Geologic Processes at the Land Surface

U.S. GEOLOGICAL SURVEY BULLETIN 2149

Front Cover. Earth from space. Photographed by Apollo 16.

Back cover. View of Earth across Moon. Photographed by Apollo 11. Quotation from Jacks and Whyte, 1939.

Frontispiece: Dust plume rises to an elevation of 1,500 m above the San Joaquin Valley southeast of Bakersfield, Calif., in December 1977 windstorm. Dust streams from canyons in the foothills of the Tehachapi Mountains (lower left). All anemometers in the southern San Joaquin Valley failed, but pre-failure records indicated wind velocities to 312 km per hour. Powerline towers were uprooted or toppled; orchards, vineyards, and vegetable crops were destroyed; fence posts were cut in two by wind-driven sand; and large areas of the valley-bounding hills were denuded, leading to massive water erosion and debris flows in subsequent rainstorms. Dust from the southern part of the valley, carrying the valley-fever fungus, was blown as much as 650 km to the north and caused an epidemic of valley fever. Photograph by Sam Chase.

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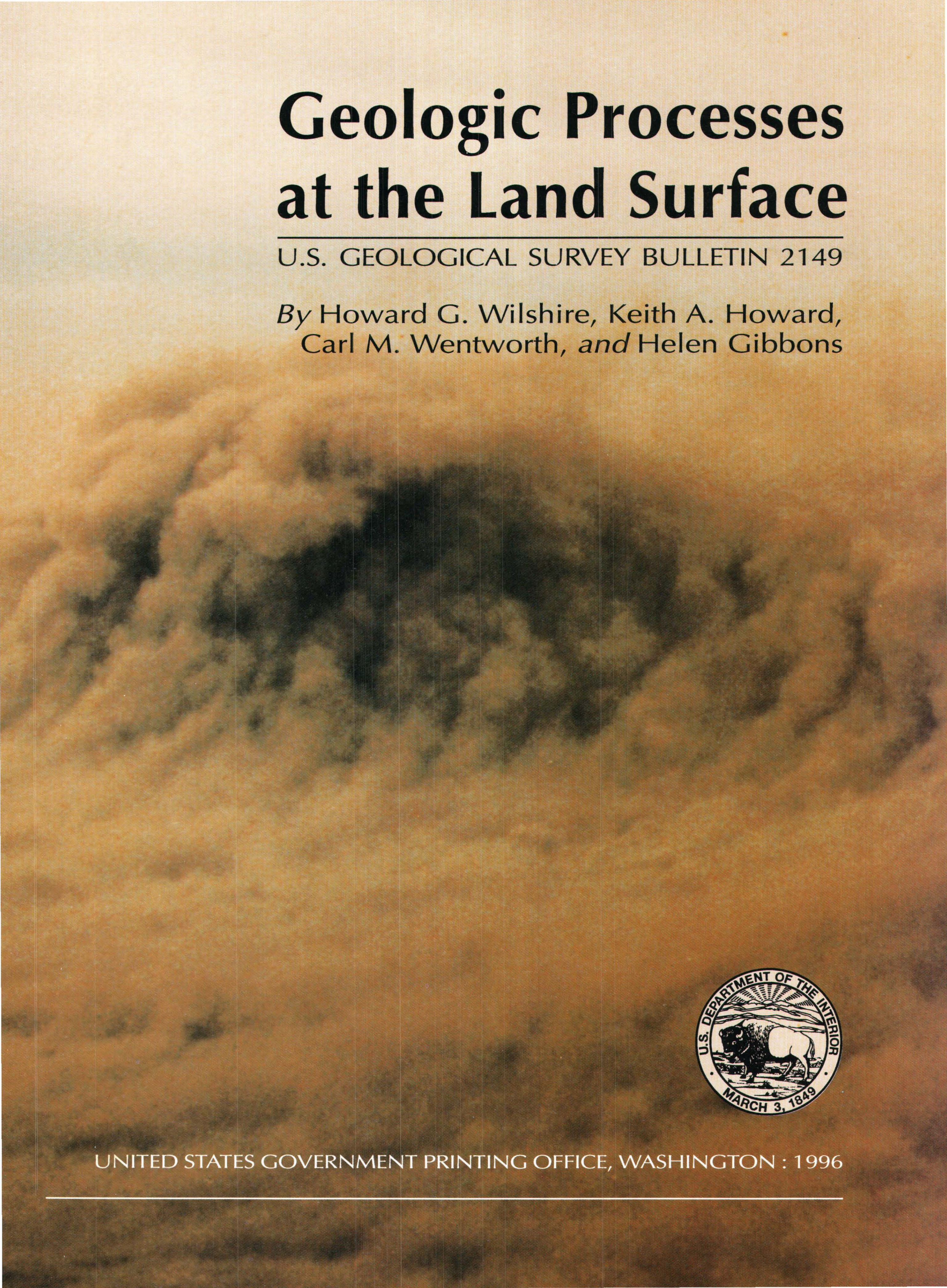
By Howard G. Wilshire, Keith A. Howard, Carl M. Wentworth, *and* Helen Gibbons



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Conversion Factors

For readers who wish to convert measurements from the metric system of units to the inch-pound system, conversion factors are listed below.

Multiply	By	To obtain
millimeters	0.039	inches
centimeters	0.394	inches
meters	3.281	feet
kilometers	0.621	miles
square meters	10.764	square feet
square kilometers	0.386	square miles
hectares	2.471	acres

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Preface

Scientific discoveries in recent years have properly emphasized the fragility and global interconnectedness of our environment. There is growing awareness of the serious global consequences of environmental disturbances, both from natural causes such as El Niño events, volcanic eruptions, hurricanes, catastrophic earthquakes, and meteorite impacts, and from human causes such as acid rain, greenhouse warming, depletion of atmospheric ozone, extinction of living species, and pollution of soil, water, and air. We urgently need to better understand the global environment in order to develop national and international policies that prevent or accommodate environmental changes. The scientific community elsewhere is responding to this need by organizing and expanding research efforts under the sponsorship of the International Council of Scientific Unions' International Geosphere-Biosphere Programme, the World Meteorological Organization's World Climate Research Programme, and the U.S. Global Change Research Program.

Improving our knowledge of the land surface and how it responds to change is of great importance in these efforts. Despite our total dependence on the land, we are endangering its richness by practices that cause such harms as irretrievable soil loss, degradation of forest and arid-land ecosystems, and pollution of soil and water with contaminants that are entering and damaging the food chain. This report focuses attention on the societal benefits and scientific opportunities of comprehensive study by the U.S. Geological Survey of the geologic processes operating at the land surface. It outlines directions for research that will provide the basis to help rectify a dangerous neglect of our land resources.

Geologic Processes at the Land Surface

Special Topics

INTRODUCTION

Natural processes operating at the land surface both make human life possible and also pose threats to that life. Those processes include erosion, deposition, soil formation, and water flow. Some of the hazards they produce take place rapidly, such as landslides, dust storms, and floods; others may be gradual events, such as topsoil loss, changes in ecosystems, and contamination of water and soil.

Land surface processes have long attracted scientific study, but only in this century have efforts begun to quantify and synthesize knowledge of these processes. Our understanding of the earth's land surface could ripen into the kind of scientific revolution that impelled new synthesis of biological observations toward the theory of evolution in the 19th century, and the synthesis of geological observations that led to the theory of plate tectonics in the middle of this century. The intellectual and technical base now exists to support real progress in comprehending the fundamental nature of the various surface processes, their rates and effects, and their responses to natural and human-caused changes.

Society's need for improved knowledge of surface processes is great, for shortsighted human use of land resources is increasingly threatening the long-term welfare and even the survival of humans in many parts of the world.

LAND AND PEOPLE AT RISK

Land-surface hazards cause major losses of life and property. Landslides cause property damage of billions of dollars and loss of thousands of lives each year throughout the world. The United States alone has perhaps 20 million landslide deposits formed in the recent geologic past (Brabb, 1991). As populations expand into vulnerable areas, more people become at risk (see box below).

Many hazards are created directly by humans who either do not understand or choose to disregard surface processes. Catastrophic failure of the Baldwin Hills Reservoir in southern California is a case in point (California Department of Water Resources, 1964). Between the hours of 12 noon and 4 p.m. on December 14, 1963, the dam failed, causing the loss of four lives and millions of dol-

LANDSLIDES—An Example in Southern California

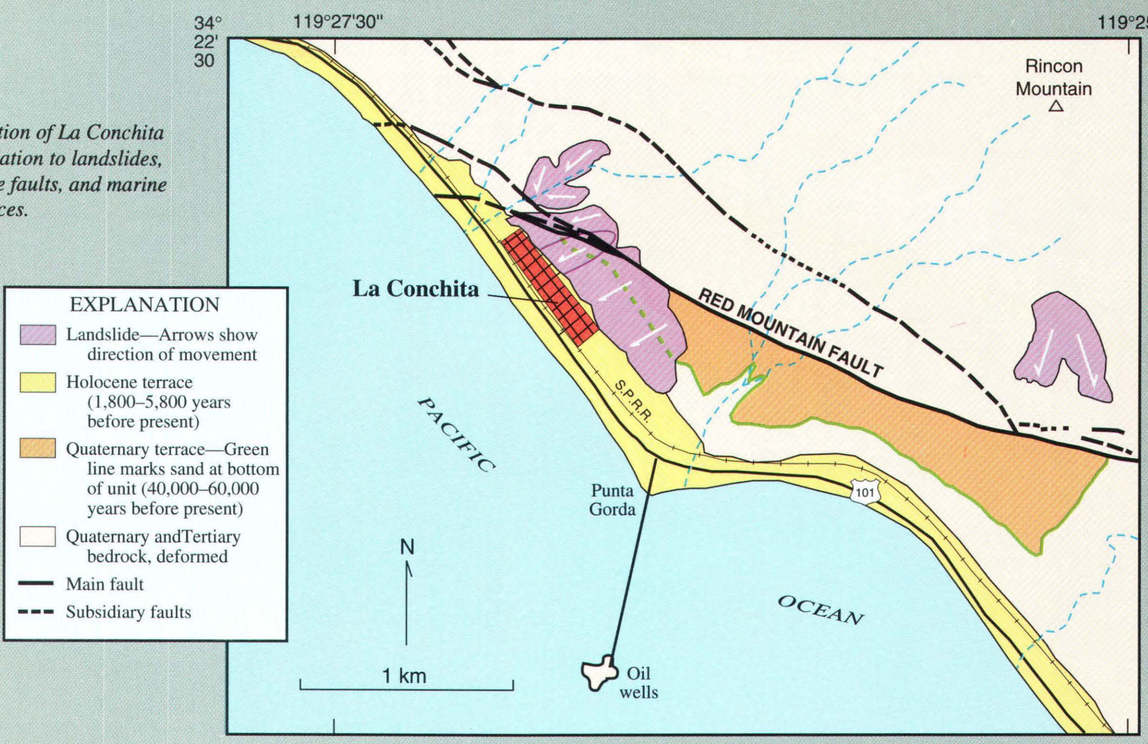
Landslides are major causes of property damage and loss of life throughout the world (Brabb, 1991). A graphic example of landslide risk occurred March 4, 1995, in the coastal community of La Conchita, California.

The community of La Conchita ("The Little Seashell") lies on a narrow strip of low land along the Pacific coast of Ventura County, Calif., wedged between U.S. Highway 101 and the Southern Pacific railroad on the ocean side, and the base of steep, wave-cut cliffs that form the base of Rincon Mountain on the landward side. The unique geologic and geographic settings of this area combine to make it picturesque and scientifically interesting—but also susceptible to several natural hazards.

Geologic mapping of the area by U.S. Geological Survey, California Division of Mines and Geology, and oil industry geologists over several decades has revealed the geologic history and identified the natural hazards to life and property in this area (Weber and others, 1973; Sarna-Wojcicki and others, 1987a). The mapping provides a basis for understanding the relationship between geologic processes and natural hazards.

The earth's crust in the western Transverse Ranges, where the community of La Conchita is located, is undergoing rapid deformation as the Pacific crustal plate moves northwest relative to the North American plate and meets the obstacle of a large, westerly bend in the San Andreas fault zone (the boundary between these plates; Wentworth and Yerkes, 1971; Morton and Yerkes, 1987). As a consequence, the earth's crust in this region is being compressed and thickened, and in places forced upward. Geologically young sediments once deposited on the deep ocean floor are now being squeezed like putty in a

Location of La Conchita in relation to landslides, active faults, and marine terraces.



lars in property damage; loss of life would undoubtedly have been much greater had the failure occurred during the night when the caretaker who observed the developing problem was off duty. The failure was caused by subsurface erosion along a fault that formed in response to land subsidence, itself caused by extraction of oil from the nearby Inglewood oil field (Castle and Yerkes, 1976). Other problems that may arise from withdrawal of subsurface fluids include collapse of pore spaces in aquifers and permanent loss of subsurface storage space (see box, page 5). The widespread subsidence problem in the United States (fig. 1, page 6) is but a small part of the global problem (Johnson, 1991).

Less visible but equally hazardous is the pollution of soil and water that results from a broad range of human activities. Problems of toxic pollution have become widely acknowledged in the last decade and today are suspected to be causes of health and congenital disorders (Devinny and others, 1990). Health problems in children living near the Love Canal in New York have been related to well-

vise and pushed up above sea level. In places north of the city of Ventura, the land is rising as much as 15 mm per year (Yerkes and others, 1987). At La Conchita, the rate is about 3 mm per year. These young sediments and rocks are poorly consolidated and very susceptible to erosion and downslope movement in the form of landslides and soil flows from the cliffs and mountain slopes above La Conchita, and floods, mudflows, and debris flows in the gullies north and south of the community.

Several large, old landslides were mapped in the 1970's in the cliffs directly behind La Conchita; some smaller, more recent landslides are nested within the older (see map, p. 2; Weber and others, 1973; Sarna-Wojcicki and others, 1987a). As a result of heavy rains in January and March of 1995, some of these landslides were reactivated, destroying nine homes near the base of the cliff (see photographs). The new slides now threaten to destroy additional homes. Highway 101 and the Southern Pacific railroad were closed down numerous times in this area by earlier landslides and debris flows before La Conchita was developed in the 1920's.

During the last several hundred thousand years, as this area was being uplifted above the ocean, the ocean itself was undergoing cyclic rises and falls in level that were climatically controlled. The ocean level fell during glacial periods, when ice was stored on land in glaciers, and rose during warm periods, when the glaciers melted and their water returned to the oceans. Over time, the uplift of the earth's crust in this region has been more rapid and continuous than the sea-level oscillations. As the land rose, the ocean carved notches into the rising Rincon Mountain during sea-level highstands. The notches show up as more-or-less flat topographic benches, called terraces, at different elevations on the mountain. The oldest terraces are high up on the mountain and have been much modified by erosion. The youngest, most recently emerged terrace is the low, flat bench on which La Conchita is built. Although a thin veneer of young alluvium and debris flows have covered the flat, beveled platform cut by the surf, the general shape of this terrace is still easily seen. Shells of clams and snails found in uplifted beach sands on this terrace yield radiocarbon ages of between about 1,800 and 5,800 years before the present (Lajoie and others, 1982).

(Continued on next page)

Oblique aerial view of the main landslide, showing houses engulfed along the toe of the slide. Light streaks forming a partial "V" on the face of the slide are broken remnants of the road that crosses the area diagonally from left to right. Small slide to left is one of four that broke out from topographic benches on the cliff face. Photograph on next page is at the right side of the toe of the slide. Aerial photograph, March 6, 1995, by AP/Wide World Photos.

documented pollution of soil by hazardous chemical waste (Goldman and others, 1985). Examples of great concern are coming to light as the industrial centers of Eastern Europe open up to world view. Uranium mining in the former East Germany has left about 500 million tons of chemical and radioactive waste spread over more than 1,200 km^2 of land. A single lake in this area contains about 22,500 tons of arsenic in solution in water and in sediments at the lake bottom (Kahn, 1993).

Solutions to problems of soil and water pollution arising from mineral- and energy-resource extraction are likely to be expensive. For example, cleanup of contamination caused by a single abandoned gold mine in Colorado (Summitville Mine) is estimated to cost $100 to $200 million (King, 1995). The magnitude of the problem can be appreciated by the fact that there are between 100,000 and 500,000 abandoned or inactive mine sites in the United States alone.

Low-quality deep water extracted during oil and gas production can present a serious disposal problem. In 1993

LANDSLIDES, continued

Much of the community of La Conchita lies at elevations of between 6 and 12 m above mean sea level, elevations usually above the reach of high tides and winter storms. However, the community is vulnerable to the surf from exceptionally large storms and tsunamis, and these processes carved the steep cliffs behind the community, oversteepening the slopes and making them prone to landsliding.

Above the level of the cliffs, at an elevation of about 120 to 150 m, is another, broader bench that represents an older marine terrace. The base of this marine terrace (shown as a green line in map on p. 2) is again recognized by the presence of a beveled, wave-cut platform that was cut into the deformed marine sediments. A beach sand lies on top of this platform and contains many fossil mollusk shells. Ages obtained on these shells by amino-acid racemization and radiocarbon analyses indicate that this terrace is between about 40,000 and 60,000 years old (Lajoie and others, 1982). This terrace is also backed by old seacliffs and covered by younger alluvium and mudflows. The old sea cliffs are less steep and are partly buried, having been modified by erosion. The elevation of this terrace increases to the southeast to levels as high as 210 m, indicating that uplift is greater in that direction.

Deformed, clayey, relatively impermeable Quaternary bedrock that underlies the beveled marine terrace is overlain by well-sorted marine sand, which is in turn overlain by alluvium and mudflow deposits. This sequence of layers makes for an unstable combination that is particularly susceptible to landsliding when the permeable sediments are water saturated.

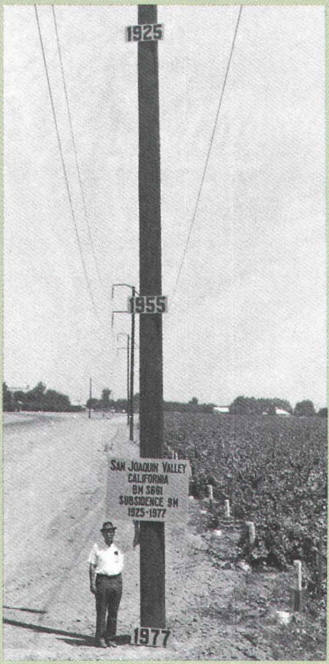
Faults just inland from La Conchita (see map, p. 2) appear to be active (Sarna-Wojcicki and others, 1979, 1987a; Yeats and others, 1987). Thus, there is a potential of ground shaking and ground rupture in the vicinity and at La Conchita. The faulted bedrock, marine terrace deposits, and old landslides above La Conchita represent a nexus of geologic circumstances that favor rapid downslope mass movements in the future. Ground rupture, ground shaking, and landslides can not only affect the houses in the community, but can also block the highway and railroad, and sever offshore and onshore oil pipelines, causing oil spills. Pacific Operators Offshore, Inc., which operates a crude-oil pipeline along the road above La Conchita, was forewarned of problems by the appearance of cracks in the road in late August 1994. The company took an elaborate series of precautions that averted a spill when the slide ruptured the pipeline.

The lessons of La Conchita underscore the importance of geologic studies as elements of land-use planning.

House on left was pushed onto the house at right by the slide. Photograph by Howard Wilshire.

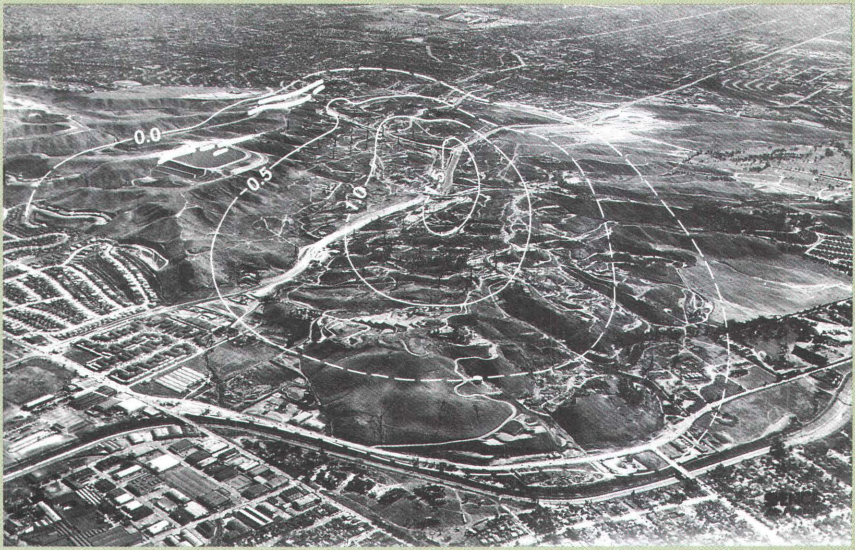
Prepared by Andrei M. Sarna-Wojcicki

SUBSIDENCE IN PARTS OF CALIFORNIA



⇐ The magnitude of subsidence caused by groundwater withdrawal during the period 1925–1977 at bench mark S661, near the center of greatest subsidence in the San Joaquin Valley (see Johnson, 1991) is illustrated by J.F. Poland, U.S. Geological Survey, who stands alongside a powerline pole. The approximate position of the land surface in 1925, 1955, and 1977 is shown. The land surface subsided about 9 m from 1925 to 1977. Photograph courtesy of Ivan Johnson.

Displacement along surface ruptures caused by the subsidence illustrated in aerial photograph (below) led to subsurface erosion (piping) of the dam foundation and failure of the Baldwin Hills Reservoir dam. Photograph taken December 1963; from Los Angeles Department of Water and Power.



An oblique, south-southeast aerial view across the Baldwin Hills, Calif., shows the approximate configuration of cumulative subsidence caused by oil withdrawal, 1911–1964 (Castle and Yerkes, 1976), centering on the Inglewood oil field. Contours (light lines, dashed where approximate) show amount of subsidence in meters. Also shown are active surface ruptures (heavy lines) and the location of the Baldwin Hills Reservoir (crossed by lower set of surface ruptures). Photograph by Spence Air Photos, 1952.

Subsidence caused by withdrawal of underground fluids, such as water or oil, is a widespread problem (Poland and Davis, 1969; Poland, 1984; Johnson, 1991) that may affect fluid circulation and sediment distribution at and below the earth's surface. Extraction of fluids and concomitant depressurization of the underground reservoirs has produced significant surface effects in such places as Wilmington-Long Beach Harbor, Calif.; Venice, Italy; and Tokyo, Japan.

Subsidence produced by extraction of oil from the Wilmington oil field caused encroachment of the sea in the Wilmington-Long Beach Harbor area. Protection of the urban infrastructure, including, ironically, the production facilities of the oil field itself, required construction of elaborate dikes and pumping facilities.

The impact of subsidence over more than 14,000 km^2 in the San Joaquin Valley of California (photograph, upper left) has also been significant. The large drop (about 9 m) in ground level between 1925 and 1977 caused by pumping of groundwater for crop irrigation represents a largely permanent loss of storage capacity in the subsurface aquifers (Poland and others, 1975). In addition, millions of dollars have been spent on repair of water-well casings and water transportation systems ruptured by uneven subsidence.

The area and amount of subsidence caused by extraction of oil in the Inglewood oil field, southern California, is shown in aerial photograph, above. Subsurface compaction that produced the subsidence led to the formation of several sets of surface ruptures along the east side of the zone of subsidence. One set of these fractures caused the failure of the Baldwin Hills Reservoir dam (photograph, upper right; Castle and Yerkes, 1976).

Prepared by Robert Castle

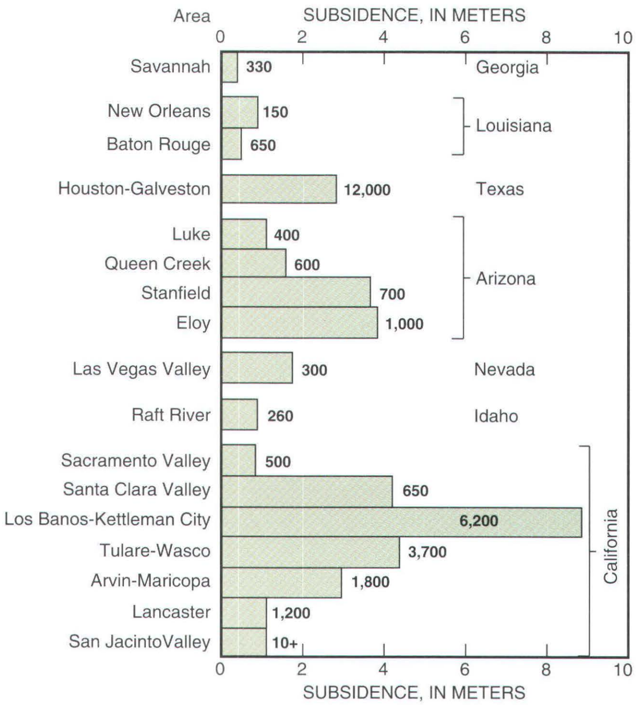


Figure 1. The magnitude of land subsidence due to groundwater withdrawal in the United States. The numbers in or beside the shaded bar indicate the area in square kilometers; horizontal scale indicates average subsidence in meters. From Poland (1984).

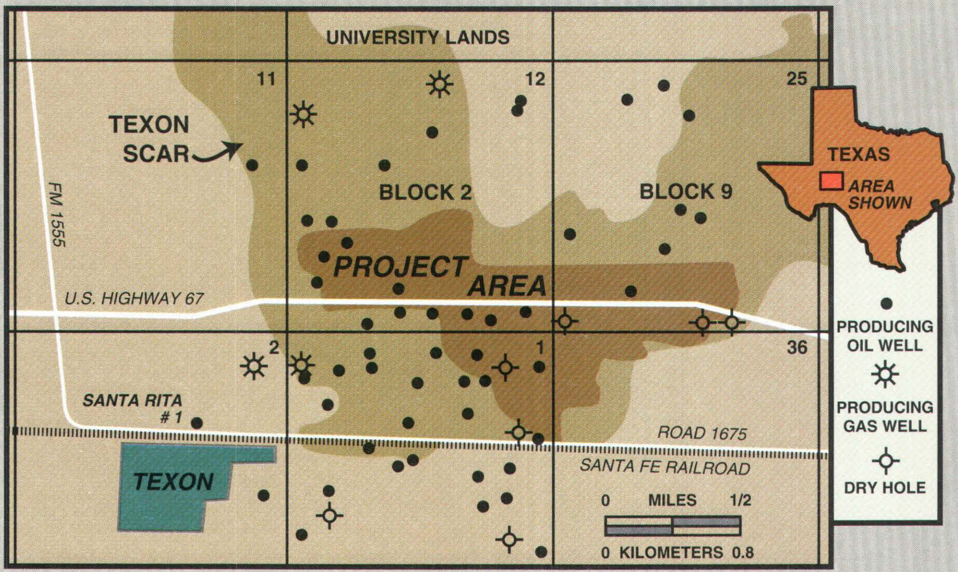
alone, an estimated 25 billion barrels of water were produced with 2.5 billion barrels of oil in the United States, or 10 barrels of water for each barrel of oil (Kharaka and Wanty, 1995). The water is commonly more saline than seawater and may contain toxic organic and inorganic (some radiogenic) contaminants, such as phenols, benzene, toluene, radium-226, radium-228, radon-222, and various metals including, in places, lead and zinc (Kharaka and Thordsen, 1992; Kharaka and Wanty, 1995). Release of these oil field brines on the ground surface has caused significant long-term damage to natural ecosystems (see box, right; Weathers and others, 1994; Kharaka and Wanty, 1995). As conventional natural-gas supplies in the United States are depleted, pressure has increased to exploit vast disseminated-gas deposits in the United States—so-called continuous reservoirs (Scott, 1995). These deposits contain small quantities of gas dispersed through large volumes of rock, are more costly to exploit, and will require close-spaced drilling of many hundreds of thousands of wells, with a high potential for production of huge quantities of brines for which satisfactory disposal procedures must be found.

Contamination of soil and water from nuclear sites is of particular public concern. Research on nuclear weapons at the Oak Ridge National Laboratory, Tennessee, resulted in massive chemical contamination of bottom sediments in a reservoir downstream. The problem was first identified by Oak Ridge National Laboratory and U.S. Geological Survey scientists who discovered very high levels of mercury and arsenic in samples of vegetation collected along streams downslope from the laboratory (Marshall, 1983). Subsequently, stream fish were discovered to have taken up the contaminants. Bottom sediments of the reservoir were found to have high concentrations of such elements and compounds as mercury, arsenic, antimony, cesium, uranium, PCB 1254 and 1260, chlorodane, cobalt, and paladium (Hoffman and others, 1990).

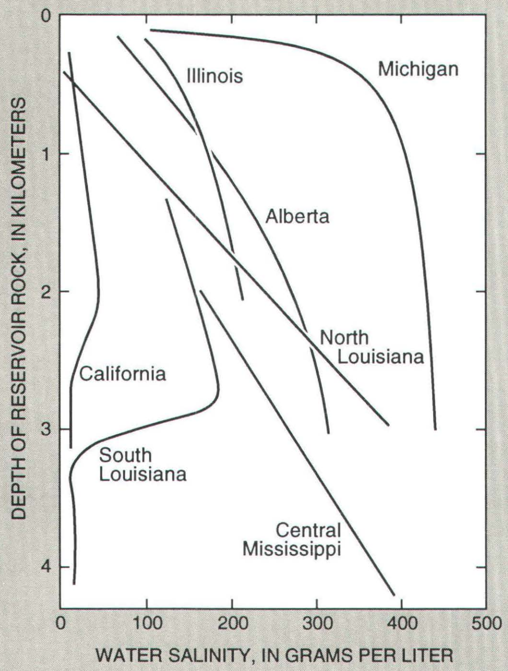
The 1986 nuclear powerplant accident in Chernobyl, Ukraine, contaminated air, water, and soil, and subsequently plants and animals, over a huge area of central and northern Europe (Bowen, 1988). Enormous clouds of radioactive smoke drifted as far as the United Kingdom and Switzerland (Bowen, 1988). Dry fallout of radionuclides contaminated about 20,000 km^2 around the site (Levi, 1991). About 135,000 people were evacuated from downwind localities in Ukraine, Belorus, and Russia. Compliance with western standards adopted for radiation exposure would not only prevent repopulation of the 30-km zone around the Chernobyl plant in the foreseeable future but would also require evacuation of another 20,000 to 30,000 people from a larger surrounding area of 10,000 km^2 that remains hazardous (Levi, 1991). In western Europe rain washed the radionuclides out of the air, producing surface gamma-radiation levels as much as three times normal; the highest levels reported for rain-washout contamination were in Scotland (Bowen, 1988). Rain-contaminated soil was then eroded and further redistributed by river transport. Concentrations of cesium-137 in the Severn River in England remained nearly an order of magnitude above background 2 years after the accident (Walling and others, 1992).

The paths toxic substances take from source to food chain commonly are detected only after much damage has been done. The path that toxic selenium in California's San Joaquin Valley follows—from sedimentary rocks to alluvial soils, then into surface water and ultimately into algae, fish, waterfowl, and other parts of the food chain at the Kesterson Wildlife Refuge and other locations—has only recently been explored in detail (see box, page 8) (Presser and Ohlendorf, 1987; Severson and others, 1991; Presser, 1994). The selenium problem exemplifies how natural geologic processes and human actions combine to create hazards. The element selenium occurs naturally in marine sedimentary rocks in the California Coast Ranges and is naturally dissolved from these rocks and redeposited where water evaporates from the valley floor. Irrigation and flushing of salts from irrigated land dis-

OIL FIELD BRINES



(Top). Map of Big Lake oil field, prepared by Michael L. Weathers.

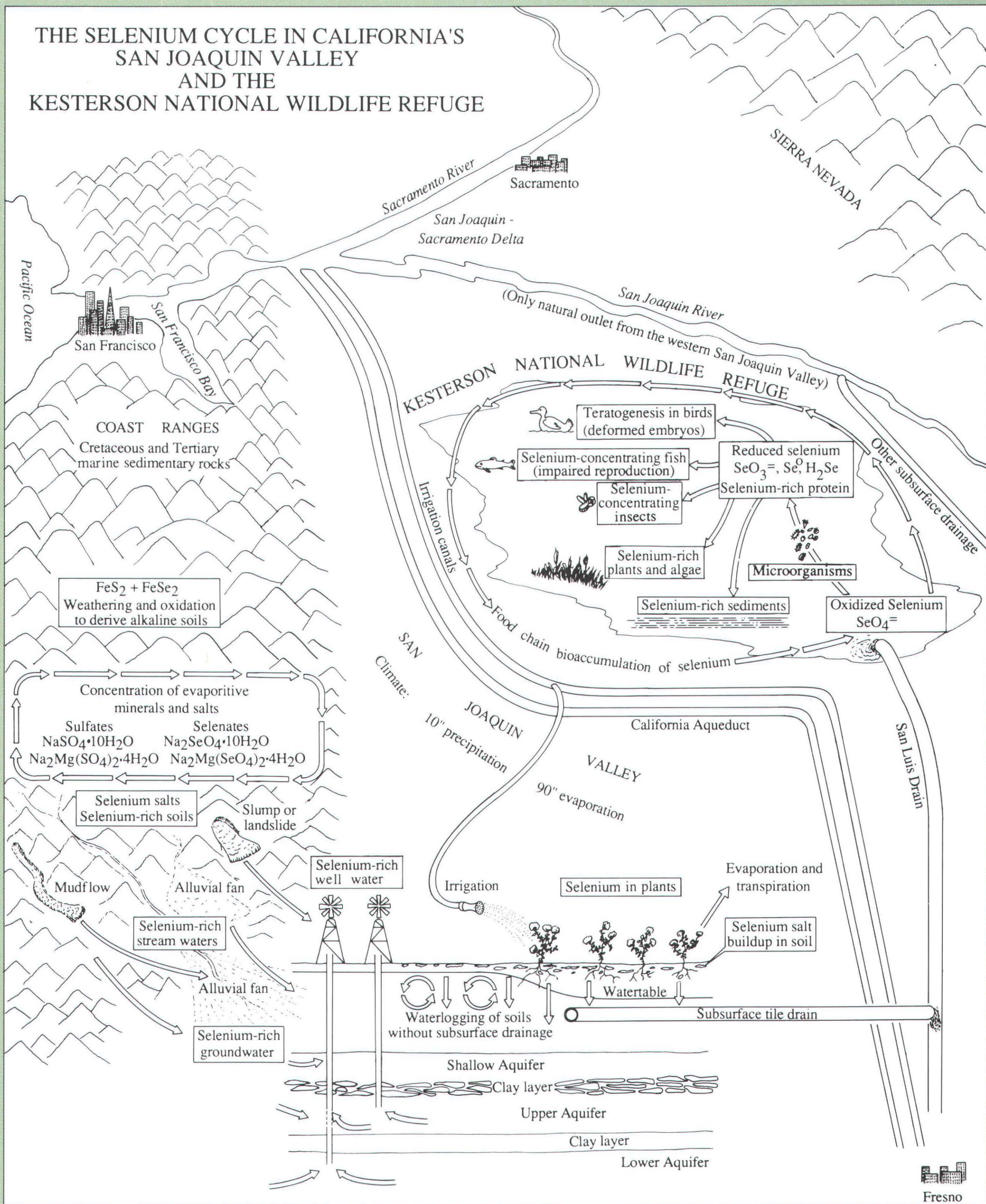


(Bottom). Salinity distribution of formation water with depth of reservoir rocks from several petroliferous basins in North America (from Kharaka and Wanty, 1995).

The discovery of the Big Lake oil field in west Texas in 1923 heralded the opening of the highly productive Permian Basin (Fritz, 1994; Weathers and others, 1994). In the following decades, brines produced along with oil in the Big Lake field were released on the surface, a practice common until the early 1960's; the brines ultimately covered an area of about 28 km^2 (see map). In all, about 200 million barrels of brine were discharged. Salts were concentrated by a shallow water table perched above a relatively impermeable carbonate-cemented layer (caliche) at a depth of about 2 1/2 meters. In the dry climate of west Texas, capillary movement of water upward from the shallow water table deposited salts in the near-surface sediments, creating conditions in which no plant life could exist. As the vegetation died and the soil was exposed, wind and water erosion removed all topsoil and subsoil sediment to depths as great as 1.2 m as shown by exposed mesquite stubs. Blinding dust storms from the barren surface created traffic hazards on U.S. Highway 67, which crosses the denuded area (see map). Earlier efforts to reclaim the area by application of fresh water and reconditioning and mulching the soils failed. In 1989, the University of Texas System, U.S. Soil Conservation Service, and Marathon Oil Co. began remediation efforts in a 1.3-km^2 area along Highway 67 with a goal of restoring the land to rangeland productivity. Through 1993, these efforts involved draining of more than 13 million barrels of saltwater; installation of an underground drainage system consisting of 38,000 m of conduit, sumps, and sump pumps; building of terraces; ripping of the land between terraces; and aerial seeding with barley. The seeding in 1991 was followed by above-average rainfall, yielding "...a fairly good density of barley over about three-quarters of the site" (Fritz, 1994). By 1992, the native plant kochia had reestablished itself over 90 percent of the site.

Although the salinity of water associated with oil and gas fields is quite variable from basin to basin (see diagram), in most cases the water is too saline to release on the surface. The safe disposal of brines produced from oil and gas fields thus raises important environmental and economic questions. As we look to the future when many more wells will be required to produce disseminated natural gas than are required to produce the same amount of gas from today's conventional fields, the problem of brine disposal will increase in importance (Rice and others, 1995; Kharaka and Wanty, 1995).

SELENIUM POLLUTION IN THE SAN JOAQUIN VALLEY, CALIFORNIA



The conditions favoring movement of the potentially toxic element selenium (Se) in the environment are especially well developed in California's San Joaquin Valley. Paths taken by Se are shown in the diagram at left (not to scale). An abundant supply of Se occurs naturally in marine sedimentary rocks of Cretaceous and Tertiary age exposed in the mountains bordering the valley on the west. Selenium is transported to the valley floor as dissolved selenate in saline streams and in particulate form by streams, landslides, and mud flows. Under natural conditions, the Se was evaporatively concentrated in saline zones in the valley where it remained because of poor drainage conditions. Subsequently the Se has been redissolved by irrigation water and flushed into artificial subsurface drainage systems. Until 1986, the San Luis Drain collected subsurface drainage and transported it to the Kesterson National Wildlife Refuge, where Se in the drainage water was taken up by organisms in the food chain.

Mechanisms by which Se accumulates in plants and animals in the Kesterson refuge include chemical reduction and methylation reactions. Concentration of Se in organs of plants and animals higher in the food chain (biomagnification) leads to impaired reproduction, inhibition of growth, mutation, and suppression of the immune system (Presser and others, 1994; Presser, 1994).

In the 10 years following discovery of the Kesterson problem, waterfowl deformities have been documented in Tulare Lake bed, California; Middle Green River Basin, Utah; Kendrick Reclamation Project Area, Wyoming; Sun River Basin, Montana; and Stillwater Wildlife Management Area, Nevada; and high selenium levels have been found in waterfowl in Malheur National Wildlife Refuge, Oregon; Salton Sea area, California; Riverton Reclamation Project area, Wyoming; Gunnison River Basin/Grand Valley Project, Colorado; Middle Arkansas River Basin, Colorado/Kansas; and Belle Fourche Reclamation Project area, South Dakota (Presser and others, 1994).

Prepared by Theresa Presser, drawn by Bruce Rogers

solves this selenium into groundwater, eventually leading to its concentrated introduction into the food chain—selenium is taken up from the water in algae and causes gross deformities in the offspring of birds that feed on the algae. Were it not for agricultural irrigation, most of the selenium would remain in the saline zones where it is relatively harmless. Were it not for the selenium, irrigation would not have such a negative effect on the food chain. Despite our improved understanding of the interconnected processes, the increasing selenium contamination of the Kesterson Wildlife Refuge has remained a problem since it was discovered more than 10 years ago. In fact, a recent Federal court decision (U.S. District Court, 1994) ruled that the U.S. Bureau of Reclamation must complete the San Luis Drain, which would carry the contaminated agricultural waters to the San Francisco Bay, or provide some other out-of-San Joaquin Valley solution. Disposal in the San Francisco Bay would add to existing problems of local industrial selenium contamination (Brown and Luoma, 1995). Selenium resulting from disposal of agricultural wastewater has been identified at levels known to cause deformities in waterfowl at five additional areas in the Western United States, and at levels near or exceeding thresholds for adverse reproductive effects at six more sites (Presser and others, 1994); none of these are yet being corrected.

Diversion of water from one region to another provides further examples of land use with potentially adverse long-term consequences to public health and land resources. Since 1913 the Owens River in California has been diverted to supply water to the San Fernando Valley and Los Angeles far to the south. The diversion dried up Owens Lake, whose dry bed now yields as many as ten major dust storms per year (Saint-Amand and others, 1986) and is the largest single source of dust in North America (Gill and Cahill, 1992a). The dust storms (fig. 2) can impact the health of about 50,000 people who live downwind in the frequently impacted areas (Gill and Cahill, 1992b). Water diversion throughout five continents has had similar effects (Gill, 1994). The Aral Sea of central Asia has shrunk by more than 40 percent since 1960 as a consequence of upstream water diversion. About 40 million tons of alkaline dust is blown annually from the dry bed and deposited in the region from the Black Sea to the Arctic Ocean (Gill and Cahill, 1992b; Micklin, 1988; Ellis, 1990).

Long-term changes in vegetation in arid and semiarid regions have been caused by agriculture, domestic-animal grazing, road-building, wood-gathering, and military and recreational activities in arid lands. These changes produce national and global desertification (fig. 3) when productivity of arid land declines or arid ecosystems show a long-term change such as the invasion of preexisting grasslands by shrubs (Schlesinger and others, 1990). Sixty percent of Australia's arid lands are in need of remedial actions to avoid or minimize irreversible damage from various human activities (Roberts, 1987). In North America, 28 percent of the arid land, nearly half of it in the United States, is severely degraded, and nearly 20 percent of the earth's arid lands are similarly afflicted (Sheridan, 1981; Sabadell and others, 1982; Dregne, 1984; Mabbutt, 1984).

One indicator of desertification is salinization, the buildup of salts in the soil caused by evaporation of irrigation water from poorly drained land. As the water evaporates, it leaves progressively more salts, derived both from the water and from fertilizers, at the surface. As salts accumulate in the soil, crops fail to grow, and the lands, already cleared of their natural vegetation, are then abandoned to accelerated wind erosion. One solution to this problem has been over-irrigation to flush the salts off the land down drainage ditches; however, the drainage water is much saltier than the incoming irrigation water, causing downstream problems. Reduction of water quality in the Colorado River by flushing of salts from agricultural land in Arizona has required expensive remediation to satisfy treaty obligations of the United States to Mexico (Sheridan, 1981). Salinization is an important problem in irrigated lands in the southwestern United States (fig. 4) and elsewhere in the world (Barrow, 1991).

Deterioration of forested lands is another long-term problem. Removal of timber and clearing of land for grazing and agricultural uses has long since stripped much of the world's easily accessible native forests in temperate climates. Now these enterprises have shifted to steeper terrain, which is highly sensitive to erosion, and to tropical rainforests, with negative consequences to streams and soils (fig. 5). In the 1980's, rainforests in ten undeveloped and developing nations were being stripped at an annual rate of more than 60,000 km^2, an area nearly the size of West Virginia (Ryan, 1992). Between 1978 and 1988, nearly 200,000 km^2 of rainforest were stripped in the Amazon basin, causing reduction of biological diversity in an area greater than 580,000 km^2 (Skole and Tucker, 1993). In the U.S. Pacific Northwest, clearcutting of old-

Figure 2. This sequence of photographs shows a dust storm as it developed on Owens dry lake, Calif., November 27, 1991 (Reid and others, 1994). The photos were taken looking westward from an automated station at Cerro Gordo in the Inyo Mountains at an elevation of about 1,500 m above the dry lake floor. A, *before the storm; 10:00 a.m.;* B, *11:30 a.m.;* C, *1:00 p.m.;* D, *2:00 p.m. Photographs by Jeff S. Reid, Air Quality Group, University of California, Davis.*

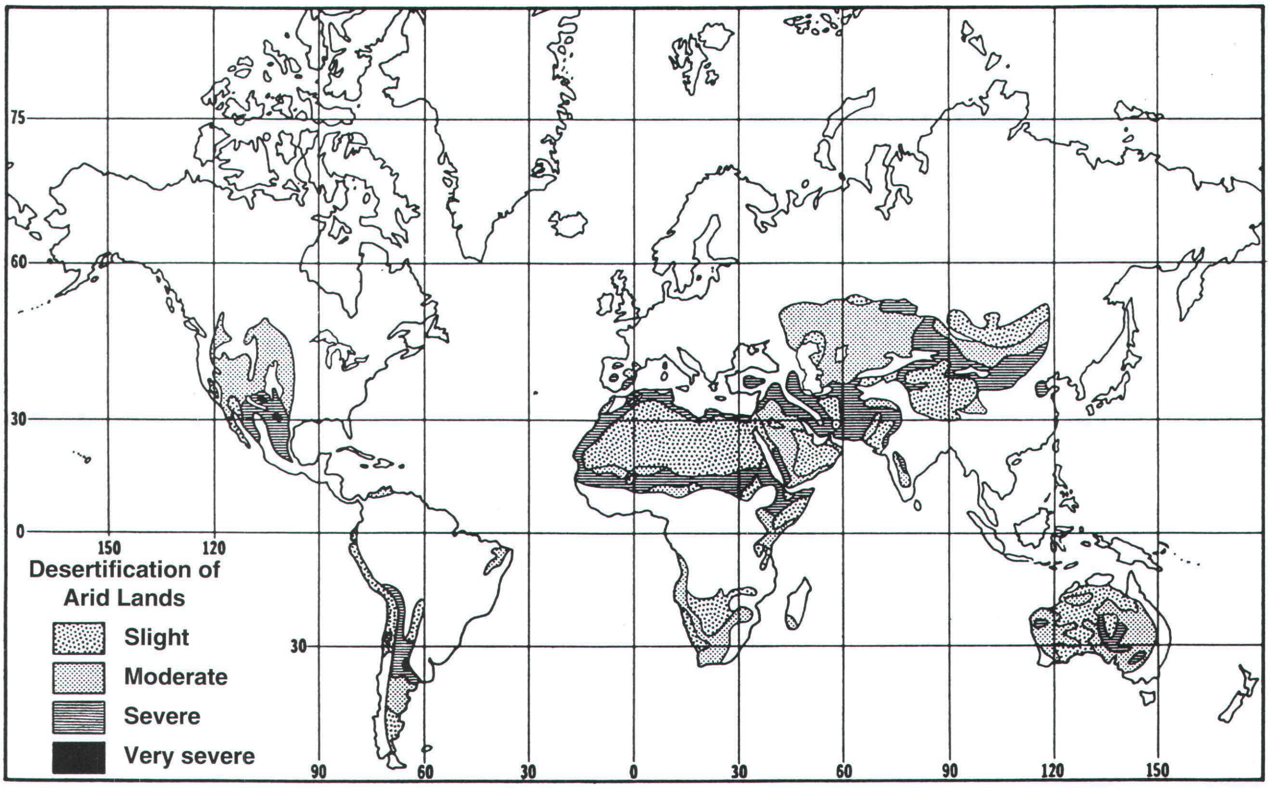


Figure 3. World map showing the degree of desertification—changes in productivity or vegetation communities due to human activities—in 1981. Note that extreme climatic deserts, such as the Sahara, are placed in category of "slight" desertification because of the sparseness of their human population and hence lightness of human impact (from Dregne, 1984).

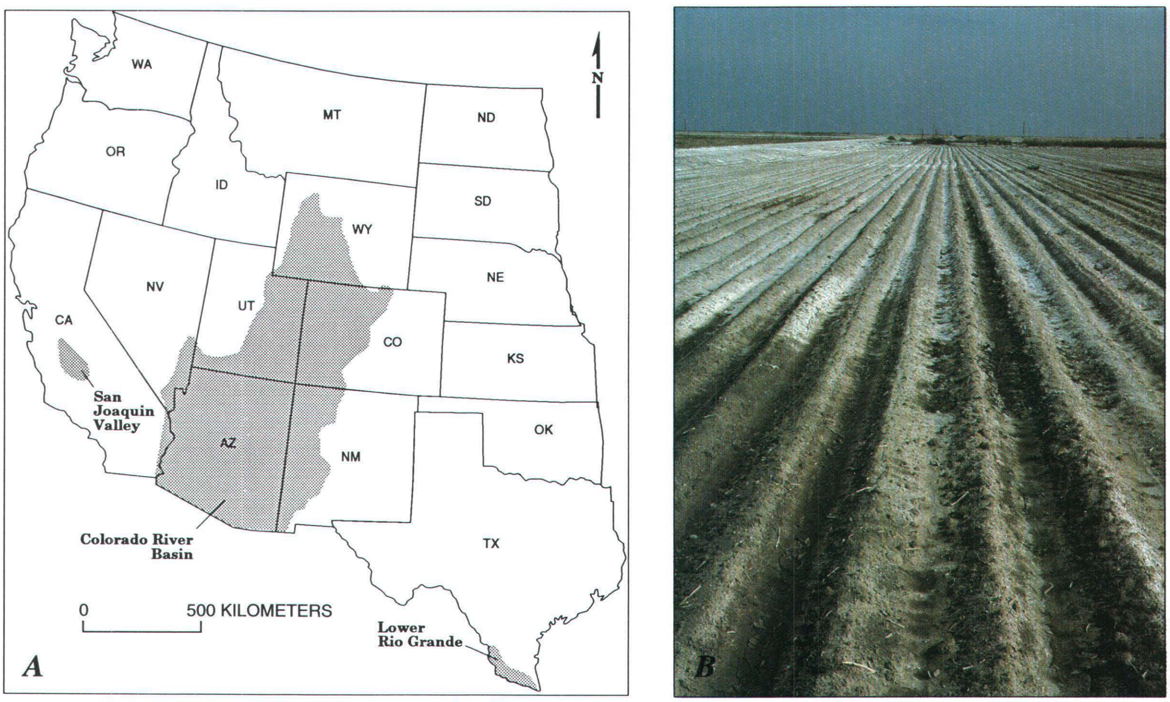


Figure 4. Salinization of irrigated farmland is one facet of the desertification problem. A, *This map shows areas with major salinity problems in the Western United States (modified from El-Ashry and others, 1985).* B, *Salt deposits form on agricultural land in the southern San Joaquin Valley, Calif., where irrigation water with dissolved salts rises by capillary action to the ground surface and evaporates. Photograph by Howard Wilshire.*

Figure 5. Problems of deforestation. A, *Deforestation and annual grass burnoffs in Madagascar's central plateau region result in massive erosion of the barren steep slopes; the scene here is north of Tananarive. The rivers are more prone to flooding because of accelerated runoff, and their heavy sediment loads cause siltation of coastal lowlands through which they pass (Jolly and others, 1984; Green and Sussman, 1990). Photograph by Frans Lanting/Minden Pictures.* B, *Pinyon-juniper forest destroyed by chaining for conversion to rangeland in Utah. In chaining, the tree cover is removed by stretching chain with hardened cutting edges between two bulldozers which traverse the forest. In steep terrain like this (east of Zion Canyon National Park, Utah), soil loss can be severe before grasses are established. Photograph by Howard Wilshire.* C, *Slash-and-burn deforestation in the upper Amazon basin in Ecuador. Stripping of vegetation for farming results in high erosion rates and rapid deterioration of the soil. Photograph by Howard Wilshire.*

growth forest in steep terrain results not only in rapid erosion but also in degradation of an additional land area, comparable to or larger than the clearcut area itself, from exposure of forest edges to wind, water pollution, downstream erosion and sedimentation, and microclimate changes (Janda, 1978; Council on Environmental Quality, 1981; Brown and others, 1991). New Zealand's lowland rainforests have been largely removed in the past 100 years (Salmon, 1980), and the once prolific and varied forests have been replaced by rangeland and by monoculture farms of single imported tree species (fig. 6). Similar problems exist in the U.S. rainforests of Puerto Rico and Alaska, and in Canada, Australia, and other nations.

Desertification, deforestation, and many agricultural practices contribute to serious national and global soil degradation. Nations have thrived or failed historically according to the ability of their land to sustain agricultural productivity (Carter and Dale, 1974; McCracken, 1987). Moderate to extreme soil degradation globally affects nearly 3 billion acres, an area larger than China and India combined (fig. 7), and the global rate of topsoil loss is 7 percent per decade (Brown and Wolf, 1984). About 30 million acres of arable land are destroyed and abandoned annually worldwide (Pimentel and others, 1995). Soil degradation and topsoil loss, in turn, exacerbate the global problem of food scarcity in the face of a growing population (Brown, 1981; Fyfe, 1989; Pimentel and others, 1995). In addition to loss of productivity, soil erosion also causes air and water pollution, with attendant health effects (Huszar and Piper, 1985). Pimentel and others (1995) estimated the annual direct and indirect costs of soil erosion in the United States to be $44 billion, and the annual cost worldwide to be nearly $400 billion.

Processes of land degradation are mostly cumulative. Because the rates of soil regeneration and natural cleansing of contaminated soil are slow, a comprehension of how to balance the rates of degradation with the rates of regeneration is crucial to human survival. We already have

Figure 6. Clearcutting of lowland rainforest on North Island, New Zealand. A, *Steep slopes and high rainfall have led to major problems of landsliding and soil erosion.* B, *Monoculture forest of imported pines replaces lowland rainforest. Trees are planted like row crops up-and-down the slopes. This configuration, combined with periodic harvesting, leads to heavy soil loss (average annual rainfall is about 250 cm). Photographs by Howard Wilshire.*

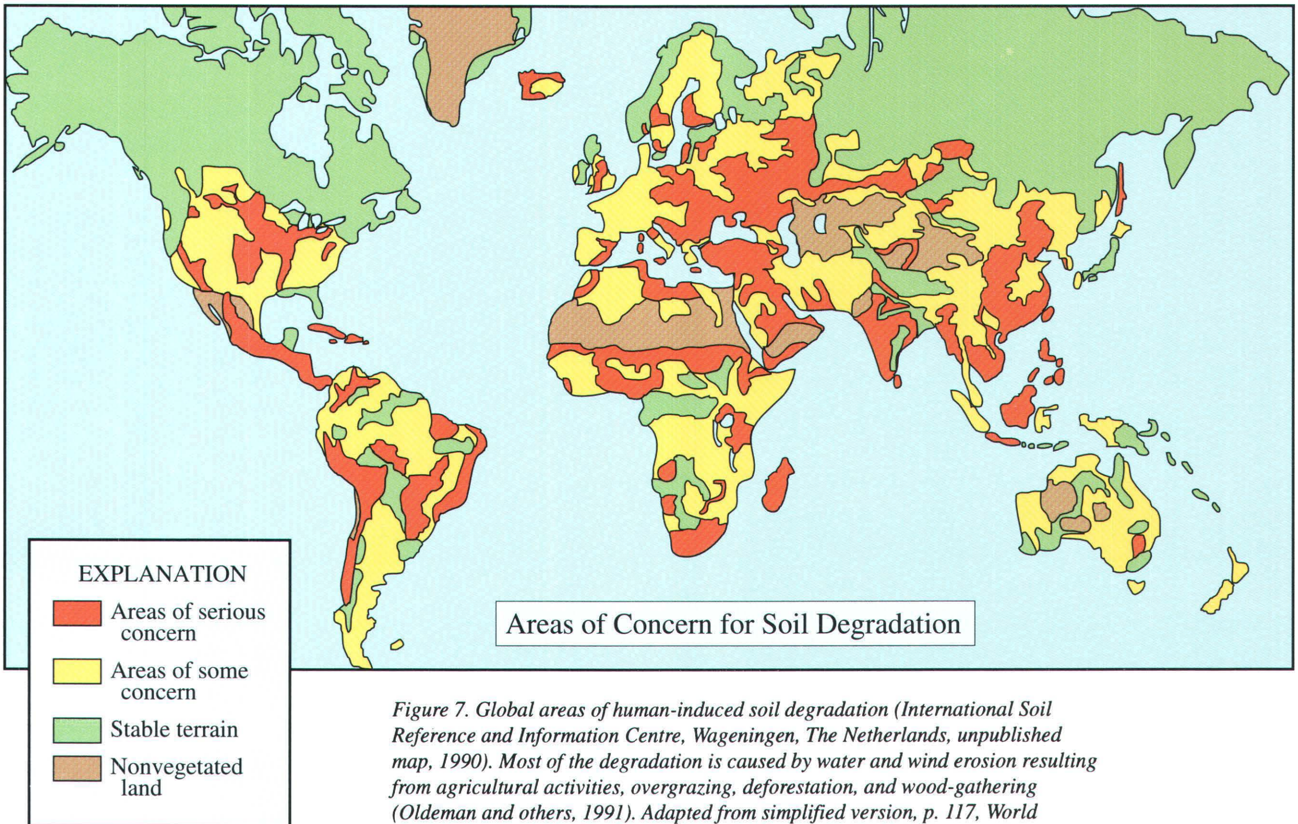


Figure 7. Global areas of human-induced soil degradation (International Soil Reference and Information Centre, Wageningen, The Netherlands, unpublished map, 1990). Most of the degradation is caused by water and wind erosion resulting from agricultural activities, overgrazing, deforestation, and wood-gathering (Oldeman and others, 1991). Adapted from simplified version, p. 117, World Resources Institute (1992).

extensive pollution of public lands in the United States from mine wastes, oil and gas production, landfills, and other sources (National Academy of Sciences, 1992). Even where problems of contaminated soil and water can be corrected, the cleanup costs are measured in billions of dollars (U.S. Congress, 1993; World Resources Institute, 1987; California Commission for Economic Development, 1985), and some lands and bodies of water have been so badly contaminated as to be unusable by humans for the foreseeable future, or to present overwhelming cleanup problems (U.S. Congress, 1991a,b). Indeed, in the case of long-lived contaminants and irreplaceable soils (ones formed under climatic conditions that no longer exist), we may necessarily come to an appreciation that avoidance of degradation is the only viable alternative.

RESEARCH CAN HELP

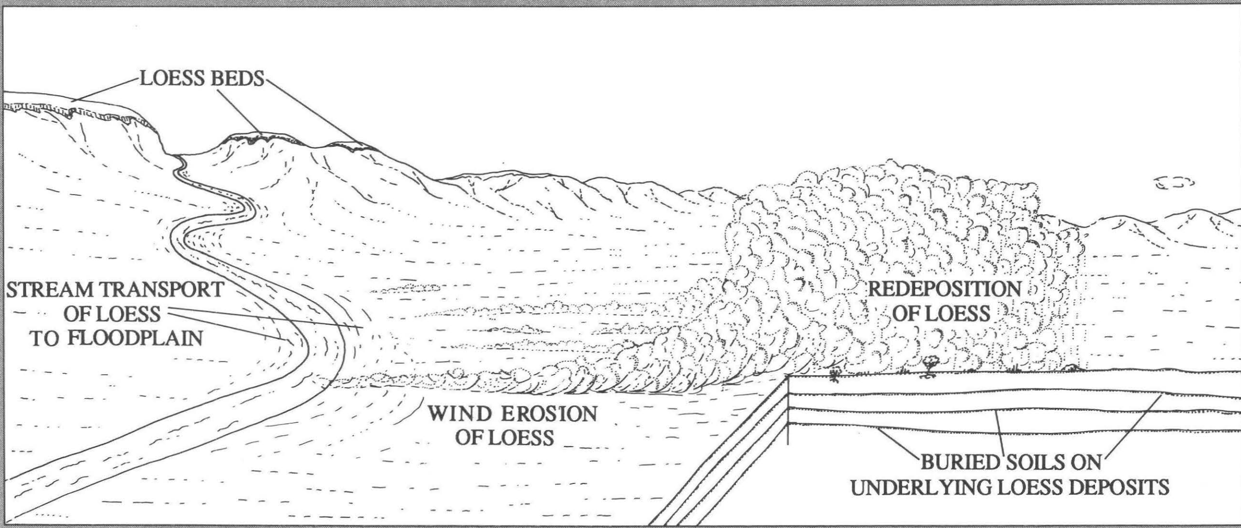
For a growing populace to live safely on the land and to protect land resources requires improved knowledge of how the earth's surface works. We need to understand the nature and rates of the surface geologic processes themselves and the magnitudes, frequencies, and causes of the geologic events they govern. So armed, we can evaluate and to some extent forecast the likely geologic effects and interactions of natural and human-caused changes to the land surface. Appropriate actions to moderate negative effects can then be taken.

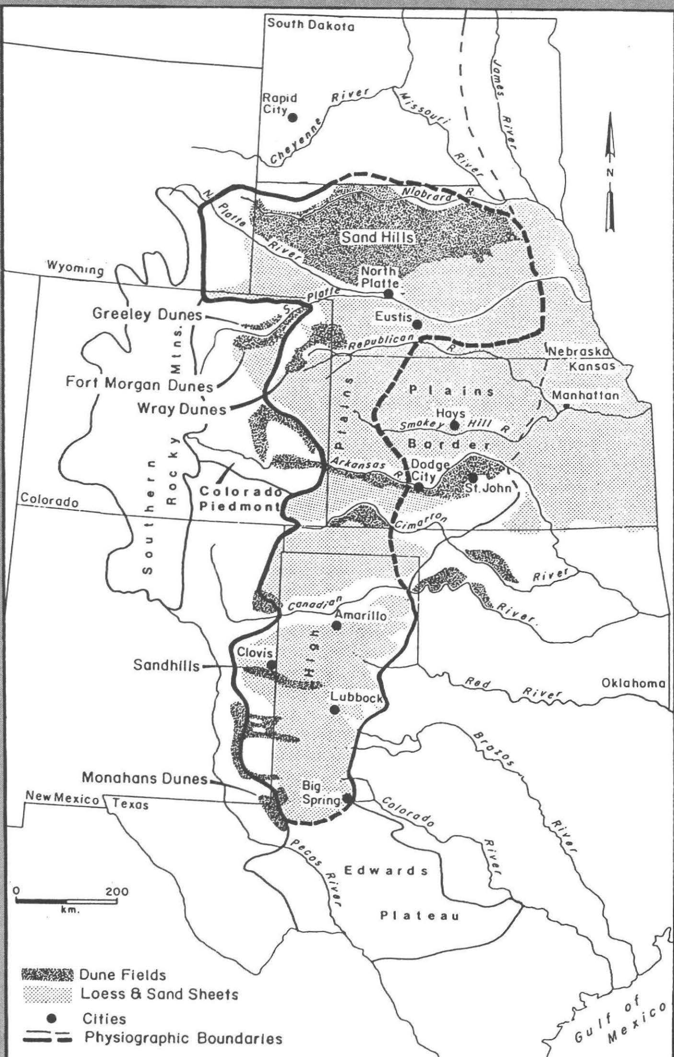
To achieve a higher level of knowledge requires research into some basic questions. How do rates of soil regeneration compare with rates of erosion or with rates of chemical degradation caused by fertilizers and pesticides used in various farming and forestry practices? Given time, soil eroded away or chemically degraded by pesticides will restore itself, but an important question is whether the amount of time needed is really available in terms of human life expectancy. Moreover, a restored soil may not function in the same way or as well as the soil that was lost. For example, extensive areas of the Midwestern United States have a natural mulch formed by windblown dust (loess) derived from wind erosion of outwash plains of continental glaciers that no longer exist (see box). Loess soils are more productive than those derived from underlying rock materials. Once lost, they are gone forever . Such irreversible loss has already occurred in areas of thin loess cover. A blanket of loess, rarely more than half a meter thick, contributed substantially to the prosperity of early farming in New England but has largely been lost through erosion of the agricultural lands, exposing less fertile underlying gravels and sands (Kaye, 1976).

Other questions that arise include: How are the natural functions of watersheds impaired by erosion, sedimentation, and chemical contamination of surface materials? What are the repeat intervals and durations of high water levels in inland lakes, and peak runoffs in major river systems, information that is essential for minimization of flood damage? What factors affect the long-term integrity of landfill and toxic-waste sites, and how and where should such sites be located?

As answers come to these and other questions, we can gain a firmer and more comprehensive appreciation of surface processes, their rates, and their effects. Ultimately, the goal is the ability to model processes and make forecasts that help us manage our land and water resources prudently. It is well to bear in mind, however, that theoretical models of the complex processes operating at and near the earth's surface are based on idealized assumptions that must be continually reexamined. A modern trend toward mathematical formulation of surface processes, in the form of supposedly predictive models, has come increasingly into question, especially with regard to hydrologic processes (Oreskes and others, 1994; Konikow and Bredehoeft, 1992). The lesson is that idealized models can complement but not substitute for thorough evaluation of the geologic record (Baker, 1994).

LOESS—A Disappearing Resource





Soils that have loess as an important component are widespread in the central United States. The location of some loess deposits (and sand dune fields) in the High Plains and other parts of the Great Plains are shown on the map (from Holliday, 1987). Loess is fine-grained material—predominantly silt and clay—that is buff-colored and commonly contains shells and other fossils. Loess is generally believed to have been derived in the Pleistocene Epoch as dust that was blown off the outwash of melting glaciers and deposited as a thick blanket over hills and valleys downwind. Subsequently, during periodic droughts when hillside vegetation deteriorated, water erosion redeposited the silt in broad valley bottoms, from where it was again eroded and redeposited by wind (see diagram; Jorstad and others, 1986; Holliday, 1987). Agricultural practices are causing progressive loss of the loess component of soil by erosion into major river systems. The loess is a natural mulch and an important element of soil fertility; its loss is of particular concern because it cannot be replaced.

Prepared by Howard Wilshire, drawn by Bruce Rogers

PROCESSES: PRINCIPLES, RATES, AND SENSITIVITY TO CHANGE

To improve our knowledge of surface processes, basic research is needed on a spectrum of topics. Information is needed on the mechanics and rates of the geologic processes of erosion, transport, and temporary storage of eroded materials on hillslopes and in stream courses, and of sedimentation in the long-term resting places of eroded materials, such as standing bodies of water and desert playas. Variations in these and other processes, particularly during the geologically recent Holocene Epoch (from 10,000 years ago to the present) and late Pleistocene Epoch (from 1.7 million to 10,000 years ago) (fig. 8), need investigation. Strata formed during these times provide detailed records of an environment that was sometimes much like the one in which we now live and sometimes very different, showing major variations on a thousand-year scale. These records provide an opportunity to learn more about frequencies and magnitudes of environmental change and thresholds of change than can be gleaned from historical records alone (Koltermann and Gorelick, 1992). Improved knowledge is needed of the mechanisms and rates of chemical and physical weathering and soil formation; of the processes of infiltration, runoff, evaporation, and evapotranspiration of water at the land surface; of the movement of shallow groundwater and its

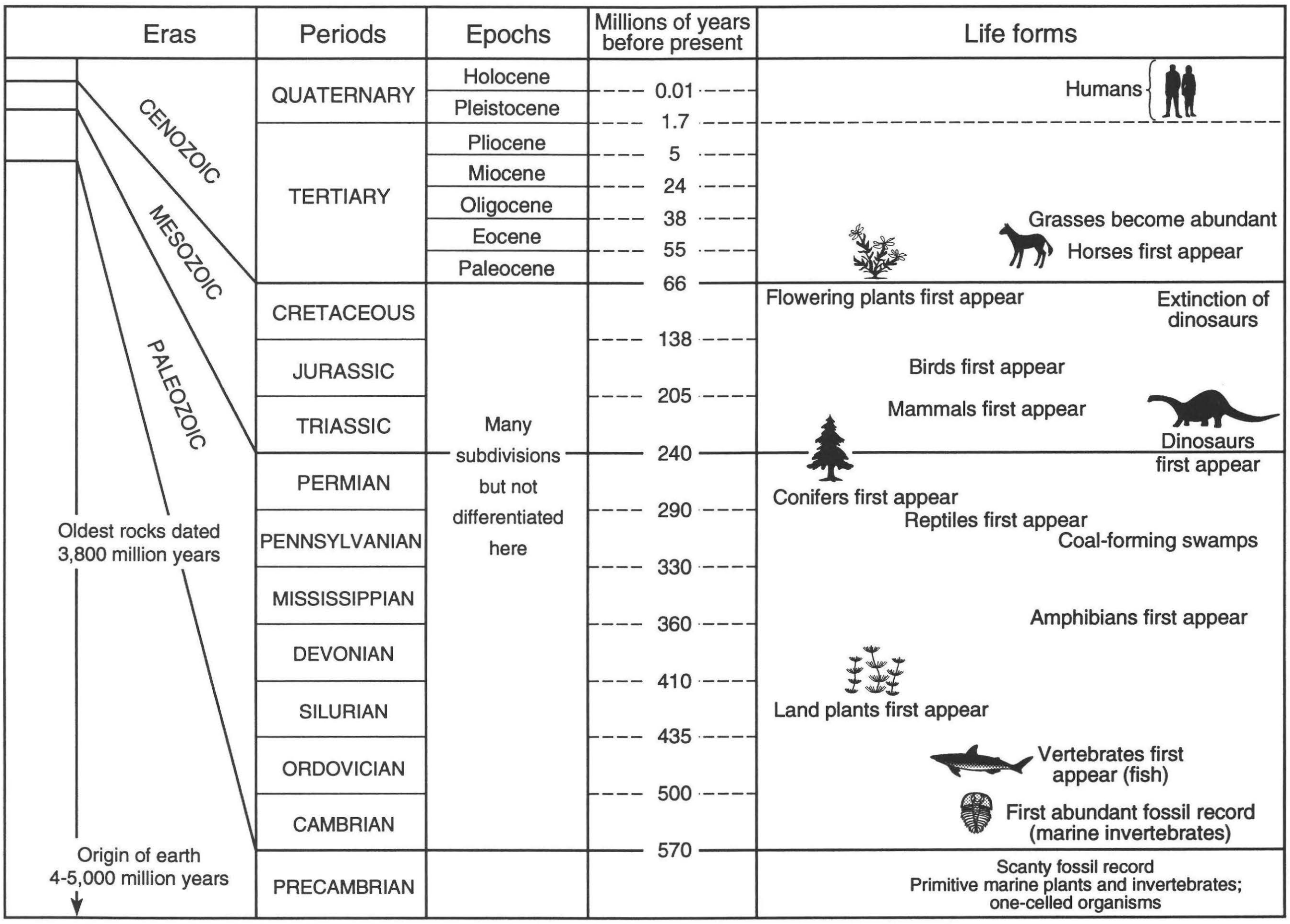


Figure 8. Geologic time scale. The earth is about 4.5 billion years old. The rock layers containing most of the evidence for development of life date from about 570 million years ago to the present, as illustrated in this diagram. These rock layers—like pages in a long and complicated history book—record events that have shaped the planet on which we live. The geologic record representing the late Tertiary and Quaternary Periods, in particular the Pleistocene Epoch (about 1.7 million to 10,000 years ago) and the Holocene Epoch (10,000 years ago to the present) are both the most complete and the most relevant records on which to base predictions about our future. Modified from Molenaar (1987).

interaction with soil particles; and of the role of plants and animals, including people, in all of these processes.

The nature and rates of surface processes vary with the materials on which they act. Wind and water erosion in the arid Western United States etch every variation in rock strength onto cliff faces—soft layers are cut back and hard ones stand out boldly. Acid rain acting on old graveyards in the Eastern United States leaves granite tombstones relatively well preserved whereas many limestone tombstones are so deteriorated as to be illegible.

External factors such as tectonic deformation and climate also control the nature and rates of surface processes. Deformation of the earth's surface by fault movement or by uplift of mountain ranges accelerates water erosion and landsliding by increasing the slope of the surface. Recent studies have shown that important climate changes at scales of decades, centuries, and millenia have punctuated Holocene time (Dickinson, 1995), despite the broadly held view that the Holocene is a period of drying after a relatively cooler and wetter Pleistocene. We do not as yet understand the reasons for these fluctuations. Regional analysis of ancient flood frequency and size also indicate markedly changing patterns of local precipitation through time (Webb and Betancourt, 1992; Ely and others, 1993), which are little understood yet may have drastic effects on human projects.

By integrating an improved understanding of the processes in action today with the recent geologic record, the frequency and magnitude of geologic events such as floods, windstorms, and land deformation that may drastically alter our living environment can be better assessed. The predictive capability that this allows will help us plan for inevitable natural events.

Knowledge Gaps

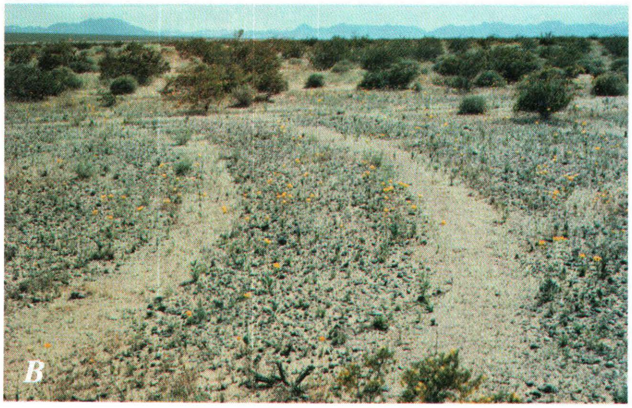
In the past decade, much progress has been made in characterizing sequences of soils that formed from similar parent materials under similar climatic conditions. In these cases, the degree and nature of soil development depends primarily on time. Further study of soil sequences in different climatic zones and on different parent materials allows us to begin to assess average rates of soil-forming processes and to determine the climatic conditions of their formation (Bockheim, 1980; Harden, 1988). The geochemistry and timing of weathering processes, however, are still poorly known. It is likely, for example, that soil formation takes place in a series of discontinuous steps rather than as a smoothly continuous process, but we cannot now describe these steps with any precision. Such knowledge is essential to understanding the consequences of soil degradation and the processes of soil formation and regeneration.

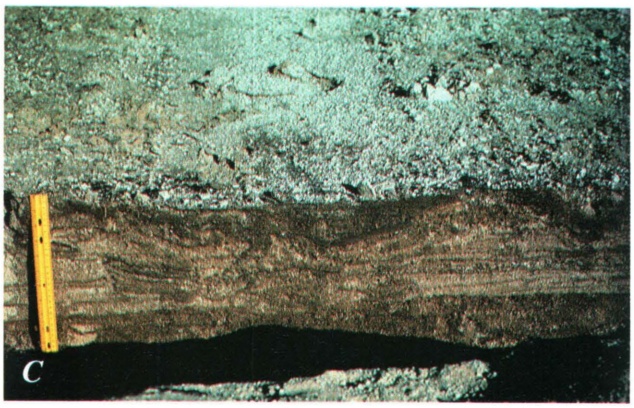
A great deal is now known about stream hydraulics and the nature and amount of sediment transported by the Nation's rivers, but we still know little about how a unit of sediment is transported from the top of a hill to the base of the slope and into a river system. We cannot predict whether that unit will remain intact or where any of it will be at any time, how it has been chemically or physically transformed, where it may temporarily come to rest, and what characteristics it will have in the next increment of time.

Much remains to be learned about the chemistry and physics of microscopic mineral-water interfaces, which govern such things as weathering rates and the formation of calcrete and silcrete (hard, relatively impervious layers composed of chemically precipitated calcium carbonate and silica at the base of certain soil horizons). Processes of adsorption of water on soil particles, chemical interchanges between pore water and solid components of the soil, and distribution of heat in soils are all vital parameters in development and productivity of soils. The processes are highly vulnerable to change from human activities. A single passage of an army tank on maneuvers over desert soil can dramatically alter water infiltration, soil moisture, and heat distribution, and consequently biological productivity, for more than 50 years (fig. 9).

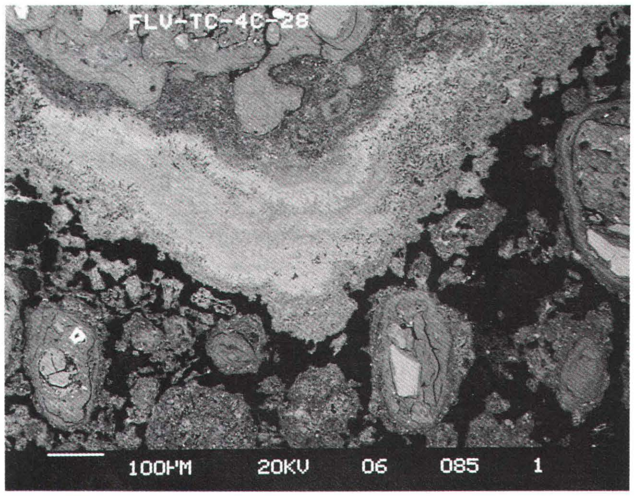
The physical and chemical processes that control transmission and adsorption of water also control the distribution of toxic substances in soils because most toxic substances can either be dissolved or carried as particles by groundwater. To understand how to stop or slow the movement of toxic chemicals in groundwater, we must appreciate how varying adsorption characteristics control the rate of movement, some toxic elements and compounds being readily adsorbed onto soil and rock surfaces and others not (Devinny and others, 1990). Research into such processes has wide application to agricultural and rangeland management and also to toxic- and radioactive-waste disposal. Other applications include predicting movement of fluids in petroleum and natural-gas reservoirs and predicting chemical reactions between ore-bearing fluids and their host rocks to produce mineral deposits.

These important processes have received little attention because their study requires teams representing widely varying scientific disciplines, and such teams are difficult to assemble and maintain as funding for scientific research shrinks. Moreover, we have only recently developed some of the necessary tools, such as high-resolution electron microscopes with analytical capability and ion microprobes, which can amass detailed information on the chemical interchanges among mineral, water, and





⇐Figure 9. Impacts of military maneuvers in the Mojave Desert of California. A, *Lichen crust (dark growth on ground between shrubs) on sandy soil destroyed in tracks left by light tank traffic in World War II-vintage (1942–43) maneuvers has not recovered in 50 years. These intershrub organic crusts are important in stabilizing the soil, fixing nutrients, and holding moisture. Photographed in 1986 by Doug Prose.* B, *Annual plants and surface texture have not recovered in tracks left by the single pass of a tank in the maneuvers of 1942–43. Photograph by Howard Wilshire, 1987.* C, *Face of a trench dug across a single 1942–43 tank track, showing persisting compaction of the soil. Soil compaction inhibits infiltration of water and plant growth. Photograph by Doug Prose, 1984.*



⇑Figure 10. This highly magnified back-scattered electron image of a thin slice of soil shows mineral and rock fragments with concentric coatings of alternating calcite and opal laminae. The scanning electron microscope has allowed new approaches to the study of interfaces between fluid and solid particles in soils, which control availability of nutrients and water for plant growth. The bar scale is 10 µm long.

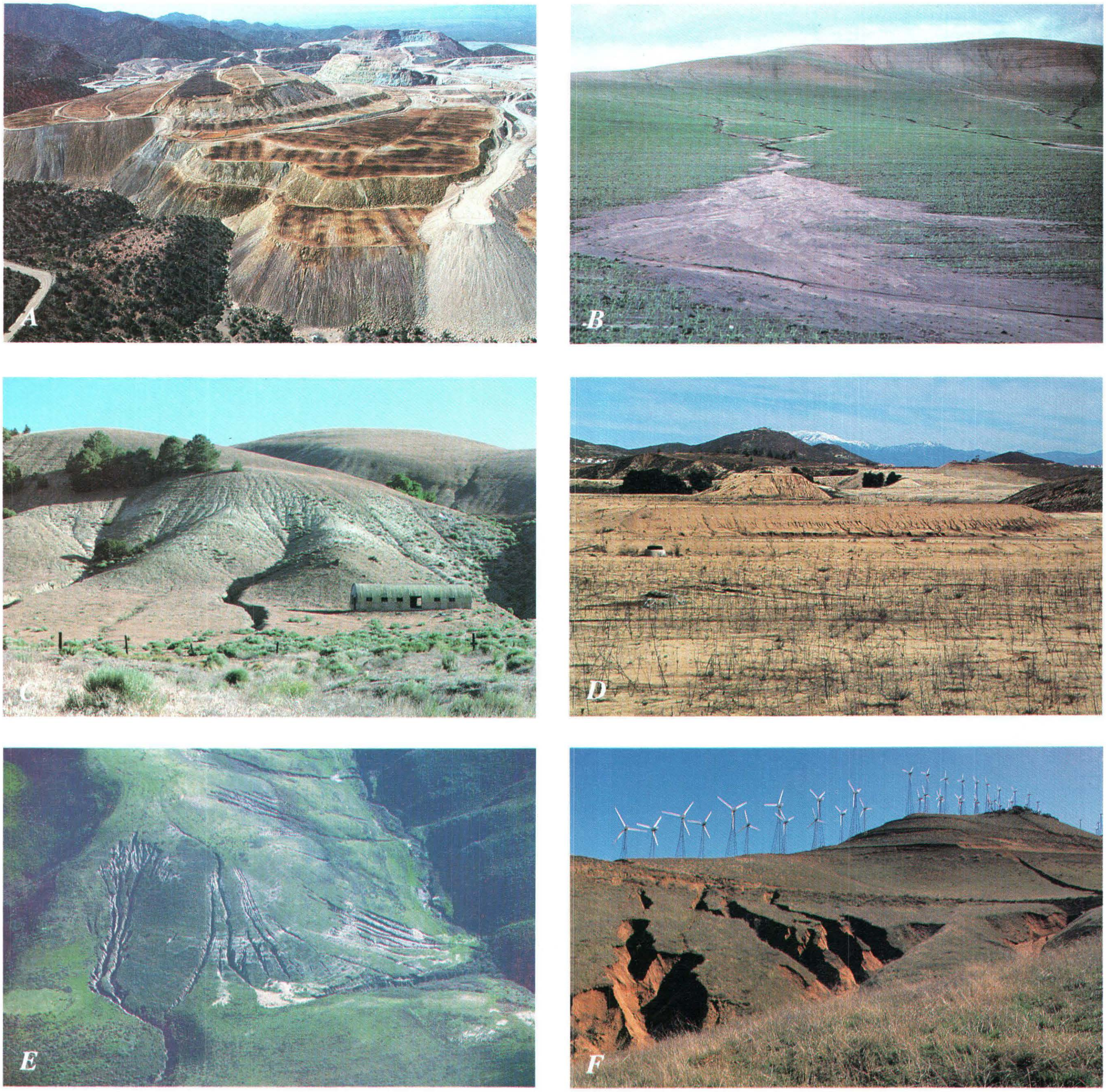
organic components of the soil, and which can directly image minute features of mineral-fluid interfaces (fig. 10).

Empirical observations have been used over the years to develop methods for predicting rates of soil erosion, leading to the Universal Soil Loss Equation, which is stated as

$$A = RKSLCP$$

where A = soil loss per unit area, R = rainfall factor, K = soil-erodibility factor, S = slope-gradient factor, L = slope-length factor, C = cropping-management factor, and P = erosion-control-practice factor (Wischmeier, 1976; Wischmeier and Smith, 1978). This equation attempts to predict the loss of soil from an area in terms of factors that assess rainfall, erodibility, slope and uninterrupted length of slope, vegetative cover, and erosion-control planning. There is a parallel equation for wind erosion. Since the 1970's, erosion prediction has been the single most widely used tool for soil-conservation planning in the United States, and the predictions based on the Universal Soil Loss Equation have been applied to agricultural and grazing lands, construction sites, road cuts, mine dumps, and other disturbed sites (fig. 11).

Tests reveal, however, that these predictions are not uniformly successful. Predictions of erosion of mine spoils prove reasonably accurate, whereas wide discrepancies emerge between predicted and measured erosion of graz-



ing lands (Trieste and Gifford, 1980). The equation incorrectly assumes steady runoff flow (uniform sheet flow across a hillslope as opposed to flow concentrated in small channels) and does not deal adequately with interactions that control detachment of soil particles from the surface and their transportation and deposition (Lane and others, 1988). The equation cannot become universally applicable until it accurately incorporates processes of sediment detachment and the mechanics of sporadic or concentrated flow. For more accurate prediction of erosion, we need to know how the shape of the land surface affects overland flow of water and how the intrinsic sensitivity of different terrains governs their susceptibility to erosion.

Figure 11. Erosional problems caused by human activities. A, *Mineral Park copper mine, Mohave County, Ariz.; erosion of mine spoils pollutes surface and groundwater.* B, *Gullies and depositional fans, dryland farm area, State Highway 46, San Louis Obispo County, southern California; episodic soil loss has diminished the productivity of these farmlands.* C, *Overgrazing by sheep, Tehachapi Mountains, Calif., has caused severe soil loss.* D, *Erosion of land cleared for housing development, Interstate Highway 15, north of San Diego.* E, *Gullies were initiated when coastal chaparral was stripped for flax crops, near Santa Cruz, Calif.* F, *Gullies formed where runoff from maintenance roads and pads for electricity-generating windmills is concentrated (see Wilshire and Prose, 1987). Photographs by Howard Wilshire.*

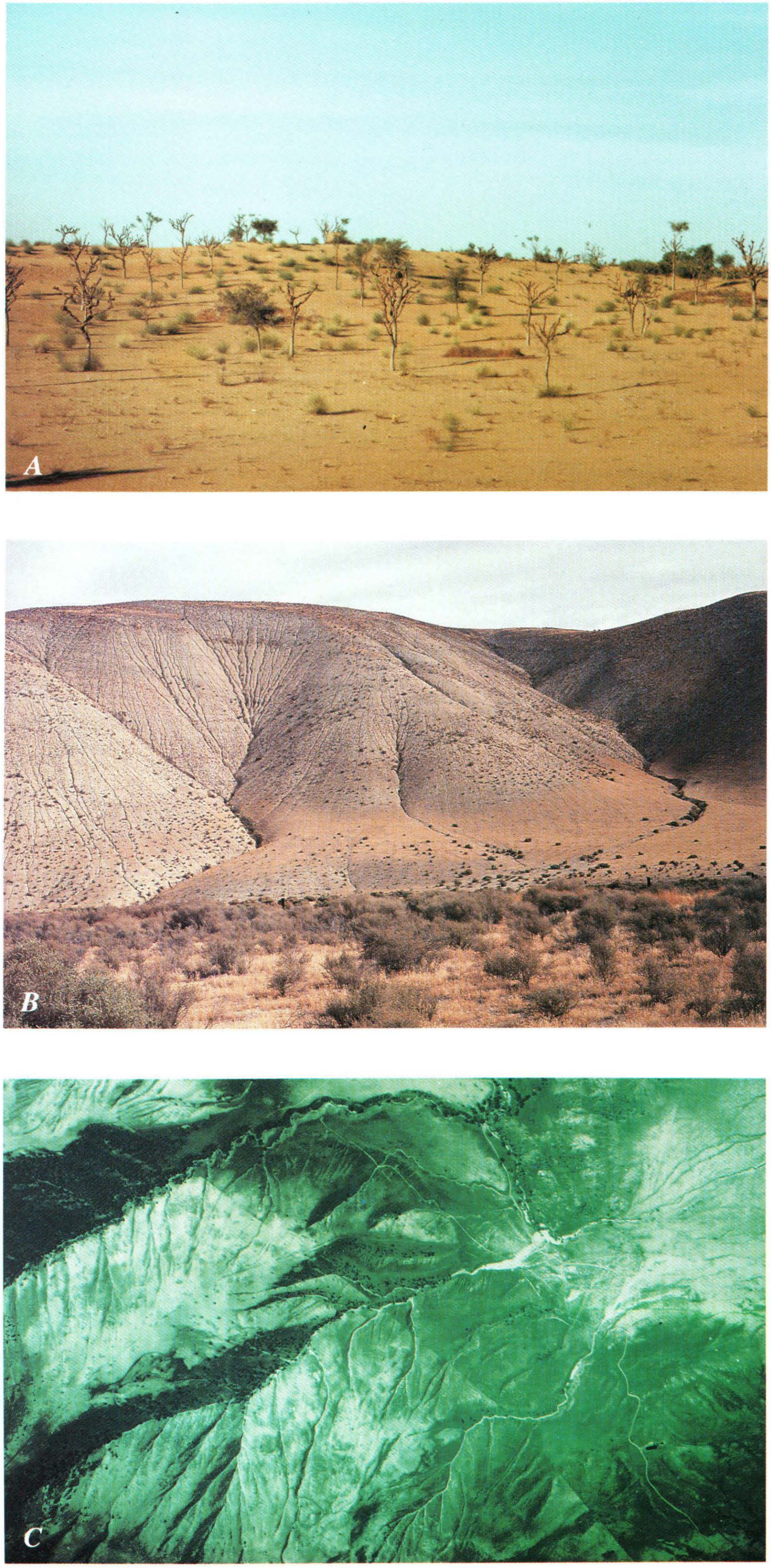


Figure 12. Overgrazing can cause extensive soil exposure and accelerated erosion. A, *Near Bikaner, northwestern India. Virtually all understory plants have been stripped, and much soil has been lost to wind and water erosion. Photograph by Carol Breed.* B, *In the Temblor Range, southern California, intensive cattle grazing on steep slopes exposed the soil to erosion, causing formation of gullies. Photograph by Howard Wilshire.* C, *In the Tehachapi Mountains, southern California, the fenceline (diagonally across center of photograph, from upper left to lower right) separates heavily grazed land (light colored due to stripping of vegetation in 1977 windstorm) from still-vegetated (dark) ungrazed land. Photograph by California Department of Transportation.*

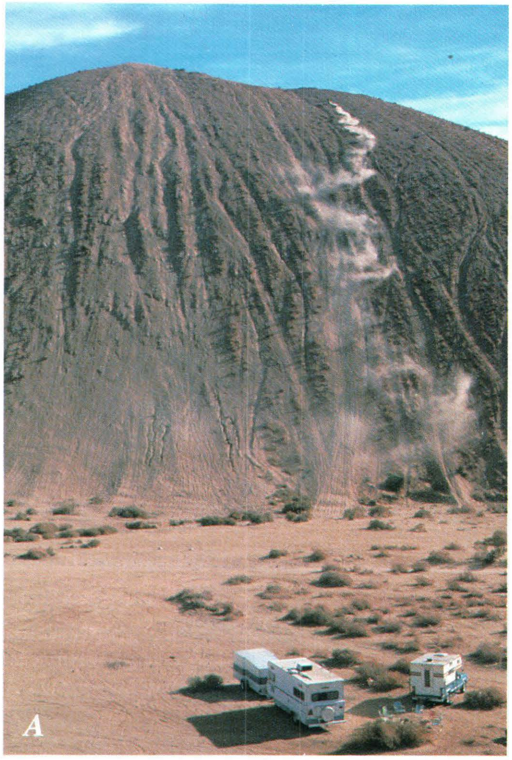
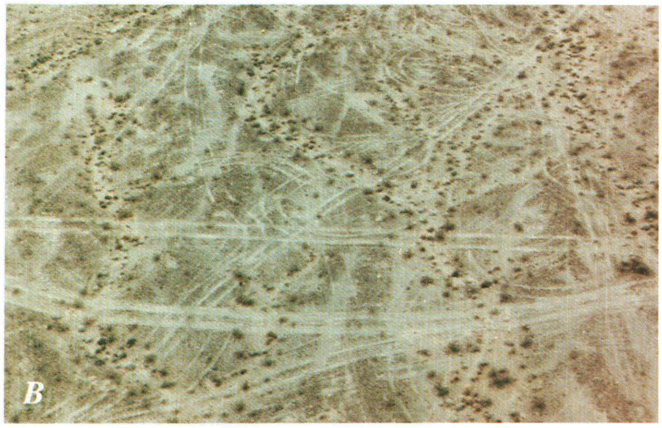


Figure 13. Soil modification and highly accelerated erosion were caused by military and recreational vehicles in the California desert. A, *Hillside scarred by recreational motorcycles, northwestern Mojave Desert (Webb and Wilshire, 1983). Photographs by Howard Wilshire.* B, *Tracks left by tank exercises in 1942–43 and 1964 in the eastern Mojave Desert, photographed in 1985 (Prose, 1986).*



Thresholds and Irreversible Change

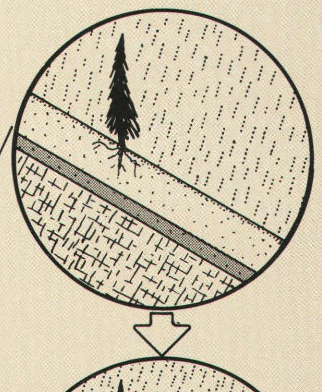
Our ability to understand and predict the rates and effects of erosion and other surface processes has been greatly advanced by the concept of thresholds. A threshold is a point at which processes or rates in surface systems change rapidly or abruptly. There are many kinds of geologic thresholds, such as those that govern whether a glacier advances or retreats, and when rocks begin to melt when heated. Of particular importance are those thresholds that lead to irreversible change, such as the breaking of rocks under stress, or to long-term loss, such as soil erosion (Coates and Vitek, 1980).

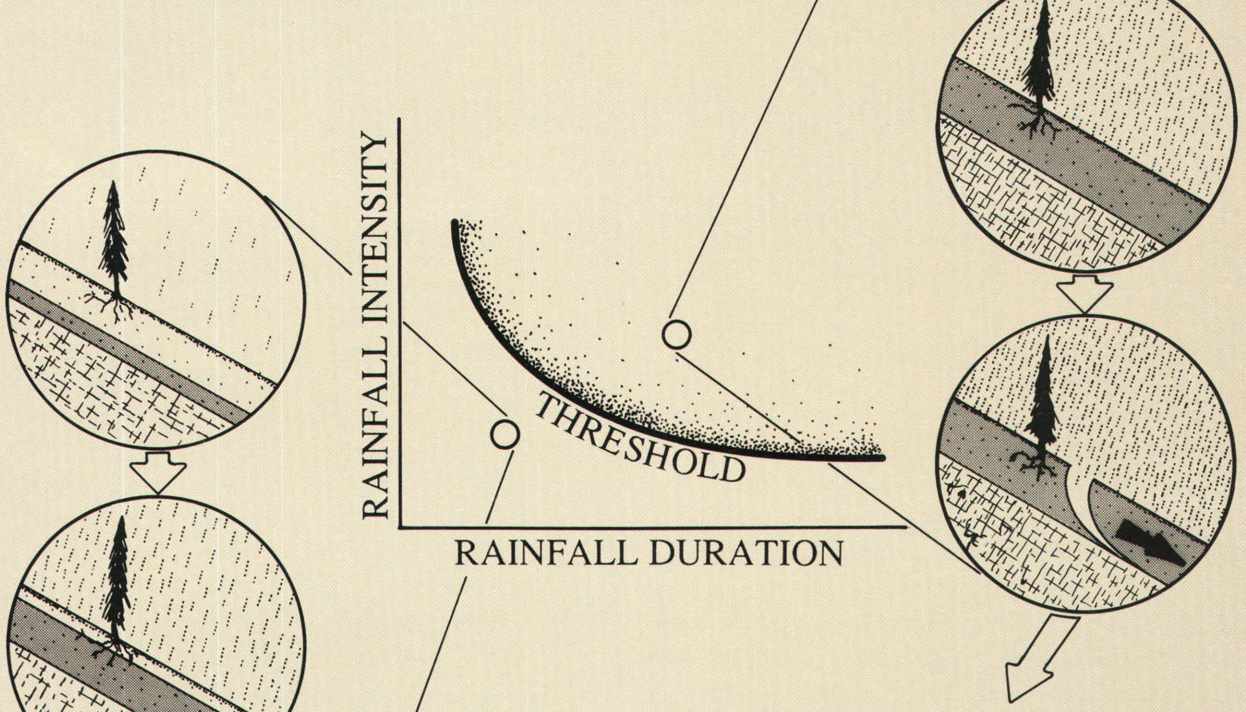
The abrupt change associated with thresholds contrasts sharply with the gradual change, or even constancy, that most people perceive for landscape. Not widely appreciated, for example, is that sandy soils in arid lands commonly are stabilized by lichen mats that form crusts only a few centimeters thick, or by barely visible masses of algal filaments that bind soil particles in the upper 2 to 3 cm. Other soils or surface sediments in arid lands may be cemented by hard inorganic crusts of clay, carbonate, or salt. A single pass of a bicycle or a hiker is often sufficient to break the surface and expose loose soil below to wind erosion. Thus, even slight disturbances of the natural crusts on arid-land soils can exceed a threshold and lead to active erosion of a previously stable ground surface. The sand released by the disturbance can itself abrade the surrounding crusted soils, spreading the damage. Practices that exceed such thresholds, ranging from livestock grazing in the Saharan fringe (Mabbutt, 1984; Dregne, 1983) to off-road traffic in the Western United States (Webb and Wilshire, 1983), have contributed to desertification throughout the world. Grazing and off-road vehicle damage is illustrated in figures 12 and 13.

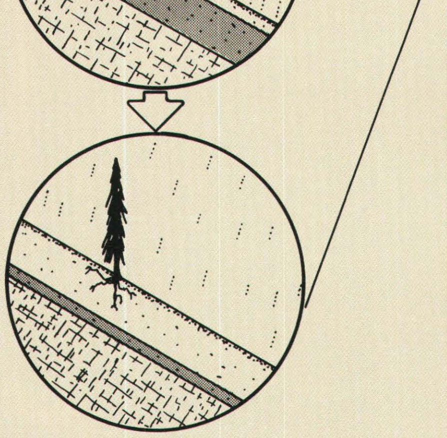
A study of soil slips and resultant flows that formed during a severe rainstorm in the San Francisco Bay region in 1982 established a threshold value of rainfall intensity above which widespread debris flows occurred (see box, next page) (Cannon and Ellen, 1988; Cannon, 1988). This threshold and a network of recording rain stations provide the basis for debris-flow alerts issued by the U.S. Geological Survey through the National Weather Service in the San Francisco Bay region. Other important hydrologic thresholds include the threshold of critical stream power that separates erosional from depositional modes in rivers (Bull, 1979) and the threshold of average annual precipitation in semiarid lands that controls the vegetative cover of hillslopes and hence their sensitivity to erosion (Langbein and Schumm, 1958; Schumm, 1968). Studies of the latter threshold found that erosion rates are greatest in regions with average annual precipitation of 30 to 40 cm, and thus are greater in semiarid regions than in arid or humid ones. When precipitation is less, runoff is too small to cause much erosion except where the precipitation is delivered by thunder storms. More precipitation supports sufficient vegetation to reduce erosion rates.

RAINFALL THRESHOLDS FOR DEBRIS FLOWS

Rainfall thresholds determine whether debris flows are triggered during rainstorms. Subthreshold storm rainfall (below left) simply raises groundwater levels in hillside soils. (Soils are indicated in the diagrams by a dotted pattern, ground water by gray shading. X's indicate impermeable bedrock below the soils.) Rainfall conditions above the threshold (right) raise groundwater levels high enough to trigger failure in soil types that can liquify. The resulting mass, which flows suddenly and rapidly downslope, can destroy buildings and claim lives within moments after movement starts. The debris flow pictured at lower right destroyed a home in Marin Co., Calif., in January 1982. Photograph by Stephenson Ellen.







Prepared by Stephenson Ellen and Bruce Rogers

A study of soils developed on carefully dated lava flows in the Mojave Desert unexpectedly identified a threshold of wind erosion of dry lakes. Soils formed on lavas that range in age from about 150,000 to 20,000 years old are similar, indicating that they were all produced not by a continuous process of soil formation but instead by dust fallout from short wind-erosion events triggered by drying of lake beds and playas in the last 20,000 years (McFadden and others, 1984).

Thresholds in surface systems thus may have an immediate bearing on people and their pursuits. Thresholds are also fundamental to understanding the processes themselves and to interpreting the geologic record of their frequency. Most commonly the geologic record is interpreted in terms of uniformitarian principles, embodied in the saying "The present is the key to the past." The concept of thresholds, which has received rapidly increasing attention in the past decade, indicates that abrupt changes may take place in normal system operations, and that repeat intervals of such changes may be long compared to human life expectancy. The geologic record teaches an appreciation of past—and future—events from a longer view than can be observed in the present.

Important thresholds may be vulnerable to both climate change and human activities. A warmer, drier climate resulting from greenhouse warming would make land now above the vegetation-precipitation threshold more vulnerable to erosion through reduction of vegetative cover. Accelerated erosion in turn exacerbates water and air pollution. With sufficient understanding, we might be able to predict when such thresholds will be exceeded and thus to accommodate or even prevent the change. The obvious tactic to ameliorate damage from climate change would be to reduce greenhouse gas emissions, but other actions also are feasible, such as reducing grazing loads to give vegetative communities better chances to adapt.

Another example is found in studies of the effects of dams on the Colorado River (Turner and Karpiscak, 1980; Lucchitta, 1991). The dams act as sediment barriers. Most sediment entering reservoirs settles out in the reservoirs; the sediment-free water released from the dams has great power to erode and transport sediment below the dams. The practice of accommodating peak daily demands for electricity by large discharges of water results in swamping of beach sands, which may slump into the river when the water levels drop; in other cases, former sand beaches have become marshlands. Resupply of sediment from the main river system is now prevented by the dams, but tributaries remain unaffected and continue to deposit sand, gravel, and boulders at their mouths. Although sand is redistributed, the river lacks the peak flood power to move the larger sediment. As a consequence, rapids are gradually becoming bigger at the confluences of tributaries and the river. Before the dams were built, there was a dynamic equilibrium between annual seasonal high discharges and low water such that sediment delivered by the tributaries was constantly redistributed downstream. Now, even during major periods of high water, such as occurred in spring of 1983, the river lacks the power to redistribute the boulder deposits that make up the rapids. The public works projects have artificially raised thresholds that, under previous natural conditions, were regularly exceeded so that erosion and deposition were balanced.

TECHNIQUES

The study of surface processes is based on observations of both natural and experimental systems. Hypotheses are drawn from observations, then tested, refined, and tested again. Such study addresses the fundamental nature of processes, their organization into systems, and their variation across the landscape and over time.

In the early part of this century, sciences that dealt with the land surface—geomorphology, soil study, and allied fields—were largely descriptive. As these sciences have matured, the focus has shifted from simple description to comprehending how the processes work, and findings and principles have become ever more likely to be expressed quantitatively. These changes were led by progress in the mathematical description of streamflow, and they are facilitated by the application of the threshold concept to geomorphology, by the improved ability to determine the ages of Pleistocene and Holocene deposits and events, and by recent advances in the geochemistry of stable isotopes that allow dating of surface exposure as described in a following section.

Clear understanding of specific surface processes requires field study of ancient and modern examples, field and laboratory experimentation, and theoretical analysis. We can observe active surface processes directly in the field by monitoring test areas, by conducting experiments, and by studying events of extreme magnitude, intensity, or duration. These events are particularly valuable for stimulating the discovery of new concepts.

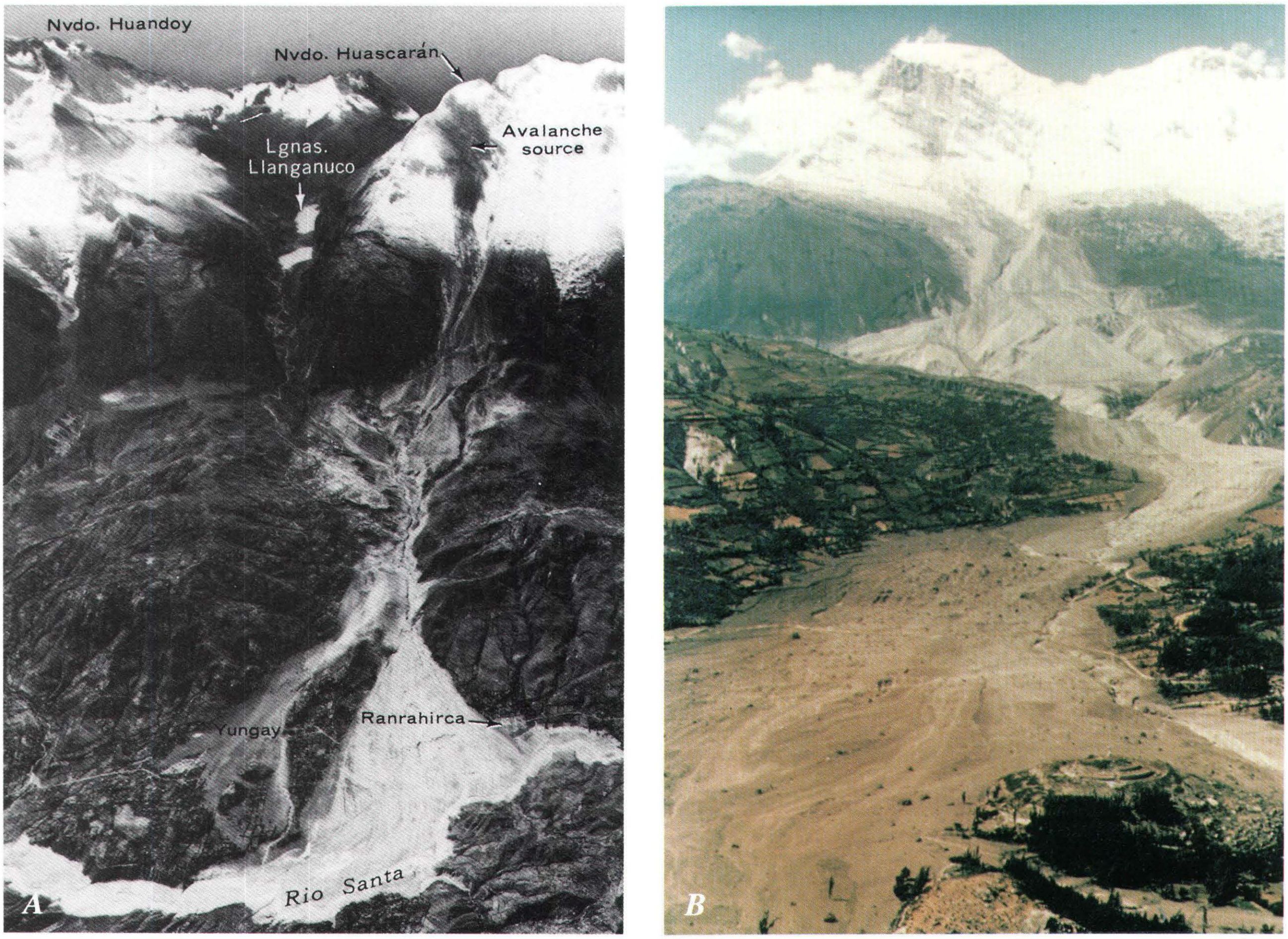


Figure 14. Catastrophic Nevados Huascarán avalanche, Peru, 1970, was triggered by an earthquake. A, *Debris that was derived from elevations between 5,400 m and 6,500 m traveled 16 km to elevations at 3,000 m and lower. The avalanche had an average velocity of 280 km per hour, and large boulders launched into the air reached velocities estimated to be about 1,000 km per hour (Plafker and Ericksen, 1978). Photograph courtesy of George Plafker.* B, *The town of Yungay lay in lower middle ground (compare photographs* A *and* B*). Some of the low hills not overtopped by the 1970 avalanche were formed by deposits of previous avalanches, including some prehistoric ones much larger than the 1970 avalanche. Photograph by George Plafker.*

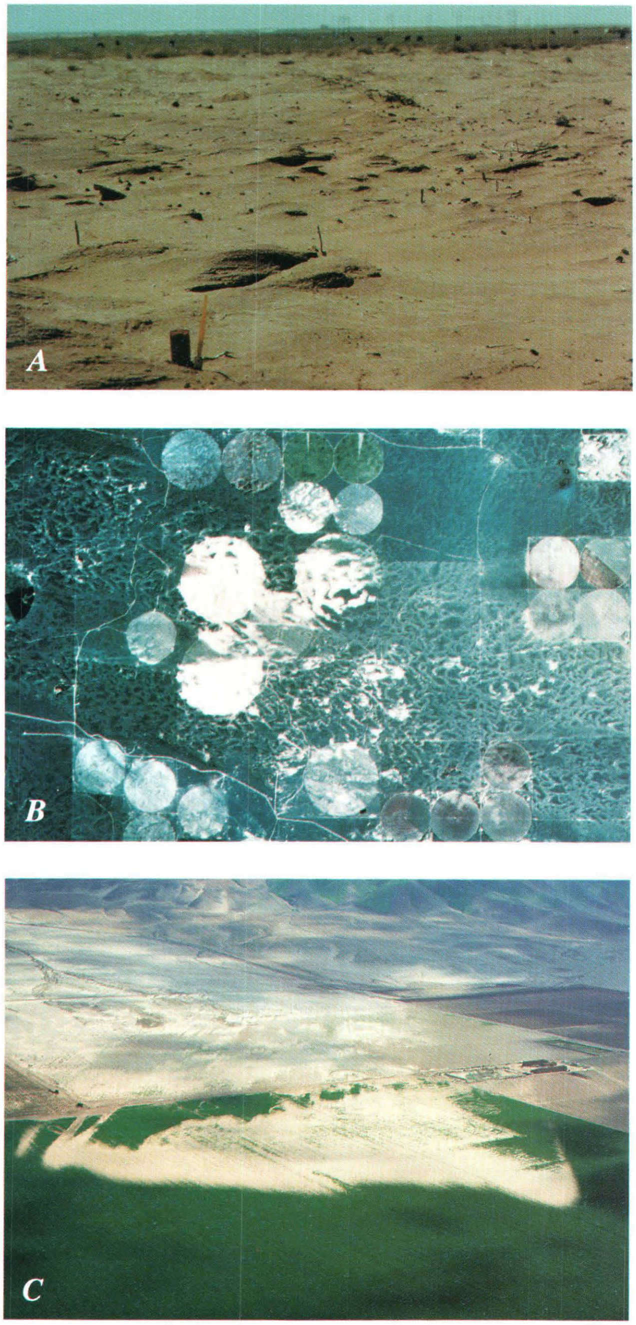


Figure 15. Wind erosion and deposition. A, *About 1 m of soil was eroded in 7 hours from this plowed field in eastern New Mexico in the windstorm of February 1977 (McCauley and others, 1981). The storm removed all the crop, the plow furrows, and the loose soil, leaving the streamlined knobs ("yardangs," about 1 m long) of the harder subsoil. Photograph by Carol Breed.* B, *Aerial photograph of the Portales, N. Mex., area in 1983, showing highly active wind-blown sand in three large circular fields (light colored) with center-pivot irrigation systems. In contrast, uncultivated parabolic sand dunes surrounding the circular fields are mostly stabilized by vegetation (Muhs and Maat, 1993). Photograph courtesy of Daniel Muhs.* C, *Deep erosion (as much as 0.5 m into bedrock) of grazed land (foothills in background) and agricultural land (middle ground), and deposition of sand in an alfalfa field (foreground), was caused by a severe windstorm of 24-hours duration in the southern San Joaquin Valley, Calif., December 1977 (Wilshire and others, 1981). Photograph by Howard Wilshire.*

Knowledge Gained from Extreme Events

Comparison of the effects of 1969 Hurricane Camille and 1972 Tropical Storm Agnes on the Eastern United States demonstrated strong contrasts in landscape response under conditions of intense rainfall (Williams and Guy, 1973; Costa, 1974; Wolman and Gerson, 1978). In the mountainous Blue Ridge Province, the intense rainfall caused debris flows; comparable rainfall in the hilly Piedmont Province caused massive flooding. Most deaths in the Blue Ridge Province were caused by boulders and trees carried by debris flows (Williams and Guy, 1973), whereas most deaths in the Piedmont Province were caused by drowning. The different responses to intense rainfall of the two areas resulted from differences in physiographic features such as basin size, shape, and slope; altitude; land use; soils; and surficial and bedrock geology (Costa, 1974).

The 1970 Nevados Huascarán debris avalanche in Peru, triggered by an earthquake, taught that flows of soil and rock debris can travel at extreme speeds and spill over major topographic barriers (Plafker and Ericksen, 1978) (fig. 14). The avalanche overtopped a hill 700 m high and destroyed the town of Yungay, killing an estimated 18,000 people.

Accelerated wind erosion resulting from agricultural and grazing practices led to complete stripping of the soil over large areas in both New Mexico and California in 1977 during brief, violent windstorms (fig. 15; frontispiece). Dust from the storm in New Mexico was tracked by satellite across the Eastern United States and over the Atlantic Ocean (McCauley and others, 1981). Most of the dust carried in this storm came from plowed lands in areas known to be highly susceptible to wind erosion. The soils, stable in their natural vegetated condition, had originally formed on sediments deposited by wind about 10,000 to 22,000 years ago. Breaking of the surface soils and removal of natural vegetation made the land vulnerable to wind erosion; because the storm struck in February, substantial areas were unprotected by crops.

The California windstorm, in the San Joaquin Valley, carried and deposited sands and gravels so coarse (rock fragments as large as 10 cm across were bounced across the surface) they previously were thought impossible for wind to move (Wilshire and others, 1981). This discovery revealed a need to establish criteria to distinguish riverborne from wind-borne gravels to correctly interpret the geologic record. The same storm formed desert pavements (surfaces coated by thin pebble layers) in hours, contradicting previous assumptions that thousands of years were required to create them. The storm also taught that windborne dust can be a causal factor in disease epidemics

Figure 16. Mount St. Helens, before and after the eruption of May 18, 1980. A, *View from Johnston Ridge, one day before the May 18 eruption. Photograph by Harry Glicken.* B, *View from Johnston Ridge, September 10, 1980, showing massive changes in the shape of the volcano and destruction of the forests seen in photograph* A, *due to the May 18 eruption. Photograph by Harry Glicken.* C, *View from Johnston Ridge, March 30, 1987, showing major stream-channel incisions in the surface created by the May 18 eruption. In this setting, physical modifications of the surface have occurred more rapidly than biological regeneration. Photograph by Lyn Topinka.*

because it spread valley fever, coccidioidomycosis, a lung disease caused by a fungus endemic in creosote-bush soil, hundreds of kilometers to the north end of California's Great Valley.

Study of the 1980 eruption of Mount St. Helens revealed how swelling of the volcano's north flank due to magma rising inside the volcano culminated in an enormous landslide that released a lateral blast of hot volcanic gas and rock debris. The eruption killed 57 people, triggered debris flows that temporarily stopped shipping on the Columbia River and disrupted highways and rail lines, and transformed a landscape of dense green forest into a volcanic wasteland (Wright and Pierson, 1992; fig. 16). Continued study is documenting the nature and rate of hydrologic, geologic, and biologic recovery on the severely modified landscape in the vicinity of the volcano (Foxworthy and Hill, 1982; fig. 16*C*). Such information will provide new insights into surface processes that can be applied to interpreting the geologic record and will prove invaluable for planning for future large-scale land-surface modifications from either natural or human causes. The lessons from Mount St. Helens led to the discovery that huge catastrophic slope failures are typical at growing volcanoes worldwide (Francis and Self, 1987; Moore and others, 1989).

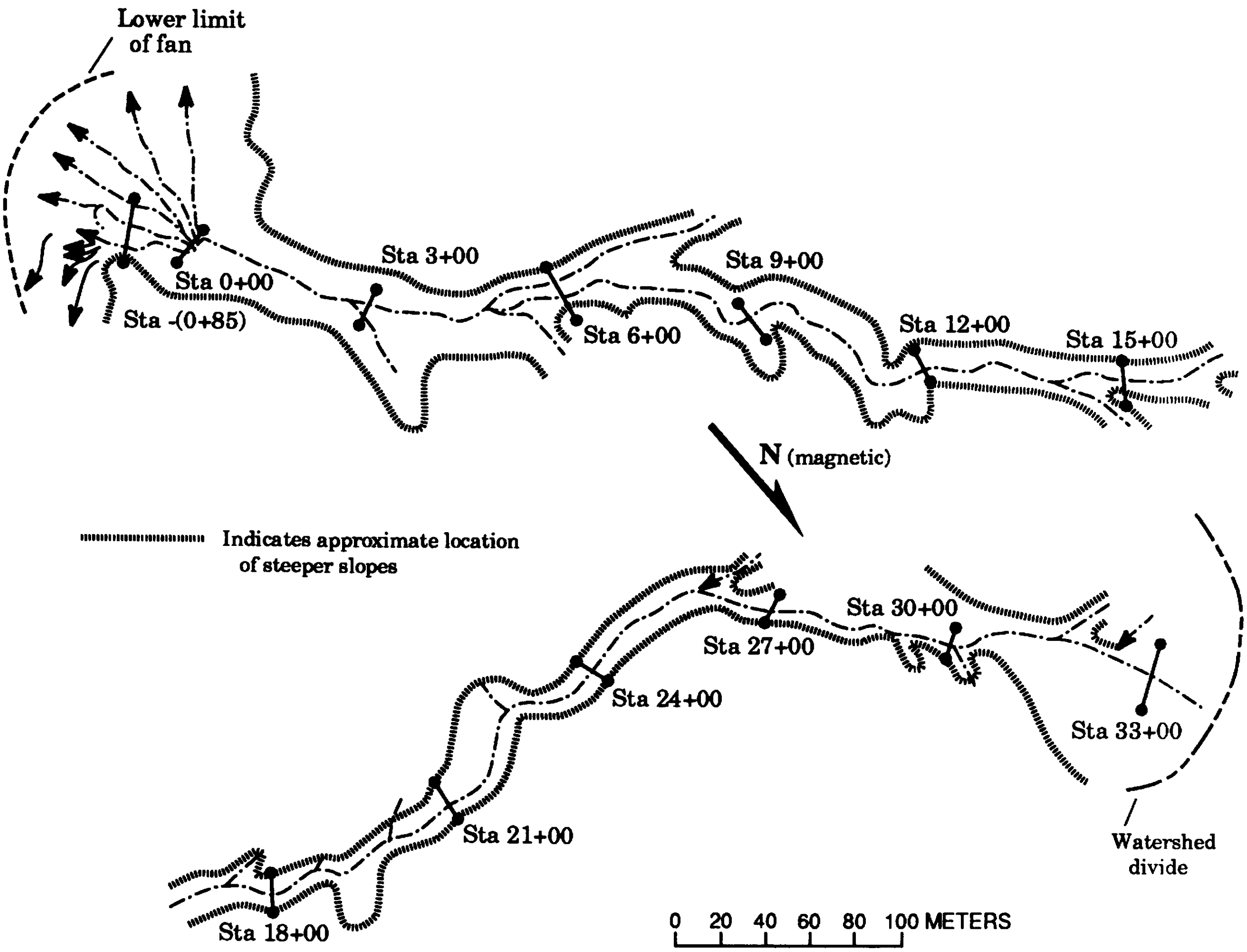


Figure 17. Example of a Vigil Network study site, at Last Day Gully, Wyo. Gully is shown in two halves to better fit page. Each bar denotes location of cross section measured between two bench marks. Station numbers are elevations (in feet) with reference to Station 0+00; arrows near top of gully indicate inflow; arrows at bottom indicate channel directions on alluvial fan at mouth of gully. From Osterkamp and Emmett (1992).

Long-Term Monitoring

Long-term monitoring of both natural and disturbed test areas is an important way to study processes and their rates. The Vigil Network of sites (Emmett and Hadley, 1968; Osterkamp and others, 1990) was started in 1962 to establish baseline monitoring of hydrology and landscape change in selected hydrologic and geomorphic settings, now numbering 82, dominantly in the United States and Sweden (Osterkamp and others, 1991). The aim of this program is to establish reference points that can be systematically remeasured over long periods of time in order to detect and quantify changes in the land surface and in the distribution of surface and near-surface water. Preservation of the records for use in the future is a paramount goal, because changes that take place over the period of one or several lifetimes cannot be evident in the data gathered to date, or they may be wrongly interpreted in terms of our present understanding of the systems involved. Measurements that are being recorded include shape, depth, and width of stream channels; thickness of channel fill; hillslope profiles; reservoir sedimentation; and vegetation type and cover (fig. 17). These and other measurements made over long periods of time allow assessment of causal relationships between changes in the landscape and land-use and climatic factors. Even over a short period of time this monitoring has proved useful. Emmett (1974) used 10 to 12 years of geomorphic records from eight Vigil Network sites to show that an arroyo-cutting cycle, known to have begun about 1880 in the arid and semiarid southwestern United States, had reversed and that channels were filling. Other programs such as the Long-Term Ecological Research program (Bhowmik, 1987) make many of the same kinds of measurements as the Vigil Network. Integrating and expanding these programs internationally through the auspices of the United Nations would provide major benefits for understanding global changes that affect surface processes.

Large-Scale Experimentation

Recently developed facilities for large-scale experiments on infiltration, runoff, landslides, and debris flows are likely to provide important new information about basic processes. At the National Research Institute for Earth Science and Disaster Prevention in Tsukuba, Japan, a large-scale rainfall simulator has been built to conduct experiments on the effects of rainfall on surface processes. The rainfall simulator consists of a building about 80 m long by 50 m wide and four stories high. The entire building is mounted on railroad tracks so that it can be moved to different experimental plots, some designed to study infiltration and runoff, others to study landslides. International groups of scientists have collaborated at the Japanese facility to examine the conditions that turn landslides (a general term for masses of rock or soil moving downhill) into debris flows (swift downhill flows of water-saturated rock debris; Iverson and LaHusen, 1989).

The U.S. Geological Survey and U.S. Forest Service built a large flume at the H.J. Andrews Experimental Forest in Oregon in 1991 to conduct experiments on debris flows. The flume is allowing, for the first time, experimental study of all stages of the debris-flow process, from initiation through deposition (Iverson and others, 1992). Among the research objectives are testing of existing mathematical models (Iverson and LaHusen, 1993), development of new models for interpreting and forecasting debris-flow behavior, and development of improved technologies for mitigating the destructive effects of debris flows (Iverson and others, 1992).

Dating Geologically Young Events

Advances in methods of determining the age of geologically young materials can provide the time control crucial to identifying synchronous events and to calibrating time sequences. Accurate dating of soils lets us determine recurrence rates of El Niño global-climate events and of landslides or other sudden geologic events, and makes possible time correlations across climatic boundaries so that we can determine effects of time and climate on soil formation.

The carbon-14 system has long been used to date organic materials. Carbon-14 is produced in the atmosphere by a variety of nuclear reactions and is incorporated in CO_2 molecules by exchange with stable carbon isotopes (Faure, 1977). Organisms adsorb carbon-14 in CO_2 from the atmosphere while alive. Upon the organism's death, the adsorption of carbon-14 ceases and the carbon-14 in the dead tissue declines by radioactive decay with a half-life of 5,730 years. The time of death can be determined by comparing the activity of carbon-14 in the dead tissue with that in living tissue. The potassium-argon (K-Ar) method of dating, based on decay of ^{40}K to ^{40}Ar, has wide application to surface processes because potassium is an important element in many rock-forming minerals. A derivative method that measures the ratio of $^{40}Ar/^{39}Ar$ is simpler and can be used with very small samples, thereby eliminating problems of measuring absolute abundances of K and Ar and of sample inhomogeneity. A promising new application is extension of $^{40}Ar/^{39}Ar$ dating from older materials into the age range (tens of thousands of years) of carbon-14 (Hu and others, 1994). Other highly reliable and flexible dating techniques include tephrochronology and fission-track dating (Rosholt and others, 1991). Tephrochronology (Sarna-Wojcicki and Davis, 1991) identifies volcanic ash deposits by detailed chemical analysis of volcanic glass particles; it can be used to distinguish even individual ash beds erupted from the same volcano. Because ash beds represent an instant in time and may cover huge areas, both on land and on the ocean floor, they are extremely valuable time markers that allow correlation across climatic boundaries and measurement of such phenomena as rates of sedimentation in many natural environments (fig. 18). Fission-track dating (Naeser and Naeser, 1988) makes use of naturally occurring impurities of uranium-238 in certain minerals such as apatite (fig. 19) and zircon and in fresh volcanic glass. Spontaneous fission of the uranium-238 releases particles whose paths through the mineral or glass are preserved as fission tracks that can be examined under the microscope. Because heating above a certain temperature anneals fission tracks, thus resetting the fission-track clock, fission tracks can be used to determine how long a sample has been at temperatures cooler than the annealing temperature of the mineral examined. They can be used, for example, to determine the age of young volcanic glasses or to determine the time of uplift of rocks to levels near the earth's surface where temperatures are cooler than the annealing temperature.

Promising new and emerging dating techniques for geologically young materials (Rosholt and others, 1991) include thermoluminescence (Wintle and Huntley, 1982; Lamothe and others, 1984), electron-spin resonance (Grun, 1989), rock-varnish chemistry (Dorn, 1982; Harrington and Whitney, 1987), and measurement of several short-lived cosmogenic isotopes such as chlorine-36, beryllium-10, aluminum-26, and helium-3 (Nishiizumi and others, 1986, 1989; Phillips and others, 1986, 1990; Lal, 1988).

The property of thermoluminescence (TL) is imparted by natural nuclear radiation, which causes the release of electrons within mineral grains. The electrons accumu-

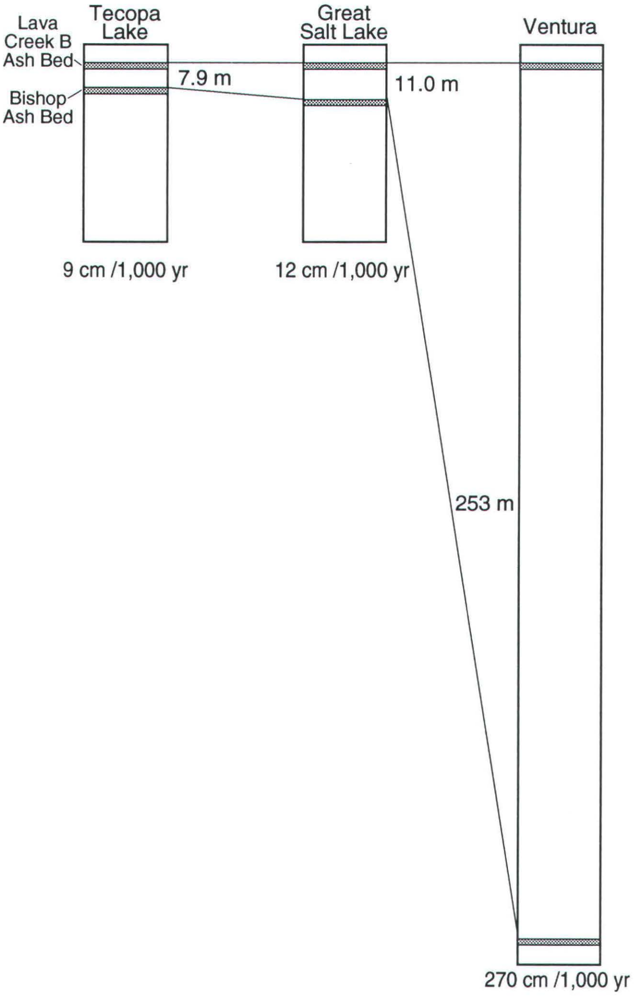


Figure 18. Applications of tephrochronology. Cores from three lake deposits revealed the presence of widespread volcanic ash beds, the Bishop ash bed that is 758,000 years old and the Lava Creek B ash bed that is 665,000 years old. These beds were identified by tephrochronologic techniques, thus allowing correlation from core to core, and were dated by $^{40}Ar/^{39}Ar$ laser fusion techniques. The amount of sediment that accumulated in the 93,000 years between ash falls varies from 7.9 m in Tecopa Lake in southern California, to 11 m in the Great Salt Lake in Utah, to 253 m in an area of rapid marine deposition near Ventura, southwestern California (data from Sarna-Wojcicki and others, 1987b; Eardley and others, 1973).

late in "electron traps." During laboratory heating, these electrons are moved to sites within the mineral structure from which light is emitted. The intensity of the emitted light is a measure of the time that has elapsed since the mineral grain became shielded from sunlight. Electron-spin resonance (ESR) dating also measures the effects of natural radiation on mineral grains. These two techniques can be used, for example, to date the formation of mineral grains in subsurface soil horizons, or to determine the age of a lava flow that buried measured mineral grains and thereby started their TL and ESR "clocks."

Several approaches have been made to dating rock varnish, which is a thin coating of iron-manganese oxides, clay minerals, and minor organic material that accumulates on exposed rock surfaces in arid environments. The ability to accurately date these surfaces would provide important information about rates of climate change. Cation ratios change with age and are measured on samples of varnish scraped from rocks or by scanning-electron microscopy on varnish still adhering to rock samples. The ratios have been calibrated by dating of the same rock units by other methods. (Attempts to date the earliest organic component of varnish by the carbon-14 method using accelerator mass spectrometry on scraped samples (Dorn, 1991) have not yet proved reliable and require additional research (Reneau and others, 1991)). The dates that have been acquired so far suggest that alluvial surfaces covered by varnished desert pavement have been stable for tens of thousands to hundreds of thousands of years. These time scales indicate the huge recovery times required when these surfaces are disturbed.

The chronology of soil formation is being pursued by new techniques using isotopes produced by cosmic radiation, such as aluminum-26 and beryllium-10 (Nishiizumi and others, 1986, 1989), chlorine-36 (Phillips and others, 1986, 1990), and helium-3 (Phillips and others, 1986; Cerling, 1990; Kurz and others, 1990). These techniques allow dating of young deposits and geomor-

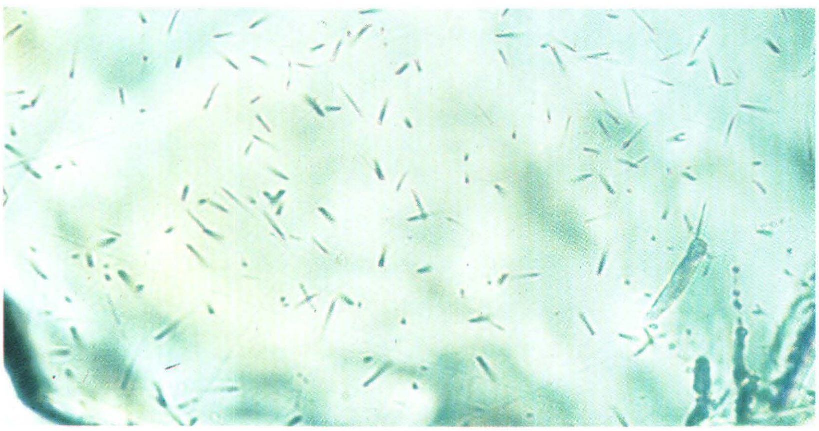


Figure 19. This photomicrograph of a thin slice through an apatite crystal shows fission tracks formed by particles released by spontaneous fission of ^{238}U enclosed in the crystal when it formed. The abundance of tracks and source uranium allows determination of the age of the crystal when it last cooled through its annealing temperature (about 100°C). Width of photo is about 150 µm. Photograph by Charles Naeser.

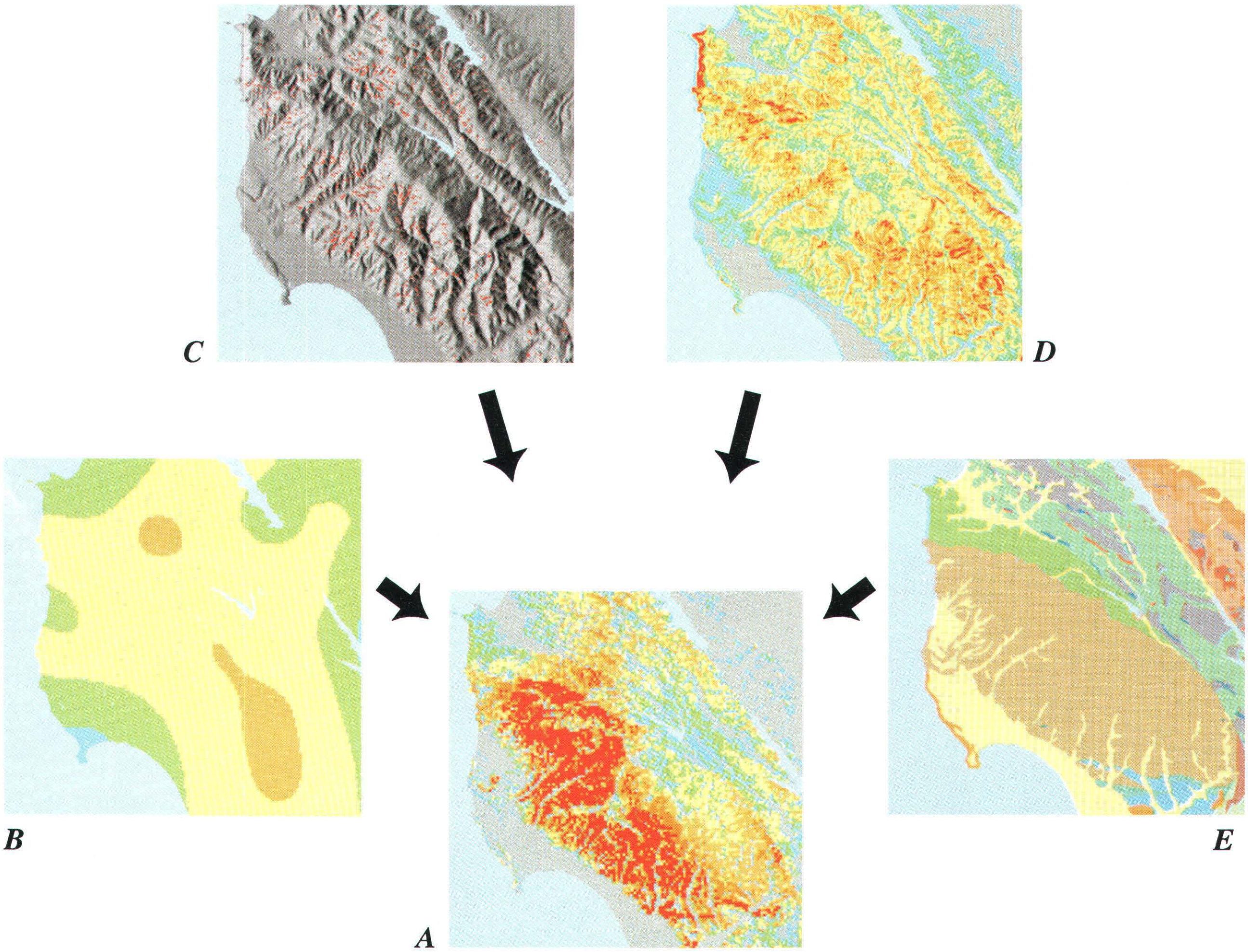


Figure 20. Computer mapping using geographic information systems (GIS) technology permits the systematic combination of different mapped features of the earth's surface to generate new maps. In this example, a map, A, *showing areas of the Santa Cruz Mountains, northern California, that are at risk from fast-moving, fluid landslides called debris flows (or mudslides) has been generated by combining maps of* B, *rainfall that triggered debris flows in a severe storm in 1982 (warmest colors indicate greatest rainfall);* C, *locations (red dots) of debris flows triggered by the 1982 storm;* D, *steepness of hillslopes (warmest colors indicate steepest slopes); and* E, *geologic materials, including soils and bedrock (Mark, 1992). In map* A, *warmest colors indicate greatest debris-flow hazard. Designed by Stephenson Ellen.*

phic surfaces, and determination of weathering and erosion rates. The isotopes record how much time the material has been exposed to cosmic rays, that is, how long it has been exposed at the land surface. The beryllium isotope beryllium-10 is produced both at the land surface and in the atmosphere, from which it is delivered to the surface by precipitation. Under appropriate conditions and soil acidity (pH about 5 to 8, slightly acid to very slightly basic), beryllium-10 is adsorbed by fine-grained soil components, so that its concentration in a soil profile can be used to estimate the minimum age of the soil (Pavich and others, 1984).

Significant problems remain with all methods of dating young materials. Ages estimated for volcanic rocks in southern Nevada on the basis of K-Ar and $^{40}Ar/^{39}Ar$ isotopic clocks (Turrin and Champion, 1991) are five to eight times older than ages based on landform and soil development (Wells and others, 1990) and cosmogenic isotopes (Wells and others, 1991). These discrepancies, and the need for their resolution, take on a very practical meaning when applied, for example, to the problem of determining the recurrence rate of past volcanism to assess whether future volcanism is likely to disrupt the high-level radioactive waste repository proposed for Yucca Mountain, Nevada (Turrin and Champion, 1991; Wells and others, 1990). Variations over time in flux of cosmic radiation, and contamination by young carbon of carbon-14-dated material, even after sample collection (Bradley, 1985), are among the many problems that require further study.

Cartographic and Satellite-Based Aids

The U.S. Geological Survey has undertaken a program of digitizing topography throughout the country from 1:24,000-scale maps. This program offers the opportu-

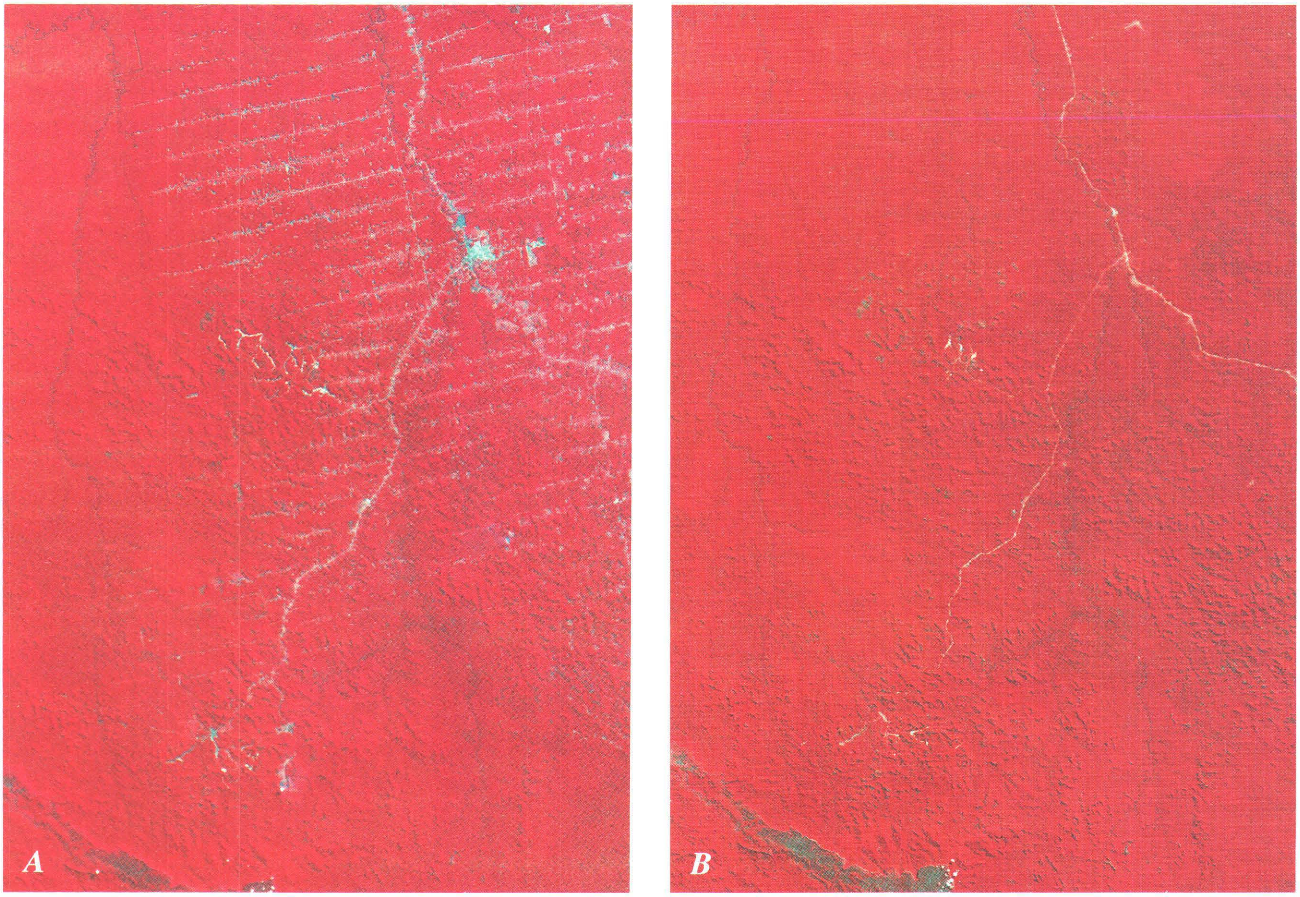


Figure 21. Landsat infrared images of part of the Amazon rainforest in the state of Rondonia, Brazil, showing the dramatic increase in deforestation between 1975 and 1986 (see Stevens and Kelley, 1992; Skole and Tucker, 1993). A, *In 1975.* B, *The same region in 1986. Red areas are forested, blue areas are stripped of forest. Linear patterns are roads along which access to the cleared areas was gained.*

nity to numerically describe and classify terrains and landforms, such as drainage basins (Moore, 1991), in sufficient detail to build direct, quantitative ties to process and history. Emerging geographic information systems (GIS) technology is creating new ways to store, analyze, and manipulate a host of interrelated data in map form (Wadge, 1988; Dikau, 1989). Using GIS computer programs, researchers can create large databases of information about a region, subsets of which can be displayed in map form. Each subset of graphically displayed information forms a layer that can be overlaid on other layers from the data set. One layer of information about a given region might show topography, a second might show show average annual rainfall at various points, a third might show what types of soil are found in various areas, a fourth might show deposits of past landslides, a fifth might show types of vegetation, and a sixth might show human structures. Layers can be overlaid to highlight and study functional relations between the different types of information. For example, layers can be combined to examine the effects of soil type, topography, and rainfall on the likelihood of landsliding (Mark, 1992) (fig. 20) or to assess the potential for landslide damage to human structures. Traditionally, combination of such information layers was created manually on paper and transparent overlays, a process that took much time and yielded products that could not easily be modified. Using GIS software, such layers can be created electronically, and easily manipulated and mathematically related. Analysis can be quicker, more imaginative, and vastly more thorough. The benefits achieved from these approaches to mapping much exceed their modest costs (Bernknopf and others, 1993).

Satellite-based remote sensing provides a comprehensive view of large areas of the earth's surface. Use of remote sensing is receiving increasing emphasis in national and international programs that monitor the global environment and changes brought about both by natural events such as drought and by human activities such as deforestation (Short and Blair, 1986; Stevens and Kelley, 1992) (fig. 21). Linkage of the large-scale view of surface effects with detailed on-the-ground studies of surface processes can provide a basis for regional and global models that explain the evolution of the land surface and predict future changes (Franklin, 1991).

CONCLUSION

We cannot remain blind to the almost daily warnings from a wide spectrum of scientists about the gradual decay of the earth's human life-support systems under ever-increasing population load. Land resources and land hazards profoundly affect the lives of every person on earth. Yet, we proceed as if fully confident of our ability to undo any damage that we inflict on the land, secure in a mistaken belief that the land can meet all of our desires and remain all that it was.

The extent of our ignorance of how natural surface systems operate underscores a need for action. Earth scientists studying the land's surface need to work toward two main goals:

• To understand—comprehensively—the origin and evolution of life-sustaining resources at the earth's land surface, the rates of their formation and decay, and their sensitivity to change. We must learn to assess accurately the present condition of these resources and of the interdependent systems of which they are a part and to predict what their future condition will be.

• To explain our research to decision makers and the public so that sound land-use policies can be formulated. We must offer honest and convincing explanations of the carrying capacity of land-surface resources, by defining in defensible scientific terms the rates of their formation and replenishment.

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Glossary

absorb To take up and hold mechanically, as water in soil pores.

acid rain Rainwater altered to a toxic or corrosive composition by adherence or solution of pollutants in the air.

adsorption Adherence of molecules or ions in solution to surfaces of solids; adsorbed fluids are more strongly bound than absorbed fluids.

alluvial deposits Materials deposited by running water.

arid Dry; said of a climate, hot or cold, having less than about 25 cm of annual precipitation as water or its equivalent as snow.

arroyo Small, intermittent stream channel with steep or vertical walls; term applied to such ephemeral stream channels in arid and semiarid areas of the southwestern United States.

ash (volcanic) Fine-grained material (<4 mm) erupted from volcanoes.

avalanche A type of landslide in which snow or rock debris slides or falls rapidly down steep slopes.

background radiation Radiation from natural sources such as cosmic rays and the earth's naturally occurring radioactive substances.

baseline monitoring Provision of a set of measurements with which subsequent measurements can be compared to assess change.

bedrock Hard or consolidated rock, either exposed at the surface or lying beneath soil or other unconsolidated surficial deposits.

chaparral Vegetation community dominated by dense growth of shrubs.

chemical weathering Alteration of rocks and minerals by chemical reactions that transform them into new chemical combinations that are stable at the earth's surface.

climate The combination of temperature, precipitation, and their seasonal variations that characterizes a region.

correlation Establishment of a relation between one geologic phenomenon and another, for example by demonstrating that isolated deposits were formed in the same event, in the same time period, or in the same type of environment.

cosmogenic Originating outside of the Earth-Moon system.

debris flow A form of landslide in which water-saturated soil and rock debris flow rapidly downstream or downslope on hillsides.

deposition The accumulation of rock material that was suspended in or transported by water or air, or moved by gravity.

desert An area, hot or cold, characterized by low annual precipitation (<25 cm/yr), generally with small and sparse vegetation.

eolian Relating to wind, such as transportation by wind currents.

erosion Removal of soil or rock materials by running water (either by physical detachment or solution), wind, or mass movement under the influence of gravity.

evaporite A chemical deposit formed by evaporation of water or some other solvent.

evapotranspiration Loss of water by evaporation from the soil and transpiration from the leaves and stems of plants.

flume A natural or artificial channel through which water is conveyed.

fluvial Pertaining to rivers.

geomorphology The study of the nature, origin, and development of present landforms and their relation to underlying rocks.

glacier A large mass of stationary or moving ice formed, at least in part, on land.

glass (volcanic) Liquid rock cooled too rapidly to permit crystallization of minerals.

groundwater Water occurring beneath the surface of the ground in the saturated zone, where interconnected pores are all filled with water.

hydrologic Pertaining to water.

hydrosphere The waters of the earth, including surface water and groundwater.

infiltration The movement of fluids into soil or rock through fractures and pores.

isotopes Atoms of the same element that have different atomic weights.

landform A physical feature of the earth's surface having a characteristic shape formed by natural processes.

landslide A general name applied to mass movement of rock or soil downslope under the influence of gravity.

outwash Rock debris washed out from the front of glaciers by melt water.

parabolic dune A U- or V-shaped dune formed when the middle part of a dune has moved forward with respect to the ends of the dune; open end faces upwind.

playa A dried-up, vegetation-free, flat-floored area composed of thin sheets of clay, silt, and sand representing the lowermost part of a shallow, undrained desert lake basin.

pore water Water residing in the interstices of soil or rock.

precipitation The discharge of water (as rain, snow, hail, sleet, dew) from the atmosphere to the earth's surface.

river basin The entire area drained by a river and its tributaries.

runoff That part of precipitation that flows from the surface rather than sinking into it.

saline zone A zone on or within the soil in which salts have accumulated.

sedimentation Deposition of rock particles and organic debris from water or air, or accumulation of chemical precipitates from water.

semiarid Relatively dry; said of a climate, hot or cold, with about 25 to 50 cm of annual precipitation.

sensitivity (of a landscape) The intrinsic responsiveness of a landscape to external forces, such as extreme rain or wind. Governed largely by the character of the rock and soil materials and by landforms.

slope Degree of inclination of the land surface.

soil Layer of unconsolidated material derived from weathered rock or rock materials that have been transported by wind, water, or gravity; term usually reserved for materials in which land plants can root. Weathered-rock materials that make up soil have generally, but not necessarily, been altered by physical, chemical, and biological processes.

surface water Standing or running bodies of water at the earth's surface.

topsoil Uppermost layer of soil that is especially rich in organic material and (or) is in a physical state especially conducive to plant growth.

transportation (of sediments) Movement of rock and mineral debris by dragging (traction), bouncing (saltation), or suspension in water or air.

uplift Change in relative elevation of a land mass, either by raising the land mass or dropping adjacent land.

weathering Chemical or mechanical transformation of rock materials by atmospheric, groundwater, or biological activity.

wetland Land that is permanently or episodically saturated or covered with water, such as swamps or tidal flats.

yardang Sharp-crested ridge sculpted by wind-driven sand; ranges from centimeters to kilometers in long dimension, oriented parallel to prevailing wind direction.

"Below that thin layer comprising the delicate organism known as soil is a planet as lifeless as the moon."

—Jacks and Whyte, *Vanishing Lands*, 1939