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 recently completed M.S. theses and Ph.D. dissertations that pertain to the geology of New Mexico and neighboring states.

New Mexico Institute of Mining and Technology

MICROBIAL DEGRADATION OF TOLUENE SORBED TO SURFACTANT-MODIFIED ZEOLITE, by Alana M. Fuierer, 2001, M.S. thesis, Department of Earth and Environmental Science, New Mexico Institute of Mining and Technology, Socorro, NM 87801, 111 pp.

Enhanced in situ biodegradation of organic contaminants, such as toluene, has the potential to be an efficient and cost-effective remediation technique. Laboratory studies were used to test the hypothesis that a reactive nutrient-amended microbial support system can be placed in a zone of subsurface organic contamination and, thereby, stimulate and support biodegradation of organic contaminants.

The physical microbial support system is comprised of surfactant-modified zeolite (SMZ). Because the SMZ has a large reversible sorption capacity for toluene, high aqueous phase concentrations of toluene can be reduced and retained within the support system. This allows sustained degradation of toluene as it desorbs from the SMZ. Furthermore, the SMZ can be preloaded with nutrients such as nitrogen, potassium, and phosphate. In theory, these amendments will stimulate and support the subsurface microbial degradation of toluene.

Batch isotherm experiments were used to determine the toluene sorption capacity of SMZ and nutrient-loaded SMZ (N-SMZ), as well as the sorption and desorption kinetics for toluene by SMZ. Toluene sorption on both materials was similar, and toluene desorption and sorption kinetics were rapid. Toluene-degrading microorganisms were isolated through enrichment cultures that used toluene as a sole-carbon source and an initial sample taken from a wastewater treatment plant. Aerobic solution-only and slurry-phase biodegradation experiments were conducted to compare the biodegradation rates of toluene in the presence of SMZ and N-SMZ. Preliminary studies indicated it was necessary to control the pH within the slurry-phase cultures in order to sustain microbial growth. Biodegradation of toluene occurred in the presence of SMZ and N-SMZ at similar biodegradation rates, although these rates were slower than the biodegradation rates observed in solution-only cultures. In addition, biodegradation of toluene in the presence of N-SMZ occurred without adding aqueous nutrient medium. Anaerobic biodegradation experiments in the presence of N-SMZ provided inconclusive results regarding the biodegradation of toluene in an anoxic environment.

SPATIAL VARIATION IN SOILS DEVELOPED ON FLUVIAL TERRACES, SOCORRO BASIN, RIO GRANDE RIFT, CENTRAL NEW MEXICO, by Harland L. Goldstein, 2001, M.S. thesis, Department of Earth and Environmental Science, New Mexico Institute of Mining and Technology, Socorro, NM 87801, 95 pp.

Soils are commonly used for correlation and age estimation in geomorphology. However, many of these studies do not consider the variable nature of soils in a way to validate the use of soil development as an estimator of time and a tool for correlation.

Tributary terraces in the Socorro Basin were correlated based on the height of the terrace tread above the modern stream channel. Five terrace levels are present throughout the Socorro Basin in at least four tributaries to the Rio Grande. In addition, these terraces can also be correlated to tributary and Rio Grande terraces outside of the Socorro Basin. Hypsometric analysis for each tributary drainage basin suggests that the response times, and thus the timing of terrace formation, are similar even though total drainage basin areas are different among tributaries. Therefore, because terraces are correlated independent of soil development and because the timing of terrace formation is similar, soil variability on same-aged surfaces could be determined.

To validate correlations and age estimates made in this study, soil variability was determined for 1) a single Pleistocene terrace surface in Walnut Creek, and 2) correlated terraces throughout the Socorro Basin. Statistical analysis of the Walnut Creek terrace suggests that swale soils are less variable than bar soils. In addition, only two soil parameters from correlated terraces in Socorro Canyon and Tiffany Canyon fall within the range of the Walnut Creek soils; $CaCO_3$ mass and silt + clay mass.

$CaCO_3$ accumulation rates for the Socorro Basin range from 0.067 $g/cm^3/kyr$ to 0.073 g/cm3/kyr. These rates are based on Pleistocene soils and vary from previous rates in New Mexico that are often used as guides for correlations and age estimates throughout the southwest United States.

The five correlated tributary terrace surfaces in the Socorro Basin represent regional geomorphic surfaces related to the Rio Grande. Two major fill terraces are associated with an underlying erosional surface and are late Pleistocene (oxygen isotope stage 6) and early Holocene (oxygen isotope stage 2) in age, based on calibrated soil ages. Three minor strath terraces are less widespread and preserved than the major fill terraces, and except for the highest terrace preserved (early middle Pleistocene), these terraces are estimated to be Holocene in age based on calibrated soil ages.

A STEP TOWARDS LANDMINE DETECTION: MEASUREMENTS OF 2,4-DINITROTOLUENE SOIL SURFACE FLUX FROM A BURIED POINT SOURCE, by Matthew J. Gozdor, 2000, M.S. thesis, Department of Earth and Environmental Science, New Mexico Institute of Mining and Technology, Socorro, NM 87801, 68 pp.

Anti-personnel devices, commonly known as landmines, are a danger to both the military and civilians. Current landmine detection techniques are inadequate, as they often produce false positive and false negative results. The research presented here is a first step toward determining the chemical signature, or surface vapor flux, from a simulated landmine under steady state and variable boundary conditions. The results from this thesis will be combined with computer simulations being conducted at Sandia National Laboratories and other detection techniques to create an integrated sensor that will improve landmine detection technology.

Two laboratory experiments were conducted on a packed soil column (15-cm diameter, 32-cm length) under steady state and varying boundary conditions to determine the surface vapor flux of 2,4-dinitrotoluene (2,4-DNT) from a point source. An aqueous solution of 2,4-DNT (~150 mg/L) was introduced via a syringe through a polytetrafluoroethylene (PTFE) mininert valve inserted approximately 3 cm from the top of the column. Volumetric water content was measured along the length of the column by five water content reflectometers (WCR). The surface vapor flux was determined using a solid phase microextraction fiber (SPME) placed near the center of a sweep-air plenum attached to the top of the column.

During the first experiment, the relative humidity and volumetric flow rate of the sweep gas and the matric potential in the soil remained essentially constant, and the 2,4-DNT surface flux approached steady state: approximately 70,000 pentagrams 2,4-DNT/min over a period of 29 days. The second experiment initially employed the same boundary conditions, producing nearly identical results and surface fluxes. The second experiment was then appended with an increased evaporation phase, a drying phase, and two wetting phases. Once the soil water content was decreased approximately to 8% volumetric, the soil surface flux of 2,4-DNT decreased four orders of magnitude from 275,000 pentagrams/min to 70 pentagrams/min over 25 days. Two simulated rainfall events produced 2,4-DNT surface fluxes that rose three orders of magnitude, from approximately 70 pentagrams/min to 70,000 pentagrams/min over the course of a few hours. These data suggest the optimum window to search for the chemical signature of a landmine would be the period shortly after a rainfall, immediately preceded by drying conditions.

CHARACTERISTICS OF DEFORMATION BANDS IN POORLY LITHIFIED SAND: RIO GRANDE RIFT, NEW MEXICO, by James Matthew Herrin, 2001, M.S. thesis, Department of Earth and Environmental Science, New Mexico Institute of Mining and Technology, Socorro, NM 87801, 84 pp.

Faults and fault zones, even those accommodating small amounts of displacement, can either facilitate or hinder fluid flow. The hydraulic properties of a fault zone depend largely on the character and geometry of the structural elements constituting the fault zone. The widespread occurrence of faulted sediments in aquifers and petroleum reservoirs warrants a better understanding of sediment deformation, yet few systematic studies have addressed faults that cut unlithified sediments. In this study, small-displacement normal faults that cut Tertiary sand and conglomerate have been characterized through outcrop mapping, petrographic observation, and electron microprobe imaging and analysis. Displacement across most of the 32 faults studied ranges from 0.1 to at least 1.5 m; one fault records a minimum of 6.4 m of throw. Nearly all faults in the hanging wall of the latter large-displacement fault are subparallel to it, whereas conjugate fault sets are common in the footwall. Where it cuts conglomerate, each fault consists of a 1–10-cm-wide shear zone that has a finer grain size than the protolith and includes fractured clasts. Where faults cut partially lithified sand, they are composed of multiple deformation bands arranged in simple to geometrically complex arrays. The most complex arrays are found in faults recording displacement greater than 1 m; in general, however, the geometric characteristics of these arrays are not predicated on either fault displacement or location relative to larger-displacement faults. The width of the deformation band fault zones is least at conglomerate-sand contacts and increases with increasing distance from these contacts. In contrast to previous laboratory and field studies of deformation bands in sandstone, these arrays do not show a linear increase in number of deformation bands with increasing displacement.

Deformation bands are distinguished in thin section by a decrease in macroporosity and an abundance of brown fine-grained matrix relative to undeformed protolith. Porosity within deformation bands is chiefly in the form of microporosity, defined by pore diameters <0.5 microns. Petrographic point count data and scanning electron micrographs show that the brown matrix material is created through the preferential comminution of lithic fragments and feldspar grains. Quartz grains are also fractured, but to a lesser degree. Production of this fine-grained pseudomatrix results in a five-fold reduction in mean pore size as well as porosity. Grain rotation is evident near the boundaries of deformation bands, where elongate grains have been rotated into the plane of the deformation band. This alignment is also evident within the deformation band.

The decrease in porosity and reduction in pore size within deformation bands indicate these structures should influence fluid flow. Previous studies show that under saturated conditions, deformation bands that cut unlithified or partially lithified sand will act as low-permeability barriers to fluid flow, whereas under unsaturated conditions they may act as preferential flow paths for the wetting phase.

SPATIAL BIAS IN UNSATURATED HYDRAULIC PROPERTY ESTIMATES: ORIGIN, IMPACT, AND RELEVANCE, by Robert M. Holt, 2000, Ph.D. dissertation, Department of Earth and Environmental Science, New Mexico Institute of Mining and Technology, Socorro, NM 87801, 160 pp.

In this dissertation, we show for the first time that bias in property measurements hinders our ability to characterize spatial variability and model flow and transport in heterogeneous systems. Spatial statistics of hydraulic properties can be accurately estimated when measurement errors are unbiased. Unfortunately, measurements are usually spatially biased (i.e., their spatial pattern is systematically distorted) because random observation errors are propagated through non-linear inversion models that may incorrectly describe experimental physics. Measurement bias can be experimentally evaluated and removed through the use of calibration standards. The entire instrument, including the inversion model, must be calibrated to overcome the inversion non-linearity, and this is often infeasible in hydrology because physical standards do not exist and inversion-model errors vary unpredictably between individual samples. It is also impossible to fully calibrate estimates of the spatial statistics. Therefore, the effect of bias on spatial statistics cannot be directly quantified, and instead must be examined indirectly.

We develop a new Monte Carlo approach for indirectly determining the spatial bias in field- and laboratory-estimated unsaturated hydraulic properties subject to measurement errors. We find that hydraulic properties are strongly biased by small, simple observation and inversion-model errors. This bias can lead to order-of-magnitude errors in spatial statistics, artificial cross-correlation between measured properties, and the inclusion of parameters in the inversion model that are simply artifacts of the errors, yet show realistic spatial statistics. We also find that measurement errors amplify uncertainty in experimental variograms caused by limited spatial sampling and can preclude identification of variogram-model parameters. The use of biased spatial statistics in stochastic flow and transport models causes in order-of-magnitude errors in critical transport results, including the mean velocity, velocity variance, and velocity integral scale. The effects of observation and inversion-model errors are insidious, as hydraulic property estimates may appear reasonable and generate realistic-looking spatial statistics that are, however, inaccurate and misleading.

Robust estimation of unsaturated hydraulic properties for spatial variability studies and stochastic modeling is not possible with most current instruments and inversion models, because spatial bias cannot easily be removed by calibration or error analyses such as presented here. Bias is extremely sensitive to different inversion-model errors, and it is not possible to identify a priori all types of inversion-model error that affect a particular property estimation method. Error analyses cannot be used to uniquely identify all material types or conditions under which a particular instrument or inversion model will perform best or to remove bias caused by measurement errors.

DIFFUSION COEFFICIENTS OF HYDROLOGIC TRACERS AS MEASURED BY A TAYLOR DISPERSION APPARATUS, by Ping Hu, 2000, M.S. thesis, Department of Earth and Environmental Science, New Mexico Institute of Mining and Technology, Socorro, NM 87801, 100 pp.

We developed an experimental system for measuring the diffusion coefficients of hydrologic tracers and other tracer solutes in aqueous solutions based on the Taylor dispersion technique. We give a detailed description of the instrument, experimental procedures, calibration, and data analysis for diffusion coefficient measurements. In order to test the accuracy of this system, we measured the diffusion coefficients of KCl, KBr, Kl and benzoic acid in Type l water and found that our results agreed well with published data within an accuracy of 5%. We also found that the diffusion coefficient of KCl in water decreased slightly with increasing concentrations and that our measured diffusion coefficients of KCl at different concentrations were within 2% of published data. All these results clearly demonstrated that the experimental system and methods we developed can be effectively used to measure diffusion coefficients for solutes of interest in hydrology.

Accordingly, we report the diffusion coefficients of a suite of fluorobenzoic acids (FBAs) and two chlorobenzoic acids (DCBAs) in Type l water and 0.1 M potassium phosphate buffer solution using our developed instrumentation and methods. The ranges of diffusion coefficients of these compounds in Type l water and buffer solution are 0.85×10^{-9} to 0.98×10^{-9} m^2s^{-1} and 0.74×10^{-9} to $0.98 \times 10^{-9} m^2s^{-1}$, respectively. These solutes have proven to be effective hydrologic tracers. The measured diffusion coefficients of the benzoic acid derivatives in Type l water were approximately 17% greater than those calculated from molecular structure. Also, the diffusion coefficients of these chemicals in Type l water, in which pH was reduced to 4.00–4.44 due to the dissociation of these weak acid chemicals, were consistently greater than those in potassium phosphate buffer solutions, in which pH was adjusted to 7.0. The correlation of measured diffusion coefficients of FBAs and DCBAs in Type 1 water with either their molecular weight or acid dissociation constant were quite poor. However, in 0.1 M potassium phosphate buffer solution, the diffusion coefficients for FBAs tended to decrease with increasing molecular weight and to increase with the increasing negative-log acid dissociation constant, pK_a. In addition, we noticed that for FBAs of the same molecular weight, e.g., DFBA, TFBA, or TeFBA, the diffusion coefficients varied markedly within the same group. Thus, the diffusion coefficients of FBAs and DCBAs are related to both the intrinsic properties of molecules (e.g., molecular weight and geometrical configuration) as well as external factors (e.g., temperature, pH, density, and viscosity of medium).

PETROLEUM SOURCE ROCKS IN THE BRUSHY CANYON FORMATION (PERMIAN), DELAWARE BASIN, SOUTHEASTERN NEW MEXICO, by Heidi Anne Justman, 2001, M.S. thesis, Department of Earth and Environmental Science, New Mexico Institute of Mining and Technology, Socorro, NM 87801, 106 pp.

The lower unit of the Brushy Canyon Formation consists dominantly of reservoir quality sandstones and interbedded organic-rich siltstones. Sandstones are generally massive or faintly laminated and are composed of very fine to medium-grained quartz and feldspar. The organic-rich siltstones, composed of silt-sized grains of quartz and feldspar, exhibit horizontal lamination and soft-sediment deformation features. Organic matter consists dominantly of amorphous-sapropellic and herbaceous material (type I and II kerogen) with minor woody and intertinitic components. The quantity of organic carbon is sufficient to generate significant quantities of hydrocarbons with thermal maturation. Total organic carbon levels range from 0.56 to 2.41 wt. % for the lower Brushy Canyon, and 0.54 to 1.92 wt. % in the upper Brushy Canyon member. Maturity levels of the kerogen are within the oil generation window.

T_{max} values range from 439 to 448°C with highest levels of maturity along the western and shallowest portion of the study area. Productivity index values range between 0.1 and 0.25, with an average value of 0.19. TAI values are all between 2.4 and 2.8. Kerogen within the lower Brushy Canyon organic-rich siltstones is present in sufficient quantity and is of the right type and maturation to make the units very likely sources for the oil and gas found within the interbedded channel sands. Trends of the source rock within the lower Brushy Canyon may have some influence on the location of oil fields within the Brushy Canyon Formation. Production trends match fairly well with areas high in net thickness of organic-rich siltstones. The Brushy Canyon siltstones appear to act as both source rocks for hydrocarbon accumulations and as seals for the interbedded reservoirs.

COMPARISON OF LINEAR REGRESSION AND A PROBABILISTIC NEURAL NETWORK TO PREDICT POROSITY FROM 3-D SEISMIC ATTRIBUTES IN LOWER BRUSHY CANYON CHANNELED SANDSTONES, SOUTHEAST NEW MEXICO, by Dan Leiphart, 2000, M.S. thesis, Department of Earth and Environmental Science, New Mexico Institute of Mining and Technology, Socorro, NM 87801, 52 pp.

The lower Brushy Canyon Formation of the Delaware Basin consists of a series of overlying, sand-filled channels and associated fans separated by laterally extensive organic siltstone and carbonate interbeds. This laterally and vertically complex geology creates the need for precise inter-well estimation of reservoir properties.

In this paper we integrate wireline log and 3-D seismic data in order to directly predict porosity in the area of an existing oil field in southeast New Mexico. The 3-D seismic data were used to interpret the location of major stratigraphic markers between wells, and these seismic horizons were used to constrain a time window for a volume-based attribute analysis. Step-wise regression and cross-validation were used to combine seismic attributes to predict porosity in wells where the porosity was known from the well logs. The results of a linear regression porosity model show good correlation ($r = 0.74$) between seven seismic attributes and the observed porosity logs at 11 wells in the study area, but the porosity volume created from the regression model did not display the known geologic features. A probabilistic neural network (PNN) was then trained to look for a nonlinear relationship between the input data (the seven attributes) and the observed porosity at the 11 wells. The correlation was better ($r = 0.82$), but the biggest improvement over the linear regression model came in the more geologically realistic predicted porosity distribution.

TECTONIC HISTORY OF THE PROTEROZOIC BASEMENT OF THE SOUTHERN SANGRE DE CRISTO MOUNTAINS, NEW MEXICO, by Erwin Adriaan Melis, 2001, M.S. thesis, Department of Earth and Environmental Science, New Mexico Institute of Mining and Technology, Socorro, NM 87801, 131 pp.

The southern Sangre de Cristo Mountains are a north-south elongate uplift underlain by Proterozoic basement and flanking the Rio Grande rift east of Santa Fe, New Mexico. Mississippian sedimentary rocks unconformably overlie a ca. 1.72 Ga ductily deformed and metamorphosed Proterozoic back arc sequence that retains a partial record of deformation, metamorphism, burial, and uplift from the Proterozoic to the early Cenozoic. This history has been documented through mapping, structural analysis, and $^{40}Ar/^{39}Ar$ thermochronology.

Rock types in the Proterozoic basement include the 1,720 Ma Jones rhyolite complex, a metavolcanic and metasedimentary sequence, which was intruded by the broadly contemporaneous Windy Bridge tonalite. At 1,650 Ma the Indian Creek granite intruded the Windy Bridge tonalite. An isoclinally folded S_1 preserved only in the Windy Bridge tonalite, but not in the Indian Creek granite, suggests that D_1 occurred before the Indian Creek granite intrusion and could be related to the Mazatzal orogeny. At 1,480 Ma the Macho Creek granite intruded the Jones rhyolite complex. It has no magmatic foliation but locally possesses a mylonitic foliation (S_2). S_2 partially transposes S_1 in the Windy Bridge tonalite, whereas the Jones rhyolite complex and the Indian Creek granite solely contain S_2. Microstructures found in all rock types suggest similar amphibolite-grade metamorphic conditions and consistently record dextral strike-slip with a component of normal south-side-down shearing on an east-northeast-striking foliation. The age of S_2 is constrained to be between ca 1,480 Ma, the age of crystallization of the locally mylonitized Macho Creek granite, and 1,372 Ma, the mean of $^{40}Ar/^{39}Ar$ cooling ages of largely post-mylonitic hornblende in the Windy Bridge tonalite. Mineral compositions of feldspar and hornblende in the Windy Bridge tonalite also suggest amphibolite-facies metamorphism, which locally outlasted D_2. Local evidence of retrogression to greenschist facies during D_2 is interpreted to indicate that continued deformation during cooling was locally facilitated by the availability of water. Kinematic indicators argue that D_2 in the study area was a result of transtension, rather than extension or contraction as has been previously suggested.

Following ~1,400 Ma ductile deformation, the Proterozoic basement cooled to ~350°C by 1,343 Ma at a rate of ~5°C/Ma. After 1,343 Ma the basement experienced brittle deformation, metasomatic events, and gradual cooling. Metasomatism in the Windy Bridge tonalite is mostly localized in breccia zones but locally diachronous. The breccia zones are tabular, parallel to the north-northeast-striking faults in the area, and are interpreted as fault zones, the first precisely dated Proterozoic fault zones at ~800 Ma. One metasomatic event could be associated with the Grenville orogeny at ~1,050 Ma. Brecciation and renewed metasomatism at ~800 Ma as well as accelerated cooling recorded by all samples could be associated with the breakup of Rodinia.

Thermochronologic data indicate that rocks east and west of extensive north-northeast-striking faults in the Proterozoic basement had very similar cooling histories from the Proterozoic through the Paleozoic. This suggests that these faults, including the Picuris–Pecos fault, did not accommodate significant dip-slip motion during the Proterozoic. Dip-slip displacement is constrained by field relations to be post-Carboniferous in age. A previously unidentified north-striking fault within the Pecos River valley displaced Paleozoic strata across the valley as much as 200 m (west-side-down offset). Slow, steady cooling during the Paleozoic implies that the hotter samples remained at elevated temperatures through the Silurian–Devonian and cooled quickly before uplift in the Mississippian. K-feldspar samples record no argon loss during Ancestral Rocky Mountain deformation, indicating maximum depths of burial of ~4–5 km at that time. $^{40}Ar/^{39}Ar$ thermochronology suggests renewed burial of ~4–5 km during the Mesozoic before rapid uplift at ~70 Ma during the Laramide orogeny.

SURFACE COMPLEXATION MODELING OF ARSENIC IN NATURAL WATER AND SEDIMENT SYSTEMS, by Gregory P. Miller, 2001, Ph.D. dissertation, Department of Earth and Environmental Science, New Mexico Institute of Mining and Technology, Socorro, NM 87801, 177 pp.

Sorption to solids controls arsenic mobility in most natural waters. Hydrous metal oxides are the dominant sorbing solids in many natural systems. Surface complexation theory will describe water-rock partitioning of arsenic in the laboratory with pure mineral phases; however, published application to arsenic in natural systems is scant. I compare the concentrations of arsenic sorbed to sediments from a geothermally influenced stream in Mexico (100–1,200 µg L, 6–20 mg/kg As), and two contaminated sites in Florida (10–450 µg L, 10–44 mg/kg As), to the sediment concentration predicted by a surface complexation model.

Definition of water chemistry and the properties and number of sorption sites is required for surface complexation modeling. General water quality, arsenic speciation, and trace-metal chemistry were determined. Arsenic species separation was conducted in the field. The Mexico waters are 90% As^{5-} with the remainder present as organic arsenic compounds and As^{3+}. Small amounts of As^{3-} detected in Mexico allowed determination of an in-stream $As^{3+}t_{½}$ of 0.13 h. The water from the Florida sites was approximately an equal mixture of As^{3+} and As^{5-}, with small amounts of organic arsenic present.

Water-sediment ratios were determined from gravimetrically determined porosity and bulk density. The concentration of hydrous metal oxides and sorbed arsenic on the sediments was determined using HNO_3, H_3PO_4, citrate-bicarbonate-dithionate, hydroxylamine hydrochloride–HCl, and the Tessier partial extraction techniques. The surface complexation literature provides ion-specific mass-action coefficients (K_{int}) for the pure mineral phases goethite, ferrihydrite, and gibbsite. Competition simulations used K_{int} for calcium, strontium, barium, zinc, magnesium, manganese, silicic acid, phosphate, carbonate, bicarbonate, sulfate, borate, and fluoride. Coefficients were fitted or substituted if not in the format of the generalized two-layer surface complexation model of Dzomback and Morel. The FITEQL 4.0 code was used for K_{int} fitting. Some coefficients were derived from linear-free energy relationships.

The PHREEQC code and the generalized two-layer model were used to model arsenic sorption using a component additivity approach. The component additivity approach is conceptually superior to bulk-characterization of solid-phase-sorbing properties. Partition coefficients (K_d) determined from adsorption isotherms are also inferior to a component additivity approach. Component additivity uses individual surface complexation coefficients measured on pure-mineral phases to represent the sorbing surface. A local equilibrium assumption was made, and new solid phases were not allowed to precipitate or dissolve. Water-rock interaction was simulated, and the predicted equilibrium concentration of arsenic on sediments is compared to the observed concentration as an indicator of model fit.

The simulations were very sensitive to the extraction method used to define the hydrous metal oxide phases and the iron hydroxide solid phase assumed to be present. The error level in prediction of arsenic concentration can exceed three orders of magnitude if a plausible, but inappropriate, solid sorbing phase is selected. Model fits using iron oxide surfaces defined as ferrihydrite are superior to those using goethite. When metal oxide surfaces are defined using the HNO_3 extraction data the model will closely simulate the observed arsenic concentration. The simulations using HNO_3 extraction data predict approximately 75% of the observed arsenic concentration on the sediments and are superior to simulations using other extraction data.

Sensitivity analysis of the simulations was conducted. The model response to perturbation of silica concentration, pH, or arsenic K_{int} was nonlinear. The competitive effect of silicate, phosphate, carbonate, bicarbonate, sulfate, and boron oxyanions caused large errors in model predictions (20–1,000 fold) if not treated explicitly. Silica is the most important competing species in the Rio Salado simulations. Phosphate is the most important competing species in the Florida simulations. For Rio Salado, the silica concentration is equal in importance to arsenic sorption as dissolved arsenic concentration, sorbing surface concentration, or pH. Dissolved silica at concentrations as low as 1 mg/kg influenced arsenic surface complexation in the Florida simulations. Phosphate, at half the concentration of silica, out competes arsenic and silica for sorption sites in the Florida simulations. Estimating porosity resulted in model response differing by a factor of 1.4–2.1 from the response to measured porosity. Unfiltered water analysis provided simulations with the greatest internal consistency.

The component additivity approach depends on the transferability of laboratory-derived K_{int} from the literature to field application. Sensitivity analysis of arsenic K_{int} on ferrihydrite indicated that the simulations are 10-fold more sensitive to overestimation of arsenic K_{int} than underestimation. Sensitivity to arsenic K_{int} is greatest at the lowest observed sediment arsenic level. Three published values for silica K_{int} on ferrihydrite were used in the simulations. The various K_{int} for silica caused the simulated sorbed arsenic concentration to vary over four orders of magnitude. The model is sensitive to arsenic and silica K_{int} variability. The variability in K_{int} from the literature should be evaluated using sensitivity analysis, as the simulation error from K_{int} values may equal or exceed that from poor definition of solid phases.

Successful simulation of arsenic component additivity surface complexation in natural systems requires detailed characterization of the aqueous and solid phases. The success of the approach was found to be more dependant on the quantification method used for solid phases than quantification of aqueous chemistry. The dependency on definition of iron oxide as amorphous (ferrihydrite) or crystalline (goethite) is equal to the dependency on the solid phase quantification method. The breadth of the aqueous analysis used to support the simulation is more important than the accuracy of the individual analyses. Failure to include quantification of competing species in the analysis and subsequent failure to simulate competition in the model affect the simulations to a far greater degree than the analytical error inherent to the quantification.

A reasonable simulation of the observed arsenic concentrations was obtained using competitive complexation, sorption constants from the literature, and detailed characterization of the aqueous chemistry and solid phases occurring at field sites. It was apparent that small differences in the conceptual model and data collection techniques have a large effect on the error of the simulation. Without tuning of input parameters, the explicit component additivity approach was able to predict the sediment arsenic concentration to within ± 50% of the observed concentrations.

RECEPTOR-BASED MODELING OF GROUND-WATER CONTAMINATION, PART 1, by Roseanna Marie Neupauer, 2000, Ph.D. dissertation, Department of Earth and Environmental Science, New Mexico Institute of Mining and Technology, Socorro, NM 87801, 471 pp.

Receptor-based modeling can be used to determine the prior position of contamination observed at a receptor, such as a pumping well or a monitoring well. The results of a receptor-based model are backward-location and travel-time probability distributions for the observed contamination. For a contaminant parcel that was observed at a receptor, backward-location probability is the probability distribution describing the position of the parcel at some time before detection, and backward travel-time probability is the probability distribution describing the travel time of the parcel from an upgradient position to the detection location. The receptor-based (backward) model can be used to improve characterization of known sources of ground-water contamination, to identify previously unknown contamination sources, and to delineate capture zones.

Backward probabilities are related to adjoint states of resident concentration; therefore, the governing equations of backward probability are adjoints of the forward governing equation. We formally show the relationship between adjoint states and backward probabilities. Using the advection-dispersion equation as the model of forward contaminant transport, we derive the backward governing equation for many conceptual models including one-and multi-dimensional domains, homogeneous and heterogeneous aquifers, uniform and non-uniform flow, steady and transient flow, and conservative and reactive solutes. Each governing equation contains the adjoint of the advection-dispersion operator and a load term that defines the particular adjoint state. The load term depends on both the type of probability and the type of receptor. We show that forward-location and travel-time probabilities are also related to the same adjoint states.

The backward governing equations are similar to the forward model; therefore, any forward contaminant transport code can also be used to solve the backward model. The load terms contain generalized functions that cannot be implemented explicitly in numerical codes, so approximations must be used. We show the appropriate load term approximations that can be used with general cell-centered finite difference models and finite element models with linear triangular or prism elements.

In practical situations, contamination is sampled at multiple locations and times, and the concentrations of the samples are known. This additional data provide more information that can be used to characterize the prior position of contamination. This additional information should reduce the variances for the location and travel-time probability distributions and improve the characterization of the contamination source. We present approaches for incorporating multiple detections of contamination and concentration measurements into the backward probability model. The variances of the probability distributions are reduced using multiple detections. If the source mass is well constrained, the variances are also reduced using concentration measurements.

As a test case for applying the backward probability model, we use data from a trichloroethylene (TCE) plume at the Massachusetts Military Reservation on Cape Cod to obtain information about the prior positions of the observed TCE. The backward model was based on a forward flow and transport model that had been used to simulate remediation conditions. We adapted the model to pre-remediation conditions and used it to obtain backward probability distributions for detected contamination. The results indicate a low probability that the contamination originated from the major suspected source. This could indicate that other sources of contamination were more likely or that the model was not optimized for pre-remediation conditions.

RECEPTOR-BASED MODELING OF GROUND-WATER CONTAMINATION, PART 2: NUMERICAL IMPLEMENTATION OF THE BACKWARD PROBABILITY MODEL.

Backward-location and travel-time probabilities can be used to characterize known and unknown sources of ground-water contamination. Backward-location probability describes the probability distribution for the position of the detected contamination at some time in the past; backward travel-time probability describes the probability distribution for the amount of time before detection that the contamination was released from its source or was at an upgradient location. The governing equation for backward probabilities is the adjoint of the governing equation for contaminant transport. Many numerical codes have been written to solve the advection-dispersion equation for contaminant transport in an aquifer. These codes can also be used to solve the adjoint equation for location and travel-time probabilities; however, the interpretation of the results is different and some approximations must be made for the probability load terms. We present the governing equations for backward-location and travel-time probability for several situations. We then provide appropriate numerical approximations for these equations using general cell-centered finite difference models, and finite element models with linear triangular elements in two dimensions and linear triangular prism elements in three dimensions. Finally, we show one- and two-dimensional implementations of the backward probability model using MODFLOW-96 (Harbaugh and McDonald, 1996) and MT3DMS (Zheng and Wang, 1999).

MICROBIAL REDUCTION OF HEXAVALENT CHROMIUM UNDER VADOSE ZONE CONDITIONS, by Douglas S. Oliver, Jr., 2001, M.S. thesis, Department of Earth and Environmental Science, New Mexico Institute of Mining and Technology, Socorro, NM 87801, 137 pp.

Improper disposal of hexavalent chromium [Cr(VI)] in arid and semi-arid regions has led to contamination of underlying vadose zones and aquifers. To remediate Cr(VI) contamination, soluble Cr(VI) can be reduced to insoluble Cr(III). The objectives of this study were to assess the potential for immobilizing Cr(VI) contamination using a native microbial community to reduce Cr(VI) to Cr(III) under conditions similar to those found in the vadose zone, and to evaluate the potential for enhancing biological reduction of Cr(VI) through the addition of nutrients. Batch microcosm and unsaturated flow column experiments were performed. Native microbial communities in subsurface sediments with no prior Cr(VI) exposure were shown to be capable of Cr(VI) reduction. In both batch and column experiments, Cr(VI) reduction and loss from the aqueous phase were enhanced by adding both nitrate (NO_3) and organic carbon (molasses). These results suggest that biostimulation of microbial Cr(VI) reduction by nutrient amendment is a promising strategy for remediation of Cr(VI)-contaminated vadose zones. This thesis presents a journal article, submitted to *Environmental Science & Technology*, that describes the experiments performed and discusses the results of these experiments. Supporting data for the journal article are provided in the thesis appendices.

$^{40}Ar/^{39}Ar$ INVESTIGATIONS OF THE OCATE VOLCANIC FIELD, NORTH-CENTRAL NEW MEXICO, by Brian W. Olmsted, 2000, M.S. thesis, Department of Earth and Environmental Science, New Mexico Institute of Mining and Technology, Socorro, NM 87801, 86 pp.

Eighty-two $^{40}Ar/^{39}Ar$ analyses from 70 basaltic samples from the Ocate volcanic field reveal that the field was episodically erupted in approximately 16 pulses between 8.2 and 0.8 Ma. In general, a north-to-south time progression of volcanism occurred during the evolution of the field. Two major eruptive episodes, 5.13–4.35 and 3.36–2.85 Ma, produced approximately 32 and 40 vol. % (28 and 36 km^3) of the field (90 km^3 total), respectively. Between 8.2 and 4.4 Ma a period of erosion without tectonic activity occurred, which supplied sediment for the Ogallala Formation. After the 5.13–4.35 Ma eruptions, a period of tectonic activity with extensive down-to-the-west faulting took place within the western portion of the field. Following the 3.36–2.85 Ma eruptions, a period of decreased eruptive activity with small localized eruptive centers ensued within the central and southern portions of the field. Regionally, the Ocate, Taos, and Raton–Clayton volcanic fields all experienced eruptive activity near 5.7, 5.1, 4.7, 3.5, 3.0, and 2.3 Ma with each field displaying an overall peak in eruptive activity between 5.1 and 2.3 Ma.

Modeling and comparing the mineral chemistry and petrographic characteristics of five basaltic groundmass samples from the Ocate volcanic field with the corresponding age, K/Ca and $^{37}Ar_{Ca}$, $^{38}Ar_{Cl}$ and $^{39}Ar_K$ release spectra show that the styles of argon release in a basalt sample are dependent on the crystallinity, chemistry, and modal abundance of the phases present. From first to last, the phases degas in the following order: interstitial phases, feldspar rim, feldspar core, olivine/oxide, and pyroxene. Flow interior samples in which most of the potassium is contained within the feldspar rim display convex upward $^{39}Ar_K$ release patterns. In contrast, flow surface samples in which most of the potassium is contained within the interstitial phases display descending $^{39}Ar_K$ release patterns. Convex upward shaped K/Ca spectra reflect high degrees of recoil redistribution and are seen dominantly in flow interior samples, whereas descending K/Ca spectra are seen dominantly in flow surface samples that reflect low degrees of recoil redistribution. Flow interior samples are concluded to yield more precise ages with heating steps comprising a greater percentage of the total $^{39}Ar_K$ released than flow surface samples.

Analysis of plagioclase, pyroxene, and olivine phenocryst concentrates, along with the corresponding groundmass analyses, confirms previous findings that phenocryst phases degas at temperatures higher than ~1,025°C. In addition, for the samples studied here, apparent ages associated with the degassing of the olivine and pyroxene phenocryst phases are found to yield geologically inaccurate ages, whereas the plagioclase yielded apparent ages in agreement with the corresponding groundmass analysis. Excess ^{40}Ar found within the olivine and plagioclase phenocryst concentrates is calculated to be at most 9.58×10^{-14} and 1.64×10^{-13} moles/g, respectively, suggesting that excess ^{40}Ar has a minor effect within these samples.

Comparison of basalt samples step-heated with both the furnace and CO_2 laser shows that the laser technique reproduces the radiogenic yields, K/Ca, Cl/K, and age gradients seen in the furnace analyses. Based on this, the CO_2 laser step-heating technique is concluded to be an effective alternative approach to dating basalt samples using the $^{40}Ar/^{39}Ar$ dating method.

A COMPARISON OF SEDIMENT PRODUCTION ON CHEMICALLY TREATED AND UNTREATED SAGEBRUSH RANGELAND IN THE RIO PUERCO HEADWATERS NEAR CUBA, NEW MEXICO, by Regina G. Rone, 2001, M.S. thesis, Department of Earth and Environmental Science, New Mexico Institute of Mining and Technology, Socorro, NM 87801, 186 pp.

Chemical treatment of sagebrush rangeland with herbicides has been utilized in the southwest United States for two decades and has improved overall rangeland conditions. Though sagebrush eradication allows for increased vegetative cover, reduced runoff, erosion, and sediment transport, the lack of monitoring and evaluation of grazing land after treatment has resulted in the need to gather baseline data on vegetation changes and sediment production.

A small first-order drainage basin in Arroyo Chijuilla, an ephemeral stream near Cuba, New Mexico, was chosen to study the effects of sagebrush treatment on sediment movement. Rainfall simulations on 1 m^2 plots were used to collect runoff data from a total of 36 plot-runs. Half of the simulations were performed over initially dry soil (dry run), whereas the other half were carried out over the partially saturated soil the following day (wet run). Additional vegetation assessments, erosion pins, infiltration measurements, and soil analyses were used to evaluate vegetation changes and soil properties on treated and untreated sagebrush rangeland.

Chemical treatment resulted in significant decreases in sediment concentrations (kg/ha-mm) for both grass and three shrub plots. Dry runs between grass plots produced similar sediment yields, whereas wet runs showed a nine-fold increase in sediment yield from treated plots compared to untreated. Sediment production on untreated shrub plots was about 5 times higher for the dry and 8 times higher for the wet run than from treated plots. Treated shrub plots produced less than half of the sediment yield of the grass plots. Bare plots acted as controls and showed no significant differences between treated and untreated areas.

Chemical treatment resulted in increases in vegetative cover on all grass and shrub plots. Treated areas not only have greater quantities of ground cover than untreated areas, but also contain slightly more diverse species, especially grasses. Although the percentage of area covered by bare ground was less in the treated plots, the average size of the bare patches was only slightly smaller. The decrease in bare area is therefore controlled by frequency of bare patches rather than their size.

Estimates of Green-and-Ampt conductivities were used to evaluate variations in saturated conductivity between treated and untreated rainfall simulation plots. Conductivity values are significantly higher during wet runs on grass plots and both dry and wet runs on shrub plots between treated and untreated areas. The differences are due to percent vegetative cover and related root growth rather than to changes in soil properties.

Density and spatial arrangement of vegetation appear to exercise the strongest controls on the amount of runoff and erosion. Increased growth of herbaceous ground cover affects sediment movement through: (1) formation of continuous barriers that slow runoff velocity; (2) enhanced surface microtopography; (3) increased infiltration due to ponding; and (4) detainment of sediments. Sagebrush treatment therefore encourages the re-establishment of herbaceous ground cover, thus effectively reducing sediment movement.

CORRELATION-BASED PHASE PICK CORRECTION AND SIMILAR EARTHQUAKE FAMILY IDENTIFICATION IN LARGE SEISMIC WAVEFORM CATALOGUES, by Charlotte A. Rowe, 2000, Ph.D. dissertation, Department of Earth and Environmental Science, New Mexico Institute of Mining and Technology, Socorro, NM 87801, 151 pp.

This thesis describes the development of an automatic, adaptive algorithm that improves the consistency of picking arrival times of seismic phases in digital seismic waveform catalogues and calculates quantitative errors of these picks. The resulting improved pick consistency reduces the random component of earthquake hypocenter location and permits better definition of interpretable seismogenic structures; the improved picks and their associated standard deviations may also be useful in other applications that depend upon these parametric data.

Pick adjustments are obtained by comparing station-common waveforms that have preliminary picks, and estimating relative lags between these picks. Relative lag estimation between pairs of traces proceeds in two steps: an integer-sample correction is made, followed by a sub-sample refinement. For stations with multiple components, we first use polarization filtering to improve signal-to-noise levels before waveform comparison. Automatic, adaptive, cross-coherency filtering is then applied to the waveform pair. A suite of cross-correlation functions is calculated from narrow-band-filtered representations of the waveforms to estimate integer correlation lags and associated standard deviations.

The technique uses a cross-spectral phase slope method for subsample estimates. Multitaper spectral estimation provides the best estimate of the cross-spectrum, as well as statistically and dimensionally meaningful estimates of the subsample standard deviation. Summing the integer and subsample lag estimates provides the total pick adjustment for each waveform pair. The associated pick standard deviation is estimated as the quadrature sum of the coarse and fine standard deviations. The resulting system of inter-event constraints is solved using an iterative Polak–Ribiere conjugate gradient minimization of the L1-norm residual, refined by conservatively rejecting outliers based on interim solutions and successively resolving the system. After a satisfactory solution is found we obtain final pick adjustments for the reduced system and calculate 1-sigma error bars on this solution via Monte Carlo propagation of Gaussian data errors.

A hierarchical, dendrogram-based clustering method is employed to separate large catalogues into similar event families, each of which may be solved independently for intra-cluster relative pick adjustments. A technique of stacking and stack correlation adjusts inter-cluster picks for consistency within the full catalogue.

The algorithm is applied to two different waveform catalogues. Manually repicked waveform data from a subset of microearthquakes at the Soultz-sous-Forets geothermal reservoir, Alsace, France, are used to test the algorithm against careful human repicking, then the technique is applied to a ~7,000-event dataset from the reservoir. Relocated events exhibit significantly more structure than was seen in the preliminary hypocentral cloud, and delineate numerous intersecting joint features in the reservoir. In a second application, some 4,000 volcanic earthquakes associated with the 1989–1990 eruption of Redoubt volcano, Alaska, are relocated. These relocations show significant improvement in location consistency for volcanic long-period events arising from a stationary volumetric source, and show increased clustering of volcano tectonic events into discrete seismically active clusters as well as fractures or joints at depth. Routine use of the technique may enhance observatory operations and improve monitoring capabilities at dangerous volcanoes.

EXCESS ARGON ($^{40}Ar_E$) IN MELT INCLUSION BEARING QUARTZ AND SANIDINE FROM THE BISHOP AND BANDELIER TUFFS, by Jeffrey A. Winick, 2000, M.S. thesis, Department of Earth and Environmental Science, New Mexico Institute of Mining and Technology, Socorro, NM 87801, 66 pp.

$^{40}Ar/^{39}Ar$ experiments on melt inclusion bearing quartz (MIBQ) from the Bishop and Bandelier Plinian pyroclastic fall deposits indicate high concentrations of excess argon ($^{40}Ar_E$) in trapped melt inclusions. Two rhyolite-glass melt-inclusion populations are present in quartz: exposed melt inclusions (EMI) and trapped melt inclusions (TMI). Air-abrasion mill grinding and hydrofluoric acid treatments progressively remove EMI while leaving TMI unaffected. Laser step-heating of MIBQ yields apparent ages that increase with progressive removal of EMI, providing evidence of high $^{40}Ar_E$ concentrations hosted in TMI. TMI-only quartz from the Bishop Tuff yields a total gas age of 3.70 ± 1.00 Ma. Total gas ages for similar TMI-only MIBQ from the upper and lower Bandelier Tuffs are 11.54 ± 0.87 Ma and 14.60 ± 1.50 Ma, respectively. Single-crystal laser-fusion analyses of MIBQ represent mixtures of EMI and TMI argon reservoirs, yielding spuriously old ages that are significantly older than any crystallization or eruption event in the Bishop and Bandelier magma systems determined from Rb/Sr and ε_{Nd} isotopic data, but are younger than apparent ages of TMI.

Single-crystal laser-fusion $^{40}Ar/^{39}Ar$ analyses of sanidine from the Bishop, upper Bandelier, and lower Bandelier Tuff Plinian deposits yield weighted mean ages of 0.768 ± 0.004 Ma, 1.294 ± 0.010 Ma, and 1.607 ± 0.011 Ma, respectively. The Bishop Tuff and lower Bandelier Tuff weighted mean ages presented here are consistent with previously published $^{40}Ar/^{39}Ar$ single-crystal laser-fusion sanidine apparent ages (0.772 ± 0.010 Ma and 1.629 ± 0.022 Ma respectively; Izett and Obradovich, 1994). However, sanidine from the upper Bandelier Tuff Plinian deposit displays a weighted mean age that is both imprecise and ~20 ka older than previously determined $^{40}Ar/^{39}Ar$ ages for this deposit (1.235 ± 0.032 Ma; Izett and Obradovich, 1994). Trapped melt inclusions in Bishop and Bandelier sanidine phenocrysts may contain $^{40}Ar_E$ concentrations similar to those in MIBQ. Models based on $^{40}Ar_E$ concentrations in MIBQ, observed trapped melt inclusion abundances in sanidines, and published single-crystal laser-fusion sanidine data show that, as a result of $^{40}Ar_E$, sanidine apparent ages of the Bishop, upper Bandelier, and lower Bandelier Tuff Plinian deposits can be increased by 4,000, 38,000, and 27,000 yrs, respectively. The modeling results are consistent with the presented $^{40}Ar/^{39}Ar$ single-crystal laser-fusion sanidine age data and suggest that apparent $^{40}Ar/^{39}Ar$ ages of young sanidines (<100 ka) are particularly sensitive to $^{40}Ar_E$.

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PROTEROZOIC TO MIDDLE TERTIARY MAGMATIC HISTORY OF THE LITTLE HATCHET MOUNTAINS, GRANT AND HIDALGO COUNTIES, SOUTHWESTERN NEW MEXICO, by Ryan Anthony Channell, 2001, M.S. thesis, Department of Geological Sciences, New Mexico State University, Las Cruces, NM 88003, 110 pp.

The Little Hatchet Mountains, located in southwestern New Mexico, part of the Basin and Range physiographic province, record Proterozoic to mid-Tertiary magmatism. This record is contained in four groups of plutonic and volcanic rocks emplaced in the last 1.5 billion yrs. These rock groups provide the means for understanding the numerous tectonic episodes active throughout the southwestern United States.

The Hatchet Gap granite has a suggested Proterozoic age. Major- and trace-element data along with REE analyses from the Hatchet Gap granite were compared to geochemical analyses from Proterozoic granites throughout New Mexico and the Cambrian Florida Mountains granite. The Hatchet Gap granite demonstrates a geochemical signature similar to the 1.4–1.5 Ga granites.

Basalt flows intercalated with and capping marine and non-marine sedimentary rocks are part of the Broken Jug Formation. The Broken Jug Formation is a Jurassic sequence, which records the infilling of a continental rift. The Jurassic age is established by correlation with Jurassic Formations in southeastern Arizona.

The Sylvanite intrusive complex (SIC), diorite and monzonite intruding Bisbee Group rocks, is interpreted as the subvolcanic equivalent of the Hidalgo Formation. The Late Cretaceous age of the Hidalgo Formation is the interpreted age of the SIC. The SIC has SiO_2 concentrations between 50 and 65% and La/Ta ratios from 24.65 to 39.51, which is similar to the geochemical concentration of the Hidalgo Formation. The Hidalgo Formation and SIC represent a Laramide composite cone.

The Granite Pass granite intrudes a thrust fault between the Hatchet Gap granite, Paleozoic limestone, and the Mojado Formation. The granite yielded ages of 32.32 ± 0.17 Ma and 32.54 ± 0.69 Ma from $^{40}Ar/^{39}Ar$ age determinations, confirming a mid-Tertiary age. Numerous Tertiary silicic and intermediate dikes intrude the granitic plutons and the SIC.

The Eureka intrusive complex is a monzonite stock intruding the Late Cretaceous Hidalgo Formation. The Eureka intrusive complex could represent a separate portion of the Laramide composite cone responsible for the SIC and Hidalgo Formation. The groundmass of a diorite dike intruding the stock yielded a $^{40}Ar/^{39}Ar$ age determination of 35.5 ± 1.7 Ma, suggesting a Tertiary age for the mafic dikes.

SALT-INFLUENCED GROWTH-STRATAL GEOMETRIES AND STRUCTURE OF THE MUERTO FORMATION ADJACENT TO AN ANCIENT SECONDARY SALT WELD, LA POPA BASIN, NUEVO LEON, MEXICO, by Kevin Daniel Hon, 2001, M.S. thesis, Department of Geological Sciences, New Mexico State University, Las Cruces, NM 88003, 97 pp.

Diapirism and subsequent salt weld development produced growth-stratal geometries and faulting within the Late Cretaceous to early Tertiary La Popa foreland basin. The La Popa basin fill consists of about 5,500 m of an overall deltaic-shelfal regressive succession with subordinate limestone lenses. Several salt bodies, one of which evolved into a salt weld, penetrate this succession. A salt weld is a planar, fault-like structure that was formerly occupied by salt and separates two bodies of strata. The La Popa salt weld had two stages of development, a diapiric stage and an evacuation stage that resulted in complex but distinctive depositional and structural geometries in the adjacent strata.

The Maastrichtian Muerto Formation was deposited during the diapiric stage, during which time rising Jurassic evaporite created a local topographic high on the basin floor. Variations in sedimentation rates during deposition generated growth-stratal geometries within the adjacent strata. These geometries represent halokinetic sequences, which are relatively conformable successions of strata influenced by near-surface salt movement and locally bounded at the top and base by angular unconformities. Low sedimentation rates allowed abundant time for adjacent strata to upturn and be truncated during regressive shoreface erosion. Higher sedimentation rates did not allot the time necessary for dramatic upturning and instead resulted in onlap of the erosional surface. Repeated variation in sedimentation rates generated stacked halokinetic sequences separated by unconformities that caused the overall thinning and pinch-out of the Muerto Formation in the direction of the weld. Although conformable with the underlying Parras Shale and overlying Potrerillos Formation in most of the La Popa Basin, the contacts with these two formations are angular unconformities within 1 km of the weld, resulting in pinch-out of the Muerto at a distance of 150 m of the weld. Reduction in the width of the original salt body during Muerto deposition caused successive halokinetic sequences to encroach upon the diapir and probably also created a steep pre-Muerto normal growth fault that dipped toward the diapir. During the evacuation stage in the Eocene, salt-weld development was accompanied by faulting in all adjacent strata directly northeast of the La Popa salt weld.

SEDIMENTOLOGY, STRATIGRAPHY, AND PETROLOGY OF THE PALEOCENE UPPER SANDSTONE MEMBER OF THE POTRERILLOS FORMATION, LA POPA BASIN, MEXICO, by David Carroll Shelley, 2001, M.S. thesis, Department of Geological Sciences, New Mexico State University, Las Cruces, NM 88003, 213 pp.

The Paleocene upper sandstone member of the Potrerillos Formation is a regressional succession of marginal marine strata in the La Popa foreland basin of northeast Mexico. Deposition of the upper sandstone member was influenced by the simultaneous development of halokinetic and tectonic structures in addition to eustatic influences. The La Popa syncline, a tectonically modified salt-withdrawal structure, formed a minibasin, the Potrerillos minibasin. The minibasin was flanked to the north by a salt wall that formerly occupied the La Popa salt weld, and to the south by the El Gordo anticline, an intrabasinal detachment fold. Within the minibasin, deposition was locally affected by the El Papalote salt diapir.

Lithofacies analysis indicates that the upper sandstone member was deposited by three depositional systems: a wave-dominated marine shoreface, a tidal embayment, and a lower delta plain. Low-energy tidal systems adjacent to the diapir are correlative with high-energy tidal environments at greater distance from the diapir. Far from the diapir, paleocurrents were oriented southeast, subparallel to intrabasinal fold trends; adjacent to the diapir, paleocurrents were deflected to the northeast and east. Growth strata indicate syndepositional uplift of the diapir and the anticline. Sequence stratigraphic analysis indicates three sequences characterized by 3rd and 4th order cycles. Stratigraphic geometries demonstrate that deposition and preservation of strata were significantly influenced by both the diapir and the anticline.

The sandstone composition ranges from arkose to lithic arkose. Framework grains indicate volcanic, metamorphic, and sedimentary sources. The majority of the detritus was derived from eroding volcanic terranes to the west, and transported through the Parras Basin. Minor amounts of detritus were delivered by structure-parallel fluvial systems from the northwest.

Development of the Potrerillos minibasin was controlled by several controls that formed a feed-back loop. Salt flowed from under the La Popa syncline and into the flanking structures. Subsidence created a depositional low that controlled dispersal paths and increased sediment accumulation in the syncline, further amplifying salt withdrawal. Axial, southeastward progradation of sediments through the minibasin drove uplift of the diapir. During sea-level low stands, the minibasin became expressed as a tidal embayment, the Altos Blancos embayment.

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GEOTHERMAL SYSTEMS AND CO2 DEGASSING: THE GEYSERS—CLEAR LAKE, AND DIXIE VALLEY REGIONS OF CALIFORNIA AND NEVADA, by Deborah Bergfeld, 2000, Ph.D. dissertation, Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, NM 87131, 123 pp.

Three studies examine the occurrence of CO_2 in surficial features above active geothermal systems to obtain information regarding the underlying geothermal reservoirs. The first study combines CO_2 flux measurements and geochemical and stable isotope analyses of geothermal fluids to examine changes occurring in a fumarolic area on the northern margin of the Dixie Valley geothermal field in Nevada. These data show that after a decade of fluid withdrawal, declines in reservoir pressure were responsible for boiling fluids that occurred above an outflow plume and led to formation of new fumaroles and localized areas of plant-kill. The second investigation uses carbon isotope results from calcite veins, organic carbon, CO_2, and CH_4 to show that carbon from Franciscan Complex and Great Valley Sequence rocks is the primary source for CO_2 in geothermal fluids across The Geysers–Clear Lake region in northern California. A southwest-northeast regional trend of increasing $\delta^{13}C$-CO_2 values is attributed to variations in the local lithologies. The third study returns to the Clear Lake region to examine the CO_2 flux above a small liquid-dominated geothermal reservoir in what is now an EPA Superfund site. Flux data are used in combination with H_2S and Hg concentrations from gas analyses of vent emissions to provide information regarding the natural flux of these contaminants to the atmosphere.

TECTONIC EVOLUTION OF AN EARLY PROTEROZOIC OPHIOLITE FRAGMENT AND A STABLE ISOTOPE STUDY OF CO-EXISTING ALUMINUM SILICATES IN QUARTZ VEINS, NORTHERN COLORADO FRONT RANGE, by Aaron Joseph Cavosie, 2001, M.S. thesis, Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, NM 87131, 149 pp.

The discovery of a dismembered ophiolite in northern Colorado provides insight into the early tectonic evolution of Colorado. Tectonically intermingled amphibolite, metagabbro, clinopyroxenite, metachert, and carbonate melange are preserved within the Buckhorn Creek shear zone in the northern Colorado Front Range. Metagabbros and clinopyroxenites preserving igneous assemblages contain shallowly plunging, lineated clinopyroxenites that indicate deformation at temperatures over 1,000°C. The fabrics observed in the Buckhorn Creek shear zone amphibolites record multiple phases of deformation that provide insight into the origin and modification of the rock package: a magmatic lineation records igneous deformation conditions before Paleoproterozoic (ca 1.7 Ga) regional metamorphism, whereas metamorphic lineations are likely related to Paleoproterozoic (ca 1.7 Ga) crustal thickening during cratonization and subsequent Mesoproterozoic (ca 1.4 Ga) deformation.

The mafic rock package exposed along the Buckhorn Creek shear zone is here proposed to be a fragment of crust that originated in an oceanic transform fault zone and was exposed during subsequent tectonism.

The dismembered ophiolitic fragment likely represents the basement upon which the products of subsequent arc volcanism and sedimentation accumulated during the accretion of the northern Colorado province onto the Wyoming craton ca 1.8 Ga. The abundance of calc-alkaline plutons in northern Colorado suggests the Colorado province was the overriding plate under which a south-dipping subduction zone developed along what is now known as the Cheyenne belt. The subsequent reactivation of original ocean-floor tectonic zones in the overriding plate may be responsible for the network of regularly spaced northeast-trending shear zones in northern Colorado. Exposures of preserved oceanic crust along reactivated orogen-parallel fracture zones are known from classic island arc complexes such as the Aleutian Islands where volcanic arcs were built on oceanic crust of the overriding plate, and may represent a modern analog of tectonic processes active during the accretion of the Colorado province.

THE ROLE OF THE NORTH AMERICAN MONSOON IN THE LANDSCAPE EVOLUTION OF THE SOUTHWEST UNITED STATES, by Devin Etheredge, 2000, M.S. thesis, Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, NM 87131, 102 pp.

High-intensity rainfall in Arizona and New Mexico is associated with the North American monsoon, which brings thunderstorms to this region starting in July. Geomorphic studies of arid environments in the southwestern United States have assumed that high rainfall rates in these summer storms produce increased amounts of runoff and lead to higher sediment yields from hillslopes and in stream channels, but the true effect of monsoon rainfall on the landscape has yet to be evaluated in the field.

The objective of this study is to determine the degree of the North American monsoon's influence by observing characteristics of the hillslope and hydrologic and fluvial components of the landscape system. A comparative study was made of two Arizona mountain ranges: the Hualapai and Santa Catalina Mountains, which are similar in lithology, elevation, tectonic setting, vegetation, and annual precipitation, but differ in the proportion of annual rainfall received in the summer. The Hualapai Range receives most of its precipitation in the winter months, whereas the Santa Catalina Range is dominated by summer monsoon rainfall. Summer rainstorms over the Santa Catalina Mountains occur more frequently than over the Hualapai Mountains, although storms in both regions were found to be similar in rainfall intensity.

When compared to the Hualapai Mountains the Santa Catalina Mountains are more variable in local relief and show a dramatic increase in the extent of sub-areal exposed bedrock and in drainage density. Hillslope soils are very weakly developed at both locations but are generally thinner in the Santa Catalina Mountains. Streams in the Santa Catalina Mountains are capable of discharge rates several orders of magnitude greater than those in the Hualapai Mountains. Alluvial channels in the Santa Catalina Mountains display greater concavity in longitudinal profile, smaller width-to-depth ratios and possess a larger caliber of bed material than in the Hualapai Mountains. The hydrologic response of stream flow to monsoon thunderstorms in the Santa Catalina Mountains is variable with basin size. Drainage basins under 17 km^2 in area flood most often in response to intense thunderstorms, whereas catchments larger than 40 km^2 flood most often in response to low-intensity, winter rainfall.

NATURAL AND MINING-RELATED SOURCES OF METAL CONTAMINATION, RED RIVER, NORTHERN NEW MEXICO: A HYDROGEOCHEMICAL STUDY OF SURFACE WATER AND GROUND WATER, by Laura Beth Hagan, 2001, M.S. thesis, Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, NM 87131, 192 pp.

The presence of naturally occurring metal contaminants must be considered when assessing mining impacts to surface water and ground water. Within the Red River valley, (Taos County, New Mexico) acidic, metal-laden ground water, originating from both natural and mining-related sources, discharges into the Red River. Natural sources of metal contamination originate in naturally exposed, sulfide-enriched regions, whereas mining-related sources of metal contamination originate from waste-rock dumps associated with an open-pit mine. The purpose of this investigation is to evaluate potential mining impacts to the Red River system by considering hydrogeochemical data sampled from both a naturally impacted locality and a locality impacted by mining.

Ground-water, surface-water, and sediment samples were collected from two research localities. The Hansen Creek locality, situated near the Red River along a ground-water flow path below an extensive alteration scar, was selected to represent hydrochemical conditions associated with natural alteration scars. The Capulin locality, positioned near the Red River along a ground-water flow path below a mining-related waste-rock dump, was selected to represent conditions associated with areas potentially impacted by mining activities. Hydrochemical data suggest that ground water near mining-related waste-rock dumps contains comparatively higher concentrations of dissolved species (e.g. sulfate) associated with the oxidation of sulfides and the generation of acidic waters. For example, shallow ground-water samples collected at the Capulin Canyon locality during baseflow conditions in the Red River yielded sulfate concentrations ranging from 1,600 mg/L to 1,760 mg/L; at the Hansen locality sulfate concentrations ranged from 490 mg/L to 700 mg/L. Analyses of surface water discharging from alteration scars and waste-rock dumps support the inferred differences; sulfate concentrations generated within waste-rock dumps are more than 10,000 mg/L higher than sulfate concentrations in surface water collected from the Hansen alteration scar. Analysis of extractable metals from aquifer sediments also reveals a considerable difference in metal concentrations on aquifer sediments collected at the two localities. Hydrogeochemical data from the Capulin and Hansen localities, combined with previous investigations, suggest that past mining activities are likely impacting certain areas of the Red River system.

FAULT SEGMENTATION AND PALEOSEISMICITY OF THE SOUTHERN ALAMOGORDO FAULT, SOUTHERN RIO GRANDE RIFT, NEW MEXICO, by Dan Koning, 1999, M.S. thesis, Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, NM 87131, 286 pp.

The Alamogordo fault of the southern Rio Grande rift, New Mexico, is a major rift-flank fault along which the Tularosa Basin has been down-dropped relative to the Sacramento Mountains. The temporal and spatial distribution of late Quaternary rupture activity of the southern Alamogordo fault (adjacent to the Sacramento Mountains) was investigated by: 1) mapping proximal piedmont deposits, 2) describing exposures of offset Quaternary sediment and collecting 11 samples of datable material, 3) measuring fault scarp profiles at 40 localities, 4) mountain front and alluvial fan morphometric techniques; and 5) acquisition of subsurface data.

The ages of four late Quaternary surface rupture events are constrained by stratigraphic relationships and C-14 radiometric dates. Two older rupture events probably occurred within a time span of a few thousand years shortly before 12.6 ka (radiocarbon years). The estimated average displacement associated with each of these two events is approximately 3–4 m. North of the city of Alamogordo, the youngest interpreted surface rupture event occurred between 10.4 and 11.4 ka (radiocarbon years). South of the city of Alamogordo, the youngest surface rupture very likely occurred in the early Holocene during a period of major alluvial fan aggradation. This event probably had an average displacement of ~1 m. The alluvial fan stratigraphy suggests that these four ruptures belong to a temporal clustering phenomena that occurred over a period of ~8,000 yrs during the latest Pliocene and early Holocene. These four ruptures probably produced seismic moment magnitudes within the range of 6.8–7.3.

The discrepancy between the ages of the last rupture event north and south of Alamogordo, in addition to geophysical and geomorphic data, collectively support a rupture barrier near the city of Alamogordo. This rupture barrier serves as an important segment boundary of the Alamogordo fault, separating the Sabinata segment on the north from the Deadman segment on the south. Compared to the Sabinata segment, the Deadman segment has significantly greater throw and slip rates over 10^4–10^6 year time-scales as well as more frequent modern microseismicity. The rupture barrier between the two segments is modeled as a west-plunging, largely subsurface, structural trough containing numerous fault-bounded blocks. The structure of this barrier is interpreted to reflect reactivation of pre-Cenozoic structures due to Rio Grande rift-related extension. Although it likely attenuates all ruptures to some degree, this rupture barrier probably does not terminate very large ruptures. The large-scale segmentation of the Alamogordo fault may reflect regional partitioning of extensional strain within the Tularosa Basin.

TECTONICS AND VOLCANISM DURING DEPOSITION OF THE OLIGOCENE–LOWER MIOCENE ABIQUIU FORMATION IN NORTHERN NEW MEXICO, by Jessica D. Moore, 2000, M.S. thesis, Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, NM 87131, 147 pp.

The Oligocene–lower Miocene Abiquiu Formation was deposited under the dual influences of active volcanism and extensional tectonics. The Abiquiu Formation lies across the margin of the western Rio Grande rift and eastern Colorado Plateau in northern New Mexico, an area with a complex Tertiary tectonic history. Pre-Oligocene contractional movement on faults that had later, rift-related normal movement is evident through systematic variations in bedding orientations and stratal thickness across these faults. Thickness changes within the Abiquiu Formation demonstrate that these faults were subsequently accommodating extension before 24 Ma, and possibly as early as (or before) 27 Ma. Furthermore, a regional south-southwestward tilt prevailed from the early Tertiary to the middle Miocene. Regional structural manifestation of the nature of the tectonic transition from contraction to extension, however, remains enigmatic.

The Abiquiu Formation consists of a lower member, dominated by Precambrian cobbles and pebbles; a middle (Pedernal) member, containing layers of resistant chalcedony and calcite in addition to Precambrian-clast gravel; and an upper member of volcaniclastic sandstone. Deposition of the lower and Pedernal members of the Abiquiu Formation was contemporaneous with volcanism in the San Juan and Latir volcanic fields, but the intervening basement-cored Tusas Mountains probably inhibited southward transport of volcaniclastic sediment during deposition of these basement-clast-dominated members. Simple flexural-load modeling suggests that aggradation at this time may have been partly driven by basin formation from crustal flexure under the weight of the volcanic fields. Starting early during deposition of the upper member, when abundant volcanic detritus was reaching the Abiquiu Basin, Latir-derived material was mixed with Precambrian Tusas- (and possibly San Juan-) derived material, but soon became the dominant component of Abiquiu sedimentation. Regrading of stream profiles in response to the growth of the Latir volcanic field at the headwaters may have strongly contributed to deposition of upper Abiquiu Formation strata, as suggested by stream-profile-evolution simulations. These volcanic effects can primarily explain deposition of the Abiquiu Formation west of the nascent rift basin, and, together with early rift subsidence, account for aggradation within the rift basin.

PALEOMAGNETIC DATA BEARING ON VERTICAL AXIS-ROTATION ASSOCIATED WITH A SIMPLE-SHEAR TRANSFER SYSTEM IN THE SILVER PEAK RANGE, WEST-CENTRAL NEVADA, by Michael S. Petronis, 1998, M.S. thesis, Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, NM 87131, 264 pp.

Models of large-scale continental crustal extension must consider the role and importance of vertical-axis rotation of range-scale crustal blocks as well as horizontal-axis tilting. The Silver Peak Range, Nevada, has been reinterpreted as a transfer link between the Furnace Creek and Walker Lane Belt fault systems. Neogene, northwest-directed extension resulted in the exhumation of the Mineral Ridge metamorphic core complex. Northeast-trending, left-oblique faults bounding the Silver Peak Range probably facilitated transfer across the region since the mid-Miocene. To partially quantify rotation and tilting of the Silver Peak Range, paleomagnetic data have been obtained from appropriate rocks inferred to have spanned the period of extension. In principle, the effects of rotation and tilting can be separated with paleomagnetism, given the proper rocks and paleohorizontal reference. Sites were established in Tertiary (?) mafic intrusions (Td), upper Miocene pyroclastic rocks (Tv), and mid-Miocene lacustrine rocks (Ts_3). Eight to ten oriented samples from 123 sites were demagnetized, with 106 sites yielding interpretable results; 69 in Td, 24 in Tv, and 13 in Ts_3. Most samples contain viscous overprints removed by 10–25 mT and 100–300°C, leaving one well-defined, well-grouped magnetization at the site level. Td yield two populations of magnetization directions: northwest-declination, moderate to shallow positive inclination (329°, 37°, $\alpha_{95} = 4.32°$, κ = (37.6, n = 30 sites) and north-northeast-declination, moderate positive inclination (021°, 57°, $\alpha_{95} = 4.38°$, $\kappa = 51.1$, n = 22 sites). The remaining 17 sites yield directions similar to the Quaternary time-averaged field direction. Tv yield two populations of magnetization directions: northeast-declination, moderate positive inclination (032°, 53°, $\alpha_{95} = 8.84°$, $\kappa = 22.9$, n = 13 sites) and northwest-declination, moderate positive inclination (327°, 49°, $\alpha_{95} = 13.90°$, $\kappa = 31.3$, n = 5 sites). Ts_3 yield both normal and reversed polarity magnetizations and, after structural corrections, the data suggest most Ts_3 rocks are remagnetized. Northwest-directed data from Td are consistent with modest to considerable west- to northwest-side-up tilting of the footwall. Assuming the northeast-declination, moderate positive inclination magnetizations from Td and Tv are younger in age than the northwest-directed population, they are consistent with moderate clockwise rotation of parts of the Silver Peak Range following footwall tilting. The Silver Peak Range data imply that vertical-axis rotation, as well as horizontal-axis tilting, facilitated displacement through the transfer system.

QUARTZ–KYANITE PODS IN PROTEROZOIC ROCKS IN NORTHERN NEW MEXICO: SHEAR ZONE FORMATION ALONG AN OLDER HYDROTHERMAL ALTERATION HORIZON, by Mary Catherine Simmons, 1998, M.S. thesis, Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, NM 87131, 70 pp.

Large quartz-kyanite schist pods of unusual bulk composition enclosed by shells of sericite schist occur within the 1.7 Ga Vadito Group metarhyolite in northern New Mexico. These pods are discontinuous, lenticular, symmetrically zoned, and are stratiform within a map-scale sericitic horizon. Previous studies have not resolved whether the high-Al bulk compositions of the quartz-kyanite pods were the result of weathering, hydrothermal alteration, or shearing. Geochemical differences between the quartz-kyanite/sericite schist pods and the sericite-rich layer that connects them suggest more than one alteration process. This study uses geochemical, structural, and metamorphic data to evaluate the origin and tectonic evolution of the quartz-kyanite rocks.

Geochemical data from sampling traverses, mineral textures, and map patterns indicate that the quartz-kyanite pods obtained their unusual (high Al, low K, Na, Ca, Fe) compositions through hydrothermal alteration associated with volcanism. Geochemical profiles are symmetrical, with depletion of Ca, Na, K, Fe and enrichment of Si toward the center of the alteration zone. Higher K and Fe compositions in the sericite-rich layer that connects the pods suggest a different alteration process. Truncation of stratigraphic map units, grain-size reduction, S-C fabrics, and asymmetric porphyroblasts suggest that this second alteration process was related to a top-to-the-south shearing episode (D_1) along a bedding-subparallel zone before D_2 (N-vergent) deformation produced map-scale folds.

Microstructural studies show that kyanite is an early (S_1) metamorphic mineral produced before shearing of previously altered volcanic rock, shown by alignment and grain-size reduction of kyanite within the earliest fabric (S_1). Subsequent metamorphism and shearing may have enhanced the concentration of silica and aluminum in this zone, and linked the pods of altered rock into a map-scale, sericite-rich (S_1) shear zone. Other minerals that formed early in the deformational history of these rocks include staurolite, paragonite, and albite, indicating peak P-T conditions of ~600°C and ~6 kbar for S_1 fabrics. S_2 minerals in the quartz-kyanite pods include staurolite and chloritoid, and in the pelitic schist layer are staurolite, biotite, and garnet, indicating peak temperatures for S_2 at 575°C. These assemblages may produce looping P-T paths, as do other regions of Proterozoic rocks in northern New Mexico.

THE USE OF ^{234}U–^{238}U ISOTOPIC DATA FOR CONSTRAINING URANIUM MASS TRANSPORT: CASE STUDY OF THE TUBA CITY URANIUM MILL TAILINGS REMEDIATION ACTION (UMTRA) PROJECT SITE, NORTHEASTERN ARIZONA, by Dezbah A. Tso, 2000, M.S. thesis, Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, NM 87131, 231 pp.

Measurements of U-238 concentration and $\delta^{234}U$ on ground-water samples and rock core leachates by thermal ionization mass spectrometry (TIMS) indicate transfer of uranium from uranium processing fluids to authigenic minerals in the Jurassic Navajo Sandstone. From 1956 to 1966 the Tuba City uranium mill, located on the Navajo Reservation in northeastern Arizona, milled and leached approximately 784,000 tons of high-grade uranium ore. During that time, milling and leaching processes contributed contaminants such as cadmium, molybdenum, nitrate, selenium, sulfate, and uranium to the ground-water system and created a plume of contamination that continues today.

Samples from 23 contaminated and uncontaminated wells were collected and analyzed. Rock cores from the unsaturated and saturated zones of an uncontaminated well, well 901, and a contaminated well, well 906, were sequentially leached using 1) ammonium acetate, 2) 1N acetic acid, 3) 6N HCl, and 4) 7N nitric acid. The remaining residual solid of uncontaminated and contaminated rock cores from the unsaturated zone were digested after the nitric acid step with concentrated HF.

Analysis of rock core leachates and ground-water samples from wells 901 and 906 revealed a transfer of uranium from the contaminated milling fluid to the aquifer rock. In the unsaturated zone, using data from five leaching fractions, the uranium concentration and isotopic data indicate a transfer of about 150 ng U-238 per cm^3 of Navajo Sandstone. The mechanism of transfer is unknown. Adsorption is unlikely given the dominance of negatively charged aqueous uranyl carbonate complexes and the negative surface charge of iron oxides. It is likely that precipitation of calcite plays a major role in removing uranium to the solid phase. Ground water is oversaturated with respect to calcite in 11 wells and is near equilibrium in seven wells. Moreover, calcite rims are visible in rock-core thin sections.