Geologic and Hydrogeologic Framework of the Española Basin -- Proceedings of the 4th Annual Española Basin Workshop, Santa Fe, New Mexico, March 1-3, 2005

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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 an important source of water for many 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 forth-annual Española basin workshop, held March 1-2 of 2005 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 both the Water Research Technical Assistance Office and the Groundwater Protection Program 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 in this report submitted by U.S. Geological Survey authors 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 many 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.

AN UPDATE ON THE SURFICIAL WATER RESOURCES IN THE LOS ALAMOS AREA, NEW MEXICO

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A more complete and accurate understanding of the hydrologic conditions in the Los Alamos area is critical to the management and protection of water. During the mid 1990's, New Mexico Environment Department's Department of Energy Oversight Bureau (the Bureau) recognized that there was not an adequate inventory and characterization of local springs and surface-water resources in the Los Alamos area. To fill the information gaps, the Bureau identified surficial water resources within the area extending from Guaje Canyon to Frijoles Canyon, an area of about 365 square kilometers. The Bureau fulfilled its objective by performing field reconnaissance activities during the period 1994 through 2004. The survey resulted in the discovery of 89 previously undocumented perennial and ephemeral springs. Perennial surface-water flow from both newly discovered and previously identified springs was documented and monitored during the study to determine changes in flow rates and stream conditions (e.g., length of flow) in response to wet and dry periods. The Bureau collected information and data at these water sources including digitally corrected location coordinates via GPS; estimated and measured flow rates; geologic discharge units; field parameters such as pH, specific conductance, and in some cases major- and minor-hydrochemical constituents; natural and anthropogenic radionuclides such as tritium and uranium; and the stable isotopes δD and $\delta^{18}O$. Springs in the study area discharge from shallow, intermediate, and deep (regional) aquifers composed of sedimentary and volcanic rock units. The shallow-perched springs (perennial) primarily reside in the western portion of the Pajarito Plateau and the Sierra de los Valles, and tend to be $Na\text{-}Ca\text{-}HCO_3$ and $Ca\text{-}Mg\text{-}Na\text{-}HCO_3$ type waters with total dissolved solids ranging from approximately 40 to 250 mg/L, depending on the absence or presence of man-induced contamination. Spring discharge from intermediate- and regional-depth aquifers tend to be $Ca\text{-}Na\text{-}HCO_3$ and $Na\text{-}Ca\text{-}HCO_3$ type water, and range from approximately 70 to 250 mg/L in total dissolved solids. Ground-water ages vary within each aquifer; however, the youthful (<50 years) waters tend to be shallow versus older waters occurring at greater depths. Estimated recharge or area of precipitation elevations, as indicated by stable-isotope data, for the shallow-perched and intermediate/regional springs range from about 2,300 to 2,900 m and 2,100 to 2,400 m respectively. It is estimated that the combined flow of all identified perennially flowing shallow-perched springs supply 1.12E+6 cubic meters per year of discharge, while the intermediate and regional springs release about 1.04E+6 cubic meters per year.

HYDROGEOLOGIC STUDY OF EL DORADO UTILITIES LIMESTONE PRODUCTION WELLS, CANADA DE LOS ALAMOS GRANT, SANTA FE COUNTY, NEW MEXICO

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Eldorado at Santa Fe and associated subdivisions have built-out to over 2600 homes in the last 30 years. Prior to suburban style development, the area was ranch land with a handful of windmill wells and little perennial streamflow. The New Mexico Office of the State Engineer (OSE) recently studied production wells within the El Dorado Utilities, Inc. service area. This report describes the hydrogeology and well production from bedrock limestone wells developed since 1996. Believed to produce from the Pennsylvanian Madera Formation, 3 limestone wells have been developed, and their proximity and hydrographs indicate they produce from a common aquifer.

Eldorado occupies the piedmont plain adjoining the mountain front of the Sangre de Cristo Mountains, south of Santa Fe. Beneath the Piedmont sedimentary cover, pre-Tertiary strata dip 10 to 15 degrees west, shingling off the Sangre de Cristo Mountains. The reservoir is bounded along strike by wells that possess modest limestone reservoir qualities, and wells that show the limestone is absent by erosion. Updip to the east the limestone onlaps fractured granite bedrock and truncates by erosion. Down dip into the Espanola embayment the strata have not been tested.

Limestone thickness ranges from 0 to 180 feet within less than one mile along strike. Reports by drillers and El Dorado Utilities' geologist indicate the limestone is intensely weathered and fractured. A geophysical well log of the discovery well illustrates the productive qualities and shows the porosity concentrated near the top of the section. Pumping 250 gpm, total available drawdown in the best well was estimated by the EDU consultant at less than 70 feet. Three wells have produced over 2000 acre feet since early 1997 and provided more than half of the Utility's demand in 2003. Average water level decline rates in individual wells range from 12% to 21% per year and indicate that at current production rates the available water column could be consumed within 10 years. Well yields will diminish before available drawdown limits are reached. The Utility recently applied to the OSE for a supplemental well in the same reservoir. A customer owned Water and Sanitation District is in the process of purchasing the privately owned utility.

AN UPDATE OF HYDROGEOLOGIC CONDITIONS IN THE SOUTHERN ESPAÑOLA BASIN

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Results of hydrogeologic studies by the New Mexico Bureau of Geology, the New Mexico Office of the State Engineer, and Santa Fe County provide an update of hydrologic conditions, water level changes, and hydrogeologic properties in the Santa Fe embayment of the southern Espanola Basin. Data collection has two aspects: 1) the compilation and collection of water level and aquifer test data; 2) geologic mapping of faults and other structures in addition to the gross texture and composition of the basin fill. The geologic mapping has been compiled at a scale of 1:50,000 and includes the Tesuque and Ancha Formations of the Santa Fe Group, from which the City of Santa Fe obtains most of its groundwater. Results will provide improvements to groundwater flow models for water rights administration and well field assessments.

Interpretation of water level data demonstrates trends in water level changes and defines zones of influence surrounding large pumping centers. Combining detailed mapping of faults, USGS aeromagnetic data, and expanded water level measurements improves understanding of geologic controls on groundwater flow and well-field drawdown. The San Isidro fault and associated fault splays that deform ancestral Santa Fe River sediments in the Tesuque Formation west of the City appear to compartmentalize drawdowns from the City of Santa Fe well field and produce a strong hydraulic gradient across the fault. The gradient anomaly associated with the fault does not appear to extend north into finer-grained facies of the Tesuque Formation, but does extend south for a short distance, affecting water levels in coarse-grained Tesuque and Ancha wells. An elliptical shaped zone of influence surrounding the City well field may also result from west-dipping beds that concentrate drawdown along strike in a north-south trend. Water-level declines associated with the pumping center appear to extend north to Tano Road and south beyond Arroyo Hondo.

A hydrogeologic model, constructed using lithosome-based geologic mapping and aquifer (pump) tests, relates aquifer properties to spatial trends in gross basin fill texture and depositional facies. Percentile plots of hydraulic conductivity (derived from aquifer tests), sorted by lithosome and textural units, provide unit-specific conductivity values to about one order of magnitude. Units dominated by small-scale heterogeneity show the greatest range in hydraulic conductivity, up to 2 orders of magnitude. Units dominated by relatively coarse-grained, homogeneous channel deposits indicate hydraulic conductivities ranging over less than one-half order of magnitude. Increased variability appears to be imprinted on some units due to secondary factors such as increased cementation and either fracturing or grain-size reduction associated with faults. The total range in conductivity values for Tesuque and Ancha Formation sediments is estimated at 0.04 to 160 ft/d.

Products of this collaborative study include a series of geologic and hydrologic maps, a database of well, water level, and aquifer test data from both historic compilations and new data collection, and a new water-level monitoring network for the greater Santa Fe area.

OCCURRENCE OF ELEVATED ARSENIC AND FLUORIDE CONCENTRATIONS IN THE ESPAÑOLA BASIN

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Naturally occurring elevated concentrations of fluoride and arsenic in the Española Basin are associated with specific stratigraphic intervals and geochemical environments of the Tesuque Formation. Discrete-zone sample water-quality data have recently been obtained from well drilling projects in the Santa Fe Well Field, Buckman Well Field, Pojoaque area, Española area, and at Chimayo. Distributions of water-quality data were compared with sedimentary sequences, mapped stratigraphy, and structural features to identify geochemical flow paths in the Tesuque Formation aquifer.

Dissolved concentrations of fluoride in the Tesuque aquifer are commonly related to alkaline water (pH >9.0, carbonate >50 mg/L). Elevated fluoride is likely controlled by adsorption by kaolinite and anion exchange processes. Desorption of fluoride from kaolinite occurs when the pH is greater than 7.5. Deep test holes in Española and Chimayo have produced alkaline water elevated in both fluoride (5 to 8 mg/L) and arsenic (0.01 to 0.05 mg/L).

Elevated arsenic concentrations in the Santa Fe area appear to be associated with sediment composition (source) rather than a certain geochemical environment. Radionuclides most commonly occur in the Tesuque aquifer system along the flank of the Sangre de Cristo Mountains, which is likely related to alluvial slope deposits. Elevated arsenic appears to be associated with occurrence of radionuclides, which would support the association with sediment composition.

CONTAMINANT CONCENTRATIONS IN WATER AND BRYOPHYTES FOUND IN FOUR SPRINGS LOCATED ALONG THE UPPER RIO GRANDE, NEW MEXICO

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In November 2003, The RadioActivist Campaign (TRAC) published a report identifying detectable ^{137}Cs in water and bryophytes (aquatic mosses) from Spring 4A. Spring 4A is located downgradient of Los Alamos National Laboratory (LANL) near the Rio Grande in White Rock Canyon. The report states that the detected ^{137}Cs was of LANL origin and was the first confirmed detection of LANL radioactivity entering the Rio Grande from a ground-water pathway. In 2004, the New Mexico Environment Department's Department of Energy Oversight Bureau collected and analyzed samples of bryophytes and water from Springs 4A and 4C (a nearby spring), and two springs (Big Spring and Hemingway Spring) located 70 km and 125 km upstream on the Rio Grande. Springs 4A and 4C show anthropogenic impact/influence such as elevated levels of tritium, chloride, nitrate, and perchlorate. While this indicates that some fraction of recharge to the springs is of a young age (<50 years) and possibly from past LANL discharges, we could not confirm the TRAC detections of ^{137}Cs in water or bryophytes at Springs 4A or 4C using the best analytical technology available to NMED.

Springs 4A and 4C discharge from the upper portion of the regional aquifer or from deep perched intermediate units beneath the Pajarito Plateau. As noted earlier, Springs 4A and 4C show anthropogenic impacts indicating some portion of recharge that is of a shallow/youthful source. The two upstream springs discharge from Rio Grande basin sediments and are tritium-free indicating very old water (>100 years), and are used here to represent background conditions.

Spring samples were analyzed for ^{137}Cs, tritium, perchlorate, ^{90}Sr, ^{238}Pu, $^{239/240}$Pu, major anions, and dissolved and total metals. Bryophytes were dried for low-level perchlorate analysis, and reduced to ash for analysis for ^{137}Cs and other gamma-emitting radionuclides, ^{90}Sr, ^{238}Pu, $^{239/240}$Pu, and total metals. Spring samples were purged through a series of filters to determine if colloidal or dissolved ^{137}Cs was detectable in the spring waters. Approximately 100 liters of water were filtered through 0.45 and 0.2 µ cellulose filters followed by a 3M Empore ™ Cesium Rad Disk. The 0.2 filters were digested and analyzed to determine if detectable levels of greater than 0.2 µ (and less than 0.45 µ) colloidal bound ^{137}Cs were present in the water. The Cesium Rad Disks (0.1 µ) were used to extract cesium present in the dissolved and/or colloidal <0.2 µ but >0.1 µ fraction. These methods reduced ^{137}Cs detection limits by two orders of magnitude for water and bryophytes.

^{137}Cs and ^{90}Sr were not detected in the spring waters or bryophytes. Perchlorate was not detected in bryophytes but was detected in all four spring-water samples. The uranium isotopes 234, 235, and 238 were detected in all bryophytes and water samples, with the exception that ^{235}U was not detected at Springs 4A and 4C water. $^{239/240}$Pu was not detected in spring waters but was detected in all bryophyte samples. ^{238}Pu may have been detected in both bryophyte and water at Spring 4C but was not detected in any other spring or bryophyte sample. Concentrations of gamma emitters detected in bryophytes were generally low and near detection limits. When concentrations of metals or radionuclides in both water and bryophyte tissue were greater than detection limits, bioconcentration factors are provided.

NATURAL URANIUM IN GROUND WATER IN THE ESPANOLA BASIN

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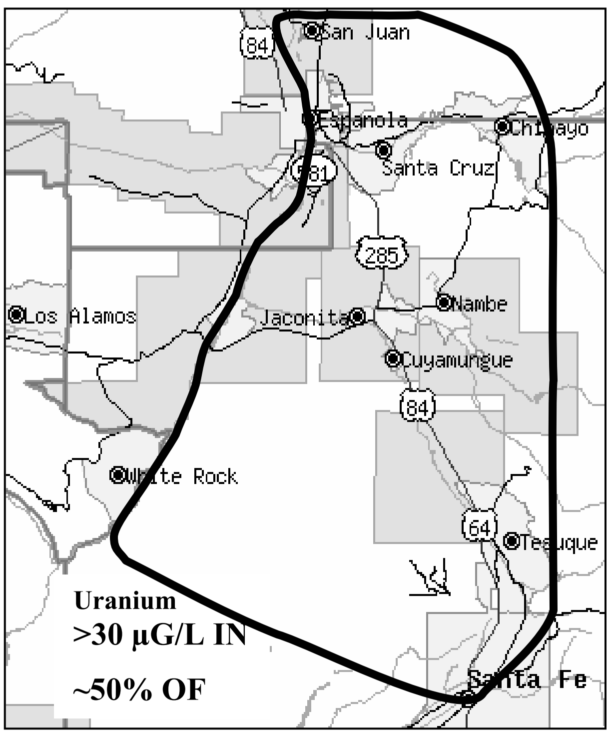
Small, laterally discontinuous, roll-front uranium deposits occur in the Tesuque Formation in the Espanola Basin. They consist of grain coatings of carnotite and other uranyl minerals that precipitated, from uranyl carbonates in ground water, onto carbonaceous sandstone, siltstone, and conglomerate. Potential sources of uranium origination include devitrification of volcanic ash, and weathering of crystalline Precambrian rocks in the Sangre de Cristo Mountains. Numerous volcanic ash layers occur within the Tesuque Formation in this area, and some have been devitrified to clay minerals including smectite. Devitrification can occur when volcanic ash (glass) reacts with ground water, and can release metals including uranium(VI) into solution.



Uranium in excess of the drinking-water standard of 30 µg/L has been detected in approximately 50% of the wells tested in the area east of the Rio Grande, extending from northern Santa Fe into Espanola. Concentrations range from less than 1 µg/L to a maximum of 1820 µg/L. Isotopic signatures are consistent with natural uranium, not depleted or enriched by anthropogenic processes. At least 27 wells serving 19 public water systems, and 209 private domestic wells, produce water with excessive uranium. Some area residents have installed anion exchange and reverse osmosis treatment units to decrease uranium in their water supply. Anion exchange units installed on two wells serving a mobile home park decrease uranium from ~100 µg/L to less than 5 µg/L. The units use proprietary resins to exchange uranyl carbonates with chloride, and are regenerated with potassium chloride brine. Disposal of waste generated by drinking-water treatment systems is an emerging issue. We anticipate that the amount of treatment waste will increase in 2007 as public water systems will be required to comply with the drinking-water standard. In this region, treatment waste is presently discharged to on-site septic systems.

High levels of indoor radon, a uranium decay byproduct, also are widespread in this region. EPA's recommended action level for indoor radon is 4 pCi/L. Concentrations in excess of 20 pCi/L have been measured in buildings in the area.

RESULTS FROM WATER QUALITY ANALYSES OF DOMESTIC WELLS IN THE POJOAQUE, NAMBE, AND TESUQUE WATERSHEDS, NEW MEXICO

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A joint study was conducted to analyze water quality in domestic wells within the Rio Pojoaque, Rio Nambe, and Rio Tesuque watersheds. The study was part of a larger evaluation of the need for a regional waste water treatment plant. Samples were brought in by the well owners, as part of the New Mexico Environment Department (NMED) water fair program. Field parameters including pH, temperature, and specific conductance were recorded and a split sample was collected by Los Alamos National Laboratory for laboratory analyses for trace elements, trace metals, and general chemistry. Field testing for fluoride, iron, nitrate, and sulfate also were conducted by NMED. Wells were located using aerial photography/GIS, for later spatial analysis.

The results showed little nitrate contamination (expected from septic tanks), but widespread elevated concentrations of naturally occurring uranium. Uranium concentrations reflected both groundwater and chemical (oxidation-reduction) gradients, with higher concentrations nearer the mountain-front recharge zone of the Sangre de Cristo Mountains. Groundwater is oxidizing with respect to sulfur and uranium based on measured concentrations within the watersheds. Calcium, sodium, and bicarbonate are the dominant major ions. Low nitrate concentrations may be due to a combination of septic tank and well spacing, depth to groundwater, groundwater mixing, and aqueous and soil geochemistry.

Results suggest residents should become educated on treatment options for their drinking water, either through individual treatment units or the development of a community water system. While the analytical results demonstrate no immediate need for a regional wastewater treatment plant, one should be considered by community planning groups to prevent potential future contamination.

GROUNDWATER PATHWAYS ASSESSMENT: UNCERTAINTY ANALYSIS OF CONTAMINANT TRANSPORT FROM MORTANDAD CANYON

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We present an uncertainty analysis of model simulations related to subsurface contaminant transport from the Mortandad Canyon within the Los Alamos National Laboratory. We describe how uncertainties are quantified and propagated through a series of coupled models and then used to predict likely future concentrations at municipal wells. Uncertainties in the contaminant source, infiltration distribution, and transport through the unsaturated and saturated zones are analyzed using a series of alternative conceptual models and stochastic model parameters. Alternative conceptual models and uncertain model parameters are defined to encompass a large range of possible uncertainties associated with potential groundwater flow and transport based on existing data and expert knowledge about the system. In all, eight alternative conceptual models having up to 38 uncertain model parameters are analyzed. For each conceptual model and related stochastic parameter realization, we simulate contaminant transport from the contaminant outfall to water-supply wells over the next 1000 years. Specifically, the groundwater transport of the nonsorbing species perchlorate, nitrate and tritium, which were released as surface water from the radioactive liquid-waste treatment facility, is predicted. We also make probabilistic predictions of contaminant concentrations that could be observed in new monitoring wells that will be drilled in the Mortandad Canyon in 2005.

ASSESSING GROUND-WATER RECHARGE THROUGH THE PAJARITO FAULT ZONE, UPPER PAJARITO CANYON, LOS ALAMOS, NEW MEXICO

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Physical processes of ground-water recharge to aquifers beneath the Los Alamos region are not well understood. In particular, there is limited knowledge concerning the role of the Pajarito fault zone as a ground-water recharge mechanism (conduit and/or barrier). The present conceptual hydrogeologic model for the Pajarito fault zone is incomplete because of the paucity of data. The New Mexico Environment Department's Department of Energy Oversight Bureau (the Bureau) has initiated a study to determine if surface water loss in the upper reach of Pajarito Canyon is occurring within the Pajarito fault zone. Hydrologic, hydrochemical, and isotopic constituents (δD, $\delta^{18}O$, and ^{3}H) are being analyzed for samples collected at the fault expression (PA-10.6) and from downgradient springs. General hydrologic conditions include a perennial surface-water reach that flows west to east for approximately 2.4 km upstream of the Pajarito fault zone. This reach is supplied by seep and spring discharges at an elevation of about 2,740 m. Under baseflow conditions, the reach abruptly terminates at PA-10.6 at an elevation of 2,470 m. Approximately 1.9 km downstream of PA-10.6, three perennial springs discharge from horizontal fractures and/or surge beds at an elevation of about 2,330 m. Various rock units of the upper Bandelier Tuff crop out at PA-10.6 and the springs. From 1997 through 2001, periodic bucket-and-stopwatch-flow measurements were made at PA-10.6 and below the springs. Recharge and discharge (water balance) measurements were nearly equivalent. Isotopic data collected in 1999 suggest that two of the three aforementioned springs (Homestead and Starmer Springs) are chemically and isotopically similar to the PA-10.6 waters. Some chemical differences were noted, however, including elevated concentrations of Cl, SO_4, and Na, which may be attributed to salt-laden-runoff infiltration along State Road 501. The third spring (Bulldog Spring) contains elevated concentrations of ^{3}H and major ions, and is slightly enriched in δD and $\delta^{18}O$ compared to water at PA-10.6, suggesting a different recharge source. Solutes produced from the Cerro Grande fire in May 2000 introduced chemical tracers that showed a direct link between water at PA-10.6 and the downgradient springs. Subsequent summer-monsoon flooding in the upper reach of Pajarito Canyon impacted water quality at PA-10.6. Hydrochemical changes at PA-10.6 included an approximate four-fold increase in dissolved HCO_3, SO_4, Ca, K, Mg, Mn, Sr, and total dissolved solids. In less than one month, these tracers were observed at Homestead and Starmer Springs. Slight hydrochemical changes observed at Bulldog Spring indicated that some connection in ground-water flow was established. Lower concentrations of these tracers were also measured during the summers of 2001 and 2003. During 2005, Los Alamos National Laboratory investigators and the Bureau will finalize this project by collecting and analyzing additional samples for ^{3}H, ^{4}He, Ar, Ne, δD, $\delta^{18}O$, and major ions to better define the hydraulic connectivity between waters at PA-10.6 and the springs. These findings will provide additional insights to the role of the Pajarito fault zone controlling ground-water recharge in the study area.

AN INVESTIGATION OF RECHARGE TO THE ESPAÑOLA BASIN UTILIZING NOBLE GASES, GROUNDWATER AGES, AND TEMPERATURE DATA

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Like most intermountain basins in the western U.S., recharge to the Española Basin in northern New Mexico is uncertain. The recharge component with the greatest uncertainty is subsurface inflow from adjacent mountains (mountain-block recharge, or MBR). Existing numerical models suggest that MBR constitutes a large fraction of recharge, particularly on the eastern side of the basin where about half of the estimated recharge is MBR from the Sangre de Cristo Mountains. In contrast, recent data from the Colorado Front Range, which receives more annual precipitation and is composed of similar Precambrian metamorphic crystalline rocks, indicate no significant MBR to the adjacent Denver Basin, calling into question the high MBR estimates for the Sangre de Criso Mountains.

Noble gas, groundwater age, and temperature data are being collected from water wells in the Española Basin in an attempt to independently estimate MBR and improve constraints on recharge to the basin. Noble gases will be used to determine recharge temperature, a reliable indicator of recharge elevation. Groundwater ages will be determined using $^{3}H/^{3}He$ and ^{14}C methods in an attempt to discern groundwater-age gradients, which are a direct function of total recharge. Groundwater temperature, a potential indicator of total fluid flux, will also be measured where possible. These data will then 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. Preliminary samples have been collected from wells along a roughly E-W transect across the basin. Initial analyses of the sensitivity of the temperature, recharge temperature, and age distributions to variations in MBR have also been performed. Most of the data will be collected in 2005 and then interpreted and reported in 2006.

VALUE OF USGS WATER SUPPLY PAPER 1525 TO CURRENT ESPAÑOLA BASIN GEOHYDROLOGY STUDIES

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An intensive multidisciplinary field study of geology and hydrology of the Santa Fe, NM area was initiated in July 1951 by staff of divisions of the USGS and NMIMT, in cooperation with the NM Office of the State Engineer (NMOSE). Most of the detailed geological fieldwork was done in 1951-2 by NMBMMR staff (B. Baldwin, F. Kottlowski, and W. Bundy). Ground-water data were collected and interpreted as a method of "hydro-geophysical" exploration by USGS staff Z. Spiegel, E. Barrows, and T. Gerber, followed by traditional subsurface geophysical exploration (NMIMT geophysicists H. Winkler and others). Spiegel and Baldwin were principal authors and editors. The report was released to open-file in 1958 and printed in 1963 as USGS WSP 1525.

The most valuable features of the report and subsequent updates and augmentation, especially to the authors, their colleagues, and students were, (1) recognition of differences in structure and lithofacies of sheets of surficial beds (Ancha Formation and overlying stream-related terrace deposits) unconformable on older westerly-dipping beds (Tesuque Formation). Lithofacies sequence of the Tesuque Formation suggests progressive inversion by erosion and local re-deposition of pre-existing strata (middle to early Tertiary age; Paleozoic and Precambrian-age rocks) to the south-east and east; (2) mapping of the base of the more permeable Ancha Formation that filled ancestral erosion valleys eroded across underlying less-permeable beds; (3) aiding interpretation of 3D ground-water flow patterns in sequences of monoclinal strata partially or fully incised by superposed streams or buried valleys, and (4) solution of the generally accepted inflow / outflow equation for the portion of the study area that contributed to a zone of measurable spring flow and readily estimated evapotranspiration, which resulted in a long-term annual average of about 1/2 inch of natural recharge to an area of 114 sq. miles (average altitude 6300 feet, average precipitation 13 inches) due to surface runoff of heavy storms into swales and arroyos.

The co-operative agreement was weakened by restrictions (1) by NMBMMR, geologic mapping of only four 7.S-min. quadrangles, and (2) by the State Engineer, that water rights matters should not be discussed. The first restriction was offset in part by (a) Baldwin's reconnaissance west of the Turquoise Hill quadrangle and later work on igneous rocks of that area with M. Sun (NMBMMR); (b) general reconnaissance to the north with colleagues, including a field conference with Luna Leopold, T. Galusha, and others; and (c) study by Spiegel of geohydrology west of the Rio Grande (1949), traverses of arroyos and ridges between Tesuque and Nambe, on foot and horse, 195258. These observations, plus data from ongoing USGS studies in those areas, helped extension of water-level contours in PI. 7 of WSP 1525 to areas north of the area of detailed study. The second restriction was offset in part by discussion in WSP 1525 of general ground-water principles; local data on ground-water recharge and natural and artificial aquifer discharge; effects of wells on water levels, springs, and streams; aquifer testing; and a simple method of extension of well life. In addition, in 1956-7, 1962-3, and from 1974 to the present, Spiegel prepared and had published (or released to open file) numerous reports with basic data and concepts that augmented the restricted published report. These reports are readily available in Santa Fe.

GROUNDWATER TEMPERATURES AND HEAT FLOW IN THE ESPAÑOLA BASIN

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Although groundwater temperatures have been used primarily to determine geothermal gradients, they can also be used to infer aspects of the groundwater flow system. In the Espanola Basin, we are using a combination of temperature data and basin-scale coupled heat-flow and groundwater flow modeling to address questions concerning large-scale recharge fluxes and deep upwelling of thermal waters. Better understanding of recharge fluxes is pertinent to water supply calculations; understanding upwelling of thermal waters is pertinent to water quality issues such as elevated uranium, fluoride, and arsenic. We present temperature data and preliminary simulation results that will provide a starting point for more detailed analyses using new noble gas data (Manning et al., 2005).

Using a limited dataset of eight wells in the basin, we estimate the average thermal gradient to be 20^{o}C/km. By calibrating a model of heat flow in the basin assuming conduction only (no groundwater flow), we were able to match temperature gradients in the wells reasonably well, although the simulated gradient was significantly higher than the measured gradient in one well (SF-2, near the Rio Grande). By adding groundwater flow to the simulations, temperatures in the upper portion of the aquifer were significantly reduced, suggesting that the impact of cooler recharge water may be measurable even in the center portion of the basin, far from recharge areas. This effect improved the match between measured and simulated temperatures in the SF-2 well. These preliminary results suggest that conduction, although an important mechanism for heat flow in the basin, does not completely dominate measured gradients and thus temperature profiles may be a useful tool for understanding recharge fluxes. Future work will test alternative conceptual models of recharge distribution and determine whether temperature data can be used quantitatively to distinguish between them.

Andrew H. Manning, Elizabeth H. Keating, Jonathan Saul Caine, and Gary P. Landis, 2005, An Investigation of Recharge to the Española Basin Utilizing Noble Gases, Groundwater Ages, and Temperature Data, 4th Annual Española Basin workshop, Santa Fe, NM.

AN UPDATE ON THE CITY OF SANTA FE'S REGIONAL GROUNDWATER FLOW MODEL

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The City of Santa Fe has continued to develop its groundwater flow model of the region to assist the City in evaluating water resources alternatives. Its existing model covers the area presented in the McAda-Wasiolek (1988) and Frenzel (1995) models. Refinements were made by the City to the Frenzel (1995) model to increase grid density in a region extending outward from its Buckman Wellfield and to include a 9th model layer to represent the alluvial aquifer beneath the Rio Grande, Rio Pojoaque and Tesuque Creek. The existing City model also updated annual pumping from existing municipal and private wells through the year 2000, simulated the rivers with the Stream package of MODFLOW, and underwent and extensive model calibration in the vicinity of the Buckman Wellfield.

Recent updates to the City's numerical groundwater flow model include expanding the model boundaries to the west, east and south to incorporate Galisteo Creek, refining the density of the model grid in the region incorporating the Santa Fe River, and refining the model layering to incorporate recent geophysical and geologic mapping undertaken by the USGS and the NMBMGR. The updated City model has also included aquifer pumping test and water level data compiled by the NMBMGR. These data have been used to revise the aquifer hydraulic conductivity distributions for the Tesuque Aquifer and to create a detailed set of water level observations used in model calibration. In addition, the City model has transitioned to a monthly time step for recent years to provide a more rigorous calibration that takes into account seasonal and short-term variations in pumping and streamflow.

LATERAL DISPLACEMENT VARIATION AND FAULT INTERACTION ON THE PAJARITO PLATEAU, RIO GRANDE RIFT, NEW MEXICO

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We propose a geometric model of the Pajarito fault (PF) system using displacement-length profiles to answer questions about the fault system's geometry. In areas of detailed mapping, we measured stratigraphic throw on displaced contacts of subunits of the Tshirege Member of the Bandelier Tuff (Qbt). As scarp height has been shown to be a reasonable approximation of stratigraphic separation in this area (Gardner et al., 2001), beyond the limits of detailed mapping we measured throw on the displaced top of the Bandelier Tuff using a LIDAR 4-ft grid (Carey and Cole, 2001). In areas of substantial distributed deformation, we estimated total throw by integrating the effects of tilt of bedding, folding, and small offset faults.

At the surface, the Pajarito fault is not a single shear surface but a complex zone of deformation with considerable lateral variation in structural style. Near Cochiti Canyon, total throw on two main down-east normal faults splays is more than 120 m on Bandelier Tuff. Maximum throw occurs near Frijoles Canyon on two splays with >200 m total displacement. At Water Canyon, the PF zone is a faulted monocline with >120 m throw, a prominent basal graben, and hanging wall bedding that dips toward the fault. At Cañon de Valle, the basal graben is well-expressed but no monocline is present. From Pajarito Canyon to Rendija Canyon, down-east displacement is accommodated by monoclinal folding and small-offset distributed normal faulting with ~35 m maximum throw on any single mapped fault. In the vicinity of the town of Los Alamos, the Rendija Canyon fault (RCF) and Guaje Mountain fault (GMF) are subparallel to and partially overlap the trace of the PF, accounting for a combined 75 m down-west throw. Between Rendija and Chupaderos Canyons, no discrete PF has been mapped. At Chupaderos Canyon, polarity changes to the down-east Santa Clara segment of the PF, continuing past Santa Clara Canyon as a single normal fault with >100 m down-east throw on Qbt.

Pronounced displacement gradients occur on the PF, RCF, and GMF where they overlap. This is also the location of an early Pleistocene fan complex and the Diamond Drive graben. The distributed nature of faulting in this sector, compared to the southern sector of the PF, suggests linkage between the PF and the RCF-GMF and that faulting at the surface has not yet completely localized onto a main PF.

In aggregate, the Pajarito fault system is composed of a principal fault plane with branched secondary fault planes at the vertical termination (ground surface) and en echelon secondary fault planes at the lateral terminations (e.g., Marchal et al., 2003). Total length is >46 km. Previous paleoseismic investigations indicate that different fault traces along the PF system have ruptured at different times. This may be a function of the distributed nature of faulting associated with upward propagation of the PF.

HYDROGEOLOGIC CROSS SECTIONS OF THE ESTANCIA GROUNDWATER BASIN, CENTRAL NEW MEXICO

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Ongoing investigations of the hydrogeologic framework of the Estancia groundwater basin (**EGWB**), and its brackish-water resources and aquifer-recharge mechanisms require a much more detailed conceptual and physical models of basinwide hydrogeology than have heretofore been developed. This poster presentation includes a set of nine new hydrogeologic cross-basin sections that illustrate the major stratigraphic and tectonic elements of the topographically *closed* and geohydrologically *undrained* **EGWB** between its northernmost edge (35° 12.5' N) and the southern basin area east of Mountainair (34° 32.5' N). Each section ends at the divide between the eastern Estancia Basin watershed and the Pecos River (surface/subsurface) drainage basin. Base-line elevation is Mean Sea Level, original map scale is 1:100,000, and vertical exaggeration for hydrostratigraphic emphasis is 10x. However, draft sections were also prepared at 1:1 scale to make sure that structural inferences and interpretations were reasonable approximations of “conceptual and spatial reality.” Sections and base maps are now available in Adobe Illustrator® format; and they should be regarded as “works-in-progress” that are available for peer review and subject to revision as more subsurface geologic and geophysical baseline information is acquired. Primary information sources for this hydrogeologic-model update include: 1) NM Bureau of Mines [Geology] & Mineral Resources and Univ. of Texas-El Paso geologic and geophysical investigations of deep-subsurface conditions (Broadhead,1997, NMBMMR Bull. 157; Barrow and Keller,1994, GSA Spec. Paper 291; Foster and Stipp,1961, NMBMMR Circ. 57); 2) NMBMMR hydrogeologic studies (Smith, 1957, Ground Water Rpt. 5; Titus, 1973, Open-file Report 69); and 3) unpublished data compiled for NMBM&MR engineering and environmental-geology programs in the **EGWB** area (O-F Rpts. 245 and 258).

Hydrogeologic-framework interpretations illustrated in the cross sections confirm Broadhead’s (1997) observation that the thin alluvial and lacustrine deposits (<100 m—late Neogene) of the central Estancia topographic basin conceal three interconnected, but distinct structural subbasins (Galisteo, West Estancia, and Perro). The latter are bounded by complex shear and dip-slip fault zones primarily produced by late Paleozoic and Neogene compressional and extensional tectonism. Major aquifer systems comprise upper Pennsylvanian carbonate rocks and gypsiferous carbonate and clastic sequences of Permian to Triassic age. The deep Perro (Ancestral Rocky Mountain-**ARM**) subbasin, beneath Laguna del Perro and adjacent playa-lake depressions of the south-central Estancia Basin, is the target area for R&D activities related to brackish-groundwater development and “concentrate” disposal. Primary mechanisms for **ARM** and Laramide structural-subbasin formation are still being debated (e.g. dextral vs. sinistral shear; see 1999 reviews by Pazzaglia et al., Woodward et al., and Karlstrom et al. in NMGS Guidebook 50); but the fracture and dissolution porosity/permeability associated with subbasin-bounding deformation zones are clearly the major factors influencing groundwater flow and quality in bedrock-aquifer systems throughout the Estancia groundwater basin.

INTRABASINAL ARCHITECTURE OF THE SOUTHERN ĔSPANOLA BASIN

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Recent geologic mapping, examination of well cuttings, high-resolution aeromagnetic data, and other available geophysical data have refined our understanding of the general structure within the southern Española Basin. Our focus for this presentation is on the intrabasinal faults and folds within the basin, many of which coincide with aeromagnetic lineaments. In places, these intrabasinal faults appear to profoundly influence groundwater flow and aquifer compartmentalization (Johnson et al., 2004).

North of the Santa Fe River, the general structure is that of a west-tilted half-graben, bounded on the west by the Pajarito fault zone near Los Alamos. Within the half-graben are numerous extension-related structures of interest. Midway across the basin, northwest of Tesuque Pueblo, there is a significant west-facing monocline with an interpreted 1000-1500 m of structural relief. This monocline is cut by numerous faults of variable displacement, and continues to the north into what Kelley (1978) referred to as the Barrancos monocline and to the south as a series of typically west-down, *en echelon* and anastomosing faults. We propose calling this structure the Barrancos fault system because it is continuous with the Barrancos monocline to the north. Faults bound the eastern margin of the basin as well, but appear to have relatively minor offset during rift tectonic activity. In addition to the Barrancos fault system, numerous west- and east-down faults are present basinward from the mountain front. West-down faults are locally coincident with west-facing monoclines.

The area south of the Tesuque–Santa Fe drainage divide is generally referred to as the Santa Fe embayment. Here, the general geologic structure is that of a north-northeast-plunging syncline. The eastern limb of the syncline is cut by normal faults of unknown offset. Many of these faults have been mapped at the surface but some are inferred entirely from the aeromagnetic data. In many cases, aeromagnetically inferred faults coincide with mapped fault segments. This reflects a convergent evolution of both field mapping and interpretation of the aeromagnetic data during our collaboration on this project. In some cases the aeromagnetically interpreted structures are offset from the mapped faults. This discordance is likely due either to a higher contrast of magnetic properties at depth (perhaps indicating subsurface fault geometry) or due to multiple fault strands that were unrecognized on the surface.

TEXTURAL AND THICKNESS VARIABILITY Of THE ANCHA FORMATION IN THE SANTA FE EMBAYMENT, RIO GRANDE RIFT, NORTH-CENTRAL NEW MEXICO

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The Ancha Formation consists of arkosic sand, silty sand, gravel, and mud that was deposited in the Santa Fe embayment during Pliocene and early Pleistocene time. Reaching a thickness of ~90 m, the Ancha Formation unconformably overlies the Tesuque Formation. The lower part of the Ancha Formation is locally saturated and forms an important aquifer for the greater Santa Fe area. We assess the spatial variability of the gross texture of the Ancha Formation and how this variability may influence hydrogeologic properties of this thin but important aquifer. Also, we present structural contour maps showing our best estimate of the elevation of the Ancha Formation basal contact, and use these maps to discuss the thickness variability of this unit and the three-dimensional shape of its lower contact.

The Ancha Formation was deposited by two different depositional systems. South of approximately Interstate 25 and north of the Santa Fe River, this formation was deposited by relatively small drainages on an alluvial slope along the southwestern flank of the Sangre de Cristo Mts. Here, sediment is characterized by poorly to moderately sorted, silty or muddy sand (mostly very fine- to medium-grained sand with subordinate coarse- to very coarse-grained sand) that contains scattered pebbles. This finer grained sediment, referred to as extra-channel sediment, is interbedded with various proportions of channel deposits that are composed of medium- to very coarse-grained sand and gravel. The overall texture of these alluvial-slope deposits (estimated by the proportion of the coarse channels relative to extra-channel sediment) becomes finer away from the mountain front. Saturated alluvial slope sediment is found only in the western part of the embayment, where the Ancha Formation is finer-grained and probably less permeable than correlative deposits near the mountain front. North of the Santa Fe River, the alluvial-slope sediment is relatively thin (18-25 m) and generally unsaturated.

Alluvium deposited by the ancestral Santa Fe River, the second depositional system of the Ancha Formation, is generally coarser than the alluvial slope sediment in the central and western parts of the embayment. Gravel is generally clast-supported, poorly sorted, and contains 50-70% pebbles and 30-50% cobbles. This unit contains relatively minor, discontinuous beds of floodplain sediment (silty or clayey very fine to fine sand). Based on available pumping test data, in the western part of the embayment this unit has higher hydraulic conductivity and yield values compared to laterally adjacent alluvial slope deposits.

Our interpretation of the base of the Ancha Formation using well data suggests that it is irregular, having a relief of up to ~40 m with significant paleovalleys. The Ancha Formation appears to thicken westward across a broad fault zone in the eastern part of the embayment. Cross-sections indicate that the slope of the basal Ancha Formation contact flattens west of La Cienega. This flattening may be due to increased discharge to the ancestral Santa Fe River from springs near La Ciengea, or it may be the result of eastward tectonic tilting of the footwall of the La Bajada fault. Stratigraphic relations suggest that local base level changes associated with the emplacement of the Cerros del Rio basalt field could have contributed to much of the aggradation of the Ancha Formation. However, 19-25 m of Ancha Formation ancestral Santa Fe River deposits lay beneath the basalt flows at the western edge of the Caja del Rio Plateau. This indicates that aggradation of the Ancha Formation commenced before emplacement of these basalts at ~3 Ma. The lack of deformation of the Ancha Formation and correlation to other weakly deformed Plio-Pleistocene deposits in the northern Rio Grande rift suggests that climatic influences might have played a role in the aggradation of this unit.

PRELIMINARY ELECTRICAL RESISTIVITY MODEL ACROSS THE LA BAJADA CONSTRICTION FOR HYDROGEOLOGIC FRAMEWORK STUDIES IN THE ESPAÑOLA AND SANTO DOMINGO BASINS, NEW MEXICO

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Geophysical methods that detect variations in subsurface lithology and structure are important for understanding controls on groundwater within the La Bajada constriction, the critical area of transition between the Española basin on the north and the Santo Domingo basin on the south. The magnetotelluric (MT) method is a deep-sensing geophysical method designed to map changes in electrical resistivity with depth that are related to these subsurface variations. The resistivity of geologic units is largely dependent upon their fluid content, porosity, fracturing, and conductive mineral content. Sixteen MT stations were collected from 2002 to 2004 to help understand the subsurface within the La Bajada constriction, along a northwest to southeast profile from the Pajarito fault on the northwest to the La Bajada fault on the southeast. Across the constriction, MT soundings have provided additional constraints on the relative position of basement and thickness of Paleozoic-Mesozoic and Tertiary sedimentary rocks, based on resistivities expected from certain geologic units. For example, moderately low resistivities (10 to 50 ohm-m) are expected for saturated Tertiary sediments that have low clay content, whereas very low resistivities (1 to 5 ohm-m) are expected for Mesozoic shales. High resistivities are expected for near-surface Tertiary basalt, andesite and rhyolite volcanic rocks (100 to 5,000 ohm-m) and for buried Paleozoic carbonates (200 to 500 ohm-m). In the footwall of the Pajarito fault zone, we model less than 1-km thickness of moderately low resistivities we interpret to be Tertiary sediments underlain by a few hundred meters of very low resistivity Mesozoic shales. Southeast of the Pajarito fault zone, the inferred Paleozoic-Mesozoic boundary is down-dropped to the southeast over 1 km to a depth of about 2 km beneath Dome Road well, where interpreted Tertiary sediments are about 1.5-km thick and inferred Mesozoic shales are about 0.7-km thick. Southeast of Cochiti fault, interpreted Mesozoic shales are about 1.5-km thick, while inferred Tertiary sediments are only about 0.1-km thick. Southeast of an unknown fault, southeast of Cochiti fault, interpreted Tertiary sediments are about 0.5-km thick and inferred Mesozoic shales are about 0.7-km thick, increasing to over 1-km thickness over the Cerrillos uplift. Southeast of another unknown fault, near the Cerrillos uplift, interpreted Mesozoic shales are less than 1-km thick, while inferred Tertiary sediments are less than 0.5-km thick, but thickening to the southeast; the La Bajada constriction appears to be bounded by this unknown fault on the southeast side and by the Pajarito fault on the northwest side. The Mesozoic shales on the northwest side of the Cerrillos uplift have an apparent northwest dip, while the shales on the southeast side have an inferred southeast dip. Two more inferred unknown faults appear on the northwest side of the profile where interpreted Tertiary sediments are about 0.5-km thick, but no significant thickness of Mesozoic shales was detected.

INSAR OBSERVED GROUND SUBSIDENCE NEAR BUCKMAN WELL FIELD, NEW MEXICO

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Interferometric Synthetic Aperture Radar (InSAR) measurements of surface deformation at the Buckman well field near Los Alamos, New Mexico over a time period of 1993-2000 show localized ground subsidence over an area of 25km2 with a maximum line of sight displacement rate of 1.5cm/yr. Based on the spatial correlation of the ground subsidence anomaly and the Buckman well field, we infer that this subsidence is a result of water withdrawal from the underlying aquifer. In 2001, a half-mile fissure with nearly twenty centimeters of offset developed on the periphery of the observed deformation anomaly. This fissure formation episode is coincident with increasing water withdrawal from the well field. However, deformation rates inferred from satellite interferometry do not show an increase over the time period before failure (1997-2000), compared to the deformation rates observed in the earlier epochs (1993-1997). We interpret these observations as indicating an anelastic response of the upper crustal rocks prior to yielding caused by the water withdrawal and concomitant ground compaction.

In order to characterize the depth and geometry of the deformation source, we employ two methods: 1) we simulate the source as a distribution of point sources the inferred production depths of individual wells and 2) we approximate the source by a prolate pressurized ellipsoid (Yang et al. 1988). Both models assume that the host rock deformation is elastic. Although the interpretation of surface deformation data is non-unique, we are able to provide constraints on the source geometry for the deformation signal.

We first model the deformation signal as a superposition of point sources in an elastic halfspace (Mogi 1958). The location of individual sources corresponds to the locations of individual wells and the depth is placed at a typical well depth of 500m. Additionally, the strength of each source is assumed to be proportional to the relative volumetric rate of water withdrawal. A scale factor for pressure was chosen such that the amplitude of the deformation signal is similar to the observed one. This model fails to explain the observations. Indeed, deformation that is occurring at the highest observed rates is north of the northernmost well location. These results imply that there is subsurface source continuity and pressure drop extends to an area greater than the well field itself.

In another set of models, we solve for the surface expression of a contracting prolate spheroid (Yang et al. 1988). The spatial shape of the deformation signal is accommodated in a more satisfactory fashion using this approach. We find that the spheroid best fitting the observed deformation field has a major axis of 5km and a minor axis of 1km and is at a depth of 1.1km. The model spheroid is in approximately the same north-south orientation as the canyon (alluvium) and is dipping at an angle of 7º. This prolate source model successfully explains the main signatures of the observed deformation field. This model also suggests source continuity to the west of the Rio Grande, implying that there is little connectivity between the river and aquifer.

A DATABASE OF GEOCHEMICAL, PETROGRAPHIC, MINERALOGIC, AND GEOCHRONOLOGICAL ANALYSIS FOR THE JEMEZ VOLCANIC FIELD TO SUPPORT THE 3-D GEOLOGIC MODEL Of THE PAJARITO PLATEAU

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Within the south-central part of the Pajarito Plateau, the Laboratory occupies about 2% of the 5000 square kilometer Jemez volcanic field (JVF). Cole et al. (2005) have constructed a 3-D geologic model to provide a computational framework for assessment of contaminant migration from sources within the Laboratory. We have integrated geological information used to support this 3-D geologic model into a large relational database. The ~3500 geochemical, petrographic, mineralogic, and geochronological analyses collected from the JVF presently within the database have been applied during a period of 10 years to create, develop, and refine this 3-D model of volcanic and sedimentary rocks. These data are partly published within literature cited by the database.

The database complies with protocols of Structured Query Language (SQL), allowing construction of relationships among these data, from micrometer-diameter spots chemically analyzed by microprobe within individual mineral grains, to stratigraphic identities for rock columns within drill holes and outcrop that exceed 1 km thickness in some cases. The database establishes rules for the proper relationships among the different types of data by defining a hierarchy for primary keys beginning with a location ID, through sample and split ID, and ending with replicate ID. These rules and examples for their application are published by Warren et al. (2003), available online at http://queeg.ngdc.noaa.gov/seg/geochem/swnvf for the southwestern Nevada volcanic field (SWNVF). The database for the SWNVF, which has an area twice as large as the JVF, has a structure identical to that for the JVF, and so provides a convenient source of comparative information.

The database is particularly robust in petrographic analyses, utilizing new techniques devised by Warren et al. (2003) that apply detailed documentation to provide precise and accurate analyses for minor and trace constituents. Petrographic analyses also include qualitative (descriptive) analyses obtained when support is unavailable for detailed analyses. Petrographic analyses can be related to whole-rock chemical analyses, whole-rock mineral analyses, and mineral identification and chemistry via electron microprobe analysis. Whole rock chemical analyses were obtained mostly by X-ray fluorescence (XRF), many with FeII/FeIII via titration (WC), and by neutron activation analysis (NAA). Most whole-rock mineral analyses employed quantitative X-ray diffraction (QXRD) analysis. In addition to mineral chemical analyses, electron microprobe analyses provide qualitative analyses within the database that confirm or correct mineral analyses documented during petrographic analysis.

We developed the database to facilitate application of extensive and varied types of information to geologic problems within the Laboratory portion of the Pajarito Plateau. We hope that the great volume of complex, interrelated data and data types within this data set will also encourage use for comparisons with other geologic datasets. We also hope that non-petrographers, non-geologists, or others will apply these data to test and develop geological or hydrogeologic models, statistical methods, data mining techniques, exploratory data analysis, and visualization techniques.

ORIGIN OF A BASALT-TO-TRACHYANDESITE/DACITE SUITE IN THE JEMEZ VOLCANIC FIELD BY UPPER CRUSTAL CONTAMINATION

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Magmatic compositions in large, long-líved volcanic fields typically evolve through a variety of petrogenetic processes. Determining their relative roles may be difficult because (1) multiple processes may act simultaneously at a single volcano, (2) different processes may produce similar compositional results, and (3) individual processes may differ significantly at different volcanoes. To isolate the major processes and avoid the complex overprinting of multiple processes in the main Jemez volcanic field (JVF), we obtained whole-rock major- and trace element compositions and mineral compositions from a small basalt-to-trachyandesite/dacite volcanic field (Cerros del Rio, CDR) adjacent to the main JVF. Lavas of the CDR field were erupted during development of the middle to upper crustal magma chamber (4-1 Ma) that resulted in formation of Toledo and Valles calderas at 1.6 Ma and 1.2 Ma respectively, but were not affected by mixing with the main chamber.

The mafic end members of this suite typically range from basanite/alkali olivine basalt to hawaiite (SiO_2 ~ 44-52%; Na_2O+K_2O ~ 4.2-6.3%), likely derived from an ocean-island-basalt (OIB)-modified lithospheric source (McMillan, 1998). Compositions range to trachyandesite and dacite (SiO_2 ~ 65-67%; Na_2O+K_2O ~ 6.9-7.2%) (classification of Le Bas et al., 1986). Trace elements (e.g., Th, Zr) are not well correlated with major elements. Phenocrysts range from olivine and plagioclase in the least evolved lavas to high- and low-Ca pyroxene and sodic plagioclase in the intermediate to silicic members. Primitive members of this series contain gabbroic xenoliths and evolved members are typified by quartzofeldspathic xenoliths and by xenocrysts of quartz and feldspar, which we infer were derived from middle to upper crust. Using only whole-rock compositions observed in the CDR, we can model the major-element compositional range assuming removal of observed phenocryst phases coupled with addition of observed xenolithic/xenocrystic material. Modeling of trace elements, assuming world-wide average values (Rudnick and Gao, 2004), is not compatible with a significant lower crustal component in these magmas.

We conclude that the simplest model for the origin of this basalt-to-trachandesite/dacite suite is fractional crystallization of OIB-modified basalt combined with significant assimilation of middle to upper crustal rocks. Although we cannot rule out more complicated models involving partial fusion of lower crust and mixing of magmas, we do not think they are necessary or likely.

COUNTERCLOCKWISE DECLINATION ANOMALY IN PALEOMAGNETISM OF THE PLIOCENE CERROS DEL RIO VOLCANIC FIELD, NEW MEXICO - AN EXPRESSION OF LATE RIO GRANDE RIFT DISTRIBUTED SHEAR?

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Distributed strike-slip shear is difficult to detect, particularly where shear is accommodated by vertical-axis rotation of fault blocks. Declination anomalies in paleomagnetic data have become the principal evidence used to detect such rotations.
The >700 sq km Cerros del Rio volcanic field (CdRVF) in northern New Mexico lies within the Rio Grande rift and overlaps the boundary between Espanola and Santa Domingo basins. The CdRVF comprises mostly flat-lying lava and pyroclastic deposits erupted from multiple basaltic to dacitic volcanic centers between 2.7 Ma and 1.1 Ma. We have sampled CdRVF units for paleomagnetic analysis at 51 sites distributed over the field. Extensive alternating-field demagnetization was required to isolate primary magnetization in many of these sites due to overprints from past lightning strikes. A mean direction of 49 sites is D = 346.3, I = 51.5, a95 = 4.5, k = 22. These data should average geomagnetic secular variation; they are distributed subequally between Gauss-chron normal-polarity sites and younger mostly reversed-polarity sites of the Matuyama chron and they sample units erupted from at least 12 volcanic centers. Compared to an expected direction calculated from a 0-Ma pole of Besse and Courtillot (2002, 2003), the CdRVF mean direction has a significantly counterclockwise (CCW) declination (-9.0° +/- 6.3°), whereas the inclination is slightly shallow (4.2° +/- 3.6°). The CCW declination anomaly confirms earlier findings by Brown and Golombek (1986) based on fewer paleomagnetic data; they attributed the declination anomaly to CCW rotation of the entire Española basin. Alternatively, CCW rotation may be linked to local shear developed as interaction increased between faults of the Espanola and Santo Domingo basins during known, late-stage narrowing of Rio Grande rifting.

GEOLOGIC FEATURES OF THE ABIQUIU QUADRANGLE, RIO ARRIBA COUNTY, NEW MEXICO

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The Abiquiu 1:24,000-scale quadrangle is located along the Colorado Plateau-Rio Grande rift margin in north-central New Mexico. The map area occurs within the Abiquiu embayment, an early extensional basin of the Rio Grande rift. Rocks exposed include continental Mesozoic rocks of the Colorado Plateau, Cenozoic basin-fill deposits, and volcanic rocks. Mesozoic units are Triassic Chinle Formation, Jurassic Entrada Sandstone, and Todilto Limestone Member of the Wanakah Formation. Cenozoic rocks are the Eocene El Rito Formation, Oligocene-Miocene Abiquiu Formation (upper and lower members), and Miocene Chama-El Rito and Ojo Caliente Sandstone Members of the Tesuque Formation of the Santa Fe Group. The upper member of the Abiquiu Formation has been dated at ~27-23 Ma (Peters, 1999; Peters and McIntosh, 2000) using the 40Ar/39Ar method. Volcanic rocks include the Lobato Basalt (~10-8 Ma; Bachman and Mehnert, 1978; Manley and Mehnert, 1981), El Alto Basalt (~3 Ma; Manley and Mehnert, 1981; Baldridge and others, 1980), and intermediate lavas of the Tschicoma Formation (~7-2 Ma; Gardener and Golf, 1984). Quaternary deposits consist of inset ancestral axial and tributary Rio Chama deposits, Holocene floodplain alluvium, fan and pediment alluvium, and landslide colluvium. Axial terrace benches are found approximately 30 to 115 m above the present Rio Chama floodplain. One set of terraces at about 115 m height is as old as 640 ka, based on the presence of the Lava Creek B ash east of the map area. Delineation of terrace alluvium was modified from Gonzalez (1993) and Gonzalez and Dethier (1993).

Tributary gravels beneath the Lobato and El Alto Basalts contain clasts of a fluvial system that probably represent several ancestral Rio Chama courses. Tops of these gravels are about 580 m and 395 m, respectively, above the modern Rio Chama. Clasts consist mostly of subrounded to well-rounded Paleozoic quartzite and granite, Tertiary volcanics, and traces of Pedernal Chert Member of the Abiquiu Formation. Gravels containing quartzite and Pedernal chert also are present under the Sierra Negra (~5 Ma; Baldridge and others, 1980) and Black Mesa (Servilleta Basalt flow) (~4-3 Ma; Manley, 1976; Laughlin and others, 1993) lavas located northeast and east of the map area, respectively.

The Cañones fault zone separates the Abiquiu embayment from the Colorado Plateau. Time of development of the embayment is constrained by the presences of two basalts on the Colorado Plateau with centers in the embayment. The Lobato Basalt (10-8 Ma) is displaced across the Cañones fault and the El Alto Basalt (~3 Ma) is not (Maldonado, 2004).

LITHOLOGIC CHARACTERISTICS AND AGE RELATIONSHIPS OF THE ANCHA FORMATION DEPICTED ON THE GEOLOGIC MAP OF THE AGUA FRIA QUADRANGLE, SANTA FE COUNTY, NEW MEXICO

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Recent 1:24,000-scale geologic mapping of the Agua Fria 7.5-minute quadrangle near Santa Fe indicates that the Ancha Formation (Spiegel and Baldwin, 1963) consists mostly of loose to weakly consolidated, stream-deposited, slightly pebbly sand to slightly cobbly, pebble gravel. The Ancha locally consists of sandy silt, silty very fine to medium sand, and pebbly sandstone that is weakly cemented by calcium carbonate. These sediments form thin (about 0.3-4 m) lenses and lenticular beds that are rich in Precambrian granite clasts and feldspar. The Ancha commonly is mantled by thin sheetwash deposits and is poorly exposed. Westward-flowing streams originating in the nearby Sangre de Cristo Range, graded to the Rio Grande, deposited the Ancha on northwest- to southwest-dipping Miocene sediments of the Tesuque Formation. The Ancha thins from south to north across the quadrangle. The Ancha is about 60 m thick near the southern boundary of the quadrangle, but thins to about 3–6 m in the northern part of the quadrangle where it forms pediment deposits. These pediment deposits project westward beneath the base of hydromagmatic deposits at the base of basaltic lava flows of the Cerros del Rio volcanic field (CdRvf). Elsewhere deposition of the Ancha Formation predates, was contemporaneous with, and postdates lava flows and related deposits of the CdRvf. The upper 30 m or more of the Ancha in the western part of the quadrangle contain varying amounts of predominately reworked basaltic tephra about 0.5–10 mm in diameter. The tephra was produced by hydromagmatic explosions contemporaneous with the eruption of extensive early phase (2.6–2.7 Ma) basaltic lavas of the CdRvf. Reworked rhyolitic pumice (1.5-1.6 Ma) erupted from the nearby Jemez Mountains is locally present in the upper part of the Ancha. Buried soils in the Ancha have thin, eroded, clay-enriched (Bt) horizons and stage I to III, carbonate-enriched (Btk, Bk, and K) horizons about 15–60 cm thick. These soils record depositional hiatuses of at least a few thousand to several tens of thousands of years. Geomorphic relationships near the Agua Fria quadrangle suggest as much as ~ 10-15 m of incision of the Ancha Formation by the Santa Fe River since about 2.6–2.7 Ma.

BASALT OF R9: THE AREALLY MOST EXTENSIVE COGNITIC SERIES Of FLOWS WITHIN THE CERROS DEL RIO VOLCANIC FIELD, NEW MEXICO

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Drilling to define the regional aquifer within the south-central part of the Pajarito Plateau and collection and analysis of numerous samples from outcrop have established a wide aerial distribution for a cogenetic series of basalt flows here named basalt of R9. The flows are at least 12 km long north to south, and 9 km wide, and therefore the most areally extensive cogenetic flows within the Cerros del Rio volcanic field. These flows provide age dates by 39Ar/40Ar of 2.4 Ma and they are reversely magnetized within the Matuyama I geomagnetic chron of the Pliocene epoch. Extensive chemical and petrographic analyses define four very closely similar flow groups within basalt of R9: from base to top these are lower and upper hawaiite and lower and upper tholeiite. The upper flows for each chemical type have modest contents of plagioclase phenocrysts, averaging 5.4% in the hawaiite and 6.3% in the tholeiite, whereas the lower flows are very poorly plagioclase-phyric, averaging 0.6% and 0.7%. Olivine phenocrysts are common within basalt of R9 but clinopyroxene is generally absent and probably xenocrystic when present. The lower tholeiite generally exhibits a very distinctive ophitic texture in thin section and is the areally most extensive flow group. Most regional wells provide all four groups but hawaiite has not been positively identified in outcrop.

The datum for basalt of R9 provides excellent control throughout an extensive region to assess structural activity that might affect groundwater flow within this portion of the Rio Grande Rift, on its final leg before reaching the Rio Grande. Three km NNW from its eruptive center, exposed immediately northwest from White Rock, the top forms a strikingly flat surface that covers 20 km2. These flat data constrain structural tilting within this structural block to <0.2 degrees and faulting to <15 m offset during the past 2.4 million years, allowing calculation of the primary depositional dip for overlying Tshirege Tuff. The top is 50-100 m lower west of this flat, unfaulted block. These lower elevations for the top of basalt of R9 are associated with higher elevations for the base of the unit, so do not represent flow down into a pre-existing paleovalley, but more likely reflect post-2.4 Ma faulting.

The base of the unit shows generally consistent elevations except within a central paleovalley, where elevations are up to 160 m lower than those within adjacent holes that penetrate the rim. The paleovalley may have narrow exits both north and south, and could be entirely erosional, but it might instead represent a structural basin, or result from a combination of structure and erosion. Within this paleovalley are river gravels, sediments interpreted as slope deposits, and older mafic units of the Cerros del Rio that occur immediately beneath basalt of R9; these substrata indicate that the paleovalley defines an ancestral course of the Rio Grande. The hawaiite filled this paleovalley, enabling the overlying tholeiite to flood the region, redirecting the Rio into its present course between Los Alamos and Ancho Canyons. The total depth of this paleovalley is unknown, but the axis may well extend below the regional water table, possibly influencing groundwater flow eastward through this feature.

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