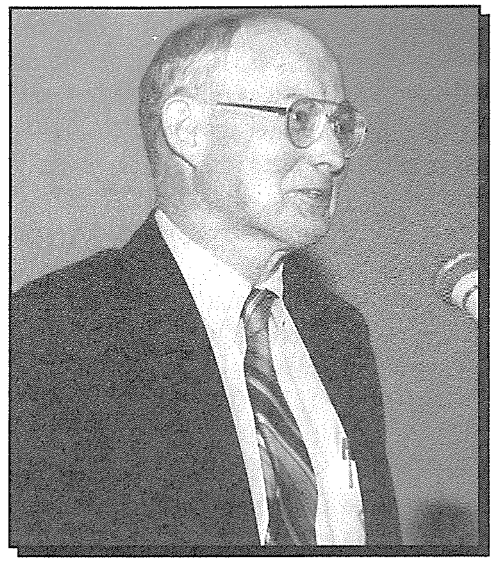
John Hawley received a Ph.D. degree in Geology from the University of Illinois in 1962. He is currently Senior Environmental Geologist with the New Mexico Bureau of Mines and Mineral Resources at New Mexico Tech and an adjunct faculty member. He manage's the Bureau's Albuquerque branch office and his current research efforts relate to assessing and mitigating impacts of water-resource exploitation and waste disposal in fragile arid and semiarid environments. He is continuing long-term research on the hydrogeologic framework of basin-fill aquifer systems in cooperation with the City of Albuquerque, the U.S. Geological Survey and Bureau of Reclamation, the New Mexico Environment Department, the State Engineer Office, and the All Indian Pueblo Council. John has authored or coauthored more than 70 publications on the geology, soils, and related environmental concerns in the western U.S. and northern Mexico. He served on WRRI's Program Development and Review Board from 1982-1989.



AN UNDERGROUND VIEW OF THE ALBUQUERQUE BASIN

John W. Hawley
C. Stephen Haase[1]
Richard P. Lozinsky[2]
New Mexico Bureau of Mines and Mineral Resources
Campus Station
Socorro, NM 87801

INTRODUCTION

Development of valid hydrogeologic models of New Mexico's "critical groundwater basins" has been a long-term objective of the New Mexico Bureau of Mines and Mineral Resources (NMBMMR), a division of New Mexico Tech. The best possible information on basin hydrogeology is needed not only for incorporation in numerical models of groundwater-flow systems, which are necessary for proper management of our limited water resources, but also for addressing public concerns relating to a wide range of important environmental issues. In the latter case, a hydrogeologist must be prepared to provide appropriate explanations of why groundwater systems behave physically and chemically as they do in both "natural" and "man-disturbed" situations. For example: Why do land surfaces subside or water-quality conditions deteriorate in some areas of groundwater "mining" and not in others; or how can we preserve valuable riparian and other wetland ecosystems at sites of shallow water-table decline; or where is it feasible (technically and economically) to "fix" overstressed aquifers with artificial-recharge or quality-remediation measures?

[1]Now with Martin-Marietta Corporation, Oak Ridge Y-12 Plant, ORNL, Oak Ridge, TN 37831-8219
[2]Now with Fullerton College, Div. of Natural Resources, 321 E. Chapman Ave., Fullerton, CA 92632-2095

Major emphasis of our public service and research programs in environmental and engineering geology has been on the series of deep structural depressions, designated the Rio Grande rift, that includes the present valley of the Rio Grande and one of the major groundwater reservoirs in the Southwest (Figure 1). Besides the Albuquerque Basin discussed in this paper, the NMBMMR and cooperating organizations have conducted detailed investigations in the Española, Palomas, southern Jornada, and Mesilla basins, as well as reconnaissance studies throughout the rift region from Colorado to Texas (Hawley et al. 1969, 1976; King et al. 1971; Hawley 1978; Gile et al. 1981; Peterson et al. 1984; Seager et al. 1984; Johnpeer et al. 1985; Lozinsky 1986, 1988, 1994; Lozinsky and Tedford 1991; Hawley and Longmire 1992; Hawley and Lozinsky 1992; Hawley and Haase 1992). These projects have been funded primarily from basic and special state appropriations to New Mexico Tech, with substantial support also provided by the U.S. Soil Conservation Service from 1962 to 1977. Matching-fund grants from the City of Albuquerque (COA), Bureau of Reclamation (USBR), U.S. Geological Survey (USGS), Los Alamos National Laboratory (LANL), NM Environment Department (NMED), and NM Water Resources Research Institute (WRRI) have provided additional project support since 1982.

Our current "underground view" of the largest and deepest rift basin in New Mexico, the Albuquerque Basin, is based on detailed field and laboratory research initiated in 1992 in cooperation with the COA Public Works Department. The best possible interpretations of the basin's hydrogeologic framework were needed at that time for incorporation into a numerical model of the groundwater flow system being developed by the U.S. Geological Survey-Water Resources Division (Kernodle 1992; Thorn et al. 1993; Kernodle et al. 1995). The first phase of work involved a New Mexico Tech research team comprising J.W. Hawley and C.S. Haase (NMBMMR), project leaders; R.P. Lozinsky and R.M. Chamberlin (NMBMMR), general geology and basin-fill petrology; and P.S. Mozley (Geoscience Department Faculty) and J.M. Gillentine (Graduate Research Assistant), petrographic and mineralogic analyses. Their provisional conceptual model of basin hydrogeology in the Bernalillo County area was described in NMBMMR Open-File Report 387, compiled by Hawley and Haase (1992). Interpretations were primarily based on (1) detailed analyses of borehole geological and geophysical data (including drill samples) to depths of as much as 3400 ft (1040 m) from 12 COA water wells, (2) recently published interpretations of commercial oil and gas exploration records, and (3) published and unpublished information from earlier investigations of Rio Grande rift basins.

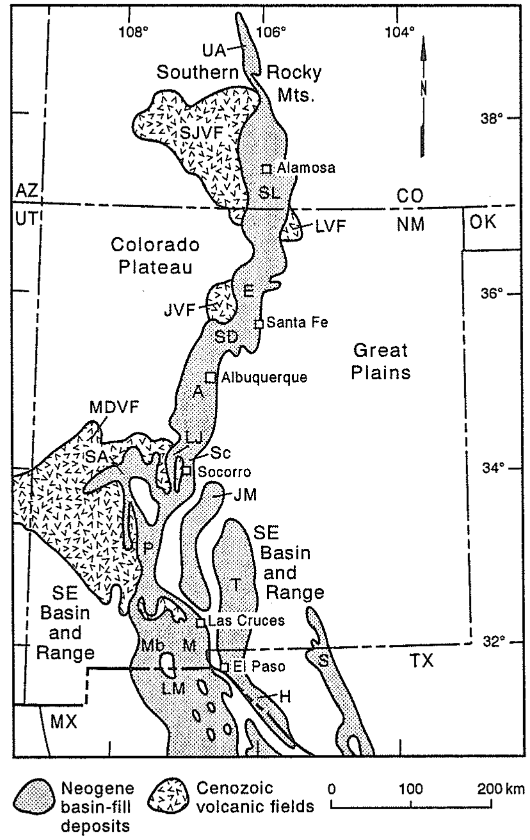


Figure 1. Index map showing major basins of the Rio Grande rift and contiguous volcanic fields. Modified from Keller and Cather, 1994. Basins abbreviations from north to south: Upper Arkansas (UA), San Luis (SL), Española (E), Santo Domingo (SD), Albuquerque (A), Socorro (Sc), La Jencia (La), San Augustine (SA), Jornada del Muerto (JM), Palomas (P), Tularosa (T), Mimbres (Mb), Mesilla (M), Los Muertos (LM), Hueco (H), and Salt (S). Cenozoic volcanic fields: San Juan (SJVF), Latir (LVF), Jemez (JVF), and Mogollon-Dàtil (MDVF).

Our basic conceptual model, which is designed for use in most of these basins, is a semi-quantitative description (graphical, numerical, and verbal) of (1) bedrock-boundary and internal-basin structure, and (2) the textural character, mineralogical composition, and geometry of various basin-fill and overlying valley-fill units, *all from a geohydrologic perspective*. Graphic displays of representative hydrogeologic component classes have a combined map and cross-section format so that basic information on geohydrologic attributes (e.g., hydraulic conductivity, transmissivity, anisotropy, and general spatial distribution patterns) can be transferred to basin-scale, three-dimensional numerical models of groundwater flow systems.

During the past two years, continued support by the City of Albuquerque and a new cooperative agreement with the U.S. Bureau of Reclamation have allowed the New Mexico Tech team to continue model refinement and validation and to expand our studies into adjacent parts of southern Sandoval County and northern Valencia County. We have now analyzed a data base that includes about 100 water wells that are at least 600 ft deep. Current studies, led by W.C. Haneberg, J.W. Hawley and T.M. Whitworth (NMBMMR), include new research on borehole geophysics and aquifer-system geochemistry, continued petrographic and stratigraphic investigations by P.S. Mozley and R.M. Chamberlin, and graduate student research by D.M. Detmer and J.M. Gillentine. Study duration, with respect to the career of the senior author, started in 1953 when he first worked in the Rio Grande rift region of south-central Colorado. Hydrogeologic study of the Albuquerque Basin, however, really started in the early decades of this century when W.G. Tight (1905), W.T. Lee (1907) and K. Bryan (1909, 1938) first looked at basin-fill geology from the perspective of facies distribution patterns, groundwater flow systems and surface water and groundwater interactions.

It must be emphasized that this is an extremely broad-based project that is still in progress. Information presented in this paper is the result of the collective efforts of many private and public institutions, scores of scientists and engineers (mostly geologically oriented), and hundreds of individuals (ranging from property owners to drilling contractors). Space limitations in this volume do not permit proper acknowledgment of all these individuals and supporting institutions; however, cited authors in the reference list include many of those whose contributions deserve special recognition.

This study could not have been done without access to proprietary subsurface information provided by ARCO Production and Exploration Technology, Shell Oil Company, New Mexico Public Service Company, Rio Rancho Utilities, New Mexico Utilities, Intel, Rinchem Company, and several Pueblos. We also must acknowledge substantial contributions by the following colleagues and institutions: Mike Kernodle, Scott Anderholm, Condé Thorn, Doug McAda and Chuck Heywood (USGS-Water Resources Division); Dave Love and Steve Cather (NMBMMR); Steve Hansen (USBR); Bill White (Bureau of Indian Affairs-Water Rights Division); Doug Earp (COA); Linda Logan (State Engineer Office); Dennis McQuillan and Bill Stone (NMED); Wayne Lambert (Texas AMU at Canyon); Sean Connell (University of California, Riverside); John Rogers (UNM Earth and Planetary Sciences Department); Tim Decker (West Water Associates); Bob Grant (Grant Enterprises, Inc.); and the staffs of John W. Shomaker and Associates, Metric Corporation, GRAM, Inc., Hydrogeology Associates, and CDM Corporation. Special appreciation is due to A. Norman Gaume and Thomas Shoemaker of the City of Albuquerque Public Works Department, Rob Leutheuser, USBR, and Charles E. Chapin, NMBMMR Director, for their steadfast support and encouragement. Kelly Summers, formerly with the COA Public Works Department, provided the initial vision and much of the hard data on subsurface hydrogeologic conditions that enabled the NM Tech-NMBMMR team to accomplish so much in so little time.

REGIONAL GEOLOGIC SETTING

Our cursory "underground view" of the Albuquerque Basin emphasizes the hydrogeologic framework of one of the largest and deepest basins of the Rio Grande rift (Figures 1-3). This zone of (earth) crustal extension forms a series of deep structural depressions (and flanking mountain and plateau uplifts) that also is one of the major topographic and hydrographic features of the southwestern United States. The rift extends more than 600 mi (1000 km) southward from the Upper Arkansas Valley of central Colorado through a west-

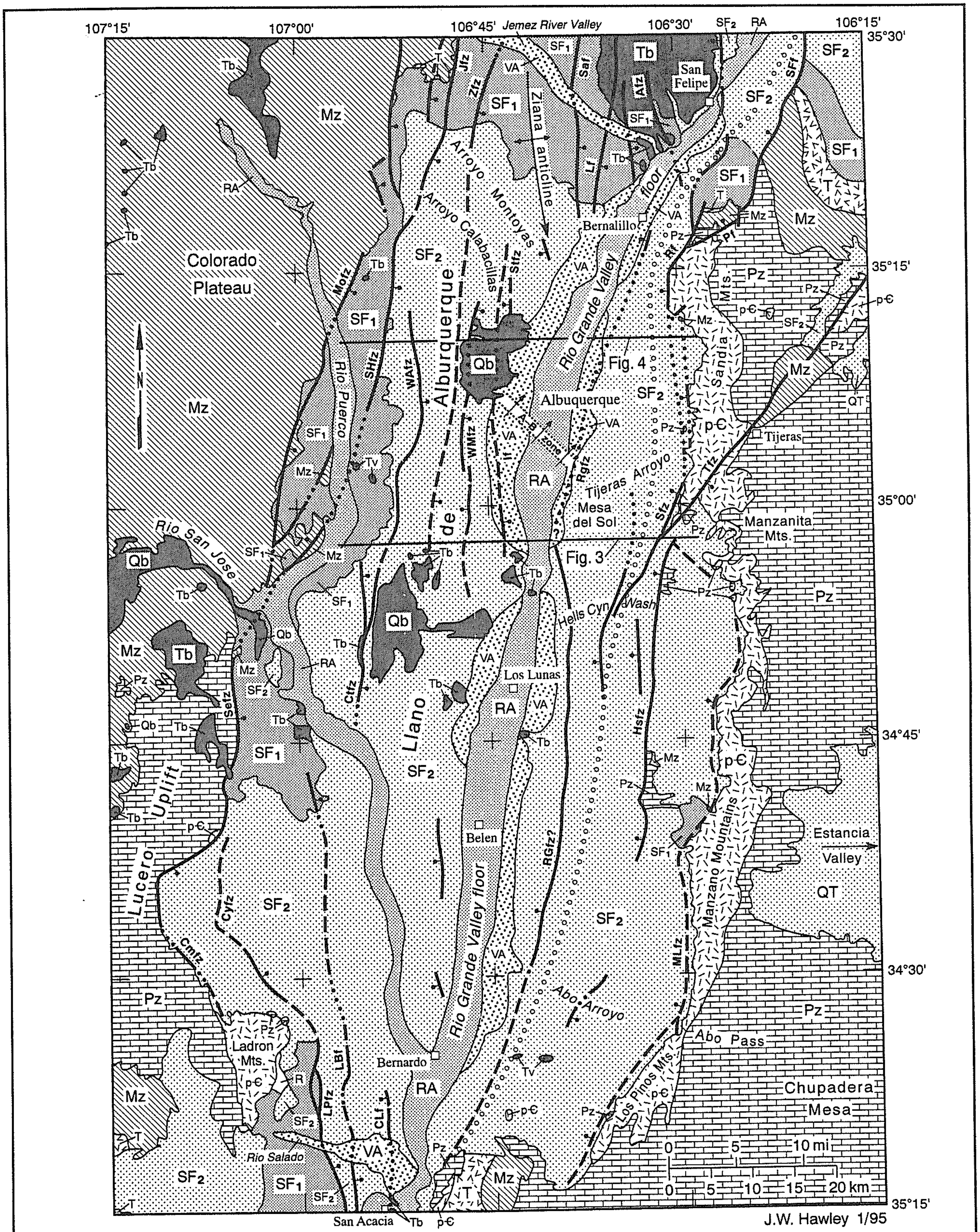


Figure 2. Simplified geologic map of the study area (modified from Anderson and Jones 1994).

Explanation of Rocks Units

- **RA** Rio Grande and Rio Puerco fluvial deposits defined in Table 1
- **VA** Alluvial fill of the lower Jemez River and Rio Salado Valley and valley–border alluvium defined in Table 1
- **Qb** Younger basaltic volcanics fields; extensive lava flows, with localized vent units such as cinder cones and lava domes, and possible feeder dikes and sills in subsurface; late middle Pleistocene
- **QT** Older alluvium, equivalent to USF–1 defined in Table 1
- **SF_2** Upper and Middle Santa Fe Group, primarily USF and MSF units defined in Table 1 (including discontinuous veneer of units VA and PA)
- **Tb** Older basaltic volcanics of the Wind Mesa and Isleta fields, extensive lava flows, with localized vent units; include possible sills and/or buried flows west of the Albuquerque volcanoes; Pliocene and Miocene
- **SF_1** Lower and Middle Santa Fe Group, primarily LSF and MSF units defined in Table 1 (including discontinuous veneer of units PA and VA)
- **Tv** Silicic to basaltic intrusive and volcanic rocks; Miocene and late Oligocene (?)
- **T** Lower and middle Tertiary sedimentary rocks undivided; primarily sandstone and mudstone; includes "unit of Isleta #2" of Lozinsky (1988), and Galisteo and Espinosa Formation correlatives
- **Mz** Mesozoic rocks–undivided; pimarily upper Cretaceous sandstone and mudstone, and local Jurassic clastic rocks, and Triassic sandstone and mudstone
- **Pz** Paleozoic rocks–undivided; including 1) sandstone, mudstone, and limestone of the Permian Abo, Yeso, Glorieta, and San Andres Formation; and 2) limestone, sandstone, and shale of the Pennsylvanian Madera Group and Sandia Formation
- **p-Є** Proterozic rocks–undivided; Precambrian igneous and metamorphic rocks
- **R** Undifferentiated pre-Santa Fe bedrock units

Normal fault, bar & ball on downthrown side; dashed where approximate; dotted where concealed

Eastern edge of axial Rio Grande deposits (USF–2)

Figure 2 (continued). Explanation of rock units. Fault-zone abbreviations: Atrisco-Barelas fault or flexture zone (A-B zone), Algodones zone (Afz), Cliff fault (CLF), Comanche-Saiz zone (Cmfz), Cat Mesa zone (Ctfz), Coyote zone (Cyfz), Hubbell Springs zone (HSfz), Isleta Fault (If), Jemez zone (Jfz), Loma Blanca fault (LBf), Loma Pelada zone (LPfz), Luce fault (LF), Moquino zone (Mofz), Manzano-Los Pinos zone (MLfz), Placitas fault (Pf), Rincon-Rancho fault (Rf), Rio Grande zone (RGfz), Santa Fe zone (Sefz), San Francisco fault (SFf), Sand Hills zone (SHfz), Star Heights zone (Stfz), Tijeras zone (Tfz), West Atrisco zone (WAfz), West Mesa zone (WMfz), and Zia zone (Zfz).

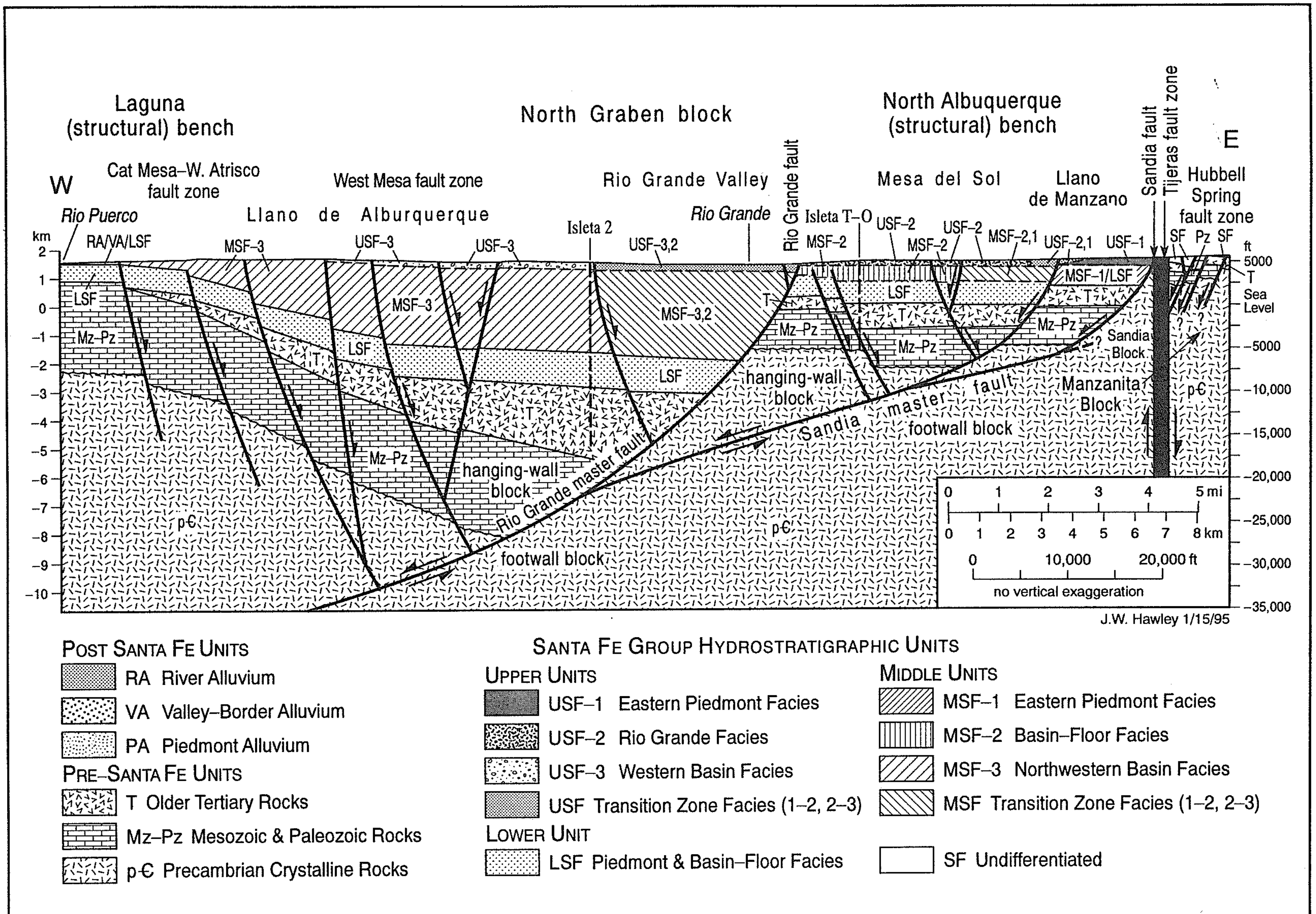


Figure 3. Schematic structural and hydrogeologic cross section of Albuquerque Basin along southern boundary of Pajarito Land Grant and across Mesa del Sol at southern edge of northern subbasin. Modified from May and Russell (1994, Figure 7), and Hawley and Haase (1992, Plate 5). Isleta 2 and Isleta T-O show the locations of the Shell Isleta 2 and Transocean Isleta 1 test wells. See Figure 2 for section location.

stepping series of *en-echelon* basins (drained by the upper and middle Rio Grande Valley system) in northern and central New Mexico. It terminates in the broad internally drained basin (bolson) region of southern New Mexico, Trans-Pecos Texas, and Chihuahua (Kelley 1952; Chapin 1971, 1988; Chapin and Seager 1975; Hawley 1978; Seager and Morgan 1979; Chapin and Cather 1994).

Besides the Albuquerque Basin, rift depressions in New Mexico include the southern San Luis and Española (-Santa Fe) "Valleys," flanked by ranges and volcanic highlands of the southern Rocky Mountains; Santo Domingo Basin (Stearns 1953), occupying a transitional area between Cochiti Dam and the northern Albuquerque Basin; and basins in the Mexican Highland section of the Basin and Range physiographic province to the south (e.g., Jornada, Palomas, Tularosa, and Mesilla; Figure 1). In the Santo Domingo-Albuquerque Basin area between Cochiti and Socorro, the rift is flanked on the west by high tablelands and volcanic uplands of the southeastern Colorado Plateau province, and on the east by the Great Plains region of the stable continental interior (craton).

In terms of deep structure of the earth's lithosphere, the rift is characterized by relatively thin, brittle, upper crust, more ductile lower crust, large negative gravity anomalies, high heat flow, young faulting, recent volcanism, and very thick basin fills. The structure, stratigraphy, and tectonic setting of rift basins is described in great detail in a volume recently published by the Geological Society of America, Inc. (Keller and Cather 1994) and is *must reading* for anyone with *deep* interest in the region's natural resources.

The complex sedimentary fill of Rio Grande rift basins (collectively) is designated the Santa Fe Group (Bryan 1938; Spiegel and Baldwin 1963; Hawley et al. 1969; Chapin 1988). This upper Cenozoic lithostratigraphic unit, ranging from about 0.5 to 30 million years (Ma) in age, constitutes one of the great aquifer systems of southwestern North America. The Group comprises partly indurated, porous clastic deposits (alluvial, colluvial, eolian, and lacustrine sediments), and associated volcanic rocks, that hold vast quantities of economically recoverable, fresh to slightly saline, groundwater. Our emphasis here is on the depositional history, lithologic (facies) composition, and basic structural organization (architecture) of basin and river-valley fills in the northern part of the Albuquerque Basin. This is one of the few rift areas (other than parts of the San Luis, Española and Mesilla basins) with a large amount of subsurface (geological, geophysical, geochemical) information on both shallow and deep basin characteristics.

GEOLOGIC SETTING OF THE ALBUQUERQUE BASIN

Physiography

The Albuquerque Basin (Figure 2) is near the northern end of the Basin and Range physiographic province in New Mexico (Hawley 1986). Its surface area is about 2300 mi^2 (6000 km^2). The Sandia (max. elev. 10,685; 3255 m) and Manzano (max. elev. 10,098; 3079 m) mountains at the basin's eastern edge include the highest peaks in the area, while the flanking uplifts of the Colorado Plateau to the west are significantly lower (max. elev. 7840 to 9176 ft; 2390 to 2797 m). Low topographic relief characterizes much of the basin interior. Surface elevations range from 4300 to 5100 ft (1300-1550 m) along the Rio Grande Valley to about 6000 ft (1830 m) at the base of the Sandia-Manzano range. The two major erosional features in the basin are the terraced valleys of the Rio Grande and Rio Puerco. The high tableland (mesa) between these valleys, with a maximum elevation of about 6700 ft (2000 m), is here designated the Llano de Albuquerque (L. de Alburquerque of Bryan and McCann 1937, 1938; Ceja Mesa of Kelley 1977). The broad, piedmont alluvial plains between the Rio Grande Valley and the Sandia and Manzano mountains are named, respectively, the Llano de Sandia and the Llano de Manzano (Bryan 1938; Lambert 1968; Machette 1985).

Basin-flanking Uplifts

The eastward-tilted Sandia-Manzano-Los Pinos range forms the most prominent basin boundary (Kelley 1977). This uplift consists of Precambrian plutonic and metamorphic rocks unconformably overlain by Paleozoic limestone, sandstone and shale. The western basin boundary with the Colorado Plateau is not as well-defined. Only the southwestern edge is sharply delineated by the Ladron and Lucero uplifts. Precambrian granitic and metamorphic rocks form the structurally high core of the Ladron Mountains; and Paleozoic limestone, sandstone, and shale capped by late Cenozoic basalt flows crop out in the gently west-tilted Lucero uplift. North of the Rio San Jose-Puerco confluence (Figure 2), the topographically subdued Rio Puerco fault zone marks the basin boundary with an east-tilted segment of the Colorado Plateau. Rocks exposed west of the fault zone include Cretaceous sandstone and shale with some exposures of Jurassic sandstone, mudstone and gypsum.

The Nacimiento Mountains and Jemez volcanic center form the northern edge of the basin (Figure 2). Precambrian plutonic and metamorphic rocks overlain by Paleozoic and Mesozoic strata crop out in the Nacimiento uplift (Woodward 1987), and mafic to silicic volcanic rocks of late Cenozoic age are the dominant units exposed in the Jemez Mountains (Smith et al. 1970; Gardner et al. 1986; Goff et al. 1989). Faults offsetting Pliocene basalt of the Santa Ana volcanic field between Bernalillo and San Felipe separate the Albuquerque Basin from the Santa Domingo Basin. The Precambrian-cored Joyita and Socorro-Lemitar uplifts flank the southern end of the basin and extend southward along the margins of the narrow Socorro Basin. The northeastern and southern hydrographic boundaries are marked by narrow reaches of the Rio Grande Valley that are located, respectively, near San Felipe and San Acacia. Thick basin fill, however, is continuous through these constrictions.

Basin Structure

The deep Albuquerque structural basin extends southward from the San Felipe fault belt north of Bernalillo to the Joyita uplift at the north end of the Socorro Basin constriction (figures 2 and 3), a distance of about 70 mi. (118 km). Basin width expands to about 40 mi (64 km) in the central basin area. Although the basin appears to be a single topographic feature, geophysical studies and deep drilling (Lozinsky 1988, 1994; Russell and Snelson 1990, 1994) indicate that it consists of two distinct structural subbasins each formed by groups of tilted blocks (half-grabens) that are down-faulted relative to adjacent (mountain and plateau) uplifts. The asymmetrical profiles (steep scarp slope vs. relatively gentle dipslope) of many rift-border ranges (e.g., the Sandia Mountains) are commonly mirrored in subsurface basin structures.

In the northern part of the basin, (hanging-wall) dipslopes of half-graben blocks tilt eastward with the same sense of rotation as the Sandia Mountain (footwall) block (Figure 3). According to Russell and Snelson (1994) northern subbasin extension is at least 17 percent. South of the Los Lunas area dominant half-graben tilt is westward and structural extension of the basin increases to as much as 30 percent. Seismic surveys by Shell Oil Company and deep natural-gas test wells support the interpretation that these opposing domains of tilted fault blocks are separated by a narrow and structurally high belt of complex deformation (Russell and Snelson 1990, 1994). This poorly defined "transfer" or "accommodation" zone (Russell and Snelson 1990; Chapin and Cather 1994) appears to follow the general southwest to west-southwest trend of the Tijeras fault zone (Tfz, Figure 2). The Tijeras zone separates highly contrasting (Precambrian) bedrock terranes of the Sandia and Manzano (-Manzanita) uplifts. It extends northeastward from Tijeras Canyon to the southern tip of the Sangre de Cristos southeast of Santa Fe and has a very complex history of both pre-rift and late Cenozoic tectonic deformation (Woodward 1982).

Internal basin structure is generally characterized by a deep, inner basin flanked by relatively shallow structural benches (e.g., North Graben block and North Albuquerque and Laguna benches, Figure 3) that step up to bordering uplifts. Faults showing the largest displacements occur several miles basinward from the topographically high basin margins (e.g., Rio Grande master fault). Structural interpretations based on seismic surveys and deep test drilling also indicate that most of the major basin-bounding and intrabasin faults have curved surfaces of displacement that flatten markedly with depths (listric-fault geometry; May and Russell 1994; Russell and Snelson 1994). Dips of master faults are as low as 15° to 20° at depths of 30,000 to 35,000 ft (about 10 km) below sea level in an inferred zone of transition between brittle upper crust and much more ductile middle to lower crust (Figure 3). Offset is primarily normal (basinward "dip-slip" along fault planes), but a significant component of left oblique shear has been noted along a few basin-boundary faults.

According to Russell and Snelson (1994, p. 105), "the northern (Albuquerque) subbasin is controlled by a major west-dipping listric-normal fault system that appears to flatten, or detach, at the base of the brittle crust." The primary component of this system is designated the *Rio Grande master fault* (figures 2-4; May and Russell 1994; May et al. 1994). This fault has more than 30,000 ft (10 km) of vertical offset, and our current analyses of deep-well data in the east Albuquerque area indicate that it is located under the east edge of the Rio Grande valley near I-25. Note that a secondary (Sandia) component of the master fault system continues eastward and approaches the modern land surface just west of the Sandia Mountain front (figures 3 and 4). There is no field evidence that this system is presently active. On a basinwide scale, updip segments of the hanging-wall block (e.g., Laguna bench, Figure 3) have hinged (inner-basin) margins that flex down to the east and are cut by relatively steep and shallowly penetrating faults. As the basin pulled apart, clockwise (eastward) rotation of the hanging-wall block produced a deep and complexly faulted inner graben (e.g., North Graben block, Figure 3). Primary (Sandia) and secondary (Albuquerque bench) footwall blocks also tilted eastward rotating clockwise away from the deep-basin axis along primary and secondary master faults (figures 3 and 4). Tectonic unloading of the Sandia Mountain (footwall) block (Figure 4) along the northeastern basin margin probably started 15 to 20 Ma ago and is reflected in the high topographic relief of that "rift shoulder uplift" (May et al.1994).

The asymmetrical half-graben morphology described above is characteristic of many rift basins throughout the world (Rosendahl 1987). This style of large-scale structural deformation (tectonism) directly influences the distribution patterns of the major environments of deposition observed in basin-fill sequences (e.g., piedmont-slope alluvial, and basin-floor playa-lake or fluvial braid-plain deposits; Leeder and Gawthorpe 1987; Blair and Bilodeau 1988; Mack and Seager 1990; Blair and McPherson 1994; Cather et al. 1994; Dart et al. 1995). These depositional features are the primary (facies) components of the lithostratigraphic and hydrostratigraphic units discussed in the following sections.

BASIN- AND VALLEY-FILL STRATIGRAPHY

Introduction

Stratigraphic units within the Albuquerque Basin consist primarily of continental sediments and have three major subdivisions: (1) pre-Santa Fe Tertiary rocks, (2) Santa Fe Group basin fill, and 3) post-Santa Fe river-valley and basin-fill deposits. Pre-Santa Fe Tertiary deposits (figures 2-4), including local volcanic units, were deposited in ancient structural depressions and valley systems that predate development of the Rio Grande rift. They are only exposed in a few places and can be properly characterized only when subsurface information is available. Lower and middle Tertiary units in the basin area have been described by Lozinsky (1988, 1994) and Cather (1992) and are only mentioned here.

The relatively simple process of rift-basin filling and recent valley cutting summarized in this report is quite complex in detail because of local intermittent volcanic activity and the continuing structural deformation of basin boundaries and interior areas. Topographic relief between individual basin segments and flanking highlands has continued to change over late Cenozoic time due to effects of both deep-seated and surface (mountain climate-driven) geomorphic processes. For example, during early stages of rift-basin filling (lower Santa Fe deposition) the present bounding range blocks had not formed or had low topographic relief. Thickest basin-fill deposits (up to 10,000 feet of the middle Santa Fe Group) were emplaced between 5 and 15 million years ago during the interval of most active uplift of the Sandia-Manzanita-Manzano range and deep subsidence of the central basin "North Graben" block (May and Russell 1994). Late stages of basin-filling and ongoing valley cut and fill cycles have been profoundly influenced by the climate-(geomorphic) process shifts of the Quaternary and late Pliocene interval (past 2 to 3 Ma).

Basin Fill

The Santa Fe Group is the major fill unit of the Albuquerque Basin and ranges in age from about 1 to 25 Ma (Bryan 1938; Bryan and McCann 1937, 1938; Wright 1946; Stearns 1953; Spiegel

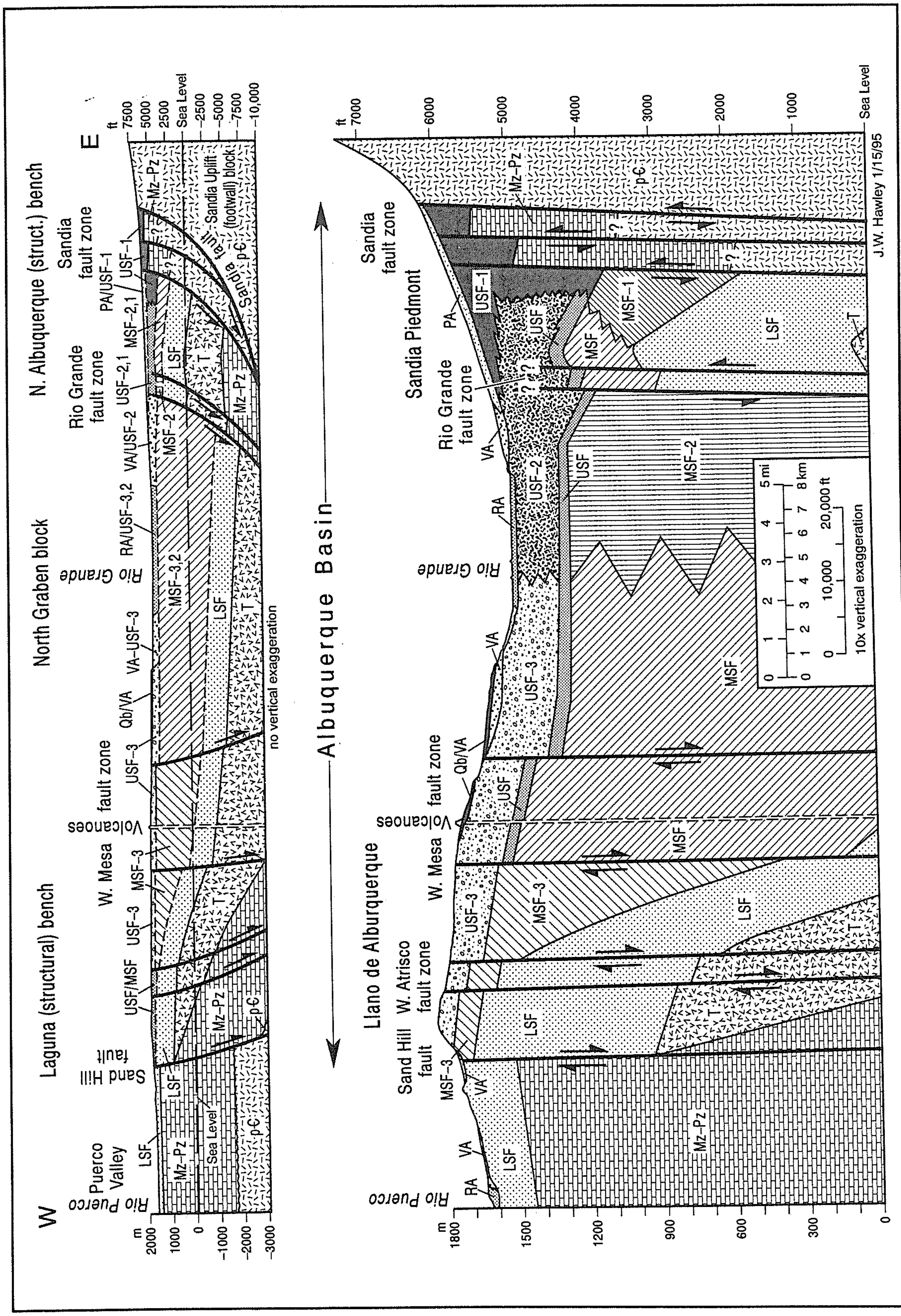


Figure 4. Schematic hydrogeologic cross section of the northern Albuquerque Basin aligned with eastern Paseo del Norte Blvd. Deep structural interpretation in upper section primarily based on May and Russell (1994, figures 2, 3, 4, and 7). Lower section modified from Hawley and Haase (1992, Plate 2) and Haneberg and Hawley (1995, Plate 2). See Figure 2 for section location and Table 1 for detailed explanation of hydrostratigraphic unit symbols.

1961; Spiegel and Baldwin 1963; Lambert 1968; Galusha and Blick 1971; Kelley 1977; Hawley 1978; Tedford 1981, 1982; Chapin 1988). The Group comprises alluvium and colluvium derived from erosion of the nearby highlands, other "fluvial" material transported to the basin by streams draining distant upland sources (primarily to the north), and locally thick lake playa, and eolian deposits (Ingersoll et al. 1990; Hawley and Haase 1992). Maximum fill thickness ranges from 3000 to 4000 ft along basin margins to about 15,000 ft in the deeper central basin area (figures 3 and 4). Volcanic flows, dikes, sills and ashbeds are scattered throughout the section (Bachman and Mehnert 1978; Kelley and Kudo 1978). Deep test well data show that most of the Santa Fe Group rests on Oligocene sedimentary and volcanic rocks, except along the eastern margin where it overlies Paleozoic, Mesozoic or lower Tertiary strata (Figure 3). The Group is informally subdivided into lower, middle, and upper (lithostratigraphic) units based on depositional environments and age (Hawley and Haase 1992; Hawley and Lozinsky 1992).

The *lower and middle parts of the Santa Fe Group* are locally well indurated and contain a large amount of fine- to medium-grained clastic material (clay, silt, and fine sand). These upper Oligocene and Miocene units were deposited on the broad central plains of an internally drained basin complex, and playa-lake sediments and associated fine-grained to sandy alluvium appear to be major basin-floor facies. With the exception of locally extensive and thick eolian sand deposits (e.g., Zia Fm in the lower Santa Fe Group), lower and middle Santa Fe units do not produce significant amounts of good-quality groundwater even though they constitute the bulk of the basin-fill sequence. The base of the *upper Santa Fe Group* is marked by widespread channel deposits of a through-going river system (the ancestral Rio Grande) that first appear in basin fill that has been dated at about 5 Ma (Figure 5). These poorly consolidated, medium- to coarse-grained sediments (fluvial sand and gravel) form the major aquifers of the region. In the northernmost part of the Albuquerque Basin, the basal fluvial beds are transitional to basin-floor facies of the middle Santa Fe Group.

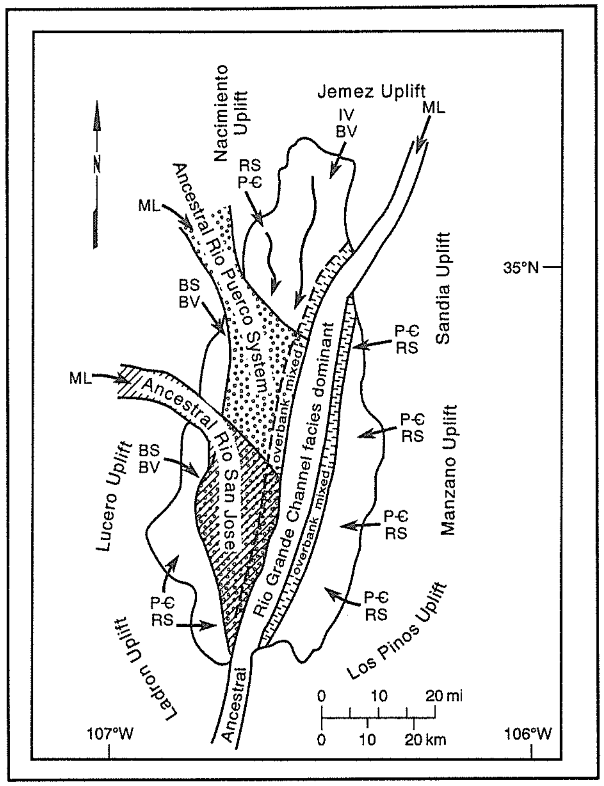


Figure 5. Schematic drawing showing the inferred contributory drainage system during deposition of the upper Santa Fe Group (Sierra Ladrones Fm and informal hydrostratigraphic unit USF). From Lozinsky and others (1991, Figure 3). Arrows indicate general flow directions and lithologic character of source terranes. Abbreviations are Precambrian igneous and metamorphic rocks (pЄ), partly reworked sedimentary rocks (RS), intermediate volcanic rocks (IV), mafic volcanic rocks (MV), mixed lithologies (ML).

The thickest documented sections of fluvial deposits in the area (greater than 1000 ft, 300 m) are preserved as a stacked sequence of braided river-channel deposits that is as much as three miles (5 km) in width beneath the "eastern heights" of metropolitan Albuquerque. This and similar sequences in the Corrales-southeastern Rio Rancho area are characterized by extensive beds of sand and pebble gravel and relatively small amounts of silt and clay. A typical cross-section view of the upper Santa Fe Group fluvial facies is shown schematically on Figure 4 (unit USF-2). This stratigraphic and structural interpretation is based on analyses of geophysical logs, samples, and other subsurface data from ten deep wells drilled along eastern Paseo del Norte Blvd (Haneberg and Hawley 1995). The inferred limit of fluvial deposits throughout the eastern Albuquerque Basin is shown on Figure 2 as a line of small circles between the Rio Grande Valley and the Sandia-Manzano range front.

The role that geologic structure (basin tectonism) has played in controlling the position of the ancestral Rio Grande (unit USF-2) is clearly illustrated in Figure 4. Episodic eastward rotation of the (hanging wall) "North Graben and Albuquerque Bench" blocks along the Rio Grande-Sandia master fault zone positioned the ancient fluvial system at the eastern edge of the half-graben and above the western margin of the Sandia Mountain (footwall) block during much of Pliocene time. The uppermost 200 to 300 ft (60-100 m) of the channel sequence contains glassy and pumiceous fragments of volcanic rocks derived from late stage eruptions of the Jemez center that culminated with the catastrophic emplacement of the Bandelier Tuff about 1.1 and 1.6 Ma ago (Goff et al. 1989). The ancestral Rio Grande shifted westward during that interval; and the present Llano de Sandia piedmont slope developed when aggrading alluvial fans also prograded westward from the Sandia Mountain front toward the present Rio Grande Valley (Unit USF-1, Figure 4).

Post-Santa Fe Deposits

Santa Fe deposition ended in the early part of the Quaternary (Ice-Age) Period when expansion of the Rio Grande fluvial system into upstream and downstream basins, and integration of drainage to the Gulf of Mexico led to rapid incision of the present river valley and termination of widespread filling of intermontane basins in the Rio Grande rift area north of the Mesilla Basin (Figure 1; Lambert 1968; Hawley et al. 1976; Bachman and Mehnert 1978; Gile et al. 1981; Seager et al. 1984; Machette 1985). Post-Santa Fe units shown in Figure 4 (PA, VA, RA) were deposited in the river-arroyo-valley system that has been episodically cut and filled during the past million years.

Cyclic stages of valley cutting and filling, which correlate with expansion and contraction of alpine glaciers in the Southern Rocky Mountains (San Juan and Sangre de Cristo), are represented by prominent river-terrace and floodplain deposits that partly fill the Rio Grande, Puerco and Jemez valleys (units RA and VA). Channel sand and gravel deposits (<100 ft, 30 m thick) below the modern river floodplain (unit RA) constitute a thin, but extensive aquifer that is locally in contact with ancient river-channel facies of the upper Santa Fe Group. These combined units form a shallow aquifer system that is the major recharge as well as discharge zone for much of the basin's groundwater. This system is clearly quite vulnerable to pollution in an urban-suburban environment (Lambert et al. 1982; Hawley and Haase 1992).

HYDROGEOLOGIC MODEL OF THE ALBUQUERQUE BASIN

Our conceptual model of the basin's hydrogeologic framework has three basic components, which are graphically presented in a map and cross-section format (figures 2-4) and summarized in Table 1:

1. Structural and bedrock features (already discussed) include basin-bounding mountain uplifts, bedrock units beneath the basin fill, fault zones within and at the edges of the basin that influence sediment thickness and composition, and the igneous intrusive and extrusive (volcanic) rocks that locally penetrate or overlap basin-fill deposits.

2. Hydrostratigraphic Units are the major hydrogeologic components of the model and comprise mappable bodies of basin and valley fill that have definable hydrologic characteristics and can be grouped on the basis of position in a stratigraphic sequence. They are defined in terms of (1) depositional environment, (2) distinctive combinations of lithologic features (lithofacies) such as grain-size distribution, mineralogy and sedimentary structures, and (3) general age of deposition. Genetic classes include ancestral-river, present river valley, basin-floor playa, and alluvial-fan piedmont deposits. The attributes of four major (RA, USF, MSF, LSF) and two minor (VA, PA) classes into which the area's basin and valley fills have been subdivided are described in Table 1 and illustrated in Figure 4. The Upper (USF), Middle (MSF), and Lower (LSF) hydrostratigraphic units of the Santa Fe Group roughly correspond to the (informal) upper, middle, and lower rock-stratigraphic subdivisions of Santa Fe Group described in the preceding section. The

TABLE 1. HYDROSTRATIGRAPHIC UNITS AND THEIR RELATIONSHIP TO LITHOFACIES SUBDIVISIONS

Unit	Description
RA	River alluvium; channel, floodplain, and lower terraces deposits of inner Rio Grande and Puerco valleys; as much as 120 ft thick. Map unit "Qf" (Kelley 1977). Forms upper part of the "shallow aquifer" system. Hydrogeologic (lithofacies) subdivision Iv*. *Age: Holocene to late Pleistocene.*
VA	Valley-border alluvium; tributary-arroyo; and thin eolian deposits in areas bordering inner Rio Grande and Puerco valleys, with locally extensive river-terrace deposits, as much as 200 ft thick. Includes older, sandy to silty, valley fill in the vicinity of Calabacillas Arroyo and the Atrisco area. Map units "Qa" and "Qt" (Kelley 1977), and "Edith, Menaul, and Los Duranes" (alluvial-terrace) units (Lambert 1968). Includes hydrogeologic (lithofacies) subdivisions Iv, II, and V. Most of unit is in the vadose (unsaturated) zone. *Age: Holocene to middle Pleistocene*
PA	Piedmont-slope alluvium; coarse-grained alluvium, mainly deposited as coalescent fans extending basinward from mountain fronts on the eastern and southwestern margins of the basin; as much as 150 ft thick; includes surficial deposits mantling piedmont erosion surfaces (including rock pediments). Includes deposits of ancestral Tijeras Arroyo system in the depression between I-40 and the SE Central-Ridgecrest Blvd. area (Lambert et al. 1982). Map units "Qfa" and "Qp" (Kelley 1977), and hydrogeologic (lithofacies) subdivisions Vf, Vd, and VI. Most of unit is in vadose zone. *Age: Holocene to middle Pleistocene*
SF	Santa Fe Group - undivided; fill of intermontane basins of the Rio Grande rift in New Mexico and adjacent parts of Colorado, Texas, and Chihuahua (Mexico). Includes alluvial, eolian and lacustrine deposits; and interbedded extrusive volcanic rocks (basalts to silicic tuffs). In the Albuquerque Basin, the Santa Fe is as much as 15,000 ft thick. It is mapped both as a formation (member subdivisions) (Kelley 1977), and as a group (formation and member subdivisions) (Hawley 1978; Machette 1978a, b; Lozinsky and Tedford 1991). Sand and gravel facies form the major aquifers in Albuquerque basin (and elsewhere in basins of the Rio Grande rift). The group is subdivided into three (informal) hydrostratigraphic units:
USF USF-1 USF-2 USF-3	Upper Santa Fe Unit; coarse- to fine-grained (fluvial) deposits of ancestral Rio Grande and Puerco systems that intertongue toward basin margins with piedmont-alluvial facies; volcanic rocks (including basalt, andesite and rhyolite flow and pyroclastic units) and thin, sandy eolian deposits are locally present. Unit is less than 1000 ft thick in most areas, but locally exceeds 2000 ft in thickness. Subunit USF-1 is primarily coarse-grained fan alluvium derived from the Sandia, Manzanita and Manzano uplifts. USF-2 includes ancestral-Rio Grande and interbedded fine- to medium-grained sediments of diverse (alluvial-lacustrine-eolian) origin deposited in a rapidly aggrading basin-floor environment. Thick alluvial and thin eolian deposits capping the Llano de Albuquerque (West Mesa) between the Rio Grande and Puerco Valleys form subunit USF-3. These gravelly to sandy, piedmont and basin-floor facies are mainly derived from the Southern Rocky Mountain and southeastern Colorado Plateau provinces. Unit includes Ceja Member of the Santa Fe "Formation" (Kelley 1977), and Sierra Ladrones Formation (Machette 1978a, b; Lozinsky and Tedford 1991); and locally, upper Cochiti and Popotosa Formation correlatives (Manley 1978). It forms lower part of "shallow aquifer" below river-floodplain areas, and main part of basin-fill aquifer system in City of Albuquerque well fields. Includes hydrogeologic (lithofacies) subdivisions Ib, II, III, V, Vd, Vf, VI, VIII and IX. Much of this unit is in vadose zone. *Age: Early Pleistocene to late Miocene, mainly Pliocene*
MSF MSF-1 MSF-2 MSF-3	Middle Santa Fe Unit; alluvial, eolian, and playa-lake deposits; partly indurated, coarse- to fine-grained piedmont alluvium that intertongues basinward with fine-grained to sandy basin-floor facies, including playa-lake and local braided-stream deposits. Basaltic to silicic volcanics are also locally present. The Rio Grande rift region extending from central New Mexico into south-central Colorado is a major sediment source area for Albuquerque Basin Fill. The unit is as much as 10,000 ft thick near the Isleta volcanic center, and commonly is at least 5,000 ft thick in central basin areas. Subunit MSF-1 is primarily coarse-grained fan alluvium derived from early-stage Sandia, Manzanita and Manzano uplifts including the ancestral Tijeras Canyon drainage basin. MSF-2 comprises sandy to fine-grained basin-floor sediments of mixed (alluvial-lacustrine-eolian) origin that intertongue eastward with subunit MSF-1, and westward and northward (beneath the Llano de Alburquerque) with subunit MSF-3. The latter subunit includes coarse- to fine-grained alluvium derived from the southeastern Colorado Plateau and Nacimiento-Jemez Mountain area. Includes much of the Popotosa Formation (Machette 1978a, b; Lozinsky and Tedford 1991) in southern Albuquerque Basin, and part of Cochiti Formation (Manley 1978) and "middle red" formation (Spiegel 1961; Lambert 1968; Kelley 1977) in northern part of basin. Forms lower part of main aquifer system in the north-central part of basin. Includes hydrogeologic (lithofacies) subdivisions II, III, IV, V, Vd, Vf, VI, VII, VIII and IX. *Age: Late to middle Miocene*
LSF	Lower Santa Fe Unit; alluvial, eolian, and playa-lake facies. Sandy to fine-grained basin-floor sediments, including thick dune sands and gypsiferous sandy mudstones, grade to conglomeratic sandstones and mudstones near basin margins (early-stage piedmont alluvial deposits). The unit is as much as 3500 ft thick in the central basin areas, where it is locally thousands of feet below sea level. Includes lower part of Popotosa Formation (Machette 1978a, b; Lozinsky and Tedford 1991) in southern Albuquerque (Belen) Basin, and Zia (Sand) Formation (Galusha 1966; Kelley 1977) in northern part of basin. Eolian sand facies of the Zia Formation are an important part of the deep aquifer system beneath the Llano de Alburquerque in northwestern Rio Rancho. Due to deep burial and abundance of silt-clay, the unit is not known to form a major part of the aquifer system in other parts of the basin. Includes hydrogeologic (lithofacies) subdivisions IV, VII, VIII, IX and X. *Age: Middle Miocene to late Oligocene*

*Lithofacies subdivisions illustrated on Figure 6.

other major hydrostratigraphic unit (RA) comprises Rio Grande and Rio Puerco deposits of late Quaternary age (<20,000 yrs) that form the upper part of the regional shallow-aquifer system. Units VA and PA include river-terrace deposits, fills of major arroyo valleys, and piedmont-slope alluvium that are primarily in the unsaturated (vadose) zone.

3. Lithofacies Units, schematically illustrated in Figure 6, are the basic building blocks of the model where detailed subsurface information is available (e.g., geophysical logs and drill cuttings). Lithofacies are mappable bodies defined primarily in terms of sediment-grain-size characteristics (gravel, sand, silt, clay, or mixtures thereof), mineral composition, degree of cementation, geometry of bodies of a given textural class, and their general subsurface distribution patterns. They have distinctive differences in geophysical and geochemical properties and in hydrologic behavior (Haase 1992; Hawley and Lozinsky 1992; Mozley et al. 1992; Haneberg and Hawley 1995). In this study, basin deposits have been subdivided into ten major lithofacies units.

Lithofacies I, II, III, V and VI are unconsolidated or have zones of induration (strong cementation) that are not continuous. Clean, uncemented sand and gravel bodies are major constituents of facies I and II, and a significant proportion of the clast assemblage is derived from source areas north of the Albuquerque Basin. Clay and sandstone zones, respectively, form a significant part of facies III and IV. Subdivision IV occurs mainly in unit LSF and includes thick eolian sand and sandy fluvial deposits that are partly indurated (common calcite cement). Lithofacies V and VI are, respectively, distal to medial and medial to proximal components of piedmont alluvial aprons (usually formed by coalescent alluvial fans). Debris-flow and sheet-flood deposits dominate subfacies Vf, while distributary stream-channel fills form a large part of subfacies Vd. Lithofacies VII and VIII are partly to well indurated piedmont-slope deposits; and facies IX and X comprise thick sequences of fine-grained basin-floor sediments that include playa-lake beds and other lacustrine sediments. These facies are major components of units MSF and LSF.

Coarse-grained channel deposits of the modern and ancestral Rio Grande system (lithofacies I and II) are the major components of the upper Santa Fe (USF-2) and river-alluvium (RA) hydrostratigraphic units. Ancestral-river deposits form the most important aquifers and potential enhanced-recharge zones in the basin. Buried arroyo-channel deposits of a large alluvial fan that spreads out from the mouth of Tijeras Canyon and similar large alluvial channels in the Rio Rancho area (facies Vd) form another major hydrogeologic unit (uppermost middle and upper Santa Fe; MSF-1, 3, and USF-1, 3) that also has greater than average aquifer performance and recharge potential. These ancient complexes of distributary channels are now partly dissected by valleys of the present lower Embudo, Campus, Tijeras, Calabacillas, and Montoyas arroyo systems.

Structural (tectonic) controls on basin-fill facies distribution patterns have already been briefly discussed in the preceding section and are illustrated on figures 2, 4, and 6. Only two examples are described here, but the topic is covered in detail in a project completion report currently being compiled by Haneberg and Hawley (1995). The east-tilted (multiple) half-graben structure of the northern subbasin has clearly controlled the position of ancestral Rio Grande (Unit USF-2, facies Ib, II, III) since basin throughflow was initiated about 5 Ma ago. In middle Santa Fe (middle to late-Miocene) time, the rapidly subsiding North Graben block was episodically a site of lacustrine deposition during intervals when tributary streams were unable to deliver the amounts of sediment needed to maintain through flow conditions. Facies IX and X are major components of unit MSF (Figure 4) in such areas of restricted drainage.

An important but poorly understood structural feature, labeled A-B (Atrisco-Barelas) zone on Figure 2, has a major influence on the behavior of the shallow and intermediate aquifers below the river floodplain. Upper Santa Fe (USF-2, 3) facies Ib, II, and III thin from about 800 to 400 ft (294–122 m) and depth to middle Santa Fe (MSF) facies IX and III decreases by about the same amount southwestward across the A-B structural trend. The A-B zone is here interpreted as either a fault or fold that is displaced downward to the northeast, and aquifer transmissivity appears to decrease by at least a factor of 2 in a downstream direction across the structure. The A-B feature was only revealed after detailed study of about 30 borehole geophysical and drilling logs from deep wells in the central and southwestern Albuquerque area.

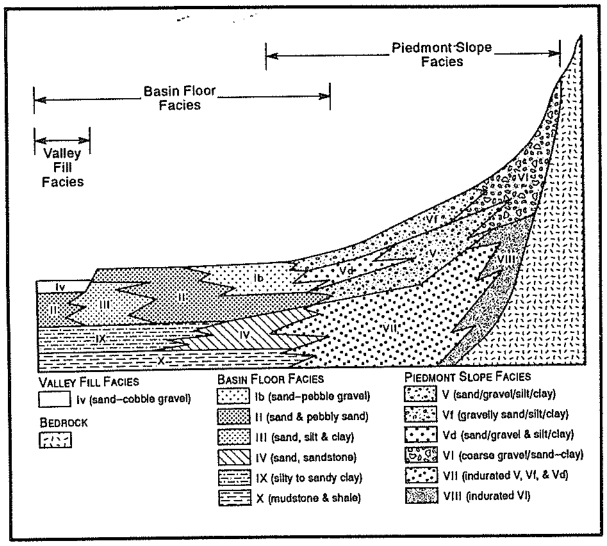


Figure 6. Hypothetical distribution of lithofacies in the Albuquerque Basin. Modified from Hawley and Haase (1992, Figure III-6). See Table 1 for explanation of facies distribution patterns in hydrostratigraphic units.

CONCLUSION

The geological and geophysical data base on subsurface conditions in the Albuquerque–Rio Ranch metropolitan area (Figure 2) is now complete enough to allow us to describe (semiquantitatively) the "architecture" of the basin-fill deposits with respect to their basic hydrogeologic properties, namely the distribution patterns of major lithologic, stratigraphic, and structural subdivisions ("hydrogeologic units") that can be defined in terms of aquifer characteristics. This data base has excellent areal coverage to depths in the 2500 to 3500 ft (750-1050 m) range, or to an average elevation of about 2500 ft (750 m) above sea level. It extends much deeper, locally several miles (up to 6 km), in a few areas where geophysical interpretations (mainly based on seismic-reflection and gravity surveys) have been confirmed by recent deep test drilling for natural gas resources.

Ongoing investigations, summarized in this paper (and described in detail in a 1995 project completion report compiled by Haneberg and Hawley) have resulted in refinements of, but no substantial changes to the conceptual model of the basin's hydrogeologic framework originally presented in Hawley and Haase (1992). This model represents a significant advancement over previous portrayals of basin hydrogeology (e.g., Bryan 1938; Wright 1946; Bjorklund and Maxwell 1961; Spiegel 1961, 1962; Titus 1961, 1963); and it definitely has provided a much improved basis for development of the current USGS model of the groundwater flow system in the Albuquerque Basin (Thorn et al. 1993; Kernodle et al. 1995).

In many parts of the basin, however, we still lack the (deep) subsurface geological and geophysical information that is necessary for accurate predictions of "hydrostratigraphic-unit and lithofacies" distribution patterns and characterization of important structural boundaries. Our hydrogeologic concepts in such places are still primarily based on working hypotheses (inferences) about the basin's tectonic and depositional history developed from surface geophysics, shallow well drilling, and geologic mapping at a reconnaissance level. In these areas, the model definitely needs to be verified by additional deep test drilling, geophysical exploration and expansion of observation-well networks.

REFERENCES

Anderson, O.J. and G.E. Jones. 1994. *Geologic Map of New Mexico*. New Mexico Bureau of Mines & Mineral Resources Open-File Report OF-408, Scale 1:500,000.

Bachman, G.O. and H.H Mehnert. 1978. New K-Ar dates and the late Pliocene to Holocene geomorphic history of the central Rio Grande region, New Mexico. *Geological Society of America*, 89:283–292.

Bjorklund, L.J. and B.W. Maxwell. 1961. *Availability of Ground Water in the Albuquerque Area, Bernalillo and Sandoval Counties, New Mexico*. New Mexico State Engineer Office Technical Report 21, 117 pp.

Blair, T.C. and W.L. Bilodeau. 1988. Development of tectonic cyclothems in rift, pull-apart, and foreland basins: Sedimentary response to episodic tectonism. *Geology*, 16:517–520.

Blair, T.C. and J.G. McPherson. 1994. Historical adjustments by Walker River to lake-level fall over a tectonically tilted half-graben floor, Walker Lake Basin, Nevada. *Sedimentary Geology*, 92:7–16.

Bryan, K. 1909. Geology of the vicinity of Albuquerqüe. University of New Mexico Bulletin 51, Geological Series, 3:24.

Bryan, K. and F.T. McCann. 1937. The Ceja de Rio Puerco: A border feature of the Basin and Range province in New Mexico, Part I. *Journal of Geology*, 45:801–828.

Bryan, K. 1938. Geology and groundwater conditions of the Rio Grande depression in Colorado and New Mexico. *U.S. Natural Resources Planning Board, The Rio Grande Joint Investigations in the Rio Grande Basin*. Washington, D.C., U.S. Government Printing Office, 1:2:197–225.

Bryan, K. and F.T. McCann. 1938. The Ceja de Rio Puerco: A border feature of the Basin and Range province in New Mexico, Part II. *Journal of Geology*, 46:1–16.

Cather, S.M. 1992. Suggested revisions to the tertiary tectonic history of north-central New Mexico. *New Mexico Geological Society, Guidebook 43*, pp. 109–122.

Cather, S.M., R.M. Chamberlin, C.E. Chapin, and W.C. McIntosh. 1994. Stratigraphic consequences of episodic extension in the Lemitar Mountains, central Rio Grande rift. *Geological Society of America Special Paper*, 291: 57–170.

Chapin, C.E. 1971. The Rio Grande rift, Part I: Modifications and additions. *New Mexico Geological Society, Guidebook 22*, pp. 191–201.

Chapin, C.E. and W.R. Seager. 1975. Evolution of the Rio Grande rift in the Socorro and Las Cruces areas. *New Mexico Geological Society, Guidebook 26*, pp. 297–321.

Chapin, C.E. 1988. Axial basins of the northern and central Rio Grande rifts. Sedimentary cover—North American Craton (U.S.). *Geological Society of America, Geology of North America*, L.L. Sloss (ed.), D2:165–170.

Chapin, C.E. and S.M. Cather. 1994. Tectonic setting of the axial basins of the northern and central Rio Grande rift. *Geological Society of America Special Paper*, 291:5–25.

Dart, C., H.A. Cohen, H.S. Akyüz, and A. Barka. 1995. Basinward migration of rift-border faults: Implications for facies distributions and preservation potential. *Geology*, 23:1: 69–72.

Galusha, T. 1966. The Zia Sand Formation, new early to medial Miocene beds in New Mexico. *American Museum Novitates*, 2271:1–12.

Galusha, T. and J.C. Blick. 1971. Stratigraphy of the Santa Fe Group, New Mexico. *American Museum of Natural History Bulletin 144*, pp. 1–128.

Gardner, J.N., F. Goff, S. Garcia, and R.C. Hagan. 1986. Stratigraphic relations and lithologic variations in the Jemez volcanic field, New Mexico. *Journal of Geophysical Research*, 91:1763–1778.

Gile, L.H., J.W. Hawley, and R.B. Grossman. 1981. *Soils and Geomorphology in the Basin Range area of southern New Mexico-Guidebook to the Desert Project*. New Mexico Bureau of Mines & Mineral Resources Memoir 39, 222 pp.

Goff, F., J.N. Gardner, W.S. Baldridge, J.B. Hulen, D.L. Nielson, D. Vaniman, G. Heiken, M.A. Dungan, and D. Broxton. 1989. Excursion 17B: Volcanic and hydrothermal evolution of Pleistocene Valles caldera and Jemez volcanic fields. *Field excursions to volcanic terranes in the western United States, Volume I: Southern Rocky Mountain region*. New Mexico Bureau of Mines & Mineral Resources Memoir 46, C.E. Chapin and J. Zidek (eds.), pp. 381–434.

Haase, C.S. 1992. Borehole geophysical data. In *Hydrogeologic framework of the northern Albuquerque Basin*. New Mexico Bureau of Mines & Mineral Resources, Open-File Report 387, pp. V–1 to V–18.

Haase, C.S. and R.P. Lozinsky. 1992. Estimation of hydrologic parameters. *Hydrogeologic Framework of the Northern Albuquerque Basin*. New Mexico Bureau of Mines & Mineral Resources Open-File Report 387, pp. VI–1 to VI–13.

Haneberg, W.C. and J.W. Hawley (eds.). 1995. *Characterization of Hydrogeologic Units in the Northern Albuquerque Basin*. New Mexico Bureau of Mines & Mineral Resources Open-File Report 402, (In preparation).

Hawley, J.W., F.E. Kottlowski, W.R. Seager, W.E. King, W.S. Strain, and D.V. LeMone. 1969.

The Santa Fe Group in the South-central New Mexico Border Region. New Mexico Bureau of Mines & Mineral Resources Circular 104, pp. 235–274.

Hawley, J.W., G.O. Bachman, and K. Manley. 1976. Quaternary stratigraphy in the Basin and Range and Great Plains provinces, New Mexico and western Texas. *Quaternary stratigraphy of North America.* W.C. Mahaney (ed.), Dowden, Hutchinson, and Ross, Inc., Stroudsburg, PA, pp. 235–274.

Hawley, J.W. (compiler). 1978. *Guidebook to the Rio Grande Rift in New Mexico and Colorado*. New Mexico Bureau of Mines & Mineral Resources Circular 163, 241 pp.

Hawley, J.W. 1986. Physiographic provinces (and) landforms of New Mexico. *New Mexico in Maps: Albuquerque*. J.L. Williams (ed.), University of New Mexico Press, pp. 28–31.

Hawley, J.W. and D.W. Love. 1991. Quaternary and Neogene landscape evolution: A transect across the Colorado Plateau and Basin and Range provinces in west-central and central New Mexico. *Field Guide to Geologic Excursions in New Mexico and Adjacent Areas of Texas and Colorado*. New Mexico Bureau of Mines & Mineral Resources Bulletin 137, B. Julian and J. Zidek (eds.), pp. 105–148.

Hawley, J.W. and C.S. Haase (compilers). 1992. *Hydrogeologic Framework of the Northern Albuquerque Basin*. New Mexico Bureau of Mines & Mineral Resources Open-File Report OF-387, 74 pp.

Hawley, J.W. and P.A. Longmire. 1992. Site characterization and selection. *Deserts as Dumps? The Disposal of Hazardous Materials in Desert Ecosystems.* C.C. Reith and B.M. Thomson (eds.), University of New Mexico Press, Albuquerque, NM.

Hawley, J.W. and R.P. Lozinsky. 1992. *Hydrogeologic Framework of the Mesilla Basin in New Mexico and Western Texas*. New Mexico Bureau of Mines & Mineral Resources Open-File Report 323, 55 pp.

Ingersoll, R.V., W. Cavazza, W.S. Baldridge, and M. Shafiqullah. 1990. Cenozoic sedimentation and paleotectonics of north-central New Mexico. Implications for initiation and evolution of the Rio Grande rift. *Geological Society of America Bulletin*, 102:1280–1296.

Johnpeer, G.D., D.W. Love, J.W. Hawley, D.J. Bobrow, M. Hemingway, and R.F. Reimers. 1985. *El Llano and Vicinity Geotechnical Study-Final Report*. New Mexico Bureau of Mines & Mineral Resources Open-File Report 226, 4 v. 578 pp.

Keller, G.R. and S.M. Cather (eds.). 1994. Basins of the Rio Grande rift: Structure, stratigraphy, and tectonic setting. *Geological Society of America Special Paper 291*, Boulder, CO.

Kelley, V.C. 1952. Tectonics of the Rio Grande depression of central New Mexico. *New Mexico Geological Society, Guidebook 3*, pp. 93–105.

Kelley, V.C. 1977. *Geology of Albuquerque Basin, New Mexico*. New Mexico Bureau of Mines & Mineral Resources Memoir 33, 59 pp.

Kelley, V.C. and A.M. Kudo. 1978. *Volcanoes and Related Basalts of the Albuquerque Basin, New Mexico*. New Mexico Bureau of Mines & Mineral Resources Circular 156, 320 pp.

Kernodle, J.M. 1992. *Summary of U.S. Geological Survey Groundwater-flow Models of Basin-fill Aquifers in the Southwestern Alluvial Basins Region, Colorado, New Mexico, and Texas*. U.S. Geological Survey Open-File Report 90–361, 81 pp.

Kernodle, J.M., D.P. McAda, and C.R. Thorn. 1995. *Simulation of Groundwater Flow in the Albuquerque Basin, Central New Mexico*. U.S. Geological Survey Water-Resources Investigations Report 94–4251, 114 pp.

King, W.E., J.W. Hawley, A.M. Taylor, and R.P. Wilson. 1971. *Geology and Groundwater Resources of Central and Western Doña Ana County, New Mexico*. New Mexico Bureau of Mines & Mineral Resources Hydrologic Report 1, 64 pp.

Lambert, P.W. 1968. *Quaternary Stratigraphy of the Albuquerque Area, New Mexico*. Unpublished Ph.D. dissertation, University of New Mexico, Albuquerque, NM, 329 pp.

Lambert, P.W., J.W. Hawley, and S.G. Wells. 1982. Supplemental road-log segment III-S: Urban and environmental geology of the Albuquerque area. New Mexico Geological Society, Guidebook 33, pp. 97–124.

Lee, W.T. 1907. *Water Resources of the Rio Grande Valley in New Mexico and Their Development*. U.S. Geological Survey Water-Supply Paper 188, 59 pp.

Leeder, M.R. and R.L. Gawthorpe. 1987. Sedimentary models for extensional tilt-block/half-graben basins. Continental Extensional Tectonics. *Geological Society of London Special Publication 28*, M.P. Coward et al. (eds.), pp. 139–152.

Lozinsky, R.P. 1986. *Geology and Late Cenozoic History of the Elephant Butte Area, Sierra County, New Mexico*. New Mexico Bureau of Mines & Mineral Resources Circular 187, 40 pp.

Lozinsky, R.P. 1988. *Stratigraphy, Sedimentology, and Sand Petrology of the Santa Fe Group and Pre-Santa Fe Tertiary Deposits in the Albuquerque Basin, Central New Mexico*. Unpublished Ph.D. dissertation, New Mexico Tech, Socorro, NM, 298 pp.

Lozinsky, R.P. and R.H. Tedford. 1991. *Geology and Paleontology of the Santa Fe Group, Southwestern Albuquerque Basin, Valencia County, New Mexico*. New Mexico Bureau of Mines & Mineral Resources Bulletin 132, 35 pp.

Lozinsky, R.P., J.W. Hawley, and D.W. Love. 1991. *Geologic Overview and Pliocene-Quaternary History of the Albuquerque Basin, Central New Mexico*. New Mexico Bureau of Mines & Mineral Resources Bulletin 137, pp. 157–162.

Lozinsky, R.P. 1994. Cenozoic stratigraphy, sandstone petrology, and depositional history of the Albuquerque Basin, central New Mexico. *Geological Society of America*, 291:73–81.

Machette, M.N. 1978a. *Geologic Map of the San Acacia Quadrangle, Socorro County, New Mexico*. U.S. Geological Survey Geologic Quadrangle Map GQ–1415, scale 1:24,000.

Machette, M.N. 1978b. *Preliminary Geologic Map of the Socorro 1 ° by 2 ° Quadrangle, Central New Mexico*. U.S. Geological Survey Open-File Report 78–607, scale 1:250,000.

Machette, M.N. 1985. Calcic soils of the southwestern United States. Quaternary Soils and Geomorphology of the American Southwest. *Geological Society of America Special Paper 203*, D.L. Weide (ed.), pp. 1–21.

Mack, G.H. and W.R. Seager. 1990. Tectonic control on facies distribution of the Camp Rice and Palomas Formations (Pliocene-Pleistocene) in the southern Rio Grande rift. *Geological Society of America Bulletin*, 102:45–53.

Manley, K. 1978. *Geologic Map of Bernalillo NW Quadrangle, Sandoval County, New Mexico*. U.S. Geological Survey Geologic Quadrangle Map GQ–1446, scale 1:24,000.

May, S.J. and L.R. Russell. 1994. Thickness of the syn-rift Santa Fe Group in the Albuquerque Basin and its relation to structural style. *Geological Society of America Special Paper 291*, pp. 113–123.

May, S.J., S.A. Kelley, and L.R. Russell. 1994. Footwall unloading and rift shoulder uplifts in the Albuquerque Basin: Their relation to syn-rift fanglomerates and apatite fission-tract ages. *Geological Society of America Special Paper 291*, pp. 125–134.

Mozley, P.S., R. Chamberlin, J.M. Gillentine, and R.P. Lozinsky. 1992. Petrologic data. *Hydrogeologic Framework of the Northern Albuquerque Basin*. New Mexico Bureau of Mines & Mineral Resources Open-File Report 387, pp. IV–1 to IV–17.

Peterson, D.M., R. Khaleel, and J.W. Hawley. 1984. *Quasi Three-dimensional Modeling of Groundwater Flow in the Mesilla Bolson, New Mexico*. New Mexico Water Resources Research Institute Technical Completion Report No. 178, 185 pp.

Rosendahl, B.R. 1987. Architecture of continental rifts with special reference to East Africa. *Annual Reviews of Earth and Planetary Sciences*, 15:445–503.

Russell, L.R. and S. Snelson. 1990. Structural style and tectonic evolution of the Albuquerque Basin segment of the Rio Grande rift. The Potential for Deep Seismic Profiling for Hydrocarbon Exploration. *Editions Technip, French Petroleum Institute Research Conference Proceedings*, B. Pinet and C. Bois (eds.), Paris, France, pp. 175–207.

Russell, L.R. and S. Snelson. 1994. Structure and tectonics of the Albuquerque Basin segment of the Rio Grande rift: Insights from reflection seismic data. *Geological Society of America Special Paper 291*, pp. 83–112.

Seager, W.R. and P. Morgan. 1979. Rio Grande rift in southern New Mexico, west Texas, and northern Chihuahua. *Rio Grande Rift: Tectonics and Magmatism*. American Geophysical Union, R.E. Riecker (ed.), pp. 87-106.

Seager, W.R., M. Shafiqullah, J.W. Hawley, and R.G. Marvin. 1984. New K-Ar dates from basalts and the evolution of the southern Rio Grande rift. *Geological Society of America Bulletin*, 95:87–99.

Smith, R.L., R.A. Bailey, and C.S. Ross. 1970. *Geologic Map of the Jemez Mountains, New Mexico*. U.S. Geological Survey Miscellaneous Investigations Map I–571, scale 1:125,000.

Spiegel, Z. 1961. Late Cenozoic sediments of the lower Jemez River region. *New Mexico Geological Society, 12th Guidebook*. pp. 132–138.

Spiegel, Z. 1962. *Hydraulics of Certain Stream-connected Aquifer Systems*. New Mexico State Engineer Special Report, 105 pp.

Spiegel, Z. and B. Baldwin. 1963. *Geology and Water Resources of the Santa Fe Area, New Mexico*. U.S. Geological Survey Water-Supply Paper 1525, 258 pp.

Stearns, C.E. 1953. Tertiary geology of the Galisteo-Tonque area, New Mexico. *Geological Society of America Bulletin*, 64:459–507.

Tedford, R.H. 1981. Mammalian biochronology of the late Cenozoic basins of New Mexico. *Geological Society of America Bulletin*, 92:1008–1022.

Tedford, R.H. 1982. Neogene stratigraphy of the northwestern Albuquerque Basin. *New Mexico Geological Society, Guidebook 33*, pp. 273–278.

Thorn, C.R., D.P. McAda, and J.M. Kernodle. 1993. *Geohydrologic Framework and Hydrologic Conditions in the Albuquerque Basin, Central New Mexico*. U. S. Geological Survey Water-Resources Investigations Report 93–4149, 106 pp.

Tight, W.G. 1905. Bolson plains of the Southwest. *American Geologist*, 36:271–284.

Titus, F.B., Jr. 1961. Groundwater geology of the Rio Grande trough in north-central New Mexico, with sections on the Jemez Caldera and Lucero Uplift. *New Mexico Geological Society, 12th Guidebook*, pp. 186–192.

Titus, F.B., Jr. 1963. *Geology and Groundwater Conditions in Eastern Valencia County, New Mexico*. New Mexico Bureau of Mines & Mineral Resources Groundwater Report 7, 113 pp.

Woodward, L.A. 1982. Tectonic framework of Albuquerque Country. *New Mexico Geological Society, Guidebook 33*, pp. 141–146.

Woodward, L.A. 1987. *Geology and Mineral Resources of Sierra Nacimiento and Vicinity, New Mexico*. New Mexico Bureau of Mines & Mineral Resources Memoir 42, 84 pp.

Wright, H.E., Jr. 1946. Tertiary and Quaternary geology of the lower Puerco area. *New Mexico: Geological Society of America Bulletin*, 57:383–456.