Geologic and Hydrogeologic Framework of the Española Basin -- Proceedings of the 5th Annual Española Basin Workshop, Santa Fe, New Mexico, March 7-8, 2006

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INTRODUCTION

By Mark R Hudson

This report presents abstracts of technical studies that are focused on the hydrogeologic framework of the Española basin, a major subbasin of the Cenozoic Rio Grande rift. The Rio Grande, Rio Chama, Santa Fe River, and their tributaries carry important surface water in the Española basin. Sediments and interbedded volcanic rocks fill the Española basin and form extensive aquifer systems for ground water. Surface and ground water provide the principal sources of water for most residents of the basin, including people in the cities of Santa Fe, Española, and Los Alamos as well as Native Americans in several Pueblos.

The abstracts describe results of technical studies that were presented either as poster exhibits or oral presentations at the fifth-annual Española basin workshop, held March 7-8 of 2006 in Santa Fe, New Mexico. The principal goal of this workshop was to share information about ongoing studies.

The Española basin workshop was hosted by the Española basin technical advisory group (EBTAG) and sponsored by the U.S. Geological Survey, the New Mexico Bureau of Geology and Mineral Resources, and the Water Research Technical Assistance Office of Los Alamos National Laboratory. Abstracts in this report have been grouped into six information themes: Basic Water Data, Water Quality and Water Chemistry, Water Balance and Stream/Aquifer Interaction, Data Integration and Hydrologic Model Testing, Three-Dimensional Hydrogeological Architecture, and Geologic Framework.

Abstracts submitted by U.S. Geological Survey authors in this report have had their technical content peer reviewed before they were included in the report. Technical reviews were not required for abstracts submitted by authors outside the USGS, although most did receive peer reviews within their originating agencies. Taken together, the abstracts in this report provide a view of the current status of hydrogeologic research within the Española basin.

NM OSE GROUND WATER MONITORING WELL PROGRAM IN THE SANTA FE REGION

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The Office of the State Engineer, in coordination with the USGS Water Resources Discipline and the USGS drilling crews from Denver, has drilled six multilevel piezometers in the Santa Fe embayment of the Espanola basin. Sites were based on proximity to present and future pumping centers in the Tertiary Santa Fe group. The Santa Fe group is the thickest unit and possesses the most favorable aquifer parameters, overall, in the basin. These monitoring wells and production wells up to 2000 feet deep only partially penetrate the Santa Fe group, which is estimated to be over 8,000 feet thick near Buckman well field.

The borehole geophysics provides the best available data on the definition of individual coarse and fine-grained units encountered in the wells. The dominant lithology in all Santa Fe group wells is sand and silt. Easternmost wells are predominantly heterogeneous "granite wash". Based on geophysical character of the Lithofacies S section in the central embayment, three types of sandy units are common: fining upward units to about 50 feet thick, thin sands 5 to 15 feet thick encased in mudstone, and blocky sands up to 60 feet thick. Very low resistivity clayey units from tens up to 40 feet thick occur in the westernmost wells. Because regional dip averages about 10 degrees to the west, correlative strata should daylight within a couple miles east of each well. This dip and widespread small faults make correlations from well to well difficult.

The Santa Fe Group is a highly heterogeneous and stratified aquifer. Because of regional dip, only the eastern wells have the potential of direct connection to the mountain front. Elsewhere, much ground water movement must occur along structural strike and by cross formational flow. Water level trends have been monitored in most wells for more than one year. Most of these wells lie within the zone of influence of production wells and are responsive to pumping stresses. Distinctive vertical gradients occur in all wells. The data are available to the public and additional study is warranted. These wells will enhance future groundwater management in the basin.

HYDROLGEOLOGIC CHARACTERIZATION OF A RIFT-BASIN AQUIFER SYSTEM: COMPARISON OF METHODS

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A sequential pair of traditional aquifer tests was performed using both municipal water supply and numerous observation wells. Initially, a 25-day aquifer test was conducted at well PM-2 at a constant discharge rate of 79 lps (1,249 gpm), while supply wells PM-4 and PM-5 were used as observation wells. Then a 21-day aquifer test was conducted at well PM-4 at a constant discharge rate of 94 lps (1,494 gpm) while supply wells PM-2 and PM-5 were used as observation wells. These data reveal horizontal propagation of drawdown in the regional aquifer beyond 2,650 m (8,700 ft) from each production well, and a pronounced resistance to vertical drawdown propagation at shallower depths. Hydraulically, the regional aquifer seems to behave like a semi-confined aquifer with leaky units located above a highly conductive layer that averages about 260 m (850 ft) in thickness. Analyses of drawdown and recovery data from individual observation wells in the first test suggest that the highly conductive layer between wells PM-2 and PM-4 has a transmissivity of about 400 m^2/day (4,250 ft^2/day) and a storage coefficient of about 0.00035. Analyses of data from the second test suggest a transmissivity of 600 m^2/day (6,450 ft^2/day) and a storage coefficient of about 0.00039. The aquifer thins between PM-4 and PM-5 to an effective thickness of about 150 m (490 ft), while the aquifer transmissivity and storage coefficient increase only slightly. It is unclear if these differences are indeed significant, or if they simply reflect combined parameter uncertainty arising from natural variability and the type-curve solution method.

While these analyses yield excellent type-curve matches, they fail to explain differences in measured vertical pressure responses from multi-screened observation wells. In addition, multi-dimensional numerical flow models mimic both horizontal and vertical hydraulic responses very well, and suggest that the aquifer is actually phreatic. These tests demonstrate that the regional aquifer below Los Alamos is strongly heterogeneous, and exhibit pronounced horizontal and vertical anisotropy in hydraulic transmitting properties. These results also illustrate that model dimensionality can influence inferred aquifer behavior, and reinforce theoretical predictions (Neuman, 1975) that say unconfined aquifers may exhibit confined or leaky-aquifer behavior at early times. Finally, the transition from leaky-confined to phreatic conditions is estimated to occur after about 200 days of continuous pumping.

STREAMFLOW ELEVATION RELATIONS FOR HIGH ALTITUDE WATERSHEDS IN THE RIO TESUQUE AND ADJACENT WATERSHEDS

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Several methods of calculation and prediction of annual streamflow in inches for high mountain watersheds in the Sandre de Christo Mountains have been used by water management agencies. Streamflow data collected at eight USGS streamflow gages from 1963 to 1973 may provide a more realistic estimate compared to the methods in use. For each of the eleven years of streamflow data collection, a close linear relation (adj R2 > .90 %) was developed relating the log transform of the runoff in inches at each outfall gaging site to the mean elevation of that watershed. Years with more snowpack have higher runoff for all eight watersheds, thus a larger regression equation intercept. However, the years with higher snowpack displayed a smaller increase in runoff with elevation because the larger snows apparently spread down to the lower elevations. A gage at just one of the watersheds can be used to calculate both the intercept and the slope of the runoff increase with elevation for any given year thereby providing a good estimate of the annual available streamflow by elevation. Snow water equivalent data from local snow survey sites also is useful in predicting annual streamflow availability at all eight watersheds and thus the increase in runoff with elevation for any given year.

PRELIMINARY RESULTS OF GEOCHEMICAL CHARACTERIZATION OF GROUNDWATER IN THE SOUTHERN ESPAÑOLA BASIN, NEW MEXICO

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Chemistry and isotopic data from groundwater and surface water in the southern Española Basin and Southern Embayment were compiled from existing sources, and supplemented with data obtained from new sampling events in 2005. Existing records from the City and County of Santa Fe, the New Mexico Office of the State Engineer, the New Mexico Environment Department, the U.S. Geological Survey, and libraries of private consultants provide baseline chemistry data spanning 50 years and 259 locations, and are combined with data from 60 new sample locations. Data sets include major and minor ion and trace element chemistry, oxygen-18 and deuterium content, and field measurements of temperature and conductivity. The data are derived from streams, springs, and wells, including municipal, commercial, and private domestic wells, and the NMOSE multi-level piezometers. Because of its large size and mixed origin, the dataset presents significant quality and management challenges. However, quality control filters have provided a high degree of confidence in the precision of the data.

The data are being used to refine a conceptual model of groundwater flow and evaluate sources of water and aquifer compartmentalization. Mapping the spatial distribution of chemical parameters in relation to streams, hydrogeologic and structural features, and geologic formations and boundaries helps to identify sources of recharge and geologic controls on groundwater movement, and provides a qualitative constraint on groundwater residence times. A wide variety of groundwater types occurs in the basin, with the most common being calcium-bicarbonate, sodium-bicarbonate, and mixed calcium-sodium water. Calcium-depleted, sodium-rich waters occur in perimeter and isolated areas of the basin, including the Buckman well field, the Las Dos and Jacona fault systems, the Espinaso Formation in the Southern Embayment, an area west of Santa Fe coincident with the synclinal axis of the basin, deep Tesuque Formation wells, and shallow discharge zones in La Cienega. Chloride- and sulfate-rich waters are associated with mountain-front, bedrock aquifers, which also possess relatively elevated total dissolved solids (TDS), conductivity, calcium, and bromide. Concentrations of these chemical parameters decrease west from the mountain front. Groundwater in the center of the basin, in the vicinity of the Santa Fe River and Arroyo Hondo, has the lowest concentrations of TDS and major ions. Elevated chloride and chloride:bromide ratios in shallow wells beneath urban areas of Santa Fe are consistent with anthropogenic sources. Changes in the distribution of some chemical ions (barium and magnesium) across the San Ysidro fault are consistent with hydrologic data that suggest the fault is a barrier to horizontal groundwater movement. An area of elevated arsenic west of Santa Fe is coincident with the eastern limit of Cerros del Rio volcanic field and the synclinal axis in the deepest part of the basin. Arsenic concentrations ranging from 7 to 54 µg/L generally occur in sodium-rich waters and appear to be constrained on the east by the San Ysidro fault. Three-dimensional imaging of the arsenic plume indicates that concentrations exceeding 10 µg/L are independent of well depth and range across the upper 1700 ft of saturated aquifer. Stable isotope ($^{2}H/H$ and $^{18}O/^{16}O$) data identify the occurrence of Pleistocene (?) groundwater at depths below 800 feet in the Buckman well field, at Horcado Ranch and Las Dos, and in multi-level piezometers at depths greater than 1000 ft in the Tesuque Formation.

INTERACTIONS BETWEEN SURFACE WATER AND GROUNDWATER ALONG IRRIGATED AGRICULTURE FLOODPLAIN CORRIDORS IN NORTHERN NEW MEXICO

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In arid regions, efforts to increase downstream river flow by reducing irrigation seepage may have the unintended effect of reducing groundwater return flow and late season river flow. Intricate seasonal dynamics between seepage, shallow groundwater flow, riparian vegetation transpiration, and river flow have made elusive the fate of seepage. The goals of this study are to advance scientific understanding of seepage effects on river flow and to provide accessible tools to evaluate effects of changing irrigation practices on river flow. Field studies initiated in 2002 at the NMSU-Alcalde Sustainable Agriculture Science Center in northern New Mexico have documented that seepage from irrigation ditches and flooded fields causes rapid recharge of shallow groundwater that flows under the irrigated floodplain towards the Rio Grande. A study newly funded in 2005 builds on previous work to show if, when, and how much the seepage from irrigation ditches and irrigated fields augments river flow in the Rio Grande in New Mexico. This project is assembling a suite of experimental process studies and recently developed modeling tools to characterize hydrologic fluxes in the agricultural lands between irrigation ditches and a river. Field studies will intensify previous efforts at the single farm scale and expand to the scale of an irrigated river valley. Underlying physical processes modeled at the farm and valley scales will synthesize analytically derived characterizations and provide input to a system dynamics model. The systems model will be an accessible tool that can be used to show how future water and land management scenarios will affect seepage, groundwater return flow and river flow at the scale of a large drainage basin.

APPLICATION OF HELIUM AND TRITIUM ISOTOPES FOR DATING GROUNDWATER AT LOS ALAMOS, NEW MEXICO

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Helium-3 and tritium were used to date young fractions of groundwater and to evaluate groundwater flow paths beneath the Pajarito Plateau, New Mexico. Stable isotopes of hydrogen and oxygen were also used to determine the source(s) and recharge elevations of groundwater. Analytical methods include isotope ratio mass spectrometry for stable isotopes; mass spectrometry for helium and neon; and helium-3 ingrowth, electrolytic enrichment, and liquid scintillation for cosmogenic and anthropogenic tritium. Results of stable isotope analyses indicate that the Sierra de los Valles serves as a recharge zone for perched intermediate groundwater and the regional aquifer west of Los Alamos, New Mexico. Additional recharge to the regional aquifer occurs along wet canyon bottoms on the Pajarito Plateau. Age of the young fraction of groundwater within the Sierra de los Valles ranges from 1 to 33 years based on activities of tritium and helium-3. Springs discharging in White Rock Canyon have stable isotope ratios very similar to regional aquifer wells sampled on the Pajarito Plateau. This indicates that the springs contain a component of groundwater originating on the Pajarito Plateau. Age of the young fraction of groundwater within the regional aquifer beneath the Pajarito Plateau ranges from 16 to greater than 62 years. Age of the young fraction of regional aquifer groundwater, discharging as springs in White Rock Canyon, ranges from 1.3 to greater than 62 years. Distributions of groundwater ages suggest that recharge continuously occurs along the Pajarito Plateau and local recharge to the White Rock Canyon springs also takes place. These results suggest that there are multiple groundwater flow paths, with varying residence times, within the vadose zone and regional aquifer.

INSIGHTS INTO RECHARGE TO THE ESPAÑOLA BASIN PROVIDED BY NOBLE GAS, GROUNDWATER AGE, AND TEMPERATURE DATA

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Like most intermountain basins in the western United States, recharge to the Española Basin in northern New Mexico is uncertain. The U.S. Geological Survey is performing a study in collaboration with Los Alamos National Laboratory and the City of Santa Fe in which noble gas, ground-water age, and temperature data are being employed, along with numerical modeling, to improve constraints on recharge rates and locations for the basin. During the summer of 2005, ground-water samples were collected from 55 different observation wells, supply wells, and springs located throughout the basin, including the adjacent Sangre de Cristo Mountains and Sierra de los Valles. Six deep (800-2200 ft.) temperature profiles along with several discrete shallow-ground temperatures (30-100 ft.) were also measured. Samples were analyzed for major ion chemistry, noble gases (including ^{3}He and ^{4}He), tritium, and carbon-14.

Maximum recharge temperatures (T_{rmax}) were computed from the noble gas concentrations assuming a recharge elevation equal to the sample point elevation. Computed T_{rmax} values range from 3° to 10°C in the mountains, from 4° to 13°C in basin-fill aquifers in eastern and northern parts of the basin, and from 11° to 23°C on the Pajarito Plateau in the southwestern part of the basin. On the Pajarito Plateau, T_{rmax} values are dominantly 19° to 23°C, consistent with stream loss on the plateau or near its western margin, and inconsistent with high-elevation recharge (mountain-block recharge, or MBR) from the adjacent Sierra do los Valles. However, all sampled wells are screened <100 ft. below the water table, so MBR fractions deeper in the Pajarito Plateau aquifers remain unknown. Temperature profiles and discrete ground-temperature measurements indicate that water infiltrating on the basin floor as stream loss in eastern and northern parts of the basin should have a recharge temperature ≥13°C. However, T_{rmax} values in these areas are dominantly 9° to 12°C, indicating that a component of the ground water either recharged at higher elevations as MBR, or recharged >10,000 years ago (at low or high elevation) when the climate was cooler (paleowater). Carbon-14 ages are currently being modeled to help distinguish between MBR and paleowater components, as well as to constrain recharge rates directly using aquifer age gradients. Many of the uncorrected carbon-14 ages are 10,000 to 40,000 years, suggesting that at least some of the cooler T_{rmax} values are likely due to the presence of paleowater. Spatial trends in T_{rmax} (e.g., decreasing T_{rmax} with depth) are also apparent, revealing spatial variations in mixing ratios between stream-loss and MBR/paleowater. Tritium and ^{3}He data indicate that ground-water residence times are dominantly <50 years in the mountains and dominantly >50 years in the basin aquifers, even close to the mountain front and near river beds. ^{3}He concentrations significantly exceed solubility and tritiogenic levels near the axis of the basin, indicating a mantle He source that is probably associated with relatively thin lithosphere and/or major crustal-scale faults underlying the basin. The noble gas, age, and temperature data eventually will be used in conjunction with an existing 3-D, finite element, coupled heat and fluid transport model to improve constraints on recharge and better understand geological controls on mountain-block fluid circulation.

USING ENVIRONMENTAL TRACERS TO UNDERSTAND VADOSE ZONE FLOW IN THE ESPAÑOLA BASIN

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The vadose zone is the region between the land surface and regional aquifer, and plays a critical role in controlling the quantity and timing of groundwater recharge and the chemistry of recharge waters. In most of the Española basin, the vadose zone is composed of thick sedimentary or bedrock units, or both. Because of the semiarid climate, variable water contents, and often extensive unsaturated conditions, it is difficult to quantify downward water movement in the vadose zone using traditional water balance approaches. However, recent applications of environmental tracers such as chloride (derived from atmospheric deposition) and stable isotopes (□^{18}O and □D of precipitation and vadose zone pore waters) have revealed a great deal about vadose zone dynamics in the southwestern U.S. over the past ten- to twenty-thousand years. This talk presents vadose zone environmental tracer results from the Española basin and describes these findings in the context of regional observations from the southwest. Results from the basin indicate that downward fluxes are often low (< 1 cm/yr), and that for at least the last ~1500 years or more, groundwater recharge has been restricted to limited and distinctive landscape positions within the basin (e.g., canyons with perennial streams).

MOVEMENT OF FLOOD IRRIGATION SEEPAGE INTO SOIL AND SHALLOW GROUNDWATER IN AN ALFALFA-GRASS CROP FIELD

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Previous investigation of irrigation ditch seepage effects on shallow groundwater at the NMSU-Alcalde Sustainable Agriculture Science Center in northern New Mexico showed short duration increases in shallow groundwater levels that were clearly attributed to flood irrigation seepage events. In 2004, we initiated a study in an alfalfa-grass crop field to investigate flood irrigation seepage effects on shallow groundwater levels. We measured initial soil moisture, field capacity, and total amount of water applied during flood irrigation. We calculated deep percolation below the 1-m effective rooting zone after five irrigation events in 2005. We measured soil volumetric water content and tracked water seepage into the soil using vertical nests of Time Domain Reflectometry (TDR) soil moisture probes. We collected soil samples and calculated soil gravimetric water content to calibrate the TDR probes. We quantified the total amount of water applied using an insertion flow meter. We collected rainfall and weather data and used the Root Zone Water Quality Model to simulate deep percolation along with other hydrology and evapotranspiration variables. We recorded hourly fluctuations in the water table below the alfalfa field in four 5 cm diameter experimental wells located on the edges and in the middle of the crop field. Similar responses for simulated and field-measured deep percolation were found. Measured deep percolation ranged from 5 cm to 18 cm and simulated deep percolation ranged from 7 cm to 18 cm depending on initial soil moisture and amount of water applied. Increases in water level of up to 38 cm were measured in one well after a particular irrigation event. The peak water level time response varied from 8 hr to 16 hr depending on well location and amount of water applied. Results from this study indicate that seepage from flood irrigation can be a significant source of shallow groundwater recharge in a northern New Mexico irrigated valley.

COLLABORATIVE GROUNDWATER MODELING IN THE SOUTHERN ESPANOLA BASIN

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The County and City of Santa Fe combined efforts to collaboratively build a regional groundwater model of the Santa Fe area that includes new geologic, geophysical and hydrologic data collected in the area over the past 20 years. The model is being used by the County primarily for development of ground water sources as part of a conjunctive use strategy. As part of this strategy, the County will overlay a Decision Analysis while selecting potential well locations. The City is using the model to evaluate long-term aquifer management options, including how to achieve long-term ground water sustainability and the aquifer storage benefits of a 'living' Santa Fe River.

The collaboration was multilevel. At the project management level, County and City staff worked together in managing the project and directing the hired consultants. At the technical level, Intera, consultant to the County, and CDM, consultant to the City, divided up different aspects of modeling and then presented work product for the other to review. A technical advisory group consisting of technical experts from the Office of the State Engineer, New Mexico Bureau of Geology, Los Alamos National Lab, the US Geological Survey, and private consultants was formed to periodically review the work in progress and to provide perspective regarding technical disagreements. The collaboration has resulted in a robust regional model that includes a larger geographic area than previous administrative models, can be used by different entities for different end goals,and will be a useful tool for all of the water resource users in the region to use in analyzing water resource issues over the next decades.

"WHAT SHOULD WE DO *THIS* YEAR?" INTERACTIVE SYSTEMS MODEL FOR WATER-RESOURCE DECISION MAKING IN THE CITY OF SANTA FE

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Santa Fe's WaterMAPS model helps municipal policy-level decision-makers, water utility and resource managers, and operations staff make decisions on how to best manage and conserve water supplies. The City of Santa Fe, with CDM, has developed Santa Fe WaterMAPS (Water Management and Planning Simulation), a STELLA-based water system simulation model that characterizes the relationship between water resources attributes. By maximizing operational use of surface water, for example, the City conserves the groundwater resources for drought protection. The model allows for easy manipulation of highly-variable attributes (e.g. surface water supply, conservation, demand), so that the effects on the behavior on other integral parts of the system, like reservoir storage, groundwater supply, nearby stream systems, or water rights, can be assessed.

The model informs both daily operational and long-range planning decision and gives utility managers and operators the unique ability to test the implications of operations decisions before implementation. In daily operations, the model helps operators choose which source to prioritize for use – particularly in lower demand seasons – based on factors such as historical hydrology, operation and maintenance costs, resource availability, best use of imported water, and effects of groundwater pumping. The model is also a long-range planning tool and has been used to optimize the use of existing supplies and to evaluate which future water supply options will best meet often-conflicting objectives such as cost, reliability, and sustainability.

APPLICATION OF A GEOLOGIC MODEL TO GUIDE PARAMETERIZATION OF A REGIONAL GROUND WATER FLOW MODEL FOR SANTA FE COUNTY

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A study is currently in progress to provide Santa Fe County and the City of Santa Fe with a management tool for evaluation of available water resources within the area. The Santa Fe County's primary objective in developing the management tool is to assess aquifer productivity and sustainability. Ground water flow models provide the best means to quantitatively represent the essential features of the ground water system by means of a mathematical analogue. It has been argued that models are essential to performing complex ground water availability analyses and to making informed decisions (Anderson and Woessner, 1992; Alley et al., 1999; and Bredehoeft, 2002). This study used an integrated approach where semi-quantitative geologic data was reviewed, assessed, and employed to construct a hydrogeologic conceptual framework that was incorporated into a fully quantitative ground water flow model.

The New Mexico Bureau of Geology and Mineral Resources (NMBGMR) and the United States Geological Survey have performed extensive geologic mapping and interpretations in the area. These agencies as well as technical staff of the Office of the State Engineer provided invaluable information and insight into the geology of this area. The available geologic maps, cross-sections and well logs from these sources as well as other consultant reports and mineral exploration wells for the region were reviewed and assessed. In many cases, the geology as mapped in a geologic quadrangle is at a local scale with many members and informal classifications. Our initial task was to correlate numerous geologic columns available from quadrangles and cross-sections and develop a consistent as well as representative hydrostratigraphic column with the focus being to capture enough of the geologic complexity to adequately inform the ground water model.

Geologic controls on the nature and extent of the principle aquifers within the Espanola Basin play an important role in the assessment of water resources. Depositional environments and volcanic events provided the basis for selecting the hydrostratigraphic units (HSUs) included in the representative section. A three-dimensional geologic model based on these HSUs was developed to provide the basis for the numerical flow model. This geologic model is the first of its kind for the area, and was assembled using the Groundwater Modeling System (GMS) software.

A Geographic Information System (GIS)-based methodology was used to integrate a variety of geologic data in support of building the GMS model. The HSUs mapped in GMS were assigned initial hydraulic properties based on the aquifer pumping test database for the area. The three-dimensional geologic solids developed in GMS were used to map hydraulic properties onto the MODFLOW-2000 grid.

An advantage of having the geologic model for the area is that it can be easily updated as new information becomes available. Additionally, the development of the geologic model allows a cohesive basin-wide view that ties together smaller scale studies and graphically identifies data gaps or inconsistencies between datasets.

A METHOD TO IMPLEMENT GROUNDWATER PUMPING IN A REGIONAL GROUNDWATER FLOW MODEL OF THE ESPANOLA BASIN, NEW MEXICO

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The City of Santa Fe and Santa Fe County have collectively developed a groundwater flow model of the region to assist in evaluating water resources alternatives. As a part of the model development a method to implement aquifer pumping over time from various types of wells was developed. In the Santa Fe Regional Groundwater Model, all aquifer pumping is categorized in four ways: municipal, domestic, irrigation or other water systems.

Municipal pumping records and well information was collected for each of the wells in the Santa Fe, Buckman, Los Alamos, Guaje, Pajarito, and El Dorado well fields. The wells in these well fields were simulated explicitly using well screen intervals and historic production records.

The domestic wells were incorporated into the model on a representative basis. The location and spatial distribution of domestic wells were identified using the New Mexico Office of State Engineers (NMOSE) W.A.T.E.R.S. database, however it was assumed that more domestic wells exist than are included in the database. The time for which a domestic well was installed was determined by ‘Start Date’ in the database. Total domestic well production was estimated using Jemez y Sangre Water Plans and NMOSE water use reports. The domestic well production estimates were used with the location information from permitted wells to simulate representative domestic wells in the region over 10-year time periods. The number of representative wells increased to almost 3300 by the year 2000, with a production per well of 0.63 acre-foot per year as representative of total domestic pumping. The domestic wells were assumed to extend into the upper model layer, to 100 feet below static groundwater levels.

Community water systems are well systems that are not specifically identified in the municipal wells and serve a small community or business. Approximately 40 community systems were identified using previous modeling reports and NMOSE Water Use Reports. The time periods and amount of pumping for each well was obtained directly from W.A.T.E.R.S. database, consultant’s reports and other available data. The wells were simulated explicitly using well screen intervals and historic production records, when available, or were assumed otherwise to extend through the upper 3 model layers, to depths of 400 to 1000 feet.

Agricultural wells were identified using the W.A.T.E.R.S. database. These wells were explicitly modeled using their specified diversion amounts, which were assumed to remain constant over time. These wells were assumed to extend into the upper 200 feet saturated deposits.

DEVELOPING ESTIMATES OF HISTORIC AQUIFER RECHARGE FOR REGIONAL MODELING IN THE ESPANOLA BASIN, NEW MEXICO

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The City of Santa Fe and Santa Fe County are collaborating to develop a regional groundwater flow model to use in water resources planning and analysis. One of the inputs to the model is recharge; both as mountain-front recharge contributing lateral inflows to the model and as arroyo-based recharge on the interior lowlands as input in the uppermost model layer. Recharge was varied both temporally and spatially across the model domain based on available data.

Recharge estimates have been developed for the historic period of the model, which extends from the mid-1940's through 2004. The estimates for mountain-front and aroyo-baesd recharge are based on long-term precipitation records for the area. Records from precipitation stations in the Jemez Mountains and in the Sangre de Cristo Mountains were used to compute separate patterns of mountain-front recharge along the west and east sides of the model, respectively. The difference between the precipitation for a given model stress period and the long-term average was determined for each subset of data. This difference was used to scale the average precipitation over time for each model stress period at a given location. Initial values for the spatial distribution of mountain-front recharge were obtained from independent water balance calculations from Wasiolek (1995) and Shomaker (2001) for portions of the Sangre de Cristo Mountains, and from calibrated models for other areas. The initial values ranged from 0.2 to 1.7 cfs/mile of mountain front. The mountain-front recharge was applied across several cells away from the basin-fill deposits and was added to the uppermost saturated layer, which in some cases was below the top model layer.

The estimates for arroyo recharge followed a similar approach to determine temporal variation compared to average values from the long-term records. Spatial variation in arroyo recharge was defined using surface geology and stream drainage density, arroyo width and contributing area for arroyo-based infiltration of precipitation. Arroyo-based recharge ranged from 0.03 to 0.05 inches/yr per unit area. In addition, areas within the model domain that contain irrigated acreage were delineated separately since the volume of irrigation-based recharge can be significant. Irrigated areas identified on Landsat imagery were used in conjunction with County water use statistics to estimate irrigation application. Recharge was estimated at 6 inches per year for these areas.

THREE DIMENSIONAL, TWO-LAYER GROUND-WATER-FLOW MODEL OF THE GREATER CHIMAYO AREA, ESPAÑOLA BASIN, NEW MEXICO

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As part of a water-supply study, John Shomaker & Associates, Inc. is currently developing a ground-water-flow model for the Greater Chimayo Mutual Domestic Water Consumers Association (Greater Chimayo MDWCA).

The ground-water model covers 28 square miles in the Santa Cruz River and Rio Quemado valleys near Chimayo, and consists of two layers with 94 rows and 120 columns. The first layer represents Quaternary-age alluvial deposits, and has an average thickness of 55 ft. The second layer represents the Tesuque Formation, and Proterozoic-age igneous and metamorphic rocks, and has an average thickness of 582 ft. Hydraulic conductivities for Layer 1 range between 5 and 20 feet per day (ft/day) with areas of high hydraulic conductivities along the Santa Cruz River. Hydraulic conductivities for Layer 2 range between 0.03 ft/day for Proterozoic-age rocks and 0.1 ft/day for the Tesuque Formation.

Model boundary conditions include stream boundaries, river boundaries, and general-head boundaries. More than 50 irrigation ditches were digitized from the Upper Rio Grande Hydrographic Survey[1], and are modeled using the MODFLOW Stream package. The Santa Cruz Reservoir is modeled using the MODFLOW River package. General-head boundaries along the first and last model column allow ground-water inflow from the Sangre de Cristo Mountains and outflow into the Española Basin.

The calibrated ground-water model will be used to evaluate ground-water development scenarios for the Greater Chimayo MDWCA that will address the quantity of ground water that can be produced from the Chimayo area, and the potential effects of producing water for the Greater Chimayo MDWCA system.

[1] New Mexico State Engineer Office, Upper Rio Grande Hydrographic Survey Report, Volume 1, Santa Cruz River Section

LATE MIOCENE SEDIMENTARY ROCKS BENEATH THE CENTRAL PAJARITO PLATEAU: RESULTS FROM RECENT BOREHOLE INVESTIGATIONS

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Stratigraphic and geochronology studies for drill holes and outcrops yield new information about the upper Miocene depositional history of the western Espanola basin. Four informal lithostratigraphic sedimentary deposits are recognized beneath the Pliocene Puye Formation fanglomerate based on lithologic variations and age constraints.

The youngest Miocene rocks are pumice-rich volcaniclastic sediments that are about 120 m thick. They consist of well-bedded horizons of light-colored, reworked tephra-rich sedimentary deposits and subordinate primary ash and pumice falls. These deposits typically contain up to 30% subangular to rounded, poorly phyric, rhyolite pumice lapilli admixed with 70 to 90% ash and volcanic lithic sand. Intercalated gravel and cobble beds contain subangular to subrounded porphyritic dacite, rhyolite and subordinate andesite and basalt. Eight 40Ar/39Ar ages from pumice falls within these deposits yield ages between 6.44 ± 0.46 Ma and 7.92 ± 0.60 Ma. The age and compositions of these intercalated pumice falls suggest the deposits are coeval with volcanism associated with the Bearhead Rhyolite. Oriented geophysical logs indicate the mean dip of these deposits is about 5° to the south and southwest, significantly different from the westerly dips of Miocene rocks exposed east of the Rio Grande.

River gravels occur beneath the pumice-rich volcaniclastic sediments in several drill holes. These river deposits are 10 to 30 m thick and include unconsolidated well-sorted sands and well-rounded gravels. Gravel clasts include well-rounded quartzite and metavolcanics (minor) as well as subangular to subrounded basalt, andesite, and dacite. These deposits are generally similar to the river deposits of the Totavi Lentil at the base of the Puye Formation, but they are stratigraphically lower and granite clasts are rare to absent. The occurrence of these fluvial deposits containing rounded Precambrian clasts indicate that through-going rivers were established in the western Espanola basin prior to deposition of the pumice-rich volcaniclastic sediments.

About 420-500 m of volcaniclastic sands and gravels underlie the old river gravels and pumice-rich volcaniclastic sediments. These deposits represent alluvial fans shed from the Miocene Jemez Mountains and consist of volcanic detritus of intermediate composition derived from Keres Group rocks and possibly from early Tschicoma Formation centers. The deposits are characterized by dark lithic sandstones and gravel and cobble deposits with subangular to rounded clasts. Intercalated basalts have 40Ar/39Ar ages between 8.45 Ma and 8.97 Ma. Local quartzite-rich beds in this unit may represent either interfingering with a quartzite-rich, axial river (newly proposed Hernandez Member) or reworking of older quartzite-rich gravel deposits from an unknown source area in the Jemez Mountains. The older volcaniclastic deposits overlie a thick sequence of older rift deposits that consist of silts and sands (with minor pebble beds) from both arkosic and volcanic sources. Basalts in these older fine-grained units yield 40Ar/39Ar ages of 10.9 Ma to 13.1 Ma.

THE 2001 AIRBORNE ELECTROMAGNETIC SURVEY OF THE PAJARITO PLATEAU AND ITS APPLICATION TO GROUNDWATER INVESTIGATIONS

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An airborne electromagnetic (AEM) survey was performed during early September, 1991, in order to characterize the electrical conductance beneath the Pajarito Plateau. The goal of this survey was to identify relevant zones of electrical conductance that could possibly help define the subsurface distribution of groundwater and groundwater pathways beneath the Los Alamos National Laboratory. Approximately 760 line-kilometers of data were obtained along flight lines that traverse the plateau at intervals of approximately 100 or 200 meters. The MegaTEM system, the deepest penetrating of available AEM systems, was used to collect time-domain, EM measurements.

The measurements have been processed by three, one-dimensional inversions or imaging methods to provide two-dimensional plots which model the conductivity/resistivity at depths along the flight lines, or at constant horizontal depths. The three inversion methods use standard flat-layered inversion models, and do not consider possible conductivity constraints provided by the existing three-dimensional hydrogeologic models for the Pajarito Plateau. However, these layered inversion results do allow an unbiased comparison of conductance with features of the hydrogeologic model.

The potential value of these AEM data and conductance models to LANL groundwater activities was evaluated through their comparison with well-constrained portions of the hydrogeologic and groundwater models for the Pajarito Plateau. The data of the three AEM inversion models were interpolated to three-dimensional grids of electrical resistivity. Known hydrogeologic features and EM induction well logs were characterized as three-dimensional objects and visually compared with the grids of the airborne EM resistivity models.

Preliminary results of visual and numerical correlations studies for these objects provide a measure of the possible hydrogeologic characterization obtainable by AEM surveys. A detailed report about our investigations will be available later in the year.

MONITORING THE ESPAÑOLA BASIN AQUIFER USING TIME-LAPSE GRAVITY MEASUREMENTS

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We have used time-lapse absolute gravity measurements, in conjunction with highprecision GPS measurements, to monitor the aquifer underlying the Española basin. We began measurements in February 2003 and continued until January 2006. Measurements were acquired using Microg-LaCoste Model A-10 absolute gravity meters, supplemented by Scintrex CG-3M and CG-5 relative gravimeters. At good sites, reproducibility of the A-10 measurements was ±4 μ Gal. Our results indicate definite trends in three sub-regions of the basin: the Pajarito Plateau (Los Alamos County), Santa Fe's Buckman well field, and the Española-Pojoaque area. Of these three subregions, data clearly indicate storage losses as well as accompanying subsidence in the Española-Pojoaque area.

Two very different trends were measured in the vicinity of the Buckman well field and the nearby Los Alamos well fields. During 2003 and 2004, both ground surface elevations and measured gravity (corrected for elevation changes) increased, suggesting a storage increase. A conceptual model of water table rise and deeper leaky-confined aquifer expansion explains these data and is consistent with measured hydraulic head changes at piezometer nest SF-2. During this same time period, both ground surface elevations and measured gravity (corrected for elevation changes) decreased just to the west in the vicinity of White Rock. These storage changes may be related to heavy pumping in the most southerly Los Alamos water supply wells. We present calculations bracketing the range of possible storage changes in relation to temporal trends in water production at these two well fields and inferences regarding aquifer properties, recharge, and discharge.

A THREE-DIMENSIONAL GEOLOGIC MODEL OF THE PAJARITO PLATEAU

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A new, three-dimensional geologic framework model is presented for the Pajarito Plateau. This model is the latest in a series of 3-D geologic models that have evolved over the past 10 years and represents our most detailed configuration of the geometry of the subsurface geologic contacts, or geologic framework, for the region. The model incorporates surface contacts from new geologic quadrangle mapping and GPS-based surface mapping, as well as new subsurface contacts obtained from characterization and monitoring wells of the Environmental Restoration and Groundwater Monitoring Programs at Los Alamos National Laboratory. New data for the age of fanglomerate units and newly identified outcrops of older dacitic volcanic units within the north-central portions of the Plateau justify significant revisions of earlier 3-D geologic models of the 4-quadrangle area that encompasses the Plateau. The new model is comprised of 28 geologic units and subunits representing the complex intermix of sedimentary and volcanic rocks within the active Rio Grande Rift system.

This geologic framework model provides the spatial controls necessary for the assignment of physical hydrogeologic properties, when modeling groundwater flow and contaminant transport beneath the Plateau. The model is also incorporated into a larger, lower-resolution model used for groundwater studies of the Española Basin.

We identify the control data used to create the individual surfaces of this new model and illustrate the fit of the computed grid surface to the control data. We detail the processes used to develop the individual contact surfaces and to blend these surfaces into the new, coherent, self-consistent geologic framework model. And finally, we provide various views of the modeled subsurface geology below the plateau. A more-detailed report of this model will be available later in the year.

GEOPHYSICAL LOG ANALYSES OF THE YATES LA MESA UNIT # 2 AND #3 OIL TESTS, SOUTHERN ESPANOLA BASIN

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Located north- and south- west of Santa Fe, the Yates La Mesa Unit # 2 And 3 wells were drilled on seismic petroleum prospects in the mid 1980's. The borehole Electrical and Lithodensity logs for each well were examined in detail and compared to reported formation tops and interpretations.

The electrical logs in each well are excellent for identifying bed boundaries and formation tops. They also help identify relatively porous and permeable units. Combining all logs allows estimates of lithology, porosity, and native water resistivity where borehole conditions are optimum and unit thickness exceeds about 15 feet. Density – Photo Electric effect crossplots were created of representative units in both wells. The differentiation of lithologies was found to be best resolved in indurated rocks beneath the Santa Fe group.

Within the YLM 2 Tertiary section only an uncentralized neutron-gamma ray log was run through cemented casing to approximately 4000'. A heavily filtered version of the digitized dataset was created and appears to portray some distinctive intervals in the deeper Santa Fe group, including a formation change below approximately 3000 feet. The casing was run into the top of volcanic rocks presumed to be Espinaso Formation. The crossplot and mudlog portrays approximately 1600 feet of interbedded volcanics and volcaniclastic units overlying bedded, predominantly calcareous sedimentary rocks. The well bottomed in granite at 7704 feet, which is also distinctive in the crossplot. The YLM-2 was plugged, leaving the casing through the Santa Fe group intact. This well has been identified as valuable to reenter and complete as a multilevel monitoring well. The deep strata should be roughly correlative to City of Santa Fe production wells. Unfortunately, it lies on private property.

In the YLM 3 the Tertiary section is extremely heterogeneous, tends to wash out, and possesses few distinctive, thicker intervals. The Santa Fe group (app. 960 feet thick including Ancha formation), the Espinaso Formation (app.1360 feet thick) and the Galisteo Formation (app.1400 feet thick) are distinctive. Most of this interval is very thin bedded and SP and electrical invasion profile criteria do not indicate high porosity and permeability. The Tertiary sediments are not cross cut by volcanics, yet the Galisteo formation lies immediately on top of a thick volcanic unit. The sill? possesses anomalously high gamma ray radioactivity, and very uniform high resistivity.

The Jurassic Morrison section lies beneath this massive 610 foot' sill. The Mancos shale is absent or replaced. The Morrison through Entrada thicknesses may be exaggerated by dip compared to measured sections elsewhere. Several sandstones within the Jurassic section are porous and permeable, although they appear to possess poor water quality. This well bottomed at the top of the Chinle.

MODELING THE GEOLOGICAL AND GEOPHYSICAL FRAMEWORK OF THE SOUTHERN ESPAÑOLA BASIN NEAR SANTA FE, NEW MEXICO

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We are using geologic and geophysical data to model the three-dimensional (3D) geometry and subsurface structure of the southern Española rift basin as a framework for hydrogeologic study and application. The benefits of such models are the ability to visualize independent geologic features from many orientations to (1) allow researchers to test geologic concepts in 3D space and (2) help non-specialists understand complex spatial relationships among geologic elements of the model. Our 3D geologic model utilizes Earthvision™ software (Dynamic Graphics Inc) that allows multiple surfaces to represent the distribution and thickness of geologic units, offset of these surfaces along faults, and display of subsurface control data (well picks, geophysical inversions, etc). A digital elevation model (DEM) of topography forms the top of the model. The rift basin is primarily filled with undivided Tesuque Formation (late Oligocene-Miocene). The base of the rift basin is modeled from depth inversions to the top of strongly magnetic Oligocene volcanic and volcaniclastic rocks (Espinaso Formation and Cieneguilla Basalt) derived from high-resolution aeromagnetic surveys. Structurally, the basin model has an overall form of a north-plunging syncline that rises across a buried escarpment to a shallow subsurface shelf in the Santa Fe Embayment. At the north end of the basin model, where basal magnetic layers are too deep to have strong signature, control points are derived from cross sections drawn using geologic, gravity, and shallow aeromagnetic constraints. Internal structures of the model include >20 faults that have sufficient length and offset to likely affect the basin geometry. A central zone of discontinuous faults transects the basin length and includes the San Ysidro Crossing fault zone, which has a known hydrologic head drop across it. The southwestern flank of the model incorporates an eastward dip that probably reflects protracted footwall uplift of the La Bajada fault zone before eruption of the mostly 2.8-2.4 Ma Cerros del Rio volcanic field (also imaged along the western flank of the model). Subsurface picks for the base of the Ancha Formation (Pliocene-early Pleistocene) derived from water-well data are included in the model to visualize its thickness and extent as well as identify potential faults that affect it.

Recently obtained aeromagnetic data along the eastern flank of the basin and adjacent Santa Fe Range will help revise the fault framework of this area. For example, preliminary interpretations indicate that both the Seton Village and Hondo faults truncate against a major north-northeast-striking basement fault zone just west of the Santa Fe range front. Understanding the structure of the mountain front is important for better characterizing recharge between the mountain-block and rift-basin aquifers.

A GIS-BASED DECISION SUPPORT SYSTEM FOR IDENTIFYING POTENTIAL SUPPLY WELL LOCATIONS

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INTERA is currently working with Santa Fe County and the City of Santa Fe to develop a regional groundwater availability model. INTERA has developed a decision support system (DSS) to be used in conjunction with the groundwater availability model to assist the County in evaluating potential well locations for ground water supply sources to supplement surface water in a conjunctive use strategy. The groundwater availability model is being used as part of a site suitability analysis DSS to evaluate the potential impacts associated with proposed supply well locations. Using a geographic information systems (GIS) approach, the DSS has identified potential supply well locations for the County that minimize impacts (and hence proximity) to existing supply wells, streams, and springs, while maximizing proximity to existing infrastructure, population centers, and areas of favorable geology and land ownership. This approach will provide County decision-makers and the public with a structured, scientifically defensible, and unbiased method of identifying potential supply well locations.

LOCATIONS AND TEXTURAL CONTRASTS OF TESUQUE FORMATION LITHOSTRATIGRAPHIC UNITS IN THE SOUTHERN ESPAÑOLA BASIN, NM, AND HYDROGEOLOGIC IMPLICATIONS

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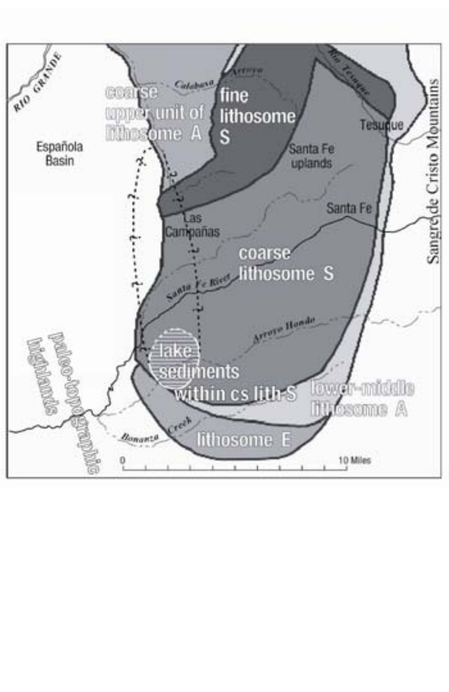
In the southern Española basin, four lithostratigraphic units of the Tesuque Fm (late Oligocene-late Miocene), representing depositional systems of unique provenance, are identified and described using outcrops and wells. Their mapped locations are shown in the accompanying figure. Lithosome S is mostly a pebbly sand, with increasing mud beds to the northwest, deposited by an ancestral Santa Fe River sourced east of the Picuris-Pecos fault. The approximate southern boundary of lithosome S is immediately north of modern Bonanza Creek. Near the N.M. State Penitentiary, this boundary turns northwestward towards La Cienguilla. The southern lithosome S boundary laterally grades into sand and silty sand of lithosome A, which drained granitic highlands in the southern Sangre de Cristo Mtns and coarsened in the latest middle Miocene. Neither lithosome S nor lithosome A is present in exposures of strata along the La Bajada escarpment to the west of the southern Española basin. Their absence there is consistent with a paleo-topographic high trending approximately north-south between the Cerrillos Hills and Tetilla Peak. Lithosome E is generally a muddy sand derived from erosion of Cieneguilla Basalt and Espinaso Formation on the eastern flanks of the paleo-topographic high and highlands south of the basin. The fourth lithosome consists of thick clay and sandy clay (possibly as much as 500 ft) observed in wells north of Arroyo Hondo in the vicinity of the Santa Fe Airport and likely continuing an unknown distance to the NNW. We interpret that the clay was deposited in a lake or playa in a closed basin, possibly during a time of rapid tectonic subsidence during the middle(?) Miocene.

Hydraulic conductivity values, derived from aquifer test data, appear to reflect the gross textural differences between these four lithosomes. For example, the coarse part of lithosome S is the coarsest of the aforementioned units (with the possible exception of the coarse upper part of lithosome A) and possesses the highest mean conductivity (7 ft/d). The grossly finer, lower-middle part of lithosome A exhibits a relatively low conductivity value of 0.4 ft/day, which is similar to the finer portion of lithosome S located north of Las Campañas. Limited data (one test value) for lithosome E suggest a hydraulic conductivity as low as 0.005 ft/d. The approach of quantifying means and ranges of hydraulic conductivity for each unit may provide improvements for regional groundwater flow models and support limits for sensitivity testing.



LATE OLIGOCENE-MIOCENE STRUCTURES IN AND WEST OF THE SANTA FE EMBAYMENT, NEW MEXICO, AND INFERENCES REGARDING TECTONISM AND PALEOTOPOGRAPHY

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Study of well cuttings and outcrops south and southwest of Santa Fe, New Mexico, allow insights about three important structural features in and west of the Santa Fe embayment, as well as inferences regarding paleotopography and tectonic activity in the late Oligocene-Miocene.

The first structural feature is the Cerrillos uplift, bounded on its west side by the proto La Bajada (i.e., Tetilla) fault zone. Along the La Bajada escarpment between the Santa Fe River and Tetilla Peak are exposures of middle(?) Miocene fluvial strata consisting of overbank sediment intercalated with coarser channel fills containing latitic gravel; paleosols are lacking and paleoflow indicators indicate a predominant WNW transport direction. These strata reflect erosion of older Espinaso Fm from a structural and paleotopographic high (the Cerrillos uplift) that trended N-S between Tetilla Peak and the Cerrillos Hills. Farther east, fans of volcaniclastic detritus (basalt and latite gravel, sand, and mud of lithosome E, Tesuque Fm) shed from these highlands extended towards the center of the Santa Fe embayment in the late Oligocene but receded westward in the Miocene, perhaps due to progressive erosion and lowering of these highlands during the Miocene.

Second, stratigraphic correlations from well data agree with previous aeromagnetic, gravity, and seismic reflection data (Black, 1984) indicating a north-plunging, broad syncline near the center of the embayment under the Plio-Pleistocene Ancha Fm. Slight thickness changes in early-middle Miocene units suggest that this syncline was actively subsiding during the early-middle Miocene.

Third, our data support the existence of a north-facing, curvilinear hinge line near the modern Bonanza Creek (Phillips and Grauch, 2004). South of this hinge, erosion caused significant paleotopographic relief (as much as 110 m) on top of the Espinaso Fm prior to burial by rift-basin fill in the Miocene through Pleistocene. At the New Mexico State Penitentiary, late Oligocene-Miocene basin-fill strata of the Santa Fe Group strike 270-275°, with calculated dips of 7-8°N for the top of lithosome E and overlying Tesuque Fm. A subunit within lithosome E thickens slightly to the north, which is suggestive of syn-depositional tilting. The top of the underlying Espinaso Fm dips greater than 14°N, implying that northward tilting in this part of the basin occurred between deposition of the Espinaso Fm and lithosome E (i.e., within the late Oligocene through early Miocene), although this interpretation is complicated by erosional paleotopography. The approximate coincidence of a younger depositional boundary between lithosomes A and S of the Tesuque Fm with the hinge line implies that early-middle Miocene tectonic tilting continued along this line.

We also infer the following from these relations: 1) the lack of paleosols and the preservation of fining-upward packages of channel fill-overbank deposits in middle(?) Miocene strata west of the Cerrillos uplift suggest that basinal deposition was relatively continuous on the downthrown, west side of the proto La Bajada fault zone, which was probably located 2-4 km east of the modern La Bajada fault zone; 2) the syncline in the Santa Fe embayment may have resulted from flexure during protracted footwall uplift along the La Bajada fault zone; and 3) formation of the Cerrillos uplift was probably due to a combination of this footwall uplift and remnant constructional topography from Oligocene shallow intrusions and volcanism.

GEOLOGICAL CHARACTERIZATION OF FAULT ZONES FROM OUTCROP OBSERVATIONS IN THE ESPAÑOLA BASIN, NEW MEXICO: IMPLICATIONS FOR GROUND-WATER FLOW

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We have examined map to outcrop scale exposures of fault zones at 50 widely spaced localities in the central and northern parts of the Española rift basin to help characterize their potential affects on ground water. The intrabasin faults are concentrated in the east side of the basin where they form part of a broad, north-trending system of normal faults that cut poorly to moderately consolidated, siliciclastic, basin-fill sediments of the late Oligocene-Miocene Tesuque Formation.

Statistical analysis of field data indicates internal structural components of basin fault zones include: (1) a narrow (≤10cm; 3.7cm average width) central core that has accommodated most of the shear displacement; (2) somewhat wider (0.1-1m) zones of sediment entrainment and less commonly grain-scale mixing that flank one or both sides of the core; and (3) relatively wide (1-20m) outer damage zones containing deformation bands, small-displacement (<3m) faults, and rarer veins and joints with strikes subparallel to the fault core. Most fault cores (91%) are composed of foliated clay and lesser sandy to pebbly clay that have very low permeability based on previous permeametry data from similar clay fault cores in the Albuquerque basin. Although most fault cores are narrow, their widths can vary two- to three-fold within a single exposure. The width of one unusually thick clay core in an outcrop in Arroyo de la Presa (northwest part of basin) ranges from 60 to 130cm.

Faults having normal to oblique-normal slip (50°-90° slickenline rakes) on steeply west- and east-dipping surfaces are typical in the basin. Dextral slip components are concentrated on north-striking (350°-010°azimuths) oblique-slip faults, whereas sinistral slip components are common on north-northeast-striking (010°-040°) faults. However, there is considerable overlap of sense of strike slip on faults with intermediate azimuths, and some faults exhibit multiple sets of slickenlines with both dextral and sinistral components.

Carbonate and silica cements are observed in some fault zones, usually within the narrow zone of sediment entrainment on one side of the fault core. A variety of oxide and hydroxide minerals typically also are present within fault zones concentrated along the eastern flank of the basin. Cements are usually present in sand-rich sediment, but locally veins of carbonate, silica, or, rarely, gypsum have cut the cemented zone or the uncemented fault core. The asymmetric cement distributions within fault zones suggest that the central low-permeability cores restricted paleo flow of the cementing fluids. Laterally persistent cements in fault zones likely further reduce cross-fault permeability.

This study builds on our similar recent fault investigations in the Albuquerque basin that revealed consistent characteristics and statistical ranges of fault zone features, particularly persistent clay-rich cores, which likely create large intrabasin heterogeneity of permeability. That faults within the Española basin can act as barriers to ground-water flow, a conclusion reached from work in the Albuquerque basin, is demonstrated by the clay-cored San Isidro Crossing fault near Santa Fe, which coincides with a marked head gradient adjacent to an area of concentrated ground-water pumping.

MAGNETOTELLURIC SOUNDINGS CONSTRAIN INTERPRETATIONS OF SUBSURFACE GEOLOGY OF THE ESPAÑOLA AND ALBUQUERQUE BASINS, NEW MEXICO

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Magnetotelluric (MT) soundings, calibrated by sparse borehole geophysical data, significantly improve geologic constraints for mapping subsurface stratigraphy and lithology in the Rio Grande Rift near Santa Fe, Albuquerque, and Los Alamos, New Mexico. Borehole geophysical records of deep wildcat petroleum exploration wells in the Albuquerque and Española basins provide a unique borehole geophysical dataset compared to other Miocene and younger alluvial basins in the southwest United States. Many of the borehole logs extend to 1.5-3 km depth, and a few to 5-7 km, much deeper than the well-documented borehole log record of the 450-600 m deep production water wells in the Albuquerque basin. Careful examination of the geophysical log response to lithology and porosity of Precambrian crystalline rocks, Pennsylvanian-Permian, Mesozoic, and Tertiary sedimentary rocks in the northern New Mexico region permits construction of physical property-based stratigraphy. Oligocene, Miocene, and Pliocene igneous rocks, encountered in a number of holes, also have distinctive physical property signatures.

In the Española basin, MT soundings, located southeast of Española, are near the Castle and Wigzell Kelly Federal # 1 well (TD 2703') that bottomed in Pennsylvanian carbonates. MT soundings south of Los Alamos are near Yates Petroleum La Mesa Unit #2 (TD 7710'). South of Santa Fe in the Santa Fe embayment and in the Hagan basin, MT soundings are near digitized Pelto Ortiz #1 (TD 7450'), Pelto Blackshare # 1 (TD 7025'), TransOcean McKee #1 (TD 8128'), and Black Ferrill #5 (TD 4252'). These wells provide significant new geologic and physical property information on Cenozoic sedimentary and igneous rocks for the Galisteo and Diamond Tail Formations (4645' thick in Pelto Ortiz #1), Santa Fe Group, Espinaso Formation, Galisteo Formation in Pelto Blackshare #1, and for older Mesozoic and Paleozoic sedimentary rocks in the TransOcean McKee #1 and Black Ferrill #5 exploratory wells. In the Albuquerque basin, MT soundings located west of Bernalillo are near Shell Santa Fe Pacific #1 (TD 11045'), Shell Santa Fe Pacific #3 (TD 10276'), and Davis Tamara 1Y (TD 8732'). West of Albuquerque, MT soundings are near Shell Laguna Wilson Trust #1 (TD 11115'), Burlington Westland 1Y (TD 7778'), Shell West Mesa Federal #1 (TD 19375'), UTEX Westland #1 (TD 16665'), and Shell Isleta #2 (TD 21266').

Preliminary evaluation of the well data indicates that the Galisteo and Diamond Tail Formations are not as clay and mud-rich as in measured sections currently published for these units in the literature. These physical property data, especially for resistivity and density of a number of Cenozoic stratigraphic units, provide important constraints for regional geophysical investigations of the Española basin and Santa Fe embayment. MT data for Santa Fe Group and the Galisteo Formations below the water table were moderately conductive (>10 ohm-m), while Tertiary igneous rocks were resistive (>100 ohm-m). Resistivity data for the Mancos Shale indicate that it is a strong (3-10 ohm-m) electrical conductor. Where the Mancos occurs in the upper kilometer of crust it may function as local hydrogeologic basement. Permian rocks generally had both conductive and resistive signatures, while Pennsylvanian carbonates and Precambrian crystalline rocks were resistive (>300 ohm-m).

VOLCANIC, TECTONIC, AND SEDIMENTOLOGICAL FEATURES IN THE GUAJE CANYON WELL FIELD OF THE PAJARITO PLATEAU, ESPAÑOLA BASIN

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The Guaje Canyon well field of north-central Pajarito Plateau contains 11 wells that supplied water to the towns of Los Alamos and White Rock and the Los Alamos National Laboratory since the early 1950s. These wells ranged in depth from 270 to 950 m (886- 3116 ft) and penetrated the main aquifer of the plateau (Purtymun, 1995). The well field lies east of the Pajarito fault zone and only four of the supply wells developed in the late 1990s are currently active.

The stratigraphic sequence within the well field varies from east to west. The stratigraphic sequence consists of fanglomerate of the Puye Formation that overlie undifferentiated sedimentary deposits of the Santa Fe Group. The coarse clastic sedimentary rocks in the upper part of the stratigraphic sequence mostly consist of volcaniclastic sediments eroded from the adjacent Jemez Mountains, whereas the undifferentiated fine- to medium-grained sedimentary rocks of the Santa Fe Group contain significant amounts of sediments derived from non-volcanic provenance to the north and east of the Pajarito Plateau.

Middle Miocene (11.55-13.18 Ma) high-alumina basaltic and basaltic andesite flows occur within the upper part of the undifferentiated sedimentary rocks of the Santa Fe Group. The middle Miocene volcanic rocks represent the second episode of volcanism in the Jemez Mountains following the localized late Oligocene to early Miocene basanite eruptions that are confined to the southern part of the volcanic field. The basaltic and basaltic andesite eruptions appear to be fissural in origin and were controlled by faults that were intermittently reactivated. In the Guaje Canyon well field, the number of volcanic flows increases westward to the Pajarito fault zone that defines the western boundary of the Española Basin. Sedimentary rocks of the Puye Formation also thicken toward the western boundary fault. The westward increase of volcanic flows and thickening of the overlying sedimentary deposits suggest faulting, subsidence, and contemporaneous volcanism and sedimentation adjacent to the rift margin since the middle Miocene. The Plio-Pleistocene Pajarito fault and its subsidiaries represent reactivated tectonic features at close proximity to middle Miocene faulting and volcanic activities.

The Guaje Canyon well field is bounded by uplifted middle to late Miocene basaltic and andesitic outcrops on the north and south sides, respectively. Moreover, the field is cut by north-south-trending normal faults that displaced the sedimentary and volcanic rocks down-to-the west, creating localized marginal grabens along the foothills of the western rift margin and down to the east step-faulted blocks. Faulting and subsidence of the sedimentary rocks and interbedded fractured lava flows along the foothills of the western rift margin probably provided pathways for recharge, subsurface flow, and reservoir in the Guaje well field and surrounding areas.

GEOLOGIC MAP OF THE ALBUQUERQUE-RIO RANCHO METROPOLITAN AREA, NEW MEXICO: REGIONAL COMPARISIONS

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The recently released *Geologic Map of the Albuquerque-Rio Rancho Metropolitan Area and Vicinity, Bernalillo and Sandoval Counties, New Mexico* (Connell, 2006; NM Bureau of Geology and Mineral Resources, Open-file Report 496, scale 1:50,000) is the culmination of more than a decade of detailed geologic mapping and stratigraphic and geomorphic work in the most populous part of the Albuquerque basin. Refinements made to the Neogene stratigraphy of the Albuquerque basin delineate an important stratigraphic boundary between upper Miocene and Pliocene deposits that have implications for regional correlations. A Mio-Pliocene disconformity, called the Rincones surface, is exposed along the northwestern margin of the Albuquerque basin, where it locally exhibits strongly developed paleosols with stage III to V pedogenic carbonate morphology. Elsewhere along the basin margin, this contact is sharp and lacks significant soil development. This disconformity is overlain by upper Pliocene (to possibly lowest Pleistocene(?)) fluviatile deposits of the Ceja Formation. East of the Rio Grande Valley, it is overlain by Plio-Pleistocene deposits of the ancestral Rio Grande (Sierra Ladrones Fm). Subsurface correlations indicate that the Ceja Formation thickens toward the basin depocenter, and the base of the Atrisco Member (Ceja Fm) overlies this boundary in deeper water-supply wells. The character of this contact is poorly understood in the subsurface, but available borehole geophysical logs suggest that it is relatively sharp.

The presence of Mio-Pliocene lacunae along the margins of the Socorro, Albuquerque, and Española basins provides a tectonostratigraphic basis for interbasinal correlation. Mio-Pliocene basin-margin stratigraphic discontinuities are commonly angular in character and include boundaries between the Sierra Ladrones/Popotosa Fm (Socorro basin), Ceja-Sierra Ladrones/Arroyo Ojito Fm (Albuquerque basin), Tuerto/Blackshare Fm (Hagan embayment), and the Ancha/Tesuque Fm and distal Puyé/Tesuque Fm (Española basin). These disconformities are likely diachronous, and the magnitude of diachroneity is interpreted to be controlled by stratigraphic onlap of overlying, generally coarser grained, commonly weakly consolidated, fluviatile sediments during Pliocene and early Pleistocene times.

MIDDLE TO LATE CENOZOIC STRATIGRAPHY AND STRUCTURE ACROSS THE NORTHERN JEMEZ MOUNTAINS, NEW MEXICO

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Geologic mapping in the northern Jemez Mountains over the past 3 years (2002-2005) has yielded numerous insights into the Miocene-early Quaternary volcanic and sedimentary history of the region. A geologic map of three contiguous 7.5-minute quadrangles (Cerro del Grant, Polvadera Peak, and Vallecitos) is presented, accompanied by an east-west cross-section that depicts the region's stratigraphic and structural trends. In addition, observations from the Youngsville and Cañones 7.5-minute quadrangles are discussed. In approximate stratigraphic chronology, our observations include:

1. The fluviatile Chama-El Rito Member of the Tesuque Formation extends westward to at least Cañones Canyon, southwest of the village of Cañones. The eolian Ojo Caliente Sandstone Member of the Tesuque Formation extends as far west as Coyote Creek.
2. Widespread deposition of the eolian Ojo Caliente Sandstone Member was followed by an episode of fluvial activity that deposited gravel of felsic-intermediate volcanic clasts and minor quartzite; these gravels may correlate with the Hernandez Member of the Chamita Fm. These gravels are present just below 7.8 to 7.9 Ma basalt at Encino Point and Mesa Escoba. Furthermore, the gravels form a lag deposit on top of the basalt capping the east end of Mesa Escoba, and a phreatomagmatic deposit containing gravel is preserved at Encino Point, suggesting that fluvial and mafic volcanic activity were coeval.
3. Two major rift-related fault zones – the Cañones fault zone and faults east of Lobato Mesa – displace the upper surface of the Ojo Caliente Sandstone Member down-to-the east by >1000 meters from west of Cañones Canyon to lower Rio del Oso. Rift-related faulting with down-to-the-east offset on the order of 60 m (e.g., Coyote Creek fault) persists tens of kilometers west of the Cañones fault zone into the Chama Basin. The 1.2 Ma Tshirege Member of the Bandelier Tuff is offset down-to-the-east ~2 to 5 m by an unnamed fault immediately west of Cañones Canyon on the Cerro del Grant quadrangle.
4. A wide range of fluvial and volcanic deposits are preserved on Mesa El Alto, south of Abiquiu, including the Puye Formation, a condensed (< 1 m) section of the Otowi Member fo the Bandelier Tuff, and obsidian-bearing Quaternary alluvium that rests on Guaje(?) pumice that may correlate to the Cerro Toledo interval .
5. Major volcanic pulses across the northern Jemez over the past 10 million years show a migration of volcanic focus from east (Lobato – Santa Clara area) to west (La Grulla Plateau) to east again (Tschicoma Peak – Cerro Pelon), ending with eruptions of El Alto basalt and El Rechuelos rhyolite.
6. The relatively low topographic region between the 3-5 Ma Tschicoma volcanic center to the east and 7-8 Ma La Grulla Plateau volcanic center to the west provided the main corridor for northward-directed pyroclastic flows of the Upper and Lower Bandelier Tuffs.

MIDDLE PLEISTOCENE EVOLUTION OF THE UPPER RIO GRANDE: COLORADO'S GIFT TO NEW MEXICO

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Prior to 300,000-400,000 years ago, the upper Rio Grande had most of its headwaters in northern New Mexico. Conversely, upper reaches of the current Rio Grande, which includes about 18,000 km^2 in southern Colorado, emptied into Lake Alamosa. This lake formed in the middle(?) Pliocene, most likely due to downstream blockage by Servilleta flood basalts between 3.7 and 4.7 Ma. These findings are a result of ongoing geologic mapping of the Alamosa and Wheeler Peak 1:100,000 scale quadrangles and new aeromagnetic data for the San Luis Basin (SLB).

On the western side of the SLB, Servilleta basalt lies at the surface as far north as Antonito, Colorado. New aeromagnetic data suggest the subsurface basalt flows continue much farther northward, to near the northwestern margin of the San Luis Hills. The aeromagnetic expression of the basalt becomes more muted northward into Colorado, where they are progressively buried by Quaternary deposits and older closed-basin sediment (Alamosa Formation). Drill holes between Antonito and Alamosa confirm basalts at depths of 30-200 m at least as far north as La Jara, Colorado.

Servilleta basalt is preserved on the eastern side of the SLB beneath the Costilla Plain, on San Pedro Mesa, and in the Culebra graben as far north as Fort Garland, Colorado. Drill-hole data show that basalt extends to Blanca in the shallow subsurface, but its northwestward extent is unknown. In New Mexico, drill holes north of Questa show that the Servilleta basalt is covered by Pliocene lake deposits (Lake Sunshine) and hundreds of meters of Quaternary alluvium.

Thus, by middle Pliocene time, the southern half of the SLB was covered by basalts that were erupted from the Taos Plateau and completely buried prior drainage courses. In Colorado, Servilleta basalt probably blocked prior south-flowing drainages. The resulting closed basin was occupied (episodically) by Lake Alamosa in which the Alamosa Formation was deposited. This formation is well known for its thick "blue clays" that form the confining layers within the major fluvial aquifer in the upper SLB.

Alluvial and lacustrine sediment nearly filled the upper SLB prior to lake overflow sometime around 300-400 ka. We have mapped high-level shorelines, barrier bars, spits and lagoons at 7650-7670 ft elevation around the northern margin of the San Luis Hills: these features are unequivocal evidence of ancient Lake Alamosa. However, as the lake rose during one of the many Pleistocene glacial cycles, it overtopped a bedrock sill in the Fairy Hills and rapidly cut a deep gorge. This integration of the upper SLB drainage into the Rio Grande led to rapid downstream incision, especially between the Red River and Culebra Creek, which had previously been the Rio Grande's northernmost tributaries.

PRELIMINARY REPORT ON THE NEWLY DISCOVERED MIOCENE FLORA OF POJOAQUE BLUFFS, ESPAÑOLA BASIN, NORTH-CENTRAL NEW MEXICO

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Several exciting Middle Miocene (Pojoaque Member of Tesuque Formation) fossil plant localities were discovered in the Española area. The plant remains come from several localities with distinct lithofacies; some are reworked volcanic ashfall deposits while others are carbonaceous shales. The area is highly faulted by generally north south trending normal faults with east sides being down thrown. Additional fossiliferous beds will likely be found as we trace fault displacements. Collections produced a variety of plant organs: flowers, cones, leaf fragments, and stems, in addition to invertebrate animal remains of gastropods, and two distinct clams. The only macro floral elements easily identified are *Pinus* sp. and *Salix* sp.

The carbonaceous strata are the first known of Miocene age in the Española Basin to produces fossil plant remains and only the second fossil plant producing Miocene carbonaceous shale in the Rio Grande rift valley (Herb Meyer PhD. Thesis on Lower Miocene Socorro flora). Volcanic ash beds from the Pojoaque type section in Los Barrancos have yielded variable age results ranging from 14.3-8.48 Ma (Izett and Obradovich,2001; McIntosh and Quade,1995) Our localities are in fault blocks west of the type section, are --stratigraphically higher, and therefore are somewhat younger in age.

The Española Valley is exceptionally well known for its fossil vertebrates. Ironically our floral localities are within the geographic range of E.D. Cope's first vertebrate collections in 1874. Ted Galusha collected the first fossil plant remains in the area; a large *Sable* palm trunk base, during the 1960's (oral com. to Chaney). Axelrod drew tentative climate inferences from the *Sable* specimen (1975.) Our new fossil plant and mollusk collection will enhance the understanding of the regional Miocene climate. This modest collection of four museum drawers of fossil plants is housed at the USGS-Denver.

COMPILATION PROGRESS ON THE EXTENDED LOS ALAMOS-ESPANOLA BASIN 1:100,000-SCALE GEOLOGIC MAP DATABASE

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Compilation of a new extended Los Alamos-Española basin 1:100,000-scale (100K) digital geologic map is well underway, largely based upon recent 1:24,000-scale (24K) geologic mapping completed during the map compilation cycle. The map includes the entire Los Alamos 100K and includes the western 4 quadrangles (Seton Village, Santa Fe, Tesuque, and Cundiyo) of the adjacent Santa Fe 100K in order to span the entire width of the Española basin, including the Santa Fe urban area. Most detailed geologic mapping of individual quadrangles is nearly complete, but work continues on matching stratigraphy and contact geology of adjoining quads mapped by different authors. The final stage of map compilation will include generalization and synthesis at a regional scale (approximate pixel resolution of 30 m, as compared to 7 m for 24K), and will be performed after archiving an edge-matched mosaic of 24K geologic map tiles.

The Los Alamos-Española basin 100K geologic map database will build upon the rich geologic expertise developed by several cooperating organizations: the U.S Geological Survey (USGS), the New Mexico Bureau of Geology and Mineral Resources (NMBGMR), Los Alamos National Laboratory (LANL), and the University of New Mexico (UNM). The starting point for geologic studies of the Jemez Mountains is the classic geologic map of the Jemez Mountains by Smith, Bailey, and Ross (1970, USGS Map I-571), compiled by the late Roy A. Bailey. The NMBGMR has taken the lead on mapping new 24K geologic quadrangles for the USGS National Cooperative Geologic Mapping STATEMAP program. Detailed geologic mapping and synthesis by Shari Kelley and colleagues in the Jemez Mountains, and Dan Koning and Adam Read in the Española basin represent a substantial NMBGMR contribution to the Los Alamos-Española basin 100K map. Gary Smith of UNM, with USGS and NM STATEMAP support, is compiling geology of the southern Jemez Mountains, an area containing Miocene-Pliocene rift-basin fill in the Santo Domingo basin and Miocene Jemez basalt-andesite-rhyolite volcanism and coeval volcaniclastic sediments. LANL has contributed through long-term geologic research in the Jemez Mountains, subsurface exploratory drilling, and geologic mapping of the Pajarito Plateau. Fraser Goff, Jamie Gardner, and Steve Reneau of LANL will provide new geologic mapping of the Valles Caldera National Preserve in the second version of the Los Alamos-Española basin 100K map. USGS efforts in the compilation have focused on the Sierra Nacimiento and San Juan basin geology (Sawyer and Kellogg) and studies of the Pliocene Cerros del Rio volcanic field (Thompson, Sawyer, Mark Hudson) as well as integrated structural geology/tectonic studies (Minor, Jonathan Caine, Hudson). Regional geophysical studies by USGS (V.J.S. Grauch, Brian Rodriquez, Jackie Williams, Jeffrey Phillips, and Viki Bankey) have provided new constraints on subsurface stratigraphy, structure, and lithology. The Los Alamos-Española basin geologic map will synthesize these contributions, and provide the foundation for subsequent regional geologic map database products.

GEOLOGY OF THE AGUA FRIA QUADRANGLE, SOUTHWESTERN ESPAÑOLA BASIN, NEW MEXICO

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Sediments, sedimentary rocks, and lava flows within the Agua Fria 7.5-minute quadrangle, in and near the city of Santa Fe, record alluvial, colluvial, and volcanic processes within the southwestern part of the Española rift basin during the Quaternary and Neogene.

The eastern two-thirds of the quadrangle includes early(?) Miocene to Holocene stream alluvium and sheetwash deposited on the distal portion of a west-sloping alluvial piedmont of the Sangre de Cristo Mountains. Upper Pliocene lava flows and related pyroclastic deposits are exposed along the eastern margin of the Cerros del Rio volcanic field (CdRVF) in the western one-third of the quadrangle. Nearly flat-lying basaltic lava flows and pyroclastic deposits of the second eruptive phase of the CdRVF (2.5-2.2 Ma) underlie, are interbedded with, and locally overlie rift-filling gravel, sand, and finer sediments of the Santa Fe Group of early(?) Miocene to early Pleistocene age. The group consists of (from older to younger) the lower unit of the Tesuque Formation, upper unit of the Tesuque Formation, and Ancha Formation, all of which contain granite-rich sediments derived from the Sangre de Cristo Mountains. Geophysical models (Grauch and Bankey, 2003) and drill-hole data (Myer and Smith, 2004) indicate that the total thickness of the Santa Fe Group (mostly Tesuque Formation) increases across the quadrangle from about 750 m near the southeast corner, to 1,210 m at Yates La Mesa No. 2 drill hole near the center, to about 2,100 m near the northwest corner.

Loose to weakly indurated, stream-deposited sand to slightly cobbly, pebble gravel of the Ancha Formation locally are major aquifers in the Santa Fe area. These sediments form thin (about 0.3-4 m thick) beds and lenses and range in total thickness from about 60 m near the southern boundary of the quadrangle to about 3–6 m in the northern part. Buried soils enriched in clay and calcium carbonate are locally present within the Ancha and record periodic episodes of surface stability.

Most of the faults in the quadrangle cut middle Miocene sediments of the lower and upper units of the Tesuque. Most strike north–northeast, dip either west or east, and exhibit normal or normal-oblique slip slickenlines. A few faults cut sediments as young as the Ancha Formation, which is Pliocene to early Pleistocene in age. Two of the faults near the northeast corner of the quadrangle cut the lower unit of the Tesuque and are cemented by silica. Most surface faults in the eastern part of the quadrangle are near, and strike subparallel to, faults inferred in the subsurface based on aeromagnetic data. A few aeromagnetic lineaments that do not correlate with surface faults may represent older buried faults or poorly exposed faults that have eluded detection at the surface.

GEOLOGY OF THE MONTOSO PEAK QUADRANGLE, ESPAÑOLA BASIN, NEW MEXICO

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The Montoso Peak quadrangle lies in the southwestern part of the Espanola rift basin and it includes the central part of the Pliocene-Quaternary Cerros del Rio volcanic field (CdRVF). The predominantly mafic CdRVF is composed of mostly flat-lying lava flows and pyroclastic deposits that were erupted from multiple basaltic to dacitic volcanic centers. The new geologic map for the Montoso Peak quadrangle thus records the late stage evolution of this part of the rift basin. This map integrates 1:24,000 scale geologic mapping with Ar/Ar dating, paleomagnetism, and interpretation of aeromagnetic signature to refine knowledge of the stratigraphy and structure of the CdRVF.

Three main phases of CdRVF volcanism are present in the quadrangle. First-phase eruptions formed large volcanoes with constructive topography such as the Montoso Peak and Cerro Colorado. These were erupted between 2.8 and 2.6 Ma during the normal-polarity Gauss magnetic chron and they are associated with positive aeromagnetic anomalies. Second-phase eruptions were of smaller volume but from sourced from numerous vents and their lava flows commonly infilled paleotopographic lows between older volcanoes. They erupted between 2.5 and 2.2 Ma during the reversed-polarity Matuyama magnetic chron, and, where sufficiently thick, they are associated with negative aeromagnetic anomlies. A final 1.5-1.1 Ma western phase of CdRVF eruptions is represented by 1.46 Ma basaltic andesite of the Cochiti Cone that extend into the western edge of the quadrangle. This lava dome is younger than and onlaps a north-striking normal fault zone that traverses the length of the quadrangle and offsets older-phase volcanic rocks down to the west.

The CdRVF overlies late stage rift sediments of the Santa Fe Group that are potential aquifers in a structural transition zone between the Espanola and Santo Domingo basins (i.e., La Bajada constriction). In the south-central part of the quadrangle the Twelve Hundred Well penetrated the base of CdRVF rocks at 256 m depth and continued through a sequence of mudstone, sand, and gravel to bottom at a depth of 307 m. In addition to marking the location of a western fault zone, the Montoso Peak quadrangle identifies many isolated and aligned zones of volcanic vents of the CdRVF that are likely to overlie feeder dikes cutting through Santa Fe Group sediments.

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