U.S. Department of the Interior
U.S. Geological Survey

U.S. Geological Survey Middle Rio Grande Basin Study--Proceedings of the Third Annual Workshop, Albuquerque, New Mexico, February 24-25, 1999

Open-File Report 99-203

Landsat thematic mapper mosaic of the Middle Rio Grande Basin, New Mexico

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U.S. Geological Survey Middle Rio Grande Basin Study--Proceedings of the Third Annual Workshop, Albuquerque, New Mexico, February 24-25, 1999

By James R. Bartolino, editor

U.S. GEOLOGICAL SURVEY

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Albuquerque, New Mexico
1999

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Front cover:

Landsat thematic mapper mosaic of the Middle Rio Grande Basin. The four scenes used in the image were acquired in September 1993. Bands 1, 4, and 7 are displayed through blue, green, and red filters, respectively. The image has been output at 30-meter resolution by cubic convolution resampling to fit the North American Datum of 1983 (NAD83) in a Universal Transverse Mercator (UTM) projection. A terrain correction was included in the processing using USGS 1:24,000-scale Digital Elevation Model (DEM) data. Image compiled by the USGS Astrogeology Program, Flagstaff Field Center. See Mullins and Hare (p. 15) for a more complete description of the image.

Back cover:

Temporal land-surface characterization (LSC) data compiled for analyzing Albuquerque's historical landscape change and modeling future urban growth.

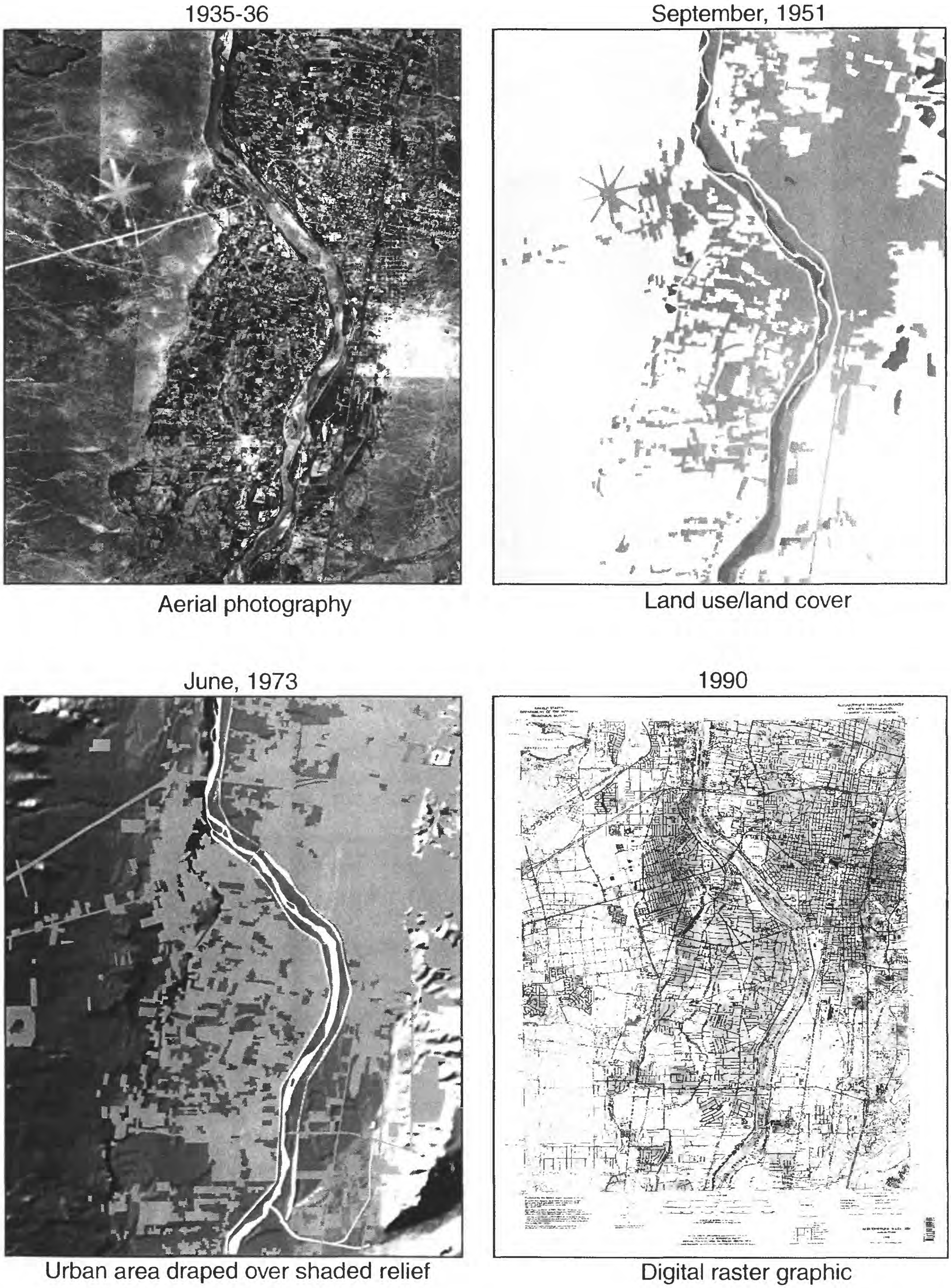
1935-36—Aerial photography mosaic of Natural Resources Conservation Service imagery obtained from University of New Mexico Earth Data Analysis Center.

1951—Anderson Level I land use and land cover (LULC) data collected from USGS aerial photography using a 2.5-acre minimum mapping unit. Urban land is shown in magenta, rangeland is displayed in green, and agricultural land is symbolized in yellow.

1973—Urban and developed lands (Anderson Level II LULC) interpreted from U.S. Forest Service aerial photography. Urban lands are draped over terrain shaded relief that was derived from USGS 10-meter DEM data.

1990—USGS digital raster graphic (DRG) scanned from published topographic map edition. Urban land is symbolized with a gray tint.

Back cover graphic and temporal LSC data compiled by the USGS Rocky Mountain Mapping Center.



Temporal data sets created for the Albuquerque West 1:24,000-scale quadrangle

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CONVERSION FACTORS, ABBREVIATED WATER-QUALITY UNITS, AND VERTICAL DATUM

Multiply	By	To obtain
hectare (ha)	2.471	acre (acre)
meter (m)	0.3048	foot (ft)
micrometers (µm)	3.937×10^{-5}	inch (in.)
millimeters per day (mm/day)	0.03937	inches per day (in./day)
millimeters per year (mm/yr)	0.03937	inches per year (in/yr)
centimeter (cm)	0.3937	inch (in.)
meter (m)	3.28084	foot (ft)
kilometer (km)	0.6215	mile (mi)
meters per day (m/day)	3.28084	feet per day (ft/day)
centimeters per second (m/s)	2830	feet per day (ft/day)
square meters per day (m^2/day)	10.76	square feet per day (ft^2/day)
cubic meter (m^3)	8.1071×10^{-4}	acre-foot (acre-ft)
centimeters per year (cm/yr)	0.3937	inches per year (in./yr)
kilogram per square meter (kg/m^2)	1.843345	pound per square yard (lb/yd^2)
metric tons per year (t/yr)	1.1023	short tons per year (ton/yr)
square kilometer (km^2)	0.3861	square mile (mi^2)
square meters per minute (m^2/min)	80.5	gallons per minute per foot (gal/min/ft)

Temperature in degrees Celsius (°C) can be converted to degrees Fahrenheit (°F) as follows:

$$°F = 1.8\,(°C) + 32.$$

Specific conductance is reported in microsiemens per centimeter at 25 degrees Celsius.

Chemical concentrations in water are reported in milligrams per liter (mg/L), micrograms per liter (µg/L), or picograms per liter (pg/L), which are roughly equivalent to parts per million, parts per billion, and parts per quadrillion, respectively, when concentrations are less than about 7,000 milligrams per liter.

INTRODUCTION

Approximately 40 percent (about 600,000 people) of the total population of New Mexico lives within the Middle Rio Grande Basin, which includes the City of Albuquerque (fig. 1). Ongoing analyses of the central portion of the Middle Rio Grande Basin by the U.S. Geological Survey (USGS) in cooperation with the City of Albuquerque and other agencies have shown that ground water in the basin is not as readily accessible as earlier studies indicated. A more complete characterization of the ground-water resources of the entire Middle Rio Grande Basin is hampered by a scarcity of data in the northern and southern areas of the basin.

The USGS Middle Rio Grande Basin study is a 5-year effort by the USGS and other agencies to improve the understanding of the hydrology, geology, and land-surface characteristics of the Middle Rio Grande Basin. The primary objective of this study is to improve the understanding of the water resources of the basin. Of particular interest is to determine the extent of hydrologic connection between the Rio Grande and the Santa Fe Group aquifer. Additionally, ground-water quality affects the availability of water supplies in the basin. Improving the existing USGS-constructed ground-water flow model of the Middle Rio Grande Basin will integrate all the various tasks that improve our knowledge of the various components of the Middle Rio Grande water budget. Part of this improvement will be accompanied by extended knowledge of the aquifer system beyond the Albuquerque area into the northern and southern reaches of the basin. Other improvements will be based on understanding gained through process-oriented research and improved geologic characterization of the deposits. The USGS and cooperating agencies will study the hydrology, geology, and land-surface characteristics of the basin to provide the scientific information needed for water-resources management and for managers to plan for water supplies needed for a growing population.

To facilitate exchange of information among the scientists working on the Middle Rio Grande Basin study, yearly technical meetings have been held for each of the first 3 years of the anticipated 5-year study. These meetings provide an opportunity to present research results and plan new field efforts. This report documents the results of research presented at the third annual technical workshop held in Albuquerque, New Mexico, February 24-25, 1999.

The report is organized into this introduction and five chapters that focus on Middle Rio Grande Basin study investigations in progress in the Middle Rio Grande Basin. The first chapter describes geographic data and analysis efforts in the basin. The second chapter details work being done on the hydrogeologic and geologic framework of the basin. The third chapter describes studies on ground-water recharge in the basin. The fourth chapter provides details on the research on the ground-water flow system in the basin, including modeling efforts. The fifth chapter is devoted to an overview of New Mexico District Cooperative Program studies in the basin.

The information in this report presents preliminary results of an evolving study. As the study progresses and individual projects publish their results in more detail, the USGS hopes to expand the scientific basis needed for management decisions regarding the Middle Rio Grande Basin.

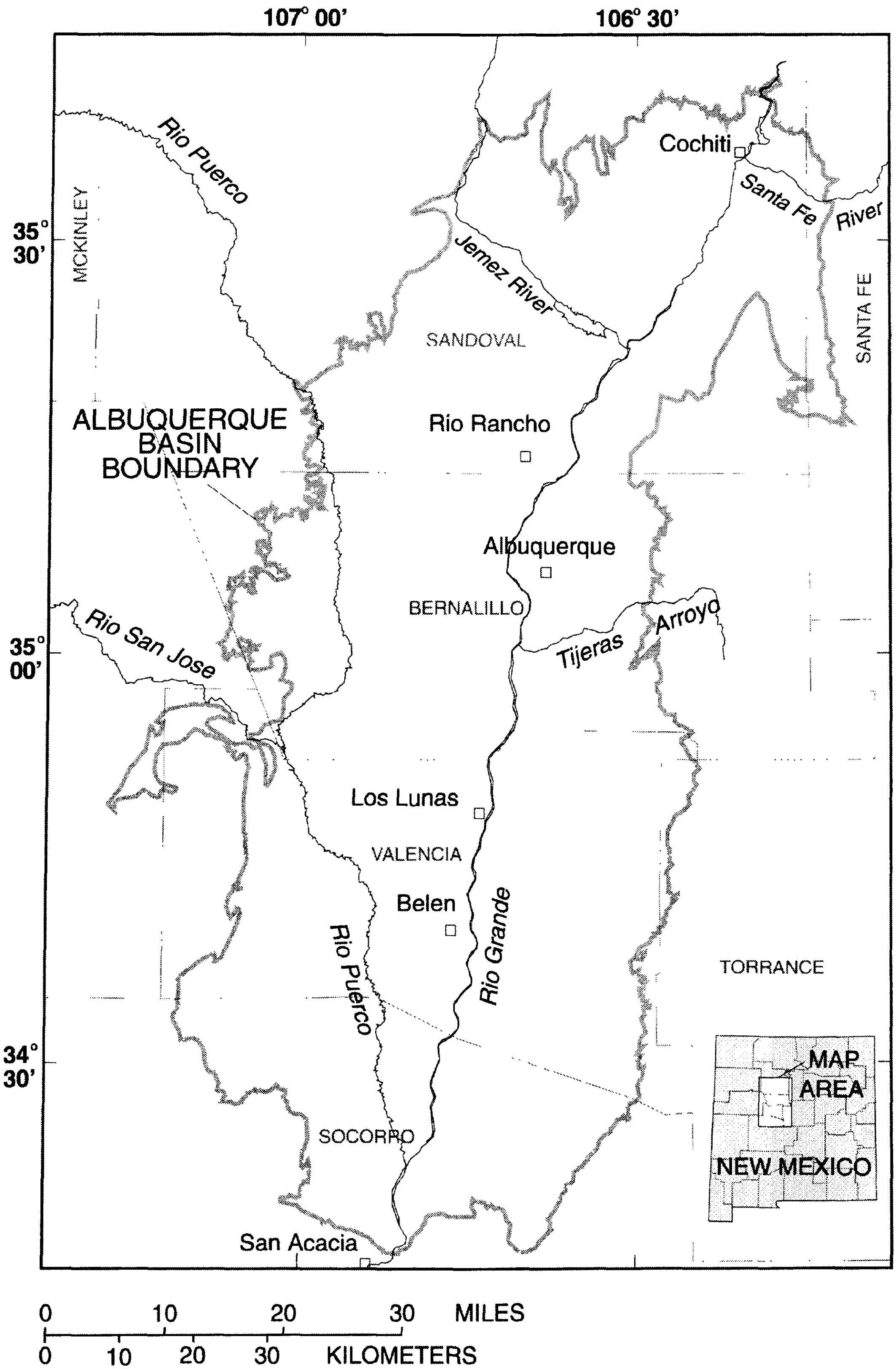

Figure 1.—Middle Rio Grande Basin, New Mexico.

GEOGRAPHIC DATA AND ANALYSIS

Development and Modeling of Focus 2050 Alternative Land Use Scenarios

Dennis R. Foltz[1], Stephen Burstein[1], David Abrams[1], and Carol Harlan [1]

The Middle Rio Grande Council of Governments (MRGCOG) is developing scenarios for growth for the region composed of Bernalillo, Sandoval, Torrance, Valencia, and southern Santa Fe Counties. The goal of the scenario process is to identify a preferred regional land use alternative that will be incorporated into the Focus 2050 Regional Plan and adopted by the MRGCOG Board of Directors. Scenarios are being evaluated for effects on land, water, transportation, air quality, regional linked open space, housing, and economic development. Public involvement through Regional Visioning, FutureScape conferences, a town hall, and public hearings is a critical part of the Focus 2050 process.

MRGCOG and Planning Technologies, LLC, developed a geographic information system (GIS)-based application called the Land Use Analysis Model (LAM) to create and model future land use scenarios using Environmental Systems Research Institute's ArcView software. Initially, a 1996/97 Existing Land Use Inventory (ELUI) was created in GIS with attached data on dwelling units and employees. The ELUI served as a starting point for a three-stage process including (1) screen scenario development; (2) model input; and (3) model allocation and output. Using LAM for all stages, MRGCOG arrived at the modeled output layers that provide socioeconomic data to quantify characteristics of the scenarios and provide input to transportation, air quality, and other models.

Focus 2050 regional growth assumptions:

1. The regional population is projected to increase from approximately 710,000 persons today to 1.55 million persons by year 2050.

2. Dwelling units are projected to increase from around 300,000 to approximately 694,000 units by year 2050.

3. Employment is projected to increase from around 365,000 jobs to 854,000 jobs by year 2050.

Screen Scenario Development

The Screen Scenarios use a classification of eight categories of urban form patterns. These categories reflect themes of relative infill, clustering, open space corridors, multiple commercial centers and corridors, agricultural lands preservation, and different housing and commercial densities. These scenarios were the subject of the FutureScape public meetings held November 1998 - January 1999.

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Model Input—Eligibility Scenarios Development

The Eligibility Scenarios were developed from the Screen Scenario and use a refined classification of 18 land use categories. Land use polygons for the scenarios included dwelling unit and employment density data (units or jobs per acre). Existing land use, proposed plans, transportation networks, surface hydrology, slope, land management status, and the templates of the screen scenarios were used in developing the Eligibility Scenarios (table 1). Expected land use changes or trends such as developing vacant urban land, expanding existing or building new commercial and employment centers, redeveloping already developed land, and building low density residential were also considered. Each completed scenario contained 20 – 40 percent more developed land area, dwelling units, and employment than needed for the horizon year in order to allow the LAM to choose and distribute growth.

Table 1.—Total developed land for existing land use and output scenarios

[Kirtland Air Force Base and developed Indian lands are not included in the total. mi^2, square miles]

Existing land use	268 mi^2
2050 scenarios:	
Trend Dispersed	593 mi^2
Contiguous Mesa Expansion	397 mi^2
Moderately Compact Infill and New Communities	330 mi^2
Compact	273 mi^2

Land Use Analysis Model Output

LAM utilizes the ArcView Spatial Analyst grid data model in the allocation process. Scoring layers were developed based on calibrating the model using relationships of existing land use to proximity to roads, major highway interchanges, and developed land. Countywide subcontrol totals were established for single family units, multifamily units, and mixed and minor commercial employment to enhance modeling performance.

The Eligibility Scenarios served as input to LAM for model allocation. Initially, the scenarios were combined with a layer of development projects known to have been built since 1996-97 or expected to develop presently. An overlay of the scoring layers and the scenario provided a grid of cells with varying scores for development potential. The model then allocated housing and employment based on land use category, densities, and scoring layers (table 2).

Table 2.—Output scenarios from the Land Use Analysis Model

Trend Scenario Major Characteristics	Contiguous Mesa Expansion Scenario Major Characteristics	Moderate Compact Infill and New Communities Scenario Major Characteristics	Compact Scenario Major Characteristics
New housing density (single and multifamily): Typically 2.5-3.0 dwelling units/acre.	New housing density (single and multifamily): Typically 3.5-4.0 dwelling units/acre.	New housing density (single and multifamily): Typically 3.5-4.0 dwelling units/acre, including multifamily at 10-15 dwelling units/acre.	New housing density (single and multifamily): Typically 3.5-5.0 dwelling units/acre, including multifamily at 25-35 dwelling units/acre.
Urban development: Ringing metro area and Valencia County municipalities with modest infill and redevelopment.	Urban development: Development on Bernalillo County West Mesa, Valencia County East Mesa, and Mesa del Sol. Infill directed to minor centers and corridors in existing communities.	Urban development: Clusters of new communities (10,000-40,000) located in West Mesa, Rio Rancho, Mesa del Sol, and Valencia County East Mesa. Infill directed to centers and corridors and to vacant and underutilized urban land.	Urban development: Adjacent to existing cities, plus Mesa del Sol and Belen West Mesa. Infill focused into a hierarchy of centers; selected redevelopment in major corridors such as Central Avenue.
Rural residential: New areas, particularly along conceptual Northwest Loop road, East Mountains, Placitas, and Edgewood. Some valley farmlands urbanized.	Rural residential: New development west of Rio Rancho, Valencia County East Mesa, East Mountains, Placitas, and Edgewood.	Rural residential: New development limited to west of Rio Rancho and Edgewood.	Rural residential: New development very limited.
Employment dispersal: Most service, retail, and basic employment in Bernalillo County and Rio Rancho; new retail in strip commercial in all counties.	Irrigated farmland preserved.	Employment dispersal: Considerable infill and redevelopment of downtown Albuquerque and other existing centers; redirection of many new jobs to new communities.	Employment dispersal: Major infill and redevelopment of existing centers emphasizing mixed use; redirection of new jobs to growing communities outside Albuquerque area. Bernalillo County and Rio Rancho predominant in jobs; modest infill and expansion of centers and corridors in all counties.

Modeling Albuquerque's Urban Growth (Case Study: Isleta, New Mexico, 1:24,000-Scale Quadrangle)

David J. Hester[1]

Introduction

Urbanization of the landscape is causing ongoing land transformations in the Albuquerque area. Urban land transformations result in drainage systems that increase the urban runoff, decrease the amount of water available for replenishing Albuquerque's aquifer, and increase the area's susceptibility to flooding. To predict future urbanization, the USGS is mapping Albuquerque's historical landscape and will use the land use/land cover (LULC) data to model the region's future urban growth. Modeling to predict urban growth helps us understand the potential impacts on the region's water resources, economy, and people.

Urban Growth

In 1993, New Mexico was the sixth fastest growing State in the United States. However, by 1998 New Mexico's population growth rate of 0.8 percent ranked only 23d in the Nation and was below the national growth rate of 1 percent for the second consecutive year (Albuquerque Journal, 1999). New Mexico's below-average growth rate is reflected in the fact that Albuquerque did not warrant a top ranking in the Sierra Club's urban sprawl report as a small city (population 200,000-500,000) threatened by low-density development (Sierra Club, 1998). One criterion for modeling future urban growth is to base the prediction on long-term historical land use and population data that include periods of rapid growth (booms) as well as periods of declining growth (busts).

Urbanization Impacts

Ongoing land development in the Middle Rio Grande Basin is currently affecting the region's natural and cultural resources. For example, in 1998 the Bernalillo County Commission imposed a 6-month ban on approving building applications for subdivision plats with six or more dwelling units; this ban was to give county officials time to investigate water availability for the rapidly growing East Mountain area. Cultural resources are being threatened by urbanization on Albuquerque's West Side as demonstrated by the Wilderness Society's designation of Petroglyphs National Monument as one of the 15 most endangered lands in the United States (Wilderness Society, 1998). Because the Middle Rio Grande Council of Governments predicts that the Albuquerque metropolitan area will have 850,000 new residents by the year 2050, the effects of urbanization are likely to continue.

Urban Land Transformations

As part of its study of the Middle Rio Grande Basin, the USGS has been mapping Albuquerque's past in order to predict the metropolitan area's future landscape. USGS temporal urban mapping

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is focusing on a pilot area encompassing Albuquerque, Rio Rancho, Edgewood, and Moriarty. Aerial photographs from the 1930's, 1950's, 1970's, and 1990's are being interpreted to map Albuquerque's historical urbanized area extent and to collect temporal LULC data.

As a case study, land transformations in the Isleta, New Mexico, 1:24,000-scale quadrangle were analyzed and used to predict urban growth. This quadrangle was selected on the basis of factors such as the following: (1) the region is on the urban fringe of the Albuquerque metropolitan core, (2) most of the area is within Bernalillo County, (3) the Rio Grande traverses the landscape, (4) urbanization is constrained by Isleta Pueblo lands, (5) the area includes primary transportation routes, such as Interstate 25, and (6) Albuquerque's corporate limits have expanded into the area. Table 3 summarizes the growth of urban land within the Isleta quadrangle from 1935 to 1991.

Table 3.—Isleta, New Mexico, 1:24,000-scale quadrangle urban land development

[--, not applicable]

Year	Urban area (acres)	Percent growth from 1935	Percent growth from previous period
1935	132.0	--	--
1951	278.3	110.8	110.8
1973	1,234.2	834.9	343.5
1991	3,638.7	2,656.2	194.8
2050	5,476.9	4,049.2	50.5

Modeling Urban Growth

As part of the Middle Rio Grande Basin study, the USGS is using the Land Cover Deltatron (LCD) version of the Urban Growth Model (UGM) developed by the University of California-Santa Barbara. The LCD version is capable either of predicting LULC or of modeling just the future urbanized area. For the Isleta case study, the USGS modeled the landscape's 2050 urbanized area. A 50-year prediction of the landscape was used to correspond with the life expectancy of major transportation and utility infrastructure being constructed today (Middle Rio Grande Council of Governments, 1997). The UGM incorporates four types of growth: spontaneous, diffusive, organic, and road influenced, which are regulated by the growth control coefficients in table 4. The growth rate of an urban area for each model iteration is the sum of all four growth types. If the growth rate is unusually high or low, the growth control coefficients are altered by the self-modification constants in table 5. Self-modification of the UGM's growth control coefficients is essential to simulate the typical S-curve growth rate of urban expansion (Clarke, 1998).

The UGM predicts the probability of an area becoming urbanized on the basis of (or by) using a limited set of data themes, such as where urban lands presently occur, what lands have slopes that are likely to develop, and how the existing transportation infrastructure will influence future land use patterns. Generating an urban growth prediction (base scenario) using the UGM does not take into consideration factors such as socioeconomic projections for population, employment, or housing. Therefore, the model can only predict where urban growth is likely to occur on the basis of historical land use trends, current landscape characteristics, and the absence of constraints such as land use zoning. The University of California-Santa Barbara plans to extend the LCD version of the UGM, so that alternative future land use scenarios can be generated by using proposed roads and planned nonurban areas, such as greenbelts, and by assigning urban growth probabilities to lands excluded from future development.

Dataset Preparation

Data used in the UGM are historical urban extent, historical roads, areas excluded from development, and slope. Aerial photographs from 1935, 1951, 1973, and 1991 were interpreted to map historical urban extent and to collect historical primary transportation routes. A minimum mapping unit of 10 acres was used for compiling the historical urban extent. Areas excluded from future urban growth were derived from the 1:24,000-scale digital line graph boundaries, hydrography, and manmade sthemes. The f tructure eatures exempt from future urbanization included Indian lands, State parks, reservoirs, wetlands, perennial streams, lakes and ponds, and cemeteries. The slope input was derived from the Isleta 10-meter digital elevation model data. Because the UGM requires Compuserve Graphics Image File (GIF) image data, the Isleta vector and (or) raster thematic datasets were converted using a 10-meter cell-size resolution.

Model Calibration

To predict future urban growth patterns, researchers calibrate the model output using the mapped historical urban area, historical roads, excluded lands, and slope data. The oldest temporal snapshot mapped (1935) is used as a seed to the calibration phase. In addition, an initial set of growth control parameters (see table 4) and self-modification constants (see table 5) are used to predict urban growth patterns for the most recent temporal snapshot, mapped in 1991.

Table 4.—Growth control parameters, Urban Growth Model calibration, Isleta, New Mexico, 1:24,000-scale quadrangle

Coefficient	Beginning value	Ending value	Step
Diffusion	1	100	20
Breed	1	100	20
Spread	1	100	20
Slope resistance	1	20	5
Road gravity	1	20	5

Table 5.—Self-modification constants, Urban Growth Model calibration, Isleta, New Mexico, 1:24,000-scale quadrangle

Constant	Value
Critical high	1.03
Critical low	0.97
Boom	1.1
Bust	0.9
Critical slope	15

Calibrating the UGM is an iterative process. Coarse, fine, and final calibration steps are performed using increasingly higher resolution input images and narrower ranges of growth control parameter values to identify the "best fit" coefficient values that are used for the next calibration step. To obtain a preliminary view of the predicted 2050 urbanized area, the USGS executed only a coarse calibration for the Isleta quadrangle. The coarse calibration performed for Isleta used one-eighth-resolution (145- by 175-pixel) GIF images and the growth control parameter values in table 4. For each iteration within the calibration step, statistics are calculated to compare the modeled urbanization to actual urbanization for the control years (that is, 1951, 1973, and 1991). Calibration results are recorded for each iteration, and a composite score is computed from the calibration statistics to identify the "best modeled" run. The UGM coarse calibration required 3,100 iterations and took approximately 22 hours CPU time to execute on a 32-bit 200 megahertz, quad-processor Silicon Graphics UNIX platform with 0.5 gigabyte of memory.

Model Prediction

Once the coarse calibration step was completed, the "best fit" growth control parameters recorded in the calibration results file were averaged. Because the UGM calibration phase was based on historical data from 1935 to 1991, the UGM was executed to predict the Isleta quadrangle's urbanization from 1991 to 2050. The most recent temporal snapshot, 1991, became the seed for predicting future urbanization. The average growth control coefficient values and parameters in table 5 were used as input to predict the Isleta 2050 urbanized area. The prediction phase used the full-resolution (1,165- by 1,405-pixel) GIF images, executed 100 model iterations, and took approximately 24 hours of CPU time to complete.

Conclusion

From 1935 to 1991, the urbanized area for the Isleta quadrangle increased from approximately 130 acres to 3,640 acres. The UGM predicted that the Isleta 2050 urban land would grow to approximately 5,480 acres (see table 3). Even though urban growth occurred on the Isleta Pueblo from 1935 to 1991, Indian lands were exempt from the 2050 urbanization prediction. As a result, the predicted 2050 urban growth was constrained to the northern half of Isleta. Even though Indian lands accounted for 60 percent of the Isleta lands excluded from development, future urban growth in the Middle Rio Grande Basin will also most likely be constrained because public and Indian lands cover approximately 40 percent of the region. During the period from 1991 to 2050, the predicted landscape exhibited urban growth on the east side of the Rio Grande around the community of Mountainview, urbanization growing northward from the I-25 and State Highway 47 (Broadway) intersection toward Mountainview, and almost contiguous infill development between State Highways 45 (Coors Boulevard) and 314 (Isleta Boulevard).

The 2050 land development patterns predicted by the UGM show all Isleta urban growth occurring within Bernalillo County. By the year 2050, the urbanized land is predicted to expand into the current City of Albuquerque's corporate limits. As part of Albuquerque's Transporation Evaluation Study, one proposal was to establish urban service areas—in essence, drawing an urban growth boundary around the city beyond which urban services would not be provided (Albuquerque Tribune, 1998). The 2050 urbanized land predicted for the Isleta quadrangle falls outside the proposed Albuquerque urban services boundary. USGS urban-growth modeling in the Middle Rio Grande Basin will help to identify areas of potential future urbanization, and the urban growth predictions can be used to assist in delineating urban service boundaries, developing comprehensive land use plans, and evaluating potential Albuquerque aquifer stresses.

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Prototype Satellite-Based Image Products for the Upper Rio Grande Basin

Stan Morain[1] and Chandra Bales[1]

Under a 5-year cooperative agreement with the National Aeronautics and Space Administration (NASA), the Earth Data Analysis Center (EDAC) is engaged in developing a suite of prototype products from satellite imagery and data. The goal is for these products to be commercially viable so that private enterprise can incorporate them as part of their suite of services available to a broader user community. These products and services will be accessible on the Internet using delivery systems that allow users to manipulate satellite and related geospatial data in a variety of ways according to their specific needs. These products will be amenable also to customization by EDAC as product definitions evolve or as new users are identified.

EDAC is focusing on three prototype products: land economics, regional hydrology, and air quality in the Upper Rio Grande Basin. Attention in 1998 concentrated on the land economics and regional hydrology prototypes. The first of these will be in beta-test by mid-1999. An air quality prototype will be initiated in 2000, after the first two are developed well enough to progress into operational and enterprise phases.

The Land Economics Prototype

The business case for land economics in the Upper Rio Grande Basin is that public land management agencies must assess the value of, and uses for, numerous fragmented land units distributed over large jurisdictions. Because each jurisdictional mandate is different, each agency must manage its lands to achieve different goals and objectives. The biggest hindrances to effective use of land cover data from satellites are:

- The datasets are too large and synoptic for land managers to accurately and efficiently find and delineate parcels that range in size from 5 acres to hundreds of contiguous acres;
- Purchasing large-area datasets on a routine basis is cost prohibitive, and data distributors often shun multisectoral or multiagency data buys;
- Even if restrictions on large-area data buys did not exist, the data are not delivered in formats convenient for site-specific management decisions; and
- Land managers are not interested in viewing endless satellite images—they want information derived from the images.

To encourage use of satellite spectral data in day-to-day management decisions, the strategy is to provide web-accessible products created from appropriate NASA datasets held at the USGS Earth Resources Observation Systems (EROS) Data Center and other sources. These will be further processed and mined for information by EDAC in collaboration with other NASA-

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sponsored university and private sector organizations, one of which will be the Information Technology and Systems Laboratory (ITSL) at the University of Alabama, Huntsville. The products derived will be served through a delivery system being designed by EDAC.

To reach the broadest community of land management agencies, the product must be accessible on an efficient, searchable system that allows practicing managers to identify a land parcel by public land survey system and by decimal degrees of latitude/longitude coordinate systems. Once a land parcel is identified, the manager may then retrieve attribute data and information related to the physical and economic environments of the parcel and the changes in these environments through time (seasonal, interannual, and decadal). The contributions of spectral data to this system lie in:

- Providing a contextual image base for each parcel as scalable, spatially registered products;
- Providing seamless, multiresolution, fly-through visualizations of the terrain so managers can fully appreciate a parcel's characteristics;
- Providing trend analyses of physical and biological attributes through geospatially registered time series datasets; and
- Merging other geospatial (economic) attributes with interpreted spectral trends to support management decisions.

The Regional Hydrology Prototype

The objective of this effort is to develop products that improve water models by providing contiguous measurements of such parameters as precipitation, soil moisture, plant cover, evapotranspiration, and atmospheric vapor. Derived from data provided by a variety of sensors, these measurements, when properly georeferenced, fused, and scaled, can be used to assess water flux at the land/air interface. Collaborators in this effort currently include the Goddard Space Flight Center, George Mason University's Laboratory for Seasonal and Interannual Climate Variability, and ITSL. Data will be extracted from virtually all parts of the electromagnetic spectrum (visible, reflective infrared, thermal infrared, and both active and passive microwave).

These ideas are not new. There are decades of remote sensing research behind each of the attributes being measured. The difference between previous research and the current approach lies in the strategy for developing and delivering the prototype products. One of the goals of NASA's Earth Science Enterprise is to shorten the time to prototype status by sponsoring a federation of organizations that parse the workload and capitalize on their collective expertise. Clusters of organizations in this federation are forming to address what have heretofore been difficult or intractable solutions to high profile applications such as water flux maps. The Internet delivery of preliminary water flux maps on seasonal, interannual, and eventually decadal bases may not be difficult, once a delivery system for the land economics prototype is developed. One can expect that operational products will be available first on global and regional scales and subsequently on subregional and local scales. Major challenges for the Upper Rio Grande Basin are to identify appropriate datasets for each of the parameters, subset them for use in water flux maps, and spatially reference them to match related datasets from other sources.

Calibration, Processing, and Production of a Landsat Thematic Mapper Mosaic of the Middle Rio Grande Basin Study Area

Kevin F. Mullins[1] and Trent M. Hare[1]

The purpose of this project was to provide the Middle Rio Grande Basin (MRGB) study team with a remotely sensed database of regional extent and moderate resolution that would provide an overview of the geology, structure, and morphology of the MRGB study area. The MRGB team requested a hard-copy base image that would meet three criteria: (1) discriminate general geologic units, (2) cartographically match existing topographic maps, and (3) be of reasonable cost to produce. The USGS in Flagstaff, Arizona, was contracted to provide an image base that would meet these requirements.

The Earth Resources Observation Systems Data Center (EDC) provides a large group of thematic mapper (TM) imagery catalogues, processed at various levels, for a wide range of applications. The Multi-Resolution Land Characteristics (MRLC) catalog met our criteria for low cost and level of processing. The MRLC program is a cooperative effort between four Federal agencies to provide land cover data of the conterminous United States at regional and local scales. The centerpiece of this effort is the acquisition of 30-meter-resolution TM data. Through this cooperative program, this TM imagery can be offered to Federal agencies at a fraction the cost of purchasing regular TM data.

Acquisition of the appropriate TM data at EDC for the MRLC program was an iterative process that provided temporal consistency by acquiring all scenes within a year, plus or minus, of 1992 (the four scenes used in this mosaic were acquired in September of 1993). Most adjacent scenes were acquired within weeks, sometimes days, of each other, providing data with little change in sun angle, vegetation state, and in many cases, atmospheric conditions. Scenes were then checked visually for cloud cover, dropped lines, and seasonal timing. These images were then processed through noise removal and geometric registration software according to methods documented on the EDC website. The geocoded images were output at 30-meter resolution by cubic convolution resampling, to fit the North American Datum of 1983 (NAD83) in a Universal Transverse Mercator (UTM) projection. A terrain correction was included in the processing using USGS 1:24,000-scale Digital Elevation Model (DEM) data.

The geometric registration production mode of these images by EDC provides a valuable dataset with the largest (and most time consuming) processing step completed before delivery to us. However, to create regional-scale mosaics for geological studies requires performing several additional steps to arrive at consistent and scientifically valid images and spectral datasets.

First, each band for every scene must be statistically analyzed to correct for tonal variations between scenes. These tonal variations are caused mostly by differences in sun angle, vegetation, or atmospheric haze changes. By choosing one scene as the master image, the others can be corrected by applying a regression analysis between each scene and the master.

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Next, the haze values for the master scene were derived through a process developed by Chavez and others (1988). This process uses a wavelength-dependent, power-law algorithm that calculates the haze value for each of the six nonthermal TM bands. These values are applied in a calibration process, developed by Chavez (1989), that corrects each band for additive and multiplicative haze influences, instrument gains and offsets, and seasonal sun elevation changes. The output is an image whose pixel values are expressed in surface reflectance. These corrected digital images can then be input into a three-dimensional cube format (lines, samples, bands) and the Integrated Software for Imagers and Spectrometers (ISIS) software used to extract individual spectra. These spectra can be plotted, classified, or compared to previously published lab spectra libraries for a variety of rocks and minerals. As a result, any color composite made using a combination of these images will be directly related to the nature of its spectral reflectance characteristics. These color composites can provide a "color-coded" image of general rock or mineral types. Because of TM's coarse spectral resolution (six bands that cover the visible to mid-infrared wavelengths) it is difficult, if not impossible, to refine the discrimination much above general rock classes. Of course, some geomorphological features can aid in the discrimination between geologic units.

After the bands had been radiometrically calibrated, it was necessary to trim the irregular edges of the images that were created during the resampling phase of the geometric correction. Stencils and masks were derived to trim those pixels whose intensity fell off near the edges of the geometrically rotated images. Once these pixels were eliminated a seamless mosaic was produced (cover illustration).

ARC/INFO software provides the ideal environment to produce geocoded mosaics of TM scenes. For our study, each band was independently mosaicked using the geodetic data provided by EDC. After the individual band mosaics were complete they were checked for seams, misregistration, and tonal variations. ARC/INFO then was used to extract and clip any smaller subareas corresponding to the required geographical coordinates. These ARC files were then exported into the ISIS cube environment. At this time, a decision was made as to which band combination best suited the project goals. In our case, we chose bands 1, 4, and 7 and displayed them through blue, green, and red filters, respectively, during the printing process. This band combination has been shown to provide the best first-order spectral discrimination of general geologic materials by numerous investigators, including Chavez and others (1984) and Davis and others (1987; 1989).

Finally, an edge-enhancement, high-pass filter was applied to each band mosaic, based on the enlargement factor needed to produce the final scaled image. A linear contrast stretch was then chosen for the three bands to enhance the data range and produce a balanced color composite. The ISIS software enabled the three chosen bands to then be combined into a single file format. This file was then input into a color film processor to produce a color-film positive. Once the film positive was created, normal photo lab techniques can be used to produce the "best" color-balanced, hard-copy image at a scale determined by the client.

A three-band color composite image is a simple, yet powerful, tool for discriminating and mapping general geologic units and for fieldwork planning purposes. It can provide overall geologic information about stratigraphy, structure, trends, and rock discrimination on both a regional and local scale. However, it must be considered as a preliminary product because it uses only a subset of the total TM spectral information. There is a great deal more spectral information to be found by examining all six nonthermal TM bands. This information can be extracted by numerous methods including band ratios, PC analysis, decorrelation stretches, and spectral analysis. Most of these methods work best if more specific geologic information is needed about a localized area. Many other higher resolution datasets are available covering smaller areas within the MRGB study area. These include Thermal Infrared Multispectral Scanner (TIMS) data (particularly well suited for discrimination of siliceous rock units) and the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) data, which consists of 224 channels, providing a high-resolution spectrum from 0.4 to 2.2 micrometers. Each of these instruments provides a valuable extension to the spectral data that TM acquires and could help in further investigations within the MRGB study area.

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Temporal Land Use and Land Cover Mapping

Michael P. Stier[1]

Introduction

The USGS has an ongoing Land Cover Characterization Program (LCCP). The four components of the LCCP are global (1:2,000,000 scale), national (1:100,000 scale), urban (1:24,000 scale), and special projects (various scales). Only the urban and special project components include the collection of historical as well as contemporary land use and land cover (LULC) data.

The urban component requires greater LULC detail because the data are collected as a large-scale product. The source materials used during LULC collection are historical and current aerial photographs, 1-meter resolution digital orthophoto quadrangles (DOQ's), and 1:24,000-scale digital line graphs (DLG's). At present, the USGS is collecting temporal LULC data for several metropolitan areas at a minimum mapping unit (MMU) of 2.5 acres. With an MMU of 2.5 acres, a more accurate assessment can be made of the land surface activity for a particular region.

Data Requirements

The demand for large-scale LULC data has increased recently, especially in rapidly growing metropolitan areas. Many State, regional, and local planning agencies require up-to-date LULC information for various applications, including modeling urban growth, determining land suitability for future development, monitoring how land use changes affect the environment, understanding land use patterns, and developing policies that could encourage or discourage certain land use development.

In response to these increasing demands, the USGS began temporal LULC collection for the Middle Rio Grande Basin, central New Mexico, and Front Range Infrastructure Resources, Colorado, projects in 1996. The time periods of interest for the LULC collection include the 1930's, 1950's, 1970's, and 1990's.

The USGS has also collected contemporary LULC data for the Arroyo Colorado Watershed Project in Texas. The collection criteria for this project were modified to use an MMU of 5 acres and an Anderson level 3 LULC classification system (Anderson and others, 1976). Additionally, new LULC categories, such as sugar cane and citrus, were collected. The resulting LULC dataset will be used to monitor the effects of agricultural pollutants on water quality.

Project Status - Middle Rio Grande Basin LULC Data Collection

A land surface analysis pilot area encompassing the city of Albuquerque, New Mexico, was defined for collecting contemporary and historical LULC data. At present, all temporal LULC periods have been compiled at 1:24,000 scale for 14 of the 28 quadrangles. An additional 14 quadrangles of temporal LULC data will be collected in the near future for the northern half of the pilot area. These additional quadrangles will be merged with the 14 quadrangles already

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completed for the southern half of the pilot area.

Temporal LULC Mapping Methodology

Procedures involved in compiling the temporal LULC data include (1) obtaining historical aerial photographs, DOQ's, and ancillary data for collecting, interpreting, and classifying the land surface features, (2) scanning, georeferencing, and mosaicking the historical aerial photographs, (3) compiling the LULC data by 7.5-minute USGS quadrangles using USGS-developed software, and (4) merging the 7.5-minute quadrangles into one seamless dataset.

Aerial Photograph and Ancillary Source Acquisition

Before the historical aerial photographs for the project area are obtained, the availability of DOQ's is investigated. Typically, a DOQ is available only for the 1990 time period. If a DOQ does not exist for a particular 7.5-minute quadrangle, the USGS or a USGS contractor will create the DOQ to be used for the contemporary LULC collection. For the contemporary and historical time periods, the availability of aerial photographs must also be researched.

Historical aerial photographs for temporal LULC collection need to be at a photographic scale larger than 1:40,000. If the USGS does not possess the necessary imagery, the historical aerial photographs must be acquired from other government or local agencies. The USGS acquired a large number of the historical aerial photographs from the Soil Conservation Service (now the National Resources Conservation Service) archives. The most desired photographs for LULC collection are color or color infrared. Aerial photographs ideally should be taken during the growing season so that vegetation land cover classes are discernible. Color imagery enhances the ability to differentiate between agricultural land cover features such as hay/pasture and small grains. For the 1930 and 1950 time periods, only black-and-white photographs are available. When black-and-white aerial photographs are used, land surface patterns must be used to identify specific land cover categories. Acquisition of ancillary material, such as National Wetlands Inventory data, USGS 7.5-minute maps, and the Bureau of Reclamation's Land Use Trend Analysis data, helps enhance the interpretation and classification of the land surface features.

Image Processing - Georectification

After acquiring the aerial photographs and ancillary data sources, the project staff scans the historical aerial photographs for each time frame. During the scanning, every other photograph in a stereopair is used to obtain complete coverage for each 7.5-minute quadrangle.

The scanned aerial photographs are mosaicked and georeferenced using image processing software. As part of the georeferencing process, control points are created by transferring coordinates of well-defined points (that is, road intersections) from a DLG to the scanned image. At least nine georeferenced control points per image are required. In areas of high terrain relief, a minimum of 15 points is recommended. The controlled part of each photograph is then clipped out and mosaicked to adjacent georeferenced aerial photographs. The objective is to create a historical georeferenced image covering each USGS 7.5-minute quadrangle within the project area.

The final processing step is to check each mosaicked image against the DLG georeferenced features and to verify complete quadrangle coverage. Subsequently, the mosaicked image is split into north and south sections to create smaller image files that the USGS LULC collection software can display efficiently.

The USGS cannot produce a complete mosaicked image for all quadrangles within a project area. Primary reasons include (1) few or no horizontal control points available on the DLG, (2) terrain too mountainous, or (3) no change in land cover classification between temporal periods in remote areas. For those quadrangles where data gaps exist in the mosaicked image, ancillary sources are used to classify the LULC category.

LULC Collection Criteria

The LULC feature collection requirements include an MMU of 2.5 acres and a minimum polygon width of 125 feet. The identification of LULC categories follows a modified Anderson classification system developed by the USGS Rocky Mountain Mapping Center. The USGS Anderson classification system developed in the 1970's has been expanded to include more category levels (see table 6). Currently, the USGS is mapping LULC features down to level 4 of the classification system. Examples of features collected at level 4 include urban parks, natural grasslands, major retail, light industry, and row crops.

Table 6.—A part of the modified Anderson classification system illustrating subcategories included in the "developed" land use category

Level 1	Level 2	Level 3	Level 4
2.0 Developed	2.1 Residential	2.11 Single-family residential	
		2.12 Multifamily residential	
	2.2 Nonresidential developed	2.21 Commercial/light industry	2.211 Major retail
			2.212 Mixed/minor retail and services
			2.213 Office
			2.214 Light industry
		2.22 Heavy industry	2.221 Petrochemical refinery
	2.3 Mixed urban		

Temporal LULC Collection

The contemporary LULC features are mapped first using the 1990's vintage DOQ's as the source. Upon completion, the 1990's LULC dataset is used as the foundation for collecting the 1970's LULC dataset. The completed 1990's LULC dataset is modified to represent the 1970's land surface by using the historical image as a backdrop to delineate the geographic extent of the LULC features. The 1950's and 1930's LULC datasets are collected by, once again, using the next most recent time period as the land surface foundation, which is modified by using the historical images to represent the temporal land surface. The temporal LULC collection is performed on a quadrangle-by-quadrangle basis. Using the more recent LULC dataset as the foundation for collecting earlier time periods avoids the redundant collection of unchanged LULC features between temporal periods.

LULC Quality Control

Once a specific LULC time period is completed for all quadrangles, the delineation and attribution of all LULC features are checked for consistency and quality assurance and, if necessary, corrected within each quadrangle. In addition, individual quadrangle edges are checked for consistent LULC feature delineation and attribution between adjacent quadrangles. After the quadrangle edges are checked, the individual 7.5-minute quadrangles are merged together to form a seamless LULC dataset for each time period of the project area.

The contemporary LULC data are checked before the compilation of the historical LULC datasets. Because the contemporary LULC data are used as the foundation for collecting the historical time periods, a quality-controlled 1990's LULC dataset reduces the possibility of correcting the same error for all historical periods, especially in those areas where temporal LULC change has not occurred.

LULC Data Applications

The temporal LULC data will be used for land use change analysis and as an input for predicting future land use for the Middle Rio Grande Basin Study area. Public access to the USGS temporal LULC data and historical imagery will be made available on the Middle Rio Grande Basin web site at http://rmmcweb.cr.usgs.gov/public/mrgb/lulc_over.html.

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HYDROGEOLOGIC AND GEOLOGIC FRAMEWORK

Electromagnetic Surveys in the Rio Grande Flood Plain, Middle Rio Grande Basin, New Mexico—Third-Year Status

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Quantifying the hydraulic linkage of the Rio Grande to the Santa Fe Group aquifer system is of prime importance in managing the water resources in the Middle Rio Grande Basin. The river and aquifer are linked through the approximately 25-meter (m)-thick sequence of inner-valley alluvium underlying the Rio Grande flood plain. These alluvial deposits, which contain sediments ranging from cobbles to clay, are a major factor controlling the volume of water that can move between the Rio Grande and the aquifer system. In the ground-water-flow model of Kernodle and others (1995) vertical hydraulic-conductivity values for the inner-valley alluvium were assumed to range from 12.2 meters per day (m/day) for most of the inner-valley alluvium to 0.15 m/day for an area of silty clay. Silty-clay layers exist within much of the inner-valley alluvium; although many of these layers are discontinuous, they are as thick as 4 to 6 m locally. Information on the distribution and geometry of silty-clay layers in the inner-valley alluvium is essential for quantifying the amount of water transmitted between the Rio Grande and the Santa Fe Group aquifer system. This article describes the results of a study evaluating the use of electromagnetic surveys to provide this information. Preliminary results of this study were described in Woodward (1997) and Sterling and Bartolino (1998). A report describing the results of the study is currently (1998) in review.

During the first phase of the study, test electromagnetic soundings were made using time-domain and frequency-domain electromagnetic methods. On the basis of these initial results, the time-domain electromagnetic method was judged ineffective because of cultural noise in the study area; subsequent surveys were made using the frequency-domain electromagnetic method. In the second phase of the study, 31 frequency-domain electromagnetic surveys were conducted along the Rio Grande flood plain in the Albuquerque area in the spring and summer of 1997 to determine the distribution and geometry of significant silty-clay layers buried in the inner-valley alluvium. For ease of interpretation, the 31 survey sections were combined into 10 composite sections.

For interpretation, sections with terrain-conductivity values larger than 40 millimhos per meter (mmhos/m) were assumed to contain detectable amounts of silty clay because of correlation with lithologic logs. In addition, sections that had stations with widely contrasting terrain-conductivity values (greater than 10 mmhos/m) for different intercoil spacings were interpreted to contain detectable amounts of silty clay because of the inhomogeneity of the measurements. By using these criteria, all or parts of 7 of the 10 composited survey lines are probably underlain by silty-clay layers. A comparison of lithology as interpreted by the electromagnetic surveys with lithologic logs from three wells near the survey lines indicated good correlation in two of the three wells. Specific conductance of ground water was evaluated and determined to not have a significant influence on survey results.

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Three-Dimensional Geologic Modeling of the Middle Rio Grande Basin

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The geologic framework of the Middle Rio Grande Basin reflects the complex interplay of tectonics and sedimentation within this segment of the Rio Grande Rift during the last 30 million years. We describe ongoing development of a digital three-dimensional model of the major faults and lithostratigraphic units for this region in support of improved hydrogeologic modeling by the Water Resources Division. The surface geologic model incorporates new geologic mapping by the USGS, the New Mexico Bureau of Mines and Mineral Resources, and the University of New Mexico The subsurface framework of the three-dimensional model is interpreted from several sets of constraining data (oil- and water-exploration wells, limited seismic reflection data, regional gravity and magnetic data, and local geophysical soundings) and from concepts of regional tectonic evolution and sedimentologic response to tectonics. The model encompasses the region from the La Bajada constriction on the north (near Cochiti Dam) to San Acacia on the south over a distance of about 100 miles (about 160 km).

Drilling, seismic reflection, and gravity data indicate that the Miocene and younger rift-filling sediments (Santa Fe Group) are several kilometers thick and locally exceed 4.4 km (about 14,500 feet). Gravity data clearly indicate that thickness varies greatly from place to place and that the Middle Rio Grande Basin consists of at least three distinct, major depositional subbasins, informally designated Calabacillas, Santo Domingo, and Belen (this last showing significant internal complexity). The major thickness changes follow linear and arcuate trends in the gravity data that most likely reflect faults and warps that were active during the earlier stages of rift sedimentation. Mapped young faults that cut the Santa Fe Group and surficial deposits (as well as those identified on high-resolution aeromagnetic surveys) are numerous and yet their cumulative offset is insufficient to account for the great thickness variations, as noted by Kelley (1977) and others. More important, the dominant northerly trend of these abundant young faults differs from the trends of the more substantial faults and warps that define the margins of depositional subbasins (interpreted from the gravity data).

We particularly note that the zones of structural culmination that separate the depositional subbasins show consistent northwesterly trends. Drill-hole data for wells along and near these culmination zones show that not only is the Santa Fe Group thin, the pre-Santa Fe Tertiary sections are thin to absent. These data suggest that the culminations mark structural accommodation zones between the Miocene depositional subbasins that were erosionally stripped as the adjoining basins subsided during rifting. The combined drill-hole data and gravity interpretations appear at odds with previously proposed northeast-trending accommodation zones hypothesized to coincide with pre-rift wrench faults (for example, Russell and Snelson, 1994).

Lithostratigraphic units within the three-dimensional geologic model are based on projections from surface mapping and drill-hole penetrations, but are largely conceptual in nature for large

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segments of the Middle Rio Grande subbasins where subsurface control is scant. Within the Calabacillas Subbasin where the most subsurface data exist, we recognize a lower, dominantly eolian part of the Santa Fe Group; a middle dominantly fluvial-sand unit; and an upper, coarse-clastic unit that reflects the establishment of through-flowing gravel streams of the Rio Grande and its precursor tributaries. Most faulting and subsidence was contemporaneous with the (middle) fluvial unit, and depositional facies were likely controlled by active fault scarps.

Far less is known about the sedimentation/subsidence history of the Santo Domingo or Belen Subbasins, but several lines of evidence indicate that each subbasin has its own local lithostratigraphy. The Belen Subbasin(s) contain exceptionally thick deposits (0.5 to 1.8 km) of Oligocene volcaniclastic sediment (unit of Isleta Well 2 of Lozinsky, 1988) as well as Miocene fanglomerate and andesite flows (Popotosa Formation) derived from southern sources that are not recognized north of the Shell West Mesa Federal 1 well. Similarly, the Santa Fe deposits in the southern Santo Domingo Subbasin lack the lower eolian unit and contain significant fanglomerate in the middle unit that may record erosion of the adjacent Sandia Mountains block (Kelley and Northrup, 1975). Distinctive debris derived from northern volcanic sources (Smith and Lavine, 1996) make up a large part of the northern Santo Domingo Basin fill that has no counterpart in the Calabacillas Subbasin. Thus, each basin records sedimentologic events pertaining to local tectonic events that were not synchronous throughout the Middle Rio Grande Basin area. Uplift histories deduced from fission track studies similarly show large local variations in timing and rate of tectonic denudation (Kelley and others, 1992). The highlands and mountain ranges that flank the current rift basins are modern source areas for rift-related sediment; some have been eroded nearly continuously through the Cenozoic (for example, Nacimento Mountains, Los Pinos Mountains), whereas others have eroded only in the Neogene (for example, Sandia Mountains and Sierra Ladron; Kelley and others, 1992).

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Preliminary Regional Compilation of Geologic Mapping Along Portions of the Albuquerque Basin, Sandia Mountains, and Vicinity, Central New Mexico

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Rapid growth of the Albuquerque-Rio Rancho metropolitan area (ARMA), the largest urban area in New Mexico, has resulted in growing concerns over the availability of ground-water resources and suitable land for development. The National Cooperative Geologic Mapping Program (NCGMP), a federally funded program administered by the USGS, mandates the production of multipurpose geologic maps in areas of socioeconomic importance. Since the inception of the NCGMP's STATEMAP Program, the New Mexico Bureau of Mines and Mineral Resources (NMBMMR) has completed geologic mapping of 15 7.5-minute quadrangles (approximately 2,300 square kilometers (km^2)) in the Albuquerque Basin, Sandia Mountains, and adjacent eastern slope. The principal purpose of this project is to provide a current and detailed geologic framework for regional ground-water resource and geologic hazard studies in this rapidly growing region. We present a preliminary compilation of a contiguous set of nine digital geologic quadrangle maps and cross sections extending from the Rio Grande to the eastern slope of the Sandia Mountains (fig. 2). These maps include the Alameda, Albuquerque East, Albuquerque West, Bernalillo, Placitas, Sandia Crest, Sandia Park, Sedillo, and Tijeras 7.5-minute quadrangles (NMBMMR open-file digital maps 10, 17, 3, 16, 2, 6, 1, 20, and 4, respectively). Mapping of the Proterozoic-Cenozoic rocks of the Sandia Mountains and vicinity was conducted at scales of 1:24,000 and 1:12,000; mapping of Cenozoic deposits in the Albuquerque Basin was completed at a scale of 1:24,000. These maps, excluding the Sandia Park and Sedillo quadrangles, are part of an ongoing compilation of the geology of the ARMA at a scale of 1:50,000 (fig. 2).

Geologic mapping of the Albuquerque Basin employs a combination of lithostratigraphic, soil-morphologic, and allostratigraphic methods. Compilation of these quadrangles, integration with available borehole data, and incorporation of biostratigraphic and radioistopic data are used to develop a regionally consistent and correlative stratigraphic framework. Deposits of the Santa Fe Group (SFG) have been provisionally assigned to the Sierra Ladrones and Arroyo Ojito Formations. Major revisions to previous mapping include the subdivision of piedmont and fluvial (ancestral Rio Grande) facies of the Sierra Ladrones Formation and delineation of a western- and northern-margin facies called the Arroyo Ojito Formation (see Connell and others, p. 30). Younger (post-SFG) deposits are divided into several major units and subunits. Integration of borehole data with geologic mapping also delineates hydrogeologically significant subsurface stratigraphic trends (Connell and others, 1998) that constrain the distribution of buried faults and aquifers. The spatial distribution of SFG fluvial facies generally corresponds to variations in well productivity. For instance, water-supply wells completed in much of the

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Arroyo Ojito Formation and in piedmont facies of the Sierra Ladrones Formation are typically less productive than wells completed in fluvial deposits of the Sierra Ladrones Formation.

Mapping and compilation of the pre-Tertiary geology have refined structural geology and lithostratigraphy of the study area. Particular emphasis was placed on mapping fault systems and joint sets in an effort to provide better data for hydrogeologic studies (delineate zones of increased fracture porosity or potential impediments to flow). Many structures, such as the La Cueva Fault, extend into the Albuquerque Basin where they may influence ground-water flow and basin-margin recharge. Lithostratigraphic mapping of Proterozoic and Phanerozoic rocks provides finer subdivision of potentially hydrogeologically important strata, such as on the Sedillo quadrangle, where coarse clastic units are differentiated from carbonate and shale in the Madera Formation.

Major structural elements within the study area are not vastly different from those described by previous investigations (Kelly and Northrop, 1975; Kelley, 1977). However, some elements of the new maps are of notable interest. Faulting of pre-Madera Formation sediments by locally mineralized northwest-striking faults suggests that these faults were related to ancestral Rocky Mountains tectonism. Laramide structural features, such as monoclines and reverse faults with associated drag folds, were, in some cases, reactivated during Tertiary extension, suggesting that these zones of crustal weakness strongly influenced the position and character of Neogene faults in the Albuquerque Basin. Another persistent feature, the Tijeras Fault System, may record a history of repeated reactivation since the Proterozoic. Minor faults near the Tijeras Fault may be synthetic Riedel faults, suggesting left-lateral motion most recently along this system. At the northern margin of the Sandia Mountains, strata between steeply to moderately dipping faults are not significantly rotated as would be expected for listric faults such as those interpreted by Russell and Snelson (1994) and Woodward and Menne (1995).

These observations and others portrayed on this new series of maps will provide a better understanding of the development of the Albuquerque Basin and Rio Grande Rift. Refining our knowledge of the geology of the entire region will continue to be of vital concern as increased demand for water resources, ground-water contamination, and exposure to geologic hazards affect rapidly growing populations. This series of digitally compiled geologic maps will allow the flexibility of relatively easy revisions and rapid dissemination of continuously evolving geologic knowledge.

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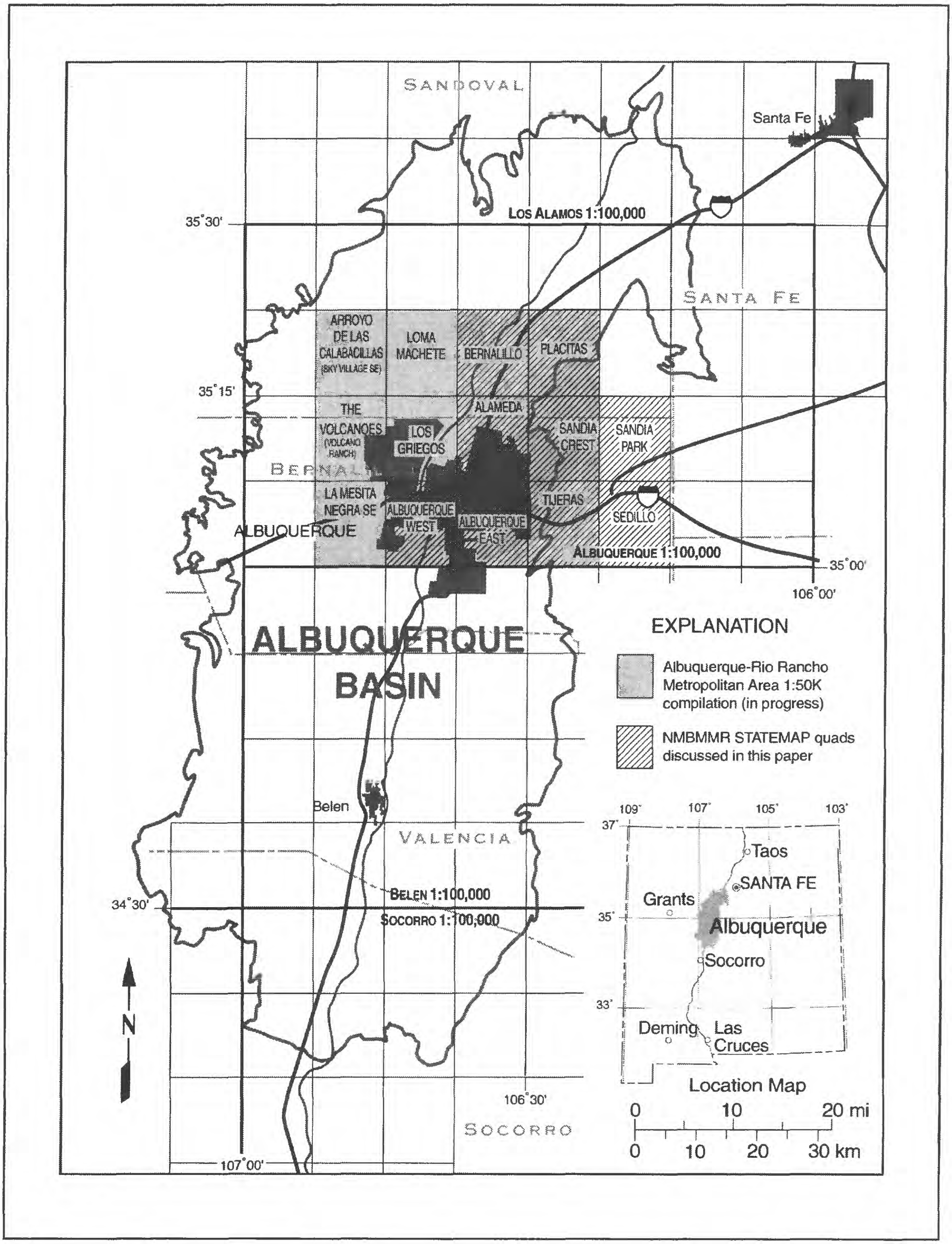

Figure 2.—Index to selected 7.5-minute geologic quadrangle maps in the Albuquerque Basin area.

Proposed Revisions to Santa Fe Group Stratigraphic Nomenclature in the Northwestern Albuquerque Basin, New Mexico: Implications for Rift-Basin Lithostratigraphy and Hydrogeology

Sean D. Connell[1], Daniel J. Koning[2], Steven M. Cather[1], and Tim Decker[3]

Geologic mapping and stratigraphic studies of a well-exposed, nearly continuous section of Santa Fe Group deposits in Arroyo Ojito (Cerro Conejo 7.5-minute quadrangle) allow for finer subdivision of the Santa Fe Group in the Albuquerque Basin. We propose four new stratigraphic terms (two formation rank and two member rank) to subdivide Santa Fe Group deposits in the northwestern margin of the Albuquerque Basin and southwestern margin of the Santo Domingo Basin. The Cerro Conejo Member of the Zia Formation is assigned to deposits previously called the middle red member of the Santa Fe Formation (see Bryan and McCann, 1937) and unnamed member of the Zia Formation (see Tedford and Barghoorn, 1997). At Arroyo Ojito, the Cerro Conejo Member contains 316 meters (m) of fine- to coarse-grained massive to tabular sandstone with minor cross stratification (fig. 3) interpreted to have been deposited in sandy fluvial and eolian environments. The Cerro Conejo Member represents a transitional unit between lower members of the primarily eolian Zia Formation and the overlying fluvially dominated Arroyo Ojito Formation.

The Arroyo Ojito Formation overlies the Zia Formation and records deposition of ancestral Rio Puerco and Rio Jemez fluvial systems draining the Colorado Plateau and Sierra Nacimiento. The term Arroyo Ojito Formation supersedes strata variously assigned to upper buff and upper part of the middle red members of the Santa Fe Formation, Cochiti Formation, and Sierra Ladrones Formation. At Arroyo Ojito, the Arroyo Ojito Formation contains approximately 437 m of moderately to poorly sorted, fine- to coarse-grained sandstone, silty sandstone, mudstone, claystone, and conglomerate (fig. 4). Clast composition is dominantly chert rich and volcanic rich at the base and becomes more heterolithic upsection. This unit is subdivided into the Navajo Draw, Loma Barbon, and Ceja Members. The Navajo Draw Member is pale yellow, has lenticular and tabular bedding, and contains predominantly brownish-yellow chert pebbles, volcanics, sandstone, and rare red granite and Pedernal chert clasts. The overlying Loma Barbon Member is pale yellow to reddish brown, contains abundant red granite clasts, and is more poorly sorted than the underlying member. Basaltic clasts also become more common upsection in this member. The overlying Ceja Member is 10-37 m thick at Arroyo Ojito and contains abundant cobbles to boulders of red granite, Pedernal chert, recycled Zia Formation sandstone, and basalt. This unit marks the top of major basin aggradation beneath the Llano de Albuquerque tableland. Deposits of the Arroyo Ojito Formation interfinger with the Plio-Pleistocene fluvial facies of the Sierra Ladrones Formation along the Rio Grande Valley (compare units 1-5, Lucas and others, 1993; Connell, 1998; and Connell and Hawley, 1998).

The Pantadeleon Formation refers to deposits associated with fault-controlled wedges produced by local accommodation space along hangingwall portions of major intrabasinal normal faults. At Arroyo Ojito, this member contains wedges of sandstone and pebble- to cobble conglomerate

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overlying a strongly developed soil on the Ceja Member. Elsewhere on the Llano de Albuquerque, this unit contains several buried paleosols (compare Wright, 1946; Machette, 1978).

Age control is limited, but biostratigraphic and radioisotopic data indicate that the Cerro Conejo Member was deposited during the middle Miocene (Barstovian and possibly Clarendonian land mammal ages, approximately 11-7 million years (Ma)). The Arroyo Ojito Formation was deposited during the late Miocene, Pliocene, and possibly early Pleistocene (Clarendonian(?)-Blancan land mammal ages, approximately 7-1.5 Ma).

Aquifer-test data for numerous water-supply wells in the northern Albuquerque Basin indicate that the Zia, Arroyo Ojito, and Sierra Ladrones Formations represent distinct hydrogeologic units. Wells completed within the Arroyo Ojito and Zia Formations west of the Rio Grande yield values of hydraulic conductivity and specific capacity of 1-21 feet per day (ft/d) (3.5×10^{-4} to 7.5×10^{-3} centimeters per second (cm/s)) and 3-13 gallons per minute per foot (gal/min/ft) (50-238 square meters per day (m^2/d)), respectively. Hydraulic conductivity is slightly lower (1-7 ft/d) in wells completed below the Ceja Member. In contrast, wells completed in fluvial deposits of the Sierra Ladrones Formation yield values of hydraulic conductivity and specific capacity of 50-71 ft/d (1.8×10^{-2} to 2.5×10^{-2} cm/s) and 66-83 gal/min/ft (1,090-1,484 m^2/d), respectively.

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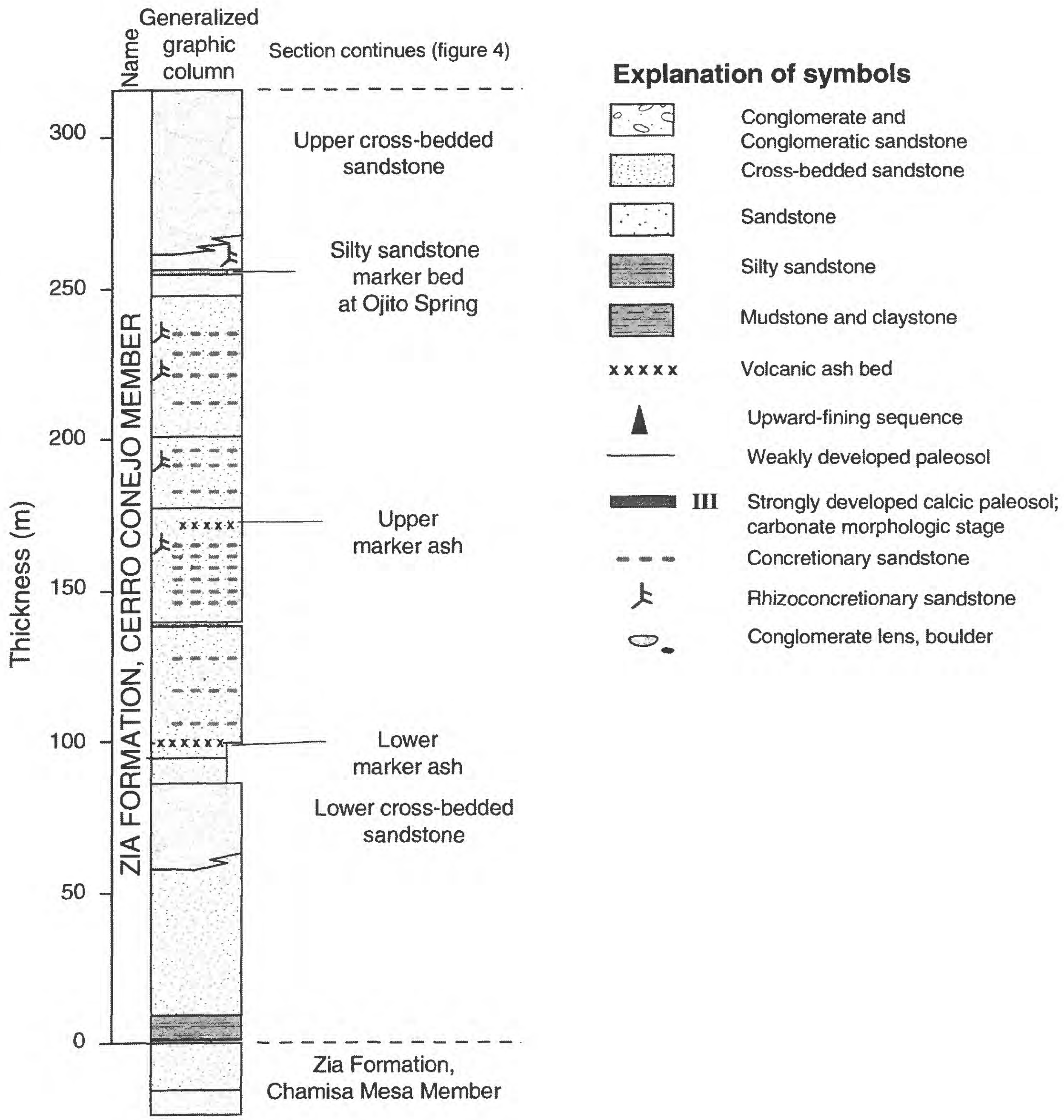

Figure 3.—Generalized stratigraphic column of the Cerro Conejo Member of the Zia Formation at Arroyo Ojito.

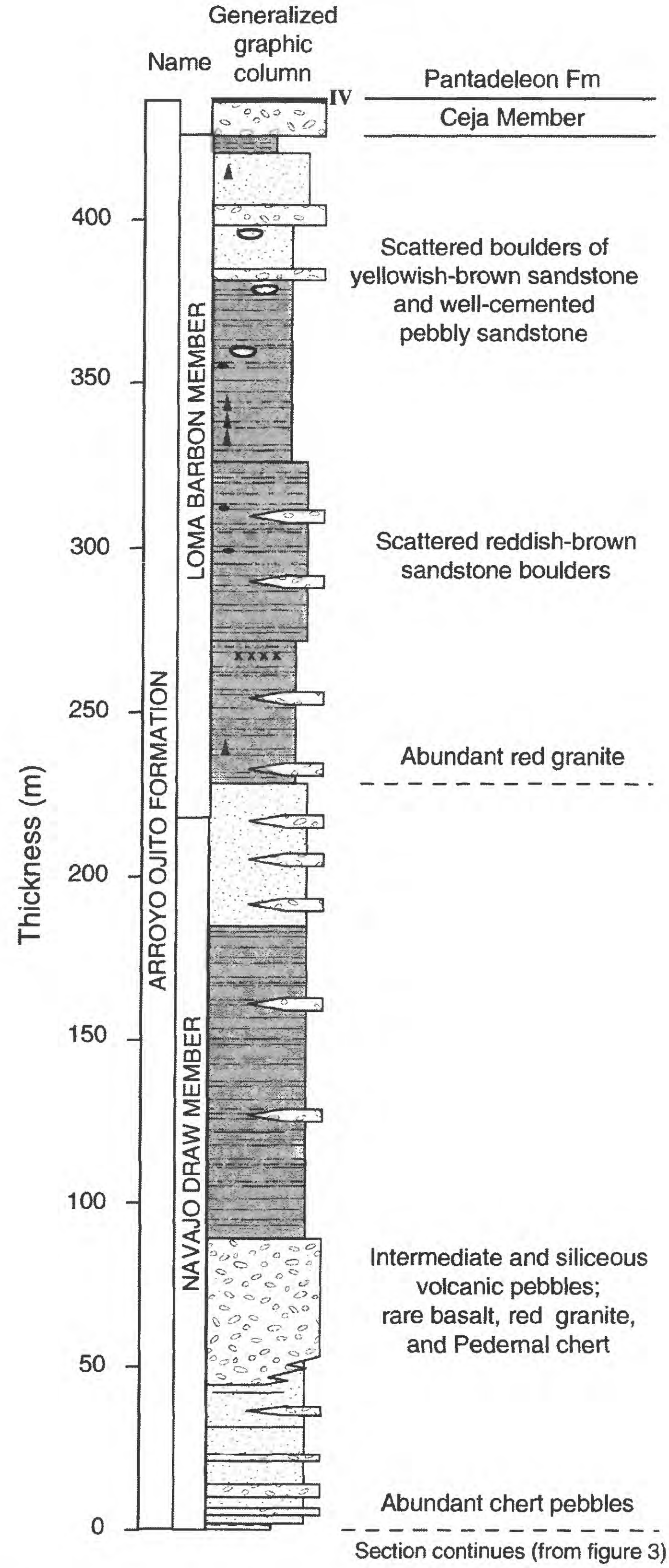

Figure 4.—Generalized stratigraphic column of the Arroyo Ojito Formation at Arroyo Ojito. See figure 3 for explanation of symbols.

Application of Electromagnetic Surveys to Geologic and Hydrologic Problems in the Middle Rio Grande Basin Area

Maria Deszcz-Pan[1], Brian D. Rodriguez[1], David A. Sawyer[2], Byron D. Stone[3], Michel Godbout[4], Jon Doucette[4], V.J.S. Grauch[1], and Victor F. Labson[1]

An airborne time domain electromagnetic (TDEM) survey was conducted in March 1997 in the Middle Rio Grande Basin in the vicinity of Cochiti Pueblo and the Rio Rancho area, New Mexico. The data from the surveys were processed by the BHP World Minerals, Discovery Technologies Group, Denver, Colorado, geophysical company using two different algorithms and applying the company's proprietary software. One approach was called conductivity-depth image (CDI) and the other was a regularized least-squares inversion program called AIRSTEM.

The CDI is a fast algorithm. It is useful in visualizing the distribution of electrical conductance with depth and in estimating the constraints on depth coverage of the time domain signal. It assumes that the earth time domain response at two successive time samples could be matched with the response of a thin conductive sheet in an infinitely resistive medium located at certain depth. The depth and electrical conductance of the sheet is calculated from successive time samples on the time domain curve. Because the decay curve collected by the system used for the surveys had 20 samples and the algorithm uses two neighboring channels to estimate depth and conductance, the CDI method provides the pattern of electrical resistivity sampled at 19 different depths for each measurement station. The depth of the sheet calculated from the earliest two channels estimated the shallowest depth from which the system received the signal; the last two channels were used to estimate the maximum depth extent.

The AIRSTEM program utilizes a regularized least-squares inversion approach. This technique assumes that the electromagnetic time domain response can be modeled by a series of flatly lying layers of varying electrical resistivity and fixed thickness. The layer resistivities use a smooth model constrain in the inversion. The parameters of the layers were varied until the match of the calculated response with the observed response was achieved at all measurement times simultaneously. In the BHP processing, 24 layers were used to model the resistivity of the earth. The layer thickness was a fixed parameter, but layer thickness increased with depth from 5 meters (m) on the surface to 100 m at the bottom of the model, corresponding to the decreasing resolution of electromagnetic signal with depth. A background resistivity of the basement was also fixed at 50 ohm-meters.

The final result gives a one-dimensional approximation of the three-dimensional distribution of electrical resistivity below the surface of the earth to a depth of about 400 m. The depth of investigation was extended by additional ground electrical resistivity (DC) and audiomagnetotelluric (AMT) studies performed in the summer of 1997. The integration of the resulting resistivity distribution with geologic mapping, airborne magnetic data, and available well logs constrains the horizontal and depth extent of subsurface geologic units.

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The resistivity maps mostly agree with the geologic interpretation of the area and with the independent information provided by wells and ground-based electrical soundings. For example, in the Cochiti Pueblo area the electrically resistive areas on the northeast correspond with the Plio-Pleistocene basaltic lava flows observed on the surface. The maximum thickness of these resistive units evaluated from the AIRSTEM model was close to 300 m and was consistent with the models from modeled magnetotelluric soundings and with observations made from detailed well logs.

Another interesting feature observed at the south center of the Cochiti survey area is a resistivity high that correlated with a magnetic high. This feature starts to develop at a depth of about 15 m, increases in lateral extent to a depth of about 50 m, and disappears almost entirely with depth except for a small circular resistivity high at a depth of 150 m that could be a feeder dike. This would suggest a shallow, local basaltic vent area and associated lava flows buried under the thin layer of Holocene sediments.

The application of the TDEM results to delineate boundaries between electrically resistive lava flows with electrically conductive Cretaceous shales is straightforward once the resistivity depth distribution is known. A more difficult problem is correlating the electrical resistivity with the known subsurface geologic units from borehole geophysical logs to delineate the facies changes within the Santa Fe Group aquifer system. It is assumed that the axial channel gravel deposits, which are the main aquifers in the Middle Rio Grande Basin, will have a higher electrical resistivity than surrounding finer grained materials of lower hydraulic permeability, though differences in the resistivity response of these units may be small.

Subsurface Constraints on the Geologic Model of the Middle Rio Grande Basin, Including New High-Resolution Aeromagnetic Data and Gravity Modeling

V. J. S. Grauch[1], Cindy L. Gillespie[2], David A. Sawyer[3], and G.R. Keller[2]

Geophysical studies for the Middle Rio Grande Basin study include acquisition of various types of geophysical data and interpretation of these data in conjunction with geologic and other subsurface information. The studies are critical to the construction of a three-dimensional geologic model that will ultimately be used to develop an improved hydrologic model for the basin. In particular, high-resolution aeromagnetic data constrain the locations of faults that offset basin sedimentary units and buried igneous rocks. Gravity data constrain the locations of major basement faults and the thickness of the basin sediments.

Aeromagnetic Data

High-resolution (closely sampled) aeromagnetic data have been acquired over most of the Middle Rio Grande and southern Española Basins (fig. 5). Data for the most recent surveys, flown at the end of 1998, are presently (1999) only in preliminary form. Images from the earlier surveys can be viewed with a web browser at http://rmmcweb.cr.usgs.gov/public/mrgb/airborne.html.

Maps from the aeromagnetic surveys show expressions of faults, igneous rocks, Precambrian crystalline rocks, anthropogenic structures, and lithologic variations within the basin sediments. The expressions of faults are the most striking and correspond to many faults or portions of faults that cannot be determined at the surface. Along with newly revealed faults, the maps suggest redefinition of the locations of portions of major faults, such as the San Francisco, Hubbell Springs, Cat Mesa, and Rio Puerco Faults. Maps of the inferred faults will help determine the lateral extent of fault-bounded units in the three-dimensional geologic model of the basin.

Expressions of buried volcanic and related intrusive rocks are concentrated near exposed volcanic centers. Many of the volcanic rocks have an aeromagnetic expression that indicates their formation during periods of reversal or transition of the Earth's magnetic field. The greatest extent of buried volcanic units is revealed near the Rio Grande in aeromagnetic maps from the Isleta-Kirtland survey (fig. 5).

Sedimentary units within the Santa Fe Group commonly have moderate magnetizations, which are strong enough to produce expressions on the aeromagnetic maps where the units vary lithologically or are offset by faults. The Espinaso Formation, which is exposed near the southernmost extent of the Española Basin, has the most prominent magnetic expression of the sedimentary units. The aeromagnetic data indicate that it underlies most of the area south of Santa Fe and is complexly faulted in the El Dorado area. In contrast, the Tesuque Formation has poor to no magnetic expression where it is exposed north of Santa Fe.

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Gravity Modeling

Previous compilations of gravity data for the Middle Rio Grande Basin did not include coverage of a large region in the southwestern part of the basin. In 1997, data were acquired over this area as part of a project at the University of Texas at El Paso in collaboration with the Middle Rio Grande Basin geophysical studies. The new data have been recently processed and incorporated with the older data, resulting in more complete gravity coverage of the basin. The isostatic residual gravity data are the most useful for modeling because the data are restricted to the effects of density variations within the top 10 kilometers of crust.

The isostatic residual gravity map expresses variations in the low density of the poorly consolidated basin fill compared to the moderate to high densities of the surrounding bedrock. In general, lower gravity values correspond to thicker fill and indicate several separate subbasins within the Middle Rio Grande and southern Española Basins, as recognized by previous workers. The new gravity data show that the southern part of the Middle Rio Grande Basin (Belen Subbasin) contains separate gravity lows on the east and west sides.

The subbasins displayed by the gravity data differ somewhat from the structural model developed by Russell and Snelson (1994), which was based primarily on seismic reflection and drill-hole data. Their model shows a narrow, hourglass-shaped basin, which is bounded on the east by a master fault near the Rio Grande and divided by a structural accommodation zone into northern and southern trap-door basins that have opposing dips. Current modeling of the gravity data seeks to reconcile these differing views of the basin by using the seismic reflection and drill-hole data as constraints on gravity modeling.

The gravity modeling uses an iterative modeling technique to separate the gravity fields of basin fill from that of pre-rift bedrock. The modeling is constrained by a variety of subsurface information including formation picks and estimates from drill holes, density logs, geologic extrapolation, and seismic reflection data.

Preliminary results from the modeling support the picture of three discrete subbasins within the Middle Rio Grande Basin. The northern subbasin (Santo Domingo) is thickest under the Santa Ana mesa. The middle subbasin (Calabacillas) extends farther east than shown by the hourglass shape outlined by Russell and Snelson (1994). The southern subbasin (Belen) has thick basin fill on the west-central side and in the center, and a north-south elongated basement high between. Another gravity low on the east side of this subbasin is apparently due to low-density rocks in the pre-Tertiary section rather than thick basin fill. This is constrained only by the presence of Triassic rocks at 1,384-meter (4,540-foot) depth in the Grober-Fuqua well, east of Belen. Other subsurface constraints in the area are unavailable.

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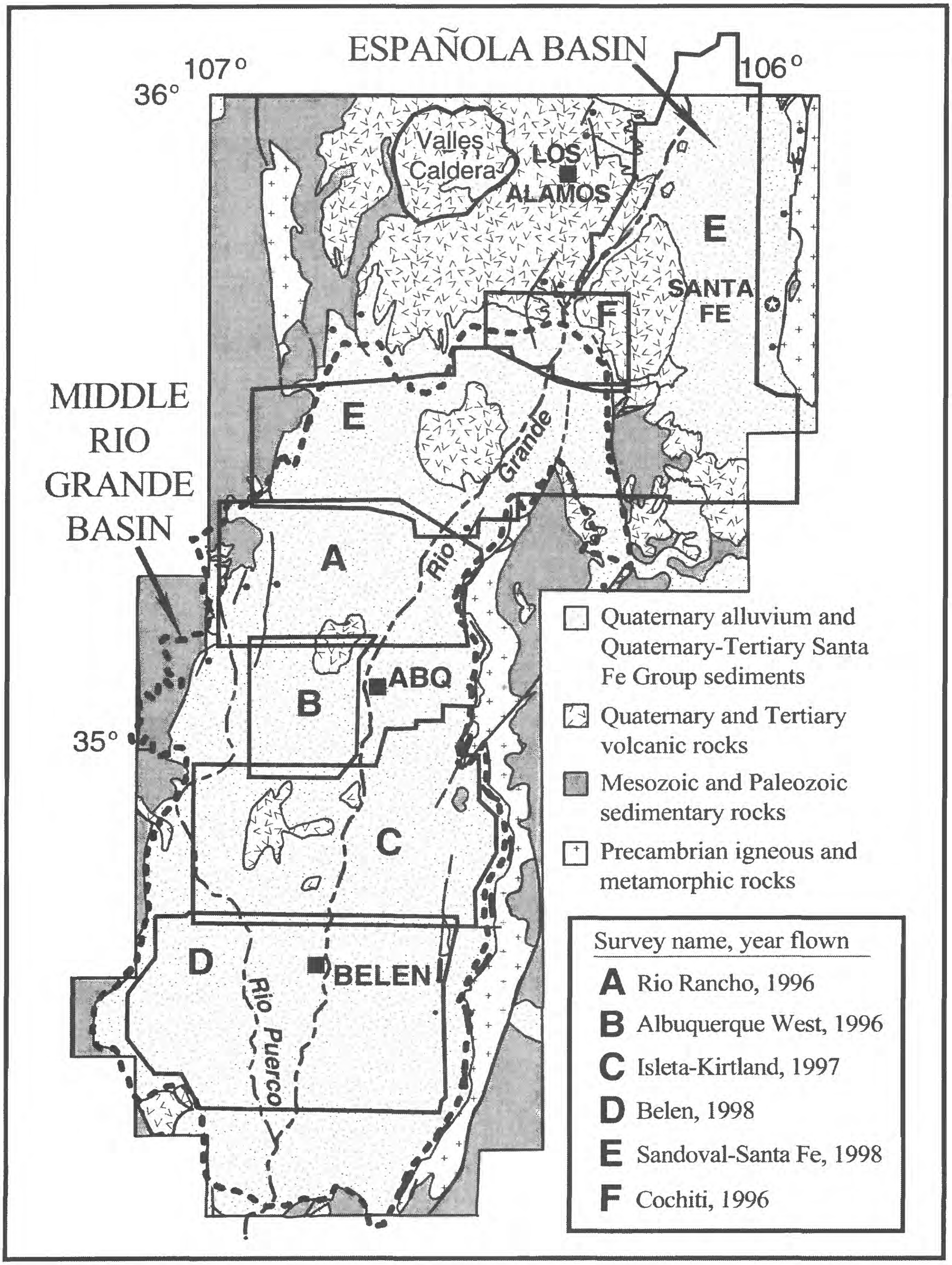

Figure 5.—Location of aeromagnetic surveys in relation to the general geology of the Middle Rio Grande Basin and vicinity. Most survey areas overlap with adjacent areas. ABQ=Albuquerque.

Preliminary Characterization of Faults in the Middle Rio Grande Basin

M.R. Hudson[1], S.A. Minor[1], V.J.S. Grauch[2], and S.F. Personius[3]

Faults have played a prominent role both in shaping the geometry of the Rio Grande Rift and in controlling thickness and facies of its basin sediments. We are compiling fault information in several geographic information system (GIS) data layers to assess the importance and geometry of faults within the middle Rio Grande composite basin. The immediate goal of this compilation is to determine which faults most strongly influence ground-water flow and should be included in a simplified, three-dimensional, 1:100,000-scale geologic model being developed for future hydrogeologic modeling.

Fault information is being gathered from several sources. Geologic maps produced by geologists at the USGS, New Mexico Bureau of Mines and Mineral Resources, and the University of New Mexico, mostly at 1:24,000 scale, give information on the strike, dip, throw, and surface geometry of faults. These data are augmented by our survey of faults in key exposures that also give information on fault kinematics and associated fracture and cementation patterns. Mapped faults are being generalized and digitized for display at 1:100,000 scale, with the faults classified as major and minor based on their trace length and displacement. Geologic map coverage of faults is most complete in the northern part of the basin due to extensive exposures of Santa Fe Group sedimentary rocks. A subset of mapped faults with probable Quaternary offset is available from a recently compiled GIS database (Machette and others, 1998). High-resolution aeromagnetic surveys that have been recently completed for nearly the entire basin reveal linear anomalies caused by magnetic contrasts of near-surface basin materials juxtaposed across faults. Magnetic lineaments have been compiled at 1:50,000 scale to give information on both the map patterns and lengths of faults. Magnetic lineaments are particularly helpful in tracing faults beneath surficial deposits, such as those abundant in the southern part of the basin. Magnetically defined faults, however, usually do not provide a sense of downthrow and they may be poorly expressed in areas of superimposed anthropogenic sources or in areas lacking sufficient magnetic contrasts within basin sediments. Isostatic residual gravity data define areas of maximum basin depth generated by faults, and they are the principal data used to define, from north to south, the Santa Domingo, Calabacillas, and Belen Subbasins within the composite Middle Rio Grande Basin. Maximum-gradient analysis of the gravity data locates those faults that are responsible for major density contrasts between basin sediments and pre-Santa Fe Group rock.

Although the analysis of faulting is still at an early phase, several observations can be made. Fault dips range from 22 to 88 degrees in 105 measurements of map-scale faults within basin sediments, but most dips are between 60 and 80 degrees, with a strong mode at 70 to 75 degrees. North-striking faults predominate at shallow depths throughout the basin, but deeply buried, northwest-striking faults are inferred from gravity-defined boundaries between subbasins. In detail, many long faults contain segments of differing strike or en echelon segments or splays. Left-stepping, north-northeast-striking, en echelon fault segments within the north-striking Hubbell Spring Fault Zone suggest that this structure accommodated a slight dextral component of slip in addition to its normal slip. This pattern, also repeated on other faults, may reflect a

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response to a west-northwest-directed least principal stress. Local transfer of strain is apparent between dominantly north-striking normal faults and transverse normal-oblique-slip faults, principally of northeast strike. This pattern is well expressed along the basin margins. In contrast, accommodation zones separating the subbasins are not discrete, basin-spanning transfer faults as previously depicted. Accommodation zones instead appear to be broad bands within which faults of opposing and like downthrow interfinger and commonly curve and lose throw. Whereas faults mostly cluster in discrete zones within the Belen Subbasin, they are distributed more evenly across the Calabacillas and Santo Domingo Subbasins. New geologic mapping and geophysical data suggest that the northeast margin of the Santo Domingo Subbasin continues east of the La Bajada Fault beneath the about 2.5-million-year-old Cerros del Rio volcanic field.

Superimposed GIS fault layers from the different geological and geophysical data will be key in interpreting which faults are most important in basin development and ground-water flow. For the geologic basin model, we anticipate emphasizing those faults having some combination of long map length, large stratigraphic offset, prominent geophysical signature, and youthful movement.

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A Double-Porosity Model of Ground-Water Flow in the Madera Formation Based on Spring Hydrographs and Aquifer-Test Analyses from Placitas, New Mexico

Peggy Johnson[1]

The Madera Formation forms a carbonate aquifer of regional significance for ground-water development in the Sandia Mountains east of Albuquerque, New Mexico. Characterization of carbonate aquifers is problematic because of the localized nature of ground-water flow in fractured limestone. Spring hydrographs and aquifer-test data indicate that ground water in the Madera aquifer moves as combined diffuse flow and fracture flow. Aquifer-test drawdown data fit a double-porosity model and show that ground water is primarily transmitted through large fractures, but most aquifer storage is attributable to the limestone matrix. Fracture transmissivity ranges from 170 to 200 square meters per day. Total storativity, for both fractures and matrix, is 0.20 to 0.25. The fractures transmitting the bulk of spring discharge are associated with faults in the Madera Formation. Spring hydrographs from fault-controlled springs near the Village of Placitas may provide a potentially valuable source of data on Madera aquifer hydraulic properties, including effective porosity, transmissivity, storage, water budgets, and recharge. Hydrograph separation (fig. 6) and recession curve analysis (fig. 7) yield preliminary estimates of dynamic storage and recharge for three Placitas springs. Further work is required before the full potential of spring hydrograph data can be utilized as a regional aquifer characterization tool in the Madera Formation.

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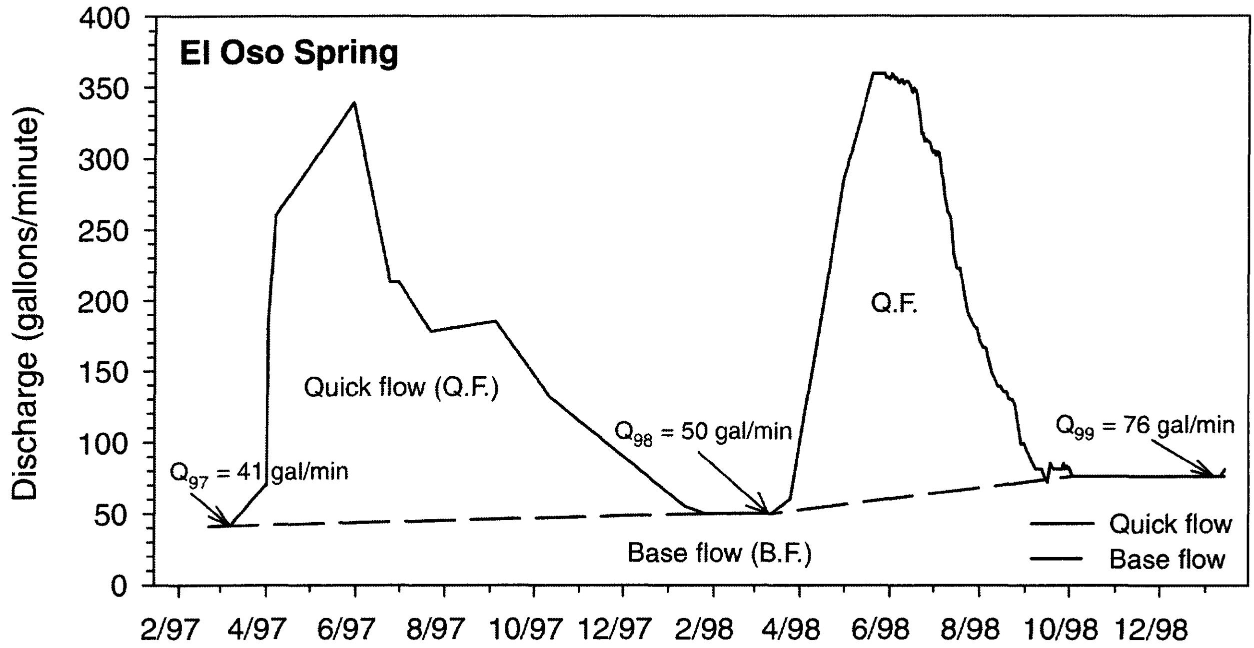

Figure 6.—Hydrograph separation analysis of El Oso Spring.

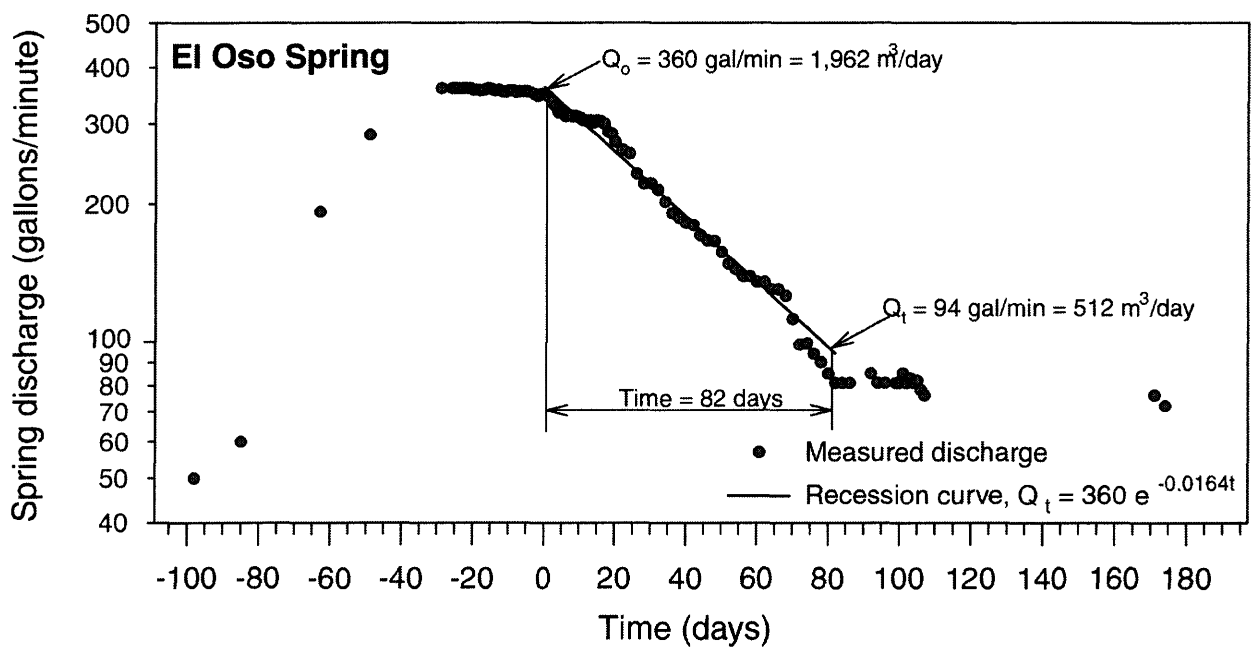

Figure 7.—Recession curve analysis of El Oso Spring.

Preliminary Geologic Map of the Dalies Quadrangle, Valencia County, New Mexico

David W. Love[1], Florian Maldonado[2], Bruce Hallett[3], Kurt Panter[4], Charles Reynolds[5], William McIntosh[1], and Nelia Dunbar[1]

The Dalies quadrangle is in the center of the Albuquerque Basin 20 kilometers south-southwest of Albuquerque near the rapidly expanding community of Los Lunas. It straddles the eastern edge of the Llano de Albuquerque, the valley border slopes and terraces, and the modern flood plain of the Rio Grande. Elevations range from 1,505 meters (m) on the flood plain to 1,815 m at the top of El Cerro de Los Lunas. Two volcanic fields are exposed at the surface: Los Lunas volcano and Cat Hills. Several north-trending and east-west-trending faults and folds offset the Llano de Albuquerque, Los Lunas volcano, and younger surfaces.

Geologic units at the surface are rift-fill deposits, volcanics, and their derivative sediments. Depths to pre-rift Cretaceous rocks beneath the quadrangle in three oil-well tests are 864 m (1 Harlan Ranch) in the southeastern corner, 2,200 m (Long 1 Dalies) in the southwestern corner, and 3,691 m (Shell Isleta No. 1) in the northeastern corner. Russell and Snelson (1994) interpreted Shell Development Company seismic lines in the vicinity, particularly a line through wells Isleta 1 and Isleta 2 farther north to show a mid-basin transfer zone with a large negative flower structure trending west-southwestward. This structure deforms some basin fill and is overlain by upper Tertiary basin fill. It is not expressed at the surface.

Two hundred meters of tilted upper Tertiary and lowest Quaternary basin fill are exposed in badlands on both the northwest and southwest sides of Los Lunas volcano. Part of this basin fill can be traced northward to local facies in the Santa Fe Group of Isleta Pueblo (Maldonado and Atencio, 1998). The two mappable units are (1) QTsi, consisting of at least 25 m of sand, silt, and clay lithofacies that fill a north-south graben and/or sag structure within the Llano de Albuquerque, and (2) QTui, sand and gravel lithofacies that underlie most of the quadrangle to an unknown, but considerable depth. Reflection seismic profiles by Reynolds adjacent to Los Lunas volcano reveal flat-lying basin sediments beneath and beyond Los Lunas volcano on the east side, but tilted, faulted, and folded sediments on the northwest side of the volcano.

The quadrangle includes six of the seven basalt flows of the Cat Hills volcanic field, the oldest of which is dated by Ar/Ar at 0.098 ±0.02 and 0.11 ± 0.03 million years (Ma) (Love, 1997; Maldonado and Atencio, 1998; Maldonado and others, 1998). The oldest flow lacks rugged surface topography--the lows have been filled with eolian sand and colluvium and the highs have been eroded. The more recent upper flows have rugged topographic highs and lows and locally include a lava tube.

El Cerro de Los Lunas consists of two or more volcanoes of different ages. Outlying volcanic rocks exposed south of the volcano and aeromagnetic anomalies (U. S. Geological Survey and

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Sander Geophysics, Ltd., 1998) show that the field is much more extensive in the subsurface. Some of the southern outliers appear to be intrusives, but do not intrude the sediments that presently surround them, perhaps indicating that they were exhumed and reburied. The older group of eruptive rocks, with a date of 3.88 ± 0.04 Ma (Love and others, 1994) consists of a lower alkalic to calc-alkalic trachyandesite-andesite-dacite flow, vent-related agglomerate, and overlying flows. The younger volcano consists of at least three vents and four lava flows of trachyandesites. The lowest of the younger flows has an Ar/Ar date of 1.22 ± 0.01 Ma (Love and others, 1994).

El Cerro de Los Lunas and sediments adjacent to it have undergone multiple stages of deformation, including folding, thrusting, normal faulting, and uplift. The older volcanic pile is tilted southward, has been cut by numerous faults, and is partially buried by later sediments. The basal flow of the younger volcano has a fault offset of at least 30 m, and the western part of the flow and underlying sediments has been raised 150 m above the rest of the landscape. Angular unconformities in basin-fill sediments exposed on the north side of the volcano may be related to deformation during emplacement of magma. The lowest exposed sediments are vertical and may have been tilted during the older eruptions. The overlying sediments are tilted northwestward up to 15 degrees by trap-door uplift during and after the eruption of the younger volcano. Tephra from the younger eruptions is folded and thrusted (northwest vergence) and then buried by debris shed from the uplifted portion of the volcano.

Post-volcano sediments include a large alluvial apron (as much as 50 m thick) on the west side of Los Lunas volcano, eolian deposits and soils of the Llano de Albuquerque, the flood plain of the Rio Grande, valley border alluvial and eolian sediments and soils descending from the Llano de Albuquerque to the modern Rio Grande flood plain, and a Rio Grande terrace known as the Los Duranes Formation.

A combination of erosion of unconsolidated sediments over lavas, local faulting and tilting, and incision of the Rio Grande Valley has caused abnormal stream courses in the southwestern and southern sides of El Cerro de Los Lunas. One meandering stream, following a tilted sediment/lava contact, has entrenched a succession of subparallel courses in lava that were abandoned as the badland-lava interface eroded lower than the stream course through lava. The stream has cut two short slot canyons 1-4 m wide and as much as 7 m deep. Its former course also was affected by faults, including a small graben that caused a right-angle turn.

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Geology of the Loma Machete Quadrangle, Albuquerque-Rio Rancho Metropolitan Area, New Mexico

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The Loma Machete 7.5-minute quadrangle underlies the northwestern corner of the rapidly expanding Albuquerque-Rio Rancho metropolitan area. This area is located in the northern part of the Albuquerque Basin, which is one of the largest grabens within the Rio Grande Rift system. All of the map area is underlain by rift-related, poorly consolidated sedimentary rocks of the Santa Fe Group. Recently completed geologic mapping and analysis of high-resolution aeromagnetic data (U.S. Geological Survey and SIAL Geosciences, Inc., 1997) add significant structural and stratigraphic details to previous small-scale reconnaissance mapping (Bryan and McCann, 1937; Spiegel, 1961; Kelley, 1977) of this part of the basin.

The best bedrock exposures are in the badlands of the Rincones de Zia at the northern margin of the quadrangle. The oldest rocks exposed here are light-gray eolian sandstone and brown fluvial sandstone, siltstone, and claystone that we correlate with the Red Member of the Santa Fe Group of Spiegel (1961) and the ash-rich middle part of the proposed Cerro Conejo Member of the Zia Formation of Connell and others (in press). These rocks, in both the Loma Machete quadrangle and Bernalillo NW quadrangle to the north, contain thick ash beds with chemical fingerprints that suggest correlation with rhyolitic tephras erupted approximately 11 million years (Ma) ago from the Snake River Plain in southern Idaho (A. Sarna-Wojcicki, U.S. Geological Survey, written communs., 1997-98). The oldest rocks are restricted to exposures in the Ziana Horst, a fault-bounded block that underlies Loma Machete. On the west side of the horst, yellowish-brown, fluvial sandstone and siltstone are in fault contact with our oldest unit; these younger rocks probably are correlative with the proposed Navajo Draw Member of the Arroyo Ojito Formation of Connell and others (in press). The yellowish-brown rocks in turn are conformably(?) overlain by reddish-brown, fluvial sandstone, siltstone, and claystone that we correlate with the proposed Santa Ana Member of the Arroyo Ojito Formation of Connell and others (in press).

Younger bedrock units exposed in the southern and northern parts of the quadrangle probably correlate with the upper Santa Fe Group. These rocks consist of a lower unit of light-gray to pale-brown sandstone, less common siltstone, and a basal pebble and cobble conglomerate. The upper unit primarily consists of light-gray sandstone and pebble, cobble, and boulder conglomerate. We correlate these units with the upper part of the Upper Buff Member of the Santa Fe Formation of Bryan and McCann (1937), the upper part of the Ceja Member of the Santa Fe Formation of Kelley (1977), and the proposed Ceja Member of the Arrojo Ojito Formation of Connell and others (in press).

Much of the map area is covered by large expanses of eolian sand and sandy alluvium associated with several large arroyo systems that drain southeasterly across the quadrangle. These deposits are especially prevalent in the central part of the map area, where they cover most of the underlying bedrock. A few deposits of main-stem Rio Grande alluvium are present along the

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southeastern margin of the map area. These fluvial deposits probably correlate with alluvium underlying the middle Pleistocene Tercero Alto terrace (Bachman and Machette, 1977). Remnants of the oldest geomorphic surface in the map area, the Llano de Albuquerque, dominate the landscape in the southwestern part of the quadrangle. This surface is characterized by extensive (stage IV) calcic soil development.

As might be expected, the structural fabric of the Loma Machete quadrangle is dominated by generally north-trending, east- and west-dipping normal faults associated with Neogene east-west extension of the Rio Grande Rift. These structures are especially well exposed in the Rincones de Zia in the northern part of the quadrangle, where they typically have throws of a few tens of meters in upper Santa Fe Group rocks. We also map several short east-trending normal faults in bedrock. Some authors (for example, Hawley, 1996) portray these latter faults as parts of basin-scale strike-slip transfer or accommodation zones. However, our mapping and analysis of aeromagnetic data show that almost all east-trending faults in the quadrangle are short, have very small displacements, and in rare cases expose slip indicators that show predominantly normal slip. We conclude that in most cases, east-trending faults are small-scale transfer or connecting faults in en echelon normal fault zones.

The most prominent structure shown on previous geologic maps of the area (for example, Kelley, 1977) is the Ziana Anticline, a 20- to 30-kilometer-long south-plunging fold that was apparently the target of the Shell Oil Company Santa Fe Pacific 1 test well. Our mapping of Santa Fe Group rocks in the Rincones de Zia shows no consistent evidence of pervasive folding of Santa Fe Group rocks in this region but rather identifies numerous horsts and grabens and a series of tilted fault blocks that dip into these bounding faults. Our interpretation is that the prominent gravity high associated with the Ziana Anticline is caused by the presence of the Ziana Horst, which must be underlain at depth by higher density basement rocks. Thus our mapping and interpretations are consistent with the original interpretation of the gravity high as an uplifted fault block (Joesting and others, 1961) rather than as a fold whose geometry is more difficult to explain in a rifting environment.

Numerous normal faults in the Loma Machete quadrangle offset upper Santa Fe Group rocks. Given the uncertainty in the age of these deposits, some of these faults probably have undergone Quaternary movement (Machette and others, 1998). However, with a few exceptions, most of these faults do not appear to offset middle Pleistocene or younger deposits or geomorphic surfaces, and thus probably have not been active since the early Pleistocene. Examples of such possible early Quaternary structures are the numerous faults near Picuda Peak and Loma Barbon in the northern part of the quadrangle and two faults that offset upper Santa Fe Group sedimentary rocks on Loma Colorado de Abajo. Evidence of Quaternary displacement is more clearly demonstrated on several faults in the southern part of the quadrangle. At least three normal faults in the neighborhood of Star Heights offset upper Santa Fe Group rocks and younger Quaternary sediments. Perhaps the youngest fault movements in the quadrangle occurred on the East Paradise Fault Zone, which has undergone multiple displacements in the late Quaternary (Machette and others, 1998). All these Quaternary faults are important because they have the potential for producing rare, large-magnitude earthquakes that could cause extensive damage in the cities of Albuquerque and Rio Rancho.

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Subsurface Geology of the Albuquerque Volcanoes and Llano de Albuquerque Area, New Mexico, Based on Geologic Mapping, Airborne and Ground Geophysics, and Limited Subsurface Information

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Geophysical investigations and geologic mapping, combined with limited subsurface information from water wells, are used to improve models for ground-water underflow, in an area west of Albuquerque where subsurface information is sparse. The main aquifers are sand and gravel deposits of the Miocene and younger Santa Fe Group within the Rio Grande tectonic rift.

Geologic mapping in the Albuquerque Volcanoes and the Llano de Albuquerque area provides stratigraphic, structural, and age constraints for Santa Fe lithologic units that control the regional hydrogeologic framework of the western Albuquerque Basin. These allow extrapolation of subsurface data from wells and from airborne and surface geophysics across much larger areas.

Electromagnetic methods are used to examine the electrical resistivity of the subsurface. Resistivities of unaltered igneous rocks are generally high. Fracture zones and faults that contain clays or water reduce the resistivity. Resistivities of unconsolidated sediments are primarily determined by rock porosity, the electrical resistivity of the pore fluid, and the presence of electrically conductive minerals, such as clays. In the Albuquerque area, experience has shown that the axial channel sand and gravel deposits of the Rio Grande, which are the main aquifers in the Middle Rio Grande Basin, are more resistive than surrounding finer grained silt and clay-rich materials. The audio-magnetotelluric (AMT) method delineates subsurface geological structures, igneous bodies, and facies changes within the Santa Fe Group aquifer system based on resistivity contrasts between the different rock units. Two subparallel east-west AMT profiles, the Llano de Albuquerque (LA) and the Albuquerque Volcanoes (AV), were conducted in the summers of 1997 (Deszcz-Pan and others, 1998) and 1998 (fig. 8).

On the western half of the LA profile, silt or possible mudstone units likely are responsible for the low resistivities at depths of about 100 meters (m) and greater. These low resistivity zones in the center of the LA profile appear downdropped by faulting to depths of about 350 m. Relatively higher resistivity values in the eastern part of the LA profile may correspond to axial sand and gravel deposits of the ancestral Rio Grande. The change from very low resistivities (silty or possibly shaley units) on the west to somewhat higher resistivities (probably sand and gravel) on the east occurs near the West Paradise Fault. This profile suggests the western limit of axial sand and gravel deposits of the ancestral Rio Grande as near the West Paradise Fault.

On the western half of the AV profile, sandy silt or possible mudstone units, overlain by more resistive sand and gravel, likely are responsible for the low resistivities at depths of about 100 m near the center of the profile. These fine-grained units appear to be downdropped to about 250 m

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depth on the western end of the profile along a splay of the Sand Hill Fault, which is also observed on the aeromagnetic data. An anomalously high-resistivity body in the central-western part of the profile, which is also observed as a high-amplitude, circular positive magnetic anomaly adjacent to the south, is inferred to be a buried basalt intrusive center or volcano. On the eastern half of the AV profile, moderate resistivity values in the upper 200 m correspond to fractured basalt of the Albuquerque Volcanoes. Very high resistivity values at depths from 5 to 1,000 m correspond to basalt vents of the Albuquerque Volcanoes. One inferred fault adjacent to and dissecting the basalt vents is very conductive, indicating high clay content, high salinity fluids, or elevated temperatures. Another inferred fault adjacent to and dissecting the basalt vents is less conductive, indicating lower clay content, lower salinity fluids, or lower temperatures.

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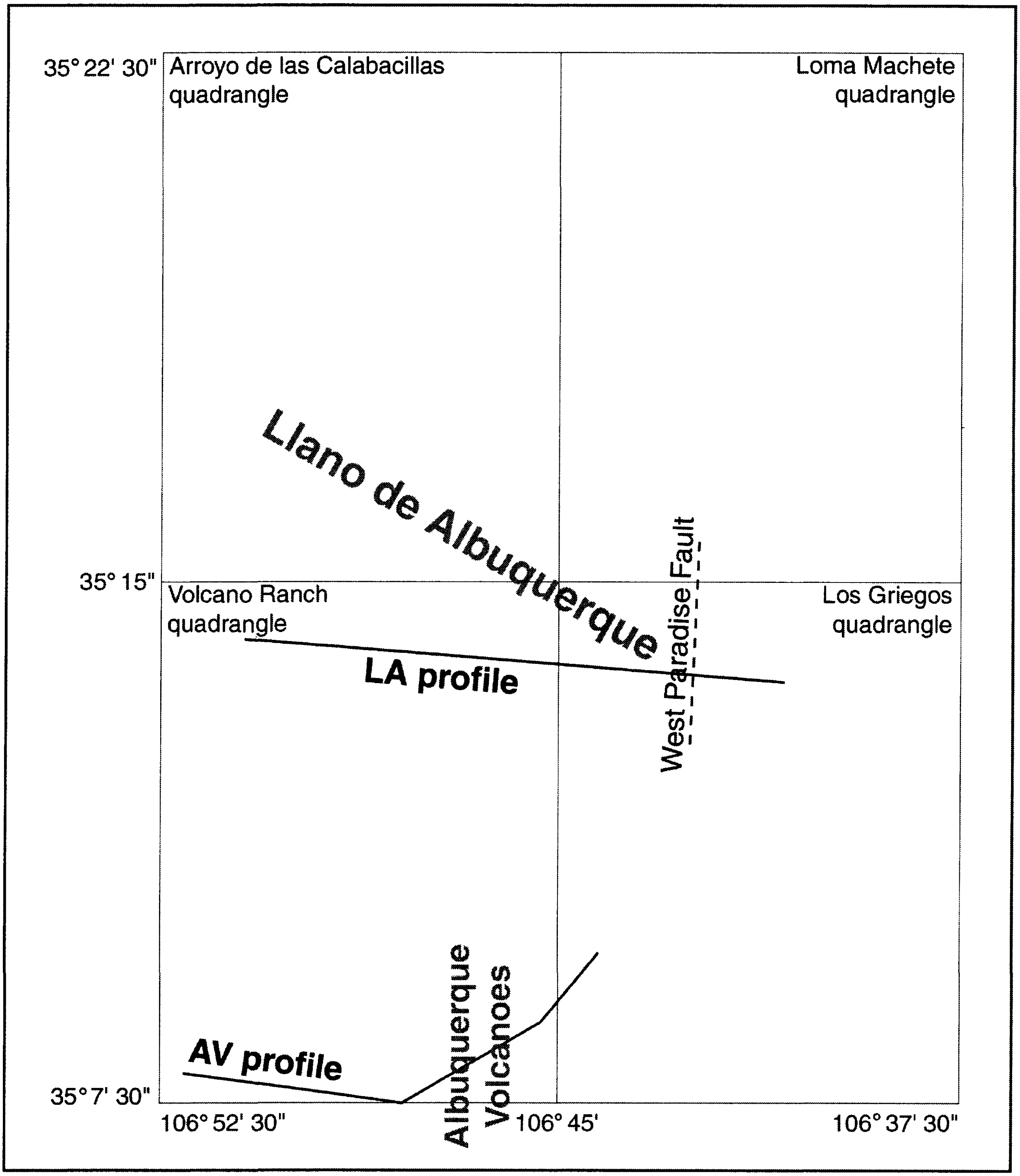

Figure 8.—Index map to audio-magnetotelluric profiles (LA and AV) acquired in the summers of 1997 and 1998 west of Albuquerque, New Mexico.

Chronostratigraphic Support to the Middle Rio Grande Basin Project from Regional Tephrochronologic Studies

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We provide chronostratigraphic support to the Middle Rio Grande Basin (MRGB) Project by analyzing tephra layers (ash beds and tuffs) and disseminated lenses or zones of pumice and ash found in the sediments. New samples of tephra layers are examined for mineralogy and shard morphology, and the volcanic glass is separated from these for chemical analysis by electron-microprobe (EMA).

The chemical compositions of new samples are then compared to those of "known" samples, and matches are made on the basis of chemical similarity. This provides two types of information:

1. Correlation within the MRGB study area, to show age equivalence of mapped stratigraphic units; and

2. Correlation of new samples found in the MRGB to dated tephra layers outside the region, which provides correlated ages to the mapped units.

The work can be divided into two main tasks:

1. MRGB mappers sample tephra layers, ashy, pumiceous, or tuffaceous zones, or other white layers and lenses in the field, which they send to us. Some of these samples turn out to be diatomite, carbonate (caliche or marl), an altered tephra layer, or sediment with only a percent or two of volcanic shards. We analyze the tephra samples that have isotropic glass. After analyzing the tephra, we sometimes discover that the sample was indeed altered even though it looked satisfactory under the microscope or that the sample does not match any tephra layer in our database. More often, however, we get a good match with a known tephra layer or even with a tephra layer that has been reasonable well dated.

2. We are conducting source studies in the Jemez Mountains and surrounding area, in order to provide a better basis for comparison and dating of the MRGB tephra samples. We are concentrating on major silicic ash flows and extensive pumice falls that contain abundant volcanic glass as the dominant phase that would likely have been transported by wind or water south to the MRGB.

In the case of lenses of ash or pumice in the MRGB, rather than air-fall layers, we assume that these volcaniclastic deposits were laid down very soon after the eruption of the tephra. At worst, matches to tephra dated elsewhere represent maximum ages for the units containing the tephra.

We have identified some well-dated, widespread tephra layers in the MRGB. One of these is the Lava Creek B ash bed, which is about 665 thousand years (ka), according to one recent redating of this unit by laser-fusion $^{40}Ar/^{39}Ar$ (Izett and others, 1992). The Lava Creek B ash bed is one of

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the most extensive stratigraphic markers in the western and central U.S. It was erupted from the Yellowstone area of Wyoming. Samples of the Lava Creek B ash bed are found in one of the higher stream terraces in the Española Basin, north of the Jemez Mountains, and in the La Mesita Negra quadrangle.

Several samples of tephra, mostly reworked pumice and ashy intervals in Quaternary alluvium of the Los Lunas area, match well or reasonably well with the Tsankawi and Guaje Pumice beds, but there is some scatter in the data. This may result from a range of compositions that are present in the plinian and ash-flow phases of these extensive volcanic units of the Jemez Mountains. Our current work in the source area is an attempt to better define the compositional ranges of the proximal material. The age of the Tsankawi and Guaje Pumice Beds are approximately 1.2 and 1.5 million years (Ma), respectively.

Other units we have identified in the area between the Jemez Mountains and the MRGB, are the air-fall pumice of the San Diego Canyon Ignimbrite, and the Nomlaki Tuff. The former is approximately 1.8 Ma (Spell and others, 1990). The Nomlaki Tuff was erupted from the southern Cascade Range in northern California. The Nomlaki Tuff is a widespread ash-flow, pumice-fall, and ash bed that has been found in California, Nevada, and Idaho. In California we find the unit in Death Valley, and in Nevada in the Willow Wash and Amargosa Valley areas (Reheis and others, 1991). This tuff is approximately 3.3 Ma. In the MRGB area, Sean Connell finds the (very) distal correlative of this ash bed in the proposed Pantadeleon Member of the uppermost Arroyo Ojito Formation.

We also have identified several upper Miocene units, some of which have been erupted from the Snake River Plain area (for example, from the Juneau-Jarbridge volcanic source area in Idaho). These are "Yellowstone-like" tephra layers, chemically similar to the younger Lava Creek B and Huckleberry Ridge ash beds erupted from the Yellowstone area, but considerably older and derived from sources to the west of Yellowstone National Park. Our tentative assignments are to a layer dated 12.1 Ma, a layer from the Trapper Creek section of Idaho (Perkins and others, 1998). Samples that match this unit are: SPT8/26/97-1, MRGB-7-LM, and DLS-100_12.4.98. These samples are from the lower Santa Fe Group, including the Zia Formation. We need to do more work, possibly by instrument neutron activation analysis (INAA) or the ion probe, to determine the best matches for these because two other close candidates from the Trapper Creek section match almost equally as well—one 11.3 Ma, and another 10.9 Ma.

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Hydrogeologic Barriers to Regional Ground-Water Flow into the Albuquerque and Santo Domingo Basins, North-Central New Mexico

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The Santa Fe Group aquifer system in the Albuquerque and Santo Domingo Basins is mainly bounded both east and west by thick sequences of low-permeability Cretaceous sedimentary rock or by Precambrian crystalline rocks of the Sangre de Cristo, Sandia, and Manzano Mountains. In developing a three-dimensional hydrogeologic model for the Middle Rio Grande area, these boundary conditions for the unconsolidated Santa Fe Group sand and gravel aquifers are important because:

1. They delimit where the ground-water basin may be hydraulically connected to late Pleistocene (120 thousand years (ka)) and Holocene (10 ka) surface-water recharge by the Rio Grande and its tributaries;

2. The lateral extents of low-permeability rock (hydrogeologic barriers) on the east and west sides of the Santa Fe Group aquifer system delineate where ground-water recharge by underflow from adjoining ground-water basins is unlikely;

3. The distribution of thick, fine-grained Oligocene volcaniclastic sediments (for example, the unit of Isleta 2 of Lozinsky, 1988) above the Galisteo and Baca Formations in the northern Albuquerque and Belen Subbasins form a basal confining-unit boundary layer beneath the unconsolidated Santa Fe Group sand and gravel aquifer. These fine-grained volcaniclastic clayey siltstones, mudstones, and silty sandstones form an effective confining unit to upward vertical flow; and

4. There is low lateral connectivity of aquifers from the bedrock margins through lower permeability early and middle Santa Fe Group sediments to the east-central Santa Fe sand and gravel aquifers.

Kilometer-thick sequences of Cretaceous marine shale (Mancos Shale) and intertonguing coal-bearing marginal marine sequences (Mesaverde Group and Crevasse Canyon Formation) flank the Albuquerque Basin to the west and the Santo Domingo Basin to the east and southeast. These shale units constitute lateral confining area or "aquitard" barriers to regional ground-water underflow and recharge of Santa Fe Group rift-axis fluvial sand and gravel aquifers. The impermeable hydraulic characteristics of the Mancos Shale (Frenzel and Lyford, 1982; Kernodle, 1996), its great thickness (commonly 670-760 meters (m)), and the lack of continuity of minor sand aquifers cause the Mancos to strongly limit ground-water flow from adjoining basins into the Rio Grande Rift. Widespread occurrence of Cretaceous petroleum fluids confined within the Mancos in the San Juan Basin indicate minimal flushing by freshwater over a time scale of tens of millions of years. Similar occurrences of petroleum fluids in the Mancos have been documented in the Hagan/southern Espanola Basin, and in the northern and southern Albuquerque subbasins (Black, 1979; 1982). Thickness of the Mesaverde Group ranges from 240 to 460 m, and its hydrology is dominated by mudstones and discontinuous channel sands of the Menefee Formation. Significant fresh ground water (in amounts suitable for irrigation or

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municipal use) within the combined Mancos-Mesaverde aquitard is extremely limited. Minor low-transmissivity sandstones within the Mancos, such as the Gallup Sandstone (south of its pinch-out), the discontinuous members of the Dakota Sandstone (Hunt, 1936), and even lesser sands (in the Menefee, Point Lookout Sandstone, and Hosta/Dalton Sandstone) are the only Cretaceous aquifer units.

East of the Santo Domingo Basin, outward-tilted kilometer-thick sequences of Mancos Shale and Mesaverde Group confining units lie between the more permeable Morrison Formation and Galisteo Formation aquifers. The hydraulic properties and east-northeast tilts of Mancos-Mesaverde sequences in the Santa Fe Embayment, Cerrillos Uplift, and Galisteo Monocline form effective barriers to ground-water-underflow recharge into the Santo Domingo Basin south of Tetilla Peak. Oligocene intrusions penetrate the Mancos-Mesaverde aquitard in the Cerrillos Hills and Ortiz Mountains and probably further decrease hydraulic conductivity in southern Santa Fe County. Uplifted Precambrian crystalline rocks in the Sandia and Manzano Mountains restrict ground-water underflow to narrow "recharge windows" (Hawley, 1996) such as the gap north of the Hagan Basin (between the San Francisco and La Bajada Faults), and where the Santa Fe Group aquifer system is in contact with Madera Limestone and Morrison Formation aquifers.

The west side of the Albuquerque Basin is bounded by the Mancos Shale and Crevasse Canyon Formation from San Ysidro to the confluence of the Rio San Jose and Rio Puerco, 13 kilometers (km) south of Interstate 40. The Cretaceous units in the upper km along this 70-km strip are principally mudstone and thin sandstones between the Dakota and Crevasse Canyon or Menefee Formations. These lithologies are offset by structures of the Rio Puerco Fault Zone and the Apache Graben (Campbell, 1967) as well as by the rift-bounding Sand Hill Fault. The net effect of these faults is to step the Cretaceous Mancos-Mesaverde aquitard downward to the east into the rift.

The Rio Puerco also transects this strike belt of erodable Cretaceous mudstones and is probably isolated from the Santa Fe Group aquifer system to the east beneath the Llano de Albuquerque. Fault offsets of 100-300 m across the Rio Puerco Fault Zone, and greater than a km on the Sand Hill Fault, make ground-water underflow into the Albuquerque Basin unlikely from bedrock aquifers to the northwest. Principal bedrock aquifers west of the Rio Puerco are the Morrison Formation and minor sands within the Mancos; sandstones in the Mancos are not continuous beneath the Rio Puerco, and Morrison aquifers are juxtaposed against the Mancos by the Apache Graben and the Sand Hill Fault. These factors cause regional aquifer recharge from the Sierra Nacimiento and Mount Taylor highlands to contribute negligible underflow recharge into the Albuquerque Basin from the northwest and west. Recharge by underflow into the Santa Fe Group from Paleozoic carbonate aquifers could be locally significant east of the Sierra Nacimiento.

In addition to the limited water availability in the Cretaceous and Jurassic sedimentary rocks, significant problems exist with water quality in the Mesozoic rocks. Water wells completed in the Mesozoic rocks generally penetrate water having 2,000 to greater than 10,000 parts per million dissolved solids; locally recharged freshwater aquifers are rare. The effect of the Mesozoic rocks on water quality may extend into the Santa Fe Group in the western part of the Albuquerque Basin. Sediment derived from Cretaceous San Juan Basin rocks in the western side of the Santa Fe aquifer system may explain: (1) high sodium sulfate concentrations from gypsum dissolution and Ca-Na ionic exchange by clays (Anderholm, 1988, p. 94, fig. 27) and (2) high clay and silt contents causing lower permeability in some western Albuquerque Basin wells (Bjorklund and Maxwell, 1961, p. 39).

Considering these boundaries, ground-water underflow into the Santo Domingo and northern Albuquerque Basins likely occurs through only a few pathways. Principal tributary ground-water underflow into the Albuquerque is from Rio Grande Rift basin-fill sedimentary aquifers immediately upgradient. These are the Santa Fe Group sand and gravel aquifer hydraulically connected to the Rio Grande and flowing south through the La Bajada constriction of Kelley (1952). Other aquifer systems that contribute significant tributary interbasin ground-water underflow are: (1) volcanic and coarse-grained volcaniclastic (Cochiti Formation) aquifers along the Jemez Mountains west of the Santo Domingo and north of the Albuquerque Basins and (2) Paleozoic carbonate aquifers that flow north from the Sandias and the Hagan Basin, from the eastern Sierra Nacimiento, and from Mesa Lucero.

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Geology of Santo Domingo Pueblo and Santo Domingo Pueblo SW Quadrangles, New Mexico

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This abstract summarizes the principal geological findings of STATEMAP mapping of the Santo Domingo Pueblo (Smith and Kuhle, 1999a) and Santo Domingo Pueblo SW (Smith and Kuhle, 1999b) quadrangles within the central Santo Domingo Basin of the Rio Grande Rift.

Age and Stratigraphic Relationships of Axial-Gravel Facies in the Upper Santa Fe Group

Quartzite-rich, ancestral Rio Grande gravel is interbedded with the upper Miocene Cochiti Formation and Peralta Tuff Member of the Bearheard Rhyolite. Axial gravel likely persists to depths of approximately 500 meters (m) and is at least as old as approximately 7 million years (Ma) (Smith and Kuhle, 1998). Deposition persisted east of the present Rio Grande until sometime following eruption of the lower Bandelier Tuff at approximately 1.61 Ma. These gravels extend at least 10 kilometers (km) west and 5 km east of the modern Rio Grande.

Age and Stratigraphic Relationships of the Cochiti Formation

Cochiti Formation volcaniclastic gravel and sand was deposited on Jemez Mountains piedmont slopes. Our mapping demonstrates that the revisions of Smith and Lavine (1996) permit consistent mapping of the Cochiti Formation with minor modifications (Smith and Kuhle, 1998). The Cochiti Formation is about 6.5 Ma at its base and locally includes the Otowi Member of the Bandelier Tuff, substantiating an earliest Pleistocene age for the youngest Cochiti Formation.

Volcanic Substrate to Cochiti Dam

Hydromagmatic tuff and basalt lava present at the base of Cochiti Dam and in cores suggest that the dam was constructed along a chain of tuff-ring craters and spatter cones, which were the source of lava flows dated at about 2.7 Ma. Criteria for recognizing hydromagmatic tuff were virtually unknown at the time of dam-foundation studies in the late 1960's, and these deposits were misidentified then as cemented conglomerate and sandstone within the Santa Fe Group. The consolidated deposits are probably less than 50 m thick and their limited lateral extent does not provide an impermeable base to the dam.

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Quaternary Terrace Stratigraphy

Four terrace gravels were mapped along the Rio Grande and correlated to terraces in tributary drainages, where a fifth (lowest) terrace is locally recognized. Elevation of terraces above the Rio Grande conforms generally with those recognized farther north by Dethier and McCoy (1993). All but the highest terrace are preserved only on the east side of the valley south of Cochiti Dam, suggesting net westward migration of the river since the middle Pleistocene. Qt_4 is overlain by approximately 60-thousand-year (ka) El Cajete Pumice, and Qt_1 terrace gravel contains the approximately 600-ka Lava Creek B tephra. Higher upland surficial deposits were also mapped, including lower Pleistocene sand underlying La Majada Mesa.

Delineation of Faults

A splay of the San Francisco Fault (Domingo Fault) extends into the map area but does not strike toward the Cochiti Fault as illustrated by Kelley (1977). The southern strand of the Pajarito Fault strikes toward the opposite-polarity Domingo Fault. Structural resolution of the confluence of the projections of the Cochiti, Domingo, and Pajarito Faults is obscured by Rio Grande alluvium. The Sile Fault uplifts upper Miocene strata in its footwall and, along with the Pajarito Fault, forms a prominent intrabasinal horst. The Camada Fault extends northward with the Peralta Fault as a major fault zone into the southern Jemez Mountains. Faults near Cochiti Dam are ill defined in outcrop but are constrained by correlations of the U.S. Army Corps of Engineers. The Pajarito, Camada, Domingo, and Cochiti Faults displace Quaternary strata, either the 1.61-Ma Otowi Member of the Bandelier Tuff or gravel containing pumice eroded from that tuff. There is no evidence for Quaternary motion on the Sile Fault or the faults near Cochiti Dam.

Significance of the Gravel of Lookout Park

Gravel cap remnants of a widespread erosion surface are found cut into upper Miocene and lower Pliocene rocks west of the Pajarito and Camada Faults. We informally name this allostratigraphic unit for superb outcrops of the gravel at Lookout Park (labeled on 1978, but not 1993, editions of the Cañada quadrangle) and have mapped it in the Santo Domingo Pueblo Southwest, Cañada, Loma Creston, and Bear Springs Peak quadrangles. The gravel generally occupies the highest landscape position except near Borrego Canyon where it is inset below 2.41-Ma basalt of Santa Ana Mesa and is disconformably overlain by the 1.61-Ma Otowi Member of the Bandelier Tuff. The upper Pliocene, unconformity-bounded gravel is correlative with some part of the continuous, conformable Miocene-lower Pleistocene Santa Fe Group in the eastern Santo Domingo Basin (Smith and Kuhle, 1998). Deposition was focused in the eastern basin during late Pliocene-early Pleistocene eastward tilting of the basin, and a hinge zone developed where aggrading streams merged westward with a broadly degrading landscape. Tectonic stability in the western basin is necessary for the widespread development of the sub-Lookout Park erosion surface and the lack of obvious thickness changes in the gravel across faults. The gravel has been subsequently faulted along intrabasinal faults and along basin bounding faults farther west in the Loma Creston quadrangle. These observations are consistent with a "see-saw" subsidence history for the Santo Domingo Basin (Smith and Kuhle, 1998).

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A Preliminary Evaluation of Metal Abundances and Associations in Drill Cuttings from Production Wells on the Western Side of Albuquerque, and Comparisons to 98th St. Core Samples

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Information concerning the composition of Santa Fe Group sediments at depths greater than about 100 meters (m) in the Middle Rio Grande Basin is limited and difficult or expensive to acquire. In an effort to expand current knowledge of element compositions and associations in Santa Fe Group sediments, drill cuttings recovered from production wells were evaluated as potential indicators of geochemical and/or stratigraphic differences within basin-fill sediments.

Archived drill cuttings from five production wells on the western side of Albuquerque (Soil Amendment Facility 1, Volcano Cliffs 3, Don 1, Leavitt 1, and Gonzales 1) and the Charles 5 well near central Albuquerque were leached using a standard technique (Briggs, 1990) followed by inductively coupled plasma-mass spectrometry (ICP-MS) analysis to determine metal abundances. The cuttings are composites that represent intervals ranging from 10 to several hundred feet; all except Gonzales 1 had been "washed" during recovery to remove drilling mud.

Metal abundances and associations from the cuttings were compared to "baseline" 98th St. core samples to determine whether cuttings provide adequate samples for examining metal associations in Santa Fe Group sediments. The 98th St. samples represent some of the most recent geochemical analyses available for deeper Santa Fe Group sediments. Data from the cuttings were also examined in light of recent stratigraphic and lithologic information to see if downhole trends (minima and maxima) in metal abundances, such as those present in 98th St. samples, could be discerned with depth at the other well locations.

Generally, metal associations in the cuttings were similar to those seen in 1-foot (ft) interval samples from 98th St. sediment cores, but regression analyses suggest these associations are not as strong as in the intact core samples. Similar to 98th St. samples, arsenic was most strongly associated with iron, cobalt, vanadium, and zinc, and weakly associated with elements such as calcium, manganese, strontium, and barium. For the relationship of arsenic with iron, cobalt, vanadium, and zinc, Gonzales 1 had high values of r (regression coefficient), which were similar to 98th St. samples (all less than or equal to 0.80). In other wells (for example, Volcano Cliffs 3), values of r for these relationships were low, ranging from 0.17 to 0.52. For other well cuttings, r values fell between these "endpoints." Thus, the relationships of arsenic to the four metals in drill cutting samples are inconsistent when compared to 98th St. core samples.

However, an important geochemical trend was revealed by the presence of elevated abundances of vanadium and zinc at the base, or near the base, of the tentatively identified Atrisco Formation (Connell and others, 1998). Despite different Atrisco Formation thicknesses and depths (relative to the land surface) at each well location, the base of the Atrisco Formation consistently exhibits increases in arsenic, iron, cobalt, vanadium, and zinc; similar increases were observed in the 98th St. core samples. Vanadium and zinc are 120 and 100 parts per million (ppm), respectively, in Gonzales 1 drill cuttings from the basal Atrisco Formation (1,370 ft); values from 98th St. are

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100 ppm vanadium and 70 ppm zinc at 25 ft above the base of the Atrisco Formation at approximately 780 ft.

Although not as large in magnitude as the vanadium and zinc anomalies, arsenic and cobalt, and in some cases iron, show similar increases in abundance at this stratigraphic horizon in both cuttings and 98th St samples. The higher levels of metals and arsenic in cuttings samples at the base of the Atrisco (compared to lower arsenic and metal levels above or below the base) suggest that the metal anomalies are not the result of contamination from drilling equipment.

Some characteristics of cuttings, such as variable grain-size distributions that may result from collection or washing; introduction of extraneous constituents such as barium in drilling muds; or a variable history of collection, handling, and preparation, require that caution be used in interpreting data from such samples. Also, an assumption was made that the sediment geochemical composition has remained constant (or has changed in a consistent manner) over time at each well location. Samples from 98th St. that were treated similarly to the cuttings are being analyzed to refine these comparisons. However, these preliminary results suggest that some drill cuttings may be useful complements to understanding the composition of Santa Fe Group sediments, especially when combined with more detailed sample analyses from nearby locations.

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GROUND-WATER RECHARGE

Mountain-Front Recharge Along the East Side of the Middle Rio Grande Basin, Central New Mexico

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Mountain-front recharge, which generally occurs along the margins of alluvial basins, can be a large part of total recharge to the aquifer system in such basins. Mountain-front recharge is infiltration of flow from streams that have headwaters in the mountainous areas adjacent to alluvial basins and ground-water flow from the aquifers in the mountainous areas to the aquifer in the alluvial basin. This study presents estimates of mountain-front recharge to the basin-fill aquifer along the eastern side of the Middle Rio Grande Basin in central New Mexico.

The Middle Rio Grande Basin is a structural feature in the arid Southwest that contains a large thickness of basin-fill deposits, which compose the main aquifer in the basin. The Middle Rio Grande Basin is bounded along the eastern side by mountains composed of Precambrian crystalline rocks and Paleozoic sedimentary rocks. Precipitation is much larger in the mountains than in the basin; many stream channels debouch from the mountainous area to the basin.

Chloride-balance and water-yield regression methods were used to estimate mountain-front recharge. The chloride-balance method was used to calculate a chloride balance on watersheds or several watersheds with similar characteristics in the mountainous area along the eastern side of the Middle Rio Grande Basin (subareas). The source of chloride to these subareas is bulk precipitation (wet and dry deposition). Chloride leaves these subareas as mountain-front recharge. The water-yield regression method was used to determine the streamflow from the mountainous subareas at the mountain front. This streamflow was assumed to be equal to mountain-front recharge because most of this streamflow infiltrates and recharges the basin-fill aquifer.

The total mountain-front recharge along the eastern side of the Middle Rio Grande Basin was about 11,000 acre-feet per year by the chloride-balance method and about 36,000 and 72,000 acre-feet per year by the two different water-yield regression equations used. There was a large range in the recharge estimates in a particular watershed or subarea using the different methods. Mountain-front recharge ranged from 0.7 to 21 percent of the total annual precipitation in the subareas (percent recharge). Some of the smallest values of percent recharge were in the subareas in the southern part of the Middle Rio Grande Basin, which have generally low elevations. The larger percent recharge values were from subareas with higher elevations.

With existing information, it is not possible to determine which of the mountain-front recharge estimates is most accurate and why there is such a discrepancy between the different estimates. The chloride-balance method underestimates recharge if the chloride concentration used in the calculations for precipitation is too small or the chloride concentration in recharge is too large. The water-yield regression method overestimates recharge if infiltration and evapotranspiration of runoff from summer thunderstorms are a significant component of total precipitation.

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Temperature Profiles of the Aquifer System Underlying the Rio Grande, Middle Rio Grande Basin, New Mexico—Third-Year Status

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An important gap in the understanding of the hydrology of the Middle Rio Grande Basin, central New Mexico, is the rate at which water from the Rio Grande recharges the Santa Fe Group aquifer system. Several methodologies, including the Glover-Balmer equation (Glover and Balmer, 1954), flood pulses (Pruitt and Bowser, 1994; Roark, 1998), channel permeameters (Gould, 1994), and numerical simulation (Kernodle and others, 1995) have been used to estimate the rate of recharge in the Middle Rio Grande Basin. In the work presented here, ground-water temperature profiles and ground-water levels beneath the Rio Grande were measured and modeled at four sites, leading to estimates of vertical ground-water flux between the river and underlying aquifer and of effective vertical hydraulic conductivity of the sediments underlying the river. The temperature measurement method is based on Lapham (1989), and the analysis is based on application of the heat and water transport model VS2DH (Healy and Ronan, 1996). VS2DH has been successfully used to estimate streambed fluxes at other locations (Ronan and others, 1998); a report describing the results of the study is currently (1999) in review.

Seven sets of nested piezometers were installed during July and August 1996 at four sites along the Rio Grande in the Albuquerque area, though only four of the piezometer nests were modeled. In downstream order, these four sites are (1) the Bernalillo site, upstream from the New Mexico State Highway 44 bridge in Bernalillo (BRN02); (2) the Corrales site, upstream from the Rio Rancho sewage treatment plant in Corrales (COR01); (3) the Paseo del Norte site, upstream from the Paseo del Norte bridge in Albuquerque (PDN01); and (4) the Rio Bravo site, upstream from the Rio Bravo bridge in Albuquerque (RBR01). All piezometers were completed in the inner-valley alluvium of the Santa Fe Group aquifer system. Ground-water levels and temperatures were measured in the four piezometer nests a total of seven times in the 24-month period between September 1996 and August 1998.

One-dimensional numerical simulations of the transport of heat and water in the subsurface were constructed for each piezometer nest using VS2DH. Model calibration was aided by the use of PEST (Watermark Numerical Computing, 1998), a model-independent computer program that uses nonlinear parameter estimation.

Modeled vertical ground-water flux for the BRN02 piezometer nest is downward (positive) for all but the October 1996 model period, and the average is 1.52×10^{-7} meters per second (m/s). Model results for the COR01 piezometer nest indicate an upward (negative) ground-water flux for all model periods except June 1998, and the average is -1.27×10^{-7} m/s. Modeled vertical ground-water flux for the PDN01 piezometer nest is downward for all six model periods, and the average is 6.25×10^{-7} m/s. For the RBR01 piezometer nest, vertical ground-water flux is downward for all model periods except June 1998, and the average is 2.27×10^{-7} m/s. Vertical hydraulic conductivities predicted by the models range from 2.1×10^{-6} to 6.6×10^{-5} m/s.

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Comparison of the modeled vertical fluxes and vertical hydraulic conductivities from this study with values from other investigations in the Middle Rio Grande Basin indicate broad agreement. For example, when compared with the results of Gould (1994), flux rates for the Paseo del Norte area differ by approximately one order of magnitude, though flux rates in the Rio Bravo area are reversed between the two studies. A comparison of vertical hydraulic conductivities with the results of Pruitt and Bowser (1994) for two sites shows that the value obtained for this study for the Paseo del Norte piezometer nest is within their range and that the value for the Rio Bravo nest is within half an order of magnitude of their lower value. In their ground-water flow model, Kernodle and others (1995) used three values of vertical hydraulic conductivity that can be compared with values obtained for the inner-valley alluvium analyzed in this study: two areas of their model layer 2 and the riverbed. The difference between their values for vertical hydraulic conductivity in layer 2 and those from this study range from 1 to 2.5 orders of magnitude. Their value for riverbed vertical hydraulic conductivity can be compared with values for all four piezometer nests and is within 1.5 orders of magnitude for all four nests.

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Recharge Estimates Interpreted from Centrifuge Hydraulic Property Measurements of Core Samples from Abo Arroyo, Middle Rio Grande Basin, New Mexico

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Unsaturated hydraulic conductivity (K) was measured for 16 core samples taken in and adjacent to a 30-kilometer (km) reach of Abo Arroyo, and from these measurements recharge estimates were made at six locations within the arroyo and five locations at various distances away from the arroyo. Hydraulic properties, including unsaturated K, have been measured through application of the steady-state centrifuge method (SSCM), a laboratory technique that allows for K measurement over a wide range of water contents. Accurate K measurement can indicate long-term average recharge rates at locations from which core samples have been obtained, provided that the samples are from depths where soil-moisture fluctuations are negligible, implying that water flow is steady (Nimmo and others, 1994). If the matric pressure gradient is known, or if it can be assumed to be negligible so that flow is driven by gravity alone (unit gradient flow), the value of K at the field water content can indicate downward flux density (q). The SSCM is particularly well suited for the hydraulic property measurements because it gives accurate K values in the low-water-content range common at arid and semiarid sites (Nimmo and others, 1987).

Flux estimates of four core samples taken at various depths from a single borehole provide evidence for the depth at which steady-state flow can be assumed. Two of the single-borehole core samples taken at 0.4 and 0.5 meter (m) below the surface show very different flux estimates (60 and 470 centimeters per year (cm/yr)). These values also differ significantly from q estimates for two cores taken from the same borehole at 1.9 and 2.0 m below the surface (2,300 and 2,700 cm/yr). This variation with depth suggests that the two shallower samples are not deep enough to assume steady flow. However, the approximate equality of q estimates from the two samples taken at 1.9 and 2.0 m is consistent with the steady flow assumption. Measurements on two core samples from single boreholes at two other channel locations also give nearly equal q estimates at depths below 2 m (1,700 and 1,900 cm/yr, and 1 and 0.9 cm/yr, respectively), again consistent with the assumption of steady flow at these depths.

Results for cores taken at depths of 2 m or more give q estimates that range from 1 to 2,700 cm/yr within the active channel. Samples taken from the upper reach, where streamflow is present much of the year, give q estimates of 2,000 to 2,700 cm/yr, with the exception of a 1-cm/yr measurement several meters farther downchannel. Approximately 12 km downchannel, q is estimated to be 150 cm/yr, and roughly 8 km farther downchannel q is estimated to be 3 cm/yr, suggesting a marked decrease in recharge as one moves down the arroyo. Recharge then appears to increase again to nearly 2,000 cm/yr, 28 km downchannel, near the confluence of Abo Arroyo and the Rio Grande. Although recharge estimates are significant within the arroyo, samples taken outside the arroyo, at distances of 3.5 to 465 m, give q estimates of less than 0.013 cm/yr.

The high recharge rates in the upper reach of Abo Arroyo likely result from frequent flows in combination with generally large sediment size. The low recharge rate of 1 cm/yr near the upper

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reach of Abo Arroyo was measured on a core sample taken at a location where fine sediments have accumulated and is not generally representative of this portion of the arroyo with respect to physical soil properties. As a result, this core sample probably can be considered anomalous with respect to its hydraulic properties as well. The middle portion of Abo Arroyo has lower recharge likely due to less frequent flows and smaller sediment size. Surface sediments through this area also display a hard crust that may inhibit infiltration and promote more surface flow downchannel. The lower reach of Abo Arroyo has a high recharge rate similar to that for the upper reach. Factors that may contribute to increased recharge here include flow contributions from nearby tributaries, high permeability of loose sandy sediments at this location, and hydrologic influence of the Rio Grande because this part of Abo Arroyo lies within the modern flood plain of the Rio Grande. The significantly lower recharge estimates outside the arroyo are consistent with the expectation of nonfocused, areally diffuse recharge typical of interarroyo regions.

Results thus far indicate that the SSCM is useful for estimating recharge rates at specific locations in and adjacent to Abo Arroyo. Results suggest that recharge within Abo Arroyo is substantial (1 to 2,700 cm/yr), whereas recharge rates in the interarroyo region are very low (less than 0.013 cm/yr) and appear to drop off sharply outside the channel. Within Abo Arroyo, recharge appears to be variable along the entire reach. The upper and lower reaches appear to be areas of high recharge, and the middle portion of Abo Arroyo appears to have substantially lower recharge.

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Using Heat as a Tracer to Estimate Mountain-Front Recharge at Bear Canyon, Sandia Mountains, New Mexico

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Mountain-front recharge may be an important component of the total recharge to the aquifer system in the Albuquerque Basin (Bartolino, 1998). Heat is being used as a tracer to estimate recharge along a reach of Bear Canyon on the eastern edge of Albuquerque. Bear Canyon was selected as an example site representing approximately 100 mountain-front small ephemeral streams that recharge the basin from the Sandia and Manzano Mountains. These ephemeral streams range in length, but all possess the common characteristics of being bedrock-controlled in their upper, gaining reaches and alluvium-controlled in their lower, losing reaches. The study reach in Bear Canyon extends from the exposed bedrock at the mountain front downslope in a westward direction for about 3 kilometers (km). The stream is intermittent below the bedrock exposure at the mountain front, and rarely flows more than 2 km from the mountain front due to a limited source and rapid streambed infiltration. Vertical thermocouple nests were installed between 40 and 300 centimeters below the streambed at two sites about 1 and 1.5 km west of the mountain front to estimate streambed infiltration rates. By the use of a variably saturated heat and ground-water flow model, VS2DH (Healy and Ronan, 1996), to simulate the measured sediment temperatures, water flux was estimated for various times when flow was present in Bear Canyon. Thermal parameters for Bear Canyon sediments at residual moisture content were determined by matching the temperature signals when flow was absent, simulating heat conduction only. Combining optimal parameter estimation with the simulation modeling improves the model's match to the measured temperature signals, leading to more accurate streambed flux estimates. This method also provides a range in the flux estimate based on sediment thermal parameter uncertainty and a confidence interval on the flux estimate as a function of the simulated temperatures' sensitivity to the model's parameters. Modeling estimates of downward fluxes at the upper thermocouple site were 6.61 meters per day (m/day) for May 1997, 5.79 m/day for June 1997, 1.43 m/day April 1998, and 3.11 m/day for June 1998. At the lower site, flux estimates were 5.63 m/day for May 1997, 2.18 m/day for April 1998, 5.49 m/day for May 1998, and 2.61 m/day for June 1998. These results compare well with streambed percolation rates reported for Tijeras Arroyo, New Mexico, which is a larger stream at the seam between the Sandia and Manzano Mountains, less than 10 km south of Bear Canyon (Constantz and Thomas, 1996). These high percolation rates generally result in extinction of streamflow. Temporal variations in the flux rate at each site during the presence of flow were attributed to variations in stream stage and depth to the water table. Surface temperature probes were installed along the entire study reach to monitor the presence and duration of streamflow using a technique described by Stewart and Constantz (1998). Temperature probes indicated that flow was present in Bear Canyon between the months of April and June for 1997 and 1998. The cumulative wetted area available for streambed infiltration is being calculated from the surface temperature probes and streambed cross-sectional area surveys. These results in conjunction with the streambed-temperature-estimated fluxes will produce estimates of the annual potential recharge at Bear Canyon during the study period. Comparison of recharge results for the study reach at Bear Canyon will form the basis for a general estimate of mountain-front recharge from the Sandia and Manzano Mountains during the study period. The relative contribution of

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mountain-front recharge as a component of total basin recharge can then be developed for the basin.

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Developing a Long-Term Water Balance for Abo Arroyo, New Mexico

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In many arid and semiarid environments ephemeral streamflow represents the largest contributor of recharge to a ground-water basin (Keppel and Renard, 1962). Although the area of the stream channel is several orders of magnitude less than that of the vast interarroyo areas, the channel may be a primary source of potential recharge to the aquifer. Soil moisture in the interarroyo terrace material is often only significant in the top few feet of alluvium. Estimates of recharge from interarroyo areas suggest negligible recharge outside the channel (Lewis and Nimmo, 1998; Stonestrom and Akstin, 1998). To reliably estimate recharge from streams in arid environments, a quantitative characterization of ephemeral streamflow is needed, including an understanding of the temporal and spatial patterns of streamflow under a variety of hydrological conditions. Estimating long-term recharge from ephemeral streams requires an understanding of the stream-water/ground-water interactions in such environments. Abo Arroyo, located in the southeastern portion of the Middle Rio Grande Basin, has been selected as a representative large, dry arroyo. A 30-kilometer (km) reach of the arroyo is being utilized to develop a water balance for Abo Arroyo. The study reach runs east to west, from the mountain-front fault zone at the base of the Manzano and Los Piños Mountainst to its confluence with the Rio Grande.

The propagation of an ephemeral floodwave downchannel and the transmission loss into the streambed are dependent on a variety of parameters, including the upstream flood hydrograph, channel geometry and slope, streambed sediment permeability, water temperature, and antecedent channel moisture. The goal of this project is to develop a simulation model of streamflow and potential recharge based on measured parameters and historical streamflow records. Abo Arroyo is one of the primary sites for model development and testing.

Measurement of the spatial and temporal behavior of streamflow in ephemeral streams is extremely difficult. Stream discharge is often large and flashy, occurring over a short period of time. Therefore, the placement and stability of any measurement or monitoring equipment must be well thought out. Measurement of streamflow in Abo Arroyo is made at the bedrock mountain front by the USGS permanent gage (number 08331660). The presence or absence of streamflow is measured along the downstream reach utilizing temperature probes (single-channel waterproof data loggers with streambed surface temperature thermistors). Occurrence of streamflow in the arroyo results in a dramatically different temperature signal than when the streambed is dry. Use of the temperature probes allows tracking of the surface water through time. With knowledge of channel geometry, estimates of wetted surface area for the arroyo may be made at any given time for a given upstream hydrograph. Eight temperature probes have been installed along Abo Arroyo along with two benchmark probes on the interarroyo area near the channel to delineate air temperature changes from hydrological conditions.

Streambed heterogeneity, both across the channel and with depth, influences transmission loss of the floodwave. Ring infiltrometer measurements have been made along Abo Arroyo to better understand transverse and longitudinal variability in near-surface permeability. Results from the ring experiments suggest a gradual decrease in hydraulic conductivity from the upstream gage

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toward the Rio Grande. However, within a km of the Rio Grande, the arroyo conductivities increase due to predevelopment fluvial activity. These results have been corroborated by sediment textural analysis (D.A. Stonestrom and K.C. Akstin, U.S. Geological Survey, personal commun.). Transverse heterogeneity is important in determining the difference in infiltration rates across a specific arroyo cross section. A threefold difference in saturated hydraulic conductivity was measured along one transverse cross section at Abo Arroyo.

Vertical movement of ground water beneath the streambed has been measured utilizing heat as a tracer (Constantz and Thomas, 1996). Two thermocouple nests were installed in the upper reaches of the arroyo in 1996-97 and removed in October 1998. The thermocouples continuously measured the subsurface vertical temperature profile. The computer code VS2DH (Healy and Ronan, 1996) computes heat and water movement through the subsurface. VS2DH may be calibrated with data obtained from the thermocouples. This procedure allows computation of flux direction and magnitude through the sediment (Ronan and others, 1998); through optimization and model calibration thermal and hydraulic characteristics of the sediment may also be inferred.

Characterization of the hydrologic and geomorphic setting at Abo Arroyo will aid in the development of a coupled surface-water/ground-water ephemeral flow model. This model will be used in the estimation of recharge from Abo Arroyo flows.

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Comparison of Methods to Determine Infiltration and Percolation Rates Along a Reach of the Santa Fe River Near La Bajada, New Mexico

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Two methods, one a surface-water method and the second a ground-water method, were used to determine infiltration and percolation rates along a 2.5-kilometer reach of the Santa Fe River near La Bajada, New Mexico. The surface-water method employs standard stream-gaging and seepage-measurement techniques; the ground-water method uses heat as a tracer to monitor infiltration into the shallow streambed. Data collection began in September 1996 and continued through December 1997. During that period the stream reach was instrumented with three streamflow gages and temperature profiles were monitored from the sediment-water interface to about 300 centimeters below the streambed at four sites along the reach.

The surface-water method yielded infiltration-rate estimates that ranged from 92 to 270 millimeters per day (mm/day) for an intense measurement period for June 26-28, 1997, and from 72 to 260 mm/day for September 27-October 6, 1997. Investigators calculated infiltration-rate estimates from current-meter, streamflow measurements; stream-surface-area measurements; and evaporation-rate estimates. Infiltration accounted for about 94 to 99 percent of streamflow loss. Evaporation-rate estimates ranged from 3 to 6 mm/day based on data collected for a similar study (Thomas, 1995) and accounted for about 1 to 6 percent of streamflow loss.

The ground-water method yielded infiltration-rate estimates that ranged from 43 to 108 mm/day for June 26-28, 1997. Infiltration rates were not estimated for the September 27-October 6, 1997, period because a late summer flood removed the temperature sensors from the streambed. Investigators used a heat-and-water flow model VS2DH (variably saturated, two-dimensional heat) developed by Healy and Ronan (1996) to calculate near-surface streambed infiltration and percolation rates from temperatures measured in the stream and streambed.

The surface-water, streamflow-loss method gave greater infiltration rates than the ground-water, heat-and-water transport method. The surface-water method accounts for loss over the entire stream reach, whereas the ground-water method is dependent on point measurements. Also, the ground-water method neglects the nonvertical component of heat and water fluxes, so the method may underestimate infiltration.

The use of stream-stage relations to determine streamflow losses outside the period of record when seepage runs are used as a rating tool proved to be too inaccurate because the difference in flows between stations was of the same magnitude as errors from the stream-stage relation. To use stream-stage relations, the flow loss between any two measurement points may need to be greater than 10-15 percent, which is the estimated error for records rated good to fair (Ortiz and others, 1998, p. 15).

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In general, the ground-water, heat-and-water transport method may be preferred over the surface-water method when the nonvertical component of heat-and-water transport is insignificant. The ground-water method has several advantages: it is less labor intensive than seepage measurements and relies on temperature, an easily measured property. Temperature measurements can be collected frequently through the use of a data logger. The ground-water method also eliminates the difficulty of measuring or estimating evaporation from the water surface, and is therefore, a more direct method.

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GROUND-WATER FLOW SYSTEM

Historical Summary of U.S. Geological Survey Ground-Water Flow Models in the Albuquerque Basin

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The USGS has developed several mathematical ground-water flow models of the Albuquerque Basin during the last four decades. Although other investigators have developed models as well, this abstract focuses on the USGS models. The term "model" can be applied to many types of representations of a physical system. This discussion is limited to mathematical representations of the basin-scale ground-water flow system.

A mathematical ground-water flow model of an aquifer system is a combination of the equations (computer code or model code in the case of a numerical model) or rules that control the operation of the model and the numerical values that describe the hydrologic characteristics of the physical system. Prior to the availability of digital computers, mathematical models were limited to simplified representations of aquifer systems so that the mathematical equations could be solved manually with direct analytical solutions. This generally limited the model to one or two dimensions with uniform aquifer hydrologic characteristics and idealized boundary conditions. With the availability of digital computers, numerical methods can be used to closely approximate solutions to the differential ground-water flow equation (Pinder and Bredehoeft, 1968) in as many as three dimensions. This allows including the complexity of the three-dimensional variation in boundary conditions and aquifer hydrologic characteristics throughout the aquifer system. In addition, digital computers allow numerical models to be run many times so that a model can be calibrated--that is, values of simulated aquifer and recharge characteristics can be adjusted to better match historical observations.

Using analytical methods, Reeder and others (1967) provided the first basin-scale mathematical model of the Albuquerque Basin. The objectives of this model were to calculate the effects of ground-water withdrawals in the vicinity of Albuquerque on water-level declines in the aquifer and on flow in the Rio Grande. The analytical methods required a two-dimensional representation of the aquifer system. The model area extended from the Jemez River on the north to the southern Bernalillo County line on the south, and from just east of the Rio Puerco on the west to the base of the Sandia Mountains on the east. The sides of the model were represented as impermeable boundaries, and the Rio Grande was represented as a recharge boundary. Image-well theory was used to calculate the effects of these boundaries. The recharge boundary of the Rio Grande divided the model into two isolated pieces, where ground-water withdrawal on one side of the river could not affect the calculated drawdown in water levels on the opposite side of the river, and drawdown remained zero at that boundary. Aquifer hydrologic characteristics were based on information from Bjorklund and Maxwell (1961) and were assumed to be uniform for each side of the Rio Grande.

The model area was divided into blocks one-quarter township (9 square miles) in size, in which the average ground-water withdrawal for each decade between 1920 and 2000 (projected withdrawal from 1960 to 2000) was summed to form pumping centers. Using time-distance-drawdown relations (Theis, 1935) and using image-well theory for the boundaries, Reeder and

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others (1967) calculated drawdown in 10-year increments (to 2000) resulting from the incremental increase in withdrawal rate for each decade at each pumping center. The drawdown resulting from each pumping center, calculated at designated drawdown points throughout the area, was summed to calculate the total drawdown from all pumping centers. Reeder and others (1967) also calculated the amount of ground-water withdrawal that was derived from the Rio Grande from each pumping center for each decade. They then summed the amounts for each decade to calculate the total percentage of pumping derived from the river.

Kernodle and Scott (1986; steady-state model) and Kernodle and others (1987; transient model) constructed a three-dimensional numerical ground-water flow model of the part of the Albuquerque Basin from near the Jemez River on the north to San Acacia on the south. The model simulated the 1907-79 period. The objectives of the model were to simulate the effects of ground-water withdrawal on water levels in the aquifer and on the Rio Grande flood-plain ground- and surface-water system. The model area was divided by a grid containing 41 rows and 65 columns. The grid spacing varied from 0.5 mile (mi) on a side near Albuquerque to 3 mi by 6 mi at the southwest basin margin. The vertical dimension of the model was divided into six layers, ranging in thickness from 200 feet (ft) for the top layer to 2,250 ft for the bottom layer, creating a total simulated aquifer thickness of 6,075 ft. The flood plain of the Rio Grande was simulated as a constant-head boundary for the top model layer. The initial aquifer hydrologic characteristics included in the model were largely based on the previous works by Bjorklund and Maxwell (1961) and Reeder and others (1967). However, the three-dimensional numerical model allowed the simulated aquifer hydrologic characteristics to vary in the model to represent the variation that was observed or interpreted in the physical aquifer system.

From the early 1960's through the late 1980's development in the Albuquerque area continued at a substantial rate. Ground-water withdrawal for the City of Albuquerque's public water system increased from about 41,000 acre-feet (acre-ft) per year in 1960 to 117,000 acre-ft per year in 1990 (City of Albuquerque records). A large amount of data and interpretation regarding the aquifer system in the vicinity of Albuquerque also accumulated over that time. Hawley and Haase (1992) interpreted and combined this information into a revised hydrogeologic framework of the basin in the vicinity of Albuquerque.

Kernodle and others (1995) constructed a three-dimensional numerical ground-water flow model of the Albuquerque Basin based on the framework provided by Hawley and Haase (1992). The objectives of this model were to simulate historical and possible future effects of ground-water withdrawal on water levels in the aquifer system and to calculate the effects of City of Albuquerque withdrawals on flow in the Rio Grande. Although the City of Albuquerque production wells and the Albuquerque area were emphasized in this model, the boundaries of the model extended to the boundaries of the Albuquerque Basin, from Cochiti on the north to San Acacia on the south. This model used 11 layers, 244 rows, and 178 columns (310,376 active cells), and had a horizontal grid spacing ranging from 656 ft on a side in the Albuquerque area to 3,281 ft on a side at the basin margins. Layer thicknesses ranged from 20 ft in the flood-plain area for each of the top four layers to 500 ft for the bottom layer. The total aquifer thickness simulated ranged from 1,730 ft below the flood plain to 2,020 ft at the basin margin. The detail in the model descretization was designed to accommodate simulation of (1) the complex hydrologic interactions between the ground-water system and the flood-plain system, which includes the Rio Grande, canals, drains, irrigated land, septic tanks, wetlands, and riparian vegetation and (2) ground-water-level declines at a scale based on individual well withdrawals rather than well-field total withdrawals. Kernodle and others (1995) simulated the 1901 to 1994 historical period and projected possible future withdrawals to 2020. Kernodle (1998) updated the model to include additional interpretations on the hydrogeologic framework by Hawley and others (1995), included 1995 in the historical simulation, and reran the future withdrawal scenarios.

Numerical ground-water flow models are commonly calibrated by trial and error—that is, simulated values of aquifer hydrologic characteristics are adjusted within reasonable ranges in an effort to more closely match simulated results with historical data, such as water levels or stream loss or gain. Nonlinear-regression methods (Cooley and Naff, 1990) are available in which optimal parameter values may be estimated by minimizing the squared weighted difference between observed and model-simulated values (the objective function). In this "inverse" method of calibration, a model code such as MODFLOWP (Hill, 1992) can be used to define parameters based on aquifer hydrologic characteristics and to specify observations to which simulated values are compared. The model code can then be used to estimate optimal parameter values that minimize the objective function (see Cooley and Naff, 1990; and Hill, 1992 for limitations).

Tiedeman and others (1998) applied nonlinear-regression methods to calibrate a numerical model of the Albuquerque Basin and to test hypotheses about the basin subsurface. The model was a modified version of the Kernodle and others (1995) and Kernodle (1998) models. Modifications included coarsening the model discretization both spatially and in the number of stress periods to decrease simulation time so that the numerous iterations of the nonlinear regression method could be accommodated. Six basin-subsurface configurations were tested, each using the same horizontal grid but either six or nine model layers to represent a simulated aquifer thickness of 1,600 or 5,000 ft, respectively. The horizontal grid used 113 rows and 60 columns with a grid spacing ranging from 2,460 ft in the Albuquerque area to 16,400 ft at the basin margin. In the six-layer configuration, thicknesses ranged from 40 ft for the top layer to 800 ft for the bottom layer. In the nine-layer configuration, thicknesses of the top six layers were the same as in the six-layer configuration and the additional bottom three layers ranged in thickness from 1,000 to 1,300 ft. The New Mexico Office of the State Engineer (NMOSE), which is responsible for administering water in New Mexico, has initiated plans to begin using a modification of the Tiedeman and others (1998) model as a water-administration tool for the Albuquerque Basin.

Much of the information base regarding the aquifer system in the Albuquerque Basin is concentrated in the central part of the basin, the Albuquerque area, where most development has occurred. The USGS Middle Rio Grande Basin (MRGB) study was initiated in 1995 to "improve the understanding of hydrology, geology, and land-surface characteristics of the Middle Rio Grande Basin" (Bartolino, 1997). Particular aspects of the study are described in Bartolino (1997), Slate (1998), and in articles included in this volume. Areas of emphasis in the study include extending the information base on the aquifer system beyond the central part of the Albuquerque Basin and improving the understanding of ground- and surface-water hydrologic interactions in the basin. One of the last phases of the MRGB study, which is being done in cooperation with the NMOSE and the City of Albuquerque, is to integrate current (1999) knowledge, including that gained by the MRGB study and associated studies, into an improved three-dimensional ground-water flow model of the Albuquerque Basin. This model could then be used to provide an integrated water-administration tool for the basin.

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Tracing and Dating Ground Water in the Middle Rio Grande Basin, New Mexico—A Progress Report

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Concentrations of environmental tracers and other chemical and isotopic substances were determined in ground water from the Santa Fe Group aquifer in the vicinity of Albuquerque, New Mexico, and regionally throughout the Middle Rio Grande Basin. The analyses included major- and minor-element chemistry, tritium (^{3}H), tritiogenic helium-3 (^{3}He), chlorofluorocarbons (CFC's: CFC-11, CFC-12, CFC-113), sulfur hexafluoride (SF_6), oxygen-18 (^{18}O) and deuterium (^{2}H) in water, carbon-13 (^{13}C) and carbon-14 (^{14}C) of dissolved inorganic carbon (DIC), sulfur-34 (^{34}S) of dissolved sulfate, and dissolved gases (including dissolved oxygen, nitrogen, argon, methane, helium, neon, and carbon dioxide (CO_2)). These data are being used to (1) identify recharge areas, (2) date the young (0- to 50-year) and old (greater than 1,000-year) water in the aquifer, (3) trace the movement of ground water throughout the basin, (4) estimate recharge rates, (5) trace seepage from the Rio Grande and from the drains and laterals that has entered the Santa Fe Group aquifer in the Albuquerque area, and (6) provide geochemical data that can be used to help refine the USGS ground-water flow model (Kernodle and others, 1995) developed for the Albuquerque Basin (see Sanford, p. 86).

Two hundred eighty wells (including 116 monitoring wells, 34 domestic wells, 82 production wells, and 45 windmills) and eight springs were sampled throughout the basin during the summers of 1996 through 1998. In addition to the more complete ground-water sampling, water from the Rio Grande and adjacent drains and laterals, Tijeras Arroyo, Bear Canyon, the Rio Puerco, and the Jemez River was sampled and analyzed variously for CFC's, stable isotopes, tritium, and major- and minor-element chemistry on a monthly basis. Samples of air and unsaturated zone gas were analyzed for CFC's, SF_6, and ^{13}C of CO_2 gas. Ground-water samples collected at all operational City of Albuquerque production wells in summer 1997 were analyzed for stable isotopes. Archived ground-water samples from City of Albuquerque production wells, water from the Rio Grande, and precipitation from the 1980's were also analyzed for stable isotopes.

Ground-water sampling was completed in summer 1998, and surface-water sampling ended in March 1999. Although the results are still preliminary, these data, plotted on maps of the basin and vicinity of Albuquerque, are being examined to aid in interpreting sources of water, direction of ground-water flow in the basin, and ground-water age. Most wells sampled intercept water in the upper 500 feet (ft) of the upper Santa Fe aquifer. Therefore, the mapped chemical patterns apply mostly to the upper part of the aquifer. Geochemical data from a series of piezometer nests in the vicinity of Albuquerque provide additional data on variations of the chemical parameters with depth, to depths as much as 1,500 ft below the water table.

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Specific conductance, stable isotope composition of water, most of the major-element chemistry, and ^{14}C activity of DIC show significant regional patterns that can be mapped throughout the basin. Most of these patterns have a strong north-south component. These regional patterns appear to reflect recharge from the basin margins and possibly from the Rio Grande. Other more local patterns appear to delineate recharge from the Rio Puerco, the Ladron Peak area to the southwest, Abo Arroyo, and Tijeras Arroyo.

The median value of specific conductance of ground water sampled in the basin is 473 microsiemens per centimeter at 25 degrees Celsius (μS/cm), but specific conductance exceeds 27,000 μS/cm in discharge from a spring on the southwestern boundary. Specific conductance is typically large (greater than 5,000 μS/cm) along the western boundary due to elevated sulfate concentrations and other solutes derived from gypsum-bearing Cretaceous and Permian rocks along the western margin of the basin. Recharge from the eastern and northern mountain fronts is relatively dilute, with specific conductance smaller than that of recharge along the western boundary but larger than that of water in the Rio Grande (352 ± 28 μS/cm). Recharge from Abo and Tijeras Arroyos can be traced from the basin margin several miles into the basin as zones of relatively large specific conductance (values average about 2,000 μS/cm for water in Abo Arroyo and 1,000 μS/cm for Tijeras Arroyo), large dissolved-sulfate concentrations, and δD values elevated relative to surrounding waters in the basin. The elevated sulfate concentrations are probably derived from dissolution of gypsum in Permian rocks that occur in the drainage areas for the arroyos. Water from Abo and Tijeras Arroyos is enriched in ^{2}H relative to water from the mountain, in part because of the lower altitude of the drainage areas for the arroyos relative to the mountains. Ground water under most of the City of Albuquerque has low specific conductance and has concentrations of dissolved sulfate and chloride and δD values similar to those of water in the Rio Grande in the vicinity of Albuquerque. Shallow ground-water samples in the inner valley of the Rio Grande have elevated dissolved-solute content, at least partly due to enrichment associated with evapotranspiration occurring there.

Some locally elevated concentrations of dissolved chloride in the Bernalillo area and extending southward across Sandia Pueblo into the northeast part of Albuquerque may represent leakage of thermal waters along faults. Elsewhere, the concentrations of chloride and sulfate in ground water beneath Albuquerque are similar to those of the Rio Grande. The median chloride concentration in the basin is 17 milligrams per liter (mg/L), and the average in the Rio Grande in the vicinity of Albuquerque is about 10 mg/L. The median sulfate concentration in the basin is 66 mg/L, and the average in the Rio Grande is about 50 mg/L. Other chloride-rich thermal waters were found in the southeast part of the basin near Abo Arroyo and may also represent leakage along faults.

Stable-isotope data have been particularly useful in recognizing water sources in the basin. A total of 335 measurements of δD and $\delta^{18}O$ in ground water from the basin are best described by the least-squares line $\delta D = 7.6\ \delta^{18}O + 2.4$ (in per mil). All water samples from the Rio Grande and associated drains and laterals in the vicinity of Albuquerque have an average δD of –90.5 per mil, and winter-spring Rio Grande water averages –92.5 per mil in δD. Local recharge from the basin margins and from the Jemez River, the Rio Puerco, and arroyos entering the basin is enriched in δD by more than 10 per mil relative to that of the Rio Grande. Most ground water in the center of the basin is depleted in stable-isotope composition relative to that of the basin margins. Rio Grande water is depleted in stable-isotope composition relative to local mountain-front recharge in the Middle Rio Grande Basin, probably because it contains runoff from higher elevations in the Rocky Mountains in Colorado. The stable-isotope data appear to separate ground water derived from the mountain front from ground water possibly derived from the Rio Grande at Albuquerque by approximately 10-15 per mil in δD. Some stable-isotope values in ground water beneath Albuquerque, and particularly in a north-south striking zone extending from the Jemez River along the western half of the basin to areas southwest of Albuquerque, are depleted relative to water from the Rio Grande. The isotopically depleted waters are also some of the oldest waters in the basin and probably represent water recharged during the last glacial period some 20,000 radiocarbon years ago.

Preliminary study of the chemistry of ground water from the piezometer nests in the vicinity of Albuquerque indicates four types of waters beneath the city. The most abundant of these appears to be water similar in composition to that of the Rio Grande in the vicinity of Albuquerque, based on dissolved-chloride and -sulfate concentrations and stable isotope composition. The Rio Grande-type water has probably been altered geochemically by cation exchange reactions affecting dissolved calcium, magnesium, sodium, and potassium. The other types of ground water found in the vicinity of Albuquerque include (1) eastern mountain-front recharge, which appears to enter the basin, spread to the west to points approximately one third of the distance between the mountain front and the Rio Grande, and flow primarily southwest, mixing with water from Tijeras Arroyo across Kirtland Air Force Base; (2) thermal waters from faults in north Albuquerque in which chloride, helium, arsenic, and temperature are elevated relative to surrounding waters; and (3) waters with elevated concentrations of sodium, bicarbonate, and sulfate at depths greater than 500 ft below the water table in the southwestern vicinity of Albuquerque.

Concentrations of dissolved arsenic are typically less than or equal to 3 micrograms per liter (μg/L) throughout the basin. However, elevated concentrations are found northwest of the Jemez River, in parts of Santa Ana Pueblo, parts of Rio Rancho, and zones in the northeast and southwest parts of Albuquerque. Elevated concentrations of arsenic in northeast Albuquerque and near Abo Arroyo in the southeast part of the basin are thought to be associated with thermal waters along faults. Arsenic concentrations in the Rio Grande in the vicinity of Albuquerque averaged 3.5 μg/L. Arsenic concentrations increase with depth in most monitoring wells beneath Albuquerque and vicinity, reaching about 95 μg/L at 1,300 ft below the water table in an area southwest of Albuquerque.

Concentrations of dissolved silica are typically 20 mg/L (as SiO_2) along the basin margins and markedly elevated (50-70 mg/L) in a north-south zone throughout the center part of the basin. The elevated silica concentrations probably reflect diagenetic reactions with siliceous clay minerals associated with fluvial sediment, and possibly weathering of volcanic glass.

Alkalinity (as HCO_3^-) is less than 200 mg/L throughout most of the basin. Alkalinity is less than 150 mg/L in a zone extending north-south through the east-central part of the basin and over large areas of the west mesa, and is somewhat elevated in ground water recharged from the basin margins in the southwest, northwest, and eastern boundary. The median alkalinity is 164 mg/L for all basin waters.

Carbon-14 activities in ground water in the basin range from 123 to 0.1 percent modern carbon (pmc). The median ^{14}C activity of 265 measurements is 36.8 pmc. Waters with ^{14}C activities greater than 100 pmc contain tritium and are likely enriched in ^{14}C from atmospheric sources associated with the mid-1960's atmospheric testing of nuclear weapons. Samples that are likely representative of pre-nuclear detonation recharge waters have ^{14}C activities near 100 pmc. The ^{14}C activity of pre-nuclear detonation Rio Grande water was also likely near 100 pmc. The median $\delta^{13}C$ value for DIC in ground water throughout the basin is –8.2 per mil (Pee Dee Belemnite), indicating little water-rock interaction affecting the dissolved inorganic carbon content of ground water in the basin. Preliminary unadjusted radiocarbon ages suggest a bimodal distribution of ground-water ages throughout the basin, with one group of values centered at about 18-20 thousand years (ka) and a second group centered at about 7 ka. However, locations of the ground-water samples included in this distribution are not evenly distributed throughout the basin. The younger group of unadjusted radiocarbon ages represents most ground water in the upper 500 ft of the aquifer beneath Albuquerque and is partly biased by samples from City of Albuquerque production wells that produce ground-water mixtures. All piezometer nests show significant decreases in ^{14}C activity with depth beneath Albuquerque. Some of the oldest waters are also depleted in δD and occur west of Albuquerque. Throughout the basin, the ^{14}C data indicate relatively young waters along most of the basin margins and in approximately the upper 200 feet of the inner-valley sediment. Very old water occurs through most of the western half of the basin and at depths greater than 500 ft below the water table.

Additional chemical and isotopic data are in the preliminary stages of interpretation. CFC and tritium data are being used to recognize areas receiving recharge within the past 30 to 50 years. These tracers of modern recharge are found in some ground water and springs near the basin margins and in ground water from the upper 200 ft of the inner valley. CFC and/or tritium data are also being used to recognize water samples with potential for contamination of old ^{14}C with modern sources. Some piezometer nests in the vicinity of Albuquerque show strong gradients in helium concentration, indicating an upward flux from deep parts of the basin. Elevated concentrations of SF_6 occur in water associated with crystalline rocks. SF_6 appears to be a useful tracer of recharge from the Precambrian crystalline rocks along the eastern basin margin. The dissolved gases (argon and nitrogen) are being used to determine recharge temperature and quantities of excess air trapped in ground water during recharge.

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Estimating Parameters for a Ground-Water Flow Model Using UCODE and Environmental Tracers

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USGS scientists have spent 3 years collecting and analyzing data on the chemistry and isotopic composition of ground water throughout the Middle Rio Grande Basin (MRGB) (Plummer and others, this volume). These data include major- and minor-element concentrations, ^{2}H, ^{3}H, ^{3}He, ^{4}He, ^{13}C, ^{14}C, ^{18}O, ^{34}S, dissolved N_2, Ar, SF_6, and chlorofluorocarbon (CFC-11, CFC-12, CFC-13) concentrations. The ^{14}C data provide valuable information on the rates of ground-water flow in the basin aquifer system, whereas the other data provide information on the ground-water source areas. This information could be used to constrain and improve the USGS ground-water flow model of the MRGB. Improvement of this flow model has been one of the major objectives of the entire MRGB study. Although ground-water chemistry data are being used increasingly to constrain and improve conceptual models of ground-water flow and transport, the data have typically been used in a qualitative or simple quantitative manner. The objective of this study was to test the capabilities of the USGS parameter estimation model UCODE (Poeter and Hill, 1998) to incorporate ground-water chemistry data directly into a parameter-estimation routine.

Before UCODE will be applied to the MRGB model, two datasets that are currently being upgraded need to be completed--geologic data, which are currently being compiled to improve the hydrogeologic framework of the flow model, and the ground-water chemistry data. Because these data will not be available until April of this year, UCODE was tested on synthetic data generated from one forward simulation in a hypothetical, MRGB-like basin. Parameters were estimated for an inverse model based on a comparison of the synthetic data of the forward model and the simulated data of the inverse model. Synthetic data have the advantage that the actual parameters and fluxes of the system are known exactly, so comparisons can be made with the final estimated parameters to see how closely the model came to reproducing the true values.

The "synthetic basin" was constructed using parameters that approximate the conditions in the MRGB. The grid was 40 kilometers (km) wide by 80 km long by 1,200 meters (m) deep, and a river was added just off-center down the model length to represent the Rio Grande. A three-dimensional, randomly correlated, heterogeneous hydraulic conductivity (K) field was created for the synthetic basin using a mean hydraulic conductivity of 1 m/day and correlation lengths of 5 km, 20 km, and 50 m for directions along the basin width, length, and depth, respectively. Mountain-front recharge was added to the western, northern, and eastern top edges of the model. Pumpage was simulated from 100 wells from 1950 onward in rates and trends that were similar to those in the vicinity of Albuquerque. Observation wells were located at 104 locations across the entire basin, and an additional 48 multiple-depth piezometers were located in the center of the basin. The finite-difference discretization of the forward model resulted in a total of 1.7 million cells. When the forward run was made using MODFLOW (McDonald and Harbaugh, 1988), 104 basinwide water levels were recorded during simulation year 1950, followed by 48 water levels at the nests in both 1995 and 1999. After the MODFLOW simulation, MODPATH (Pollock, 1994) was used to calculate travel times or "ages" (in lieu of ^{14}C ages) from the wells back to the source areas for 102 basin wells and 48 piezometer-nest wells. MODPATH was also

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used to calculate the direction to the source area from each of these wells by comparing the well location with the exact location where that flow line entered the basin. For the field data, the direction information can be provided by the location of the source area, which is in turn provided by some of the geochemical tracer data.

The parameter-estimation simulations were made with UCODE using three different cases in which observations consisted of: (1) water levels only, (2) water levels and travel times, and (3) water level, travel times, and travel directions. Each inverse model was created beginning with six parameters and then adding an additional parameter until 25-30 parameters were estimated for each case. The inverse model had 64,000 finite-difference cells. The estimated parameters included horizontal K, vertical K, storativity (S), and mountain-front recharge from each side. The basin volume was divided into smaller and smaller rectangular sections as the number of parameters was increased. Porosity, specific yield, and the riverbed conductance were all fixed. UCODE was used to repeatedly call MODFLOW and MODPATH and then run a linear regression to minimize the error between the observed and simulated data. All of the model cases were able to make reasonable estimates for K and S values. The inverse models did less well at estimating the overall basin fluxes. The goodness of the inverse models was therefore evaluated on the basis of how well they were able to reproduce the overall fluxes. These fluxes were river inflow and outflow, recharge, and water released from storage.

Case 1 (water-level observations only) was unable to produce reasonable estimates of the mountain-front recharge. Although there was some improvement as the number of parameters was increased, the model still overestimated recharge by a factor of four when 30 parameters were estimated. Case 2 (water levels and travel times) estimated recharge more accurately than case 1. The estimates continued to improve as the number of parameters estimated increased, and the best estimate of recharge was within a factor of two of the actual recharge. Case 3 (included travel directions) gave better recharge estimates between case 1 and case 2. This may suggest that the travel times are the most valuable observations related to the flux estimates. A series of 25 simulations that progressed from 6 to 30 estimated parameters took about 2 weeks to run on a Silicon Graphics Origin2000. UCODE was shown to run successfully with proxy environmental tracer data, and with several months of time yet available to run the real MRGB model before the end of this project, there should be ample time remaining to run parameter estimation simulations using UCODE and the environmental tracer data.

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NEW MEXICO DISTRICT COOPERATIVE PROGRAM

AND RELATED U.S. GEOLOGICAL SURVEY PROGRAMS

Summary of Water-Quality Data for City of Albuquerque Drinking-Water Supply Wells, 1988-97

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The City of Albuquerque has collected and analyzed more than 5,000 water-quality samples from 113 water-supply wells in the Albuquerque area, including many drinking-water supply wells, since May of 1988. As a result, a large water-quality database has been compiled that includes data for major ions, nutrients, trace elements, carbon, volatile organic compounds, radiological constituents, and bacteria. These data are intended to improve the understanding and management of the ground-water resources of the region, rather than demonstrate compliance with Federal and State drinking-water standards. Summary statistics have been compiled for selected physical properties and chemical constituents for ground water from wells used by the City of Albuquerque for drinking-water supply between 1988 and 1997. Maps have been generated to show the general spatial distribution of selected parameters and water types around the region. Although the values of some parameters vary substantially across the city, median values for all parameters included in this study are less than their respective maximum contaminant levels in each drinking-water supply well. The dominant water types are sodium plus potassium/carbonate plus bicarbonate in the western part of the city and calcium/carbonate plus bicarbonate in the eastern part of the city.

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The U.S. Geological Survey Global Climate Change Program in the Rio Puerco Basin, New Mexico

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The arroyo cycle and its relation to climate and land use are of scientific and practical interest. The 15,200-square-kilometer (km^2) Rio Puerco Basin in central New Mexico has had several cycles of arroyo cutting and filling in the late Quaternary. The most recent cutting cycle, initiated in the late 19th century, is being investigated to determine the role of climate in landscape change. The objectives of the USGS Global Climate Change Program are to: (1) examine geologic and modern rates of upland and channel erosion, (2) model water and sediment discharge in the main channel, (3) document land use history and erosion control in the basin, (4) map geomorphic surfaces in the basin and their ages, (5) better understand transmission losses in the bed of the main channel and the arroyo's role in channel evolution, and (6) establish the chronostratigraphy of Holocene and late Pleistocene colluvium and alluvium.

Analysis of cosmogenic isotopes, ^{10}beryllium and ^{26}aluminum, sampled in bedrock of the Arroyo Chavez Basin, a 2.21-km^2 subbasin of the Rio Puerco (E.M. Clapp, University of Vermont, written commun., 1998), provides evidence for upland erosion rates of 80 to 150 meters per million years (0.08-0.15 millimeter per year)(mm/yr). Plot studies on various geomorphic surfaces of the Arroyo Chavez Basin between 1995 and 1998 indicate upland erosion rates of 0.03 to 2.1 mm/yr. The highest sediment yields of 1.33 to 11.6 kilograms per square meter (kg/m^2) per year occur on the alluvial valley floor immediately adjacent to the main channel of Arroyo Chavez. The mesa and side slope surfaces in the Arroyo Chavez Basin have the lowest sediment yields, ranging from 0.15 to 0.97 kg/m^2 per year. Eolian flux sampled in collection buckets indicates that the total eolian contribution to the Arroyo Chavez Basin is 11.0 to 26.6 metric tons per year, which is 0.5 to 1.1 percent of the total suspended sediment transported out of the Arroyo Chavez Basin from October 1, 1996, to September 30, 1997 (2,350 metric tons).

^{14}Carbon analysis of alluvium provides a record of periods of aggradation in the Rio Puerco channel. Results show ages ranging from the late Holocene to greater than 20,000 years; most of the fill is Holocene. Results for Arroyo Chavez show that colluvial storage on hillslopes may be dominantly Holocene; gaps in the aggradation record, presumably periods of arroyo degradation, correspond to gaps in the packrat midden record compiled by Betancourt and others (1993) for New Mexico. Cycles of aggradation and incision of the Rio Puerco do not appear to be correlated with frequent wet/dry climatic transitions over the past 2,000 years. The geomorphic state of the channel or the stage in the arroyo cycle may be the most important factor in determining response to climate.

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Southwest Ground-Water Resources Project

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The Southwest Ground-Water Resources Project is part of the Ground-Water Resources Program of the USGS. The issue addressed by the Southwest Project is the interaction of ground water and surface water and the relation of that interaction to availability and sustainability of ground-water resources in the Southwestern United States. The study will focus on the following five aspects of the interaction of ground water and surface water:

1. Regional synthesis of information on the interaction of ground water and surface water,

2. Assessments of the effects of ground-water development on riparian systems,

3. Assessments of the effects of climate variations on recharge to and discharge from ground-water systems,

4. Development of improved methods of quantifying recharge to ground-water systems from streams and application of these methods in the Southwest, and

5. Development of improved methods of simulating interaction of surface water and ground water.

The geographic area under consideration encompasses aquifer systems in the arid to semiarid basins in southwestern States including California, Nevada, Utah, Arizona, and New Mexico. The regional synthesis of information includes assembly of databases and geographic information system coverages of riparian areas, land use, water use, ground-water and surface-water data, and extents and types of aquifer systems. New projects are underway in various locations in the Southwest to study climate variations and riparian systems and to quantify recharge. As part of the efforts to better understand recharge processes, four recharge study sites will be established. At each study site, recharge will be estimated by a variety of methods including geochemical, heat-transport, Darcian-flow, channel-loss, and geophysical analyses.

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Proposed Expansion of the City of Albuquerque/U.S. Geological Survey Ground-Water-Level Monitoring Network for the Middle Rio Grande Basin, Central New Mexico

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The Middle Rio Grande Basin in central New Mexico extends from Cochiti Lake on the north to San Acacia on the south, and covers an area of about 3,060 square miles. Because of rapid increases in population and associated ground-water pumpage, a network of wells was established by the USGS in cooperation with the City of Albuquerque between April 1982 and September 1983 to monitor changes in ground-water levels throughout the basin. Prior to October 1998, the network consisted of 36 wells and 51 piezometers in 17 nests. Officials with the USGS and the City of Albuquerque recognized gaps within the coverage provided by the existing network and have proposed expanding the monitoring effort to provide adequate coverage areally and with depth in the Santa Fe Group aquifer system. The proposed expansion includes 50 City of Albuquerque piezometers in 17 nests, 34 wells from Kirtland Air Force Base, 29 wells from the Pueblo of Isleta, and 30 wells from the Intel Corporation. Ground-water-level data from Kirtland Air Force Base, the Pueblo of Isleta, and Intel will be reported; ground-water-level data from the remaining wells and piezometers will be collected by USGS personnel.

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New Mexico District Cooperative Program in the Middle Rio Grande Basin, Fiscal Year 1999

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The New Mexico District of the USGS has established and fostered for many decades a dynamic Federal-State Cooperative Program in the Middle Rio Grande Basin, central New Mexico. In the Cooperative Program, investigative projects and data-collection activities are jointly identified, planned, and funded by the USGS (as much as 50 percent) and by State and local agencies. Generally, the State and local agencies provide at least one-half the funds, and the USGS does most of the work. The collective results of the Cooperative Program have provided the scientific basis and the institutional framework for developing the USGS Middle Rio Grande Basin study that began in fiscal year 1996. This article briefly describes the historical highlights of the Cooperative Program in the Middle Rio Grande Basin and the components of the present program. Of the approximate $4.0 million allocated in fiscal year 1999 for USGS work in the basin, about $1.3 million was from the Cooperative Program. The major agencies in the Cooperative Program in the basin study are the City of Albuquerque (City), the New Mexico Office of the State Engineer (NMOSE), and Bernalillo County.

One of the earliest highlights of the Cooperative Program in the Middle Rio Grande Basin was the report on the availability of ground water in the Albuquerque area by Bjorklund and Maxwell (1961). They presented regional maps of the geology and water-table configuration in the area. Reeder and others (1967) provided a quantitative analysis of the water resources in the Albuquerque area, with computed effects on the Rio Grande from ground-water pumpage. They presented projected water-table declines and depletions of Rio Grande flow due to projected ground-water withdrawals. Following a period primarily devoted to data-collection activities, the development, construction, and documentation of the Albuquerque Basin ground-water-flow model rank as a recent significant milestone in the Cooperative Program with the City of Albuquerque. Thorn and others (1993) described the geohydrologic framework and hydrologic conditions used in the flow model, and Kernodle and others (1995) presented the results of the flow model. McAda (1996) detailed a plan of study to quantify the hydrologic relations between the Rio Grande and the Santa Fe Group aquifer system in the Albuquerque area; 13 essential activities and informational needs were identified and prioritized. The most recent highlight of the Cooperative Program is the drilling, completion, and monitoring of a series of nested piezometers located throughout the Albuquerque area. By the end of calendar year 1998, 17 piezometer nests--generally, each with three piezometers--were completed at 15 different sites. The nests commonly have piezometers that measure water levels near the water table, near the middle of the "production zone" in the City wells, and near the base of the "production zone" in the City wells.

The current (1999) Cooperative Program with the City contains the following components: (1) assistance to the Upper Rio Grande Water Operations Model; (2) continuation of the ground-water-level monitoring network; (3) expansion of the monitoring network by completion of more nested piezometers; (4) estimation of seepage rates from the Rio Grande, canals, and drains in the Albuquerque area; (5) monitoring of low-flow conditions in urban storm drains; (6)

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determination of mountain-front recharge by chloride-balance methods; (7) assessment of water-quality trends in City production wells; (8) dissemination of hydrologic information over the Internet; (9) update of the regional ground-water-flow model; (10) coring and aquifer testing in the bosque; (11) slug testing of the City piezometer nests; and (12) investigation of aquifer compaction and land subsidence. Many of these activities focus on quantifying hydrologic relations between the Rio Grande and the aquifer system, as identified in the McAda (1996) plan. The current (1999) Cooperative Program with the NMOSE contains the following components: (1) revision of the Albuquerque Basin ground-water flow model; (2) participation in the estimation of physical and hydraulic characteristics of canals and drains; (3) participation in the drilling and completion of the nested piezometers network; (4) participation in a large-scale aquifer test in Albuquerque; and (5) continuation of the long-term ground-water-level monitoring network. The 1999 Cooperative Program with Bernalillo County provides for the drilling and completion of a series of deep nested piezometers.

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