Geologic and Hydrogeologic Framework of the Española Basin -- Proceedings of the 3rd Annual Española Basin Workshop, Santa Fe, New Mexico, March 2-3, 2004

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INTRODUCTION

By Mark R Hudson

This report presents abstracts of technical studies that pertain to the hydrogeologic framework of the Española basin, a major subbasin of the Cenozoic Rio Grande rift. Sediments and interbedded volcanic rocks that fill the Española basin comprise an aquifer system that is currently the primary source 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 eleven Pueblos.

The abstracts describe results of technical studies that were presented either as poster exhibits or oral presentations at the third annual Española basin workshop, held March 2-3 of 2004 in Santa Fe, New Mexico. The principal goals of this workshop were to share information from ongoing studies and to seek input on important topics for further study.

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, Los Alamos National Laboratory, and the City of Santa Fe. The abstracts have been grouped into 6 information themes. Members of EBTAG developed five themes: Basic Water Data, Water Quality and Water Chemistry, Three-Dimensional Hydrogeological Architecture, Water Balance and Stream/Aquifer Interaction, and Data Integration and Hydrologic Model Testing. For details on these themes see http://climchange.cr.usgs.gov/ebtag/Espwk3_themes.html. A sixth theme, Geologic Framework, concerns geologic studies that provide background to the other themes, particularly the Three-Dimensional Hydrogeological Architecture.

Abstracts in this report submitted by U.S. Geological Survey authors have had their technical content peer reviewed before they were included in the report. There was no technical review requirement for abstracts submitted by non-USGS authors (although many did receive peer or agency review). Taken together, the abstracts in this report provide a snapshot of the current status of hydrogeologic research within the Española basin.

HYDROLOGIC CONDITIONS IN THE SOUTHEASTERN ESPAÑOLA BASIN BASED ON RECENT DATA COLLECTION NEAR SANTA FE, NEW MEXICO – A VIEW FROM MIDSTREAM

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The New Mexico Bureau of Geology, the New Mexico Office of the State Engineer, and Santa Fe County are engaged in a multi-year hydrogeologic study of the eastern portion of the Española basin and the Santa Fe Embayment. Data collection from year one of this multi-year program has focused on compilation of historic water level data, collection of new water level data, renovation of the monitoring network for five-year and annual water-level measurements, compilation of aquifer test results and interpretation of all data in the geologic framework of a basin-scale 1:50,000 geologic compilation by Read and others (see abstract in these proceedings). Fieldwork in 2003 has focused on well locations north and west of Santa Fe. Fieldwork in 2004 will focus on the Ancha Formation and underlying Tesuque Formation south of the City. Preliminary results and interpretations from this ongoing study include a water table (potentiometric) surface reflecting 1998-2003 hydrologic conditions. This water table surface and a comparison with historic hydrologic conditions support several interpretations:

1. The area of regional water level declines associated with the City of Santa Fe well field extends south to Arroyo Hondo, north to the Santa Fe landfill, east to St. Francis Drive, and west to Range 8/9 East. Additional data collection can better constrain the area of influence.
2. Rates of water level decline range from 3 to 4 ft/year near the center of the well field, from 1 to 1.5 ft/year in intermediate zones, and decrease to 0.2 to 0.3 ft/year at the perimeter of the area of influence. Rates of decline also decrease vertically away from the pumping horizon. Shallow wells show lower decline rates (~1 ft/year). The deep piezometer at St. Michaels, completed ~1000 ft below the pumping horizon, shows a water-level decline of 0.7 ft/year.
3. The shape of the area of influence of the city well field is elongate north-south along the direction of strike of the Tesuque Formation. This north-south trend of the drawdown “cone” suggests that anisotropy imparted by the west-dipping orientation of the layered Tesuque Formation and/or compartmentalization by north-south trending faults (for example the San Ysidro fault), influence how the effects of pumping propagate through the Tesuque Formation aquifer. The San Ysidro fault at the Santa Fe River is associated with a gradient anomaly and attenuation of water-level decline rates.
4. The area of water-level declines also shows a southwest-northeast trend localized along the axis of the Santa Fe River and crossing the strike of faults and Tesuque Formation bedding. Water-level declines in wells near the river indicate a hydrologic response in the shallow aquifer associated with the river corridor. Possible explanations include reduced recharge through the river channel accompanying reduced surface water flow, or a lack of cementation in Tesuque Fm sediments along the river corridor (sedimentologic investigations along the Santa Fe River by Koning note significantly less cementation here versus surface exposures to the north in Horcado Ranch Quadrangle) due to dissolution of carbonate cement by infiltration of oxygen-rich recharge waters. An associated increase in horizontal hydraulic conductivity localized along the river corridor would facilitate propagation of pumping effects across the bedding planes. Additional data are required.

CITY OF SANTA FE BUCKMAN WELL NOS. 10-13 PROJECT

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As a necessary emergency measure to partially mitigate water shortages due to persistent drought conditions, the City of Santa Fe has constructed and is operating four new supplemental Buckman wells (Nos. 10 – 13). Without these additional wells, Santa Fe would be extremely vulnerable to drought conditions until the planned surface diversion from the Rio Grande is online (anticipated in 2008). The existing Buckman wells (Nos. 1-9) are incapable of producing an adequate supply of water to meet daily peak demands under the dry conditions being experienced in the Santa Fe region. After the Rio Grande diversion is online, the City of Santa Fe expects that the expanded Buckman well field will continued to be used at a scaled-back rate and will provide a measure of regional drought protection/water supply reliability in the event that surface water would not be available via the proposed Buckman Direct Surface Diversion project or McClure and Nichols reservoirs on the Santa Fe River.

The four new wells were completed by December 2003 and are producing water into the City's water system under an emergency permit. The four supplemental wells are located outside the existing cluster of wells within the Buckman Water Management Unit (Buckman well field), thus potentially reducing the pressure on tributaries and other resources created by the continued use of the Buckman well field. A permit to use the wells as supplements to the existing 1-9 Buckman wells, which have a combined permitted water right of 10,000 acre-feet per year, is pending before the Office of the State Engineer. The total depths of each of the wells range from 1900 to 1990 feet below ground surface (bgs). The wells have 18-inch-casings to approximately 1000 feet, and then telescope to 14-inch diameter to total well depth and produce 700-900 gallons per minute (gpm) each. Static water levels measured in Buckman Wells 10, 11, 12, and 13 before pumping test initiation were 340, 286, 260, and 330 feet bgs, respectively. Transmissivity values derived from 1000-minute pumping tests on Buckman wells 10, 11 and 12 range from 5200-14000 gallon per day per foot. No hydrologic boundaries were encountered during the tests.

THE USE OF DAILY STREAMFLOW AT TWO ADJACENT STREAMFLOW-GAGING STATIONS TO CALCULATE STREAMFLOW GAINS AND LOSSES

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In the Española basin, the U. S. Geological Survey has operated about 20 streamgages. Many of these gages are operated in cooperation with the New Mexico Office of the State Engineers and the City of Santa Fe to provide water flow information to local, State, and Federal water managers. In the last few years, real-time provisional streamflow data have become available on the World Wide Web for use by anyone with computer access. Daily mean streamflows at two adjacent gages are typically used to estimate the streamflow loss or gain for a particular reach of the river. The flow differences, losses or gains of streamflow between two gages, can be compared to the uncertainty of daily streamflow at each gage. As an example, in the Española basin, two gages on the Rio Grande about 9 river miles apart, Rio Grande at Otowi Bridge and the Rio Grande near White Rock, might be used to estimate gains and losses in the White Rock Canyon reach of the Rio Grande. The differences in daily streamflow at these two gages must be large enough to overcome the total uncertainty that is inherent in the daily flows. Total uncertainty is a combination of the uncertainty of the actual streamflow measurement and the uncertainty introduced in the calculation of daily streamflow. The daily streamflow at each of these gaging stations is calculated from the stage-flow rating curve that has been developed from periodic streamflow measurements. Gains and losses in daily streamflow between these two gages can only be estimated by comparing them to the combined total uncertainty of the daily flows.

POST CERRO GRANDE FIRE CHANNEL MORPHOLOGY IN LOWER PUEBLO CANYON: AND STORM WATER TRANSPORT OF PLUTONIUM 239/240 IN SUSPENDED SEDIMENTS

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After the May 2000 Cerro Grande fire, the New Mexico Environment Department characterized the shape and function of the channel in lower Pueblo Canyon. The stream channels in Pueblo Canyon, as well as other channels on the Pajarito Plateau, are adjusting to increased storm water flows. Peak flows and total discharge in canyons on the Pajarito Plateau have increased due to changes in forest-floor soil conditions resulting from the fire. The adjustments include channel geometry changes, increased sediment yield, and associated legacy contaminant transport from canyons within the Los Alamos National Laboratory.

We measured channel dimensions at 40 cross sections, established a 1.1-mile stream profile, and mapped the pattern of the channel bottom, and flood plain and terrace banks. These measurements were used to classify the existing stream channel and evaluate channel adjustments to impacts from the Cerro Grande fire. We assessed the channel dimensions, profile, and stream patterns in relationship to geomorphic units and plutonium concentrations and inventories measured by the Los Alamos National Laboratory Environmental Restoration Group. We also collected storm-water samples in Pueblo Canyon to determine the rate and volume of sediment and plutonium transport from this area.

We found the rates of normal channel adjustments, degradation, aggradation and subsequent sediment mixing; have accelerated since the Cerro Grande fire. Destabilized channel banks are mostly limited to the pre-fire active channel and lower flood plain banks, where legacy waste contaminant inventories are the smallest. In some areas, floodwaters have flowed over terraces, causing erosion, sediment mixing, and net deposition on them. Where the floodwaters return to the main channel, bank erosion of older sediment units that contain larger plutonium concentrations and inventories is common. We estimate 21 mCi of plutonium-239/240 in 5,800 tons of suspended sediment were transported out of Pueblo Canyon in 6 of 35 runoff events from 2000 to 2002. For the remaining 29 runoff events, the storm water data were insufficient to estimate the amount of plutonium or sediment transport.

Pueblo Canyon channel adjustments have accelerated since the Cerro Grande fire causing an increase of legacy waste transport. In response to our findings we recommend that efforts begin or continue in three categories; runoff controls, channel stabilization, and monitoring.

AQUEOUS GEOCHEMISTRY OF URANIUM, LOS ALAMOS AND SURROUNDING AREAS, NEW MEXICO

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This presentation provides analytical results for groundwater obtained during four characterization-sampling rounds conducted at several regional aquifer and perched-intermediate wells at Los Alamos National Laboratory. Springs discharging in White Rock Canyon and in the Sierra de los Valles have also been sampled as part of this investigation. Uranium is a trace element of interest because natural background generally is less than 2 μg/L, depending on the reactive-phase mineralogy of aquifer material, aqueous chemistry, and age and residence time of groundwater. Uranium has been processed at Los Alamos National Laboratory since the early 1940s for a variety of purposes.

Analytical results for the wells near Los Alamos National Laboratory show that solute concentrations within the regional aquifer are presently below maximum contaminant levels (MCLs) established by the EPA, including those for uranium (MCL of 0.030 mg/L). Groundwater collected from the regional aquifer and perched zones at Los Alamos National Laboratory is dominantly a calcium-sodium-bicarbonate type and is relatively oxidizing. Natural uranium concentrations in the regional aquifer increase east of the Pajarito Plateau and Rio Grande.

Geochemical calculations using the computer programs PHREEQC2.2 and MINTEQA2 were performed to evaluate solute speciation, mineral equilibrium, and adsorption/desorption in assessing uranium aqueous chemistry and transport. Results suggest that the regional aquifer approaches equilibrium with respect to amorphous silica phases or volcanic glass and $CaCO_3$ and that the aquifer is undersaturated with respect to $USiO_4$, $UO_2(OH)_2$, $MnCO_3$, and $SrCO_3$. Groundwater shows variable saturation with respect to $Ca(UO_2)_2(Si_2O_5)_3{\cdot}5H_2O$ (haiweeite), based on silica activity and pH. Surface complexation modeling (diffuse layer) of U(VI) shows that ferrihydrite partly adsorbs uranyl carbonato species, which is in agreement with experimental and field observations.

SEQUENTIAL APPLICATION OF SURFACTANT FLOODING AND ANAEROBIC REDUCTIVE DECHLORINATION TO REMEDIATE A DNAPL SOURCE ZONE

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A multi-component remediation system is being designed to restore groundwater quality at the North Railroad Avenue Plume (NRAP) Superfund Site in Española, New Mexico. Two municipal supply wells have been closed because of this contamination. The NRAP Site is a groundwater plume that contains tetrachloroethene (PCE) dense non-aqueous phase liquid (DNAPL) as a result of historical disposal practices from a dry cleaning facility. Based on analysis of continuous soil cores and multi-level groundwater sampling data, the DNAPL source zone appears to be confined to an area immediately adjacent to the dry cleaning facility with dimensions of approximately 40 ft by 40 ft. The source zone is confined vertically within the shallow alluvial aquifer to a depth of approximately 22 ft below ground surface by a localized clayey silt layer, which has acted as a competent capillary barrier and has prevented DNAPL from migrating to greater depths within the aquifer. A dissolved-phase plume of PCE has emanated from the DNAPL source zone and has migrated approximately 3,500 feet downgradient towards the Rio Grande. The presence of biodegradation daughter products, trichloroethene and cis-1,2-dichlorethene, and the lack of vinyl chloride and ethene downgradient from the source zone indicate that PCE is being partially biodegraded in this moderately-reducing aquifer.

The remediation design includes a surfactant-enhanced aquifer remediation (SEAR) system to remove residual DNAPL from the source zone and an enhanced bioremediation system to act as a "polishing" step to treat dissolved-phase chlorinated solvents in the source zone following SEAR treatment. For the SEAR, a surfactant solution consisting of 4% sodium dihexyl sulfosuccinate (commercial name Aerosol MA-80I), 1.25% sodium chloride, and 0.2% calcium chloride will be flushed through the source zone. The performance of the SEAR will be evaluated by the collection and analysis of soil cores and produced fluids before, during, and after treatment, and through detailed monitoring of the dissolved-phase chlorinated solvent plume within and immediately downgradient from the DNAPL source zone.

Following the SEAR, the source zone and a delineated "hot spot" area immediately downgradient from the source zone, will be flooded with an electron donor solution. This solution will provide an auxiliary source of organic carbon to decrease redox levels and to stimulate the reductive dechlorination of PCE and daughter products. Soil-water microcosm studies were conducted to select an appropriate electron donor from a range of potential candidates including acetate, lactate, formate, and whey. No reductive dechlorination occurred, except in microcosms that were bioaugmented with a microbial consortium known to contain dechlorinators. The bioremediation amendments will be introduced into the subsurface through direct injection and recirculation systems to treat dissolved-phase chlorinated solvents *in situ* and also to serve as a "bio-curtain" to reduce the mass flux of contaminants exiting the source zone following DNAPL removal.

GROUND-WATER POLLUTION BY SEPTIC TANKS IN THE ESPAÑOLA BASIN

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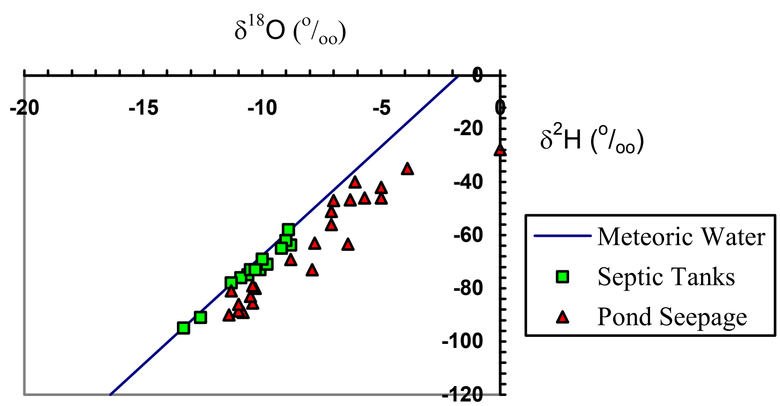
Septic tanks and leachfields have long been used to treat and dispose of sewage in rural areas where many households also utilize on-site wells for domestic water supply. Septic-tank effluents have caused widespread ground-water pollution with nitrate and anoxic conditions, and have polluted more supply wells and more acre-feet of ground water in New Mexico than all other sources combined. In the Española basin, septic tanks have contaminated ground water in Alcalde, Chamita, Chimayo, Cuyamungue, El Rancho, Española, Hernandez, Jacona, La Puebla, Las Placitas, Medanales, Nambe, Pojoaque, Quartales, Santa Cruz, Santa Fe, Tesuque, and Velarde. Nitrate contamination typically occurs in oxidizing environments where the depth to ground water is approximately 30 ft or deeper. Anoxic contamination (iron, manganese, and hydrogen sulfide) occurs in reducing zones where ground water is shallower. Elevated chloride and contamination with sewage-related microbes can occur in both oxidizing and reducing conditions. If nitrate is present, the nitrogen isotope ratio, $\delta^{15}N$, is typically in the range of approximately +8 to +12, and will be greater if ground-water denitrification has occurred. Stable isotope ratios for oxygen, $\delta^{18}O$, and hydrogen, $\delta^{2}H$, show that ground waters contaminated by septic tanks are similar to meteoric water, and have not been subject to significant evaporation, as compared to ground-waters contaminated by wastewater ponds.

Stable Isotope Ratios for Ground Water Contaminated by Septic Tanks and Pond Seepage



Lot size is a critical factor in the degree to which septic tank effluents degrade ground-water quality. Lots up to ½ acre have been shown to pollute ground water in excess of standards, and we are conducting studies on larger lots. In areas with vulnerable aquifers, aerobic wastewater treatment systems are being required, instead of conventional septic systems, for new residential developments on lots less than ¾ acre. Natural attenuation is the only economically and technically practical means of cleaning up aquifers contaminated by septic tanks. Public water and sewer service is provided to these areas on a priority basis. A health assessment will be conducted in the Española basin this summer to determine if residents of areas using private wells and septic tanks have higher rates of enteric illness than do people served by public water supply systems in the same region.

EVALUATING STREAM DEPLETIONS DUE TO PUMPING FROM THE BUCKMAN WELLFIELD

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The City of Santa Fe has expanded its Buckman wellfield in 2003 to help provide supplies during future drought periods and to reduce drawdown effects in the pre-existing wellfield. A series of analyses were conducted to identify annual pumping rates for the four supplemental Buckman wells and for the existing 9 wells in the wellfield. One of the analyses was to estimate the rate and magnitude of stream depletion in the Rio Grande, Tesuque Creek, and Rio Pojoaque under each of two different pumping scenarios.

Both pumping scenarios envision pumping the existing wellfield (Buckman wells 1-9) at a total of 6105 acre-feet per year (AFY) through the year 2006, and the supplemental wells (Buckman 10-13) at increasing rates from 2003 to 2006 of 348 to 1738 AFY. The first pumping scenario then assumes that all Buckman wells will pump at a total average rate of 1000 AFY through the year 2060. The second pumping scenario assumes wells 1-9 will pump at 6105 AFY through the year 2060 and that wells 10-13 will pump at gradually increasing total rates of up to 3620 AFY through 2011, then at this same rate through 2060. The pumping scenarios represent potential wellfield production rates that the City evaluated for planning purposes only. The City has not committed to these nor other production rates in upcoming years.

Stream depletions were evaluated using the MODFLOW model for the region developed by McAda and Wasiolek (1988), using updated pumping information. The model-computed stream depletions are identical through the year 2006, with depletions of 2950 AFY for the Rio Grande, 18 AFY for Tesuque Creek, and 66 AFY for the Rio Pojoaque. Stream depletions differ by an increasing amount for the two pumping scenarios through the remainder of the model simulation period. By the year 2060, stream depletions for the first scenario are 680, 40 and 70 AFY, for the Rio Grande, Tesuque Creek and the Rio Pojoaque, respectively, and are 4500, 170 and 330 AFY, respectively, for the second scenario. These model results suggest a significant rebound in groundwater levels in the vicinity of the existing wellfield, but increased rates of stream depletion in Tesuque Creek and the Rio Pojoaque under both pumping scenarios.

STREAMFLOW AND INFILTRATION IN THE ARROYO HONDO, NORTH-CENTRAL NEW MEXICO

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As part of the Southwest Ground-Water Resources Program, a 3-year study of streamflow and streambed infiltration was conducted in the Arroyo Hondo, north-central New Mexico. Data were collected from October 1999 through October 2002.

Empirical estimates of mean annual streamflow, derived from equations relying on basin characteristics (including annual precipitation, channel width, and watershed area), ranged from 77,000 to 410,000 cubic meters. Total annual streamflow in the Arroyo Hondo ranged from zero to 474,000 cubic meters during the study period. Temperature-based methods were used to (1) estimate the presence and duration of streamflow throughout the Arroyo Hondo and (2) to estimate streambed infiltration rates. A variably saturated, two-dimensional, heat transport model (VS2DH) was used to simulate streambed infiltration during streamflow events; the simulated event-average infiltration rate was 1.4 meters per day. Cumulative annual streambed infiltration was estimated from simulated streambed infiltration rates, channel widths, and the downstream extent of streamflow; cumulative annual streambed infiltration ranged from zero to 250,000 cubic meters.

Snowmelt-induced streamflow events resulted in a larger total streamflow upstream from the mountain front and produced more streamflow downstream from the mountain front than monsoon events, indicating that snowmelt events are more likely to result in streambed infiltration than monsoon events.

Measured streamflow and estimates of cumulative streambed infiltration are lower than previous estimates of streamflow (660,000 cubic meters; Speigel and Baldwin, 1963) and of streambed infiltration (625,000 cubic meters; McAda and Wasiolek, 1988) for every year during the study period. Lower precipitation rates during this study period might account for the smaller measured streamflow and smaller estimates of cumulative streambed infiltration.

Empirically estimated streamflow is closer to measured streamflow and estimates of cumulative streambed infiltration than previous estimates of streamflow. This indicates that the empirically derived equations used in this study are more representative of actual streamflow in the Arroyo Hondo than previous estimates.

POTENTIAL APPLICATIONS OF NOBLE GAS, GROUNDWATER AGE, AND TEMPERATURE DATA IN THE ESPAÑOLA BASIN, NEW MEXICO

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Noble gas, tritium, and temperature data are potentially useful for characterizing groundwater flow in intermountain basins, particularly when combined with geologic investigation and numerical flow modeling. Successful studies in other intermountain basins point to three possible applications of these tracers in the Española basin that could assist local decision-makers in managing groundwater resources.

1) Identifying and constraining the flow of groundwater from mountain block to basin (mountain block recharge or MBR). Previous studies in the Española basin suggest that MBR may be a significant component of basin recharge, but the estimates carry large uncertainties and range widely. Noble gases dissolved in groundwater are inert and generally unaffected by human activities. Recharge temperatures derived from noble gas concentrations can provide information on the elevation of recharge in the mountain block. Noble gas concentrations from range-front wells can therefore be used to identify MBR in the basin aquifer and place useful constraints on the fraction of recharge consisting of MBR. This method has been successfully applied in the Salt Lake Valley, UT, and the Denver Basin, CO. In addition, promising results from Handcart Gulch in the Colorado Front Range suggest that $^{3}H/^{3}He$ groundwater ages and temperatures in conjunction with structural geologic data, collected in the mountain block, constrain the two primary factors controlling MBR: (a) the rate of recharge to the mountain bedrock aquifer, and (b) the depth of active groundwater circulation in the mountain block (deeper-circulating water is less likely to discharge to local streams and more likely to become MBR). This approach could be particularly useful in the Española basin if groundwater ages and temperatures (especially vertical profiles) were integrated into a new or existing coupled heat and groundwater transport model. Interpreting results of both approaches in the context of the lithology and geologic structure of the mountain block might significantly improve our understanding of the permeability structure of the mountain block and thus MBR.
2) Quantifying the rates of mountain-front recharge (MFR), a composite of both MBR and stream seepage near the mountain front, that is very likely the largest component of recharge to the Española basin, yet existing estimates are variable and uncertain. $^{3}H/^{3}He$ ages collected from basin wells near the mountain-front might reveal groundwater age gradients in the aquifer, if the sampled water is younger than 50 years. This age gradient could be used to better constrain the MFR rate, particularly if used in conjunction with a new or existing numerical groundwater flow model.
3) Identifying and quantifying local recharge in the Española basin. Studies in the Salt Lake Valley and the Denver Basin suggest that $^{3}H/^{3}He$ ages might be used to identify local recharge due to seepage from reservoirs or streams because locally recharged water would likely be considerably younger than water in the regional flow system. Further, these ages could be used to constrain the rate of local seepage, given that the flow-pathway length would be known. If MBR is indeed significant, local seepage should also have a warmer recharge temperature than regional groundwater.

THE ROLE OF SCIENCE IN ASSESSING SUSTAINABILITY OF GROUND-WATER RESOURCES

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For much of the previous century, the concept of “safe yield” has been a governing principle for development of ground-water resources. Although safe yield has been defined in many different ways, early concepts related safe yields to rates that water could be withdrawn continuously without depleting the storage reserves and that could be economically sustained. The limitation of not depleting storage reserves was commonly interpreted to mean that a yield was “safe” if the amount of annual withdrawals from an aquifer annually were no greater than the average annual recharge to the aquifer. Later definitions introduced limitations to yield based on undesirable consequences of withdrawal. More recently, the concept of “sustainability” has been applied to ground water and other natural resources. Sustainability, like safe yield, is defined in many different ways (Alley and Leake, 2004). A definition proposed by Alley and others (1999) is that a ground-water development is sustainable if it can be maintained indefinitely without causing unacceptable environmental, economic, or social consequences. The concepts of safe yield and sustainability are clearly related, and it also is clear that neither is purely a scientific concept. Decisions on the acceptability of consequences of ground-water withdrawals rest not with hydrologists, other earth scientists, or engineers, but instead with society in general; however, scientists and engineers can play a key role in the decision making process by assessing the likely magnitude and timing of consequences of ground-water withdrawals. Such consequences may be related to storage changes in an aquifer as well as to changes in flow entering and leaving an aquifer. Theis (1940) was the first to clearly articulate the consequences of withdrawal of water from an aquifer by wells, indicating that the essential factors in controlling the response of the aquifer to a withdrawal are (1) the distance to and nature of the recharge, (2) the distance to the discharge locations, and (3) the character of the cone of depression. A common shortcoming in assessments of consequences of withdrawals of ground water, particularly in the Southwest, is an undue focus on storage changes in the locality of the withdrawal without adequate assessment of likely changes of flow into or out of the aquifer. In aquifers of the Southwest, such as the Española basin of New Mexico, ground-water withdrawals are much more likely to decrease (capture) outflow than to increase inflow. Because of possible large distances from pumping areas to discharge locations, analysis of capture may involve model simulations of flow for decades or even centuries after the onset of the withdrawal. Such analyses need not be considered predictive, but may more appropriately be viewed as interpretive simulations that can give some idea of the range of time over which outflow from an aquifer might be captured. Results relating to the magnitude, location, and timing of capture can be used in societal decisions regarding development of ground water.

BASIN-SCALE GROUNDWATER FLOW - INCORPORATING UNCERTAINTY IN MODELS

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Although there is much room for improvement in our understanding of the hydrogeology of the Española basin, due to inherent limitations of data collection methodologies there will always be substantial uncertainty in key factors such as recharge rates, discharge rates to streams and rivers, and aquifer properties. Explicitly accounting for these uncertainties in model predictions is an important requirement for any modeling study. Traditional approaches, such as sensitivity analysis, typically force the model well out of calibration and ignore parameter correlations. As a result, it is impossible to directly measure the effect of parameter uncertainty on the model prediction of interest. Using a nested pair of models (basin-scale (Española basin) and site-scale (Pajarito Plateau)), we present a quantitative approach to estimating the impact of uncertainties on model predictions such as pre-development fluxes into and out of the aquifer beneath the Pajarito Plateau and the impact of current and future pumping on discharge to the Rio Grande. Our approach utilizes statistical methodologies imbedded in inverse analysis (PEST, Doherty, 2002). These methods can be used to bound the range of plausible predictions and to prioritize future data collection.

TRANSIENT CAPTURE ZONE ANALYSIS OF WATER-SUPPLY WELLS ON PAJARITO PLATEAU

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Transient analyses of capture zones of water supply wells are, in many practical cases, superior to the commonly applied steady-state analyses. Several recent case studies on this topic have been published in the hydrogeological literature, but most of them took into account the advection only (similar to most steady-state studies). However, for the transient case, including advection without dispersion can be theoretically inaccurate for representing potential contaminant transport towards water-supply wells. In the steady-state case, advective flow paths ignoring dispersion have been shown to produce adequate predictions of the mean behavior of the simulated contaminant plume. However, our more recent work shows that this may not be the case for the transient flow situation. Therefore, capture zone analyses in transient flow systems should include dispersion in order to be accurate. This work presents a case study of water-supply wells in the Española basin in the vicinity of Los Alamos National Laboratory to demonstrate our conclusions. Transient capture zone estimates are shown to be very sensitive to heterogeneity and the hydrologic and transport properties of the medium, including porosity and dispersion parameters.

GEOLOGIC SETTING OF DEEP PERCHED GROUNDWATER BENEATH THE PAJARITO PLATEAU

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Identification deep perched systems beneath the Pajarito Plateau comes mostly from direct observation of saturation in boreholes, from borehole geophysics, or by the installation of wells to monitor these zones. Additional information is provided by surface-based electrical geophysics, although these types of investigations are generally limited by their relatively shallow depths of investigation and poor vertical resolution. Identification of perched groundwater in boreholes is generally reliable, but use of drilling fluids, which is necessary in most boreholes, may mask small or relatively unproductive zones. Defining the lateral extent of saturation is more problematical because of the costs associated with installing wells to such great depths. Despite these limitations, substantial new information has been gathered about deep, perched zones on the plateau.

The vadose zone ranges in thickness from 180 m (590 ft) to more than 365 m (1200 ft) thick, and it consists of Pliocene alluvial fan deposits covered by thick Pleistocene ash-flow tuffs. The Pliocene sediments interfinger laterally with lavas from the Jemez volcanic field to the west and the Cerros del Rio volcanic field to the east. Perched groundwater is found within canyon-bottom alluvium and within bedrock units of the vadose zone. To date 27 occurrences of perched groundwater in bedrock have been detected in boreholes across the Pajarito Plateau. Perched groundwater occurs across northern and central parts of the plateau with depth to water ranging from 36 to 272 m (118 to 894 ft). Saturated thicknesses vary from 1 to 128 m (3 to 421 ft). Little is known about perched water in the southern part of plateau because few deep boreholes are located there.

The principal occurrences of perched groundwater occur in 1) the large, relatively wet Los Alamos and Pueblo Canyon watersheds, 2) the smaller watersheds of Sandia and Mortandad Canyons that receive significant volumes of treated effluent from LANL operations, and 3) in Cañon de Valle area in the southwestern part of LANL. Perched water is most often found in Puye fanglomerate and Cerros del Rio basalt, but it also occurs to a lesser extent in units of the Bandelier Tuff. Anthropogenic chemicals are present in some deep, perched groundwater, indicating a connection to surface water. Groundwater travel times from the surface to deep groundwater systems are on a decadal time frame.

PRELIMINARY INTERPRETATIONS OF STRUCTURAL AND STRATIGRAPHIC CONTROLS ON GROUND WATER QUALITY IN CHIMAYO, ESPAÑOLA BASIN, NEW MEXICO

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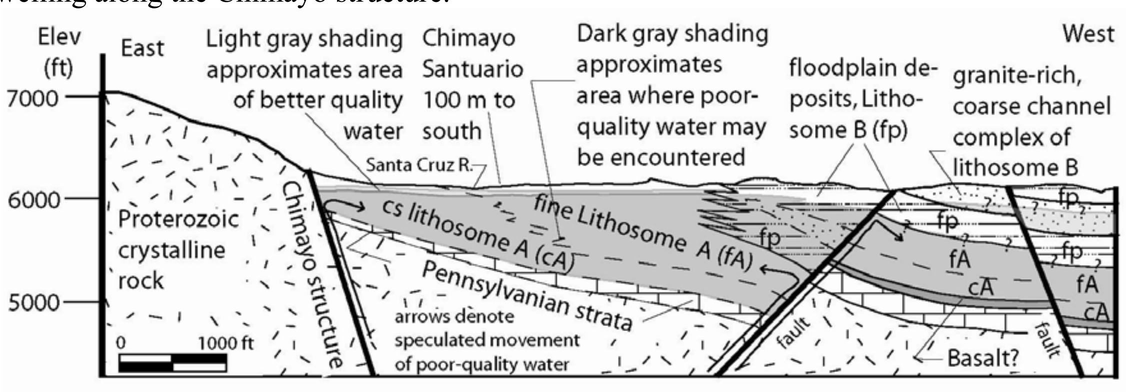
Several wells within ~ 1 km of Chimayo, NM, have very poor quality ground water with elevated concentrations of dissolved solids, fluoride, and iron. This ground water also has notably high dissolved carbon dioxide (pCO_2) that has episodically produced a geyser in one particular well and may be a factor in the upwelling of this poor quality water. An earlier isotopic study interpreted a mantle origin for the carbon in the CO_2, so this water may be coming from significant depths. We offer a preliminary explanation regarding the spatial distribution of this poor quality ground water. Geologic mapping indicates that a significant north-trending, down-to-the-west fault and monocline, called the Chimayo structure, lies at the base of the granite-cored hill immediately east of the town of Chimayo. We interpret that the poor quality water is transmitted upwards within fractures in crystalline rocks along the Chimayo structure, from where it flows into the overlying Tesuque Formation aquifer. The Tesuque Formation near the mountain front consists of relatively coarse, granite-rich sediment called lithosome A, which generally fines westward to a silty fine sand. Beyond ~ 1 km west of the Chimayo structure, exposed lithosome A interfingers with lithosome B. Lithosome B was deposited by larger streams or rivers, compared to lithosome A, and is marked by significant clayey to silty floodplain deposits, within which are interspersed 3-10% channels of pebbly sandstone.

Wells having poor ground-water quality typically are east of a N-NE-trending boundary ~ 1 km west of the Chimayo structure. The southern part of this water-quality boundary coincides with a 45-55°, east-dipping fault (local strong silica cementation in the hanging wall suggests a similar upwelling of ground water along this conjugate fault as in the main Chimayo structure). In the Tesuque Formation, this fault may act as a barrier to flow. However, the water-quality boundary also approximately coincides with the interfingering contact of lithosomes A and B. The muddy floodplain deposits of lithosome B may act as a barrier to the westward and/or upward propagation of poor quality ground water in the upper part of the Tesuque Formation. There are some wells east of the water-quality boundary possessing water fit for human consumption. The very localized occurrence of this better-quality water may be due to high-permeability channels orientated such that they conduct ground water flow from better-quality source areas compared to the interpreted upwelling along the Chimayo structure.



LITHOSOME S OF THE TESUQUE FORMATION: HYDROSTRATIGRAPHIC AND TECTONIC IMPLICATIONS OF A NEWLY DELINEATED LITHOSOME IN THE SOUTHERN ESPAÑOLA BASIN, NEW MEXICO

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Sedimentologic investigation of the Tesuque Formation in the southern Española basin supports the designation of a new lithosome called lithosome S. It is characterized by extensive channel deposits of pebbly sand with subordinate sandy gravel and sand. Floodplain deposits are present but comprise less than 5% of the strata observed in outcrop; however, these may become more abundant down-dip in the subsurface. The main differences of lithosome S ("S" standing for Santa Fe) compared to lithosome A (established by Cavazza, 1986) to the north are: 1) composition, 2) its paucity of silty sandstone extra-channel deposits, 3) its weaker consolidation and lesser degree of cementation, and 4) channel geometries. Lithosome S channels are stacked and generally comprised of thin, lenticular to broadly lenticular to planar beds with only minor ribbon forms; lithosome A channels are commonly thicker and have more discrete ribbon-like forms interbedded in extra-channel sediment. Whereas the gravel in lithosome A is typically greater than 90% granite south of the Santa Cruz River (with the remainder being quartzite and yellowish Paleozoic siltstone), lithosome S generally contains 35-65% granite, 10-30% Paleozoic clasts, 10-25% quartzite (including a distinctive black quartzite), and 1-5% chert. The sand fraction of lithosome S differs from lithosome A in that it has minor Paleozoic grains (estimated at 1-7%) and trace-2% chert and dark quartzite grains; these are much less abundant in lithosome A. Lithosome S grades laterally northward into lithosome A (over a distance of about 2 km) west of Tesuque Pueblo and just north of, and paralleling, the Rio Tesuque east of Tesuque Pueblo. Lithosome S grades upward into lithosome A (age of contact is ~13-14 Ma) north of Arroyo Calabasas. Near the mountain front, lithosome S is gradationally underlain by lithosome A (interpreted to be 25-28 Ma), which in turn is underlain by the Bishops Lodge Member (BLM) of the Tesuque Formation. Northeast of Bishops Lodge, the BLM is underlain by, and interfingers with, ~ 400 m of strata somewhat similar to lithosome S; these lower strata, however, differ from lithosome S above the BLM in that they have less than 5% quartzite and no or trace chert.

Lithosome S is significant for both geohydrologic and paleotectonic reasons. Its overall coarseness, channel connectivity, and lesser cementation likely make it a more productive aquifer than lithosome A. Lithosome S was deposited on an alluvial slope by a relatively large drainage that is interpreted to have crossed the present-day divide of the Santa Fe Range, so that it was sourced in the headwaters of the modern Pecos River. The tongue of lithosome A (thinning to the south) between the Bishops Lodge Member and lithosome S may represent uplift of the Santa Fe Range at approximately 26-29 Ma, during which the drainage depositing lithosome S was likely diverted to the south as the hanging wall of the Española basin bowed upwards. Lessening of uplift rates, perhaps combined with stream piracy, allowed the drainage associated with lithosome S to shift back to north of Arroyo Hondo. Comparison of the thickness of a measured interval of lithosome S along the Santa Fe River with an interpreted correlative section in the Yates #2 well differs by approximately 300-400 m (with a lower value in the well). This suggests that the structural high on which the well is situated was uplifted, at least in part, in the early to middle Miocene.

GEOLOGIC AND HYDROSTRATIGRAPHIC MAPPING PROGRESS IN THE SOUTHERN ESPAÑOLA BASIN

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Long-term drought in the Southwest is causing water shortages for the city of Santa Fe. This, coupled with challenging groundwater supply and management issues due to rapid population growth and declining well-field productivity, has led to a critical need to understand the geologic and hydrologic architecture of local aquifers. Located in the southern Española basin, this region is underlain by clastic sediment of the Santa Fe Group (upper Oligocene–lower Pleistocene fill of the Rio Grande Rift), which serves as a sole-source aquifer for Santa Fe and surrounding communities.

To improve understanding of geologic history and hydrogeology of the region, geologic mapping of six 7.5-minute quadrangles was recently completed at scales of 1:24,000 and 1:12,000. These quadrangles are: Horcado Ranch, Tesuque, Agua Fria, Santa Fe, Turquoise Hill, and Seton Village. Additionally, part of the White Rock quadrangle was remapped for this study because the Buckman wellfield is located there and serves as an important municipal water source for Santa Fe.

Bedrock mapping along the mountain front emphasized faults, folds, and fractures with the hope that recharge zones could be better understood. This work has added considerable detail to that of previous studies. Basin mapping emphasized identification of faults as well as study of provenance, paleochannel characteristics, and textural criteria. These criteria were used to subdivide the basin fill into lithostratigraphic units that may have distinctive hydrostratigraphic characteristics. The general structure of the southern Española basin, as inferred from geologic mapping, examination of subsurface data, and available geophysical data, is that of a north-plunging syncline south of the Santa Fe River. To the north, two N-S-striking monoclines, having structural reliefs in the range of 300-1300 m, have developed in the tilted hangingwall of the Española basin half-graben; one lies close to the mountain front and the other is west of the Pojoaque fault zone.

These new maps and cross sections provide a framework for identifying and characterizing subsurface hydrostratigraphic units and, when integrated with hydrologic data, lay a critical foundation for addressing hydrogeologic questions such as the influence of faults, sedimentologic trends, and dipping strata on regional groundwater flow and well-field drawdowns. This work will aid effective placement of new production wells and in understanding the geologic controls affecting the aquifer. Preliminary work suggests that the aquifer, in places, is strongly compartmentalized by faults. This is particularly apparent along the Las Dos and San Ysidro Crossing faults, where water table elevations decrease by ~100-400 feet west of the fault zones. The maps and the hydrologic interpretations derived from them will generate improvements to groundwater flow models for water-rights administration and resource management.

These maps continue to evolve as new data and interpretations emerge. This mapping is being integrated into a basin-scale 1:50,000 compilation, but detailed mapping at scales of 1:24,000 and larger continues and both scales of work are being updated concurrently. Drafts of these maps and of the compilation will be available for download from the NM Bureau of Geology website in advance of the EBTAG meeting (*see: http://geoinfo.nmt.edu/maps*).

COMPARISON OF PERMEABILITY AND GRAIN SIZE DIFFERENCES IN TESUQUE FORMATION DEPOSITS AT THE SANTA FE RIVER AND BUCKMAN WELL FIELD AREAS, ESPAÑOLA BASIN, NEW MEXICO

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In the eastern Española basin, Tesuque Formation sediments were deposited in an alluvial slope environment from streams of various sizes. Recent work demonstrates that a larger, westward-flowing drainage system deposited relatively coarse-grained channel sediments (called lithosome S) in the vicinity of the Santa Fe River and northwards to roughly the latitude of Tesuque Pueblo. Lithosome A was deposited north of lithosome S by relatively smaller drainages exiting the granite-cored Sangre de Cristo Mountains to the east. Near the Buckman well field, distal lithosome A interfingers with fluvial sediment deposited by a broad, southward-flowing axial river (SAR). Previous measurements of hydraulic properties for channel deposits in lithosome A and SAR show that permeability and grain size vary with magnitude of flow and are essentially bi-modal: high-permeability channel sands and gravels are interbedded within thick beds of low permeability silty, fine-grained sand. We present and compare new measurements of hydraulic properties for lithosome S, lithosome A, and SAR deposits, and discuss implications regarding aquifer yield at these two different areas.

Lithosome A and SAR were characterized by conducting a permeability – grain size transect along the deposits exposed in the west-flowing arroyo immediately south of Buckman Mesa, in the northern Buckman well field. Lithosome S deposits were characterized along a three mile reach of the Santa Fe River in the City of Santa Fe and the Village of Agua Fria, which are near several city water supply wells. Selected outcrops at both areas were mapped and photographed. *In situ* permeability measurements were collected on a 2 m^2 grid using a portable air mini-permeameter at each selected outcrop. Grain size distributions were determined by sieving following air permeability measurements.

Our results reveal that permeability is relatively greater in lithosome S deposits compared to lithosome A and SAR deposits in the northern Buckman well field. Lithosome S deposits are typically coarser grained and have larger mean and maximum permeability values than the Buckman area deposits. A notable exception is a coarse, upper unit of lithosome A, which was the coarsest-grained unit studied but has lower permeability than the coarsest lithosome S deposits. We observed in lithosome S several sizeable channel deposits that are greater in width and thickness values than typical lithosome A channels at Buckman. The large clast sizes in the lithosome S channels precluded air permeability measurements with our instrument; however, these coarse lithosome S channels are likely to have the greatest permeability of any of the Tesuque sands and gravels we studied. Unlike most gravel channels at the distal lithosome A outcrops, the lithosome S channels are poorly cemented. If the outcrops studied are representative of subsurface conditions, lithosome S deposits are significantly better aquifer material than the Tesuque deposits at the Buckman well field given the observed differences in grain size distributions, cementation, and permeability.

BASAL GALISTEO AND FRACTURED GRANITE ENCOUNTERED IN HORST BLOCK AT BEND IN THE MOUNTAIN FRONT FAULT SUNLIT HILLS AREA, SANTA FE COUNTY, NEW MEXICO

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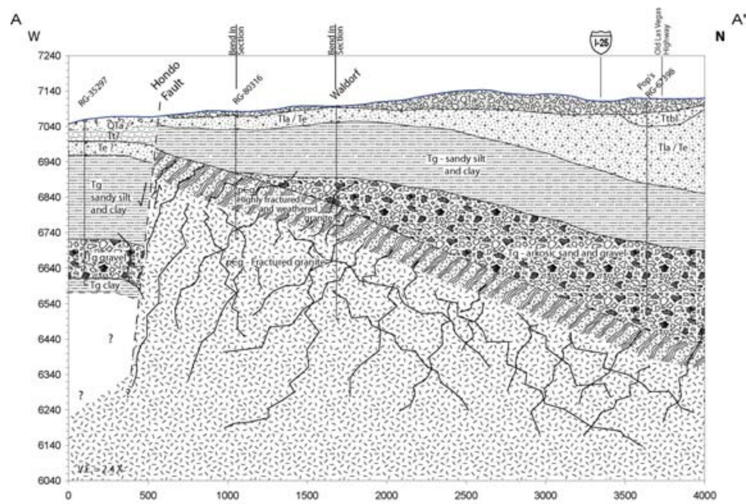
The Santa Fe Waldorf School property is located approximately one-half mile north of Arroyo Hondo and approximately 1.3 miles southeast of Arroyo de los Chamisos in Santa Fe County. The geometry of Arroyo Hondo is structurally controlled by northeast- and southeast-trending faults. There is brecciated granite at the edge of the mountain front to the south and east of the property. Although geologic maps do not show a trace of the fault, these brecciated areas and the uplifted section of granite indicate the presence of the Hondo Fault. A geologic cross section crosses the Hondo fault between wells RG-35297 and RG-80316. These two wells are at approximately the same elevation, but penetrate different lithologies at depth. RG-35297 penetrates the Ancha over the Espinaso and Galisteo Formations. Well RG-80316 penetrates thin Ancha, Espinaso, and Galisteo over highly fractured and weathered granite at a depth of 175 feet bgs.



The difference in depth to the granite in RG-80316 and the Waldorf well and the lack of granite in well RG-67398 suggest that these wells are located in a northeast dipping horst fault block located between the Hondo Fault to the west and the mountain front fault(s) to the east (off the cross-section to the east). Well RG-67398 penetrates the Ancha, Tesuque Bishops Lodge Member, a thick sequence of Espinaso volcaniclastics, and a thick section of Galisteo Formation with a highly permeable, coarse-grained aquifer in the lower half of the penetrated formation. The thicker sequences of Espinaso and Galisteo in RG-67398 and the Waldorf well suggest that this fault block was actively tilting during deposition of the Galisteo and Espinaso. The thick sequence of coarse, arkosic sand and gravel in the lower half of the penetrated Galisteo Formation is likely due to the proximity to the mountain front and may be due to active faulting during deposition. The mountain front fault zone is a generally down-to-the-west system that likely contributed to the tilting of the Waldorf area fault block.

The highly weathered and fractured nature of the upper granite may indicate that this zone was a paleo-surface exposed to weathering, freeze-thaw opening of fractures, and some minor soil development prior to the tilting of the fault block and deposition of the Galisteo Formation. The porosity and permeability of the sedimentary and crystalline rocks underlying the school site and the surrounding area have been significantly enhanced due to fracturing associated with faulting. The Waldorf well and RG-67398 have higher than average production rates for this area.

PETROGRAPHIC ANALYSIS OF CUTTINGS FROM THE YATES #2 LA MESA WELL AND TERTIARY TECTONIC HISTORY OF THE SOUTHERN ESPAÑOLA BASIN

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Considerable controversy surrounds the interpretation of formations present in the lower part of the 2350 m (7710') Yates La Mesa #2 exploration well. Volcanic or volcaniclastic rocks in the well are variously interpreted as Oligocene Espinaso Formation or Miocene Abiquiu Formation. Limestone is variously interpreted as part of the Eocene Galisteo Formation or Paleozoic in age. The well is interpreted to bottom in either Precambrian basement rock or Galisteo Formation. Petrographic analysis of 46 thin sections of cuttings is underway to resolve these controversies, and their implications for the tectonic history of the southern Española basin.

Tesuque Formation overlies 625 m (3966'-6018' in the well) of volcanic and volcaniclastic rocks. The upper 318 m (3966'-5012') of volcanic material consists of mafic rocks. These rocks are rich in olivine and clinopyroxene and lithologically correlate to basanite and basalt lava flows of the Cieneguilla "limburgite" that crop out near La Cienega. The abundance of vesicular tachylite and sideromelane glass (some replaced by zeolite) suggests proximity to a vent. The lower 307 m (5012'-6018') of volcanic material petrographically resembles the latitic lava flows and sedimentary deposits of the Espinaso Formation, and is characterized by a higher gamma-ray response than the overlying mafic rocks.

Cuttings taken from below the volcanic interval are a mixture of limestone and clastic-sedimentary fragments above Precambrian basement at 2297 m (7534'). Many limestone fragments contain characteristic fossils of Paleozoic marine facies; for example: crinoids, brachiopods, bryozoans, benthic foraminifera, and bivalves. The 462 m (6018'-7534') of sedimentary rocks between the Espinaso Formation and basement rocks are, therefore, interpreted as Upper Paleozoic strata

These results are consistent with Cather's (1992) hypothesis that the Laramide Pajarito uplift occupied the area of the current Española basin. There is a little if any Eocene sediment in the La Mesa well and the concept of an Eocene "La Mesa limestone" is inconsistent with the diagnostic Paleozoic fossils in the cuttings. Volcanic rocks buried the denuded Laramide uplift before or during early rift-basin subsidence.

We acknowledge Steve Cather, NM Bureau of Geology and Mineral Resources, for providing the thin sections and encouraging this study.

THICKNESS OF SANTA FE GROUP SEDIMENTS IN THE ESPAÑOLA BASIN SOUTH OF SANTA FE, NEW MEXICO, AS ESTIMATED FROM AEROMAGNETIC DATA

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In the southern Española basin south of Santa Fe, New Mexico, weakly magnetic Santa Fe Group sediments of Oligocene to Pleistocene age, which represent the primary aquifers for the region, are locally underlain by moderately to strongly magnetic igneous and volcaniclastic rocks of Oligocene age. Where this relationship exists, the thickness of Santa Fe Group sediments, and thus the maximum thickness of the aquifers, can be estimated from quantitative analysis of high-resolution aeromagnetic data. These thickness estimates provide guidance for characterizing the ground-water resources in between scattered water wells in this area of rapid urban development and declining water supplies.

We present one such analysis based on the two-step extended Euler method for estimating depth to magnetic sources. The results show the general form of a synclinal basin located between the Cerrillos Hills and Eldorado with gradual northward thickening of Santa Fe Group sediments along the basin axis from the erosional edge on the south to 300 feet (91 meters) thick at about latitude 35°22'30"N, then abrupt thickening further north to reach 2,000 feet (610 meters) at the Cerrillos Road interchange at Interstate 25, north of latitude about 35°36'N. South of Gallina Arroyo, the Santa Fe Group sediments are represented primarily by Ancha Formation, whereas generally north of the arroyo, the Santa Fe Group includes Tesuque Formation below 0-300 feet (0-91 meters) of Ancha Formation. The depth analysis indicates that, superimposed on the general synclinal form, there are many small areas where the Santa Fe Group sediments may be thickened by a few hundred feet, presumably due to erosional relief on the underlying Oligocene volcanic and volcaniclastic rocks. Some larger areas of greater apparent thickening occur where the presence of magnetic rocks directly underlying the Santa Fe Group is uncertain. Where magnetic rocks are absent beneath the Santa Fe group, the thickness cannot be estimated from the aeromagnetic data.

GEOPHYSICAL TOOLS FOR UNDERSTANDING THE 3D HYDROGEOLOGICAL ARCHITECTURE OF THE ESPAÑOLA AND SANTO DOMINGO BASINS, NEW MEXICO

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Geophysicists can use indirect methods to probe below the Earth's surface--a cost effective alternative to drilling. For example, measuring variations in the Earth's gravity or magnetic field on the surface gives information on the density or magnetization of the rocks underground, which are commonly related to geologic structure and differences in rock type. Measuring the effects of an electric current transmitted through the ground gives clues to the three-dimensional variation in electrical resistivity, which is a measure of how well or how poorly the materials and their fluids conduct electricity. Recording the time it takes for seismic waves to reflect from interfaces between formations having different acoustic velocities can provide information about the depths to these interfaces, which can be used to image the type and structure of geologic layers at depth. Understanding the variations in these physical properties at depth allows interpreters to infer certain aspects of the geology and hydrogeology of the subsurface, especially when the information is integrated with other, independent data sets.

In the Española and Santo Domingo basins, investigators at the U. S. Geological Survey, Summer of Applied Geophysical Experience (SAGE) program, and Los Alamos National Laboratory have successfully employed several different geophysical methods to detect certain aspects of the subsurface hydrogeology. The thickness of the hydrologically important Santa Fe Group and the faults that offset these sediments can be inferred throughout the basin by integrating interpretations from different geophysical methods that are constrained by drill hole or other independent information. Gravity data reflect general variations in thickness of these low-density sediments. Aeromagnetic data can be used to estimate the depth to the highly magnetic volcanic rocks that directly underlie the Santa Fe Group in certain areas and have characteristic expressions over many major intrabasinal faults. Electrical geophysical methods can detect fine- versus coarse-grained facies and have been especially useful in mapping the depth to the Santa Fe Group in volcanic covered areas. In certain situations, these methods can also detect the water table. Interpretation of seismic-reflection profiles gives information on depth to geologic units, dip of beds, and locations of faults from the Santa Fe Group down to the Precambrian basement. All of these methods, especially when synthesized in conjunction with other geologic and hydrogeologic information, provide important constraints on our understanding of the three-dimensional hydrogeological architecture of the Española and Santo Domingo basins.

SUBSURFACE MAPPING OF ELECTRICAL RESISTIVITY FOR HYDROGEOLOGIC FRAMEWORK STUDIES IN THE ESPAÑOLA AND SANTO DOMINGO BASINS, NEW MEXICO

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Airborne time-domain electromagnetic (TEM) and magnetotelluric (MT) data are used to map changes in electrical resistivity with depth that are related to lithologic and subsurface structural variations. These subsurface lithologic and structural variations are important to critical aquifers in the groundwater system hydraulically connected to the Rio Grande as it passes from the Española basin into the Santo Domingo basin. The resistivity of geologic units is largely dependent upon their fluid content, porosity, fracturing, and conductive mineral content.

In the eastern Cerros del Rio volcanic-field terrane, the northern boundary of the Cerrillos uplift is newly constrained by MT results. MT soundings indicate that along a north-south line between stations MT-4 (southeast of Tetilla Peak) and MT-5 (southeast of the Twelve Hundred well), a 2 ohm-m conductor caused by the Cretaceous Mancos Shale is down-dropped from a depth of 180 m at MT-4 to a depth of 1150 m beneath the surface at MT-5. This offset is evidence for 800 m of Tertiary structural relief at the north end of the Cerrillos uplift. The shallow Mancos Shale located at MT-4 provides the furthest northwest constraint for the edge of the Cerrillos uplift, and is consistent with the subsurface extent of the uplift based on gravity data. The Tetilla fault appears to form the western boundary of the east-dipping conductive Mancos Shale, based on airborne TEM results south of two northeast-trending power lines (south of the Eight Hundred well). We do not see the same east-dipping conductive material in the terrane north of the power lines, near MT-4, but rather we see minor breaks in what otherwise looks like fairly flat-lying conductive (5 to 10 ohm-m) material. Northeast-bearing, moderately resistive (25 to 50 ohm-m) material at about 1750 m elevation, between MT-4 and MT-5, is at least 100 m in thickness and is about 2 km in width, is surrounded by moderately conductive (10 to 25 ohm-m) material. This moderately resistive structural block has resistivities similar to Santa Fe Group sediments. In the northern part of the central La Bajada constriction, a large area of moderately conductive (10 to 20 ohm-m) material, defined by the airborne TEM results, coincides with a silt and/or clay lacustrine unit in the upper Santa Fe Group deposits. In the central part of the study area, moderately resistive (25 to 50 ohm-m) material corresponds in part to ancestral Rio Grande axial-gravel deposits. In the western St. Peter's Dome block, MT soundings have provided additional constraints on the relative position of basement and thickness of Paleozoic-Mesozoic and Tertiary sedimentary rocks across the Pajarito fault zone. As a result of modeling these data, we conclude that there is a much greater thickness of the early Tertiary Galisteo Formation in the footwall at St. Peter's Dome.

HYDROGEOLOGIC FRAMEWORK OF THE LA BAJADA CONSTRICTION: PARTLY BURIED STRUCTURAL TROUGH CONNECTING THE SANTO DOMINGO AND ESPAÑOLA BASINS

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The hydrogeologic framework of the La Bajada constriction (LBC) area in the vicinity of Cochiti Pueblo and the Cerros del Rio volcanic field is summarized in a new geologic map and set of serial cross sections. The LBC was originally defined by V.C. Kelley as the area where the Rio Grande rift narrows between the Española and Santo Domingo basins, but new geologic mapping and geophysical investigations indicate that a wider distribution of thick Santa Fe Group rift-fill aquifer deposits exist in the area. Synthesis of the surface geologic mapping and subsurface geophysical imaging has improved delineation and characterization of the rift-flank structural uplifts that bound the constriction. The LBC is bounded on the southeast by the Cerrillos uplift, a rift-flank structural high buried by younger rift sediments and lava flows of the Cerros del Rio volcanic field. Ground magnetotelluric soundings in a north-south profile across the center of the Cerros del Rio define the buried northern limit of shallow Cretaceous marine shale confining units in the Cerrillos uplift and the northern boundary of the LBC where basin-fill sediments thicken to >250m. North of Canada de Santa Fe, the western border of the Cerrillos uplift is formed by a concealed N-striking segment of the Tetilla fault zone, whereas to the south the border jumps west to the younger parallel La Bajada fault zone. The northeastern flank of the Cerrillos uplift consists of a ~15^{o}-dipping ramp that projects southeastward from the northern Tetilla fault zone (or another buried structure) toward the southern end of the Española basin. The northwest boundary of the LBC is the Pajarito fault zone, which bounds the uplifted St. Peter's Dome block. Young movement on the Pajarito fault zone has offset the 1.22 Ma Bandelier Tuff, but southwest of Peralta Canyon gravity data suggest that an older segment of the Pajarito fault projects southwest beneath late Miocene-Pliocene deposits and connects with subsurface fault(s) that form the northwestern boundary of the Santo Domingo basin.

Numerous northwest-striking, interleaved normal faults of opposing dip obliquely transect the LBC where it opens into the northern Santo Domingo basin; these faults affect the thickness and subsurface architecture of basin-fill deposits that form the regional Santa Fe Group sedimentary aquifers. Between the San Francisco fault zone and the Cerrillos uplift three intrabasin structural blocks are identified from surface geology and aeromagnetic data--from west to east, the Cochiti graben, reservoir horst, and La Majada graben. The La Majada graben in the hanging wall of the northern La Bajada fault zone is bounded on the west by the newly identified Sanchez fault, a mostly concealed, down-to-the-northeast normal fault. Lithologic logging of cuttings from the Santa Cruz Springs tract well by Gary Smith (University of New Mexico) indicates that hydraulically conductive axial-river gravel of the ancestral Rio Grande was deposited within La Majada graben after the main period of 2.5-2.7 Ma Cerros del Rio volcanism. In the footwall block of the northern La Bajada fault zone, axial gravel deposits exposed beneath the Cerros del Rio lava flows indicate that the Rio Grande has migrated toward the southeastern boundary of the LBC at least twice during the last 3 million years.

ON THE LACK OF GEOCHEMICAL ANOMALIES ASSOCIATED WITH FAULTING IN POORLY LITHIFIED, SILICICLASTIC SANTA FE GROUP SEDIMENTS, NM

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Mechanical and geochemical assimilation are two fundamental ways that materials are incorporated into upper-crustal, brittle fault zones. Mechanical assimilation physically entrains protolith materials into the core of a fault. Geochemical assimilation involves aqueous geochemical reactions, also localized in the fault core. Both types of assimilation are typically coupled in well-lithified protoliths and can include processes such as stress build up, brittle fracturing and fault-rock comminution, transient permeability enhancement and fluid and heat flow, and chemical reaction that results in fault rocks that no longer retain the mechanical and geochemical characteristics of the original protolith. However, faulting in poorly lithified sediments resulting in clay-rich fault cores may involve limited geochemical assimilation due to dominantly plastic or particulate flow deformation mechanisms that restrict the development of brittle fracture-dominated permeability, fluid flow, and thus geochemical reaction.

Many faults cut poorly lithified Santa Fe Group sediments in the Albuquerque and Española basins. Nearly all of these faults have persistent, well-developed, clay-rich fault cores. To better understand the geological processes that form these low permeability clay cores, we have studied the San Ysidro extensional fault zone, in the northwestern Albuquerque basin. It has at least 615 m of down-to-the-east displacement and is well exposed along its north-south strike for almost 10 km. Numerous types of "hydroplastic" structures (e.g., deep tool marks, convoluted tubes of sediment aligned parallel to slip, and various types of impressions imprinted into slip surfaces) are observed in clay-rich and siliciclastic fault core rocks and are indicative of dominantly plastic deformation and mechanical assimilation in water-saturated sediments. To better understand the role of geochemical processes, samples from the footwall (FW) to hanging wall (HW) protoliths and fault core were collected along traverses across the fault. X-ray diffraction, quantitative clay mineralogy, and inductively coupled plasma mass spectrometry for major, trace metal, and rare earth elements (REE) were completed on the sample suite.

None of the resulting analytical data show distinctive mineralogical and elemental anomalies associated with the San Ysidro fault core as compared to the protolith sediments. Two major lithologic components are associated with the fault: (1) siliciclastic and variably carbonate-cemented sediments that dominate the protolith and provide source materials to the core and (2) clay that is dominant in the fault core. Although the clay core is geochemically distinct from the FW and HW siliciclastic sediments, the protolith does contain a few clay beds and interstitial clays that are essentially identical to the clay core in mineralogical and elemental composition. Light REEs and trace metals in all clays are enriched to the same degree, and the heavier REEs are essentially the same in the clays and siliciclastic sediments. These data, field and thin section observations, and work of other researchers on other Albuquerque basin faults are consistent and indicate that (1) little if any neomineralization occurred, (2) the faulted sediments were likely saturated with groundwater but did not facilitate extensive geochemical reaction due to the lack of water movement in a dominantly plastically deforming media, and (3) thus mechanical assimilation was the dominant process that formed the persistent clay core of the San Ysidro fault zone. This contrasts to faults formed in well-lithified rocks that are often characterized by significant fault core geochemical anomalies and neomineralization formed by the coupling of mechanical and geochemical assimilation in more brittlely deforming media.

ALONG-STRIKE VARIATION IN A FAULTED MONOCLINE, PAJARITO FAULT, LOS ALAMOS, NEW MEXICO

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Field studies of the geometry of extensional fault-related folds provide key contextual data for paleoseismic investigations in the Española basin of the Rio Grande rift. The Pajarito fault (PF) zone forms the active western boundary of the rift near Los Alamos, NM, where it strikes north to northeast along the western margin of Los Alamos National Laboratory. Along strike, the PF is expressed at the surface as a large normal fault, a faulted monocline, and a distributed zone of deformation with significant down-east vertical displacement on the 1.2 Ma Tshirege Member of the Bandelier Tuff (Qbt). Stratigraphic and geochemical correlations of Qbt subunits allow us to estimate displacement on the PF, even where mass wasting extensively modifies the escarpment. Detailed field studies of 7 km of the 52-km-long PF show that the geometry of the fault varies appreciably along-strike.

Maximum stratigraphic separation occurs south of the study area, where the PF is expressed at the surface as two down-east normal faults with >200 m of displacement on Qbt. Farther north, within the study area, the main PF is a faulted monocline with >120 m stratigraphic separation, a narrow (300-m-wide) zone of deformation west of the main escarpment, a prominent basal graben, and a zone of subsidiary faulting, folding, and fracturing that extends at least 1500 m east of the main escarpment. Down-east displacement on Qbt increases slightly in the central portion of the study area, the zone of deformation broadens, and bedding dips suggest no monocline is present. In the northern sector, significantly decreased down-east displacement is again accommodated by monoclinal folding and small-offset distributed normal faulting, which exhibits only ~35 m maximum displacement on any single mapped fault within an increasingly wider zone of associated deformation west of the main PF escarpment. The youngest dated surface ruptures along the PF (late Holocene) and recent small-magnitude earthquakes occurred near the north end of our study area.

An improved understanding of the geometry and stratigraphy within and west of the PF will considerably aid in assessing kinematics of the fault zone and shall provide a valuable framework for future hydrogeologic modeling and drilling projects in this area.

A CHRONOSTRATIGRAPHIC REFERENCE SET OF TEPHRA LAYERS FROM THE JEMEZ MOUNTAINS VOLCANIC SOURCE, NEW MEXICO

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We have completed analysis of a set of tephra layers from the Jemez Mountains volcanic source area of New Mexico, collected by us and others. Electron-microprobe analyses were done on volcanic glass separated from ~50 pumice fall and ash flow tephra units spanning a time range from 12.4 to ~0.05 Ma. Many of these units have been directly dated by others using K-Ar and $^{40}Ar/^{39}Ar$ techniques. Undated units are bracketed between dated tephra layers. The major groups of Jemez Mts. tephra layers analyzed in this study are listed below in stratigraphic order and essentially concordant age (youngest to oldest)

Unit	Approximate Age
El Cajete (pumice fall)	~40-60 ka
Tshirege Member of the Bandelier Tuff (ash flows)	~1.21 ka
Tsankawi Pumice of the Bandelier Tuff (pumice fall)	~1.21 Ma
Cerro Toledo Rhyolite Member of the Bandelier Tuff (pumice falls)	~1.21-1.60 Ma
Otowi Member of the Bandelier Tuff (ash flows)	~1.60 Ma
Guaje Pumice Member of the Bandelier Tuff (pumice fall)	~1.60 Ma
San Diego Canyon Ignimbrite (ash flows and pumice falls)	~1.75-1.78 Ma
Puye Formation tephra layers (pumice falls)	(not dated)
Bearhead Member of the Peralta Formation (ash flows, pyroclastic breccias, and pumice falls)	~6.5-6.7 Ma
Peliza Canyon – Canovas Canyon Formations (ash flows and pumice falls)	~7.4-12.4 Ma

Tephra erupted from the Jemez Mts. sources have been deposited either by direct airfall, or have been reworked by stream erosion and transported into depositional basins adjacent to the Jemez Mts. (for example, the Española basin). These data, combined with those for dated and analyzed tephra from sources other than the Jemez Mts, provide a reference framework for studies of surface and subsurface chronostratigraphy, structure, and hydrogeology in the Española and middle Rio Grande basins. Our studies indicate that (1) The Cerro Toledo tephra layers are readily distinguishable from the overlying and underlying units of the Bandelier Tuff on the basis of glass composition; (2) airfall pumice of the San Diego Canyon Ignimbrite is correlated from its type area in the southeastern Jemez Mts. to the upper part of the Puye Formation on the eastern side of the Jemez Mts.; (3) airfall pumice in the Horcado Ranch beds, overlain by basalts of the Caja Del Rio tableland in western Espanola basin, correlates with the Bearhead Member of the Peralta Formation on the southeast side of the Jemez Mts. Analyses of ~60 tephra layers collected from the adjacent basins have been completed, and approximately 50 additional samples are currently being analyzed.

CROSS SECTION OF UPPER CRETACEOUS ROCKS (DAKOTA SANDSTONE UP TO POINT LOOKOUT SANDSTONE) FROM GALLUP TO LAMY, NORTHERN NEW MEXICO

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Rocks along this west-east cross section include, in ascending order, the intertongued Dakota Sandstone and Mancos Shale (middle and late Cenomanian age), the Bridge Creek Limestone Member (late Cenomanian and early Turonian), the main body of the Mancos containing the Fairport, Blue Hill, and Semilla Members (all middle Turonian), and the Juana Lopez Member (middle and late Turonian). In the western one half, the intertongued Gallup Sandstone and Crevasse Canyon Formation (late Turonian-late Santonian) crop out and are identifiable in well logs. Farther east these strata are separated by the Montezuma Valley (late Turonian), Multatto (Coniacian), and Satan (Santonian) tongues of the Mancos. The youngest marine unit is the Point Lookout Sandstone (early Campanian) that is overlain by nonmarine Menefee Formation (early Campanian). Progressively from SW to NE, Gallup, Dalton, and Hosta shoreface sands grade into offshore marine shales of the Western Interior Seaway. In Santa Fe and easternmost Sandoval Counties, east of the Rio Grande rift, the pinch-out of the Hosta-Dalton is exposed in the Hagan basin; northeast, the upper Mancos Shale contains no conspicuous sandstone markers with which to subdivide the unit. In the lower Mancos, the Bridge Creek Limestone Member and the Juana Lopez Member (which has a type and reference section northwest of Madrid) are readily identifiable about 100-400 feet above the Dakota Sandstone. The unconformity between the Carlile and Niobrara is obscure, but most of the 2,000-2,200 foot thickness of the Mancos is equivalent to the Niobrara Formation of the Raton Basin and near Pueblo, Colorado. Approximate positions of age-diagnostic molluscan fossils are indicated in the cross section. The western one half of the cross section is well documented by Molenaar and Baird (1992) and Molenaar et. al. (1996), but the eastern one half requires additional study. Most of the fossils in the cross section can be related to a sequence of Western Interior ammonite and inoceramid zones (Landman and Cobban, in press) shown separately in the chart.

GIS APPLICATION OF THE NEWLY DIGITIZED USGS-DENVER CRETACEOUS FOSSIL MOLLUSK COLLECTION

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Computer databases and GIS have revolutionized the way georeferenced data are stored, queried, analyzed, and graphically presented. We recently digitized the USGS Denver Cretaceous fossil mollusk collection. The collection has three primary components: 1) Core collection (approximately 14,000 localities) represents the fieldwork career of Dr. Cobban, his colleagues as well as specimens submitted from outside the Survey. The focus of this collection is the North American Cretaceous interior seaway. 2) A subset (approximately 1,000 localities) of fossil mollusks from historically early USGS Washington collections. 3) The Conlin collection, which was acquired from Texas cartographer James P. Conlin, (approximately 4,000 specimens), is perhaps the finest collection of North American Gulf ammonites. Our first GIS application of the data was on behalf of the USGS Rio Grande Basins Project. We converted locality coordinates from the standard township/range format to decimal degrees utilizing mathematical algorithms and topographical maps. This enables GIS software to import and portray the spatial distribution of sample sites within the Mancos Shale of Santa Fe County, New Mexico. The distribution of fossil localities was used to generate a map that delineates the Cretaceous seaway in Santa Fe County during the Upper Cretaceous Cenomanian through Campanian Stages.

PALEOMAGNETISM AS A LINK BETWEEN GEOLOGIC AND AEROMAGNETIC MAPPING OF THE CERROS DEL RIO VOLCANIC FIELD, RIO GRANDE RIFT, NEW MEXICO

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Pliocene to Quaternary lava flows and related pyroclastic rocks of the Cerros del Rio volcanic field (CdRVF) have surface area of about 700 km^2, and they overlap the boundary between the Española and Santa Domingo basins within the Rio Grande rift in New Mexico. The CdRVF records the eruption of basaltic to dacitic magmas through basin-fill sediments during late stages of rifting. An aeromagnetic survey in 1998 revealed a rich texture of magnetic anomalies over the CdRVF that are interpreted to mostly reflect remanent magnetization captured when the volcanic rocks erupted and cooled between 3 Ma and 1 Ma during normal or reversed polarities of the Gauss or Matuyama geomagnetic chrons. As such, the aeromagnetic anomalies have potential to aid ongoing geologic mapping of volcanic units that is based on other geologic criteria (e.g., petrography, geochemistry, isotopic ages), particularly where younger surficial deposits mask volcanic units.

As a field test of the magnetic polarities sensed from aeromagnetic anomalies, we have collected oriented samples for paleomagnetic analysis at 56 sites distributed over most of the CdRVF. The primary remanent magnetization in CdRVF rocks has been strongly overprinted at many sites due to past lightning strikes. To date, samples from 38 sites have been subjected to extensive alternating-field demagnetization to try to isolate their primary magnetization; the magnetic polarity was successfully determined for 36 of these sites.

Comparison among the paleomagnetic polarities and aeromagnetic anomalies, considered in the context of mapped geologic units, reveals three relations. In locations where prominent aeromagnetic highs or lows correlate with topographic features held up by single geologic units, paleomagnetic data almost always confirm the remotely sensed magnetic polarity. Where aeromagnetic signatures are more neutral or do not clearly correlate with terrain, their link with surface geology is less clear. In these areas, paleomagnetic data allow correlation of geologic sequences between areas of clear aeromagnetic signature. In a few areas the paleomagnetic polarities are opposite to those initially inferred from aeromagnetic anomalies. In one case a reversed-polarity dike intrudes a cinder cone whose aeromagnetic anomaly indicates normal polarity, showing that the dike was not a magma source for the cone deposits. In other areas, surface lava flows with polarity opposite to coincident aeromagnetic anomalies are inferred to be thin deposits whose aeromagnetic signature is too weak to mask the aeromagnetic signature from underlying units of opposite polarity.

Major insights from these studies include better map definition of younger reversed-polarity volcanic strata erupted during the Matuyama chron (< 2.58 Ma) where they overlie or are inset into older, normal-polarity units of the Gauss chron (> 2.58 Ma), as well as the possible identification of normal-polarity units deposited during Reunion events (~2.2-2.1 Ma) of the Matuyama chron.

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