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Abstract

Potential geologic hazards in New Mexico include earthquakes; land subsidence caused by collapsing soils, ground-water withdrawal, limestone and evaporite karst, and collapse of abandoned mine workings; earth fissures; expansive soils; slope instability; radon availability; and volcanism. As the state agency responsible by law for original investigations of geology and mineral resources in the state, the New Mexico Bureau of Mines and Mineral Resources has an active interest in the identification, assessment, and remediation of geologic hazards. Although the nature and general location of many potential hazards are well known, many detailed questions about potentially hazardous geologic processes remain unanswered. Unfortunately, a general lack of interest in the use of geologic information in planning decisions means that the state's response to geologic hazards is one of reaction rather than prevention.

Introduction

Why worry about geologic hazards? Better yet, why spend tax dollars to study them? One reason is that the cost of ignorance is far higher. For instance, five people were killed and 14 injured on September 12, 1988, when a large boulder struck a bus traveling through the Rio Grande gorge along NM-68. Less than three years later, the same highway was closed by landslides, debris flows, and floods mobilized during heavy storms in late July 1991. Parts of southern Rio Arriba and northern Santa Fe Counties were declared disaster areas in December 1984 when a number of homes east of Española were condemned because of damage caused by hydrocompactive soils. The appearance of a large earth fissure interrupted construction of I–25 near San Marcial in 1981. A June 1990 debris flow near the town of Cordova temporarily diverted the Rio Quemado and destroyed several acres of prime pasture land. Land south of Deming has been subsiding at a rate of about 1 cm per year since the 1950s, creating large earth fissures in at least 13 locations, related to agricultural ground-water withdrawal. The list of geologic hazards, as well as the number of New Mexicans affected by them, goes on.

Purpose

This paper is a generalized survey of hazardous and potentially hazardous geologic processes occurring throughout the state, emphasizing work by the New Mexico Bureau of Mines and Mineral Resources (NMBMMR) and cooperating agencies. References are generally limited to published documents that an interested reader should be able to obtain through interlibrary loan. This means that some occurrences have been omitted because much of the information about geologic hazards within the state exists only in unpublished reports or, worse, in the memories of practicing geologists and engineers. Because this is not an exhaustive inventory, there are no doubt authors whose published work has been inadvertently overlooked. Some important hazards, such as flooding, water quality, and the natural occurrence of potentially toxic chemicals (with the exception of radon), are not covered at all. Finally, this highly generalized overview is not a substitute for field investigations by qualified engineering geologists or geotechnical engineers and must not be used as a basis for planning, design, or construction.

We at NMBMMR often receive telephone calls and letters asking if a specific geologic hazard occurs in a certain area and whether we have maps available showing the locations of earthquake faults, sinkholes, and so forth. Although at first the notion seems to be an attractive one, this paper does not include small-scale maps showing the distribution of geologic hazards in New Mexico. There are three primary reasons for this. First, there are relatively few published reports about geologic hazards in New Mexico, so information, where it exists at all, is spotty and inconsistent. Second, the preparation of useful hazard maps is an expensive and time-consuming chore and one that is well beyond the scope of this overview. Existing hazard maps are cited in the text where appropriate. Third, quickly produced and highly generalized small-scale hazard maps are by and large useless for serious geological work and could be misused by those in search of quick and easy answers to difficult questions. Readers with questions about specific geologic hazards in specific areas are urged to contact NMBMMR for more information.

Economics

Although there is no detailed estimate of the total costs associated with geologic hazards in New Mexico, collateral evidence suggests that they are significant. Brabb (1989) estimated that slope stability problems caused at least $4 million damage to state roads and private property in New Mexico between 1973 and 1983. The National Research Council (1991) estimated losses of up to $1 million per year from mining-induced subsidence, up to $1 million per year from sinkholes, and between $1 million and $10 million per year from hydrocompactive soils in New Mexico. Robinson and Spieker (1978) estimated losses from floods, earthquakes, landslides, coastal erosion, expansive soils, and other geologic hazards to be about $4.9 billion per year in the United States. Assuming a 5% average rate of inflation, their estimate projects $9.3 billion per year, or about $37 per person per year, in 1991. If flood damage is excluded, the last two figures drop to $6.0 billion per year and $24 per person per year. Based upon these national figures, annual damage costs in New Mexico are estimated to be on the order of tens of millions of dollars.

Experience in other states suggests geologic hazards in New Mexico can be avoided or alleviated through careful land-use planning and engineering design. In a study of geologic hazards in California, Alfors et al. (1973) concluded that up to 90% of landslide damage costs could be eliminated by a combination of geologic investigation, engineering design, and enforcement of zoning laws. Subsequent research has shown that this three-tiered strategy has reduced the costs of landslide damage associated with new construction in California by 92% to 97% (National Research Council, 1985). Bernknopf et al. (1988) conducted a study to assess the potential effectiveness of different planning strategies on landslide damage in the Cincinnati, Ohio area. They concluded that if grading provisions specified in Chapter 70 of the Uniform Building Code were enforced without regard to site-specific details, the benefit:cost ratio would be 0.98:1. However, if Chapter 70 provisions were enforced only in areas with steep slopes, the benefit:cost ratio would increase to 1.82:1. Finally, if both slope and bedrock type were taken into account, the benefit:cost ratio would rise even further, to 2.21:1. Simply put, enforcement of only the most basic grading requirements would save more than twice as much money as it would cost.

Sources of information

The primary source of geologic information about New Mexico is NMBMMR, which is also the Office of State Geologist and the state agency responsible by law for original investigations of geology and mineral resources in New Mexico. NMBMMR maintains a small environmental and engineering geology staff, which is responsible for 1) determining potential environmental impacts caused by intensive development of mineral, water, and land resources; 2) evaluating the hazard potential of natural geologic processes such as landslides, debris flows, earthquakes, and ground subsidence; 3) siting waste management facilities; and 4) developing a comprehensive database, including reports and maps, on these subjects. Lists of publications and open-file reports, as well as the quarterly *New Mexico Geology*, are available from the NMBMMR publications office.

Other sources of engineering geologic and geotechnical engineering information include the New Mexico State Highway Department Geotechnical Section, the New Mexico Water Resources Research Institute, the U.S. Geological Survey, the U.S. Soil Conservation Service, the State Engineer Office, and geology departments and geological engineering programs as the University of New Mexico, New Mexico State University, and the New Mexico Institute of Mining and Technology (New Mexico Tech). Additional sources are included in Johnpeer (1986). The Geology Section of the New Mexico State Highway Department has produced a series of geologic and aggregate source atlases of considerable interest to those involved in construction. Guidebooks compiled for the annual fall field conferences and other special publications of the New Mexico Geological Society constitute a valuable source of basic geologic information, as well. Sources for maps, aerial photographs, satellite imagery, thermal imagery, and radar imagery covering the state are listed in Rex (1991).

General issues related to geologic hazards and land use planning are discussed at an introductory level by Robinson and Spieker (1978) and Hays (1981), and at a more advanced level by Cooke and Doornkamp (1990). Hawley and Love (1981) presented a generalized summary of geology as related to environmental concerns in New Mexico, and Hawley and Longmire (1991) discussed geologic considerations bearing on hazardous-waste site selection and characterization in New Mexico. The engineering and environmental geology of the Albuquerque area is summarized by Lambert et al. (1982), Clary et al. (1984), and Hawley and Love (1991, p. 134–144). Johnpeer and Hamil (1983) provided a similar synopsis of the Socorro area. Johnpeer et al. (1987) and Barrie (1987) summarized the engineering geology of the northern Estancia basin with regard to siting of a proposed superconducting supercollider. The book *New Mexico in Maps* (Williams, 1986) contains a collection of thematic maps covering both the geography and geology of New Mexico. NMBMMR is currently beginning to compile maps for a county atlas series, which will consist of 1:500,000 thematic maps of interest to county planners, elected officials, and residents. Map themes will include generalized geology, mineral resources, geologically young faults and volcanic deposits, 100-year floodplains, depth to water, water chemistry, ground-water pollution potential, slope instability potential, collapsible and/or expansive soil potential, and other topics.

Geologic hazards and geologic events

The distinction between a geologic **hazard** and a geologic **event** (e.g., Rahn, 1986) is an important one. A geologic event is the occurrence of any geologic process, perhaps a landslide or an earthquake. A geologic hazard, on the other hand, is a geologic event which has a significant impact upon humans or their works. In many respects this distinction is analogous to the adage of a tree falling in a forest with no one to hear the sound. Thus, a large landslide in a remote area would be classified as an event, whereas the same landslide in a heavily developed mountain resort would be classified as a hazard. It is also useful to define potential hazards and potential events as those which geologic evidence suggests may have occurred in the past, and which may occur in the future, but for which there is little or no evidence of recent activity. Examples of potential hazards or potential events might include dormant volcanoes or landslide complexes. This distinction has practical significance for states such as New Mexico, in which limited resources must be used largely to address specific problems rather than to compile state-wide inventories covering vast, sparsely populated areas.

Earthquakes

Historic activity

Instrumental recording of earthquakes in New Mexico commenced with the installation of the New Mexico Tech seismograph network during the early 1960s, as well as several other seismographs in and around the state during subsequent years. Seismograph networks were established in northern New Mexico by Los Alamos National Laboratory in 1973 and throughout the Albuquerque–Belen Basin by the U.S. Geological Survey in 1976. Sanford et al. (1981) reported a total of 247 earthquakes with magnitude $M > 1.5$ recorded in New Mexico between 1962 and 1980, with hundreds more of lesser magnitude. (Note: There are several different ways in which to calculate earthquake magnitude, which can yield slightly different results for the same earthquake. This paper, however, assumes that the differences are small and uses only generic magnitudes. Those interested in a comparison of different magnitude scales should consult a reference such as dePolo and Slemmons, 1990.) These earthquakes were clustered along the Rio Grande rift, the High Plains, the Jemez lineament, and the margin of the Colorado Plateau. Sanford et al. (1981) speculated that earthquakes in the High Plains of southeastern New Mexico, which were unknown before 1964 but occur in an area of several major oil fields, may have been induced by injection of oilfield wastes. Recent seismic activity has included a swarm of 34 earthquakes of $2.0 < M < 4.7$, with epicenters between Belen and Socorro, between late November 1989 and early April 1991 (A.R. Sanford, personal communication, 1991). These shocks, like other historic activity throughout the area, are characterized by swarms apparently related to the injection of a mid-crustal magma body and attendant crustal deformation near Socorro (Sanford et al., 1981; also see Larsen and Reilinger, 1983 and Sanford, 1983). Sanford et al. (1991) provided the most recent summary of seismicity along the Rio Grande rift, including maps showing earthquakes of magnitude 2.5 or greater recorded between 1962 and 1986 (Fig. 1).

Based on extrapolation of instrumental data collected between 1962 and 1975, Sanford et al. (1981; also see Sanford et al., 1972)

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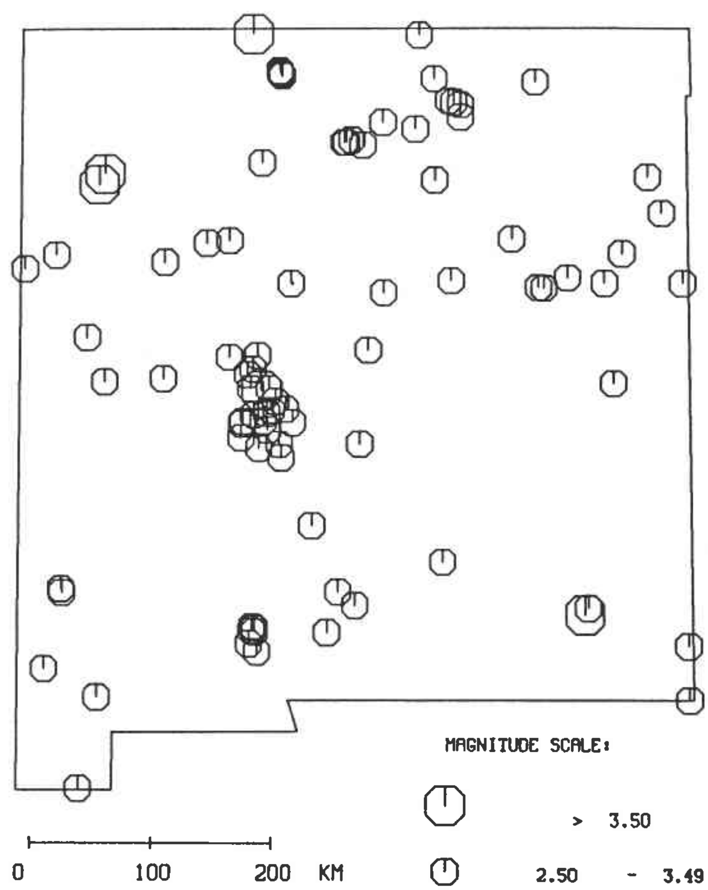

FIGURE 1—Map showing New Mexico earthquakes of magnitude 2.5 or greater recorded between January 1962 and March 1986 (Sanford et al., 1991). In most cases, earthquakes with smaller magnitudes are not felt by humans. Because this map shows neither earthquakes with epicenters outside of New Mexico nor large earthquakes that occurred before 1962, it may not provide an accurate picture of seismic hazards in the state.

predicted one earthquake of $M = 4.8$ every 50 years and one earthquake of $M = 5.1$ every 100 years. Similar estimates for the Los Alamos area suggest an earthquake of $4.5 < M < 5.0$ with an epicenter within 70 km of Los Alamos once every 100 years (House and Cash, 1988). Algermissen et al. (1991) used historical seismicity and identification of earthquake source areas to estimate maximum horizontal acceleration in rock of between 0.05 and 0.18 g, where $g \approx 9.81$ m/s^2 is gravitational acceleration, in the central and far southwestern portion of the state, with 90% probability of not being exceeded in 50 years. One of these maxima follows the Rio Grande valley from central Socorro County northward into Valencia and Bernallilo Counties where much of New Mexico's population is concentrated. Throughout the rest of the state, maximum probable horizontal acceleration is estimated to 0.03 g or less. A similar map showing maximum horizontal acceleration with a 90% probability of not being exceeded in 250 years has much the same pattern, but maximum values increase to 0.48 g. Estimating the structural response of buildings to seismic shaking is a complicated undertaking, and one far beyond the scope of this paper. A general rule of thumb, however, is that unreinforced masonry (including adobe) is typically damaged when horizontal acceleration exceeds 0.1 g.

Reservoir-induced seismicity has been documented between 1976 and 1984 at El Vado and Heron reservoirs near Chama in north-central New Mexico (El–Hussain and Carpenter, 1990). Maximum magnitude was $M = 2.7$, with a sharp drop in the frequency of higher magnitude earthquakes. Correlation of earthquake activity with reservoir levels showed that swarms of small earthquakes tended to occur when the reservoir levels exceeded previous maxima, consistent with patterns of reservoir-induced seismicity throughout the world.

Although earthquakes have been recorded instrumentally for only the past few decades, written description of seismic activity date back as far as the Territorial period of the middle 19th century. Northrop (1976) found descriptions of 1,111 earthquakes in New Mexico during the period 1849–1975, of which 523 descriptions or recordings were definite and 588 were less definite or vague. Of those earthquakes described with certainty, 508 had epicenters in New Mexico and 3 were produced by atomic testing, including the explosion of the first atomic bomb at the Trinity Site. Northrop (1976) stated that 76% of the earthquakes with New Mexico epicenters occurred along the Rio Grande rift. As noted by Sanford et al. (1981), though, this figure is most likely an artifact of settlement patterns. Well-documented, pre-instrumentation swarms along the rift occurred in 1849–1850, 1893, 1904, 1906, and 1935, with virtually all earthquakes of Modified Mercalli Intensity of VII or less (Northrop, 1976).

Young faults, paleoseismicity, and long-term earthquake hazards

Callender et al. (1983) showed the locations and ages of late Tertiary and Quaternary faults in New Mexico. Most of the youngest faults, which cut middle to late Quaternary deposits, are concentrated along the Rio Grande valley. Structure contours on top of the Ogalla Formation also indicate low-amplitude, post-Tertiary anticlines and synclines in east-central New Mexico. Authors of many other reports and papers, some cited below, note geologically young faults in various parts of the state.

Studies of young fault scarps suggest that estimates of seismicity based upon instrumental observation may significantly underestimate long-term earthquake hazards in New Mexico. Machette (1986, 1988) used soil geomorphology and slope degradation models to estimate a recurrence interval of 6,000 to 7,500 years for $M = 7.0$ Pleistocene and Holocene earthquakes along the La Jencia fault near Magdalena in Socorro County. In a similar study, Machette (1987) estimated an area-wide recurrence interval of some 2,000 years for $7.0 < M < 7.5$ earthquakes in the vicinity of the White Sands Missile Range. Foley et al. (1988) estimated a maximum credible earthquake of $M = 7.25$ along the Caballo fault near Elephant Butte and Caballo Reservoirs in Sierra County. Seager and Mack (1991) described a 4-m-high scarp offsetting upper Pleistocene fan alluvium along the Red Hills fault, a southern continuation of the Caballo fault, indicating either late Pleistocene or Holocene movement. They also infer post-middle Pleistocene movement along the nearby Derry Hills fault but could find no evidence suggesting that upper Pleistocene or Holocene alluvium had been displaced. Menges (1987, 1990) likewise estimated magnitudes on the order of $5.8 < M < 7.1$ for Quaternary and Holocene earthquakes along the western Sangre de Cristo front, with recurrence intervals on the order of 10,000 years. Gile (1987; also see Machette, 1987) described late Holocene movement, perhaps as recently as 1,000 years ago, along the Organ Mountains fault near Las Cruces (Fig. 2). Although he did not estimate magnitudes, Gile stated that movement "must have been accompanied by severe and extensive earthquake activity," and Beehner (1990) cited an unpublished maximum credible earthquake of $M = 7.5$. These paleoseismic analyses all suggest recurrence intervals of several thousands of years for $M = 7$ earthquakes on individual faults or fault segments, implying that the long-term seismic hazard in New Mexico may be about an order of magnitude greater than that estimated by Sanford et al. (1982) from short-term observational data.

There is, in general, little public concern about earthquake hazards in New Mexico; therefore, not much time and money have been invested in earthquake hazard studies. This is probably due to low levels of historic earthquake activity. This lack of foresight is particularly acute along the Rio Grande valley, including parts of Albuquerque, where liquefaction of saturated alluvium is likely to present a hazard during strong earthquakes. The only statewide earthquake hazard assessment is that of Johnpeer et al. (1986), who used distributions of historic earthquake damage, young volcanic rocks, young faults, probabilistic horizontal acceleration, shallow ground water, and major lifelines to produce a qualitative earthquake hazard map. According to their work, earthquake hazards are very low to low throughout most of New Mexico; moderate along the Rio Grande rift, southwestern, and south-central mountains; and high only in populated areas, as expected from the definition of a geologic hazard. Gardner and House (1987) produced a similar series of hazard maps showing geology, geomorphic surfaces, surface rupture potential, zones of potentially hazardous mass-wasting, and culture in the Los Alamos area.

Salyards (1991) used published fault lengths, fault slip rates, length-moment relationships, and attenuation curves to produce a probabilistic earthquake hazard map for the southern Rio Grande rift in New Mexico. The highest 100-year probability of 0.1 g horizontal acceleration, just below 2.5%, occurs over a broad area

FIGURE 2—Trench across the buried Organ Mountains fault scarp excavated as part of a paleoseismic investigation described by Beehner (1990). The downthrown block is buried beneath a dark colluvial wedge behind the survey rod near the break in surface slope. A water tower and buildings at the White Sands Missile Range headquarters are visible in the background. Photo courtesy of D. W. Love.

in the center of the Tularosa Basin, including the White Sands Missile Range Headquarters. The Las Cruces area has a 1.5% chance of experiencing 0.1 *g* horizontal acceleration in 100 years, compared to probabilities of less than 1% for Truth or Consequences, New Mexico and El Paso, Texas. Salyards' map did not, however, take into account faults outside of the map area, which may have produced unrealistically low values in areas near the map edges.

Land subsidence

Land subsidence is a widespread phenomenon that can be attributed to many different geologic processes. Hydrocompactive soils, ground-water overdraft, consolidation of saturated clays, dissolution of soluble sedimentary rocks, and collapse of mine workings are among the causes of land subsidence (e.g., Holzer, 1984a). It is impossible for engineers to determine the underlying geologic process or processes by examining structural damage alone. Moreover, cause of subsidence may be deep seated, and not readily evident from geologic maps showing only the rock and soil types exposed at the surface. It is the job of an engineering geologist to determine the nature and extent of subsidence mechanisms acting at any given site.

Hydrocompactive or collapsible soils

Hydrocompactive soils lose a significant amount of volume through reduction of porosity when wetted and have damaged roads and structures in several parts of New Mexico. Research by NMBMMR (Reimers, 1986; Johnpeer et al., 1985a,b; Shaw and Johnpeer, 1985a,b), prompted largely by damage to single-family dwellings and public works near Española, New Mexico, and by the New Mexico State Highway Department (Lovelace et al., 1982) has produced a large body of information concerning the identification and avoidance of hydrocompactive soils. In addition to the Española–Santa Fe region, hydrocompactive soils are known to have caused damage in Albuquerque, Alamogordo, Belen, and Socorro.

Hydrocompactive soils are typically composed of poorly sorted fine sand, with minor amounts of clay or evaporites, deposited by recent debris flows (incorrectly referred to as mud flows by some) on gently sloping alluvial fan complexes. More often than not, the potentially hydrocompactive deposits are of Holocene age and have never been irrigated. Before collapse, soil structure is porous and open with sand grains supported by point-to-point contacts and bound by thin veneers of clays or evaporites. In many cases, hydrocompactive soils can be identified in the field by their geologic setting, low unit weights (typically less than 16,000 N/m^3) or high void ratios (typically greater than 1.0), and disaggregation when immersed in water. Standard penetration-test blow counts, however, are not an effective method of hydrocompactive soil identification, as these soils can be strong when dry. Laboratory tests for hydrocompactive soils include a modified consolidation test, in which a dry sample is subjected to its original confining pressure, plus any structural loads, and then saturated for 24 hours. Details of the modified consolidation test are given in Das (1984) and other modern foundation engineering textbooks. The change in sample thickness upon saturation can then be used to calculate the axial compaction, with values of less than 1% generally considered to pose little hazard. Values much higher than 1% present moderate to severe hazards and should be specifically addressed in geotechnical site investigations and foundation designs. Based upon their experience in the field, however, some practitioners question the validity of modified consolidation tests on soils that disaggregate upon immersion (G. Johnpeer, 1991, personal communication).

Hydrocompactive soil deposits can extend to tens of meters in depth and remedial measures can be prohibitively expensive, so these problem soils are best identified before design and certainly before construction. Clemence and Finbarr (1981) reviewed foundation design considerations for hydrocompactive soils. Pre-construction treatments include removal of shallow deposits, injection of water to induce collapse (e.g., Shaw and Johnpeer, 1985b), dynamic compaction, vibrofloatation, deep plowing, and flooding (Lovelace et al., 1982). Heavily reinforced concrete slabs (Fig. 3), cast-in-place concrete piers or belled caissons, or driven piles can also be used to support structures on hydrocompactive soils (Curtis and Toland, 1964; Shaw and Johnpeer, 1985b). Elimination of water sources, including sewer or water line leaks, lawn watering, and septic tanks can reduce the potential for collapse if problems are discovered after construction. Although hydrocompactive soils can be detected during preliminary geotechnical investigations, well before design and construction, they promise to remain a hazard as mountain-front communities continue to grow unchecked.

Limestone and evaporite dissolution

Sweeting (1972) described solution-subsidence relief near Santa Rosa, which she attributes to dissolution of both limestone and gypsum in Permian San Andres Limestone and the collapse of overlying Santa Rosa Sandstone (Fig. 4). Kelley (1972) also described limestone karst as a minor geologic hazard in the area. Hill (1987) described the geologic evolution of Carlsbad Cavern, which is more a tourist attraction than a geologic hazard, and uses geochemical evidence to suggest that the caverns were dissolved by sulfuric rather than carbonic acid. The source of the necessary sulfur seems to have been H_2S leaking from nearby petroleum reservoirs.

A problem much more prevalent than limestone karst is the dissolution of Permian evaporites, predominantly halite, and col- ☞

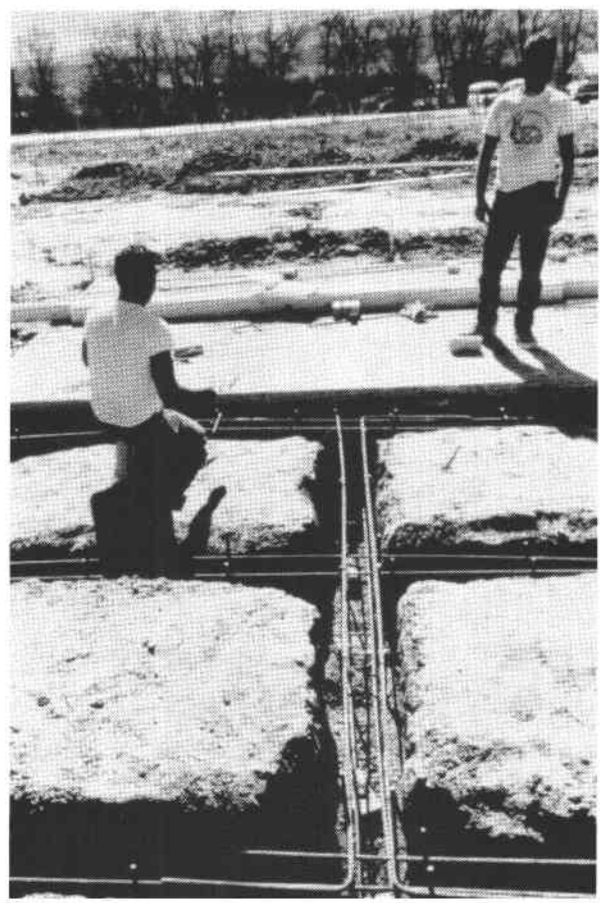

FIGURE 3—Construction of an experimental, heavily reinforced concrete slab as part of a NMBMMR hydrocompactive soils research project near Española (Shaw and Johnpeer, 1985a,b). Reinforced slabs resist cracking and structural damage caused by differential settlement of hydrocompacted soils and should be used in areas of New Mexico where hydrocompactive soils are a problem. The potential for damage from hydrocompactive soils can also be reduced by limiting infiltration of water from lawn-watering, storm runoff, septic tank discharge, and other sources. Photo courtesy of D. W. Love.

lapse of overlying strata, which has been occurring along the Pecos River valley since Pliocene time (Osterkamp et al., 1987, p. 193; Gustavson and Finley, 1985; Bachman, 1974, 1984). Simpkins et al. (1981) described the development of sinkholes, closed depressions, extensional fractures, and faults associated with evaporite dissolution in the Texas Panhandle and neighboring parts of New Mexico, as well as damage to highways, stock tanks, and reservoirs. Remedial measures include filling of depressions in asphalt pavements with additional asphalt, and mud-jacking rigid concrete pavements such as I–40.

Evaporite dissolution has also been an issue in the siting of the Waste Isolation Pilot Plant (WIPP) near Carlsbad, where transuranic nuclear waste will be stored in Permian salt beds. Anderson (1981), for example, believed that the presence of a structurally complex disturbed zone beneath part of the WIPP is evidence for early stages of salt dissolution at the site. Davies (1989) reviewed a number of locations with evidence for large-scale evaporite dissolution, including a sinkhole in western Texas, two collapse chimneys in southeastern New Mexico, and a structural depression beneath the WIPP site, and proposed a generalized hydrologic model for dissolution of a salt layer underlain by a leaky aquifer. He also suggested that deformation related to evaporite dissolution can be characterized by two end-members, ductile downwarping and brittle collapse, that are functions of deformation rates.

Collapse of abandoned mine workings

Roads and structures have been damaged as a result of collapse of abandoned coal mines in the Cretaceous strata of the San Juan Basin in northwestern New Mexico (D.W. Love, 1991, personal communication). Likewise, road damage from subsidence in the Ambrosia Lake mining district has been reported (W. Bennett, 1991, personal communication). However, these problems have never been properly described in the geologic literature. Berzins (1985) conducted a numerical study to determine the feasibility of using gravity surveys to map abandoned mine workings, using the Heaton Canyon area near Gallup as a case study (Fig. 5). He calculated that anomalies associated with individual workings would be small, on the order of 0.1 milligal or less, and concluded that the anomalies would in many cases be overshadowed by observational errors in gravity field data. A companion study by Berzins and several other authors, which would have described the results of gravity surveys in Heaton Canyon, was never completed.

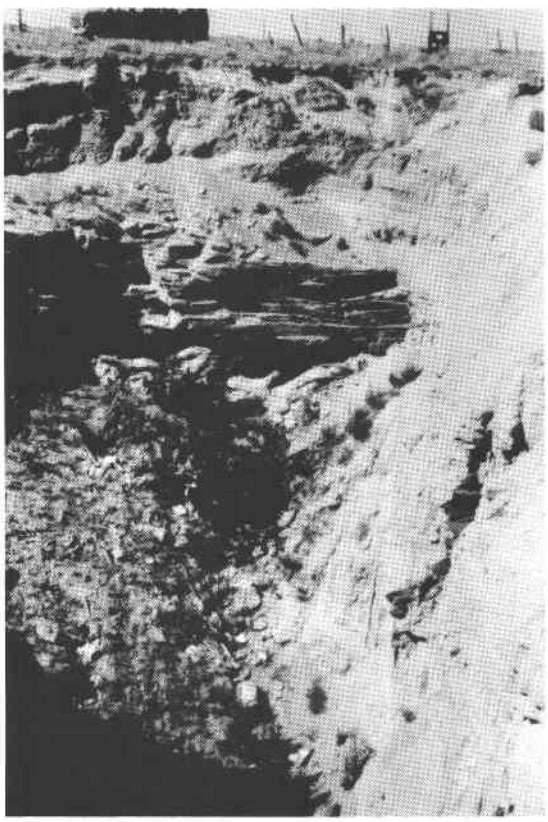

FIGURE 4—Sinkhole collapse near Santa Rosa. Dissolution of Permian limestones and evaporites at depth removed support for the shallower Santa Rosa Sandstone, which then failed under its own weight. The occurrence of karst features in an area with relatively insoluble sandstone near the surface emphasizes the fact that geologic hazards generally cannot be predicted on the basis of oversimplified geologic criteria, such as outcrop patterns on regional maps. Photo by J. W. Hawley.

Consolidation under loading

Consolidation of normally consolidated to underconsolidated engineering soils under heavy loads is a common geotechnical problem in New Mexico, as well as many other areas. For example, saturated alluvium along the Rio Puerco settled nearly 1 m during construction of I–40 near Gallup; however, early discovery allowed highway engineers to alleviate the problem by using reinforced-earth bridge abutments. The bridge that carries US–666 over I–40 in Gallup, however, was founded on piles. Therefore, the bridge remained stationary while the surrounding alluvium consolidated, requiring the design of unusually steep approaches (W. Bennett, personal communication, 1991). Similar problems occur in wet meadows in the Rio Fernando de Taos drainage just south of Taos where several houses have settled and cracked. Engineered structures in the area, including a large grocery store, appear to have suffered no damage. Similar problems no doubt occur along New Mexico's many alluvial valleys. Consolidation of saturated soils is a well-known problem in foundation engineering that can almost always be predicted during routine geotechnical investigations, however, and mitigated through proper engineering design.

Ground-water overdraft

Prudent regulation of ground-water consumption, particularly for irrigation, has allowed New Mexico to avoid the severe land subsidence problems encountered in Arizona, California, Nevada, and Texas. The only area of documented land subsidence associated with ground-water overdraft in New Mexico is in the Mimbres Basin near Deming in Luna County (Contaldo and Mueller, 1988, 1991a,b). Heavy agricultural demand since the turn of the century has created a basin-wide cone of depression with maximum water-level declines of approximately 30 m recorded south of Deming. Level lines across the Mimbres Basin have never be

FIGURE 5—Government-subsidized home damaged by subsidence over abandoned coal mines, Sky Village subdivision, Gallup. Photo courtesy of D. W. Love.

re-surveyed, so it is impossible to estimate accurately the magnitude of subsidence. However, comparison of changes in the elevation of isolated benchmarks and protruding well casings (Fig. 6; also see Contaldo and Mueller, 1991a,b) suggest that subsidence has been occurring at a rate on the order of 1 cm/yr. Integrated over eighty years of overdraft from the Mimbres Basin, total subsidence is estimated to be on the order of 1 m. Evaluation of subsidence potential is not routinely incorporated into ground-water resource studies in New Mexico, for example in the rapidly expanding Albuquerque and Las Cruces, New Mexico–El Paso, Texas areas. This is probably due to the lack of documented subsidence problems. One notable exception is a study by MacMillan et al. (1976), who evaluated the potential for land subsidence associated with the withdrawal of large amounts of saline ground-water from the Tularosa Basin in south-central New Mexico.

Earth fissures

A particularly striking form of ground failure is the development of large, open earth fissures, which have been reported in many areas of the Southwest (e.g., Holzer, 1984b). Contaldo and Mueller (1991a,b) described 13 occurrences of earth fissures in silty to gravelly basin-fill deposits in the Deming area, all within the cone of depression produced by ground-water overdraft. In some cases the fissures form polygonal or orthogonal networks, whereas in other cases the fissures appear as curvilinear features several hundreds of meters long. The fissures first appear as hairline cracks but can increase to several meters wide after erosion and piping during heavy storms. Unlike many earth fissures in central Arizona (e.g., Holzer, 1984b), which are generally attributed to draping of thin basin-fill deposits over bedrock irregularities along basin margins, the Deming fissures are clustered near the center of the basin. Haneberg (1990) and Haneberg et al. (1991) used a combination of shallow seismic reflection surveys, gravity surveys, and mathematical modeling of monoclinal flexure to investigate the geologic setting and possible origin of one Deming fissure, which apparently lies above several buried normal faults in basin-fill sediments. Friesen and Haneberg (1992) installed water-level monitoring wells and sensitive borehole tiltmeters to monitor deformation near the same fissure and reported diurnal, fortnightly, and annual cycles of deformation. The first two cycles are most likely related to daily barometric pressure fluctuations and earth tides, whereas the annual cycle is most likely related to seasonal irrigation schedules. Using subsidence data compiled by Contaldo and Muller (1991a,b), Haneberg (1992) estimated the vertical component of land subsidence as 3% of the observed water-level change and used this value to constrain the deflection of a thin elastic plate with spatially variable rigidity. His model showed that 12 of 13 fissure locations were within a zone of maximum concave-upward bending moments; however, bending-induced tensile stresses at depth were calculated to be much smaller than compressive lithostatic stresses from the weight of the plate. Therefore, the relationship between regional subsidence and fissure location in the Mimbres Basin remains unclear. The Deming fissures occur in sparsely populated range land so, although one fissure passes within several meters of an occupied mobile home, no structural damage has been reported. Nonetheless, the presence of large, open cracks presents a hazard to children, cattle, and vehicles.

Although earth fissures in the Deming area are clearly associated with ground-water overdraft both in space and time, other fissures are located in areas where ground-water withdrawal can be safely eliminated as a possible cause. Sanford et al. (1982, 1983) studied a 1,400-m-long earth fissure that appeared in valley-fill sands and gravels along the Rio Grande rift near San Marcial, New Mexico during a maintenance and overlay project along I–25 in 1981 (Fig. 7). The fissure could not be attributed to any known seismic activity and, on the basis of regional geophysical and tectonic data, Sanford et al. (1982, 1983) suggested that the fissure may have been the result of differential compaction of unconsolidated deposits over a buried fault scarp, a theory confirmed by the detailed geophysical investigations of Haneberg et al. (1991). Similar fissures, with no apparent relationship to ground-water withdrawal, have been reported elsewhere. For example, Bell and Hoffard (1990) and Bell et al. (1989) described fissures in

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FIGURE 6—Protruding water-well casing and pump near the center of the Mimbres Basin. The concrete pad was originally at ground level, but the land surface has been subsiding at an average rate of about 1 cm/yr since large scale irrigation withdrawals began in the early part of the century. Former NMBMMR engineering geologist Gary Johnpeer is standing next to the pump. Photo courtesy of D. W. Love.

FIGURE 7—Oblique view of a 1375-m-long earth fissure that opened across I–25 south of the San Marcial exit in 1981. When first observed, the fissure ranged from a hairline crack to a meter or so wide. Geophysical surveys (Haneberg et al., 1991) show that the fissure is located above a buried graben and is probably a product of differential compaction of basin-fill sediments and/or aseismic creep. Similar fissures south of Deming, however, are clearly related to ground-water overdraft in the Mimbres Basin.

Nevada, which probably formed in response to aseismic creep along known faults. Keaton and Shlemon (1991) and Baumgardner and Akhter (1991) described a network of earth fissures at a proposed low-level radioactive-waste disposal site near Fort Hancock, Hudspeth County, Texas. Keaton and Shlemon consider several geologic factors that may be responsible for the Texas fissures but do not favor any one explanation; Baumgardner and Akhter, however, speculate that the fissures may be related to **natural** dewatering of basin-fill sediments.

[Article will conclude in next issue.]

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