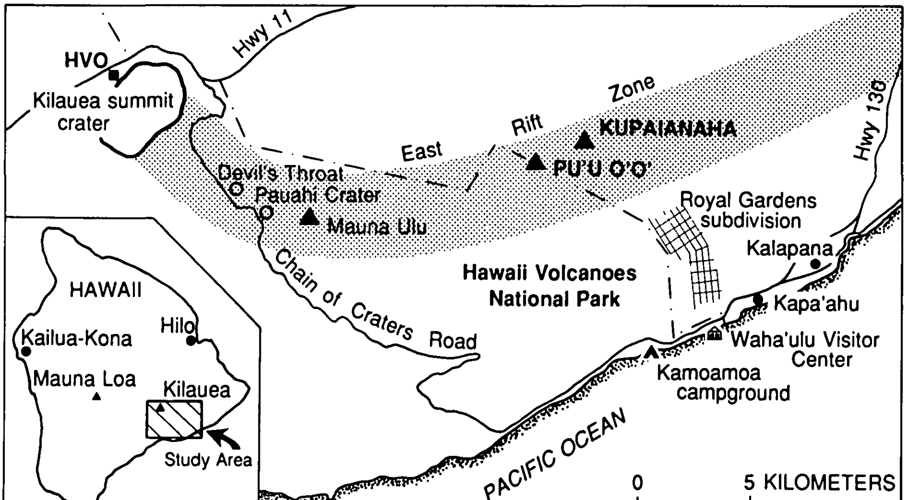
Episodes 4-47: Building the Pu'u 'O'o Cone

By episode 4, which began on June 13 and ended on June 17, activity had settled at the Pu'u 'O'o vent, located slightly up the rift (westward) from the 1123 vent. During the next 3 years, 44 separate episodes of high fountain eruption, most lasting less than a day, built Pu'u 'O'o to a height of 255 m. 'A'a lava flows from Pu'u 'O'o repeatedly entered the Royal Gardens

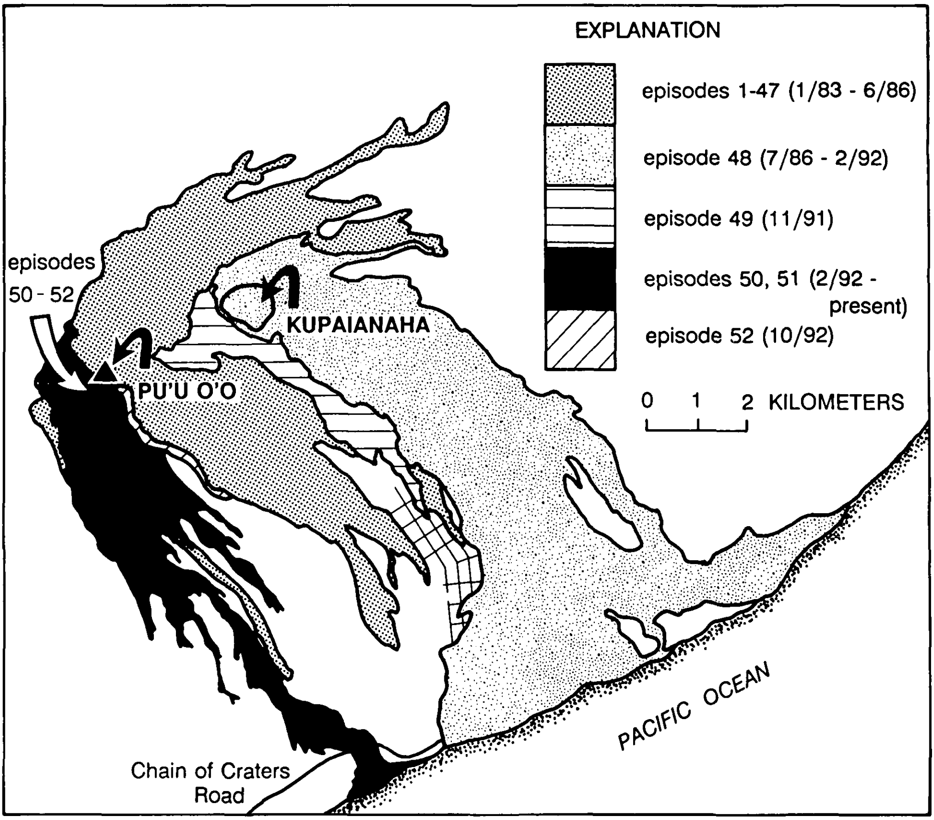
A Note from the Editors

Kilauea volcano on the island of Hawaii has entered its 11th year of eruption, the longest period of rift-zone eruption on the island in the past 200 years. This article is an account of the first 10 years of Kilauea's ongoing eruption. Since the activity began in 1983, the eruption has changed the landscape, devastated communities, destroyed precious rain forest, and vented noxious gasses that have irritated residents and reduced farm yields. This activity is a painful reminder to residents that they live on the slopes of an active volcano. Intense monitoring of the eruption at the U.S. Geological Survey's Hawaiian Volcano Observatory (HVO) has provided extraordinary new data on the processes that build Hawaiian shield volcanoes. As dramatic as this activity seems to us now, each new outpouring of lava is only an increment of thousands of such eruptions that have built Kilauea and the island of Hawaii.

Scientists have divided the first 10 years of Kilauea's eruption into 52 episodes, each defined by either a discrete period of eruption or an eruption from a newly formed vent. Individual episodes may last from less than 24 hours to as long as several years. The eruption has created two new volcanic edifices on the southeast flank of Kilauea. Lava fountains during the first three years of activity built the imposing volcanic cone known as Pu'u 'O'o. In the Hawaiian language, pu'u means hill, and 'o'o refers to an extinct bird. In 1986 continuous outpouring of lava from a new vent built a gently sloping shield on Kilauea. People from Kalapana, the community closest to the new vent, named the growing shield Kupaianaha, which means mysterious or extraordinary in Hawaiian. Less than 5 years later, lava flows from Kupaianaha engulfed the town.

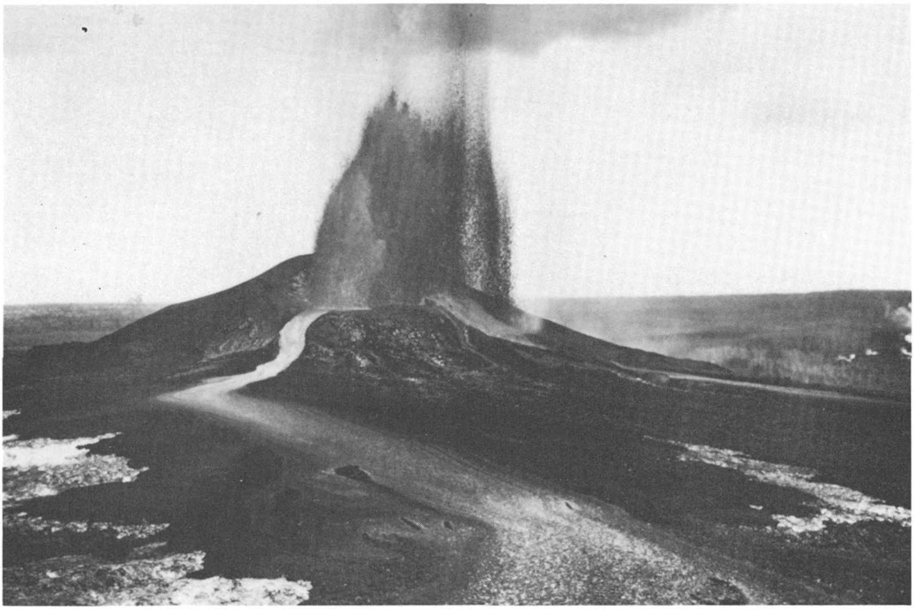


Map showing the East Rift Zone (shaded area) of Kilauea Volcano and the principal topographic and cultural features of the study area on the island of Hawaii, the so-called *Big Island. Kilauea and Mauna Loa are gently sloping shield volcanoes built by basaltic lava flows. These two volcanoes are the youngest of five shield volcanoes, which in aggregate form the island of Hawaii.*



Map showing areas covered by lava flows during eruptive episodes 1-52 (January 1983 through December 1992) on Kilauea's southeast flank. Eruptions from Pu'u 'O'o and Kupaianaha have repeatedly threatened communities on Hawaii's southeast coast. Residents usually have plenty of time to evacuate, but the eruptions have destroyed nearly 200 homes; first in the Royal Gardens subdivision, then in the coastal community of Kapa'ahu, and finally in Kalapana (see preceding map).

Lava flows of basalt composition have two characteristic forms, 'a'a (pronounced "ah-ah") and pahoehoe (pronounced "pah-hoy-hoy"). 'A'a flows are characterized by a rough, jagged surface. In contrast, pahoehoe flows have a smooth, billowy or ropy surface. Both terms are Hawaiian.



A high lava fountain and lava flow erupt from the Pu'u O'o cone. Lava fountains are jets of incandescent lava powered into the air by the expansion of gas bubbles as magma approaches the surface. Brief outbursts of lava fountains built Pu'u 'O'o, a volcanic feature known as a cinder and spatter cone, during episodes 4 through 47. Photograph by Jim Griggs, June 30, 1984.

subdivision in 1983 and 1984, destroying 16 residences (see accompanying maps). Lava had covered 42 km^2 of land by July 1986, when the eruption shifted 3 km down the rift (eastward).

Episode 48: The Kupaianaha Shield

Continuous, quiet outpouring of lava characterized the next vent to appear, Kupaianaha. A lava pond formed over the new vent, and its overflows built a broad, low shield. After weeks of eruption, the main lava channel leading from the pond roofed over, forming the beginning of a lava tube that would reach the ocean, nearly 12 km away, by December 1986. Fed by lava tubes, pahoehoe lava flows destroyed 11 homes in sparsely populated Kapa'ahu; a separate flow to the east destroyed an additional 17 homes in the more densely populated Kalapana Gardens subdivision. Over the next several years, lava continued to reach the

A lava tube forms when the top of a lava channel crusts over. When the supply of molten lava is interrupted, the channel empties, leaving behind a tunnel called a lava tube within the solidified flow. Later, fresh lava may use this tube as a conduit.

ocean through a complex and changing network of tubes, destroying the Hawaii Volcanoes National Park Visitor Center at Waha'ula and an additional 33 homes in Kapa'ahu, lower Royal Gardens, and the National Park, as the flow field widened.

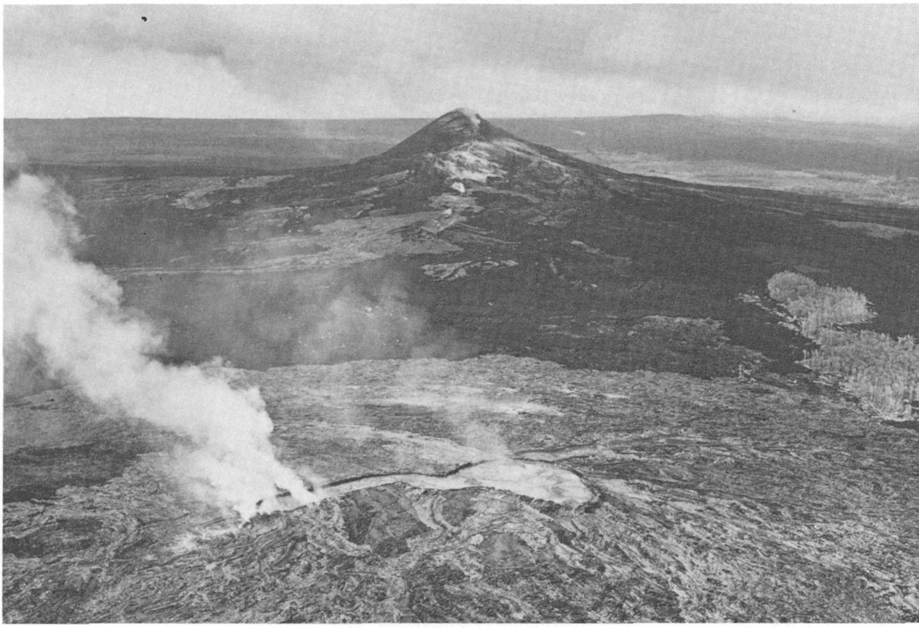
In April 1988, the eruption stopped for one week—the first period of repose since July 1986. A series of 12 brief pauses in the eruptive activity occurred in the period from February until November 1990. During the first of these pauses, the lava tubes feeding lava to the ocean were blocked. When the eruption resumed, surface lava flows once again threatened Kalapana. The volume and depth of the active lava in the Kupaianaha pond steadily diminished during early 1990, and the pond emptied by June 1990. Lava now flowed directly from the vent into the tube system without appearing on the surface. By the end of 1990, tube-fed lava flows had overrun all of Kalapana, destroying 100 additional homes.

Upper East Rift Zone Intrusions

In December 1990, and again in March and August 1991, fresh magma from the summit intruded into the upper East Rift Zone. At first this had little effect on the ongoing eruption at Kupaianaha. However, by the middle of 1991, the volume of lava erupted at Kupaianaha began to decrease. As the level of lava flowing in the tube system dropped, collapses of tube walls and roofs blocked the lower reaches of the tube system. The flow of lava to the ocean near Waha'ula slowed and stopped altogether in early September 1991. As the tube system deteriorated over the next 2 months, the terminus of individual tubes retreated closer and closer to the vent. In October, some of the last large surface flows to erupt from Kupaianaha destroyed two additional homes in Royal Gardens.

Episode 49: A New Fissure

On November 8, 1991, the character of the eruption abruptly changed once again. A curtain of fire erupted from a series of discontinuous fissures between Pu'u 'O'o and Kupaianaha. This event, episode 49, continued until November 26. The eruption fed 'a'a flows which reached the top of Royal Gardens but did not overrun any of the remaining houses. The flows mainly covered earlier lava flows from Pu'u 'O'o and Kupaianaha. At the same time, and continuing after episode 49 came to a halt, small tube-fed pahoehoe flows erupted from nearby Kupaianaha. The volume of lava erupted from Kupaianaha, however, declined after



In the foreground, a pond of fuming, molten lava marks the summit of the Kupaianaha shield. Hundreds of interfingering lava flows have spilled over the lip of the lava pond to form a lava shield about 1 km wide. A lava pond perched atop a broad shied results when lava pours onto the surface continuously from a single vent or a series of closely-spaced vents. The initial outpourings of lava quickly form a lip or ramp around the vent(s). As more lava spills over the lip, a pond of lava becomes "perched" higher and higher above the surrounding ground. At the same time, as lava flows away from the lip, a broad volcanic shield grows taller and larger in diameter. The volcanic cone in the middle distance is Pu'u 'O'o. Photograph by Jim Griggs, December 19, 1986.

episode 49. On February 6, 1992, the last sluggish flows from Kupaianaha issued from the mouth of a lava tube about 2 km downslope from the vent.

Episode 50: Fissure on the Flank of Pu'u 'O'o

On February 17, 1992, a new 150-m-long fissure opened on the western flank of the Pu'u 'O'o cone. Lava extruded from this fissure formed a large perched lava pond just north of the rift. This eruption abruptly shut down on March 3, coincident with yet another intrusion in the upper East Rift Zone near Pauahi Crater.

Another Upper East Rift Zone Intrusion

The seismic swarm associated with the March 3 intrusion included nearly 2,400 recorded earthquakes. At the same time, the summit region of Kilauea began

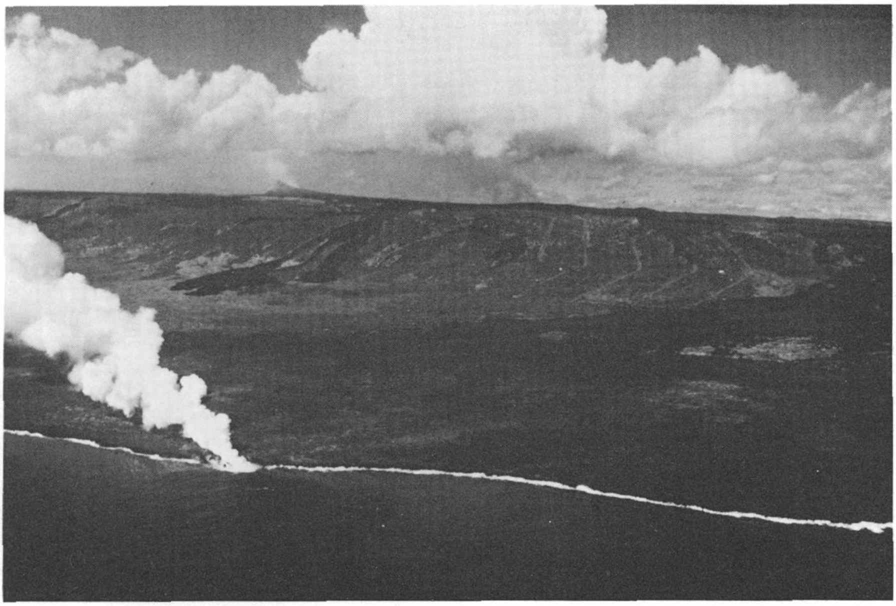
Ropy, pahoehoe lava flows from the Kupaianaha vent block the Chain of Craters Road during Episode 48. Photograph by Jim Griggs, June 6, 1987.

to deflate sharply as magma migrated away from the chamber beneath the summit and toward the rift zone. As the magma intruded into the upper East Rift Zone, the area around Pauahi Crater rose by about 5 cm. A new ground crack about 15 cm wide crossed Chain of Craters Road near the crater called Devil's Throat. Measurements made after the intrusion showed a total of 30 cm of extension between Devil's Throat and Pauahi Crater.

Episode 51: Fissure Activity Resumed

On March 7, 1992, the episode-50 fissure extended slightly higher onto the flank of Pu'u 'O'o and formed several new vents, marking the onset of episode 51. These new episode-51 vents have been sporadically active ever since. More than a dozen eruptions lasting from 8.5 hours to 20 days have taken place, interrupted by repose periods lasting from 3 hours to 6 days.

By the end of 1992, outpourings from the episode-51 vents produced a 60-m-high lava shield on the western flank of Pu'u 'O'o and formed a broad lava-flow field that extended southward from the shield. The vents soon settled into a period of relative quiescence



A steam plume rises from the end of a lava tube that delivers lava from the Kupaianaha vent to the ocean. Most of the gasses within the lava have escaped during the journey to the sea. The plume at the ocean consists of steam and hydrochoric acid and is called "Laze" (LAva haZE). On the horizon, a light plume appears above the Pu'u 'O'o cone on the left, and a darker plume marks the Kupaianaha shield on the right. Photograph by Jim Griggs, December 27, 1989.

broken only by low-level spattering. A lava pond filled a depression at the top of the shield early in episode 51. Although it resembled the Kupaianaha pond, which was fed by vents directly beneath it, this new pond was fed via a tube leading from vents about 50 m to the east. By mid-July, the lava tube had bypassed the pond, which has remained empty ever since.

Changes at Pu'u 'O'o

Since the eruption shifted to Kupaianaha in 1986, the 20-m-wide conduit within Pu'u 'O'o has grown into a gaping crater 300 m across. At the same time, the summit of Pu'u 'O'o has been reduced in height by about 20 m due to internal collapses and unstable structure within the volcano. Although an active lava pond has filled the crater at most times during the last several years, no lava flows have originated from Pu'u 'O'o since 1986. The

A USGS scientist performs a geophysical survey on the side of Pu'u O'o. Such field surveys help to identify the location and the amount of lava discharge through active lava tubes. Volcanic fume (mostly sulfur dioxide) rises from a spatter cone (low mound above the scientist's head) built by lava fountains during episode 51. Spatter is composed of flattened blobs of basaltic lava that were still plastic when they struck the ground. Photograph by Tari Mattox, March 9, 1992.

active pond occupies about a third of the crater floor; the level of this pond varies from about 35 m to more than 75 m below the lowest point on the crater rim.

Episode 52 and More of Episode 51

A new eruptive fissure opened on the night of October 2, 1992. A magnitude 4.3 earthquake beneath Kilauea's south flank accompanied the onset of the new episode. This lightly felt shock had a focal depth of 7 km and an epicenter between the new fissure and the ocean. Two main vents on the new fissure fed a vigorous pahoehoe flow that changed into a channeled 'a'a flow as it advanced to the south. The episode-51 vents, in repose at the time of the earthquake, resumed eruptive activity on the following day. Both the episode-51 and episode-52 vents were active for the next three days, and then activity at the episode-52 vents began to wane. By mid-October, the episode-52 vents were dead, while the episode-51 vents continued to erupt.

The earthquake which initiated episode 52 apparently altered the plumbing to the episode 51 vents. Since the earthquake, there has been only a single 24-hour-long pause in the eruption. In October, fresh lava reached the top of a steep slope above the seacoast via a lava tube leading to the south edge of the episode-51 shield. Lava immediately began to flow down the steep slope on the surface. By November 8, lava had again crossed the Chain of Craters Road and reached the ocean at Kamoamoa. In December, virtually all of the lava erupted at the episode-51 vents reached the ocean directly via lava tubes. Lava flows buried the Kamoamoa campground and picnic area near the coast. Flows also covered a new black-sand beach formed earlier of Kupaianaha lava, that had cascaded into the ocean farther to the east. These new flows also built a new, triangular-shaped, lava delta that extended as far as 300 m into the sea, forming 60 acres of new land. On the evening of November 24, spectacular steam explosions formed a 7- to 8-m-tall cone where lava entered the sea. Subsequent flows have partially buried this cone. The lava delta soon began to break apart with the formation of cracks parallel to the coastline. On December 26, a large piece of the delta slid into the ocean.

Summary

More than 1,000 million m^3 of lava have erupted since the Pu'u 'O'o-Kupaianaha eruption began in1983. In comparison, Mauna Ulu, the previous most long-lived, historic eruption on the East Rift Zone, erupted about 350 million m^3 of lava between 1969 and 1974.

In the first 10 years of the current eruption, lava destroyed 181 homes and many other buildings. Total losses have exceeded $61 million. As long as the eruption is confined to the episode-51 vents, it poses no immediate threat to residential areas. The ongoing eruption continues to imperil archaeological sites and native plant life in Hawaii Volcanoes National Park.

The rates of lava extrusion today are relatively low compared to those measured only a few years ago. This suggests that the eruption could be winding down. This winding-down process apparently began at the time of the upper rift intrusions in December 1990. The Kupa-

Geologic mapping on Kilauea indicates that lava flows less than 1,100 years old cover about 90 percent of the volcano's surface. Pahoehoe lava, delivered to the surface through lava tubes, makes up about 67 percent of these flows. Lava tubes play an important role in building Hawaiian shield volcanoes.

Identifying and evaluating geologic hazards is one of the principal roles of the U.S. Geological Survey. When HVO scientists recognize that a short-term hazard exists, they alert Hawaii County Civil Defense and the National Park Service. Scientists also develop hazard-zonation maps used by planning agencies for long-term land-use planning.

ianaha vent shut down in February 1992, further evidence that the eruption may be waning. In addition to progressively smaller eruptive volumes, the locations of active vents have begun to migrate towards Kilauea's summit. If these trends continue, activity in the lava pond inside Pu'u 'O'o could cease, followed by activity at the episode-51 vents. At the same time or shortly thereafter, volcanic activity may migrate up the rift towards the summit. Alternatively, the eruption could be over at that point. It is clear that predicting when, and even where, eruptions will start is easier than predicting when they will end.

The record of prehistoric lava flows from sources along the lower and middle East Rift Zone suggests that more eruptions are highly likely in this area, even after this eruption finally concludes. There is no reason to expect that this eruption will mark the end of activity on Kilauea's middle to lower East Rift Zone, where eruptions occurred in 1955, 1960, 1961, 1963, 1965, 1968, 1977, and from 1983 until present. The 1955 eruption, the first in this sequence of eruptions, followed a 115-year-long period of quiescence during which no eruptions occurred along this part of the rift. Future eruptions pose even greater risks to private property in the area, which has developed rapidly since the last eruption on the lower East Rift Zone in 1961.

Tracking the Movement of Hawaiian Volcanoes: Global Positioning System (GPS) Measurements

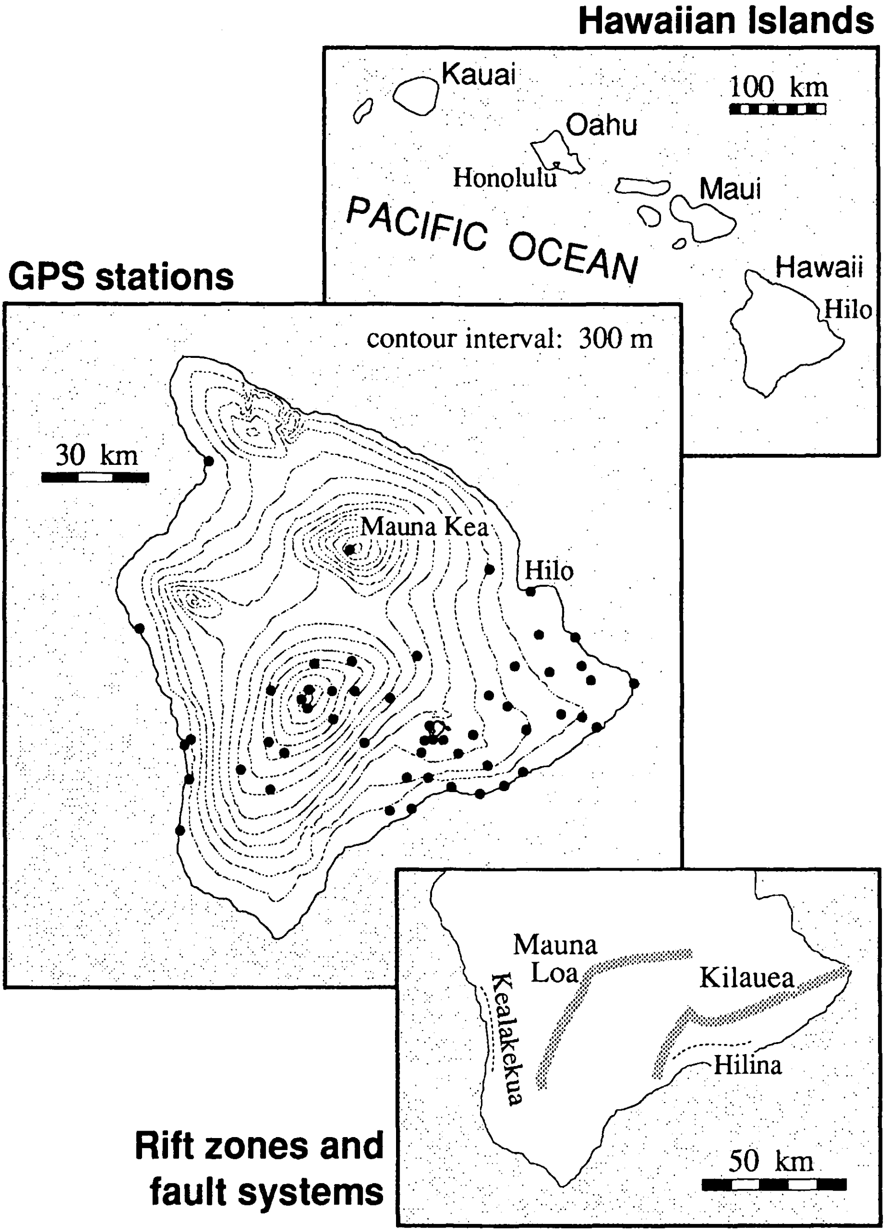
By John J. Dvorak
U.S. Geological Survey
Cascades Volcano Observatory

Introduction

Most, if not all, volcanic eruptions are preceded by surface movements near the volcano. These ground movements are the response of the shallow crust to the accumulation of magma or the buildup of magma pressure within a subterranean reservoir beneath the volcano. As the magma reservoir expands, the summit and the flanks of the volcano rise and spread apart. Measurements made at many volcanoes show that slow ground movement may precede an eruption by as many as several years. Sudden increases in the rate of ground movement often precede an eruption by a few hours or days.

At some well-studied volcanoes, surface movements of at least several centimeters take place out to distances of about 10 km from the summit of the volcano. Widespread deformation of this type is relatively easy to monitor, because the necessary survey stations can be placed at favorable sites some distance from the summit of the volcano. Examples of deformation of this type include Kilauea and Mauna Loa in Hawaii, Krafla in Iceland, Long Valley in California, Campi Flegrei in Italy, and Sakurajima in Japan. In contrast, surface movement at some other volcanoes, usually volcanoes with steep slopes, is restricted to places within about 1 km of their summits. Examples of this class of volcanoes include Mount St. Helens

The Global Positioning System (GPS) uses information broadcast by orbiting satellites to accurately monitor changes in the horizontal and vertical position of survey points on volcanoes—data on deformation needed to forecast future eruptions. The radio signals transmitted by GPS satellites include time, ranging data, and information on the predicted position of the satellites in space. Deformation studies on volcanoes often involve a procedure called relative positioning. To carry out this procedure, one receiver is situated at a stable control station and the other is set up at a point where the change in relative position is to be determined. Although a detailed description of how the system works is beyond the scope of this article, the central core of GPS operations is the simultaneous determination of distances between a ground station and sets of four or more satellites. This is accomplished by distance ranging. The ground-station receiver simultaneously records time-coded ranging signals from the satellites. The ground station also continuously generates a time-tagged replica of the ranging signal sent by the satellites. The time codes are embedded in the signals in such a way that the source-to-receiver transit time can be recovered from the data stream. Multiplication by the speed of light gives the corresponding distances.



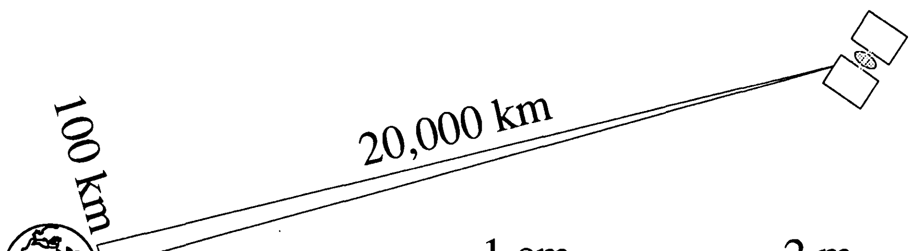
Maps showing the principal islands of the Hawaiian Islands (top), distribution of GPS stations and generalized elevation contours on the island of Hawaii (middle), and rift zones and fault systems on the southern half of Hawaii (bottom). On the map at the bottom, dark bands represent rift zones on Kilauea Volcano and Mauna Loa Volcano, and dotted lines denote the Hilina and Kealakekua fault systems.

in Washington, Etna in Italy, and Tangkuban Parahu in Indonesia. Local movement on remote, rugged volcanoes of this type is difficult to observe using conventional methods of measuring ground movement, which generally require a clear line-of-sight between points of interest. However, a revolutionary new technique, called the Global Positioning System (GPS), provides a very efficient, alternative method of making such measurements. GPS, which uses satellites and ground-based receivers to accurately record slight crustal movements, is rapidly becoming the method of choice to measure deformation at volcanoes.

The Global Positioning System

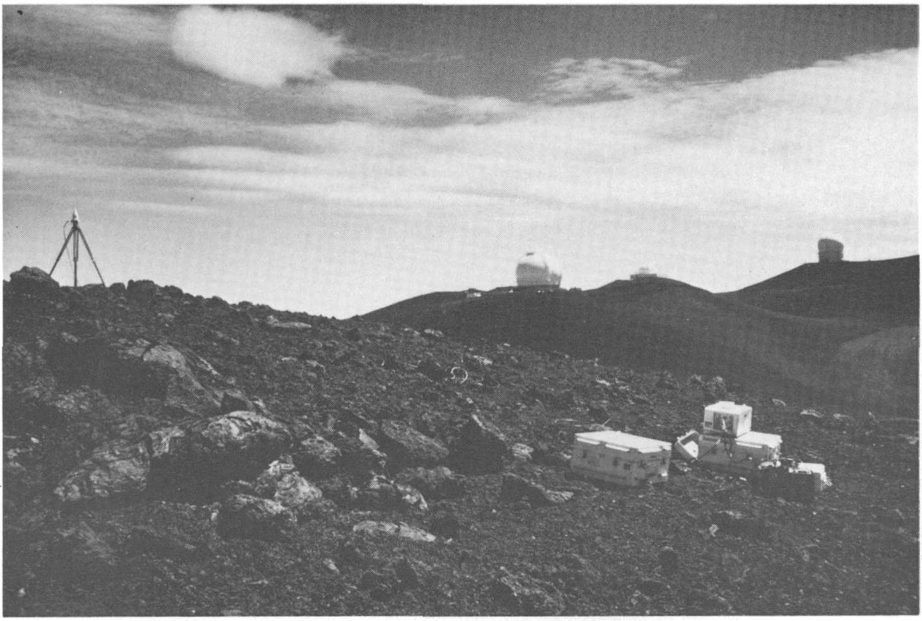
A constellation of orbiting satellites continuously sends radio signals that can be used with proper receiving equipment and computer processing to determine the relative positions of points on the Earth's surface. Positions can be determined to within about a centimeter using GPS. This high precision means that slight surface movements of geophysical interest, such as the movements around active volcanoes, can be tracked by repeating measurements at the same survey marks.

To understand how this high precision is possible, think of the narrow triangle formed by a pair of receivers on Earth and a GPS satellite in a 20,000-km-high orbit. The satellite is used as a reference point with a predictable position in space. The precision of the measured distance between the receivers depends on how well we know the distance between a receiver and the satellite.



$$\frac{1\text{ cm}}{100\text{ km}} = \frac{2\text{ m}}{20{,}000\text{ km}}$$

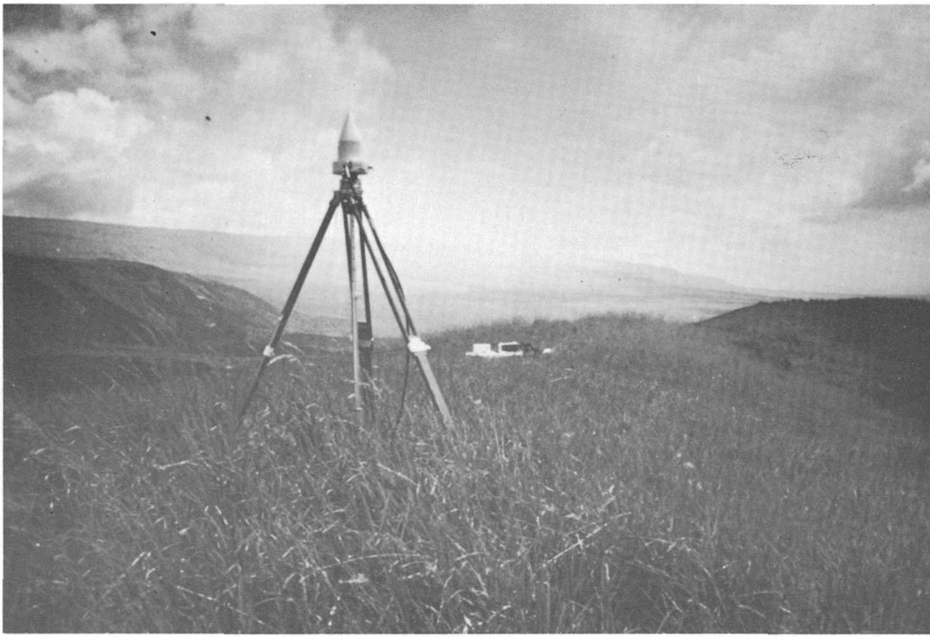
A high precision in ground position is possible with GPS because the positions of the GPS satellites are known to within a few meters. Due to the geometry of the triangle under consideration, the uncertainty of the distance between the ground stations is a tiny fraction of the uncertainty of the ground-to-satellite distance.



GPS survey in progress at the 4-km-high summit of Mauna Kea volcano on the island of Hawaii. The antenna fixed to tripod on the horizon at the left is located above a survey benchmark; equipment in the right foreground consists of a GPS receiver, batteries, and a magnetic tape recorder. The three domes on the horizon house astronomical telescopes, including the world's largest, the 10-m Keck telescope. Photograph by J. Dvorak.

For example, if we wish to know to within a centimeter the distance between two receivers separated by 100 km, then we must know the position of the 20,000-km-high satellite to within a few meters. How is it possible to achieve such high precision of the position of a satellite moving in orbit at 5 km/s?

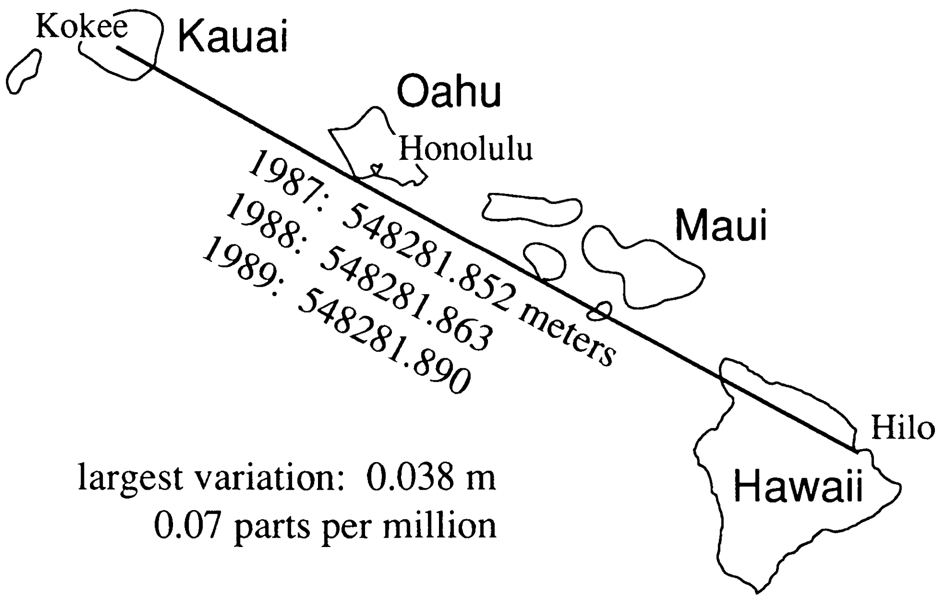
Technology and orbital mechanics have developed to the point that we can now account for small shifts in orbit that result from nonspherical components of the Earth's gravity field, solar radiation pressure, thermal emission of the satellites, and gravitational attractions of the Moon and Sun. Furthermore, we can construct simple models of the Earth's atmosphere and ionosphere to account for time delays of the radio signals from a satellite. The actual procedure of making these calculations is very complex and requires huge chunks of computer time. This has somewhat limited our use of GPS. However, improved schemes to process GPS



Closeup of a GPS antenna and tripod in the field. The positions of GPS ground stations are determined relative to satellites with predictable space coordinates. The fact that GPS does not require lines-of sight between ground stations gives GPS a distinct advantage over conventional surveying techniques. Because extremely accurate timekeeping is critical to the program, GPS satellites are equipped with atomic clocks. An error of one-billionth of a second in time translates into an error of 30 cm in distance. Photograph by J. Dvorak.

measurements and the development of receivers that simultaneously track eight or more satellites indicate that GPS will be applied to more and more studies of crustal movements in the future.

Conventional land-surveying techniques have been used extensively in the past to record ground movements around volcanoes, including those in Hawaii. However, use of these techniques limits the choice of potential survey marks. These marks, which are usually located near a road, must be visible from other survey marks. In contrast, GPS survey marks can be located almost anywhere, even in remote and rugged terrain, as long as the site has a clear view of the sky. Furthermore, GPS measurements can be made in almost any weather condition. In contrast, unfavorable weather often seriously restricts, or precludes, the use of conventional techniques. In addition, repeated GPS measurements determine both vertical and horizontal components of ground movement. In the case of conventional techniques, determination of horizontal and vertical components requires combination of different sets of conventional observations, such as leveling and distance ranging with the use of laser beams. Finally, GPS receivers are portable, require only one person to set up the equipment, and can operate unattended for several months on batteries and solar panels. These many advantages mean GPS will probably supplant conventional land-surveying techniques as the principal method of monitoring small shifts in the Earth's crust.

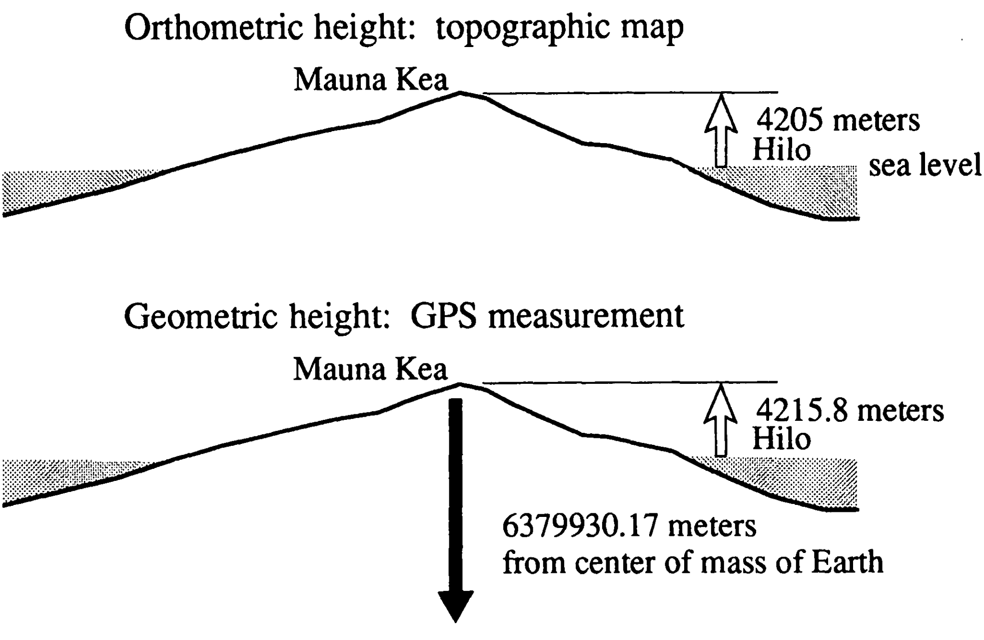


Observed consistency between successive GPS measurements of the distance between a pair of relatively stable points, a survey mark at Hilo on the island of Hawaii and a mark at Kokee on the island of Kauai. GPS measurements were repeated in each of three years (1987, 1988, and 1989).

To illustrate the capability of GPS, we repeated measurements of the distance between a pair of relatively stable stations, a station at Hilo on the island of Hawaii and another station several hundred kilometers distant at Kokee on the island of Kauai. The largest variation among our three independent measurements, carried out in each of three consecutive years, was 0.038 m, or about 1.5 in.

Elevations can also be determined with GPS. However, elevations determined by GPS observations differ from the elevations shown on topographic maps. The more familiar topographic elevations, called orthometric heights, are determined by techniques that make use of a local horizontal surface, such as the surface of a standing body of relatively quiet water. Most topographic elevations refer to the height above mean sea level determined by conventional leveling. Near a large, massive mountain, such as a volcanic island rising high above the seafloor, mean sea level is warped slightly because the mountain has a slight gravitational

What is the elevation of Mauna Kea?



Comparison of orthometric and geometric heights of Mauna Kea. Different systems of measurement and different conceptual models yield different elevations for Mauna Kea. The elevation of Mauna Kea obtained by conventional leveling is 4,205 m above mean sea level. The corresponding elevation based on GPS measurements is the difference between two estimates of the distance to the center of mass of the Earth, the first determined from the top of Mauna Kea and the second measured from mean sea level at Hilo. The elevation of Mauna Kea determined by the GPS method is approximately 4,216 m. Most of this 11 m difference between the two estimates corresponds to the gravitational warping of the sea level surface when continued beneath Mauna Kea.

attraction on seawater. Because GPS uses orbiting satellites, GPS-derived elevations, called geometric heights, are referenced to the center of mass of the Earth, not to sea level.

To illustrate this difference, consider two different estimates of the elevation of Mauna Kea, the highest mountain in the Pacific Ocean, one elevation indicated on a topographic map and the other determined by GPS. On the MAUNA KEA quadrangle map, the summit has an elevation of 4,205 m above mean sea level, the orthometric height determined by conventional geodetic techniques. A GPS measurement on March 25, 1989, yielded a distance of 6,379,930.2 m between the center of mass of the Earth and the top of Mauna Kea. Another GPS measurement in 1989 determined that mean sea level at Hilo Bay was 6,375,714.4 m from the center of mass of Earth. Subtraction yields the geometric height or GPS elevation of Mauna Kea, 4,215.8 m. Thus, as shown in the accompanying graph, the geometric height of Mauna Kea is about 11 m greater than the orthometric height. However, this ambiguity does not pose a big problem when measuring a change in elevation. The quantity of primary interest is the difference between two determinations of the point, each carried out using the same scheme of measurement. The GPS method gives extremely accurate estimates of these differences.

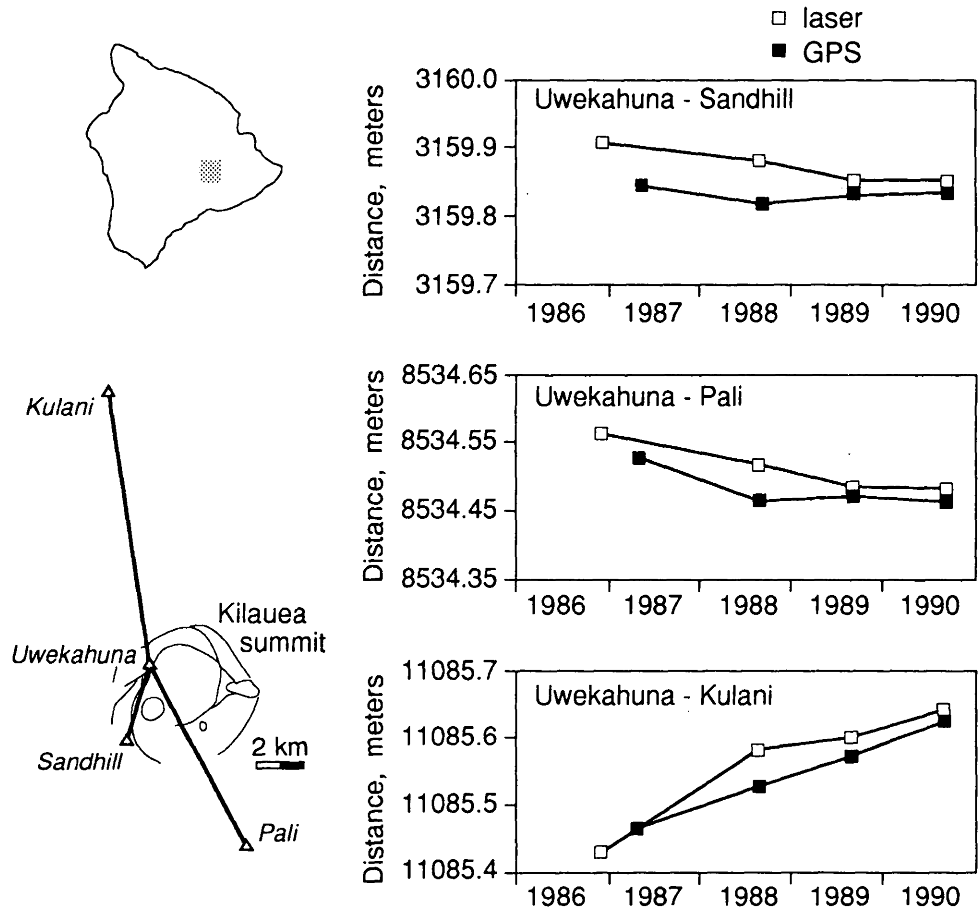
Hawaiian Volcanoes

The USGS selected the island of Hawaii as a starting point for making GPS measurements on active volcanoes for several reasons. Hawaiian volcanoes are among the most active in the world. Kilauea volcano on Hawaii has erupted almost continuously for more than 10 years (see preceding article). Slow subsidence of the summit area has accompanied the eruption. The most recent eruption of nearby Mauna Loa, a 21-day-long eruption in 1984, sent a lava flow within a few kilometers of Hilo, the second largest city in the State. Future eruptions of Mauna Loa volcano could endanger newly developed areas of Hilo.

Although far from the world's most earthquake-prone regions, such as the seismic belt encircling the Pacific Ocean, Hawaii is vulnerable to large earthquakes. In the last 42 years, five destructive earthquakes have struck Hawaii. These include a 7.2-magnitude earthquake in 1975, one of the largest in the U.S. this century. An earthquake is the result of the sudden release of strain accumulated in the Earth's crust. Along the west coast of California, where earthquakes are frequent, strain accumulates along the San Andreas fault zone, a tectonic plate boundary where the North American and Pacific plates slide laterally past each other. In contrast, in Hawaii, strain accumulates as a result of repeated injection of magma and other effects related to volcanism (which compresses the flank of a volcano). The accumulated strain (compression) is relieved suddenly by occasional large earthquakes (which moves the flank of the volcano seaward). The study of earthquakes in both Hawaii and California gives us the opportunity to compare different tectonic environments, both capable of producing destructive earthquakes.

Another reason the USGS chose Hawaii is that extensive networks to measure ground movements were already in place on Kilauea and Mauna Loa, so that a comparison could be made between GPS measurements and measurements using conventional land-surveying techniques. Furthermore, 35 years of intensive study of Kilauea has led to a reasonably good understanding of how this volcano works. By providing more frequent measurements of ground movements over a wider area than previously possible, GPS measurements should improve this understanding and enhance our capability to monitor ongoing volcanic activity. Improvements in monitoring are expected in several areas including (1) detection of movement of magma along a rift zone as one magma reservoir empties and another fills, (2) detection of rapid, upward growth of an eruptive fissure, and (3) determination of ground movements at greater distances from the summit areas and rift zones. Deployment of arrays of GPS receivers will also enable us to monitor volcanic activity at greater depths.

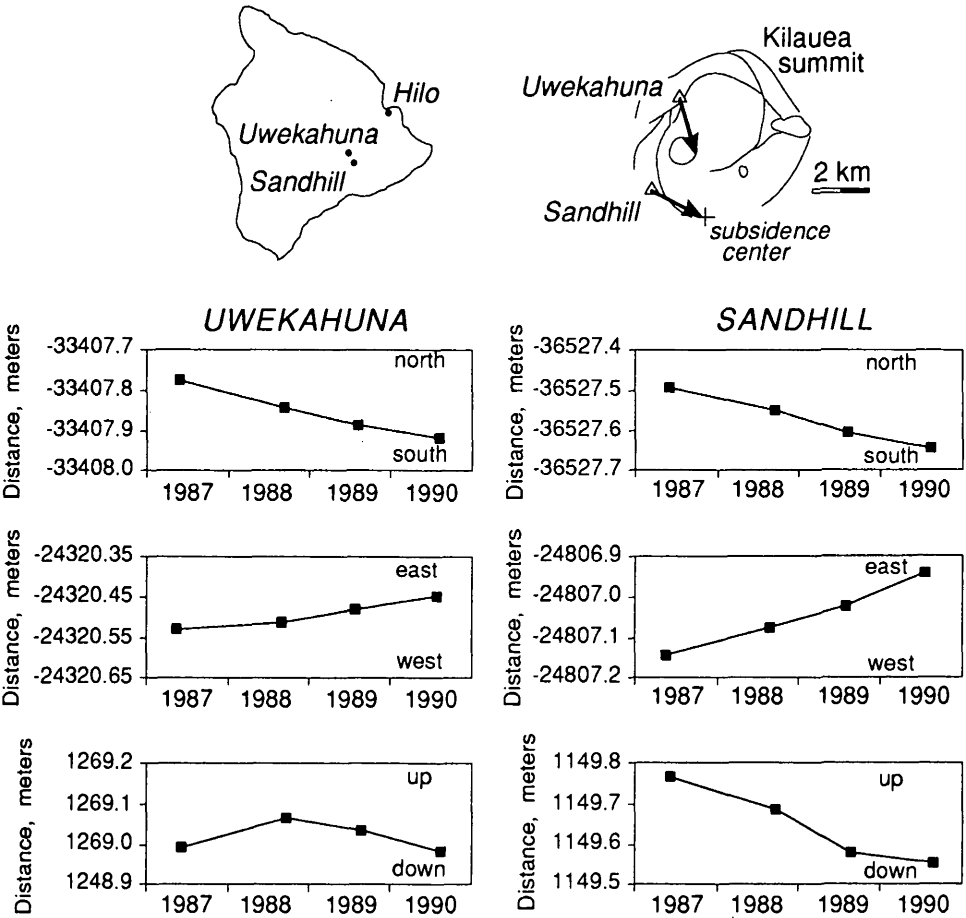
Although additional stations were established to take advantage of the greater versatility of GPS over other techniques, many Hawaiian GPS stations coincide with survey marks established earlier during conventional land surveys. Five GPS surveys have been conducted since 1987. Although most previous surveys concentrated on Kilauea, USGS scientists have also made observations on Mauna Loa and along the Kealakekua fault system on the western flank of Mauna Loa. A 6.8-magnitude earthquake—comparable in size to the Loma Prieta earthquake that shook the San Francisco Bay area in October 1989—occurred beneath the west flank of Mauna Loa in 1951.



Comparison of trilateration measurements made using laser technology (open squares) and GPS measurements (solid squares). The plots on the right refer to distances between Uwekahuna, a station on the rim of the caldera atop Kilauea, and three nearby stations.

Kilauea

To test GPS results against results obtained by conventional techniques, rates of ground movement on Kilauea determined from GPS measurements were compared with laser measurements of changes in distance between intervisible survey marks. The GPS and laser observations show almost the same changes in distance between Uwekahuna, a station on the rim of the caldera at the top of Kilauea, and three other stations. However, the laser measurements always indicated a slightly longer distance for each pair of stations. This systematic difference was due to an inadequate correction for atmospheric refraction of the laser beam. When the appropriate correction can be made—this is



Three-dimensional displacements of Uwekahuna and Sandhill, two stations on the rim of Kilauea's summit caldera, relative to Hilo, Hawaii. The two small arrows in the upper right show the horizontal displacements associated with the two rim stations. When these arrows are extended southward, their intersection marks the center of subsidence due to the withdrawal of magma beneath Kilauea.

expensive because it requires flying an aircraft along the path connecting the two survey marks—the agreement is very good. GPS measurements also require a correction for atmospheric refraction, but the correction is much easier and less expensive than the correction for laser measurements.

As indicated in the accompanying figure, the three-dimensional movements of Uwekahuna and Sandhill, another survey mark on the rim of Kilauea, show the summit area has subsided slowly since 1987. The intersection of the horizontal components of movement indicates that the subsidence is centered beneath the southern part of the summit caldera. These movements and the determination of the subsidence center are consistent with other, independent measurements of ground movement on Kilauea. The slow subsidence revealed by these observations is probably caused by the withdrawal of magma from a shallow reservoir beneath the volcano.

Kealakekua fault system and Mauna Loa

We know a great deal about the pattern and rate of ground movement of Kilauea. However, we know much less about the pattern and rate of ground movement in other areas of the island, because the rugged topography and relatively poor accessibility have limited the use of conventional land-surveying techniques in these areas. GPS is expected to have a major impact on our understanding of the dynamics of Hawaiian volcanoes when it is applied to these relatively unsurveyed areas. One such area is the Kealakekua fault system on the western flank of Mauna Loa (see map, beginning of this article).

The Kealakekua fault system resembles the more active Hilina fault system on Kilauea's southern flank in several ways. Each fault system lies between the seacoast on one side and a well-developed, active rift zone on the other side. Arcuate, normal faults, which are downthrown on the seaward side, define both fault systems on the surface. Measurements begun more than 80 years ago show that the coastal side of the Hilina fault system is moving seaward. Observed rates of movement vary—some sections of the system apparently move faster than others. Recent GPS measurements (1987–1988) show rates of 50–100 mm/yr in this area.

GPS measurements at stations along the Kealakekua fault system suggest that the coastline in this area is also moving seaward. Estimated annual rates are 25 mm/yr or less. This is a factor of one-fourth to one-half the estimated rates along the Hilina system. Similarly, the frequency of earthquake occurrence along the Kealakekua fault system is one-fourth to one-half the frequency of earthquakes along the Hilina fault system

Another location where the pattern of ground movement can be studied efficiently with GPS is the summit of Mauna Loa. Methods involving heavy, conventional survey gear are difficult to use on Mauna Loa due to the isolation and 4-km-high elevation of the summit. However, the portability and low-power needs of GPS receivers are ideally suited to work in such places.

Three years of measurements have shown only slight ground movement at a survey mark on the south rim of the summit caldera on Mauna Loa. This is consistent with results of other, conventional techniques that also show little, if any, ground movement between 1988 and 1990 in this area.

Other Volcanoes and Future Monitoring

The USGS has already carried out GPS measurements at Lassen Peak, Mount Shasta, and Medicine Lake in California, as part of its Volcano Hazards Program. Future contributions to the program include GPS measurements at Long Valley in California and Mount Rainier and St. Helens in Washington. On the international scene, GPS monitoring techniques have been applied to volcanoes in Iceland, Italy, and Japan.

Most GPS surveys in the past have sampled ground movement with respect to specific time intervals. By establishing permanent GPS stations, which continuously send data to central observatories, we can also use GPS to monitor ground movement in real time. For this purpose, three permanent receivers were installed on Augustine in July 1992. Augustine is one of the most active volcanoes in Alaska and the volcano that most threatens populated areas in Alaska. A permanent GPS network is also planned for Long Valley in California.

GPS provides a tool to overcome many problems that have hampered the study of active volcanoes until very recently. With the use of GPS, instantaneous determinations of distances over baselines hundreds of kilometers long are now possible. In several documented cases, major earthquakes, involving sudden strain release over broad regions, have preceded volcanic eruptions. GPS data may answer questions concerning possible linkage between changes in regional strain associated with such earthquakes and the timing and size of volcanic eruptions.

Additional Readings

Dvorak, J.J., Johnson, C., and Tilling, R.I., 1992, Dynamics of Kilauea Volcano: Scientific American, v. 267, no. 2, p. 46-53.

Prescott, W.T., Davis, J.L., and Svarc, J.L., 1989, Global positioning system measurements for crustal deformation: precision and accuracy: Science, v. 244, no. 4910, p. 1337-1340.

Natural Hazards Research and Response: International Decade for Reducing Loss from Natural Disasters

by Walter W. Hays
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Worldwide losses from natural disasters are increasing rapidly due to population growth, urban sprawl, and increasing concentration of new construction in high-risk areas. To deal with these problems, the United Nations has designated the 1990's as the International Decade for Natural Disaster Reduction (IDNDR). The United States and more than 150 other nations signed the IDNDR resolution at the 44th General Assembly of the United Nations. The resolution calls on all nations to develop programs to reduce loss of life, economic impact, and human suffering caused by natural disasters.

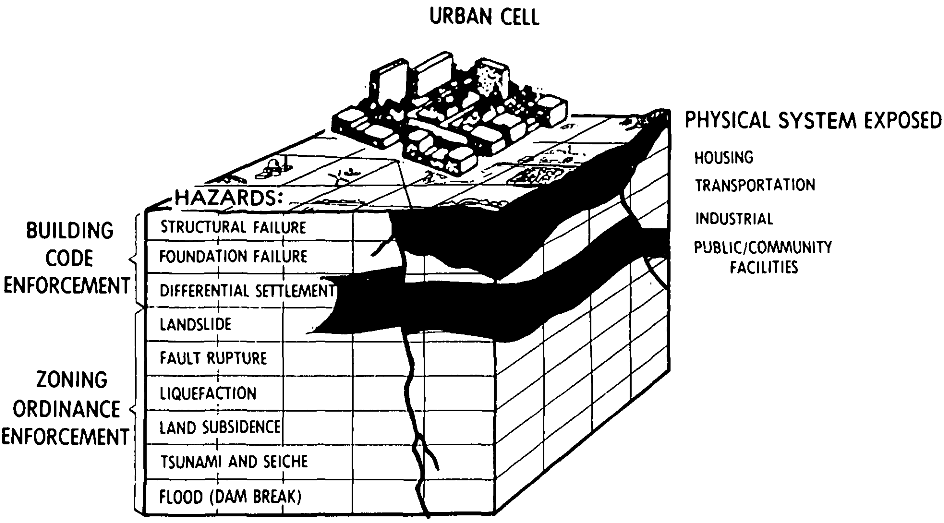
The terms hazard and risk are sometimes used interchangeably in everyday speech. Scientists assign more restricted meaning to these terms. They regard hazards as physical entities such as floods, tornadoes, landslides, and earthquakes. Risk refers to the likelihood or mathematical probability that a particular harmful event or hazard will occur.

IDNDR offers an unprecedented opportunity to apply new knowledge and technology to minimize losses in regions at high risk. The program is very challenging because full implementation requires a multidisciplinary effort on a global scale, an undertaking never before attempted. In concert with the other signatory nations, the United States is carrying out a balanced and comprehensive program of research and applications as a contribution to the IDNDR. The U.S. program is designed to reduce both loss of life and property damage from natural disasters.

The IDNDR program is a very ambitious one. Statistics compiled by the United Nations International Ad Hoc Group of Experts indicate that the Earth will experience the following events in this decade:

- One million thunderstorms;
- About one-hundred thousand floods;
- Tens of thousands of damaging landslides, earthquakes, wildfires, and tornadoes; and
- Several hundred to several thousand tropical cyclones and hurricanes, tsunamis, droughts, insect infestations, and volcanic eruptions.

Some of these recurrent natural hazards will cause disasters. Most of us think of a disaster as an event that occurs when people are killed or property is destroyed. However, professionals engaged in emergency planning



Types of actions available to local jurisdictions to make their communities more capable of rebounding after the occurrence of a natural hazard.

and making preparations to assist the victims of disasters define a disaster as any significant disruption of human activity that prevents a community from functioning normally.

The consequences of disasters are often very grave. Recall these recent U.S. disasters: floods in the Central U.S.; tornadoes in New York, Alabama, and Indiana; wildfires in Wyoming, California, and Oregon; earthquakes in California; hurricanes along the Gulf and Atlantic Coasts; volcanic eruptions in Hawaii and Alaska; and droughts in the Midwest, Southeast, and California. The worldwide consequences of disasters, taken as a whole, are alarming. For example, the World Health Organization reports that natural disasters killed more than 2 million people between 1964 and 1983. During these years, natural disasters left almost 750 million people homeless, orphaned, sick, or injured.

Achieving the IDNDR goals poses a great challenge to the United States. Nearly every U.S. State and Territory has communities that are at risk. Some regions are at risk from natural hazards that recur at relatively short intervals. Such intervals range from approximately every year for floods, landslides, tornadoes, hurricanes,

A landslide in the Oregon Coast Range on April 4, 1991. In the photograph, the landslide blocks a 185-m-long section of the Wilson River Highway east of Tillamook, Oregon. In addition to interrupting traffic on the highway, the slide partially dammed the Wilson River. A light dusting of snow covers the ground in the photograph. The slide involved about 400,000 m^3 of soil and rock. Removal cost approximately \$3.6 million. Photograph by Dana Olsen of the Portland Oregonian.

Clean up on Main Street in Ferndale, California, following a trio of earthquakes in the 6.6–7.1 magnitude range on April 25–26, 1992. Most of the debris in the foreground is from the fall of a parapet wall. Unreinforced masonry parapets on older buildings continue to pose a danger in earthquake-prone regions. Photograph by Cherl Easter, obtained through the courtesy of Lindie Brewer.

and wildfires to once every few years for damaging earthquakes and droughts. Other regions face high risk from major disasters that recur after longer time spans such as several decades, every century, or even longer. These catastrophic events include major earthquakes in Alaska, California, and the Mississippi Valley, and large volcanic eruptions in the Pacific Northwest and Alaska.

Although these natural disasters occur infrequently, collectively they cause direct economic losses that average more than $20 billion per year. At great risk is the Nation's multitrillion dollar inventory of dwellings, office buildings, schools, hospitals, government facilities, military installations, industrial complexes, utilities, lifelines, and communication systems. These and other facilities are scattered throughout the Nation in hazard-prone regions such as

- near active volcanoes
- in regions prone to tornadoes

The Paonia Reservoir Landslide on April 7, 1993, severed State Highway 133 between McClure Pass and Paonia in western Colorado. Although one car suffered extensive damage, no one was injured. Photograph courtesy of Terry Taylor, Colorado State Patrol.

- in flood plains subject to inundation
- on unstable slopes susceptible to landslides
- adjacent to fault zones capable of generating damaging earthquakes
- along coasts swept by waves from hurricanes, storm surges, or tsunamis
- along wilderness-urban interfaces vulnerable to wildfires
- in regions subject to periods of drought or insect infestations.

Lifelines bring the necessities of life to people. They include highways, railroads, waterways, electrical power lines, and pipelines that transport water, petroleum, and natural gas.

New public and private construction adds $400 billion per year to the value of the Nation's investment in buildings, lifelines, and other infrastructure. The total value of new construction during the 1990's will reach approximately $4 trillion. Earthquakes and hurricanes alone have the potential to cause greater average annual loss to structures than all other hazards combined. For example, consider the devastating one-two punch delivered in 1989 by Hurricane Hugo and the Loma Prieta earthquake in California. This pair of disasters–a Saffir-Simpson category 4 hurricane and a Richter magnitude 7.1 earthquake–caused direct losses of $15 billion and indirect losses of $30–$45 billion. Together they resulted in the deaths of more than 100 people, injured several thousand more, rendered tens of thousands homeless or jobless, and left communities facing a long, complex recovery process.

The U.S. program for the IDNDR was planned by a committee convened by the National Research Council of the National Academy of Sciences and Engineering and Federal science and disaster-reduction agencies in 1989. Representatives of the the Federal science and disaster-reduction agencies also meet as the Subcommittee on Natural Disaster Reduction under the direction of the President's Office of Science and Technology Policy.

Implementation of IDNDR goals at the local and State level involves about 30,000 jurisdictions and several million people. Local jurisdictions are encouraged to adopt and enforce policies that reduce losses from natural hazards through

- hazard and risk assessment
- preparedness and mitigation measures
- awareness and education for all society
- prediction and warnings for natural hazards
- improved planning, siting, design, and construction practices
- loss reduction based on lessons learned from disasters throughout the world
- cooperative national and international endeavors designed to collect, analyze, and share data, experiences, and mitigation techniques for specific natural hazards.

As the U.S. program unfolds, each jurisdiction is free to emphasize those program elements that best suit their needs. The success of the IDNDR program will be measured in terms of increased understanding of the physical and social aspects of natural disaster reduction and improved risk assessment, emergency response, and rapid recovery plans.

The Saffir-Simpson scale of hurricane severity increases from category 1 (minimal damage) to category 5 (catastrophic damage). Category 4 refers to extremely damaging hurricanes with wind velocities in the 131–155 mph range.

EARTHQUAKES
July–August 1992

by Waverly J. Person
National Earthquake Information Center
U.S. Geological Survey
Denver, Colorado

There were two major earthquakes (7.0≤M<8.0) during this reporting period. A magnitude 7.5 earthquake occurred in Kyrgyzstan on August 19 and a magnitude 7.0 quake struck the Ascension Island region on August 28. In southern California, aftershocks of the magnitude 7.6 earthquake on June 28, 1992, continued. One of these aftershocks caused damage and injuries, and at least one other aftershock caused additional damage. Earthquake-related fatalities were reported in Kyrgyzstan and Pakistan

California

Aftershocks of the Landers earthquake on June 28 continued in southern California; many had magnitudes of 4.5 or greater. On July 1 at 40 minutes after midnight PDT, a magnitude 5.2 aftershock occurred about 40 km west-northwest of Twentynine Palms. The shock was felt in Imperial, Kern, Los Angeles, Riverside, San Bernardino and San Diego Counties.

A magnitude 4.6 quake on July 5 (3:56 a.m. PDT), centered about 60 km north-northeast of Victorville, shook parts of San Bernardino County.

The two strongest aftershocks during this reporting period were on July 5 at 2:18 p.m. PDT and July 8 at 6:44 p.m. PDT. Both quakes had magnitudes of 5.5. The first quake, centered about 40 km south-southeast of Barstow, was felt strongly in Kern, Los Angeles, Orange, Riverside, and San Bernardino Counties and in parts of western Arizona. The second earthquake, centered about 30 km north-northeast of Banning, injured at least 16 people and caused additional damage in the Big Bear Lake area. The quake was felt throughout a large part of southern California including the Los Angeles area.

On July 11 at 11:14 a.m. PDT, a magnitude 5.5 earthquake occurred approximately 20 km north-northeast of Mojave. It was felt at Arvin, Bakersfield, Edwards, Mojave, Ridgecrest, Riverside, and Taft and in much of the Los Angeles area. The quake was felt in parts of Kern, Los Angeles, Orange, Riverside, San Bernardino, and San Diego Counties.

A pair of earthquakes, both having magnitudes of 4.7, occurred on July 24, the first at 11:15 a.m. PDT and the second at 9:32 p.m. PDT. The epicenters of both earthquakes were about 20 km east-northeast of Palm Springs. The first earthquake caused intensity MM V effects at Calimesa and Yucca Valley and MM IV effects at Cabazon, Indio, Lake Elsinore, Morongo Valley, and Pioneertown. The second quake produced intensity MM V effects at Indio and MM IV at Calimesa, Joshua Tree, Moreno Valley, and Yucca Valley. Both earthquakes were felt throughout a large part of southern California including Los Angeles, Orange, Riverside, San Bernardino, and San Diego Counties.

On August 5 at 3:23 p.m. PDT, a magnitude 4.7 earthquake struck an area near Barstow about 60 km north-northeast of Victorville. Felt strongly at Barstow, this earthquake was also felt at Daggett, Fort Irwin, Helendale, Hinkley, Newberry Springs, Pasadena, Rancho Cucamonga, Redlands, Trona, Wrightwood, and Yermo.

Montana

The northwestern part of this state experienced a minor earthquake on July 2 at 7:10 a.m. MDT. The epicenter of the magnitude 3.8 earthquake was approximately 110 km east-northeast of Kalispell. People at Browning and East Glacier Park felt the earthquake.

Nevada

Nevada experienced many earthquakes during this reporting period.

Three of these shocks occurred on July 4. The first, a magnitude 2.5 quake at 1:31 a.m. PDT, struck an area approximately 50 km east of Las Vegas. Residents of Boulder City and Lake Mead felt the earthquake. A second shock on July 4, this one a magnitude 4.0 earthquake at 11:16 p.m. PDT, occurred about 90 km southwest of Tonopah near the California border. This quake was felt strongly at Dyer, Nevada, and at June Lake, California. The third event on July 4, a magnitude 4.4 earthquake at 11:54 p.m. PDT, and was centered about 50 km east-southeast of Beatty. It was felt at Beatty and in the area of Las Vegas in Nevada, and at Death Valley and Tecopa in California.

On July 9 at 11:43 p.m. PDT, a magnitude 3.1 earthquake hit an area approximately 20 km east of Carson City. It was felt in the Dayton area.

A series of light earthquakes began in the Fernley area on July 20 at 10:22 a.m. PDT. The three largest, all on July 20, were a magnitude 3.5 at 10:36 a.m. PDT, a magnitude 3.8 at 12:07 p.m. PDT, and a magnitude 4.1 at 1:10 p.m. PDT. These earthquakes, each centered about 30 km east-southeast of Fallon, were felt in the areas of Fernley, Fallon, and Silver Springs.

On July 22 at 12:36 p.m. PDT, a very minor earthquake occurred about 20 km east-southeast of Las Vegas. This magnitude 2.5 tremor was felt at Nellis Air Force Base, Boulder City, and in parts of Las Vegas.

Arizona

North-central Arizona experienced a light earthquake on July 5 at 8:18 a.m. MST. The epicenter of this magnitude 4.0 earthquake was about 100 km north-northwest of Flagstaff. The shock was felt at Grand Canyon.

Kuril Islands

A strong earthquake hit the Kuril Islands on July 10 at 7:31 p.m. local time. The magnitude 6.5 earthquake was centered about 140 km east-southeast of Kurilsk. No felt reports were received from this remote area.

Washington-Oregon Border Region

A light earthquake shook the southeastern part of Washington and neighboring parts of Oregon on July 14 at 1:02 p.m. PDT. Centered near Walla Walla, Washington, and about 50 km northeast of Pendleton, Oregon, the magnitude 4.1 earthquake was felt at College Place and Walla Walla in Washington and also in the Milton-Freewater and Pendleton areas in Oregon.

On August 7 at 10:23 a.m. PDT another light earthquake hit an area west of the above epicenter. This magnitude 3.9 earthquake was centered 50 km northwest of Pendleton, Oregon near Paterson, Washington. This earthquake was felt at Paterson, Washington, and at Boardman, Hector, Irrigon, and Umatilla, Oregon.

Kansas

A minor earthquake shook central Kansas on July 14 at 9:57 p.m. CDT. The epicenter of this magnitude 3.3 earthquake was about 30 km southwest of Hays. Ellis and Hays reported Intensity MM IV effects. Localities about 15 km north of Hays and about 11 km southeast of Hays also felt this minor shock.

Japan

A strong earthquake struck off the east coast of Honshu, Japan on July 18 at 5:37 p.m. local time. This magnitude 6.9 earthquake was centered about 200 km east-northeast of Sendai. It was felt at Aomori, Hachinohe, Tateyama, and Utsunomiya on Honshu and also at Kushiro, Nemuro, and Obihiro on Hokkaido. A local tsunami was generated with maximum wave heights (peak-to-trough) of 46 cm at Ofunato, 42 cm at Miyako, 28 cm at

Aikawa, and 24 cm at Hachinohe. No damage was reported.

Wyoming

A light earthquake occurred in Yellowstone National Park on July 20 at 1:04 a.m. MDT. The epicenter of this magnitude 3.7 earthquake was about 130 km south-southeast of Bozeman, Montana. The quake was felt in parts of Yellowstone National Park.

Northern Wyoming experienced a minor earthquake on August 30 at 7:40 p.m. MDT. This magnitude 3.6 earthquake, which was centered 110 km south of Sheridan, was felt in the Barnum and Kaycee areas.

Alaska

A strong earthquake struck in the region of the Gulf of Alaska on August 7 at 10:19 a.m. ADT. This magnitude 6.5 earthquake was centered about 280 km south of Yakataga. It shook Yakutat strongly and was felt throughout much of southern and southeastern Alaska from Anchorage to Juneau including Chitina, Chugiak, Cooper Landing, Cordova, Elfin Cove, Fort Richardson, Larsen Bay, Moose Pass, Pelican, Petersburg, and Skagway.

The Andreanof Islands in the Aleutian Islands chain were struck by a strong earthquake on August 18 at 3:58 p.m. AHDT. Felt on Adak and Atka, the magnitude 6.1 earthquake was centered about 200 km south-southwest of Atka.

Oklahoma

A very minor earthquake occurred in the eastern part of Oklahoma on August 9 at 4:06 p.m. CDT. Centered about 20 km east of Ada, the magnitude 2.2 tremor was felt lightly at Ada.

Another small earthquake occurred in the south-central part of Oklahoma on August 10 at 3:03 p.m. CDT. This quake had a magnitude of 2.9. The epicenter was about 40 km east-southeast of Chickasha and 60 km northeast of Duncan. Intensity MM IV was observed in McClain County.

Texas

A very minor earthquake occurred in the southern part of this state on August 9 at 8:58 p.m. CDT. The epicenter of this magnitude 2.8 tremor was approximately 50 km south of San Antonio. People in the Jourdanton area felt this minor earthquake.

Kyrgyzstan

A major earthquake struck Kyrgyzstan on August 19 at 6:05 a.m. local time. The magnitude 7.4 earthquake was centered about 120 km east-southeast of Talas. An estimated 75 people were killed, including 14 people killed by landslides in Taluk. Several villages, including Taluk, were destroyed (maximum intensity MM IX) in the Susamyrtau Mountains. At least 8,200 dwellings were damaged beyond repair. Intensity VII effects were noted at Andizhan and Namangan, Uzbekistan. There was structural damage to buildings at Bishkek, Kyrgyzstan. The quake was felt strongly at Fergana, Tashkent, and Samarkand in Uzbekistan and at Osh in Kyrgyzstan. It was also felt at Alma-Ata in Kazakhstan. Elevation changes of as much as 4 m were observed in the Susamyr Valley. Liquefaction occurred in the epicentral area. Many aftershocks followed the mainshock; the largest aftershock, a magnitude 6.6 quake at 8:28 a.m. local time, probably caused additional damage.

South Carolina

This state experienced a sharp earthquake on August 21 at 12:32 p.m. EDT. This magnitude 4.4 earthquake was centered about 15 km north-northwest of Goose Creek and 40 km north-northwest of Charleston. Some minor damage occurred in the epicentral area, and the quake was felt strongly in the Charleston, Goose Creek, North Charleston, and Summerville areas. It was also felt at Alvin, Bonneau, Columbia, Eastover, Green Pond, Grover, Huger, Jacksonboro, Jamestown, McClellanville, Mt. Pleasant, Pawleys Island, Pinopolis, Ridgeville, and Russellville.

Missouri

A minor earthquake occurred in the Cape Girardeau area at 42 minutes after midnight CDT on August 26. The magnitude 3.5 earthquake was centered approximately 40 km north-northwest of Cape Girardeau. The quake was felt in the Cape Girardeau area and in the Carbondale, Illinois, area.

Pakistan

A damaging earthquake struck Pakistan on August 28 at 5:51 a.m. local time. The epicenter of this magnitude 5.7 earthquake was about 10 km northeast of Kalat and 130 km south-southwest of Quetta. At least four people were killed, several were injured, and damage occurred in the Kalat area. The earthquake was felt at Manguchar, Mastung, and Quetta.

Idaho

A light earthquake occurred in the eastern part of Idaho on August 28 at 9:26 a.m. MDT. Centered about 70 km east of Challis, this magnitude 3.9 earthquake was felt at Arco and Leadore. It was also felt slightly at Butte, Montana.

Mid-Atlantic Ridge

A major earthquake hit the Mid-Atlantic Ridge on August 28 at 5:19 p.m. local time. This magnitude 7.0 earthquake was centered in the South Atlantic Ocean about 770 km north of Ascension Island and about 860 km south-southwest of Monrovia, Liberia. There were no reports that this earthquake generated a tsunami.

Fatalities
JULY–AUGUST 1992

Kyrgyzstan	75
Pakistan	4
Total	79

U.S. ACTIVITY*
JULY–AUGUST 1992

Alaska	10
Arizona	2
California	50
Hawaii	2
Idaho	1
Illinois	1
Kansas	1
Missouri	1
Montana	2
Nevada	12
Oklahoma	2
Oregon	2
South Carolina	1
Texas	1
Washington	2
Wyoming	2
Total	92

*Felt earthquakes as reported from many sources.

PRELIMINARY LOCATIONS
JULY–AUGUST 1992

Date	Origin time UTC	Region	Coordinates Lat	Long	Depth km	Mag
Jul 1	0 40 29.8	Southern California	34.3 N	116.5 W	9	5.2MD
Jul 2	13 09 51.0	Montana	48.6 N	113.0 W	10	3.8ML
Jul 4	08 31 24.0	Southern Nevada	36.2 N	114.6 W	5	2.5ML
Jul 5	06 16 18.5	California-Nevada border region	37.6 N	118.1 W	1	4.0ML
Jul 5	06 54 12.4	California-Nevada border region	36.9 N	116.3 W	5	4.4ML
Jul 5	10 55 43.2	Central California	35.0 N	117.0 W	1	4.6MD
Jul 5	15 17 30.0	Western Arizona	36.0 N	112.2 W	5	4.0ML
Jul 5	21 18 27.1	Southern California	34.6 N	116.3 W	0	5.5MD
Jul 9	01 43 57.6	Southern California	34.2 N	116.8 W	0	5.5mb
Jul 10	06 43 15.5	Nevada	39.2 N	119.5 W	5	3.1ML
Jul 10	09 31 26.0	Kuril Islands	44.7 N	149.5 E	11	6.5MS
Jul 11	18 14 16.1	Central California	35.2 N	118.1 W	11	5.5MD
Jul 14	20 01 51.5	Washington	46.0 N	118.3 W	12	4.1MD
Jul 15	02 56 40.6	Kansas	38.7 N	99.6 W	5	3.3mbLg
Jul 18	08 36 39.7	Off east coast of Honshu, Japan	39.4 N	143.4 E	3	6.9MS
Jul 20	07 03 31.0	Yellowstone region, Wyoming	44.6 N	110.3 W	5	3.7ML
Jul 20	17 36 05.3	Nevada	39.4 N	119.1 W	5	3.5ML
Jul 20	19 06 57.2	Nevada	39.4 N	119.1 W	5	3.8ML
Jul 20	20 09 31.4	Nevada	39.3 N	119.1 W	5	4.1mb
Jul 22	19 35 50.0	Southern Nevada	36.1N	114.9 W	5	2.5ML
Jul 24	18 14 36.2	Southern California	33.9 N	116.3 W	9	4.7MD
Jul 25	04 31 59.9	Southern California	33.9 N	116.3W	6	4.7MD
Aug 5	22 22 40.8	Southern California	35.0 N	117.0 W	0	4.7MD
Aug 7	17 23 17.8	Washington-Oregon border region	45.9 N	119.6 W	1	3.9MD
Aug 7	18 19 19.3	Gulf of Alaska	57.6 N	143.0 W	10	6.5MS
Aug 9	21 05 52.1	Oklahoma	34.8 N	96.5 W	5	2.2MD
Aug 10	01 57 46.9	Central Texas	29.0 N	98.5 W	5	2.8mbLg
Aug 10	20 03 04.2	Oklahoma	35.0 N	97.5 W	5	2.9ML
Aug 19	00 57 43.6	Andreanof Islands, Aleutian Islands	50.5 N	174.8 W	33	6.1mb
Aug 19	02 04 36.5	Kyrgyzstan	42.1 N	73.6 E	22	7.4MS
Aug 21	16 31 55.1	South Carolina	33.1 N	80.1 W	10	4.4mbLg
Aug 26	05 41 38.4	Cape Girardeau, Missouri	37.6 N	89.7 W	5	3.5MD
Aug 28	00 50 54.2	Pakistan	29.1 N	66.7 E	33	5.7mb
Aug 28	15 26 16.2	Eastern Idaho	44.6 N	113.3 W	5	3.9ML
Aug 28	18 18 45.3	North of Ascension Island	1.0 S	13.6 W	10	7.0 MS
Aug 31	01 40 14.2	Wyoming	43.8 N	107.0 W	5	3.6 ML

EARTHQUAKES
September–October 1992

by Waverly J. Person
National Earthquake Information Center
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Denver, Colorado

This reporting period was very active in terms of earthquake occurrence; there were six major earthquakes (7.0≤M<8.0) during the second half of October. Earthquake-related deaths were reported in Iran, Nicaragua, Egypt, Colombia, Morocco, Zaire, and the Republic of Georgia.

In the United States, a damaging earthquake occurred in Utah on September 2 and a magnitude 6.8 struck Alaska's Aleutian Islands on September 29.

Nicaragua

A damaging earthquake struck near the coast of Nicaragua on September 1 at 6:16 p.m. local time. The magnitude 7.4 earthquake was centered offshore about 90 km south-southwest of Chinandega and 120 km west-southwest of Managua. A very damaging tsunami followed the earthquake. At least 116 people were killed, about 68 were reported missing, and about 1,143 houses and 185 fishing boats were destroyed along a 250-km-long strip of Nicaragua's west coast. Some damage was also reported in Costa Rica. Most of the damage and casualties were caused by the tsunami which swept the west coast of Nicaragua and Costa Rica. Wave heights reportedly reached as high as 8 m. A tsunami ran inland about 1,000 m at Masachapa, Nicaragua, where at least 15 people were killed. Maximum wave heights (peak-to-trough) in centimeters at selected tide stations were 111 at Baltra Island, 83 at Easter Island, 28 at Socorro Island, 18 at La Libertad, Ecuador, 10 at Valparaiso, Chile, and 10 at Hilo, Hawaii. The earthquake was felt in Chinandega and Leon Departments, Nicaragua. It was also felt at El Crucero, Managua, and San Marcos, Nicaragua, and at San Jose, Costa Rica. This tsunami is believed to be the first to have caused deaths in Nicaragua. Many aftershocks have followed but no additional damage has been reported.

Utah

The southwestern part of Utah reported a damaging earthquake on September 2 at 4:26 a.m. MDT. The magnitude 5.9 earthquake was centered near St. George at a site about 70 km south-southwest of Cedar City. Some damage (MM VI) occurred at Cedar City, Hurricane, Kanab, New Harmony, Santa Clara, Springdale, St. George, Toquerville, Virgin, and Washington. The earthquake triggered a large landslide which destroyed three houses in Springdale. Intensity MM V effects were experienced at Glendale, Gunlock, Hatch, Kanarraville, La Verkin, Orderville, Panguitch, and Rockville. Intensity MM V effects were also experienced at Fredonia and Grand Canyon, Arizona. It was felt throughout a wide area including much of southwestern Utah, northwestern Arizona, and southeastern Nevada. The felt area extended northwest to Caliente and Pioche, Nevada, northeast to Richfield, Utah, southeast to Flagstaff, Arizona, and to the Las Vegas, Nevada, area on the southwest.

Idaho

Eastern Idaho experienced a light earthquake on September 3 at 10:54 p.m. MDT. The epicenter of this magnitude 4.0 earthquake was about 90 km east-southeast of Pocatello. The relatively minor earthquake was felt at Georgetown, McCammon, Montpelier, and in the Soda Springs area.

Iran

A damaging earthquake struck the southern part of Iran on September 8 at 4:08 a.m. local time. The magnitude 5.1 earthquake was centered about 70 km southwest of Shiraz. One person was killed and 11 people were injured in the Firuzabad area. Landslides blocked roads in the epicentral area, where at least 200 houses and 3 bridges were destroyed. Bonu, Darenjan, Giah Zar, and Meygali also reported damage. Kazerun and Shiraz felt the earthquake.

Zaire

A damaging earthquake hit Zaire on September 11 at 5:57 a.m. local time. The magnitude 6.7 earthquake was centered about 250 km south-southeast of Kibombo. At least 8 people were killed, 37 people were injured, and several buildings were destroyed at Kibombo. The earthquake was also felt at Bujumbura, Burundi.

Alaska

A moderate earthquake hit the Alaska Peninsula on September 12 at 7:00 a.m. ADT. The magnitude 5.5 earthquake was centered about 170 km west-southwest of Kodiak. The earthquake produced intensity MM V effects at Kodiak. It was also felt at Akhiok, Egegik, and Port Lions.

On September 27 at 9:48 a.m. ADT, a magnitude 5.7 earthquake occurred about 250 km southeast of Sand Point. This quake was felt at Sand Point, King Cove, and Perryville.

A series of earthquakes struck the Andreanof Islands in Alaska's Aleutian chain in late September and October. The first, a magnitude 5.9 earthquake on September 29 at 6:28 p.m. AHDT, was centered about 140 km west-southwest of Adak. Intensity MM V effects were observed on Adak, and the quake was also felt on Amchitka. This quake was followed by a magnitude 6.8 earthquake at 8:34 p.m. AHDT on the same day. It caused intensity MM V effects on Adak and was also felt on Amchitka. Also on the same day, September 29, a magnitude 5.5 quake occurred at 9:03 p.m. AHDT and a magnitude 6.0 hit the same area at 12:43 p.m. Both of these earthquakes were felt on Adak. The last of the stronger earthquakes in the series occurred on September 30 at 8:03 p.m. AHDT. This earthquake, a magnitude 6.0 shock, produced intensity MM IV effects on Adak. The larger earthquakes in this series during October were as follows: a magnitude 5.3 at 8:19 a.m. AHDT on October 7, a magnitude 5.7 on October 8 at 7:35 a.m. AHDT, and a magnitude 5.3 on October 9 at 3:17 a.m. AHDT. Each of these earthquakes shook Adak at the intensity MM IV level.

Nevada

A light earthquake occurred in the western part of Nevada at 4:46 a.m. PDT on September 13. It was centered approximately 50 km east-southeast of Beatty and 120 km west-northwest of Las Vegas. The earthquake was felt at Beatty and Pahrump, Nevada.

The western part of the state experienced another light earthquake on October 21 at 7:26 p.m. PDT. This magnitude 4.1 earthquake was centered about 40 km southeast of Carson City. Intensity MM V effects were noted at Smith and Yerington.

California

Aftershocks of the magnitude 7.6 earthquake near Landers on June 28, 1992, continued in southern California. A magnitude 4.8 aftershock occurred on September 15 at 1:47 a.m. PDT. It was centered about 30 km west of Twentynine Palms. Intensity MM V effects were noted at Angelus Oaks and Big Bear City. Intensity MM IV effects were observed at Brea, Carlsbad, Duarte, Garden Grove, Hesperia, Highland, La Quinta, Mecca, Morongo Valley, Palm Springs, Pioneertown, Temecula, and Yucca Valley. The shock was felt in many parts of Los Angeles, Orange, Riverside, San Bernardino, and San Diego Counties. Another aftershock, a magnitude 4.4 quake, occurred on October 2 at 12:20 a.m. PDT. It was located about 50 km southeast of Barstow and was felt at Apple Valley, La Quinta, and Victorville.

On September 15, a magnitude 4.3 earthquake occurred at 11:15 p.m. PDT in central California. It was centered about 40 km east-southeast of Coalinga. The earthquake was felt at Avenal, Kettleman City, Lemoore, Lindsay, Reedley, and Riverdale.

In northern California, a magnitude 4.9 earthquake occurred at 4:05 p.m. PDT on September 19. The epicenter of this earthquake was about 40 km southeast of Ukiah. The quake was felt at Calistoga, Clearlake, Clearlake Park, Cobb, Finley, Kelseyville, Lower Lake, Middletown, and St. Helena.

On September 23 at 4:11 a.m. PDT, a magnitude 4.2 earthquake struck northern California about 60 km south-southwest of Eureka. This earthquake was felt at Arcata, Eureka, Ferndale, Fortuna, Freshwater, Honeydew, Miranda, Petrolia, Redcrest, Shelter Cove, and Weott. It is believed to be an aftershock of the magnitude 7.1 earthquake on April 25, 1992.

A magnitude 4.2 earthquake occurred in central California on September 27 at 9:59 a.m. PDT. Centered about 40 km east-southeast of Coalinga, it was felt at Avenal and Kettleman City.

Washington

A very minor earthquake occurred in the southeastern part of this state on September 22 at 9:32 p.m. PDT. This magnitude 2.8 earthquake was located near Walla Walla, Washington, about 50 km northeast of Pendleton, Oregon. The tremor was felt in the Walla Walla area.

South-central Washington experienced a minor earthquake on October 25 at 11:56 p.m. PST. The magnitude 3.5 earthquake was centered about 20 km south-southwest of Ellensburg. Intensity MM V effects were noted at Naches and the quake was also felt at Selah.

On October 26 at 10:10 p.m. PST, a magnitude 2.5 earthquake occurred about 90 km southeast of Tacoma. Intensity MM IV effects were noted at Packwood and the earthquake was also felt in the Randle area.

Indonesia

A strong earthquake struck a remote part of the island of Halmahera on September 27 at 7:16 a.m. local time. The magnitude 6.6 earthquake was centered about 200 km east-northeast of Ternate, Indonesia. No information on damage or intensity were received.

Arkansas

A very minor earthquake occurred in the northeastern part of this state on September 30 at 9:41 p.m. CDT. The magnitude 2.7 earthquake was centered near Blytheville, Arkansas, about 80 km north of Memphis, Tennessee. It was felt at Blytheville.

Hawaii

The southeastern part of the Island of Hawaii was hit by a magnitude 4.3 earthquake on October 3 at 7:52 p.m. HST. This quake was located about 40 km south of Hilo. It was felt at Hilo, Honomu, Pahala, in the Kona District, and throughout the southeastern part of the Island of Hawaii.

On October 9 at 9:25 p.m. HST, a magnitude 4.0 earthquake occurred near Hilo. The earthquake was felt at Hilo, Glenwood, Pahala, and Volcano.

Wyoming

The southwestern part of this state experienced a light earthquake on October 10 at 9:47 a.m. MDT. The magnitude 4.0 earthquake was centered about 110 km northwest of Rawlins. Intensity MM III effects were noted at Hudson and Lander.

Egypt

Egypt experienced a devastating earthquake on October 12 at 3:10 p.m. local time. The magnitude 5.9 earthquake was centered about 20 km south-southwest of Cairo. Preliminary estimates put the death toll at 552 people; more than 9,929 people were injured. About 8,300 buildings were damage or destroyed in the Cairo area. The preliminary evaluation of damage was about $300 million. The earthquake was felt in a wide area extending from Alexandria to Aswan in Egypt and from Elat to Tel Aviv and Jerusalem in Israel. The type of building construction in the region and the proximity of the epicenter to Cairo, a very large population center, are believed to be the major reasons that this moderate-sized event caused such severe destruction. Many aftershocks followed, including at least one that caused additional deaths. This aftershock, a magnitude 4.5 quake, occurred on October 22 at 7:39 p.m. local time. It killed 4 people and injured at least 50 other people in the Cairo area.

Vanuatu Islands

A major earthquake struck the Vanuatu Islands in the Southwest Pacific on October 16 at 9:37 a.m. local time. The magnitude 7.1 earthquake was centered about 130 km northwest of Santo and about 2,020 km northeast of Brisbane, Australia. There were no reports of damage associated with this shock.

On October 17 at 1:52 p.m. local time, another major earthquake, this one with magnitude 7.0, struck the Vanuatu Islands. The epicenter was well south of the quake listed above. This earthquake was centered about 210 km southeast of Port Vila and 1,900 km east-northeast of Brisbane, Australia. Again, there were no reports of damage.

Colombia

Northern Columbia experienced two major earthquakes in this reporting period.

The first was a magnitude 7.0 quake at 3:33 a.m. local time on October 17. It was centered about 130 km west-northwest of Medellin. About 20 people were injured and 90 percent of the buildings were destroyed in Murindo. The quake was felt throughout northwestern Colombia from the cities of Cali and Bogota to Cesar Department.

This earthquake was followed by a magnitude 7.3 quake on October 18 at 10:12 a.m. local time. This quake was centered about 170 km west-northwest of Medellin. Damage occurred in the Murindo-Apartado-Medellin area. One person was killed and about 50 people were injured. There were some landslides in the epicentral area. Liquefaction was observed in the Murindo area and as far north as Apartado. At least 10 people were killed, 65 people were injured, and 1,500 people were left homeless by the explosion of a mud volcano in the San Pedro de Uraba area. There was slight damage at Bogota. The quake was felt in much of northwestern Colombia as far south as Cali. It was also felt strongly in Darien Province, on the Azuero Peninsula, and at Panama City, Panama; at Caracas and Valencia, Venezuela; and on Aruba. A small island emerged from the Caribbean Sea off San Juan de Uraba, Colombia. Many aftershocks followed but no additional damage was reported.

Kermadec Islands, New Zealand

A major earthquake struck these remote islands on October 22 at 9:04 p.m. local time. The magnitude 7.2 earthquake was centered about 470 km west-southwest of Raoul Island, where it was felt. This earthquake was followed by a magnitude 6.5 earthquake on October 23 at 11:09 a.m. local time and a magnitude 6.6 shock on October 24 at 7:23 a.m. local time. There were no reports of damage from the three quakes; the last earthquake was felt on Raoul Island.

Morocco

This country experienced a damaging earthquake on October 23 at 10:11 a.m. local time. The epicenter of this magnitude 5.2 earthquake was about 70 km south of Er-Rachida and 390 km southeast of Rabat. There was damage and at least two people were killed in the Rissani area. The earthquake was felt throughout much of Morocco from Fes to Marrakech.

New Britain region, Papua New Guinea

A major earthquake, magnitude 7.0 shock, struck the remote New Britain region on October 23 at 11:05 a.m. local time. This earthquake was centered about 130 km south-southeast of Rabaul. There were no reports of damage.

Caucasus

A strong earthquake shook the eastern part of the Caucasus region on October 24 at 2:20 a.m. local time. The magnitude 6.5 earthquake was centered about 60 km south-southeast of Vladikavkaz, Russia, and about 90 km north of Tbilisi, Georgia. At least one person was killed, 10 people were injured, and several houses were damaged in the area of Barisakho, Georgia. Landslides were reported in the epicentral area. The earthquake was felt in parts of Russia, Georgia, and Azerbaijan.

Fatalities
SEPTEMBER–OCTOBER 1992

Rep. of Georgia	1
Colombia	11
Egypt	556
Iran	1
Morocco	2
Nicaragua	116
Zaire	8
Total	695

U.S. ACTIVITY*
SEPTEMBER–OCTOBER 1992

Alaska	27
Arizona	1
Arkansas	1
California	58
Hawaii	2
Idaho	1
Nevada	3
New Hampshire	2
Oklahoma	1
Utah	1
Washington	3
Wyoming	1
Total	101

*Felt earthquakes as reported from many sources.

PRELIMINARY LOCATIONS
SEPTEMBER–OCTOBER 1992

Date	Origin time UTC	Region	Coordinates Lat	Long	Depth km	Mag
Sep 2	00 15 57.5	Near coast of Nicaragua	11.8 N	87.4 W	10	7.4MS
Sep 2	10 26 20.9	Utah	37.1 N	113.5 W	15	5.9ML
Sep 4	04 54 15.0	Eastern Idaho	42.7 N	111.4 W	5	4.0ML
Sep 8	00 38 14.3	Southern Iran	29.1 N	52.1 E	10	5.1MS
Sep 11	03 57 26.2	Zaire	6.1 S	26.7 E	10	6.7mb
Sep 12	14 59 36.1	Alaska Peninsula	57.3 N	155.2 W	55	5.5mb
Sep 13	11 46 20.1	California-Nevada border region	36.7 N	116.3 W	5	4.4ML
Sep 15	08 47 11.2	Southern California	34.1 N	116.4 W	9	4.8mb
Sep 16	06 14 33.3	Central California	36.0 N	119.9 W	12	4.3MD
Sep 19	23 04 47.1	Northern California	38.9 N	122.8 W	2	4.9ML
Sep 23	04 32 16.8	Washington	46.0 N	118.4 W	6	2.8MD
Sep 23	11 10 30.5	Near coast of northern California	40.3 N	124.5 W	8	4.2mb
Sep 26	22 15 57.2	Halmahera, Indonesia	1.2 N	129.1 E	26	6.6MS
Sep 27	16 59 14.0	Central California	36.0 N	119.9 W	14	4.2MD
Sep 27	17 48 12.9	South of Alaska	54.0 N	157.3 W	33	5.7mb
Sep 30	03 27 59.1	Andreanof Islands, Aleutian Islands	51.4 N	178.6 W	26	5.9mb
Sep 30	05 34 00.3	Andreanof Islands, Aleutian Islands	51.3 N	178.1W	33	6.8MS
Sep 30	06 03 25.4	Andreanof Islands, Aleutian Islands	51.2 N	178.2 W	33	5.5ML
Sep 30	09 42 50.9	Andreanof Islands, Aleutian Islands	51.1 N	178.2 W	14	6.0MS
Oct 1	02 40 58.0	Arkansas	35.9 N	90.0 W	5	2.7mbLg
Oct 1	05 02 36.7	Andreanof Islands, Aleutian Islands	51.1 N	178.0 W	33	6.0mb
Oct 2	07 19 57.3	Southern California	34.6 N	116.6 W	4	4.4ML
Oct 3	05 51 41.8	Hawaii	19.4 N	155.1 W	9	4.3MD
Oct 5	04 44 08.6	Oklahoma	36.4 N	97.5 W	5	2.8MD
Oct 6	15 38 04.2	Vermont-New Hampshire border region	43.3 N	71.5 W	5	3.4mbLg
Oct 6	17 19 08.2	Andreanof Islands, Aleutian Islands	51.2 N	177.9 W	33	5.3mb
Oct 8	16 34 56.1	Andreanof Islands, Aleutian Islands	51.1 N	177.8 W	43	5.7MS
Oct 9	12 16 54.6	Andreanof Islands, Aleutian Islands	51.5 N	176.9 W	33	5.3mb
Oct 10	15 46 56.5	Wyoming	42.8 N	108.3 W	5	4.0ML
Oct 10	17 25 26.5	Hawaii	19.7 N	155.0 W	48	4.0mb
Oct 12	13 09 56.3	Egypt	29.9 N	31.2E	25	5.9mb

PRELIMINARY LOCATIONS
SEPTEMBER–OCTOBER 1992 (cont'd)

Date	Origin time UTC	Region	Coordinates Lat	Long	Depth km	Mag
Oct 15	22 37 07.1	Vanuatu Islands	14.5 S	166.6 E	33	7.1MS
Oct 17	02 51 53.8	Vanuatu Islands	19.3 S	169.5 E	33	7.0MS
Oct 17	08 32 39.9	Northern Colombia	6.9 N	76.8 W	10	7.0MS
Oct 18	15 11 59.3	Northern Colombia	7.1 N	76.8 W	10	7.3MS
Oct 20	05 28 08.9	Central California	35.9 N	120.5 W	10	4.7MD
Oct 22	02 25 39.8	California-Nevada border region	38.9 N	119.4 W	5	4.1ML
Oct 22	09 04 24.9	Kermadec Islands, New Zealand	30.0 S	177.3 W	33	7.2MS
Oct 22	17 38 58.3	Egypt	29.5 N	31.5 E	10	4.5mb
Oct 22	23 08 31.8	Kermadec Islands, New Zealand	39.7 S	177.2 W	42	6.5MS
Oct 23	09 11 08.9	Morocco	31.3 N	4.3 W	28	5.2MS
Oct 23	13 04 41.1	New Britain region	5.3 S	152.6 E	33	7.0MS
Oct 23	23 19 47.2	Eastern Caucasus	42.5 N	45.1 E	33	6.5MS
Oct 24	08 23 04.3	Kermadec Islands, New Zealand	29.4 S	177.4 W	41	6.6MS
Oct 26	07 56 35.1	Washington	46.8 N	120.7 W	0	3.5ML
Oct 27	06 10 27.1	Washington	46.6 N	121.8 W	9	2.5MD

Back Cover Photograph. *Two views of Kalapana on the Big Island of Hawaii, a community destroyed by lava flows from Kilauea Volcano in 1990. The top photograph, taken on May 2, 1990, shows lava flows consuming homes on the outskirts of the settlement. One lobe of the flows has already crossed Highway 130. The bottom photograph, taken on June 3, 1990, shows nearly complete devastation. Photographs by Jim Griggs.*

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