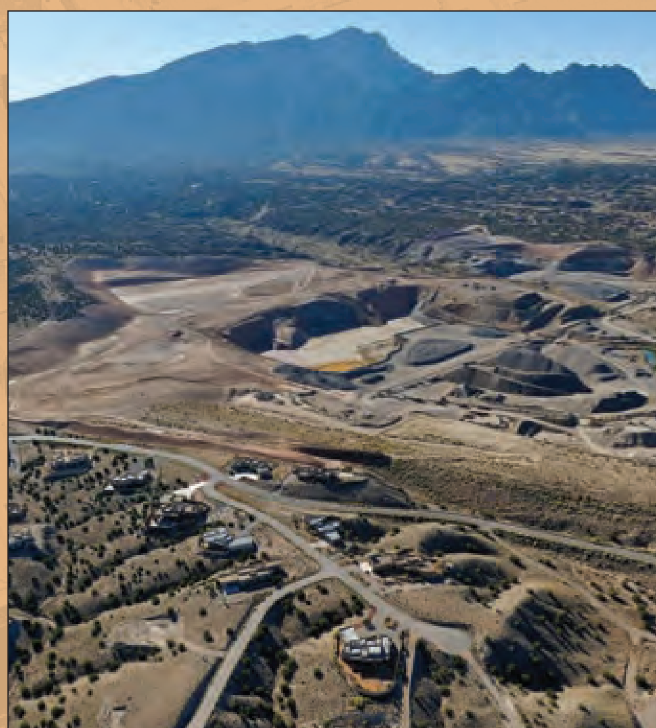
CHAPTER THREE

GEOLOGIC ISSUES ASSOCIATED WITH URBAN GROWTH

DECISION-MAKERS
FIELD CONFERENCE 2009
The Albuquerque Region



Lafarge North America's Placitas pit aggregate operation in Sandoval County.

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Mineral Resources and Urban Growth in the Albuquerque Region

Douglas Bland, *New Mexico Bureau of Geology and Mineral Resources*

It is a national disgrace that in a country as talented and affluent as America we should lack a clearly defined concept for the well-being of our natural resources—a concept that could be accepted and uniformly applied to all levels of government, by all of industry, and by all of our people.

—James Coxey, in *Fifth Forum on Geology of Industrial Minerals*, Pennsylvania Geological Survey Bulletin M64, 1970.

The greater Albuquerque area has experienced major growth in recent decades, as have many urban areas across the country. Urban development requires large quantities of natural resources, and today's society consumes them at increasing rates. This article will focus on mineral resources in the greater Albuquerque area, including the Rio Grande corridor from north of Bernalillo south to Belen, and the Rio Puerco from west of Rio Rancho east to Tijeras and the East Mountains area.

The geology of the Albuquerque region determines where specific rock and mineral resources are located. Most of the metropolitan area lies in the Rio Grande rift, which is both a topographic and structural low. It is filled with as much as 15,000 feet of sediments generally less than 20 million years old, largely clay, silt, sand, pebbles, and cobbles carried down the Rio Grande and eroded off the nearby mountains. The main marketable resource found in these sediments is aggregate. These rocks continue on the tableland westward beyond the Albuquerque volcanoes, visible on the western horizon from Albuquerque and Los Lunas. These volcanic cones and associated basaltic lava flows are the notable exceptions to this vast area of stream-derived sediments.

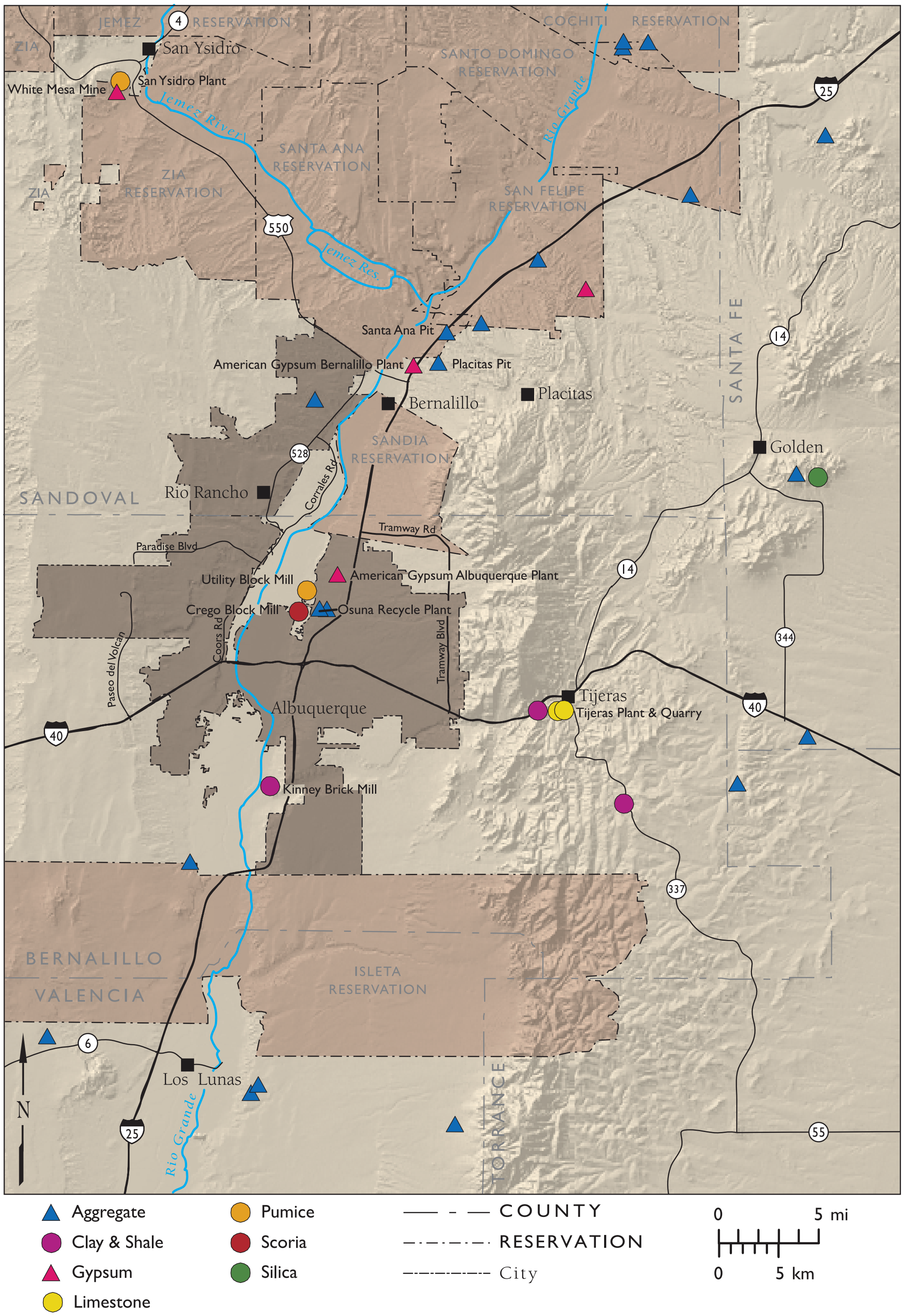
The eastern side of the Albuquerque area is bordered by the Sandia Mountains, where Proterozoic igneous and metamorphic rocks are exposed on the west face of the mountains. They are overlain by younger sediments, mostly limestones between 100 and 325 million years old that are found on the east side of the Sandias and in the Tijeras–Golden corridor. Mineralized areas have produced relatively small amounts of precious metals as well as industrial minerals and aggregate products.

In the early to mid-1900s minor amounts of gold, lead, and silver were mined from the Tijeras Canyon mining district in the southern Sandia Mountains, and small amounts of copper, lead, and silver were extracted from the Placitas area in the northern Sandias. All of these deposits are in veins in Proterozoic metamorphic and igneous rocks. Just to the east in the San Pedro Mountains southeast of Golden, more than $5 million ($13 million in today's dollars) worth of gold, copper, lead, zinc, and silver was produced in the early and middle parts of the twentieth century. The main orebody is in Pennsylvanian-age Madera limestone, which was metamorphosed by later igneous intrusions. The town of Golden still has remnants of its early mining heritage. None of these areas are currently being mined for metals, and potential for future development is low, although gold panning in streams and arroyos can still be productive. But the primary mineral resources in the Albuquerque area are aggregate, industrial minerals, and associated processing facilities.

INDUSTRIAL MINERALS MILLS

Gypsum, pumice, limestone, scoria (also called cinders), and clay are manufactured into finished products at mills and processing plants in and around the city. It is not essential to locate such facilities adjacent to the raw materials, and there are distinct economic advantages to locating them close to transportation corridors, machinery and materials suppliers, a work force, and consumers. Except for the Tijeras cement plant, all the mills in the Albuquerque area truck raw materials in from as far away as 75 miles. Processing plants have a smaller footprint than most mines and usually have fewer environmental impacts. However, plants engulfed by urban sprawl may come under public pressure to close or relocate due to perceived negative impacts (such as dust and noise) as land in the area shifts away from industrial use.

The Tijeras quarry and cement plant, visible just south of I–40 near the town of Tijeras, is the largest non-aggregate mining operation in the Albuquerque area. Limestone and shale from the Madera Formation are extracted and processed into cement on site. The operation has been active since the early 1960s



Mines and industrial minerals mills in the Albuquerque area, 2008. All mill facilities are labeled; sites without labels are mines. Currently there is virtually no mining taking place in urbanized Albuquerque because the land can be put to higher-valued uses. Several mills (most established decades ago) still exist within city limits, close to markets, suppliers, transportation corridors, and the work force. Data provided by Susan Lukas-Kamat, Mining and Minerals Division, New Mexico Energy, Minerals and Natural Resources Department.

Quarry wall in the Placitas pit, operated by Lafarge North America. The upper reddish overburden layer is unsuitable for aggregate development and must be removed and stockpiled for later use in reclamation. The underlying gray ancestral Rio Grande gravel deposits are loaded onto a conveyor belt (visible in the foreground) that transports the material to the screening and crushing plant.

and is the only cement plant in the state. American Gypsum operates two wallboard plants that process gypsum from the White Mesa mine just south of San Ysidro. The Bernalillo plant was opened in the early 1990s to supplement supply from the Albuquerque plant. Kinney Brick Company manufactures bricks at a plant on south Second Street near Rio Bravo. Until 1946 it used clay found on site; a pit in the Manzano Mountains now supplies the raw material. Utility Block Company uses pumice from the Jemez Mountains to manufacture concrete and masonry blocks in northwest Albuquerque. The Crego Block Mill, operated by Old Castle APG West on north Second Street in Albuquerque, utilizes red scoria from the La Cienega mine near Santa Fe to manufacture concrete blocks. Total sales from these mills in 2007 was valued at more than $150 million.

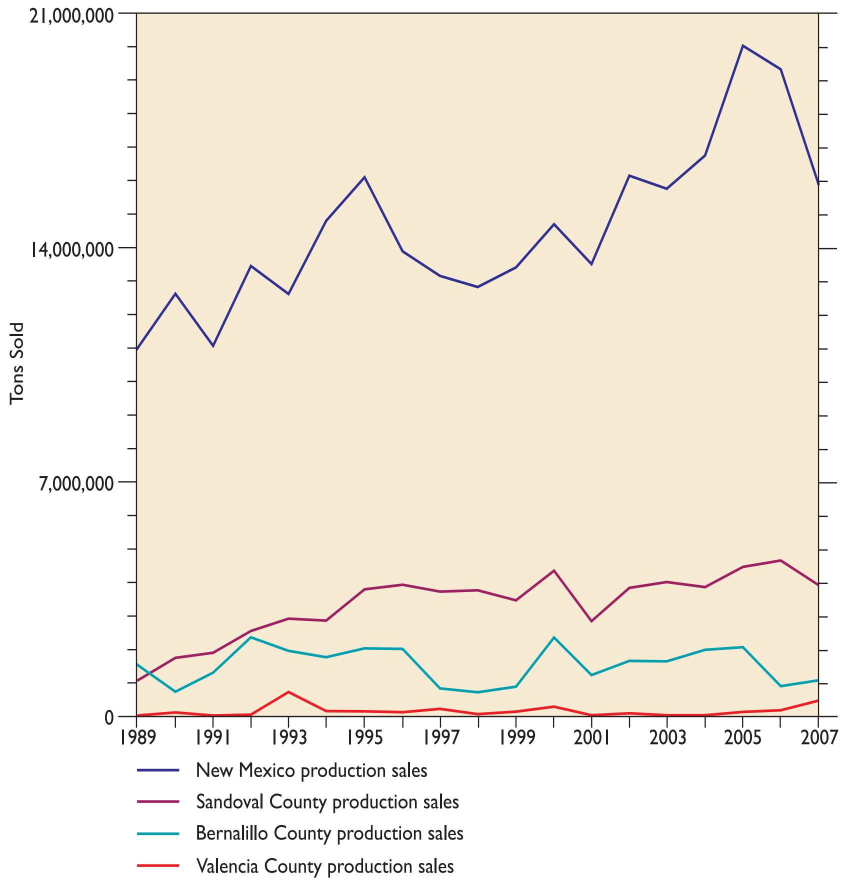
Aggregate

The earliest human settlements in the area used locally derived clay, sand, gravel, and rocks to construct dwellings and other buildings. Today aggregate and stone products are fundamental to the construction industry. Most are used in concrete, which is 85 percent aggregate, and in road construction. The valley-fill deposits around and under Albuquerque contain abundant sand and gravel, but most are not suitable for construction use. The aggregate required for products such as concrete must meet stringent specifications for composition, grain size, roundness, hardness, durability, and strength. Even though most of the near-surface geologic formations found in and around Albuquerque contain gravel, sand, silt, and clay in various proportions, operators seek deposits that require the least amount of processing and generate minimal waste. An ideal deposit is near the surface to minimize overburden removal costs and contains proper ratios of sand and gravel with specific rock characteristics. It has minimal silt and clay because there is lower demand for these materials. The ideal deposit is thick and laterally extensive. Most sedimentary formations contain layers of sandstone, mudstone, and gravel in varying thicknesses, and removing undesirable material is costly. Loosely consolidated deposits do not require blasting and simplify grain separation. Few deposits meet these geologic criteria, so operators must search for the formations that come closest to meeting their needs.

The typical aggregate operation transports the raw material by truck or conveyor belt to a processing plant on site. Here it is sorted by grain size by passing it over a series of screens, and it may be washed to remove fines (silt and clay). Some finished products must be angular in shape so that the material can interlock, increasing aggregate strength. Crushers convert cobbles into smaller fragments and create the desired angularity. If the operation supports a road construction project, an on-site “hot mix plant” combines aggregate with heated asphalt to make asphaltic concrete, or blacktop. Water is used primarily for dust suppression and washing. Water used for washing is usually recycled.

The Pleistocene-age Edith Formation, a Rio Grande terrace deposit less than one-half million years old, was an excellent source of aggregate. Found near the surface just west of I–25 primarily between I–40 and Tramway Boulevard, it is 10–35 feet thick, but it has now been largely mined out of the Albuquerque area. The largest aggregate operations in the area currently are located north of Placitas in older ancestral Rio Grande deposits of the upper Santa Fe Group, which are more than one million years old.

Aggregate extraction is big business in New Mexico. About 15.2 million tons of aggregate were sold in New Mexico in 2007, valued at $140 million. This is a drop of almost 20 percent from 2006 volumes, although sales value remained flat. Aggregate sales mirror activity in the construction and road building industries. The downturn in the economy in 2007 caused the reduction in sales from the previous year, whereas the spike in energy costs that year is reflected in the increase in unit sales price. Sales of 4.4 million tons valued at just over $50 million were reported from operations in the Albuquerque area, including Bernalillo, Sandoval, and Valencia Counties. Total 2007 employment at aggregate and industrial minerals mines and mills in these three counties was 649 with a payroll of about $23 million.



Aggregate sales in New Mexico and the Albuquerque area. In 1989 Bernalillo County produced over half of the aggregate in the metro area, but by 2007 most production had shifted to outlying areas in Sandoval County. The spike in 2000 was due to Big-I construction, and the drop in 2007 reflects the beginning of the current economic and construction decline. Data provided by Susan Lukas-Kamat, Mining and Minerals Division, New Mexico Energy, Minerals and Natural Resources Department.

CURRENT ISSUES

In an urban setting, a continuous supply of aggregate is required for new housing, commercial and industrial construction, and infrastructure such as roads, sidewalks, parking lots, and public works projects. Construction of an average American home requires 400 tons of aggregate; construction of one mile of a four-lane highway requires about 38,000 tons of aggregate. And it’s not just about growth; resources are required to maintain existing infrastructure as well. Quarries supply virtually all aggregate because recycling is usually not cost effective, although Lafarge Southwest, Inc. operates a facility on Osuna Road that recycles used concrete and other materials into other aggregate products.

Aggregate is a high-volume, low unit-price material, so there are significant economic advantages if it can be produced locally. One of the largest cost components of aggregate and stone products is transportation from the source to the point of use, most often by truck. Therefore, costs to the consumer go up dramatically as distance increases. If you want to buy gravel for your driveway, delivery costs can double or triple the total cost to you if you live 50 miles or more from the retail outlet. Temporary aggregate pits are opened near road construction projects in order to hold down trucking costs, then closed when the project is completed. Fuel costs are the primary factor; therefore, rising energy costs drive up the price of aggregate.

All mining, including aggregate extraction and processing operations, create environmental and social impacts that affect where such operations can be located. Permits and authorizations may be required that address air and water quality, noise, dust, water use, waste disposal, worker safety, and post-mining land reclamation. Some locations have land use or zoning restrictions. Most aggregate is transported using large haul trucks, which are subject to traffic laws and highway restrictions. Obtaining all the necessary permits to begin an operation may take years. Land owners may be reluctant to enter into leasing contracts if royalty income is delayed due to lengthy permitting time frames. In addition, land value can affect the economic viability of a potential operation. Large sites can cover hundreds of acres, and acquiring or leasing this acreage may be rendered uneconomic by competing residential, commercial, or industrial development opportunities that drive up the value of the land. For example, in recent decades the East Mountain area has seen rapid population growth and development as an extension of the greater Albuquerque area. As a result, land values have risen dramatically, making mining less feasible. Once development takes place, the area is "sterilized" for future mineral development because costs to acquire and re-develop the area for mining are prohibitive. In addition, there is often vocal opposition to aggregate operations located where they will impact the public.

In Albuquerque, as in most urban areas, higher transportation costs are overshadowed by other economic, environmental, and social factors, causing a migration of aggregate operations farther from population centers. Over 50 percent of the aggregate produced in Bernalillo, Sandoval, and Valencia Counties in 1989 came from Bernalillo County, which has become increasingly urban in recent decades. By 2007 it was less than 10 percent.

Sustainable Resource Management

New Mexico contains abundant aggregate resources; not all areas of the country are so fortunate. However, most sand and gravel deposits are not suitable for development for geologic, environmental, or social reasons. As a result, New Mexico operators are having increasing difficulty in locating and permitting deposits that are economic. The Albuquerque area is currently supplied by several large operations north of the city. But, resources available for extraction at these locations will be exhausted within the next 20 years, and replacement sites must be found. How can we ensure supplies will be available in the future? Recognition of the issues and planning can help. Certain areas of the country such as the Salt Lake City and Denver metropolitan areas have grown to the point where sources of aggregate are no longer available near where they are needed, largely due to resource sterilization. Laws, ordinances, and stakeholder groups have been established here and elsewhere to address the need for a continuous supply of aggregate at reasonable cost, to ensure certain known resources remain available for future use, and to address public concerns.

Compared to most mining operations, aggregate quarries are relatively benign. They involve a temporary use of the land, usually for a few decades at most. Although significant changes to the landscape will occur, proper operation management and site reclamation can help prevent environmental contamination and guarantee that a beneficial post-mine land use is achieved. For example, the Edith Formation aggregate operations along I–25 in Albuquerque were conducted before other development, and almost all of these sites have since been converted into commercial and industrial uses as the city has expanded. Rural sites can be contoured and revegetated with native seed to return the land to grazing or wildlife habitat. Reclamation is currently required for all operations on federal and state-owned lands, and those under contract to supply material to the New Mexico Department of Transportation for highway projects. Most large corporations now have company-wide reclamation policies.

Aggregate is important not only for urban growth, but also for maintenance of our infrastructure, residential neighborhoods, and commercial and industrial facilities. Even without significant growth in Albuquerque, it is essential that we maintain a continuous supply into the future. Citizens today expect to have significant involvement in decisions regarding if and how mining is conducted, and where such operations are located. Only with coordinated stakeholder involvement and improved planning can we ensure an adequate supply of aggregate while minimizing environmental and societal impacts.

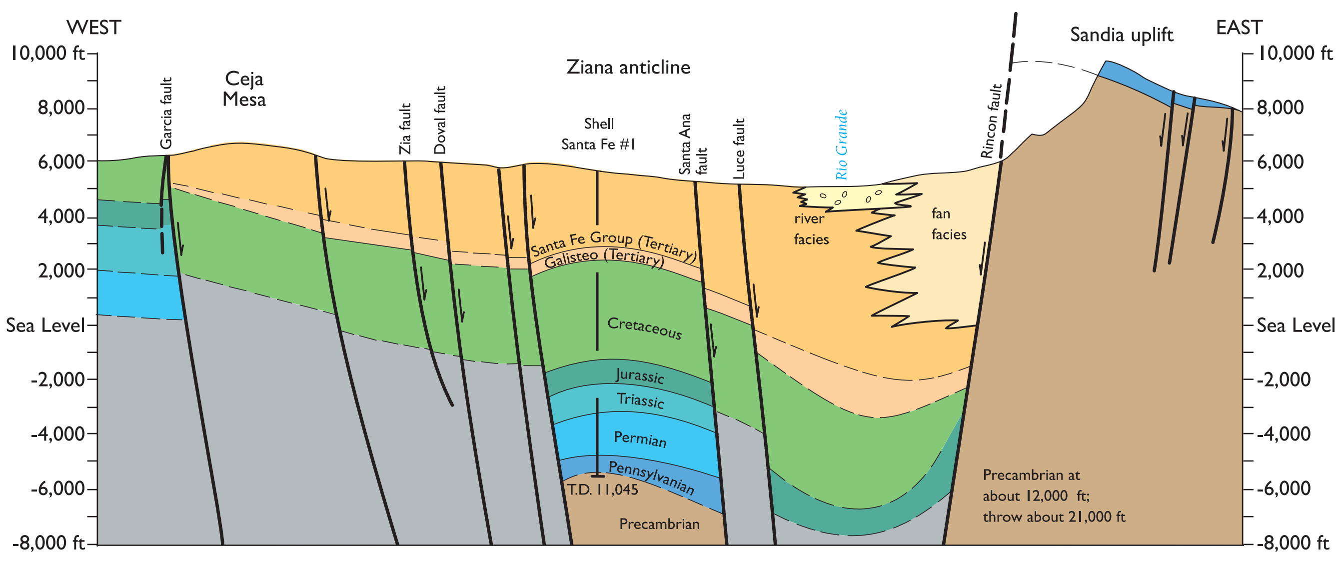
Oil and Natural Gas Potential of the Albuquerque Basin

Ron Broadhead, *New Mexico Bureau of Geology and Mineral Resources*

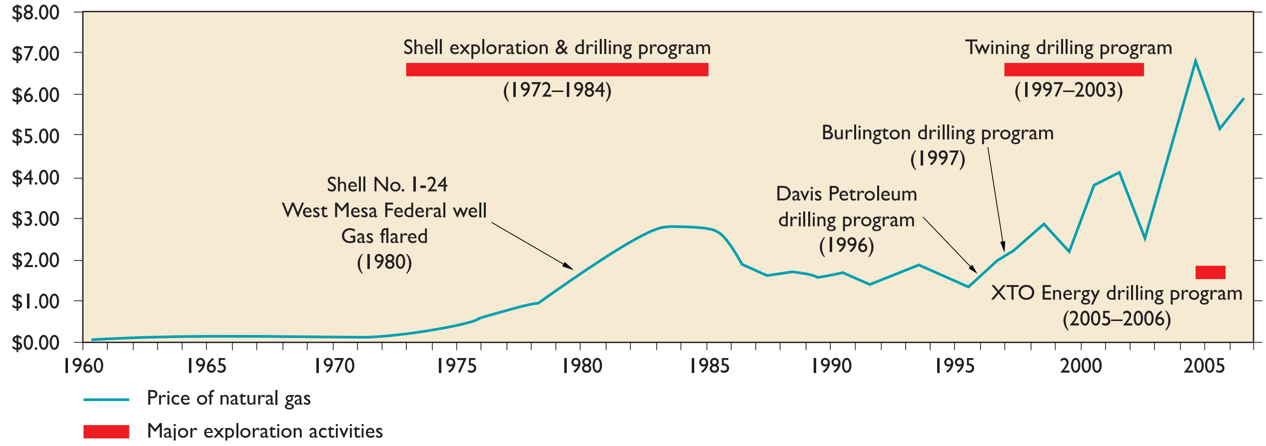
The Albuquerque Basin is one of several north-south aligned basins in New Mexico that form the Rio Grande rift. The Albuquerque Basin was formed by extensive faulting during the Tertiary Period, and its thick fill of Tertiary-age sands, gravels and clays (more than 4 miles thick in places) reflect its history of Tertiary faulting, subsidence, and sedimentary infilling. Beneath the Tertiary sediments lies a thick section of Cretaceous strata (as much as 5,000 feet thick) that is broadly similar in character to Cretaceous strata that are prolifically productive of natural gas in the San Juan Basin of northwestern New Mexico. Beneath the Cretaceous are 2,500 feet of Jurassic and Triassic strata, 2,000 feet of Permian sedimentary rocks, and almost 3,000 feet of Pennsylvanian-age sandstones, shales, and limestones. Cretaceous sedimentary rocks have been the objects of considerable oil and natural gas exploration since the 1950s. Some recently acquired data indicate that the deeper Paleozoic (Permian) section may have some intriguing natural gas possibilities as well.

In order for oil and/or natural gas to be present in a basin, four geologic elements are required: source rocks, reservoir rocks, seals, and traps. For an oil or gas field to form, all four of these geologic elements need to be present, and they need to be present in a geologically suitable arrangement. Oil and natural gas are generated from organic matter in a source rock after it is heated by deep burial in the earth's crust. The organic matter in the source rock is the altered remains of organisms that died at the time of deposition of the sedimentary rock and were incorporated into the rock-forming sediment and preserved through its burial. After the source rock is buried and heated to high temperatures for a sufficient period of time (millions or hundreds of millions of years, depending on the maximum temperatures attained), oil and/or natural gas are generated from the organic matter and expelled under pressure into adjacent reservoir rocks. In essence the elevated temperatures, if persistent over a long period of time, cause the organic matter to be "cooked."

Reservoir rocks are porous and permeable, that is, they contain a system of interconnected microscopic holes (pores) that allow oil, gas, and water to move through the rock. The pore system in reservoir rocks is filled with water (usually fresh at shallow depths and saline at greater depths) before oil and gas are generated in the source rocks. When oil or gas is expelled from the source rock into the reservoir, it



West-to-east cross section through the Albuquerque Basin showing distribution of strata and major structures. Cretaceous strata (shown in green) are the major targets for natural gas exploration in the basin. After Kelley 1977.



Average annual price of New Mexico natural gas (in dollars per thousand cubic feet) and major exploration activities in the Albuquerque Basin. Based on data from the New Mexico Taxation and Revenue Department, the New Mexico Energy, Mineral and Natural Resources Department, and the New Mexico Bureau of Geology and Mineral Resources.

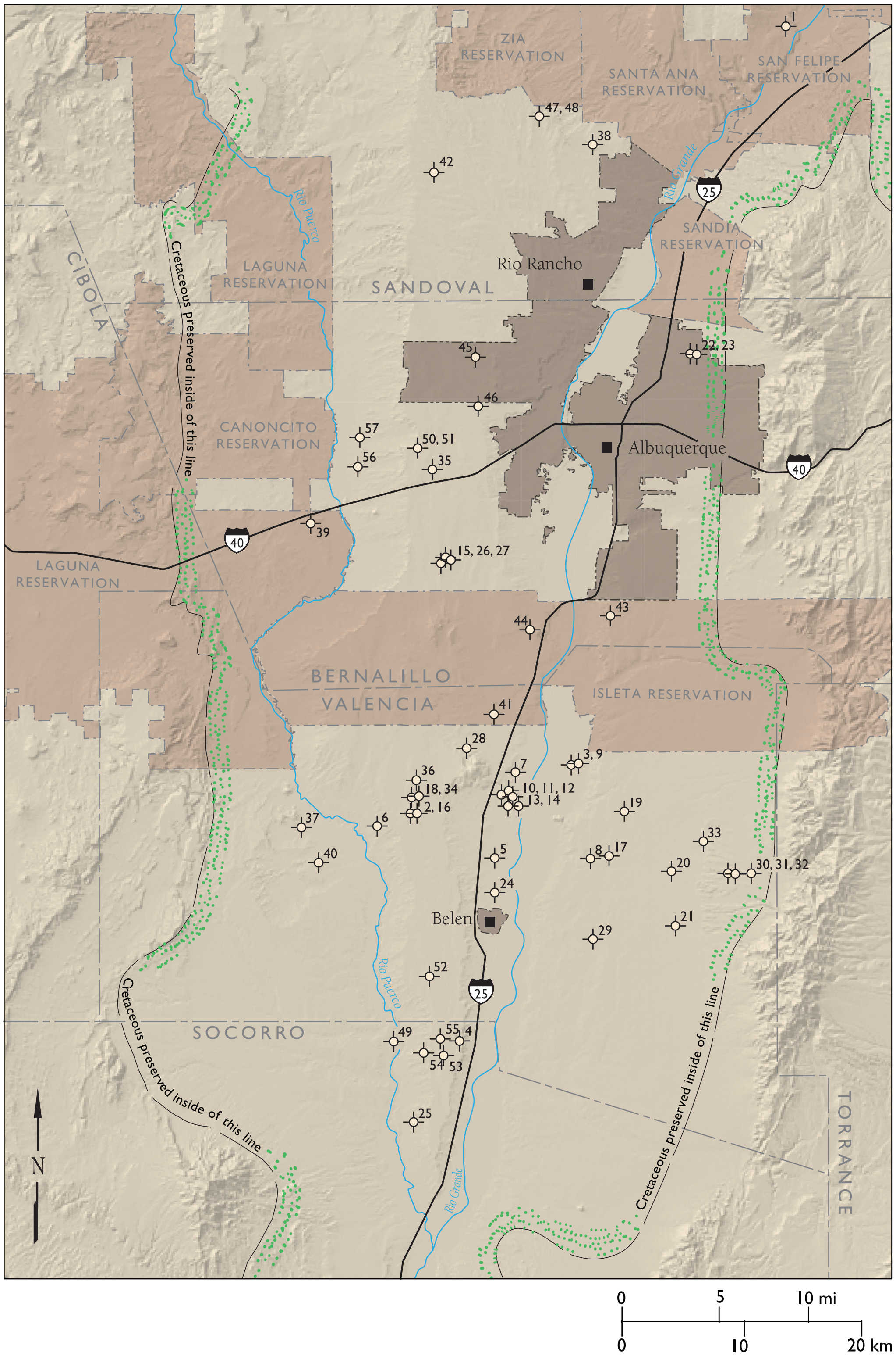
moves upward through the water-saturated pore system, because both oil and gas are less dense than water. Both the water and the oil and gas are contained in the reservoir by seals: nonporous, impermeable rocks that block the movement of fluids in the subsurface. When the oil or gas has moved upward to a place where further upward movement is blocked, a trap is formed, which results in an oil or gas field.

In the Albuquerque Basin, organic-rich source rocks are found in black, organic-rich shales of Cretaceous age. In the shallower parts of the basin, analyses of drill cuttings reveal that these rocks have not been heated to a sufficiently high temperature for a sufficient length of time to have generated maximum amounts of oil and gas—essentially they are undercooked in these areas. In deeper parts of the basin, the organic-rich Cretaceous shales have been cooked sufficiently to have yielded the maximum amount of oil and gas possible given their organic content—in geologic parlance, they are thermally mature. In many of the deeper areas, temperatures have been sufficiently high so that oil has been naturally refined into natural gas and gas liquids (including propane). The types of organic matter present in the Cretaceous shales indicate that they have generated mostly natural gas with secondary amounts of oil in places where they are mature. Therefore, the primary potential in the Albuquerque Basin is for natural gas. Reservoirs are Cretaceous sandstones that are interlayered with the shales. The shales form the seals as well as the source rocks. Exploration focuses on finding geographic areas that may be underlain by traps. The primary potential is for gas and associated natural gas liquids (including propane) or light oils in the deeper (greater than 15,000 feet) parts of the basin. Where shallower areas with immature source rocks are connected by migration pathways with deep areas of mature source rocks, the shallower areas are favorable as well. To date, most verifiable major shows of gas and oil encountered by exploratory wells have been in the deeper parts of the basin.

DRILLING AND EXPLORATION HISTORY

Oil and natural gas have been the targets of exploratory drilling in the Albuquerque Basin since the Tejon Oil and Development Corporation No. 1 well was drilled to a total depth of 1,850 feet between July 1912 and July 1914. By 1952 a total of 36 wells had been drilled, mostly to shallow depths less than 5,000 feet. These early wells were drilled primarily into Tertiary-age strata. Their locations and drill depths were based on concepts that lacked a modern understanding of the geology and geometry of the basin as well as a modern understanding of how oil and natural gas form and accumulate. Noncommercial "shows" of oil and gas were reported from many of the wells. However, because the nature of the shows was often not described, the authenticity of some of them may be in question.

The first well to penetrate and evaluate a significant thickness of Cretaceous strata was the Humble No. 1 Santa Fe Pacific well, drilled in 1953. Until this well was drilled, the presence of a deep rift basin filled with Tertiary-age sands, gravels, and clays as much as 22,000 feet (4 miles) thick was unrecognized. This well marked the beginning of modern exploration in the basin and provided the first geologic information on the depth, structure, and origin of the basin. A



Exploratory oil and gas wells that have been drilled in the Albuquerque Basin. Also shown is the limit of Cretaceous strata that defines the basin boundaries for exploration purposes. Well numbers refer to those in the table on the following pages.

nineteen-year hiatus ensued before the next exploratory well was drilled in the Albuquerque Basin.

During the 1970s and early 1980s the first sustained oil and natural gas exploration effort began in the basin. During this period Shell Oil Company conducted extensive seismic reflection surveys and drilled seven unsuccessful deep (and expensive) exploratory wells, several of which encountered noncommercial volumes or "shows" of oil and natural gas. As expenses for the exploration program mounted without a return on investment, Shell partnered with other companies to drill an additional two wells. Natural gas was reportedly flowed and flared at the Shell No. 1 West Mesa Federal well, but large expenses associated with drilling this deep (19,375 feet) well, combined with the low price of natural gas and apparently limited flow rates, contributed to the noncommercial nature of the reservoir encountered by the well. The UTEX Oil No. 1 Westland Development was drilled by UTEX Oil Company in collaboration with Shell and represented the last unsuccessful gasp of the Shell effort. Still, the wells drilled by Shell and its partners provided invaluable geologic information that has helped geologists develop an understanding of basin geology and has provided the foundation for all subsequent exploratory efforts.

The basin saw no further exploratory drilling until the post-Shell exploration phase began in 1995. In that year Davis Petroleum, in conjunction with Vastar Resources, drilled two exploratory wells. The first well was drilled near the northern end of the Albuquerque Basin. This well drilled the entire Cretaceous section but encountered only minor shows and was subsequently abandoned and converted to a water supply well. The second well was drilled at the southern end of the Albuquerque Basin and was abandoned when they reached volcanic rocks of Tertiary age. Similar to early wells in the basin, drilling depth was inadequate to penetrate Cretaceous strata, the primary exploration targets in the basin.

Burlington Resources followed by drilling two wells in the West Mesa area in 1997 outside of Albuquerque. These wells were located in the relatively shallow western part of the basin. Again, no production of either oil or natural gas was established. The Burlington No. 1Y Westland Development well was re-entered by Tecton Resources in 2007; a test of the Jurassic-age Morrison Formation near the bottom of the hole apparently resulted in recovery of water. Plans were announced to move uphole and test the Cretaceous-age Dakota Sandstone, but work of this nature had not taken place when this article was written. Further to the west and also on the West Mesa, XTO Energy drilled two wells during 2005 and 2006 to test the Cretaceous Menefee Formation, a known coal-bearing rock layer, for coalbed methane potential. After coring and extensive evaluation, the wells were plugged and abandoned without establishing production. Minor gas shows were recorded in at least one of the wells.

At the southern end of the basin, Twining Drilling Corporation drilled a series of wells during the late 1990s and early 2000s. Little data are available for these wells. Apparently most of the wells were drilled to an insufficient depth to penetrate Cretaceous strata, the primary modern exploration targets in the basin. None of the wells established production.

THE FUTURE OF OIL AND NATURAL GAS EXPLORATION IN THE BASIN

Rising prices for natural gas have generally been associated with increased exploration in the Albuquerque Basin. Within the last decade, average annual prices for natural gas have risen from less than $2 per thousand cubic feet to more than $5 per thousand cubic feet, with prices in 2008 exceeding $10 per thousand cubic feet on occasion. As a result, interest in exploration for natural gas and associated natural gas liquids and light oils has increased and will no doubt persist into the future. Wells drilled as part of Shell's exploration program in the 1970s and the post-Shell exploration that began in the 1990s have yielded an abundance of geologic information that previously did not exist and have provided invaluable information with which to understand the geology and petroleum potential of the basin. The refined geologic models derived from these data, as well as advanced, modern geologic concepts, will be used to identify target areas that have a maximum potential for yielding natural gas and oil and therefore lowering, but certainly not eliminating, the risk of drilling unsuccessful exploratory wells. The steep rise in natural gas prices over the past few years, plus improved exploration, drilling, and completion technology, will enhance the economics of exploring for, drilling for, developing, and producing natural gas in a basin such as Albuquerque where the target reservoirs occur at depths of 15,000 to 20,000 feet or more over large parts of the basin. Wells at these great depths will each cost several million dollars to drill, test, and complete. Higher natural gas prices can turn an uneconomic well into a commercial one. The high costs of drilling and inadequate technology were at least partially responsible for the abandonment of several of the deep

WELL NUMBER AND NAME	LOCATION (SECTION-TOWNSHIP-RANGE)	YEAR COMPLETED	TOTAL DEPTH (FEET)	REMARKS
1 Tejon Oil Development	7-14N-6E	1914	1,850	Reported oil show @ 1,000 ft.
2 Cal-New Mexico Dechares No. 1	8-6N-1E	1925	2,900	Reported oil & gas show.
3 Stone No. 1	25-7N-2E	1926	1,405	
4 Belen Oil Seipple No. 1	23-4N-1E	1926	3,545	Reported oil show.
5 Gilmore & Sheldon No. 1 Tome Grant	30-6N-2E	1926	1,180	
6 Hub Oil No. 1 HNTH	13-6N-1W	1926	3,425	
7 Stone No. 1 Horland	32-7N-2E	1927	2,144	Reported oil show.
8 Gilmore & Sheldon No. 1 Tome	30-6N-3E	1928	1,100	
9 Stone No. 2	25-7N-2E	1928	1,976	Reported oil show.
10 Harlan No. 1 Harlan Ranch	5-6N-2E	1930	4,223	Reported gas show.
11 Harlan No. 2 Harlan Ranch	5-6N-2E	1930	4,021	
12 Harlan No. 3 Harlan Ranch	5-6N-2E	1931	6,474	Reported gas shows.
13 Harlan No. 4 Harlan Ranch	5-6N-2E	1931	3,820	Reported oil & gas shows.
14 Harlan No. 5 Harlan Ranch	5-6N-2E	1931	4,007	Reported gas shows.
15 Norins No. 1 Pajarito Grant	22-9N-1E	1931	5,104	Reported oil & gas shows.
16 Western Natural Resources No. 1	5-6N-1E	1932	1,725	
17 Mills No. 1 Tome	29-6N-3E	1933	507	
18 Big Three No. 1 Dalies	5-6N-1E	1937	6,113	Reported oil shows.
19 Mills No. 2 Tome	9-6N-3E	1932	446	
20 Ringle Development Co. No. 1 Fee	36-6N-3E	1935	1,115	
21 Ringle Development Co. No. 1 Fuqua	13-5N-3E	1935	100	
22 Norins No. 1 North Albuquerque Acres	19-11N-4E	1935	573	
23 Norins No. 2 North Albuquerque Acres	19-11N-4E	1935	5,024	Reported CO_2 gas show.
24 Ringle Development Co. No. 1 Ringle	6-5N-2E	1935	750	
25 Central New Mexico Oil Co. No. 1 Brown	17-3N-1E	1937	2,840	Reported oil & gas shows.
26 Norins No. 2	22-9N-1E	1928	385	
27 Norins No. 3 Pajarito	22-9N-1E	1938	2,780	Completed as water supply well.
28 Joiner Petroleum No. 1 San Clemente	23-7N-1E	1939	5,606	Reported gas show.
29 Grober No. 1 Fuqua	19-5N-3E	1940	3,978	
30 Ringle No. 1 Tome	34-6N-4E	1947	823	Reported gas shows.
31 Ringle No. 2 Tome	35-6N-4E	1947	890	Reported oil show.
32 Ringle No. 3 Tome	34-6N-4E	1947	597	
33 S.M. Castleberry No. 1 Tome	20-6N-4E	1947	500	

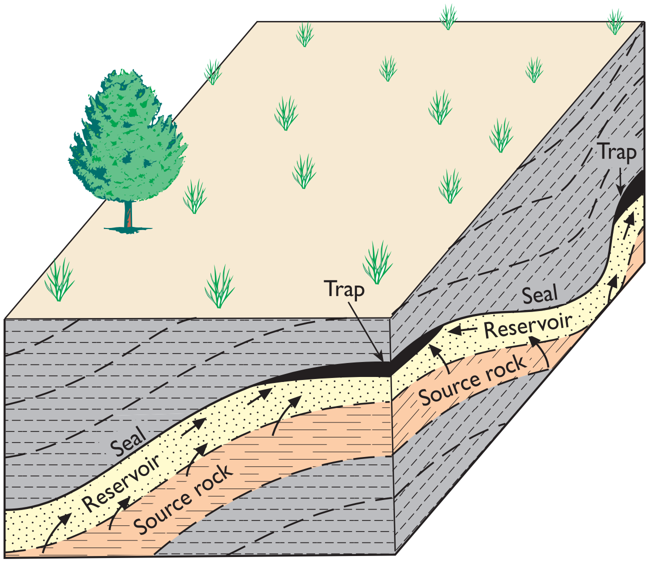
WELL NUMBER AND NAME	LOCATION (SECTION-TOWNSHIP-RANGE)	YEAR COMPLETED	TOTAL DEPTH (FEET)	REMARKS
34 Von Glahn No. 1 Dalies	5-6N-1E	1949	6,096	Reported oil & gas shows.
35 Carpenter No. 1 Atrisco	28-10N-1E	1948	6,652	
36 Long No. 1 Dalies	32-7N-1E	1952	6,091	Reported show oil & gas.
37 Humble Oil Co. No. 1 Santa Fe Pacific	18-6N-1W	1953	12,691	Reported gas show. Cretaceous strata from 9,930 to 12,691 ft.
38 Shell No. 1 Santa Fe Pacific	18-13N-3E	1972	11,045	Reported oil & gas shows in Cretaceous strata.
39 Shell No. 1 Laguna Wilson Trust	8-9N-1W	1972	11,115	Reported gas shows from Cretaceous strata.
40 Shell No. 2 Santa Fe Pacific	29-6N-1W	1974	14,305	Reported gas shows in Cretaceous strata.
41 Shell No. 1 Isleta	7-7N-2E	1974	16,346	Well reported to have flowed noncommercial volumes of gas from Cretaceous strata.
42 Shell No. 3 Santa Fe Pacific	28-13N-1E	1976	10,276	Reported minor gas shows in Cretaceous strata.
43 Transocean Oil Co. No. 1 Isleta	8-8N-3E	1978	10,378	Reported gas shows in Cretaceous strata.
44 Shell No. 2 Isleta	16-8N-2E	1979	21,266	Did not reach Cretaceous rocks.
45 Shell No. 1 West Mesa Federal	24-11N-1E	1980	19,375	Gas flared from Cretaceous reservoirs.
46 UTEX Oil No. 1 Westland Development	1-10N-1E	1984	16,665	T.D. in Tertiary basin fill.
47 Davis Petroleum No. 1 Tamara 3	3-13N-2E	1995	1,087	Well abandoned due to drilling problems. Replaced by No. 1Y Tamara (No. 49).
48 Davis Petroleum No. 1Y Tamara	3-13N-2E	1996	8,732	T.D. in Triassic. Minor shows reported. Converted to water supply well.
49 Davis Petroleum No. 1 Angel Eyes	19-4N-1E	1996	8,074	T.D. in Tertiary-age volcanic rocks.
50 Burlington Resources No. 1 Westland Development	21-10N-1E	1997	1,833	T.D. in Tertiary-age sediments. Well abandoned due to drilling problems. Replaced by No. 1Y Westland Development (No. 52).
51 Burlington Resources No. 1Y Westland Development (re-entered by Tecton Resources in 2007)	21-10N-1E	1997 (2007)	7,800	T.D. in Triassic. Re-entry perforated Morrison Formation (Jurassic) and recovered water.
52 Twining Drilling Corp. No. 1 NFT	33-5N-1E	1997	7,441	T.D. in Tertiary sediments. Plugged & abandoned.
53 Twining Drilling Corp. No. 3 NFT	27-4N-1E	2001	6,908	T.D. in Tertiary sediments. Perforated 4,784–4,904 ft with no reported shows.
54 Twining Drilling Corp. No. 2 NFT	28-4N-1E	2002	9,160	T.D. in tertiary sediments. Converted to water supply well.
55 Twining Drilling Corp. No. 1 NAT	22-4N-1E	2003	12,320	Perforated & fractured 11,936–12,279 ft. Plugged and abandoned.
56 XTO Energy No. 1 Armijo Trust	27-10N-1W	2005	6,080	Coalbed methane exploration well. Plugged and abandoned.
57 XTO Energy No. 15 Westland 1	15-10N-1W	2006	6,697	Coalbed methane exploration well. Plugged and abandoned.

GEOLOGIC ELEMENT	DESCRIPTION	PRIMARY OCCURRENCE IN ALBUQUERQUE BASIN
Source rocks	Organic-rich sedimentary rocks. Generate oil and/or natural gas when buried deeply for long periods of time.	Cretaceous shales
Reservoir rocks	Porous and permeable rocks through which oil and natural gas can move and accumulate.	Cretaceous sandstones
Seals	Impermeable rocks that block the movement of oil and gas.	Cretaceous shales
Traps	The geometric arrangement of a reservoir rock and a seal (or seals) that stops the natural upward movement of oil and gas through a reservoir rock.	Domes or anticlines associated with deep fault blocks.

Geologic elements needed to form an oil or natural gas field.

wells drilled by Shell in its exploratory effort in the basin. As already discovered productive gas reservoirs throughout the U.S. (including New Mexico) gradually become depleted, interest in exploration in "frontier" basins such as Albuquerque will increase along with the need to replace reserves that have been produced elsewhere.

If a future well encounters natural gas and natural gas liquids in a reservoir thought to have commercial viability, additional wells will be drilled to confirm the discovery and to evaluate field distribution and size. If the field as a whole is then considered to be economically viable, development wells will be drilled and production will follow. Given the great depths to potentially productive reservoirs in the deeper parts of the Albuquerque Basin, regulatory well density (or spacing) would likely limit the productive wells to one or two per section (square mile), although this may be doubled to two to four wells per section if the reservoir has low permeability. With the depths and reservoir pressures anticipated, this well density will allow for efficient recovery of gas from the reservoirs.



Typical arrangement of a folded reservoir rock, seal, and source rock that forms a trap.

Gas wells typically flow natural gas and associated liquids (natural gas condensates and light oils) to the surface, so that large pumping units typically associated with oil fields are not needed. Instead, only a small wellhead assembly will be visible, and the gas will be transported to market in underground pipelines. Unlike natural gas, liquid hydrocarbons can be stored temporarily onsite in above-ground storage tanks and trucked to market periodically. If the volume of liquids is sufficient, a separate pipeline system can be used to transport these commodities to market. By modern regulatory mandate, drilling sites are reclaimed and revegetated after drilling operations have ceased, whether the well is successful or not. Drillers are required to post a bond to ensure reclamation before any drilling can begin.

Suggested Reading

Oil and Gas Exploration in the Albuquerque Basin, B. A. Black, New Mexico Geological Society Guidebook 33, 1982.

Recent Oil and Gas Exploration in the Albuquerque Basin, B. A. Black, New Mexico Geological Society Guidebook 50, 1999.

Geology of the Albuquerque Basin, New Mexico, V. C. Kelley, Memoir 33, New Mexico Bureau of Mines and Mineral Resources, 1977.

Geologic Hazards in the Albuquerque Area

Dave Love and Sean D. Connell, *New Mexico Bureau of Geology and Mineral Resources*

Civilization exists by geologic consent, subject to change without notice.

—Will Durant

The study of geologic hazards is part of a broader sub-discipline of geology that addresses human/environmental relationships, where natural ecosystems interact with and are affected by human endeavors and values. This sub-discipline developed along with the environmental movement of the 1960s–1970s, so much of the defining literature comes from that era. According to the Federal Register, a geologic hazard is "a geologic condition, process, or potential event that poses a threat to the health, safety or welfare of a group of citizens or the functions or economy of a community or a larger governmental entity."

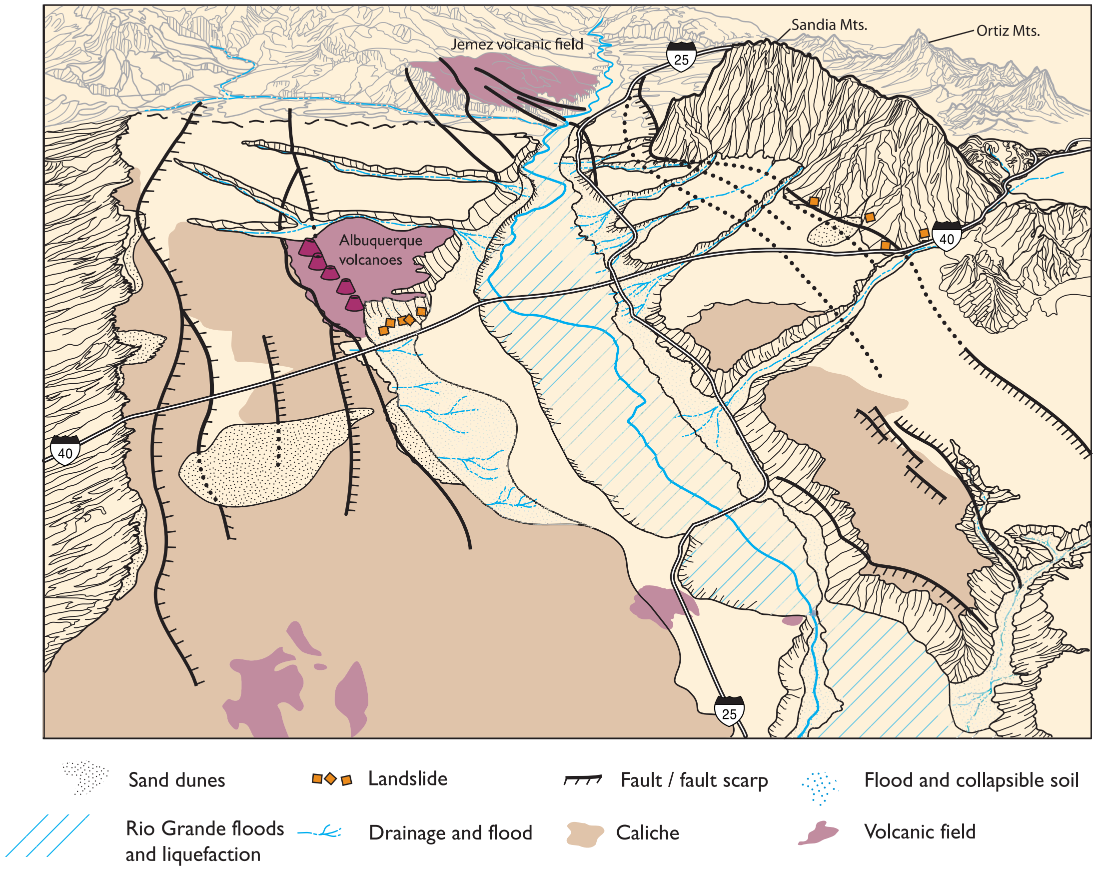
Geologists consider most geologic conditions and processes as natural and largely beneficial. Deposits laid down during ancient floods provide the skeleton of the regional aquifers, and the rocky remains of long-dead volcanoes provide aggregate to build city infrastructure. The term *hazard* implies unfortunate consequences for humans if they are nearby or ignore the evidence of ongoing destructive processes that episodically sculpt the earth. Geologists use the term *risk* to address the vulnerability and magnitude of consequences of natural hazards for human populations. Risk increases as hazard and vulnerability increase, and it reflects human attitudes and values. Risk is largely due to the types and extent of human activities without regard for natural processes. In New Mexico as in other parts of the world, human attitudes range from being fatalistic to anticipating natural disasters, recognizing the long-term benefits of mitigation procedures, and practicing responses to infrequent, high-consequence events. In the long run, many natural hazards are inevitable and others are avoidable, so the loss of life and property depends on our attitudes and willingness to prepare.

Evaluating risk involves probabilities, cost/benefit ratios, comparison to other risks, consequences of legal processes, and consideration of potential political consequences. We all measure risks in our daily lives and modify our behavior to reduce them. Insurance is one common type of risk preparedness. Seatbelts are a form of risk reduction. We cannot stop all accidents, but by building safer cars and wearing seatbelts, we can lessen injury to ourselves if an accident happens.

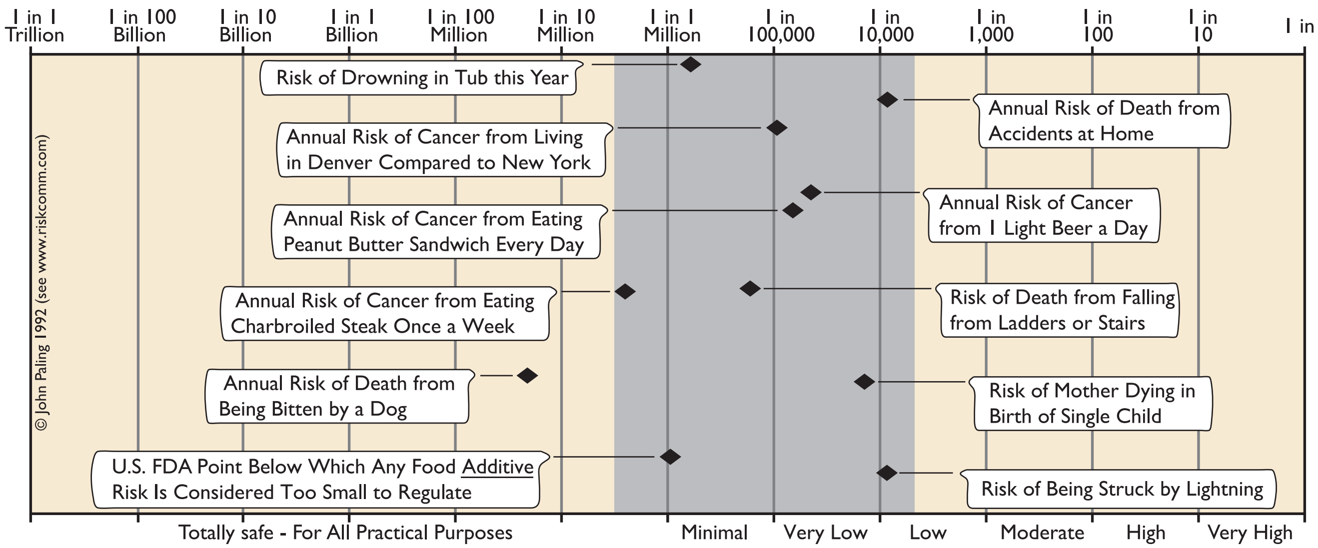
Just as human risks range from annoyances to major threats, natural hazards come in many shapes, sizes, and types, which range from local nuisances (daily dust) to major disasters (tornadoes or magnitude 7.0 earthquakes). Some hazards become disasters with an instantaneous onset such as earthquakes and rockfalls. Other hazards have a gradual build up until a related event triggers a disaster. And some hazards, particularly those geochemical accumulations in the ground, are gradual and have no triggered result. Major disasters tend to occur less frequently than minor ones, so we are more apt to put up with minor nuisances and regard major disasters as too far removed from daily living to prepare plans for action.

Sudden disasters can produce a cascade of related events and consequences that may be anticipated and avoided through engineering design. Floods in the valley can cause disruptions to transportation, drinking water, sewer lines, and other utilities. Large earthquakes commonly produce related disasters (including fire, ruptured water and sewer lines, building distress or collapse, and transportation disruptions) that may overwhelm our ability to respond.

Humans modify their environment to suit their immediate purposes with little regard for the long-term consequences. For example, at a well site near Lincoln Middle School in Rio Rancho, the ground had natural vegetation and no paved roads in 1981. Construction of the school began in 1982, and by 1986 all nearby roads and the school parking lot were paved, and several houses had been constructed across from the school. The dark asphalt, sidewalks, roofs, and other structures absorbed sunlight and heat, much of which formerly was reflected back into the atmosphere. Temperature logs of the well showed a 6.7° F increase in surface temperature after the area was paved. This addition of heat to the shallow subsurface will undoubtedly contribute to the "heat island" effect of higher daytime and nighttime temperatures observed in most urban settings. The absorbed heat will probably affect the number of heating- and cooling-degree days for the school and homeowners. Use of light-colored, more reflective surfaces in the built environment should reduce the amount of heat added.



Computer-generated oblique view of the greater Albuquerque area illustrating some of the locations of geologic hazards.



Comparative risks for death from various causes. The Paling Perspective Scale © John Paling 1992, showing risks with which we are "at home." Horizontal scale is a logarithmic one. All rights reserved. See www.riskcomm.com.

Geologic hazards can be put in three categories: surface processes, deep-seated processes, and geologic materials. Albuquerque's geologic hazards stem from natural, dynamic, long-term processes and from properties associated with certain geologic materials. Geologic processes that take place at the earth's surface or in the subsurface include sand storms, flash floods, earthquakes, and volcanic eruptions. Hazardous geologic conditions pertain to whole landscapes, individual landforms, or the properties of geologic materials. Hazardous conditions commonly develop more slowly and tend to be more widespread, subtle, and harder to detect and mitigate. For example, soils that are dry and loose build up in alluvial fans on the piedmont slopes west of the Sandia Mountains and in fans that border the Rio Grande valley. These deposits were created during many ancient runoff events over thousands of years. They support the foundations of thousands of houses and buildings in the Albuquerque area. Problems occur when people add extra water to these soils. When wetted, loose grains settle closer together, soils compact, and the surface subsides unevenly, damaging foundations not designed for this type of soil. Soil subsidence breaks water and sewer lines, disrupts other utilities, and causes undulating thoroughfares.

In developing the information we need to address issues of hazard and risk, we must be specific about the particular questions that need to be asked. Are local conditions being examined before siting and design of critical facilities that must remain operational after a disaster? Are we meeting the differing requirements for land stability in the design of a reservoir, nuclear reactor, hospital, school, or residence? Are designers considering the potential for damage from more distant sources of hazard, such as an earthquake fault? Engineers can design structures to resist many types of hazards, but such hardened construction is far too expensive to implement except for critical facilities.

HAZARDS RELATED TO GEOLOGIC PROCESSES

Runoff and Channel Migration

Intense, short-duration rainfall is common during the summer months in New Mexico. Large volume rainfall quickly overwhelms the soil's ability to absorb moisture, resulting in rapid runoff and flooding. In uninhabited areas, the resulting runoff is considered normal and beneficial. In urban areas, the natural soils have been replaced with impervious pavement and concrete. With adequate storm drains, street runoff is a minor inconvenience, but in rapidly developing areas or areas without adequate artificial drains, floods and related debris run-out zones are nearly annual events with high costs to individual property owners, farmers, government agencies, and many others. The frequency of such disasters tends to increase with the expanding footprint of development. Although the effects of global climate change on the central New Mexico environment are not entirely well understood, it is likely that the normal rhythms of rainfall and flooding will change in the future. So forecasting the frequency of major flood events, such as the so-called "hundred-year flood," will become increasingly problematic.

Flooding along Lomas Boulevard between Morningside and Washington in August 1990.

Natural river and tributary channels migrate from side to side, and meander bends tend to migrate downstream through time, eroding and shifting their banks and channels as they go. Channel incisions tend to migrate upstream, deepening the channels through time. Large pulses of eroded sediments, on the other hand, migrate downstream. Each of these processes and resulting removal and/or addition of sediment can cause problems for humans who expect their environment to stay the same. Some of the earliest lawsuits in Spanish New Mexico were because the Rio Grande and Rio Puerco channels shifted across their valleys, affecting the demarcation of land grant boundaries. Even now urban developers fail to recognize the natural changes in river and tributary channel morphology. Development can increase the frequency of floods and the risks to private property. Flood control in Albuquerque is addressed specifically in the chapter by John Kelly and Fritz Blake in this volume.

Earthquakes

Earthquakes are generated when stresses at depth overwhelm the strength of the rocks, and they break and are offset. In New Mexico much of the subsurface stress is related to east-west stretching across the Rio Grande rift and the Basin and Range province. The offsets along the faults are also responsible for many of the mountain ranges along the rift boundaries, such as the Sandia Mountains. Earthquakes can also be generated by stresses related to molten rock in the earth's crust, particularly in the region near Socorro.

Based on measured quakes since 1962, New Mexicans may expect about 19 earthquakes per year of magnitude 2.0 or greater (which can be felt by most nearby humans), and four quakes per year of magnitude 3.0 or greater. The largest earthquakes in New Mexico since 1850 rattled the Socorro area in 1906, three with estimated magnitudes of 5.6, 5.8, and 6.2. These quakes were part of a swarm that began in 1906 and continued into 1907. Other significant swarms of earthquakes have shaken Belen (in 1937), Mogollon (in 1938), and Raton (in 2008). No ground-rupturing earthquakes with extensive damage to structures are known to have taken place since the Spanish arrived in New Mexico more than 400 years ago. Of the Rio Grande pueblos, only Santa Clara Pueblo has a word for earthquakes; the pueblo is close to the very active Pajarito fault system. South of the New Mexico–Arizona border in 1887, a magnitude 7.4 earthquake devastated the region along the Pitaycachi fault, rupturing the ground surface as much as 13 vertical feet along the fault scarp for 63 miles. During the 1887 earthquake, whole villages were knocked down; chimneys in Silver City fell, and church bells rang as far north as Santa Fe. In New Mexico dozens of fault scarps tens of feet high from repeated movements show that on average large earthquakes shake the state about every 400 years.

The greater Albuquerque area has experienced a number of moderate earthquakes in the past. In 1893 several adobe buildings in the village of Los Lunas were knocked down, and dust filled the valley. In 1971 a magnitude 4.7 quake shook Albuquerque, causing $30,000 to $40,000 damage ($162,000 to $216,000 in inflation-adjusted dollars) to the University of Albuquerque and its closure (it later became St. Pius High School), and causing a Persian gazelle at the zoo to panic, run into a wall, and die.

Twenty-seven young faults (younger than 1.8 million years) have been identified within 25 miles of downtown Albuquerque. The formally designated County Dump fault near the top of Nine-Mile Hill on the west side of Albuquerque has had as many as 14 ground-rupturing earthquakes in the past million years, with the last three events occurring at about 30,000, 40,000, and 85,000 years ago. Based on an earthquake scenario of a magnitude 7.0 quake along the Sandia–Rincon fault by Ivan Wong and others, violent shaking with Modified Mercalli Intensity of IX would damage most structures from Placitas to Four Hills.

Liquefaction is one of the many consequences of earthquakes. In soils with a potential for liquefaction, violent shaking during an earthquake causes shallowly buried and water-saturated sediment to flow as a slurry of sand grains and water. Liquefied soils can no longer support the weight of buildings or energy infrastructure, and structures may sink, roll, or spread apart. These soils are only temporarily liquefied during an earthquake, but they can cause considerable damage. Saturated sand beneath the Rio Grande floodplain is particularly susceptible to liquefaction. However, long-term pumping has lowered the water table in many places under the Rio Grande valley below 32 feet, the depth at which liquefaction is effectively low.

Volcanic Activity

Albuquerque is surrounded by volcanic fields, so it is reasonable to consider the potential hazards of living near volcanoes. Many of the volcanic features near Albuquerque formed as the result of relatively short-lived volcanic eruptions during which lava flowed smoothly away from vents. This type of volcano is not normally explosive, but lava buries anything in its path. The youngest volcanic features are at Petroglyph National Monument, where lavas flowed from a series of vents into the Rio Grande valley about 156,000 years ago. Younger eruptions have occurred south and west of Albuquerque. Eruptions north and south of Albuquerque (those associated with Canjilon Hill, for example) heated ground water to generate violent steam and ash explosions.

It is possible that parts of Albuquerque will be affected by volcanic activity in the future, but modern monitoring of volcanoes indicates that eruptive events tend to give warnings. Before a volcano can erupt, subterranean conduits must first be formed. These would likely be recognized by changes in ground water quality and an increase in heat flow and water temperatures.

Distant but violent volcanic eruptions could also affect the Albuquerque area. A major eruption in the Jemez Mountains would shroud the region in volcanic ash, damaging vegetation, houses, and automobiles. However, the ash might also provide nutrients to the soil and temporarily decrease alkalinity in caliche soils.

HAZARDS RELATED TO GEOLOGIC MATERIALS

Geologic materials such as silt and sand are defined by their inherent geochemical properties and the physical organization of mineral grains and cements between the grains. These properties reflect the geologic conditions under which the grains and cements formed, and their subsequent modification. When humans modify the natural environment, they may upset the stability or geochemical environment locally or within larger areas. Here are a few examples of how these basic properties of materials pose hazards for unwary people.

Boulders lifted off bodies

Three people died on July 11, 2008, in Gallup when boulders, one weighing as much as 25 tons, broke loose during a rainstorm and fell on them. Headline from *The Gallup Independent* newspaper. In September 1989 five passengers were killed and 14 injured when their bus was struck by a large boulder as it traveled along NM–68 between Embudo and Pilar.

Caliche Soil

Gardeners in Albuquerque and throughout New Mexico complain that it is difficult to grow plants in "hardpan" or caliche soil. Caliche is a natural buildup of powdery calcium carbonate (limestone) just below the ground surface. The abundance of calcium carbonate in the soil is unique to the semiarid regions of the southwestern U.S. These soils are not found in moister environments, and their presence points to geologically long-term aridity and drought. The thickness of this type of hardpan tends to be related to the age of the deposit; older stable desert soils have more caliche than young soils.

Even though caliche is not a threat, its accumulation influences the welfare of the population because it affects the agricultural properties of soil, making it less permeable, more alkali, and less hospitable to plants. Less permeable soils increase the potential for runoff during intense rainstorms. Caliche also affects the geochemical properties of the soil, enhancing the corrodibility of metal pipes and cables used by utilities. Uranium and other radioactive elements also tend to concentrate in caliche soils. Very old soils have accumulated so much calcium carbonate that utility companies find it difficult to excavate trenches to lay pipes and cables. This difficulty affects the cost of development and commerce. Caliche is a minor irritant to people's eyes, skin, and respiratory tract, but may be a beneficial source of calcium, similar to acid-reducing properties of antacids such as Tums™.

HAZARD	FREQUENCY
Hailstorm with hail greater than 0.75 inch in New Mexico	There have been 400 such events in the past 40 years in June alone
Hailstorm with hail greater than 2 inches in New Mexico	There have been 100 such events in the past 40 years
Overbank flow (out-of-channel natural "flood") along perennial stream	1/2 or one event every 2 years
Overbank flow along ephemeral stream	1/5 or one event every 5 years
Earthquake greater than magnitude 6.5 in New Mexico	1/400 or one every 400 years
Earthquake in Socorro area yielding a peak ground acceleration of at least 15 percent of gravity (damage to some structures)	About 1/10 in 50 years or one every 500 years
Volcanic eruption in New Mexico	1/10,000 or one every 10,000 years
Caldera-forming eruptions in the Jemez Mountains	1/1,000,000 or one every million years

Ranges of frequency of natural events (*hazards*) in New Mexico.

Indoor Radon Gas

Radon is a colorless, odorless, radioactive gas that may cause lung cancer when elevated concentrations are inhaled over long periods of time. Radon is a daughter product by decay of uranium from natural fission; it in turn decays to other radioactive solid particles that are more difficult to inhale. Radon is in outside air in extremely low concentrations but may build up in rock fractures, soils, and in water. It can become a hazard by leaking into houses through cracks in foundations, from natural building material such as adobe or certain rocks, or via water usage. Radioactive daughter products may also adhere to dust and subsequently be inhaled or ingested. To lower the health risks associated with radon, test living areas for radon concentrations using a commercially available detector, and ventilate those areas if radon is above the limits established by the U.S. Environmental Protection Agency (EPA).

Arsenic in Ground Water

Elevated levels of arsenic in drinking water have created a major and costly headache for the city of Albuquerque, which has developed a broad strategy to deal with the problem and meet the EPA standard of 10 ppb (parts per billion). For perspective, 1 ppb is comparable to the area of one nickel on the 94-acre Albuquerque Balloon Fiesta Park. Arsenic is a natural element in many rocks and in ground water and has been long promoted for its questionable therapeutic value at hot springs. However, high levels of arsenic can cause cancer, skin problems, and circulatory problems, and arsenic is a developmental, cardiovascular, gastrointestinal, and liver toxicant. Arsenic is ranked as one of the top ten natural chemical hazards to humans. Water wells in Albuquerque contain varying amounts of arsenic, with some wells having more than 50 ppb. Arsenic in Albuquerque ground water is apparently natural and not related to past use of pesticides or other human activities. This arsenic was probably dissolved from iron-rich coatings on sand grains, clays, volcanic rocks, hydrothermal deposits like travertine, and iron sulfides. The Albuquerque Bernalillo County Water Utility Authority is currently removing arsenic from ground water or diluting ground water with water from the San Juan–Chama Project.

Collapsible Soils

Collapsible soils are soils that compact to lesser volume as they are wetted. Originally these soils consist of loosely packed grains of sand, silt, and clay with a lot of open void space between the grains. As water is added, the grains slip closer together to fill the void space between them, a process called *hydrocompaction*. The loss of volume can be significant—as much as 10 percent of the initial volume. Collapsible soils are common in the Albuquerque area outside of the well-watered valley. Extensive damage to homes, business facilities, roads, and utilities have been reported from the northeast heights, Rio Rancho, and Sandia Pueblo.

At Albuquerque's Montessa Park in Tijeras Arroyo, several warehouses have been severely affected by collapse underneath their foundations, where differences in elevation are between 2.0 and 2.6 feet and the foundations and door frames are buckled. As much as 80 feet of poorly sorted and unconsolidated sand and mud underlie the buildings above the water table. The upper 59 feet of soil without the weight of the buildings would compact about 5 percent and would cause surface subsidence of about 4.25 feet. The added weight of the buildings would increase the amount of compaction, so the subsidence seen at the surface is far from complete.

Collapsible soils, for the most part, are relatively simple to delineate. In the Albuquerque area, they tend to be common in geologically young alluvium that forms the floors of arroyos and broad fans along the margins of the Rio Grande valley. These soils can be identified by geotechnical tests. In areas that have not been developed, soils should be tested for collapsibility as well as other problems (shrink/swell potential, corrosiveness, and depth to bedrock). If collapsible soils are thin, they may be removed and compacted with heavy machinery. If collapsible soils are thick, large tracts may be settled by wetting the soils to depth before development takes place. Roadways have also been compacted by repeatedly dropping heavy weights from a large crane. New foundations should follow construction guidelines of the National Research Council's Building Research Advisory Board. Pylons not fixed to solid subsurface materials and "slurry jacking" do not work in collapsible soils.

In areas that have already been developed and then are later discovered to contain collapsible soils, property owners should try to keep as much water as possible from seeping into the ground. Downspouts and storm sewer lines should be installed to remove rainfall runoff from near the foundation as quickly as possible. Xeriscaping should replace thirsty lawns and shrubbery, particularly near building foundations. Municipal water and sewer lines rather than individual wells and septic tanks should be used.

Another type of collapsible soil is present beneath the floodplain of the Rio Grande. As the inner valley of the Rio Grande filled with sediment, thin lenses of low-density peat, representing former ponds and marshes, became buried. As pumping of ground water from parts of the valley progresses, these peat deposits dry and compact, resulting in local damage to buildings in the North Valley.

Buckling of the south end of the Kaibab Warehouse #1 at the city's Montessa Park facility due to soil collapse of about 2.5 feet. The cracks in the foreground encircle the deepest part of the collapse feature, to the left of the building. Runoff from the roofs, pavement, and facility water use entered the soil, causing it to compact. Subsurface tests show that more subsidence is likely unless all surface runoff is eliminated.

Land Subsidence

Land subsidence is the sinking of the earth's surface caused by the extraction of petroleum or ground water. Differential subsidence can damage buildings and stress pipelines, resulting in costly repairs or condemnations. Cities such as El Paso and Phoenix, which have extracted ground water from alluvial aquifers, have suffered extensive damage due to land subsidence. Until recently Albuquerque derived all of its domestic water supply from alluvial aquifers, resulting in local declines of more than 120 feet in the water table (see map in the paper by Dianna Crilley in this volume). Parts of Albuquerque have changed elevation slightly in response to ground water pumping but have not encountered any obvious significant damage. A reason why Albuquerque has not yet suffered from subsidence due to long-term ground water pumping is that the Rio Grande has cut a relatively deep valley into the upper part of the aquifer, which effectively preconditioned the aquifer to ground water pumping. Computational models of land subsidence predict that with continued pumping, Albuquerque may someday feel the effects of land subsidence.

WHAT CAN WE LEARN ABOUT NATURAL HAZARDS?

Although nature often seems quiet and serene, much of our present geologic landscape formed during short, energetic fits that were ultimately responsible for creating the foundations of our city. The notion of geologic hazards may instill a sense of futility, but much can be done to either avoid them altogether, or at least to minimize their impacts. Citizens should be aware of their surroundings and not assume that nature is always benign or controllable. The risks from most geologic hazards can be estimated. Recognizing the risks of costly or catastrophic geologic hazards can promote rational avoidance and mitigation plans. These strategies have proven very cost effective in other western states and tend to have benefits for mitigating other hazards.

Geologic input is essential to understanding geologic hazards. Geologists are generally quite knowledgeable about hazard processes, frequency, and severity. Geologic maps and other databases may be used to identify possible hazards for a specific area, but some site-specific investigations may be required. Risk management, including avoidance or mitigation of many hazards, is well understood; however, preparation and mitigation won't be done without the continuing support of public officials and the citizenry.

Suggested Reading

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Flood Control Challenges in Bernalillo County

John P. Kelly, P.E., *Albuquerque Metropolitan Arroyo Flood Control Authority*
Fritz Blake, *U.S. Army Corps of Engineers (retired)*

The flood control system in the Albuquerque area consists of three distinct elements:

- The upland arroyo and flood control dam system, which flows by gravity into the Rio Grande.
- The valley storm sewer and storm water pump station system, which pumps storm water into the Rio Grande.
- The Albuquerque levee system, which parallels the Rio Grande on either side of the river and protects the area from high flood flows in the Rio Grande.

Operation and management of the flood control system involves many agencies within Bernalillo County, with some overlapping areas of responsibility. Each agency has distinct roles in providing this important element of public infrastructure. Local and state agencies involved in the design, construction, or maintenance of flood control facilities include the Albuquerque Metropolitan Arroyo Flood Control Authority (AMAFCA), the City of Albuquerque, Bernalillo County, the Middle Rio Grande Conservancy District (MRGCD), the Office of the State Engineer Dam Safety Bureau, and the New Mexico Department of Transportation. Federal agencies involved include the U.S. Army Corps of Engineers and the Bureau of Reclamation.

The drainage facilities in the Albuquerque area, as well as the agency responsible for maintenance of each facility, are shown on the folded map that accompanies this volume.

THE UPLAND ARROYOS

The east side upland flood control system includes the natural arroyos coming off the Sandias. Fifteen major arroyos are intercepted by the AMAFCA North Diversion Channel, which drains a 110-square-mile watershed north into the Rio Grande. Four arroyos on the southern end of the Sandias are diverted south into Tijeras Arroyo, which flows into the AMAFCA South Diversion Channel and then into the Rio Grande south of the city. The end result is that every major arroyo on the east side of the Rio Grande is intercepted by either the AMAFCA North Diversion Channel or South Diversion Channel, and is discharged into the Rio Grande north or south of the urban area.

AMAFCA and the city have also constructed nine large flood control dams on six major arroyos. The dams temporarily impound and meter out flood water to prevent downstream flooding.

The west side upland flood control system is much different. With no large diversion channels on the west side of the Rio Grande, most storm drainage north of I–40 is diverted into either the Calabacillas Arroyo or the San Antonio Arroyo, the only two arroyos in Bernalillo County that discharge to the Rio Grande at their historic locations. For areas that cannot drain to these two arroyos, AMAFCA has worked with the MRGCD to use portions of the Corrales Acequia and Corrales Main Canal for flood control. In each case, AMAFCA paid 100 percent of the cost for the reconstruction of the MRGCD canal, in exchange for use of the right of way. Maintenance is split, with AMAFCA taking care of storm-related maintenance and the MRGCD continuing to take care of the delivery of irrigation water.

South of I–40, the west side arroyos are captured by seven flood control dams that discharge into irrigation canals and drains owned by the MRGCD. These dams have gated outlets, and store the entire 100-year-event storm flow, with the gate opened afterwards to drain the dam when the water levels in the downstream canals and drains have receded. The U.S. Army Corps of Engineers is currently working with AMAFCA to build cross-valley drainage infrastructure to take the dam outlets directly to the river, and to allow the capacity in the MRGCD drains to be better used for valley floor storm drainage.

THE VALLEY SYSTEM OF STORM DRAINS AND PUMP STATIONS

The valley portion of the Albuquerque area is below the elevation of the Rio Grande. Thus, the north and mid-valley flood control system is composed of a series of storm sewer collection systems that convey storm water to twelve pump stations that pump storm water over the levees into the Rio Grande. On the east side of the river, one gravity outlet is available via use of the MRGCD's San Jose Drain.

North Diversion Channel outfall to the Rio Grande, looking west. The AMAFCA North Diversion Channel discharges storm runoff from a 110-square-mile drainage basin into the Rio Grande north of Albuquerque, within the southern boundary of the Pueblo of Sandia. The outfall is 2 1/4 miles upstream of the Water Utility Authority's new Drinking Water Diversion Dam, making the quality of urban runoff now even more important to the region. The pooled water in the foreground is where the diversion channel dips down five feet to go under the mainline railroad track.

On the southwest valley floor, practically no drainage infrastructure exists. The Army Corps of Engineers, in conjunction with AMAFCA and Bernalillo County, plans to widen the existing MRGCD irrigation drains to serve as the backbone of the valley floor storm drainage system. Storm sewers will be used to convey storm water to the widened drains, which will serve as linear detention ponds.

The Ladera system of dams and impoundments, on the west side north of I–40.

High-level storm flows in the drains will be sent out to the river through a new gravity outfall system, running from the Los Padillas Drain to the Rio Grande about a mile and a half south of Rio Bravo. For lower flows a new storm water pump station, in combination with a large detention pond located just north of I–25, will be used.

THE ALBUQUERQUE LEVEES

The U.S. Army Corps of Engineers designed and constructed the Rio Grande levees in the Albuquerque area in the mid-1950s to provide protection against a flood peak of 42,000 cfs (cubic feet per second). These levees, which pre-date Cochiti Dam, are maintained by the MRGCD. The Corps of Engineers levee projects did not include the spoil bank levees on either side of the river from the I–25 bridge upstream approximately three miles, and for two miles on the west side of the river in the vicinity of Montano Boulevard.

Current Federal Emergency Management Agency (FEMA) floodplain mapping has designated two of these three locations, the South Valley areas on either side of the Rio Grande, as floodplain. The levee/floodplain issue on the west side was discovered during the 2008 FEMA remapping effort. The revised mapping places 2,600 acres of the southwest valley floor into the floodplain, all of which was previously shown as protected by the levee. Flood insurance premiums in this area increased from $500 per year to more than $2,000 per year for a typical home. The MRGCD, along with funding from AMAFCA and Bernalillo County, has undertaken a $6 million emergency rebuild of this levee in order to remove the floodplain designation as quickly as possible.

ARROYO TREATMENTS AND AESTHETICS

One of the first control challenges in Albuquerque flood control was to get rid of the “ugly gray” concrete channels. Unfortunately, on the east side, given the steep slopes, resulting high velocity flows, and limited rights of way, getting rid of concrete-lined channels is not a feasible option. However, the aesthetics of recent channels has been improved by using tinted concrete, and by using a shotcrete, which gives a rough surface that also deters graffiti and skateboarders.

Given the flatter slopes of the arroyos on the west side, AMAFCA and the city have been able to use “softer” treatments. Many west side arroyos are stabilized with rock rip rap. Soil cement has also been used extensively. Soil cement is made by taking the bed material from an arroyo, mixing it with small amounts of cement and water, and placing it to form layers that look like sandstone and have the strength of a lean concrete.

Building the lining for the Amole Arroyo on the west side of the Rio Grande, using tinted shotcrete.

The Calabacillas Arroyo, the biggest arroyo on the west side, has been managed with the “prudent line” concept. This establishes an erosion buffer on either side of the arroyo. This buffer allows the arroyo to meander beyond the floodplain, but within certain limits, based on the erosion anticipated over a 30-year time frame and as a result of a single 100-year flood event. This treatment has worked fairly well, but in some locations substantial publically funded improvements have been needed where the estimate of the erosion buffer was too narrow. The “prudent line” treatment does not freeze the condition of the arroyo; in fact, it acknowledges that the arroyo will erode, meander, and become wider.

Hardscape elements in Calabacillas Arroyo between Coors and Rio Grande.

MULTIPLE USE OF FLOOD CONTROL FACILITIES

The next big challenge for Albuquerque flood control was to allow multiple use of the flood control system. AMAFCA's enabling legislation allows AMAFCA to build only flood control projects. It does not authorize AMAFCA to build recreational facilities.

Although taken for granted today, the first bike trail (1976) along the North Diversion Channel was the subject of much consternation by the AMAFCA Board of Directors. Their concerns were resolved by a licensing arrangement, whereby AMAFCA licensed the recreational use to the city, who took on all liabilities arising from the new use. This action preserved AMAFCA's tort claims immunity for the care and diversion of water, and has since made AMAFCA's drainage rights of way available for trails, parks, golf courses, little league fields, soccer fields, an equestrian center, and even a hang glider landing area.

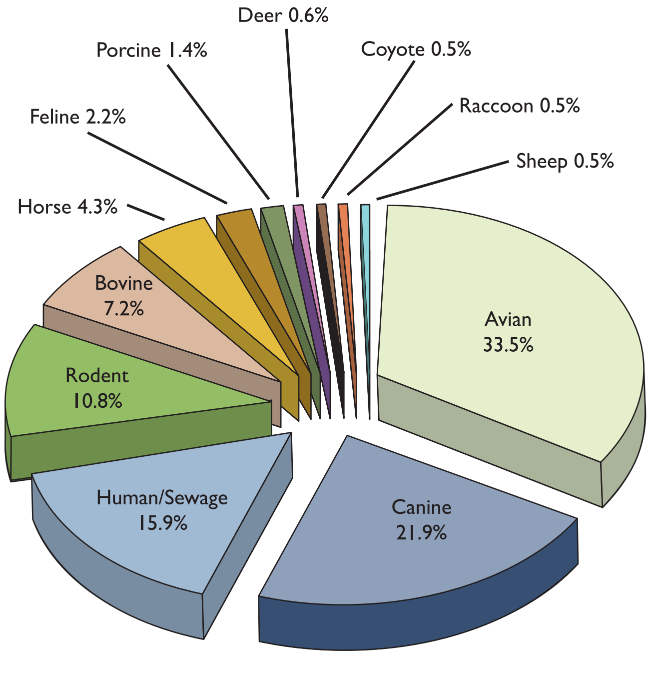
AMAFCA now works with the city and county and designs its projects with the ultimate multiple use in mind. Minor changes in grading can accommodate future trails that meet guidelines of the Americans with Disabilities Act (ADA) of 1990. Benching a flood control reservoir into multiple levels can allow agricultural use of the upper tiers, while allowing the pond bottom to be just above ground water elevation, as was done with the Sanchez Farm Detention Pond project located in the South Valley.

USING STORM WATER FOR AQUIFER RECHARGE

The question of using storm water for aquifer recharge comes up time after time for flood control agencies. Several factors restrict this ability. First, the quantity of storm water is not all it seems to be. Although a summer thunderstorm flood may double the flows in the Rio Grande for a short period of time, the annual storm water discharge for the North Diversion Channel is about 10,000 acre-feet per year, versus 1,000,000 acre-feet per year for the Rio Grande. Second, the flood control agencies have no rights to this water; it is all claimed by the state engineer under the terms of the Rio Grande Compact. The state engineer allows storage of storm water behind a flood control dam, provided that the impoundment behind the dam is drained within 96 hours. Third, even if AMAFCA could detain storm water behind its dams for an extended period, the structural design of the dam embankment is for short duration inundation, thus long term storage and resulting seepage could lead to failure of the dam.

Repairing bank erosion along Tijeras Arroyo in 2006.

Three arroyo recharge zones have been identified: along the mountain front, the Tijeras Arroyo near the Coyote Wash, and the lower reaches of the Calabacillas Arroyo. In recognition of this, flood control projects on both the Tijeras and Calabacillas Arroyos have deliberately kept a sand-bottom arroyo, and projects along the mountain front arroyos have used the prudent line concept to keep homes set back from the arroyos to preclude any need for armoring.



Sources of microbial bacteria in storm water, by percent. High fecal coliform counts during storm events are a concern; major sources are birds and pets.

Infiltration in natural arroyos midway between the mountain front and the Rio Grande has also been investigated. The results are that intermittent, short duration storm flows penetrate about 20 feet below the surface, but are subsequently drawn back up into the atmosphere through evapotranspiration.

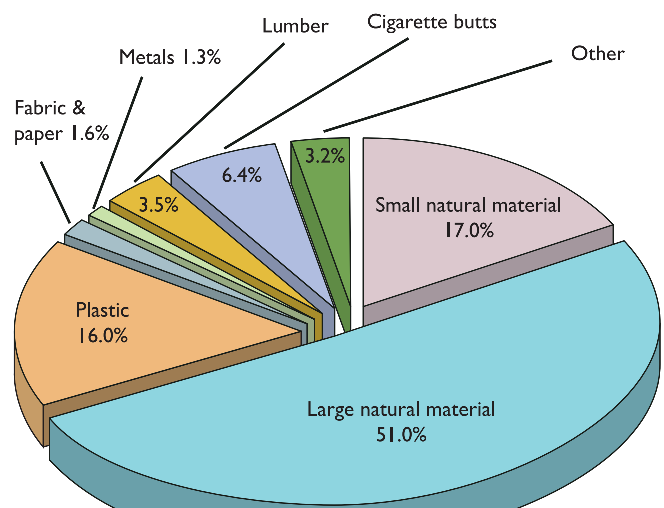
CURRENT AND FUTURE CHALLENGES—STORM WATER QUALITY

One of the biggest challenges facing flood control agencies today is continued compliance with the evolving issue of storm water quality and impacts on the Rio Grande. AMAFCA, the City of Albuquerque, the University of New Mexico, and the New Mexico Department of Transportation are all co-permittees under an Environmental Protection Agency (EPA) MS4 (Municipal Separate Storm Sewer System Permit). Permit renewal is pending.

The EPA MS4 program is designed to improve the quality of storm water discharges to the Rio Grande by use of Best Management Practices and does not set numeric standards for storm water quality. The permit mandates storm water quality sampling, evaluation of fecal sources in storm water, gross pollutant removal, and public education.

The co-permittees have used the U.S. Geological Survey for all storm water quality sampling and data collection. Although a full discourse of the sampling results is beyond the scope of this paper, the ongoing USGS monitoring program indicates that storm water quality in the Albuquerque area is generally good, with no indication of problems with heavy metals, pesticides, or hydrocarbons. High fecal coliform counts during storm events were identified as being one of the elements of concern.

The city of Albuquerque, AMAFCA, Bernalillo County, and the New Mexico Environment Department have since identified the sources of fecal matter in storm water. Two different tracking methodologies were used: one using DNA ribo-typing, the other using antibiotic resistivity analysis. In both



The results of a gross pollutant study conducted by AMAFCA and the city of Albuquerque, showing the nature of the debris removed from storm water (by volume). AMAFCA and the city have since constructed 6 debris removal structures on inlets to the North Diversion Channel, and at 24 other locations within the system.

studies avian and pet sources are major contributors, and have led to the Scoop the Poop campaigns and prohibition of putting dog parks within drainage areas.

The state has since set a TMDL (total maximum daily load) for fecal coliform in the Rio Grande. The TMDL is computed on an annual basis. Albuquerque's storm water meets the TMDL because of the constant trickle flows that offset the high counts during the few big storm events in a year.

AMAFCA and the city also completed a gross pollutant study that showed 68 percent (by volume) of the debris screened out of storm water was natural vegetation, such as leaves, grass, pine needles, and tumbleweeds. This same study showed 16 percent of the total was plastic, mainly water bottles, and (surprisingly) more than 6 percent was cigarette butts. AMAFCA and the city have since constructed six debris removal structures on inlets to the North Diversion Channel and at twenty-four other locations within the system.

The most recent water quality issue being investigated by the co-permittees is the apparent impact of storm water discharges on dissolved oxygen sags in the Rio Grande. This is a puzzling issue, as storm water is highly aerated as it comes rushing down the North Diversion Channel to the river. The USGS sampling in the channel near the river confirms this. The USGS has since installed a dissolved oxygen monitor in the Rio Grande upstream of the channel outfall, and provisional data from this past summer show similar sags in the river above the outfall. AMAFCA and the MS4 co-permittees continue to evaluate these data.

The co-permittees have had a storm water quality public education campaign over the last four years, which will become more important as the Albuquerque Bernalillo County Water Utility Authority's drinking water project comes on line. The AMAFCA North Diversion Channel discharges into the Rio Grande 2 1/4 miles upstream of the Drinking Water Diversion Dam.

Some of the large debris association with storm flows; Embudo Arroyo at Juan Tabo, July 10, 1988.

CURRENT AND FUTURE CHALLENGES—LEVEES, THE BOSQUE, AND FEMA FLOODPLAINS

The levees along the Rio Grande in Albuquerque are in a state of continued deterioration, and they have the potential to pose a significant risk to the more than $1.4 billion in property that the system was designed to protect. Though the levees still afford a high degree of protection, it is unknown how long this will last, given their rate of decline. After Hurricane Katrina, the U.S. Senate, through the 2005 Energy and Water Appropriations Bill, directed the Army Corps of Engineers to initiate an evaluation of the structural integrity of the levee system to determine if the Albuquerque levees function as originally designed. The results of the evaluation are summarized as follows:

- Although the Army Corps of Engineers' levees are 50 years old and do not meet current criteria, the levees are still capable of safely passing the 100-year event of 19,000 cfs. They cannot pass the design level event (42,000 cfs) with the design level of freeboard.
- There are three areas within the Albuquerque area that do not have acceptable levels of flood protection: the 3 miles north of the I–25 bridge on the west side of the river (in the South Valley); the 5 miles from the I–25 bridge north to the AMAFCA South Diversion Channel on the east side of the river (in the South Valley), and the Montaño levee gap on the west side of the river.
- There is an unacceptable amount of woody vegetation on or near the levees. If this vegetation dies, the root systems will rot and provide a seepage path through the levee and potentially cause failure.
- Inspection of the toe-drain system, which minimizes underseepage from flood flows saturating and undermining the levees, has revealed that the toe drains are inoperable in several locations.

- Of the 37.6 miles of levee on both banks of the Rio Grande, a total of 5.1 miles is considered a high priority for replacement.

Of particular concern is the Montaño levee gap, which extends from La Orilla Road south past Montaño Boulevard to the high bluffs on the west bank of the Rio Grande. This area was undeveloped, and no flood protection was needed when the Corrales reach of the levee system was completed by the Army Corps of Engineers in 1997. Development within the apparent 100-year floodplain (not mapped by FEMA) since then will require that any rebuilding of the Albuquerque levees include adding this 2-mile segment to the overall system.

The estimated cost for rehabilitation needed to restore the levee system to its original design capacity, using current design and construction criteria, is $120 million. If funded, rehabilitation of the levee system could be completed at the earliest by 2021. Future FEMA floodplain remapping efforts may happen before 2021. FEMA will likely then require certification that the levees meet *all* current criteria, including the current 30-foot tree-clear zones and toe drains, which cannot be met by the existing levees. As such, major portions of the urban area could be designated as in the floodplain, just as happened with the southwest valley this year.

Fortunately, these levee issues have been identified before a true emergency. Knowing that even the 30-foot tree-clear zone will have huge impacts on the bosque, the Army Corps of Engineers is investigating root barriers as an alternative. AMAFCA has been selected as one of its technical partners to assess tree and root growth along river levees in the arid Southwest. The current MRGCD levee project was authorized with the 30-foot tree-clear zone. As such, some of this research will be done on cottonwoods already slated for removal.

Suggested Reading

Middle Rio Grande Microbial Source Tracking Assessment Report, Parsons Water & Infrastructure, Inc., prepared for the New Mexico Environment Department, AMAFCA, and Bernalillo County, October, 2005. www.ose.state.nm.us/isc_regional_plans12.html

AMAFCA/Albuquerque MS4 Floatable & Gross Pollutant Study, ASCG Incorporated, prepared for AMAFCA and City of Albuquerque, October 2005.

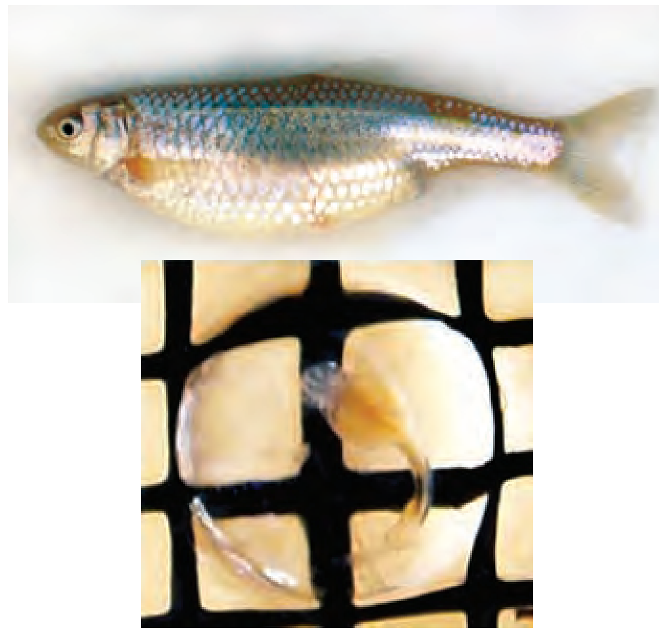
Middle Rio Grande Water Assessment, U.S. Bureau of Reclamation, prepared for the City of Albuquerque Public Works Department, 1997.

Floodwaters during the July 14, 1990 flood, AMAFCA South Diversion Channel baffle chute, just west of I–25, the highest flow on record at 2,300 cfs.

Habitat Restoration and a Conservation Strategy for the Rio Grande Silvery Minnow

C. Nicolas Medley, *New Mexico Interstate Stream Commission*

The Rio Grande was once a wild and untamed desert river, home to a diverse and abundant ecosystem of plants and animals well adapted to the river's variable hydrology. Water management and flood control activities have greatly altered the physical and biological processes that formed the natural riverine habitats in which these communities flourished. With the recognition that people and animals are both dependent upon this limited and variable water supply, and the listing of the Rio Grande silvery minnow (*Hybognathus amarus*) and Southwest willow flycatcher (*Empidonax traillii extimus*) under the federal Endangered Species Act, members of the Middle Rio Grande Endangered Species Act Collaborative Program are now trying to find reasonable solutions to promote recovery of listed species and their habitats while attempting to protect water use and development in compliance with federal and state law. Accordingly, the New Mexico Interstate Stream Commission is conducting research to understand the basic ecology and habitat requirements of these species, to identify the fundamental reasons for their decline, and to better understand how water management strategies affect them. This knowledge is necessary if meaningful recovery strategies are to be identified, especially when both water and funding are limited, and many proposed activities have consequences for both water users and the environment.



The Rio Grande silvery minnow. Photo is of a large female with eggs; inset shows a minnow egg, with the embryo visible inside. Photo courtesy of Michael Hatch.

HABITAT

The type and abundance of habitat available for a species to live in provide the primary physical framework within which it evolves. Understanding the fundamental relationships between riverine habitat, the processes that create and maintain it, and the silvery minnow's life history is essential for developing effective river restoration strategies. The form of a river channel and its associated habitat is determined by a suite of interacting variables: valley slope; the magnitude, frequency, duration, and timing of flows; the quantity and size of available sediment; and local and regional constraints upon the ability of the river to erode its banks and migrate laterally across the valley floor (e.g., underlying geology, bedrock outcrops, shoreline vegetation). Although many of these variables change naturally from year to year, over long periods of time they vary in a predictable way. It is the long-term balance between these fundamental variables and the dynamic equilibrium around a most probable state that determines a river's characteristic form. If any of these variables change, the balance will shift, and the river will evolve toward a new configuration with potentially different habitats.

Before significant human influence, the Rio Grande between Cochiti Dam and Elephant Butte Reservoir (the Middle Rio Grande) was a wide, shallow, sand-bedded river with many mid-channel islands and bars, that wandered across a wide (.5–2.5 miles) unconfined floodplain. High flows during spring snowmelt runoff inundated the floodplain for many weeks in most years. This annual "flood pulse" regularly caused extensive bank erosion and channel migration and reworked floodplain sediments, creating perennial ponds, extensive wetlands, and a complex mosaic of riparian habitats. Low summer and fall flows were punctuated by short duration, high flows associated with summer rains and were generally perennial except during extended periods of severe drought.

SILVERY MINNOW ECOLOGY

Within this environment the silvery minnow evolved a life history closely tied to the hydrology of the river. The minnow is a small (less than 5 inches), silvery fish, the last remaining member of a group of five species of pelagic spawning minnows that were once abundant in the Rio Grande. Two are now extinct, and two are still found in other river systems of the southwest U.S. but not in the Rio Grande. Adult female minnows release their eggs into the water column, often at the onset of rapidly increasing flows during spring runoff, in late April and May. The eggs are fertilized by companion males and rapidly swell, becoming very slightly negatively buoyant (with a specific gravity of ~1.00281) in clear water. Eggs drift downstream, suspended by turbulent flows, until they settle in low-velocity habitats. Eggs hatch in 24–48 hours. Newly hatched fish may stay in low-velocity areas or continue to drift until larval fish can actively find good rearing habitat (3–5 days). In most years adult silvery minnows would have moved from the main river channel and other perennial floodplain habitats to spawn on the newly inundated floodplain. Spawning here provides the advantage of greatly reducing egg drift and placing newly hatched eggs in warm floodplain environments with plenty of food, conditions that promote increased survival and growth of young fish. Upon recession of the flood pulse, silvery minnows would move back into the main river channel or stay in perennial floodplain habitats.

Human influence has greatly altered the natural channel morphology of the Rio Grande and eliminated important processes that created the historically diverse and complex habitat in which the Rio Grande silvery minnow evolved. Water storage and withdrawal has reduced the magnitude, frequency, and duration of the largest spring flows and increased the frequency of drying in certain river reaches. Watershed degradation from poor land use during the late 1800s and early 1900s, and reservoir construction and operation (generally starting in the 1940s) have greatly altered sediment dynamics. Channelization, jetty jack placement, and levee construction have straightened, shortened, steepened, narrowed, and degraded the river channel, confining it within a narrow strip of aggrading floodplain where it has little ability to move laterally. Collectively, these changes have forced the river to seek a new, stable form. Consequently, much of the river channel within the Middle Rio Grande is now disconnected from its floodplain at all but the highest expected flows. Confining most of the water within this straight, steep, uniform channel has greatly reduced habitat diversity and opportunities for egg capture and has greatly increased flow velocities, creating an efficient "gun-barrel" that can "shoot" many silvery minnow eggs and larval fish far downstream. Losses of eggs and fish from excessive downstream drift are compounded by the river drying in the downstream reaches between Isleta Dam and Elephant Butte Reservoir in periods of drought.

Initial investigations to understand minnow egg drift were conducted in the Rio Grande and the Pecos River in New Mexico in 1997 and 1998 using artificial eggs. These studies concluded that real minnow eggs may drift long distances (more than 90 miles) in the Rio Grande, and that young and/or adult silvery minnows must subsequently migrate long distances upstream to overcome downstream egg displacement. Conservation recommendations emphasized the need to keep the entire Middle Rio Grande perennially flowing and to remove or modify all irrigation diversion structures that would prevent upstream fish passage. Although the minnow is an excellent swimmer, and individual fish may move long distances upstream and downstream, the long-distance, upstream migration of large numbers of fish has not been documented. Furthermore, the recommendations downplayed the fundamental importance of habitat degradation and the loss of floodplain connectivity to spawning behavior and egg retention. The recommendations cannot be implemented in most years without the acquisition of a substantial portion of the agricultural water currently being used in the Middle Rio Grande.

More recent research conducted by the Interstate Stream Commission and SWCA Environmental Consultants Inc., an independent consulting firm, has shown that egg drift in the Middle Rio Grande may have been over estimated. This recent research has identified a suite of flow and habitat-related factors that collectively promote efficient egg retention and larval survival:

- Egg retention is greatest in wide, shallow river channels with complex channel features and connected floodplains.
- Eggs spawned during rapidly increasing flows are efficiently retained concomitant with channel storage associated with flood wave attenuation.
- Eggs released when silvery minnows spawn on inundated floodplains during high spring flows may drift only a short distance before being retained in low velocity habitats.

Left: Amphibious earthmoving equipment removing and redistributing sediment from a high-elevation, mid-channel island in the Rio Grande south of Albuquerque during construction of floodplain habitats subject to inundation at lower magnitude spring flows (3,000 cfs); winter 2006. Right: The same island nine months later, showing regrowth of vegetation and establishment of new wetland vegetation that promotes egg retention and provides excellent habitat when flooded for silvery minnow rearing; fall 2006.

- Slightly negatively buoyant eggs settle fastest in warm, clear water associated with shallow, food-rich, inundated floodplain habitats.

Fish-monitoring data also demonstrate the importance of floodplain connectivity and show that the minnow population is greatest in years and in river reaches where high spring flows provide flooded habitat (e.g., Isleta reach), and in abundant productive, low-velocity habitats that promote fish survival and growth.

These facts suggest that in the absence of observed upstream migration, river reaches that promote high egg retention and possess high-quality rearing habitat are essential to minimize downstream displacement of minnow populations. Short downstream egg drifts can be balanced by the general upstream swimming behavior of silvery minnows. For small fish with limited energy resources, selection of adaptive behaviors that take advantage of passive processes to promote egg retention may be part of a general evolutionary strategy to maximize their reproductive success. Individuals using this strategy may allocate greater energy resources to growth and reproduction and gain an advantage over fish displaced farther downstream by avoiding the need for an energetically costly upstream migration.

Accordingly, providing fish passage at dams and irrigation diversions is unlikely to offset the ultimate cause of excessive downstream egg drift. Although longitudinal connectivity within the river channel may be an important consideration in the long-term protection of genetic diversity and for eventual species' delisting, immediate conservation efforts should focus on habitat restoration to reestablish natural stream processes and to restore lateral connectivity between the river channel and its floodplain. Providing relatively short (30 miles) reaches of high-quality habitat with connected floodplains and perennial flows within the Middle Rio Grande (i.e., Albuquerque and Isleta reaches) can greatly improve the long-term viability of the minnow population. This conservation strategy is also attractive to water users and managers trying to find "water neutral" solutions to endangered species issues, because it suggests that the status of the silvery minnow population may be greatly improved by the implementation of habitat restoration projects and non-consumptive water management actions without the need to fundamentally change the water infrastructure of the river or the need to acquire prohibitive amounts of already-appropriated water.

CONSERVATION STRATEGIES

While scientists in the Middle Rio Grande Endangered Species Act Collaborative Program continue to discuss the relative merits of fish passage and habitat restoration, and struggle to agree on funding priorities, the Interstate Stream Commission has identified a group of habitat-related initiatives that collectively attempt to recreate habitat attributes important in the life history of the fish. This strategy is consistent with the available data from the Middle Rio Grande and is similar to other restoration programs in large floodplain river systems throughout the U.S. The overarching goal is to provide short river reaches with all the habitat attributes necessary for the fish to thrive: accessible floodplain at a variety of spring flows, adjacent to areas with permanent base flows, in reaches that are easiest to keep wet under current river management and water availability. While these activities will not be sufficient to solve the problem entirely, they can quickly make a large contribution to stabilizing the minnow population. Three groups of activities have been identified and are currently being implemented: habitat restoration, spring flow management, and summer low-flow management.

Habitat Restoration

"Active" habitat restoration involves the site-specific mechanical modification of existing habitats. The goal is to increase inundated floodplain habitat at flows that can be expected in most years, to promote egg retention, and to enhance survival of newly hatched silvery minnows. Restoration activities are consistent with those outlined in the collaborative program's "Habitat Restoration Plan for the Middle Rio Grande." For example, large earth moving equipment has been employed to lower and reconnect abandoned floodplain terraces of mid-channel islands and attached bars within the approximately 600-foot-wide river channel.

Since 2005 the Interstate Stream Commission has spent approximately $2.5 million to improve 140 acres of habitat in the Albuquerque reach of the Middle Rio Grande. The capture of 24,000 silvery minnows in inundated habitats during spring 2008 demonstrated that constructed floodplain habitats function similarly to natural floodplain habitats and that large numbers of silvery minnow use both during the high spring flow period. The presence of eggs and larval fish also suggests that constructed floodplain habitats are promoting egg retention and providing larval fish habitat. While this approach can provide immediate benefits for the fish, these projects are likely to be short lived without continued maintenance, because the activity does not address the fundamental conditions that initially created the need for restoration. To address this shortcoming, "passive" habitat restoration activities have also been implemented that attempt to reestablish the natural river processes and functions that historically created and maintained habitat. For example, jetty jacks and shoreline vegetation that presently armor river banks have been removed so that during high spring flows the banks can erode and the river can move laterally, in areas where this will not increase flood risk to people or property.

To date, the Interstate Stream Commission's restoration activities have mostly been conducted within the defined river channel of the Middle Rio Grande floodway, where it is assumed that it does not create additional water depletions. However, future habitat restoration outside the floodway will require offsets. The Interstate Stream Commission is currently acquiring water for this purpose.

Lateral migration of river banks in areas with little shoreline vegetation. Erosion and deposition of floodplain sediments is an important process that promotes both connectivity between the river channel and the floodplain, and the creation and maintenance of silvery minnow habitat.

Spring Flow Management

This management action attempts to remove or change the hydrologic constraints that led to habitat alteration, by restoring attributes of historic river flows that are important to the fish. The Interstate Stream Commission is working with federal agencies, Cochiti Pueblo, and the Rio Grande Compact Commission to modify Cochiti Reservoir operations to ensure that a minimum spring flow of 3,000 cfs is provided for at least seven days in most years. These flows are of a magnitude considered to be the minimum necessary to ensure some floodplain inundation under the current channel configuration, and of a duration to allow sufficient recruitment of fish to keep the silvery minnow population healthy. Currently these flows are limited to approximately 7,000 cfs by the low elevation of the San Marcial Railroad Bridge and the condition of spoil bank levees in areas of the middle valley. Plans to raise the elevation of the bridge and improve the levee system to allow passage of flows as great as 10,000 cfs are currently being considered. These high flows, although uncommon, have great potential to rework considerable floodplain sediment, to build and maintain new floodplain habitats, and to provide large areas of habitat for the fish. These benefits may be realized throughout the entire Middle Rio Grande and are potentially both long term and sustainable.

Extensive floodplain inundation near Los Lunas, New Mexico, on an actively restored site, during high spring flows (6,000 cfs); May 2006.

Summer Low-Flow Management

This is an attempt to keep permanent flows in some areas of all reaches of the Middle Rio Grande, but specifically in subreaches where habitat restoration has been conducted and in reaches that are most easily kept wet. It is anticipated that in the near future only 8,000 acre-feet of "minnow water" (stored water acquired by the Bureau of Reclamation for this purpose) will be available to augment river flows. Accordingly, the Interstate Stream Commission is currently looking at alternative ways to provide more water by the relinquishment of accrued Rio Grande credit water when available.

THE FUTURE

Implementation of the Interstate Stream Commission strategy provides a framework to improve the status of the silvery minnow in the Middle Rio Grande, but it also suggests that a long-term solution leading to recovery and delisting of the fish without intensive habitat and flow management into the foreseeable future is unlikely. However, improving the status of the Rio Grande population and reestablishing the silvery minnow in other perennial river reaches within the fish's historic range is achievable. To this end, the Interstate Stream Commission has constructed the Los Lunas Rio Grande Silvery Minnow Refugium, one of four breeding and rearing facilities that will produce fish for future stocking. Silvery minnow were reintroduced into the Rio Grande in Big Bend National Park, Texas, in December 2008.

The Los Lunas silvery minnow refugium, a project of the New Mexico Interstate Stream Commission. The refugium provides a 460-foot-long meandering stream with ponds and overbank features that function like natural environments in the Rio Grande.

Other river reaches where the silvery minnow could be augmented or reintroduced include the Rio Grande above and directly below Cochiti Reservoir, and the Pecos River between Santa Rosa Dam and Sumner Reservoir. Although these reaches provide perennial base flows, river management has greatly reduced the historic river–floodplain connection, and habitat restoration would greatly benefit newly introduced silvery minnow populations. Attempting to reestablish fish in these reaches is part of the "Move Fish to Water" strategy that, if successful, can reduce the current reliance on the Middle Rio Grande population and reduce the need to acquire large amounts of "minnow water" to maintain perennial flows within this entire reach

Within the next decade, the Interstate Stream Commission strategy may lead to down-listing of the fish from endangered to threatened. This creates the possibility of additional flexibility in future species management that better protects both water users and the silvery minnow and provides the basis for a "managed solution" to one of New Mexico's pressing endangered species issues. Significant progress has been made, but in order to fully realize this goal, additional work still needs to be accomplished, and it will require continued funding from both the state and federal government.

Suggested Reading

From the Rio to the Sierra: An Environmental History of the Middle Rio Grande Basin, Dan Scurlock, General Technical Report RMRS-GTR-5, U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, 1998.

Characterization of Rio Grande Silvery Minnow Egg and Larval Drift and Retention in the Middle Rio Grande, SWCA Environmental Consultants Inc., 2007.

Habitat Restoration Plan for the Middle Rio Grande, Tetra Tech EM Inc., 2004.