Abstracts

New Mexico Geology recognizes the important research of students working in post-graduate M.S. and Ph.D. programs. The following abstracts are from M.S. theses and Ph.D. dissertations completed within the last 12 months that pertain to the geology of New Mexico and neighboring states.

New Mexico Institute of Mining and Technology

EPITHERMAL GOLD MINERALIZATION OF THE SAN NICOLAS VEIN, EL CUBO MINE, GUANAJUATO, MEXICO—TRACE ELEMENT DISTRIBUTION, FLUID INCLUSION MOCROTHERMOMETRY, AND GAS CHEMISTRY, by *Reyna L. Abeyta*, 2003, M.S. thesis, Department of Earth and Environmental Science, New Mexico Institute of Mining and Technology, Socorro, NM 87801, 86 pp.

The bonanza-gold San Nicolas vein is located in the Guanajuato, Mexico, silver mining district. With an average grade of 6.8 g/ton Au and 141 g/ton Ag, this vein is unique because it has gold/silver ratios five times greater than most other veins in the district. This research uses paragenetic relationships, trace element geochemistry, fluid inclusion microthermometry, and fluid inclusion gas analyses to study the San Nicolas vein and determine the cause of its anomalously high gold concentrations.

The San Nicolas vein developed in three paragenetic stages: an early vein opening event involving wallrock silicification and brecciation (Stage I), an ore mineralization stage associated with brecciation, amorphous silica, and bladed calcite (Stage II), and the collapse of the hydrothermal system as evidenced by the presence of amethyst and blocky calcite (Stage III).

Gold occurs as electrum intergrown with polybasite, aguilarite, chalcopyrite, bladed calcite, and amorphous silica and is associated with brecciation. Zones of alteration in the wallrock of the San Nicolas vein consist of a lowermost propylitic zone of green wallrock and abundant pyrite, a middle zone of grey, white, and yellow clay, and an uppermost zone of reddish-orange clay. Two XRD analyses reveal that the clays in the middle and uppermost zones are respectively illite and smectite.

Trace element geochemistry shows that Au, Ag, Cu, Pb, Zn, As, and Sb are concentrated in the northeast and in the southwest ends of the San Nicolas vein. Gold concentrations correlate well with Ag and moderately with Cu, Pb, Zn, and Sb.

Fluid inclusion homogenization temperatures Th and salinities range from 172–282°C and 0–2.95 wt% NaCl eq. Bladed calcite associated with ore mineralization was deposited from ~225°C fluids containing 0.5 wt% NaCl eq. Late stage amethyst crystallized from ~238°C fluids containing 0.8 wt% NaCl eq., and blocky calcite crystallized from ~221°C fluids with 1 wt% NaCl eq. The coexistence of both liquid-dominated and vapor-dominated fluid inclusions in the San Nicolas vein, along with the occurrence of bladed calcite and electrum intergrowths, indicates that ore mineralization occurred from boiling fluids. Salinity and Th analyses show both boiling and mixing trends when plotted together which suggests both processes were operating during San Nicolas mineralization.

Fluid inclusion gas analyses indicate that San Nicolas fluids were dominantly meteoric in origin with possibly a minor input of magmatic fluids. Hydrogen sulfide concentrations were sufficient to transport Au complexed with HS^- and deposit the San Nicolas ores. Most gas analyses show a boiling trend when plotted on a CO_2/N_2 vs. total gas discrimination diagrams.

Intergrown gold, bladed calcite, and amorphous silica associated with breccia fragments indicate that gold mineralization occurred in response to catastrophic depressurization and extreme boiling. Homogenization temperatures indicate fluids and wallrock temperatures are 220–238°C. Amorphous silica can only be precipitated if temperatures decreased to 180°C or if about 40% water was removed by boiling. Bladed calcite is deposited in response to CO_2 loss caused by boiling. The most reasonable explanation for the presence of Au in association with minerals deposited in an extreme boiling environment is that Au was deposited as a result of this environment as well.

Intense boiling coupled with sufficient H_2S to transport > 10 ppm Au were crucial to creating the bonanza-Au San Nicolas vein. This mechanism of ore mineralization was absent or not preserved during the development of other vein systems in this mining district such as the Veta Madre and La Luz system.

STABLE ISOTOPE PARTITIONING OF EVAPOTRANSPIRATION ACROSS A SHRUB-GRASS ECOTONE FOLLOWING A PRECIPITATION EVENT, SEVILLETA NATIONAL WILDLIFE REFUGE, USA, by *John R. Boulanger*, 2004, M.S. thesis, Department of Earth and Environmental Science, New Mexico Institute of Mining and Technology, Socorro, NM 87801, 66 pp.

The Sevilleta National Wildlife Refuge (SNWR) in central New Mexico exhibits the widespread shrub encroachment onto former semiarid grasslands that is common throughout the southwestern United States. Many factors, such as fire suppression and high levels of herbivory, have been suggested causes for the widespread shrub encroachment. The encroachment may be related to alternate factors, since it has continued in the SNWR to the present day despite a lack of fire suppression and high levels of herbivory for nearly half a century. Current research in the SNWR evaluates plant response to drought. The results provide evidence that water cycling plays a role in the advancement of shrubs onto grasses. To address wet-season water cycling, the evaporation (E) and transpiration (T) rates were estimated for the shrub and grass ecosystems in the SNWR following a precipitation event. The plant with the higher T rate limits the availability of soil water to the competing plant, and the former plant population will likely increase and expand.

Soil samples were collected from both the shrub ecosystem and the grass ecosystem. For both ecosystems, samples were obtained from control (unaltered) and treatment (no transpiration) plots along a shrub-grass ecotone in the SNWR before, immediately after, and for six consecutive days following a wet-season precipitation event. Samples were selected by means of a random sampling procedure. The soil samples were analyzed for stable isotope ($\delta^{18}O$ and $\delta^{2}H$) composition and water content.

Given the removal of plants and thus transpiration from the treatment plots, the E rate from the treatment plots was expected to be higher than the E rate from the control plots. The treatment plots have more soil water available for evaporation because T is absent. As the soil water content decreases, the E rate decreases. The treatment plot soil waters for both ecosystems were expected to show more stable isotope enrichment and a higher water content than control plot soil waters. Transpiration (or soil water extraction by plants) has been shown to be non-fractionating. It was then assumed that T would not influence the soil water stable isotope signature that results from evaporation.

The treatment plot soil waters showed more stable isotope enrichment and higher water content than the control plot soil waters. A stable isotope balance model was necessary to quantitatively estimate the evaporation and transpiration rates for each ecosystem. The results of this study will demonstrate that transpiration affects the amount of soil water available for evaporation, and therefore influences the extent of stable isotope fractionation. The model results show that the evaporation rate from the treatment plots was higher than the control plots for both ecosystems. The water content, however, remained higher in the treatment plots because the control plots had additional soil water loss due to transpiration. The level of stable isotope enrichment does not depend only on total soil water loss. The greater level of stable isotope enrichment in the treatment plots is due to the fraction of soil water loss by evaporation being greater in the treatment plots than the control plots.

Of the total post-precipitation soil water loss in the shrub ecosystem, 16–21% was transpired by the shrubs and 79–84% was evaporated. Of the total post-precipitation soil water loss in the grass ecosystem, 30–48% was transpired by the grasses and 52–70% was evaporated. Six days after the precipitation event, these figures translate into 9.0–13 mm of soil water transpired by the grasses, whereas the shrubs transpired from 7.5 to 9.0 mm of soil water. This study shows that the shrubs do not have an advantage over grasses, with respect to removing soil moisture that infiltrates following a typical wet-season precipitation event. Additional work is necessary to assess how the contrasts in water use between grasses and shrubs varies throughout the year, and how this contributes to the long term changes in ecosystem structure associated with the shrub encroachment.

DISCRETE ANALYSIS OF THE ROLE OF PORE FLUIDS IN THE GENESIS OF OPENING MODE FRACTURES IN THE SHALLOW CRUST, by *David F. Boutt*, 2004, Ph.D. dissertation, Department of Earth and Environmental Science, New Mexico Institute of Mining and Technology, Socorro, NM 87801, 242 pp.

The work presented in this dissertation focuses on specific problems of coupled fluid-solid mechanics in porous media. These types of problems have been studied for many years with continuum methods. Continuum methods yield information about the behavior of systems but rarely provide significant insight into underlying physics. The work presented here is a departure from continuum methods and explores the application of discrete physics to coupled fluid-solid mechanics in porous media.

I use these discrete methods to examine the behavior of both dry and fluid saturated rock. My specific interest is in identifying the role of fluids in the genesis of natural hydraulic fractures (NHFs) in the subsurface.

Much debate exists over the importance of NHFs, with a considerable amount of effort devoted toward understanding the conditions under which they form. The goal of this dissertation was to explore what control fluids and hydrologic properties of rocks exert on the initiation and propagation of opening mode fractures. I present porous media analyses using the coupled fluid-solid mechanics code LBDEM. Novel comparisons to classic poroelasticity problems (such phenomena as pressurization from an applied stress) indicate that this approach captures the essential physics. The LBDEM is used to explore the detailed physics of natural hydraulic fracturing, through the conceptualization of laboratory experiment. Results of the tests indicate that fluid permeability and porosity either inhibit or prohibit the intensity of fracturing depending on the magnitude of each. Heterogeneities pore throat size (local fluid permeability) are considered, and are shown to increase the formation of fractures where pore throats are increased relative to the surrounding matrix. The experimental approach I developed is subsequently shown to produce fluid-induced extension fractures. For a bedding perpendicular sample of the Abo Formation, one large macroscopic fracture and many microscopic extension fractures were formed. These results indicate that hydrologic heterogeneities, which cause pore fluid pressure gradients, are important for the genesis of natural hydraulic fractures. This implies that rocks with different hydraulic diffusivities will exhibit unique mechanical behavior under similar stress conditions, as rocks with lower dffusivity can maintain higher pore fluid pressure.

LIQUEFACTION SUSCEPTIBILITY MAPPING OF THE SHALLOW ALLUVIUM, INNER VALLEY, RIO GRANDE BASIN, ALBUQUERQUE, NEW MEXICO, by *Jodi A. Clark*, 2004, M.S. thesis, Department of Earth and Environmental Science, New Mexico Institute of Mining and Technology, Socorro, NM 87801, 87 pp.

Albuquerque lies within the seismically active Albuquerque Basin, one of the largest tectonic basins within the Rio Grande rift. Although there have been few large historical earthquakes, there are many Quaternary faults in the Albuquerque area. Therefore, there is a potential for future earthquakes and liquefaction-related damage in the region. The purpose of this study is three-fold: 1) to develop a database of shallow geotechnical borehole data for use in this study and for the benefit of future work in this study area, 2) to establish three-dimensional GIS-based procedures for evaluating liquefaction susceptibility, and 3) to compare the results of these methods to an existing two-dimensional liquefaction susceptibility study for the same area.

The study area for this project is restricted to the inner valley of the Albuquerque Basin and extends from the southern boundary of Sandia Pueblo to the northern boundary of Isleta Pueblo. The inner valley is a 4.5–6.5 km (2.8–4 mi) wide lowland valley and floodplain that is underlain by unlithified and predominantly sandy alluvium. Clay and gravel lenses are locally present but generally not laterally persistent. The shallow water table in this region intersects the ground surface along the Rio Grande and gently slopes away from the river in both directions.

The first phase of this study was to compile a database of well log information for use in engineering geologic and liquefaction susceptibility studies. Data from 407 boreholes were included in this database. This database was the basis for study of the spatial distribution of shallow alluvial sediments within the inner valley of the Albuquerque Basin and GIS-based liquefaction susceptibility analyses.

A recent liquefaction susceptibility study of the Albuquerque area focused on the surficial geology and did not take into account vertical variations of soils that could cause potential liquefaction problems. I developed a GIS-based approach to incorporate these vertical variations by evaluating liquefaction susceptibility for three depth intervals and then combining these to form the overall liquefaction susceptibility for the study area. I also developed a second GIS-based method that used standardized standard penetration test (SPT) blow count data as a proxy for the calculated peak ground acceleration (PGA) trigger to minimize data calculation and processing time. The data for this study are clustered, sparse, and show a high level of spatial variability. These characteristics create some uncertainty with the GIS-based liquefaction susceptibility analysis on a regional scale, but would likely not pose a problem with more localized analyses with more evenly distributed data.

The results of these two methods are compared to the previous surficial geology based results. The three methods can be compared, but there is no way to evaluate the relative or absolute accuracy of the three methods for liquefaction susceptibility presented in this study and be able to definitively say any one is better than another unless they are compared to the resultant liquefaction in the event of an earthquake. All three methods show the same regional trend, which is highest risk of liquefaction along the river and floodplain with decreasing liquefaction susceptibility to the east and west as the elevation increases and the depth to ground water increases. Each of the methods is best suited to particular uses, but none of them are without uncertainty or inherent error. The surficial geology approach used in the previous study provides a regional overview of the liquefaction susceptibility distribution, but masks some localized areas where the potential for liquefaction could be higher than the surficial geology indicates, and should primarily be applied to areas with little or no vertical variability. The methods developed for this study provide more localized detail, but when applied on a regional scale introduce uncertainty and bias based on the distribution of the data.

STABLE ISOTOPIC EVIDENCE FOR FLUID MIXING IN THE TERTIARY ALKALIC-TYPE EPITHERMAL AU-TE DEPOSIT, CRIPPLE CREEK, COLORADO, by *Amber N. McIntosh*, 2004, M.S. thesis, Department of Earth and Environmental Science, New Mexico Institute of Mining and Technology, Socorro, NM 87801, 124 pp.

The Au-Te deposit at Cripple Creek, Colorado, is the largest alkalic-type epithermal deposit of the North American Cordillera and a historical world-class producer of gold. The Tertiary Cripple Creek volcanic-subvolcanic complex intrudes a suite of Precambrian metamorphic and plutonic rocks that comprise the basement lithologies in the region. Intrusions hosting mineralization range in composition from phonolite to lamprophyre and become successively more mafic with time. Lamprophyre emplacement was followed by hydrothermal brecciation, gold mineralization, and intense potassium metasomatism extending several kilometers outside the diatreme. Structurally controlled gold mineralization is manifested by high-grade, epithermal Au-telluride (± quartz ± fluorite ± carbonate ± adularia ± pyrite ± trace barite/celestite and base metal sulfide minerals) veins with halos of K-metasomatism containing disseminated gold, mineralized hydrothermal breccias, and low-grade bulk-tonnage deposits.

Past research has documented consistent characteristics for the mineralizing fluids at Cripple Creek. Mineralization took place at relatively low temperatures (125–225ºC) and salinities (< 5 wt. %), and like other alkalic-type deposits, Cripple Creek has heavy $\delta^{18}O$ values (3–9‰) for vein minerals and calculated fluid values, which are consistent with a magmatic source for mineralizing fluids. Most studies on the Cripple Creek district to date acknowledge a minor shift in the stable isotope data to lighter $\delta^{18}O$ values during later stages of mineralization, suggesting that mixing with meteoric fluid may have been a factor; however, convincing data to support the presence of meteoric fluid is lacking.

In an attempt to further explore the role of meteoric fluid, this study presents a stable isotope survey encompassing ore related and barren carbonate (± quartz ± fluorite ± carbonate ± pyrite ± trace barite/celestite and base metal sulfide) veins from the entire district. Measured $\delta^{18}O$ and $\delta^{13}C$ mineral values for carbonates range from –7.4 to 23.0‰ and –8.6 to 5.5‰, respectively. Fluid inclusion temperatures collected from this study (T_H = 108 to 321ºC) were applied to published fractionation factors to calculate fluids with $\delta^{18}O$ values of –15.8 to 12.1‰ and $\delta^{13}C_{HCO3-}$ values of –11.8 to 14.4‰, documenting a much broader range of fluid compositions than previous research. $\delta^{34}S_{H2S}$ values from vein pyrites (–14.5 to –1.1‰) and calculated fluids (–15.4 to –0.1‰) fall within a range of values reported in previous studies, and overlap the range of values typically seen in alkalic-type deposits.

New stable isotope and fluid inclusion data from carbonates represent a broader spatial and temporal view of the district than previous research, which has focused on ore-stage mineralization. When these data are examined at a district scale, geochemical and spatial trends emerge, suggesting mixing between magmatic and meteoric fluids. Spatially, the data are divided into broad zones with a central magmatic isotope signature, transitioning into more meteoric signatures toward the margins of the diatreme.

A SOIL CO_2 GAS SURVEY OVER THE LIGHTNING DOCK KNOWN GEOTHERMAL RESOURCE AREA, ANIMAS VALLEY, NEW MEXICO, by *Kristie S. McLin*, 2004, M.S. thesis, Department of Earth and Environmental Science, New Mexico Institute of Mining and Technology, Socorro, NM 87801, 138 pp.

Soil CO_2 flux measurements were taken over the Lightning Dock Known Geothermal Resource

Area (LDKGRA) located in the Animas Valley, New Mexico, to determine if structures could be identified using these measurements. The Animas Valley, located southwest of Lordsburg, New Mexico, trends north-south, typical of Basin and Range extension. The Animas Valley fault is a normal fault bounding the eastern edge of the valley. A shallow geothermal reservoir at greater than 100°C lies approximately 26 m below the surface in the valley fill sediments. Originally, it was thought that geothermal fluids were degassing beneath the surface and that these gases were diffusing to the surface through valley fill sediments above these faults. Soil CO_2 flux measurements ranging from 0 to 11 g $m^{-2}day^{-1}$ were measured over the area, and a cumulative probability plot indicated the possibility of multiple populations of flux data. However, stable isotope and compositional analysis of soil gases sampled over the LDKGRA indicates that vegetation and soil properties, not geothermal gas flux, are the dominant controls on soil CO_2 flux values in this area.

The $\delta^{13}C$ values for soil CO_2 at 50 cm depth range between –9.2 and –22.1‰ relative to PDB. The $\delta^{13}C$ values indicate various degrees of mixing between vegetative and atmospheric end members of CO_2 within the soil. Lighter $\delta^{13}C$ values correspond to high flux values, indicating the strong influence of root respiration from C_3 vegetation in the area. The $\delta^{18}O$ values for soil CO_2 at 50 cm depth range from 24.4 to 44.0‰ relative to SMOW. Oxygen isotope values indicate that either soil water $\delta^{18}O$ values are not homogeneous throughout the study area or that various soil properties are influencing the rate at which soil CO_2 isotopically equilibrates with soil water. Compositional analyses of the soil gas samples also indicate that plant respiration and atmosphere contribute to the CO_2 found in soil gases in this area. Small inputs of organic molecules such as CH_4 and C_2H_6 correlating with CO_2 values in soil indicate that there are small areas within the soils where anaerobic processes dominate. Although anomalously high soil CO_2 fluxes (> 4 g $m^{-2}day^{-1}$) coincide with the Animas Valley fault, the coincidence is not related to a geothermal flux. A northeast-southwest trend in flux anomalies is also observed. More productive vegetation or changes in soil properties over the fault may explain the correlation between high soil CO_2 flux measurements and the location of the Animas Valley fault. Future work should include full descriptions of soil properties, vegetation type and quantity, as well as soil gas sampling at 10 cm increments throughout the soil profile to fully understand the processes influencing soil gases and soil CO_2 flux.

QUANTIFYING SALINIZATION OF THE RIO GRANDE USING ENVIRONMENTAL TRACERS, by *Suzanne K. Mills*, 2003, M.S. thesis, Department of Earth and Environmental Science, New Mexico Institute of Mining and Technology, Socorro, NM 87801, 397 pp.

The Rio Grande has undergone a consistent pattern of salinization with distance downstream for the past century, but its causes have remained elusive. To reveal the causes of this salinization, 100 yrs of historical data as well as data from high-spatial-resolution synoptic sampling campaigns from 2000–2003 were analyzed. During these 3 yrs, Rio Grande salinization was manifested by a 50-fold increase in total dissolved solids between the river headwaters in Colorado and the U.S.–Mexico border. Environmental tracer data from August 2001 and January 2002, including $\delta^{18}O$ and δD, chloride and bromide concentrations, and the $^{36}Cl/Cl$ ratio, indicate that a significant percentage of Rio Grande salinization is due to inflow of deep sedimentary brines. A simple chloride and bromide instantaneous mass balance model for August 2001 emphasizes the significance of salt input due to deep brine discharge to the river, particularly at the downstream ends of local sedimentary basins of the Rio Grande rift. Two water- and salt-instantaneous mass balance models of the Rio Grande for August 2001 and January 2002 including major tributaries and agricultural return flows suggest that inflow of natural tributaries, deep brine, and wastewater treatment plant effluent and Elephant Butte Reservoir dynamics account for 25%, 37%, 26%, and 9% of the chloride burden increase between the headwaters and Ft. Quitman, Texas, respectively. These models also indicate that evapotranspiration accounts for 55% of increase in chloride concentration, with natural tributaries, deep brines, and wastewater treatment plant effluent respectively accounting for 3%, 30%, and 13% of the chloride concentration increase along this distance. Historical analysis and environmental tracer data suggest that the role of the irrigated agricultural systems in influencing salinization of the Rio Grande is their interception of deep basin brines, rather than flushing of shallow saline ground water or evapotranspirative concentration as previously thought. This indicates that Rio Grande salinization is geologically controlled by structures serving as brine conduits, and is anthropogenically facilitated by agricultural drains as well as reservoir operations and inflow of wastewater effluent.

COLLAPSE AND RESURGENCE OF THE VALLES CALDERA, JEMEZ MOUNTAINS, NEW MEXICO—$^{40}Ar/^{39}Ar$ AGE CONSTRAINTS ON THE TIMING AND DURATION OF RESURGENCE AND AGES OF MEGABRECCIA BLOCKS, by *Erin H. Phillips*, 2004, M.S. thesis, Department of Earth and Environmental Science, New Mexico Institute of Mining and Technology, Socorro, NM 87801, 200 pp.

$^{40}Ar/^{39}Ar$ ages for rocks from the Valles caldera of New Mexico imply that resurgent uplift of the caldera floor occurred within 27 ± 27 k.y. of caldera collapse. Redondo Peak, part of the resurgent dome of the Valles caldera, was uplifted at least 1,000 m above the surrounding caldera floor during resurgence. The lower time constraint on resurgence is the eruption of the upper Bandelier Tuff, which occurred concurrently with collapse of the Valles caldera. The upper time constraint is the emplacement of the oldest post-collapse ring fracture dome complex, Cerro del Medio, which displays no apparent faulting or deformation due to resurgence. $^{40}Ar/^{39}Ar$ dating places these time constraints at 1.256 ± 0.010 Ma (2σ) for the upper Bandelier Tuff and 1.229 ± 0.017 Ma for Cerro del Medio. Therefore, resurgent uplift of the Valles caldera resurgent dome occurred at an average rate of ~3.7 cm/yr and probably not less than 1.9 cm/yr.

The Deer Canyon and Redondo Creek Members of the Valles Rhyolite erupted before and during resurgence; both units stratigraphically overlie the upper Bandelier Tuff and are intricately interbedded with caldera fill sediments. Sanidine phenocrysts from the Deer Canyon Member yield $^{40}Ar/^{39}Ar$ single crystal laser fusion ages ranging from 1.229 ± 0.013 Ma to 1.283 ± 0.017 Ma (n = 7). $^{40}Ar/^{39}Ar$ ages for the Redondo Creek Member range from 1.208 ± 0.017 Ma to 1.239 ± 0.017 Ma (n = 2). With one exception from the Deer Canyon Member and one from the Redondo Creek Member, all ages obtained for these units are indistinguishable from the upper Bandelier Tuff at the 2σ confidence interval, indicating that eruption of these post-collapse rhyolites probably commenced very soon after caldera formation. The possibility of excess argon in melt inclusions in post-collapse units was investigated. Although $^{40}Ar/^{39}Ar$ analysis of melt inclusion bearing quartz phenocrysts from the Deer Canyon Member demonstrates that some amount of excess argon resides in melt inclusions, there is no measurable effect on sanidine phenocrysts.

Whole rock analyses of the Deer Canyon and Redondo Creek Members show that they are rhyolitic in composition and could have been part of the zoned upper Bandelier Tuff magma chamber. One possible scenario for their origin is one in which residual, zoned magma was left in the chamber after the eruption of the upper Bandelier Tuff and subsequently tapped after caldera collapse. This residual magma included the Deer Canyon rhyolites in the middle to upper parts of the felsic portion of the chamber and the Redondo Creek rhyolitic magma near the base. This model is supported by high Ba, Sr, and Ti content in the Redondo Creek Member, which is similar to enrichments observed in the least evolved upper Bandelier Tuff. In addition, magnetite/ilmenite pairs from the Redondo Creek Member yield eruption temperatures of 810 ± 6°C, which correspond to published temperatures for the latest erupted upper Bandelier Tuff.

Megabreccia blocks are found surrounded by intracaldera upper Bandelier Tuff in the Valles caldera and provide insights into the events that were occurring during collapse. The distribution and sources of intracaldera megabreccia blocks are highly variable. $^{40}Ar/^{39}Ar$ ages of selected megabreccia blocks indicate that they are composed of older pre-caldera units that include the lower Bandelier Tuff (1.68 ± 0.03 Ma), and a dacitic tuff dated at 8.205 ± 0.083 Ma. The ages of these blocks and their field relationships suggest that they were emplaced due to catastrophic sliding of oversteepened caldera walls during and immediately after collapse.

BTEX REMOVAL FROM PRODUCED WATER USING SURFACTANT-MODIFIED ZEOLITE, by *John M. Ranck*, 2003, M.S. thesis, Department of Earth and Environmental Science, New Mexico Institute of Mining and Technology, Socorro, NM 87801, 165 pp.

Produced water contains large amounts of various hazardous organic compounds such as benzene, toluene, ethylbenzene, and xylenes (BTEX). With increasing regulations governing disposal of this water, low-cost treatment options are necessary. This study evaluated the effectiveness of surfactant-modified zeolite (SMZ) for removal of BTEX from produced water. The long-term effectiveness of SMZ for BTEX removal was investigated along with how sorption properties change with long-term use. The results from these investigations showed that SMZ successfully removes BTEX from pro-

duced water, and that SMZ can be regenerated via air-sparging without loss of sorption capacity. The BTEX compounds break through laboratory columns in order of decreasing water solubility and of increasing K_{ow}. The most soluble compound, benzene, began to elute from the column at 8 pore volumes (PV), whereas the least soluble compounds, ethylbenzene and xylenes, began to elute at 50 PV. After treating 4,500 pore volumes of water in the column system over 10 sorption/regeneration cycles, no significant reduction in sorption capacity of the SMZ for BTEX was observed. The mean K_d from these column experiments ranged from a low value of 18.3 L/kg for benzene to the highest value of 95.0 L/kg for p-&m-xylene. Batch sorption experiments confirmed the column results showing no significant loss of capacity for BTEX sorption after 10 sorption/regeneration cycles, although the batch K_d values were consistently lower than K_ds from the column experiments. Batch K_ds ranged from a low of 6.71 L/kg for benzene to a high of 39.4 L/kg for o-xylene.

Laboratory columns were upscaled to create a field-scale SMZ treatment system. The field-scale system was tested at a produced water treatment facility near Wamsutter, Wyoming. We observed greater sorption of BTEX in field column tests than predicted from laboratory column studies. In the field column, initial benzene breakthrough occurred at 10 PV and toluene breakthrough began at 15 PV, and no breakthrough of ethylbenzene or xylenes occurred throughout the 80 PV experiment. These results, along with the low cost of SMZ, indicate that SMZ has a potential role in cost-effective produced water treatment system.

GROUND WATER AND PRODUCED WATER QUALITY OF THE PERMIAN BASIN, SOUTHEAST NEW MEXICO, by *Naomi Jean Rosenau-Davidson*, 2003, M.S. thesis, Department of Earth and Environmental Science, New Mexico Institute of Mining and Technology, Socorro, NM 87801, 126 pp.

The objective of this project is to use existing ground water and produced water databases to describe the ground water chemistry of geologic formations, to map the geochemical distributions and trends of solutes, and to discover where, and in which formations, ground water flushing (in which relatively fresh water moves through a formation, eventually replacing the original saline brine) is taking place. The two main databases used for this purpose include the State Engineer's ground water quality database, and the USGS database of produced water. Although trends are present, water quality in both databases is highly variable within formations and short sampling distances. Locations for three geologic cross sections across Lea and Eddy Counties were chosen after sample distribution was mapped.

In general, shallow ground water samples found in formations at or near the surface have low chloride concentrations, with the majority of samples having a chloride concentration of less than 1,000 mg/L. Their high quality most likely reflects their origin as meteoric water and short residence time within the aquifer. Where the number of samples is sufficient, spatial trends are usually evident, and are usually shown as decreasing chloride concentration with distance away from the Pecos River.

There are distinct chemical trends in the deep basin ground waters, which are controlled by the flushing of meteoric water through high permeability formations. Stueber (1998, AAPG Bulletin, 82, 1652–1672) and Bein and Dutton (1993, GSA Bulletin, 105, 695–707) used stable isotopes, strontium isotopes, and Cl/Br ratios in order to differentiate connate brines from meteoric waters. Unfortunately I lack these types of measurements; however, the major ion data can be used to break out similar groups, or genetic classifications.

The work of previous investigators, together with hydrogeological data gathered in the course of this project, has indicated that several patterns of water movement should be expected. These include 1) eastward regional flow, 2) relatively high flow through highly fractured carbonates such as the reef zones in the Capitan and Abo, and regionally extensive carbonates such as the Mississippian through Ordovician, 3) more intermediate flow rates through carbonates with interbedded shales such as the Pennsylvanian and Wolfcamp, and 4) low flow rates through formations with variable lithology including carbonates, evaporites, red beds, and shales, including the Artesia Group and upper Leonardian formations. The Delaware Mountain Group and Ochoan formations, composed of low permeability fine-grained sandstone and evaporites, respectively, are expected to have very low flow rates and briney waters.

Although there is a large amount of variability between samples, these trends are born out in general. A major exception is the presence of brines within the Ordovician despite its carbonate composition; this is because the Ordovician is cut off from the recharge zone by a major fault zone (the Central Basin platform) and is not vertically connected with the upper formations.

The Permian Basin in southeast New Mexico is complex both geologically and hydrologically. The basin lithology and history, combined with the interaction of ground water as it moved through the deep basin aquifer through geologic time, has greatly influenced the chemical characteristics of waters within the basin in a reasonably consistent and predictable fashion. The uplift and eastward tilting of the area in the late Tertiary and Quaternary is likely the cause of much of the chemical distribution of the waters that we see today, although it is impossible to tell the timing of ground water flushing without more detailed chemical analyses and modeling.

EVALUATION OF SURFACTANT-MODIFIED ZEOLITE FOR CONTROL OF *CRYPTOSPORIDIUM* AND *GIARDIA* SPECIES IN DRINKING WATER, by *Charlotte Maria Salazar*, 2004, M.S. thesis, Department of Earth and Environmental Science, New Mexico Institute of Mining and Technology, Socorro, NM 87801, 166 pp.

Gastrointestinal infection due to biological contamination of drinking water supplies is a major health issue worldwide. Naturally occurring and inexpensive modified materials such as surfactant-modified zeolites (SMZ) have net positive surface charge, which may prove useful for adsorption of pathogens such as *Cryptosporidium parvum* and *Giardia intestinales* (*lamblia*). SMZ is engineered by modifying the concentration of surfactant hexadecyltrimethylammonium (HDTMA) on the surface of zeolite media. Two different SMZ formulations (cationic SMZ and hydrophobic SMZ) were engineered to develop the most effective media for pathogen removal the most effective media for pathogen removal from drinking water.

In the laboratory, batch experiments of SMZ, raw zeolite, and sand were conducted to determine pathogen sorption to the media. Then, vertical columns packed with SMZ or zeolite material were used to evaluate pathogen transport. Tritium tracer tests were used to determine hydraulic properties of the materials. Synthetic microspheres were used as surrogates for the pathogens, which simulated the size and charge characteristics of *Cryptosporidium* and *Giardia*. The effectiveness of the various SMZ formulations was evaluated by comparing linear distribution coefficients of the batch experiments and removal efficiencies of the microsphere breakthrough curves (BTCs) obtained from the column experiments.

Surfactant-modified zeolite removed *Cryptosporidium* and *Giardia* surrogates from solution in the batch experiments with K_d values 10–20 times higher than those for zeolite or sand. This may be due to electrostatic and or hydrophobic interactions between the positively charged SMZ formulations and the negatively charged microspheres. However, column experiments did not show similar results. Based on column studies, all materials had relatively the same removal efficiencies in the range of 79.7 (± 1.6) to 82.3 (± 0.8)% for the *Cryptosporidium* surrogates and 99.1 (± 0.4) to 99.3 (± 0.1)% for the *Giardia* surrogates, which indicates that physical filtration or gravitational settling were the dominant mechanisms of removal rather than electrostatic or hydrophobic interactions.

PREFERENTIAL FLOW AND TRANSPORT THROUGH DEFORMATION BAND FAULTS IN THE SEMIARID VADOSE ZONE OF THE RIO GRANDE RIFT, NEW MEXICO, USA, by *John Sigda*, 2004, Ph.D. dissertation, Department of Earth and Environmental Science, New Mexico Institute of Mining and Technology, Socorro, NM 87801, 311 pp.

Discerning preferential flow and solute transport through the arid and semiarid sedimentary basins of the American Southwest is critical to preserving and protecting vital ground water resources. Commonly found throughout these basins, deformation band faults are tabular dipping structures with severe reductions in grain and pore sizes relative to their parent sands. These faults act as barriers to saturated flow and, potentially, as preferential flow paths through the vadose zone. This study presents the first measurements of unsaturated hydraulic properties for these faults and modeling of fault-induced preferential flow and transport through poorly lithified vadose-zone sands.

The hydraulic properties of intact samples from five faults, with different displacements, and their associated parent sand (protolith) were measured using standard laboratory methods and the Unsaturated Flow Apparatus (UFA). The UFA is a centrifuge system equipped to measure the moisture content–matric potential, $\Theta(\Psi)$, and hydraulic conductivity–moisture content, $K(\Theta)$, relationships. Measured hydraulic relations were used in simple, one-dimensional, steady flow models to assess the potential for preferential flow and transport through faulted sands under semiarid and arid conditions. X-ray diffraction revealed the samples have two different mineral assemblages in their clay size fraction (CSF): samples from one

study area contain pure and possibly authigenic smectite, whereas samples from the other area contain a mixture of smectite and other minerals. At saturation, hydraulic conductivity (*K*) for sand protolith from the area with pure smectite CSF is at least two orders of magnitude less than the *K* for sand protolith from the other area with mixed clay minerals in the CSF.

Deformation band faults possess strikingly different saturated and unsaturated hydraulic properties than their parent sands. Saturated *K* is one to three orders of magnitude lower in faults than protolith. As conditions become drier, unsaturated *K* decreases more abruptly in protolith than faults, so that protolith and fault unsaturated *K* reach equivalence (crossover point), and, for still drier conditions, fault unsaturated *K* exceeds protolith unsaturated *K* by several orders of magnitude. Crossover points and fault unsaturated *K* functions differ with CSF mineral composition. Fault unsaturated *K* functions do not vary significantly for the range of vertical displacements studied (from 0.2 to ≥ 3 m).

Simple one-dimensional models of water movement, solute transport, and diagenesis reveal that deformation band faults can act as conduits through moderately dry vadose-zone sands. Capillary wicking through finer-grained deformation bands significantly accelerates water and solute transport, driven downward by gravity or upward by evaporation, for a range of moderately dry vadose-zone conditions like those observed in the Rio Grande rift of central New Mexico. Observed fault spatial densities are sufficient for capillary wicking to locally enhance recharge or evaporative discharge. Faults can also accelerate contaminant migration because capillary wicking shortens solute residence times by several orders of magnitude under moderately dry conditions. Diagenesis is much more likely to occur in faults than protolith because faults are predicted to transmit up to 10^4 pore volumes in the time needed to transmit a single pore volume through the protolith, given the same moderately dry conditions. Under conditions slightly drier than the crossover point, vapor-phase transport dominates in the protolith, whereas liquid-phase transport dominates in the fault. Far drier conditions are required for vapor-phase transport to also dominate in the fault. CSF composition and the density of deformation bands within the fault significantly affect flow and transport, but the range of fault displacements studied appears to have little effect.

Two-dimensional numerical simulations reveal that non-vertically dipping faults can act as catchments under relatively wet climates. Like a surface-water catchment, such faults intercept and channel infiltrating water, creating a zone of enhanced water content perched atop the fault. This zone of enhanced water content accelerates infiltration and reduces solute residence time. Catchment behavior could also occur along large-displacement faults, clastic dikes, and other non-vertically dipping geologic structures.

Deformation band faults can hasten infiltration, exfiltration, contaminant migration, and diagenesis through vadose-zone sands. By acting as conduits in moderately dry climatic conditions or as catchments in wet climates, deformation band faults create preferential flow and transport pathways through poorly lithified sands.

SEDIMENTOLOGY AND PERMEABILITY CHARACTERISTICS OF THE ARROYO OJITO FORMATION (UPPER SANTA FE GROUP) ADJACENT TO THE SAND HILL FAULT, ALBUQUERQUE BASIN, NEW MEXICO, by *Dustin G. Smyth*, 2004, M.S. thesis, Department of Earth and Environmental Science, New Mexico Institute of Mining and Technology, Socorro, NM 87801, 96 pp.

Many important aquifers and reservoirs in the United States are found in faulted basins filled with poorly lithified sediments. Recent studies have shown that hydrologic behavior of faults in such environments differs from that of solid rock. The significance of fault-related sedimentation for fluid flow in normal-faulted sedimentary basins has not been addressed previously, although the physical characteristics (porosity, permeability, and lithofacies distribution) of the sediments in the hanging-wall block undoubtedly exert a strong control on fluid flow.

This study used 1:8,000 lithofacies mapping and stratigraphic section measuring to characterize the geometries and textures of lithofacies in the hanging-wall block of the Sand Hill fault, a high-angle normal fault on the western margin of the Albuquerque Basin and the Rio Grande rift. I divided the sediments of the study area into five mappable lithofacies: coarsening upward, laminated, and cross-stratified sands and gravels (QToug); massive, laminated, and cross-stratified sands with gravel channel deposits (QTous); interbedded silt and silty clay (QToum); massive sands (QToup); and cross-stratified sands with gravel channel deposits (QTouc). These sediments were deposited in two major depositional environments: 1) regional axial fluvial sediments composed of channel deposits, overbank floodplain and pond deposits, and minor eolian deposits (QToug, QTous, and part of QToum); and 2) bioturbated colluvium, eolian, possibly sag pond, and fault-parallel fluvial deposits (QToup, QTouc, and part of QToum), which I interpret to collectively constitute fault-scarp-controlled sediments deposited in a syntectonic depositional wedge. This hypothesis cannot be fully tested due to limited exposure of hanging-wall sediments perpendicular to the strike of the fault.

The hydrogeologic properties of each lithofacies were assessed through a combination of field and laboratory measurements, including field permeability, grain-size distribution and sorting, and thin-section porosity. The sandy sediments in the field area all have similar high permeabilities regardless of depositional environment. This implies that mapping based on depositional environments is not always the most accurate representation of permeability characteristics; instead, lithofacies with similar grain-size distributions should have similar permeabilities, which can be grouped together as hydrogeologic units. Improved understanding of the relationship between sedimentology and permeability in poorly lithified sediments associated with normal faults will enhance fluid flow modeling of such systems. In many cases, it is not financially realistic to measure the permeabilities of every unit in an area the size of the Albuquerque Basin. My work will help researchers and consultants such as those in hydrology, water resources, environmental remediation, and the petroleum industry make informed decisions about how to use physical descriptions of the sediments on geologic maps to determine appropriate hydrogeologic units for flow models.

A TELESCOPIC MODEL OF GROUND WATER/SURFACE WATER INTERACTIONS NEAR SAN ANTONIO, NEW MEXICO, by *Laura Wilcox*, 2004, M.S. thesis, Department of Earth and Environmental Science, New Mexico Institute of Mining and Technology, Socorro, NM 87801, 106 pp.

Under the Rio Grande Compact, New Mexico is obligated to deliver a specified amount of water to satisfy demands in New Mexico and Texas below Elephant Butte Reservoir. Thus a finite amount of water is available to New Mexico north of Elephant Butte Reservoir for habitat preservation and agricultural, industrial, and domestic uses. Previous investigations have observed significant seepage losses from the Rio Grande to the shallow aquifer between Socorro and San Antonio. High-resolution telescopic modeling was conducted along a 6-mi reach of the Rio Grande and associated drains and canals to evaluate several management alternatives aimed at improving river conveyance efficiency.

Observed data consisted of ground water level elevations collected in 10 wells October 2001 through August 2003, surface water level elevations collected at 38 locations August 2002 through August 2003, Rio Grande and Low Flow Conveyance Channel (LFCC) seepage values collected July 2000 through August 2001, and borehole geology of 24 wells conducted October 2002 through May 2003. Model calibration was achieved by altering field values of hydraulic conductivity, storativity, and specific storage until the output matched observed data.

Simulation results indicated that the system was very responsive to changes in geologic properties, especially when such alterations improved vertical connectivity between layers. It was also shown that in the absence of the LFCC, water level elevations on the west side of the Rio Grande channel were significantly elevated, but total flow through the system was decreased to 25% of the original volume. Simulations of the system with decreased evapotranspiration rates and a relocated river channel showed less magnitude of change.

SEISMIC STRUCTURE OF THE CRUST AND UPPER MANTLE IN THE SOUTHWESTERN UNITED STATES USING TELESEISMIC RECEIVER FUNCTIONS, by *David C. Wilson*, 2004, Ph.D. dissertation, Department of Earth and Environmental Science, New Mexico Institute of Mining and Technology, Socorro, NM 87801, 118 pp.

This dissertation describes the development of receiver function processing methods to create images of the seismic structure of the crust and upper mantle from teleseismic earthquake arrivals. These methods include receiver function estimation and prestack migration techniques that reduce deconvolution instability and produce regularized, multi-phase receiver function images.

The receiver function estimation technique developed here builds on frequency-wavenumber filtering methods by transforming receiver functions into the frequency-pseudo-wavenumber domain. A filter is then applied that down-weights receiver function amplitudes that have a high degree of variability as a function of horizontal slowness (epicentral distance) while preserving receiver function phases that have consistent moveout characteristics. This technique is applied to synthetic receiver functions and shows excellent recovery of receiver function

phases in the presence of high noise. A receiver function migration technique is developed that is based on regularized Kirchhoff migration. This technique migrates both direct and reverberated P-to-S converted phases to their true subsurface position to produce an image of the velocity discontinuity structure of the subsurface. This migration technique is applied to synthetic receiver functions to demonstrate that it is especially well suited to irregularly spaced stations and uneven data coverage. An important aspect of both the deconvolution and migration techniques is that they do not require the recording of a single earthquake at multiple stations, making them especially applicable to temporary arrays that may have irregular recording times between stations and allowing the incorporation of previous teleseismic data.

The receiver function processing methods described in this dissertation are applied to teleseismic arrivals recorded in the LA RISTRA (Colorado PLAteau, Rio Grande RIft, Great Plains Seismic TRAnsect) experiment. LA RISTRA was a northwest-southeast trending, 950.7 km linear network of broadband PASSCAL seismometers, deployed during 1999–2001 from Lake Powell, Utah, to Pecos, Texas. Results from application of these methods to LA RISTRA data show much more topography at the base of the crust than has been observed in this region previously, with thickness changes as great as 7 km over lateral distances of 50 km. Crustal thickness beneath the LA RISTRA network reaches a minimum of 35 km in the center of the Rio Grande rift (RGR), and ranges from 42 to 50 km in both the Great Plains (GP) and Colorado Plateau (CP). Crustal thinning beneath the RGR is relatively symmetric about the rift axis, with the thinnest crust located directly beneath the rift axis, suggesting a predominantly pure shear stretching of the lithosphere beneath the RGR. This is further supported by the rift centered region of low velocities observed in surface wave inversions and tomography results, as well as by regional isotopic data. Colorado Plateau crust is on average 2.7 km thicker than Great Plains crust, providing as much as 0.5 km of Colorado Plateau uplift. This, along with added buoyancy from a deep, low-velocity channel imaged in surface wave analysis, may explain the excess elevation of the Colorado Plateau. Lithospheric receiver function images also indicate a prominent northwest-dipping discontinuity, ranging from 65 to 85 km deep beneath the CP, and possible sub-crustal discontinuities beneath the GP. These discontinuities, along with recent xenolith data, may indicate preserved ancient lithospheric structures such as relict suture zones or subducted slabs associated with Proterozoic subduction. Upper mantle receiver function images beneath the LA RISTRA network show a prominent discontinuity at 250–300 km depth that may correlate with similar discontinuities observed beneath eastern North America. This discontinuity may represent the base of an asthenospheric low velocity channel observed in surface wave velocity images. Upper mantle discontinuities at 410 and 660 km depth are relatively flat, indicating there is not a large scale thermal anomaly beneath the RGR at these depths.

NEW MEXICO STATE UNIVERSITY

GEOTHERMAL SALT INTRUSION INTO MESILLA BASIN AQUIFERS AND THE RIO GRANDE, DOÑA ANA COUNTY, NEW MEXICO, USA, by *Lawrence R. Bothern*, 2003, M.S. thesis, Department of Geological Sciences, New Mexico State University, Las Cruces, NM 88003, 129 pp.

During winter low flow periods the Rio Grande delivers unusable brackish water to the city of El Paso, Texas. Previously, this brackish water has been considered to result from the concentration of salts in irrigation drainage, as the water is used for agriculture in the Mesilla Valley of New Mexico. Geochemical evidence points to the mixing of geothermal water with shallow ground water that is hydraulically connected to the Rio Grande (Anderholm 1990; Swanberg 1975). The purpose of this research is to more fully understand and to quantify the saline contribution from the ground water components to facilitate a more complete water model of the basin.

Thirty-four water samples are collected from wells in the Mesilla Basin that represent a range of basin aquifer waters, as well as the river and known geothermal waters. Waters are tested for pH, temperature, conductance, and alkalinity at the sample site. Samples are analyzed in the laboratory for total dissolved solids, cations, anions, and isotopic ratios of $^{18}O/^{16}O$, $^{2}H/^{1}H$, $^{13}C/^{12}C$, $^{34}S/^{32}S$, $^{87}Sr/^{86}Sr$, and $^{234}U/^{238}U$.

Major and trace ion concentrations indicate that most geothermal and warm wells represent complex mixtures of a geothermal end-member and cold aquifer waters. The large diversity of ion concentrations in basin ground water results in nearly infinite possibilities of cold end-member water, which in turn leads to results with apparent exceptions to trends. A two end-member mixing model using total dissolved solids and chloride each plotted with sodium, bromide, and lithium shows that warm wells average from 18% to 55% of the geothermal end-member water.

Using data of Phillips et al. (2000) for the Rio Grande a three-end-member model is constructed. Rio Grande plots with low chloride (120 mg/L) and high δD (–66‰ VSMOW), cold aquifer water is low in both chloride (38 mg/L) and δD (–94‰ VSMOW), and the geothermal end-member has high values for both (1,620 mg/L and –73‰ VSMOW)). The model shows that the saltiest winter river waters vi are attained by a 13% contribution of geothermal water mixed with irrigation drainage water in East drain and Montoya drain.

QUANTITATIVE STRAIN ANALYSIS AND TIMING OF NORTH-SOUTH EXTENSION IN THE LITTLE HATCHET MOUNTAINS, SOUTHWEST NEW MEXICO, by *Michael S. Cleary*, 2004, M.S. thesis, Department of Geological Sciences, New Mexico State University, Las Cruces, NM 88003.

The purpose of this study is to determine the direction, magnitude, and timing of post-Laramide deformation in the Little Hatchet Mountains and to compare these to other coeval structures in the southwestern United States. South of a large-scale transverse fault known as the Copper Dick fault, a continuous Jurassic section of sedimentary and volcanic rocks is exposed. Large-scale and small-scale folds are common, as well as thrust faults that may have been reactivated as normal faults during Basin and Range extension. A stretched-pebble conglomerate within the Jurassic Broken Jug Formation has limestone clasts that are elongated with a consistent orientation. The elongation direction of these clasts ranges from N10E to N10W. Long axis to short axis ratios of clasts range from 2 to 10, and chert clasts within the same unit are pulled apart in the same orientation. Strain analysis on the clasts was undertaken to determine if the elongation and orientation was the result of strain or instead was a relict sedimentary feature. This analysis indicates Rs values between 2.5 and 3.1, indicating that the clasts on average were stretched to three times their original size. Because the chert clasts were not ductilely deformed, the temperature range for this deformation is probably less than 400°C.

East-west trending dikes in the southern Little Hatchet Mountains also indicate north-south stretching, and they may provide a constraint for the age of the ductile deformation. Four east-west trending dikes were dated using $^{40}Ar/^{39}Ar$ geochronology on groundmass and hornblende. These ages are 26.80 ± 0.98 Ma, 28.98 ± 0.97 Ma, 28.47 ± 0.5 Ma (all groundmass ages), and 31.20 ± 0.57 Ma (hornblende age). Although the intrusion of dikes and the ductile deformation of the conglomerate cannot be directly linked, both occurred as the result of north-south stretching following Laramide shortening in the region. It is likely that voluminous magmatic activity occurring in southwestern New Mexico and Arizona during this time provided heat that facilitated mid-Tertiary north-south stretching.

PETROLOGY OF THE PERALUMINOUS LEUCOGRANITES, WHETSTONE INTRUSIVE COMPLEX (LOWER UPPER CRETACEOUS?), SOUTHEASTERN ARIZONA, by *Christie S. Cowee*, 2003, M.S. thesis, Department of Geological Sciences, New Mexico State University, Las Cruces, NM 88003, 107 pp.

The Whetstone Intrusive Complex, in the Whetstone Mountains of southeastern Arizona, is associated with extension of the Late Jurassic–early Late Cretaceous Bisbee Basin. Originally mapped as both intrusive and extrusive, field relationships indicate that these igneous rocks are intrusions emplaced between 100 and 74 Ma. The majority of which are sills intruded along bedding planes of Bisbee Group sedimentary rocks.

Petrographic and geochemical analyses of the lower Upper Cretaceous intrusions demonstrate they are peraluminous leucogranites. Host to primary Al-rich muscovite phenocrysts, these intrusions have a peraluminosity (molecular Al_2O_3 / Na_2O + CaO + K_2O) range from 0.9 to 1.6. SiO_2 ranges from 74.6 to 78.1 wt%, and FeO + MgO + TiO_2 combined amounts to < 1 wt%. K_2O content is higher than Na_2O, averaging > 4 wt% and > 3 wt% respectively. Similar to other peraluminous leucogranites, they range from calcic to alkalic-calcic and ferroan to magnesian.

Comparisons of the Whetstone intrusions to experimental melts of metasedimentary rocks suggest a muscovite-rich crustal source rock. The lower Upper Cretaceous intrusions are chemically similar to partial melts of muscovite schists as both have low FeO, MgO, and TiO_2 and similar Al_2O_3, CaO, and K_2O. Partial melting models of crustal rocks such as the Post Archean Australian Shale (PAAS) and the Pinal Schist, a widespread Precambrian rock in southeastern Arizona, reveal that the source rocks for the rhyolitic melts are similar in composition to both. Because overall REE concentrations in the

Whetstone intrusions are lower than the modeled parent rocks, partial melting of PAAS that was diluted by 40% quartz was modeled and resulted in concentrations of REE similar to the Whetstone intrusions. Therefore, the source of the Whetstone intrusions was a muscovite- and quartz-rich metasedimentary rock.

Upwelling asthenosphere or intrusion of basalt could provide the heat source necessary for dehydration melting of a muscovite-rich source. In an extensional regime, rhyolitic magmas could rise through the crust to shallow levels where they spread out horizontally, forming sills like those observed in the Whetstone Mountains. These peraluminous sills are some of the oldest peraluminous granites found in western North America.

AGE OF DEPOSITION AND METAMORPHISM OF DEFORMED PROTEROZOIC METASEDIMENTARY ROCKS IN THE BURRO MOUNTAINS, SOUTHWEST NEW MEXICO, by *Amos E. Sanders*, 2003, M.S. thesis, Department of Geological Sciences, New Mexico State University, Las Cruces, NM 88003, 198 pp.

The metasedimentary rocks studied in this report are located in the northern Burro Mountains of southwest New Mexico. The rocks consist of metapelites, quartzofeldpathic gneisses, calc-silicate gneisses, and biotite quartzites. The dominant rock type is metapelite, which has been deformed and metamorphosed to upper amphibolite facies and consists of micas, strained quartz, microcline, garnet, and sillimanite.

The structure of the metasedimentary rocks consists of foliations striking mainly to the north-south and east-west. Folds plunge shallowly to steeply and trend mainly north-south and east-west. Lineations are defined by sillimanite and generally trend north-south. These structures indicating east-west shortening are common throughout the southwest United States and are linked to the ~1.45 Ga granite-rhyolite event. East-west folds suggest that a north-south shortening event occurred at a later time. The timing of metamorphism was investigated using electron microprobe U-Pb dating of monazite from five metapelites. Most of the ages range from 1,500 Ma to 1,400 Ma with smaller age clusters younger than 1,400 Ma and scattered ages between 2,400 Ma and 1,630 Ma. Statistical analysis of monazite ages indicates metamorphic events at ~1,470 ± 16 Ma, ~1,415 ± 14 Ma, ~1,365 ± 13 Ma, and ~1,265 ± 21 Ma (2 sigma uncertainty). Monazite ages between 2,400 Ma and 1,650 Ma with high uncertainties are interpreted as ages of detrital grains sourced from the Mojave, Wyoming, or Yavapai provinces.

The age of detrital zircon from the metasedimentary rocks was investigated using Laser Ablator Multiple Collector Inductively Coupled Mass Spectrometer (LA-MC-ICPMS) U-Pb analysis. These individual ages range from 1,892 ± 62 Ma to 1,655 ± 64 Ma with one Archean age at 2,878 ± 26 Ma. The depositional age was bracketed between 1,668 ± 27 Ma, the average age of the youngest group of detrital zircons, and 1,633 ± 5 Ma, the U-Pb age of the oldest intrusive rock in the northern Burro Mountains. The depositional age and source rock ages are similar to those from metasedimentary rocks in the Pinal block of the Mazatzal Province, but rocks of the Burro Mountains contain a higher percentage of grains older than 1,730 Ma. The detrital zircon ages are similar to basement and supracrustal rocks in the Mazatzal, Yavapai, and Archean provinces of the southwest United States.

GEOMETRIES OF STRATA IN A SALT-WITHDRAWAL BASIN AS PREDICTORS OF SHORTENING-DRIVEN DIAPIR TECTONICS—CARROZA FORMATION, LA POPA BASIN, NUEVO LEON, MEXICO, by *Brent R. Waidmann*, 2004, M.S. thesis, Department of Geological Sciences, New Mexico State University, Las Cruces, NM 88003, 131 pp.

Fluvial and growth-stratal geometries related to salt diapirism are rarely observed in outcrop, but the La Popa Basin contains superb exposures of syntectonic growth strata that resulted from combined foreland shortening and local withdrawal of salt. Early Cretaceous to early Cenozoic syndepositional salt rise influenced facies distribution and stratigraphic geometry, including positions of sandstone bodies, paleosols, and stratigraphic thickness. Evacuation of salt from an elongate diapiric wall and coeval Hidalgoan (Laramide age) shortening created a fault-like, northwest-trending structure, termed a salt weld. The La Popa weld separates an upthrown northeast block from a downthrown southwest block. The middle Eocene Carroza Formation was deposited in an asymmetrical, synclinal salt-withdrawal basin on the downthrown block of the weld. The Carroza contains growth strata with several angular unconformities near the weld and sand-rich fluvial facies near the basin axis. Growth strata thin and steepen toward the weld. Deposits of small alluvial fans derived from the elevated diapir intertongue with fluvial-plain deposits of the basin. Overbank deposits near the weld contain well-developed paleosols, which are less mature elsewhere in the small basin. Although formed in a shortening environment, the depositional systems of the salt-withdrawal basin are analogous to other types of asymmetrical basins such as foreland or half-graben basin settings.

During Carroza deposition, the northwest-trending weld was an elongate, topographically elevated diapir. Fluvial channels oriented parallel to the wall occupied the adjacent subsiding basin axis. Detritus was also shed directly into the basin from the diapiric source. Sedimentation rates were highest in the basin axis, producing the observed thinning of strata and associated paleosols near the diapir. In the salt-withdrawal basin, Hidalgoan shortening increased diapir rise rate thus influencing the location and distribution of sandstone bodies in the Carroza Formation.

UNIVERSITY OF NEW MEXICO

THE DEHYDROXYLATION OF THERMALLY TREATED BIOTITES AND BIOTITES FROM THE JEMEZ VOLCANIC FIELD, NEW MEXICO—AN INDICATOR OF PRE- AND POST-ERUPTIVE VOLCANIC PROCESSES, by *Heather A. Hibbert*, 2003, M.S. thesis, Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, NM 87131, 80 pp.

A variety of analytical techniques have been used to examine the method of dehydroxylation of both experimentally reacted biotites and natural biotites of the Bearhead Rhyolite from the Jemez volcanic field in New Mexico. Thermal dehydration experiments were performed in pure O_2 flow and water vapor with $\delta D = -90$ ‰ and $\delta D = +1{,}000$‰ in order to examine the affect of dehydroxylation on biotite δD values. Hydrogen isotope data, water contents, and electron microprobe data indicate that thermally treated biotites dehydroxylate under variable oxidizing conditions without breakdown. Dehydrogenation results in a preferential loss of protium and a deuterium enrichment, progressively increasing biotite δD values while losing water when heated to temperatures ≥ 700°C. Experimental biotite dehydrogenation data fit a Rayleigh fractionation curve with a constant $\alpha(\text{biotite-}H_2) = 0.862 \pm 0.003$.

Natural biotite data are more difficult to interpret. Alteration by meteoric fluids to more hydrous phases (vermiculite) as determined by major element biotite composition and high water content results in the overprinting of primary magmatic hydrogen isotopic values and water contents. Biotites in lava samples have undergone dehydrogenation similar to experimental biotites. However, hand sample examination indicates that the volume percentage of biotite in the Bearhead Rhyolite is extremely small (~1%), and although it is possible that in-situ dehydrogenation of biotite can contribute to the explosivity of eruptions, it is not probable that this process triggered eruption of the Bearhead Rhyolite.

Hydrogen isotope values and water content of both pyroclastic and lava glass give further indication as to a large degree of low temperature alteration of pyroclastic deposits and alteration of lavas to a lesser extent. A strong correlation between hydrated pyroclastic biotite (with fine scale vermiculite intergrowths) and pyroclastic glass δD values gives indication of a hydrogen fractionation of $1000\ln\alpha_{\text{glass-(biotite+vermiculite)}} = -17$‰.

The data presented herein allows for interpretation of both pre- and post-eruption volcanic processes including the biotite dehydroxylation mechanism, biotite alteration and breakdown, and biotite-hydrogen and biotite-glass hydrogen fractionation.

OXYGEN ISOTOPE ANALYSIS OF ALUMINUM SILICATE TRIPLE-POINT ROCKS IN NEW MEXICO AND NEW HAMPSHIRE, by *Toti Erik Larson*, 2003, Ph.D. dissertation, Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, NM 87131, 139 pp.

The Al_2SiO_5 (AS) polymorphs kyanite, andalusite, and sillimanite are among the most cited metamorphic minerals that are used to interpret the physical conditions of metamorphism in a variety of geological terranes. Two varieties of sillimanite are commonly observed in the field: coarse-grained prismatic sillimanite and fine-grained fibrolite. The AS polymorphs are refractory, have a simple chemistry, and have an invariant point at a temperature and pressure that is common to mid-crustal metamorphism. The concept of an AS polymorph triple-point assemblage in which three AS polymorphs coexist in equilibrium has been applied to Proterozoic rocks from the Truchas and Manzano Mountains of New Mexico, and near Mount Moosilauke, New Hampshire, to fix the temperature and pressure of metamorphism to the AS polymorph invariant point, which has been

used to calibrate geothermobarometers in addition to interpreting the metamorphic history of these terranes. Oxygen isotope data presented in this dissertation provide for an independent means to test the concept of an equilibrium AS polymorph triple-point assemblage by providing temperatures of growth for AS polymorphs from a suite of samples that contain divariant (one AS polymorph), univariant (any two AS polymorphs), and invariant (three AS polymorphs). Oxygen isotope results presented in this dissertation are integrated with metamorphic petrology to constrain AS polymorph-forming metamorphic reactions in various rock types.

Temperatures of growth calculated for kyanite, andalusite, prismatic sillimanite, and fibrolite from the Truchas Mountains, and kyanite, andalusite, and fibrolite from the Manzano Mountains are not consistent with the interpretation of an equilibrium triple-point assemblage. Instead, these data indicate that in the Manzano Mountains, kyanite grew during an early metamorphic event (M_1) at 500°C, whereas andalusite and fibrolite grew in equilibrium at 580°C during M_2 contact metamorphism. In the Truchas Mountains, kyanite grew during M_1 at 580°C, whereas andalusite and prismatic sillimanite grew at 620°C and 640°C, respectively. Temperature estimates of 580°C and 710°C are also calculated for fibrolite in the Truchas Mountains, indicating that multiple generations of fibrolite growth occurred. We interpret these results as indicating that Proterozoic rocks exposed in New Mexico are polymetamorphic and that the highest-grade metamorphism, which is recorded by the growth of fibrolite, reached temperatures as high as ca 710°C during M_2.

In the Merrimack synclinorium of New Hampshire, coexisting fibrolite and prismatic sillimanite preserve different $\delta^{18}O$ values, resulting in different calculated crystallization temperatures. In all samples, $T_{prismatic\ sillimanite} > T_{garnet} \geq T_{fibrolite}$.

Disparate garnet, prismatic sillimanite, and fibrolite temperature estimates reflect the ability of these minerals to retain their oxygen isotope compositions from their respective temperatures of growth, which are not necessarily the maximum temperatures of metamorphism. Similar to the AS polymorphs from the Truchas Mountains, estimates of peak temperatures of metamorphism can only be recovered from a mineral that was growing at the peak temperature of metamorphism. It appears that prismatic sillimanite was the highest temperature metamorphic mineral to form in the Merrimack synclinorium, and quartz-prismatic sillimanite oxygen isotope thermometry, therefore best record estimates of peak temperatures of metamorphism.

STREAM FLOW, INFILTRATION, AND RECHARGE IN THE ARROYO HONDO WATERSHED, NORTH-CENTRAL NEW MEXICO, by *Stephanie J. Moore,* 2003, M.S. thesis, Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, NM 87131, 78 pp.

This report presents results of a three-year study of stream flow, infiltration, and recharge in the Arroyo Hondo, New Mexico, with data collection from October 1999 through October 2002. Precipitation during the study period was below normal for 2 of 3 yrs.

Empirical estimates of mean annual stream flow, derived from equations relying on basin characteristics (annual precipitation, channel width, and watershed area), ranged from 77,000 to 410,000 m^3. Total annual stream flow in the Arroyo Hondo ranged from zero to 474,000 m^3 during the study period. Temperature-based methods were used to estimate the presence and duration of stream flow throughout the Arroyo Hondo. A variably saturated, two-dimensional heat transport model (VS2DH) was used to simulate stream bed infiltration during stream flow events; the estimated average infiltration rate was 1.4 m per day. Cumulative stream bed infiltration rates were estimated from stream bed infiltration rates, channel widths, and the downstream extent of stream flow. Environmental tracers were used to investigate the presence or absence of recharge at selected sites.

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

Measured stream flow (from zero to 474,000 m^3) and estimates of cumulative stream bed infiltration (from zero to 250,000 m^3) are lower than previous estimates of stream flow (660,000 m^3; Speigel and Baldwin 1963) and of stream bed infiltration (625,000 m^3; McAda and Wasiolek 1988) for every year during the study period. Lower precipitation rates during this study period may account for the smaller measured stream flow and smaller estimates of cumulative stream bed infiltration.

Empirical estimates of stream flow are much closer to values of measured stream flow and estimates of cumulative stream bed infiltration, with the exception of water year 2002, when annual stream flow was zero. This indicates that the empirically derived equations used in this report are more representative of actual stream flow conditions in the Arroyo Hondo (than estimates of previous investigators). These methods should be used to provide conservative estimates of stream flow for the Arroyo Hondo.

LATE HOLOCENE BEHAVIOR OF SMALL BASINS ON THE COLORADO PLATEAU NEAR BLUE GAP, ARIZONA—LITHOLOGIC, MORPHOMETRIC, AND CLIMATIC INFLUENCES, by *Anne C. Tillery*, 2003, M.S. thesis, Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, NM 87131, 167 pp.

In the semiarid landscape of the Colorado Plateau in northeastern Arizona, small basins associated with the "Blue Gap" escarpment have been rapidly aggrading over the last millennium. The mode of operation of the fluvial systems in a few sub-basins, however, has changed since the late 19th century from net aggradation to net erosion as shown by formation of deeply incised, discontinuous arroyos. Detailed study of stratigraphy and soils in the upper reaches of some of the basins, along with radiocarbon dates and dendrochronology, shows that sediment in these portions of the basins, sometimes as thick as 3–4 m, is roughly 1,000 yrs old. Sediment that is older than a millennium is not stored in the upper reaches of the basins. Additionally, the soil-stratigraphic record shows that during this period, aggradation has generally been the consistent mode of channel behavior in this area.

The observed rapid aggradation is partly attributable to the highly erodible Jurassic sandstones, siltstones, and mudstones that make up the cliffs and slopes of the escarpment. Petrologic analysis across weathering profiles of these cliff-forming sandstones is the subject of the second chapter. These analyses show that mechanical weathering, associated with hydration-dehydration cycles, enables extremely rapid sediment production on basin slopes.

The lack of paleochannels shows that until the 19th century arroyos formed, there were no previous episodes of deep channel incision. The recent switch from aggradation to incision in some of the basins could be attributed to the effects of late Holocene climate change. The timing of this switch (late 19th century) suggests that the change could be associated with the end of the Little Ice Age (LIA~1200–1850 AD).

This study reinforces previous studies (Bull 1991; McFadden and McAuliffe 1997) recognizing lithology as a key factor in dictating rates and processes of hillslope sediment production and sediment deposition. In this case, the weakly cemented sandstones of the Blue Gap field area are likely more sensitive to minor climatic changes of the Holocene than more resistant lithologies.

MESOPROTEROZOIC TECTONIC EVOLUTION OF SOUTHWESTERN NORTH AMERICA—PROTRACTED INTRACRATONIC DEFORMATION, SEDIMENTATION, AND DIFFERENTIAL EXHUMATION IN GRAND CANYON AND THE ROCKY MOUNTAIN REGION, by *J. Michael Timmons*, 2004, Ph.D. dissertation, Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, NM 87131, 314 pp.

The Unkar Group of the Grand Canyon Supergroup is one of the best-preserved remnants of Mesoproterozoic sedimentary rocks in the southwestern United States. It provides an exceptional record of intracratonic basin formation and associated tectonics kinematically compatible with protracted "Grenville-age" northwest-directed shortening. New U/Pb age determinations from tephra at the base of the Unkar Group date the onset of deposition at ca 1,254 Ma. $^{40}Ar/^{39}Ar$ K-feldspar thermochronology in Grand Canyon indicates that basement rocks cooled through 150°C between about 1,300 and 1,250 Ma, refining exhumation rates of basement rocks just before Unkar deposition. Abrupt thickness and facies changes in conglomerate and dolomite of the Bass Formation associated with northeast-striking monoclinal flexures indicate northwest-directed syn-sedimentary contraction at about 1,250 Ma. A large disconformity (~75 m.y. duration) is inferred between lower and upper Unkar Group and is located below the upper Hakatai Shale as documented by detrital zircons. A second style of Unkar Group deformation involved the development of half grabens and full grabens that record northeast-southwest extension on northwest-striking, high-angle normal faults. Several observations indicate that northwest-striking normal faulting was concurrent with upper Unkar deposition, mafic magmatism, and early Nankoweap deposition: 1) intraformational faulting in the Bass Formation, 2) intraforma-

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