New Mexico Geology recognizes the important research of students working in post-graduate MS and PhD programs. The following abstracts are from recently completed MS theses and PhD dissertations that pertain to the geology of New Mexico and neighboring states.

New Mexico Institute of Mining and Technology


The Carrizozo lava flow is an ideal isochronous (5 ka) surface to examine the influences of climate, provenance, and surface-cover types on the abundance and physical and chemical composition of loess deposits, and the early pedogenic process occurring within the deposits. The Carrizozo lava flow is 75 km long. Its complex surface topography provides catchments for eolian material accumulation, as well as for the development of a range of surface-cover types (i.e. desert pavement, grasses and cacti, and juniper trees). The Carrizozo lava flow is surrounded by various lithologies within the Tularosa Basin, and dust transport is by southwestern prevailing winds.

Surface-cover type influences the loess composition in two ways: (1) by influencing the moisture content and thus the accumulation of chemical constituents in the soil profile during pedogenesis and (2) by preferentially trapping material. In general, higher concentrations of CaO, MgO, S, soluble salts, chloride, and calcium carbonate are found in the south and are indicative of provenance effects. Strong correlations in chemistry coupled with the prevailing wind direction suggest that the evaporite gypsum dune deposit of White Sands and the dolomitic rocks from the San Andres Mountains influence the dust composition.

The Carrizozo dust flux average of 0.54 g/cm²/ka is very comparable to those found in the southwestern United States and in similar desert eolian systems around the world. The non-pedogenic calcium carbonate chemical composition of the Carrizozo loess is similar to the regional shale standard (NASC), local crustal composition, and to soils developing on the Potrillo volcanic field in southern New Mexico. As expected, high deviation in chemistry is observed when compared to the Carrizozo basalt composition, indicating that the soils are indeed of eolian origin and not basalt weathering products.

Furthermore, surface-cover type, provenance, and wind direction affect the abundance of and physical and chemical composition of the Carrizozo lava flow loess deposits, and the early developmental stages of pedogenesis. The Carrizozo lava flow has provided an opportunity to investigate the spatial variability associated with these factors, as well as the remarkable uniformity of the eolian material and accumulation over the last 5,000 yrs.


The 90-km-long Montosa fault bounds the east side of the Los Pinos and Manzano Mountains of central New Mexico. Overall fault strike is north-northeast, and dip is 55–70° west. The fault shows predominantly reverse separation and has been interpreted as Laramide in age. Local normal stratigraphic separation across the fault and normal-slip slickenlines on earlier reverse strike-slip indicate that fault reactivation occurred during Neogene Rio Grande rift extension.

Lineations and kinematic indicators on minor fault planes and fold hinges were examined to constrain the direction of maximum shortening during formation of these structures and, by inference, the sense of slip on the Montosa fault. Three different directions of shortening were determined: east-west, northwest-southeast, and north-south. Other workers have reported that structures recording east-west shortening are cross-cut by those recording north-south shortening. East-west shortening would impart dextral reverse oblique-slip motion on the Montosa fault. The central portion of the fault shows strong evidence for northwest-southeast shortening, which would cause sinistral reverse oblique-slip motion on the Montosa fault. Along the north-central portion of the fault, minor planes and folds accommodated north-south shortening, which would result in sinistral reverse oblique-slip motion on the fault. East-west shortening was the most significant stage in the movement history of the Montosa fault, resulting in reverse separation, with a component of dextral strike-slip offset. The Montosa fault also shows evidence of normal reactivation during the Neogene Rio Grande rift formation.

Apatite fission track (AFT) analysis was used to determine the thermal history of samples collected in several transects across the fault. Because the thermal history of a sample reflects the temperature history of the area, the AFT data can be used to constrain the relative timing of faulting. AFT data from along the Montosa fault indicate that denudation in early Eocene to late Eocene time (55–35 Ma) resulted in cooling of the lower elevations of the Los Pinos Mountains. Samples from the lower elevations of the Manzano Mountains cooled in early Oligocene to early Miocene time (33–22 Ma), ascribable to exhumation following Laramide uplift and during the formation of the Rio Grande rift. The southern fault tip shows normal separation of sedimentary strata, which is attributed to reactivation during north-south shortening. Samples in this area did not cool until the late Oligocene to early Miocene (25–14 Ma). Broad track-length distributions suggest that all of the samples remained within the partial annealing zone (PAZ) for apatite (temperatures range from ~60° to ~120°C) for long periods of time where elevated temperatures caused fission-track shortening. Thermal modeling of the AFT ages and track-length distributions reveal that the samples remained in the PAZ for 10–30 m.y., then cooled quickly to surface temperatures.

AFT analysis did not show significant age variation across the fault, which indicates that faulting predated cooling; therefore, movement on the Montosa fault during the Laramide orogeny must have occurred at temperatures greater than ~120°C. Fault reactivation during rift formation also occurred at temperatures greater than 60°–120°C or was too minimal to be recorded by AFT.


Teapot Dome is an asymmetric, doubly plunging, basement-cored, Laramide-age anticline. A systematic study of natural fractures within the Cretaceous Mesaverde Formation at Teapot Dome, Wyoming, indicates that lithology and structural position control outcrop fracture patterns. Lithology controls fracture, deformation band, and fault patterns in the following ways: (1) fracture intensity increases with increased cementation; (2) fracture spacing increases proportionally with bed thickness within two sandstone facies but not in carbonaceous shales where fracture spacing is inversely proportional to bed thickness; (3) coal cleats are generally oblique, by up to 20°, to fractures in sandstones; (4) most fractures in sandstone units terminate at contacts with shale layers; (5) deformation bands occur almost exclusively in a poorly cemented, high-porosity, rock-sand facies. Normal faults within well-cemented sandstones are generally expressed as fracture zones, whereas the same faults within poorly cemented sandstones are diffuse zones of subparallel deformation bands.

Three primary through-going fracture sets were documented at Teapot Dome. The oldest fracture set is oblique to the fold. The vast majority of these fractures strike northwest to west-northwest. A small number of these oblique fractures strike roughly north-northeast. Fractures that strike oblique to the fold hinge appear to predate folding. The most common fractures, which are found throughout the fold, are bed-normal extension fractures striking subparallel to the fold hinge. A third set consists of bed-normal extension fractures striking perpendicular to the fold hinge. In many areas this fracture set is spatially localized and subparallel to northeast-striking, normal, oblique-slip faults. The normal, oblique-slip faults are common along the eastern limb, but more than 90% of these faults terminate before intersecting the western limb. Conjugate fractures, deformation bands, and faults, oriented such that they have a vertical bisector to the acute angle and striking subparallel to the axis of the anticline, are common in the southwestern limb and southern arc of the anticline. Hinge-parallel and hinge-perpendicular fractures and faults are probably broadly contemporaneous with basinment-involved thrusting and folding at Teapot Dome, as suggested by their spatial relationship to the fold. Further observations suggest that fault-related, hinge-perpendicular fractures are generally the same age as hinge-parallel fractures, and that northeast-striking, normal, oblique-slip faults are oriented roughly perpendicular to the fold hinge, even where it bends, and terminate toward the southwest limb of the anticline. The oblique movement recorded on some of these northeast-striking faults may be related to differential movement across individual segments of the basinment-involved thrust.

Based on the Teapot Dome natural fracture data set, a three-dimensional conceptual model...
of fractures associated with basement-cored anticlines suggests significant horizontal permeability anisotropy, on the order of 10^6, and that IR natural- 

correlation and the interaction between fracture sets, the direction of maximum permeability can be either parallel or perpendicular to the fold hinge.

**EXPERIMENTAL EVIDENCE OF HYPERFILTRATION INDUCED PRECIPITATION OF HEAVY METALS**

Pyrite from various localities has been analyzed, and pollutant heavy-metal concentration suggest that it should be possible for concentrations of heavy-metal solute in the CPL to reach supersaturation, resulting in the precipitation of heavy-metal solute on the high-pressure membrane face. The heavy metals of interest included lead, copper, and cobalt.

In order for solute sieving to occur, there must be a head difference across the shale aquitard. Such head differences can occur as the result of rapid sedimentation of fine-grained materials or lateral tectonic compression. Head differences observed in perched and artesian aquifer systems are sufficient to drive the phenomenon. Additional theoretical calculations indicate that much lower pressure-head gradients than those used in these experiments will drive hyperfiltration in natural systems, resulting in the precipitation of heavy metals as described in this study.

The experiments demonstrate that clay-membrane induced precipitation of heavy metals can occur when undersaturated solutions pass through membranes. Mathematical analysis coupled with the findings of this study suggest that hyperfiltration may induce heavy-metal precipitation in the subsurface where contaminated aquifers are bounded by membrane-functioning shales.

**TRACE-ELEMENT CONTROL ON NEAR-INFRARED TRANSPARENCY OF PYRITE**

Pyrite from various localities has been analyzed, by means of optical microscopy, FTIR spectroscopy, bulk geochemical analysis, and electron microprobe analysis for correlations between trace-element contents and transparency in near-infrared (λ ≤ 2.0 μm). Additionally, FTIR spectra were taken in the temperature range from 28°C to 400°C to identify mechanisms responsible for degradation of the transparency of pyrite at high temperatures.

The transparency of pyrite at room tempera-

ture was found to be highly variable, with a sedi-

mentary and fine-grained pyrite being mostly opaque. Pyrite has high optical absorption, and high fluid inclusions are present in pyrite, relatively few of them are transparent enough to be suit-

able for microthermometric measurements, and their prevalent opacity can be attributed to the high refractive index of pyrite and the resulting refraction of IR light from the inclusion walls.

Six distinct absorption features caused by imperfections in pyrite, have been identified in the IR spectra: (1) raised baseline; (2) prominent absorption tail of the main absorption edge; (3) high-absorption area, with a steep low-energy slope, below the main absorption edge; (4) symmetric absorption peak centered at 2.0 μm; (5) asymmetric absorption peak with a maximum at ~2.0 μm, with a steeper low-energy slope; and (6) gradual increase in absorption, below the main absorption edge, with longer wavelengths.

The first three absorption features have been linked to the presence of large-scale mechanical defects in pyrite (e.g., cracks, grain boundaries, solid inclusions, surface imperfections), and they might be caused by reflection, refraction, and absorption (by foreign minerals) of the inci-

dent IR light. The remaining absorption features are likely caused by pyrite that has the characteristic pyrite structure, with a specific crystallographic structure. The absorption peak at 2 μm is due to the combination of CO₂ and CO₃ in the Fe₂⁺ and Fe³⁺ configuration, close to the bottom of the energy gap of pyrite. The last absorption feature listed above corre-

lates with As; however, there is no theoretical evidence to support that correlation.

The main absorption edge of pyrite shifts gradually toward longer wavelengths with an increase in temperature. The coefficient of this shift is equal to -0.50 meV/°C in the analyzed temperature range from 28°C to 400°C. The resulting high-temperature degradation in the IR transparency of pyrite can be minimized by keeping the thickness of a sample to a minimum and increasing the spectral range of the IR detector being used.

**GEOCHEMICAL CHARACTERIZATION OF GEOLOGICALLY COMPLEX MOUNTAIN FRONT AQUIFERS: PLACITAS, NEW MEXICO**

Characterization of ground-water flow across geologically complex mountain-front recharge areas can be confounded by an intricate network of structural and stratigraphic controls. Standard exploration methods are inadequate because the hydrologic nature of geologic discrete units may be difficult to discern and the collection of representative data may be prohibitive. The use of geochemical techni-

ques as a primary tool for characterizing ground-water flow and recharge in geologically complex terrain is demonstrated on the eastern margin of the Albuquerque Basin at the north end of the Sandia Mountains in New Mexico, where structural and stratigraphic controls produce hydrologic discontinuities and aquifer compartmentalization. The regional distribution of geochemical parameters such as radiometric dating, stable isotope analyses, major ion analy-

ses, ground-water temperature, and dissolved oxygen concentration, differs significantly from the distribution predicted by a standard basin model and illustrates the heterogeneity and complexity of ground-water flow in the study area.

Local scale analysis of the geochemical results from ground-water, surface-water, and precipi-

tation sampling permits the identification of recharge areas, discharge areas, preferential ground-water flow pathways, and barriers to ground-water flow. Comparison of stable iso-

tope analyses on ground water and precipitation indicates that the mountain water is recharged in the Sandia Mountains by infiltra-

tion of precipitation and runoff that is produced by winter-type storms originating over the northern Pacific Ocean. The Madera Limestone that caps the Sandia Mountains produces ground water that is typical of recharge areas and has a low temperature, low TDS concentra-

tion, and high dissolved oxygen concentration (Madera-type water). Madera-type water is also produced by isolated Mesozoic aquifers between the mountains and the Albuquerque Basin, and downgradient of basin-bounding faults. When a shale membrane partially rejects water, membrane induced precipitation of heavy metals can occur when undersaturated solutions pass through the membrane. The experiments demonstrate that clay-membrane induced precipitation of heavy metals can occur when undersaturated solutions pass through membranes. Mathematical analysis coupled with the findings of this study suggest that hyperfiltration may induce heavy-metal precipitation in the subsurface where contaminated aquifers are bounded by membrane-functioning shales.

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PROBABILISTIC SEISMIC HAZARD IN NEW MEXICO AND BORDERING AREAS, by Katalyn Liu, 1999, PhD dissertation, Department of Earth and Environmental Science, New Mexico Institute of Mining and Technology, Socorro, NM 87801, 194 pp.

Presented in this dissertation is a catalog of magnitude 2.0 or greater earthquakes for New Mexico and bordering areas for the time period 1962–1998. The catalog comprises 925 events (215 inside the Socorro Seismic Anomaly [SSA]) and covers the region longitude 101° west to 111° west and latitude 31° north to 38° north. Significant contributions to this catalog came from Los Alamos National Laboratory, U.S. Geological Survey, University of Texas at El Paso, and Texas Tech University. The unique features of this catalog include reassessment of magnitudes using a duration scale tailored to the region, and relocation of epicenters using the SEISMOs program. A major factor in improving locations was the development of an innovative subroutine that calculates a reliable first estimate of the epicenter for input into the SEISMOs program. The subroutine is based on a modified G matrix and fuzzy logic. Inclusion of it in the process avoids problems encountered when using data from small aperture networks or when confronted with earthquake phase readings containing large errors, both rather frequent occurrences with the catalog events.

Probabilistic seismic hazards for the region based on the catalog are presented in maps of 10% and 2% probability of exceedance in a 50-yr period. The hazard maps show moderate to low seismic hazard for the region, with the highest level of ground acceleration, ~0.18g, inside the SSA (10% probability of exceedance in a 50-yr period). Along the major population corridor of the state from Albuquerque to Santa Fe, the peak ground acceleration is ~0.08g, which generates SSA (10% probability of exceedance in a 50-yr period).


The primary aim of this work was to investigate the possibility of dating fluid inclusions in quartz veins from the Capitan pluton, south-central New Mexico, using the 40Ar/39Ar method. Because quartz is such an abundant vein mineral, the ability to use the 40Ar/39Ar method to date quartz would allow a wide range of ore deposit systems to be dated. Vein quartz from Capitan is considered to be deposited from primary magmatic waters and is cogenetic with vein adularia, which provides a tight constraint on the age of the quartz veins. The fluid inclusion populations are exceptionally well characterized. The inclusions have been shown to be remarkably abundant, highly saline, and relatively large. Samples of different grain sizes from several prospect pits were analyzed using fluid inclusion microthermometry to the study of ore genesis.

Electrokinetic transport theory, three-dimensional numerical model development, comparison of model predictions with experimental results, and a surfactant-coating procedure for the anode electrode casings are all described in the dissertation.

An electromigration transport model was developed based on a modified Nerst-Planck equation describing the electromigration and diffusive flux of ions in a porous medium and on the equation of continuity. A steady-state electric potential field was assumed, an assumption valid for highly buffered soils or when the electrode electrolysis reactions are neutralized. The model also assumed that advective water movement through the soil due to either electric or hydraulic potential is negligible. The transport and continuity equations were implemented in the model using public domain groundwater flow (MODFLOW) and transport (MT3D) numerical codes that were modified to allow prediction of ion transport due to an electric potential field.

Effective ionic mobility and diffusion parameters for porous media were calculated using a tortuosity function based on a closed-form solution of an equation describing electrical conductivity dependence on moisture content. The effect of ionic strength on ionic mobility was estimated using the activity coefficient calculated by the Davies equation.

One-dimensional laboratory experiments that measured anionic dye electromigration rates as a function of moisture content were used to verify the model. Laboratory experiments were conducted using a 10-mA, constant-current condition. Predicted red dye No. 40 migration rates matched the experimental data very well. Both the numerical simulations and the experimental results showed a maximum electromigration velocity at moisture contents less than satura-
tion. This maximum is believed to be due to competing effects between current density and tortuosity.

A six-month field demonstration was conducted to examine ion electromigration through heterogeneous unsaturated sandy soils. Acetate electromigration transport in the field demonstration indicated preferential transport through soil layers exhibiting higher moisture content and electrical conductivity. Modeling was used to assess the effects of spatial heterogeneities on electromigration transport at the field-scale. The measured soil properties of the field demonstration were conceptualized as a layered system or as a homogeneous system. The layered model had three layers where each layer was assigned a moisture content and electrical conductivity value. The homogeneous model represented a single homogeneous profile with average properties of the layered model. Numerical results from these models suggest that spatial heterogeneities in soil properties must be accounted for in order to predict electromigration transport in a heterogeneous soil profile. The numerical predictions of the layered model qualitatively matched observations from the field experiments.

A surfactant-coating procedure for ceramic electrode casings was developed that eliminates excess electrolyte from the contact area of unsaturated soils. Anode porous ceramic casings were treated with hexadecyltrimethylammonium chloride at concentrations above the critical micelle concentration. Laboratory experimental results suggested that the surfactant coating formed a bilayer on the ceramic surface, reversed the zeta potential, and significantly altered the electric field flow direction within the treated-ceramic pores. A six-month field demonstration confirmed the stability and effectiveness of the surfactant treatment on the porous ceramic.

The results of this dissertation illustrate the importance of moisture content and its relationship to electrical conductivity on electromigration transport, and the importance of including spatial heterogeneity in electrokinetic transport models. The steady-state electric potential field assumption allowed soil spatial variability effects on electromigration to be incorporated in a three-dimensional transport model. Electrokinetic transport models assuming homogeneous soil parameters will not adequately predict ion transport pathways at the field-scale in heterogeneous soil profiles.

GEOLOGY AND GEOCHEMISTRY OF WASTE ROCK PILES IN THE HILLSBORO MINING DISTRICT, SIERA COUNTY, NEW MEXICO, by Erik A. Munroe, 1999, MS thesis, Department of Earth and Environmental Science, New Mexico Institute of Mining and Technology, Socorro, NM 87801, 144 pp.

In New Mexico, there are more than 100,000 abandoned mine waste rock piles with variable mineralogical and geochemical compositions. To better understand the environmental consequences of metal mobility in regions of minimal precipitation, a mineralogical and geochemical study was implemented for four mine waste rock piles and their drainage systems in the Hillsboro mining district.

A sampling strategy was developed to geochemically characterize four mine waste rock piles representing four different mineral deposits: a placer gold waste rock pile (Site A), a Laramide polymetallic vein waste rock pile (Site B), a carbonate-hosted Pb-Zn waste rock pile (Site C), and a carbonate-hosted Ag-Mn waste rock pile (Site D). In addition, another polymetallic vein waste rock pile (Site E) was studied to compare physical and chemical characteristics specifically with Site B. To determine the appropriate grain size range to be sampled, six grain size fraction ranges (2–1 mm, 1–0.5 mm, 0.5–0.25 mm, 0.25–0.125 mm, 0.125–0.063 mm, <0.063 mm) were analyzed by FAAS and XRF. The <0.25 mm grain size fraction encompassing the three smaller grain size fraction ranges was used to sample the mine waste rock piles because it was determined to typically contain the highest metal concentrations. Using grid patterns unique to each of the waste rock piles, samples were obtained using sampling densities of 15, 30, and 45 sample cells. Chemical analyses by FAAS and XRF determined that these mine waste rock piles can be adequately geochemically characterized by homogenizing samples collected from a grid pattern containing 15–30 samples.

An examination of metal mobility from the waste rock piles indicates that metals are moving as mineral grains, suspended material, and dissolved material. Chemical mobility is highest in the Laramide polymetallic vein waste rock piles (Site B and Site E) than in the carbonate-hosted waste rock piles (Site C and Site D). This may be a result of pyrite-bearing waste rock piles (Site B and Site E) generating sulfuric acid that can increase metal availability to the environment. Site C and Site D, however, have less chemical movement due to the abundance of calcite. Physical movement of material from these sites is the primary cause for the metals in downdraft stream sediments.

Secondary mineral rinds play a major role in the release of metals to the environment. Iron sulfate, iron oxide, and iron oxyhydroxide form rinds on the chloropyrite and pyrite. Pyrite oxidation rinds preferentially partition arsenic. Oxidation rind thickness varies depending on mineralogy, mineral residence time in the waste rock pile, and hydrothermal history associated with the different deposits. Strong precipitation events may flush out metals partitioned in the outer rinds of oxidized sulfide grains. However, hydrothermal circulation of some mineral grains like galena may be “armored” by cerussite. This leads to a significant decrease in the lead concentration available for chemical transport in the environment. Dissolved material may precipitate soluble salts onto grains in waste rock pile and stream sediments.

Agitation tests indicate copper and zinc are preferentially partitioned in the suspended material during a simulated precipitation event. Primary clays present in the stream sediments were smectite, illite, and illite/smectite mixed-layer clays. Metal movement in a semi-arid environment is governed by local drainage characteristics, mineralogy, and grain size.


The need for effective methods of containing and remediating contamination has become increasingly important as our reliance on ground water for drinking water and the occurrence of contaminated vadose zone sites has increased. Flow and transport within the vadose zone is dependent upon the in-situ moisture-content distribution, which is often inadequately characterized by sparse hydrological measurements. Cross-borehole ground penetrating radar (GPR) is a high resolution, rapid-acquisition geophysical method that can obtain detailed measurements of the subsurface.

Ground penetrating radar estimates the velocity of the electromagnetic (EM) waves in the subsurface. This velocity can be converted to an image of moisture content because it depends primarily upon the moisture content (Topp et al., 1989).

At a vadose zone field site the feasibility of using cross-borehole GPR to image the two-dimensional in-situ moisture-content distribution was tested. Then, during an infiltration experiment, cross-borehole GPR was tested to see if it could accurately image the advancing wetting front. GPR measurements were taken along an 11-m profile, consisting of five boreholes, with a 3- by 3-m infiltrometer in the center that emitted water at a rate of 2.7 cm/d. Two-dimensional GPR moisture-content images were produced for preinfiltration and infiltration conditions. The GPR images were compared to neutron-probe measurements, and the two methods produced stratigraphic columns. The neutron measurements were collected in the same five boreholes, and the stratigraphic columns were constructed from continuous core samples taken several meters from the boreholes.

Overall, the GPR two-dimensional in-situ moisture-content distribution image correlated well with the neutron-probe and the stratigraphic-column data. By taking multiple data sets, one is able to quantify the GPR repeatability error. The average traveltime error was 1.08 ns, which in a general sense translated to an average moisture-content error of ±2%. Both errors were calculated by taking two standard deviations. The overall error was highest in areas of high moisture content and low ray density. Results indicate that the GPR moisture-content figures represent a smoothly varying image that maintains the general trend of the moisture-content distribution as compared to the neutron-probe and stratigraphic-column data. Equipment failures led to inaccurate estimation of moisture content in at least two data sets. However, this study showed that cross-borehole GPR can be an effective and feasible technique for characterizing the vadose zone.


Seismic attributes have the potential to significantly improve reservoir property predictions in interwell areas if care is taken to ensure that the results are geologically and geophysically reasonable as well as statistically significant. This study illustrates how a volume-based attribute analysis can be used to determine reservoir properties and evaluate infill drilling targets via a case study of an oil and gas field producing from the Second Sand Member of the Bone Spring Formation along the north-
ern slope of the Delaware Basin, New Mexico. The Second Sand is a stratigraphically complex subunit, supported by 2-D seismic data and, more traditionally, horizon- and interval-based attribute analysis techniques have been unable to predict porosity with the desired accuracy.

Based on an integrated analysis of well logs, cores, and 3-D seismic data, a combination of high frequency sea-level changes, variations in sediment supply, and, more recently, BSR data have resulted in a submarginal fan deposit that is largely confined to a small intraslope basin and that can be subdivided into a basin-floor fan, a slope fan, and a modified lowstand wedge. The best reservoir quality is found in the slope fan. The porosity distribution was successfully predicted using a combination of five seismic attributes. Although the predicted porosity distribution is complex, it appears to be geologically reasonable with high porosities (>10%) tending to occur in what is believed to be a channel fairway, and zones of extremely low porosity being associated with faults. Three potential drilling target were identified within the slope fan and were assigned risk factors based on the geologic setting, production history, and statistical significance. These results have implications for the way in which other attribute studies are done and for Bone Spring exploration elsewhere.


The Spraberry Formation is part of the submaine fan deposits of the Middle Basin. The unit consists of very fine grained sandstones, siltsstones, shales, and carbonate mudstones. These rocks show different degrees of lamination, bioturbation, convolute bedding, and a complex mineralogy.

The Spraberry Formation consists of two clay-rich lithofacies along the stratigraphic sequence. Fine-grained lithofacies such as dolostones and argillaceous siltstone show high percentages of water saturation, whereas low water saturation is associated with clean, very fine sandstones and siltstones richer in hydrocarbons.


A pore-scale experiment was performed to determine the rate of water vapor diffusion through a pore throat is enhanced by the presence of liquid trapped in the pore throat. The experiment demonstrated that enhanced vapor diffusion (EVD), first presented by Philip and de Vries (1957), exists on a pore scale and does not require a different gradient. A diffusion cell with two vapor reservoirs bridged by a single “pore throat” was used to test EVD. Using a brine-concentration-induced vapor pressure gradient, we demonstrate that the rate of water vapor transport through a liquid-filled pore throat is enhanced relative to the flux through a gas-filled pore throat. The enhancement is shown to be a quadratic function of liquid-island length. An ancillary experiment with two parallel pore throats showed that water vapor is transported simultaneously through both gas- and liquid-filled pores if both are available. The vapor flux through each pore in the dual-pore-throat diffusion cell is inversely proportional to the resistance of the gas- or liquid-filled pore throat. Lastly, an isotopic tracer test was performed to compare the rates of deuterium transfer through gas- or liquid-filled pore throats. The rate of deuterium transfer to the downgradient reservoir is faster in the presence of a liquid-filled pore throat despite the slower self-diffusion coefficient of deuterium through liquid than through gas.


Parameterization of flow and transport models is often complicated by the inability to make measurements at the desired scale of analysis. This disparity in scale necessitates the use of some averaging or upsampling model to compute the effective media properties from the measured data. Although numerous theoretical models have been proposed, physical data with which to test these upsampling models are sparse and high cost of obtaining high resolution upsampling data is limited in scope. Here we develop and employ a novel minipermameter test system, which we call the Multi-Support Permeameter (MSP), to physically investigate permeability upsampling. The MSP allows precise, rapid, non-destructive measurement of permeability over a range of different sample supports (i.e., sample volume and measurement). For different sample supports, subject to consistent boundary conditions and flow geometries, by simply varying the size of the minipermameter tip seal. Experiments progress by collecting thousands of measurements from each face of meter-scale blocks of rock with each of five different tip seals (0.15, 0.31, 0.63, 1.27, and 2.54 cm radius), plus a single large (7.62 cm) tip seal designed to integrate over the entire sampling domain. Upscaling is manifest in the acquired data by changes in key permeability statistics with increasing sample support.

Permeability upscaling experiments are conducted on four blocks of rock, each exhibiting differing physical attributes: (1) Berea Sandstone, a faintly laminated fluvial-deltaic sandstone, (2) Massillon Sandstone, a conspicuously cross-stratified sandstone from a high-energy fluvial or near-shore environment, (3) Topopah Spring Tuff, a dense, welded, devitrified tuff, and (4) Tiva Canyon Tuff, a poorly welded tuff. Over 150,000 permeability measurements have been collected from these four rock samples.

By comparing and contrasting results, we explore how traits distinguishing each rock sample influence the statistical and upsampling characteristics of the permeability. Results indicate that differences in the physical attributes of each rock sample give rise to measurable differences in the spatial permeability patterns, permeability distributions, and semivariograms. Results also yield insight into the effect of upsampling, for each rock sample and each statistic investigated. Specifically, as the sample support increases, the sample variance always decreases according to a power-law relation, the semivariogram range increases linearly, while small-scale (i.e., smaller than the minipermeameter tip seal) structural features are sequentially filtered from the permeability maps and semivariograms. Although each of the samples exhibits qualitatively similar upsampling trends, distinct differences are also evident. Differences between samples are manifest in the rate at which a given statistic upscales, the absolute change in the value of the statistic, and in the sense (i.e., increasing versus decreasing) of the mean upscaling. These differences are most evident between samples of differing genetic origin (e.g., sandstones versus tufts).

To aid in the interpretation of the permeability upsampling comparisons are made with a series of published theoretical models. The selected models differ according to the assumptions made about the nature of the permeability distribution, spatial structure, and uniformity/non-uniformity of the imposed flow field. Results suggest that the differences in the upsampling exhibited by the four rock samples...
can be explained on the basis of the spatial patterns distinguishing each, particularly the spatial correlation with the permeability fraction. We also find the permeability upsampling to be strongly influenced by the non-uniform flow conditions imposed by the mini-permeameter measurements. As such, these data clearly demonstrate that permeability upsampling is not an intrinsic property of a porous medium but rather depends on the characteristics of its measurement. In an effort to empirically quantitate the measurement characteristics of the MSP, spatial weighting functions are calculated from the multi-support permeability data via linear filter theory.


Rock-fluid interactions, or wettability, influence both the rate and amount of oil produced by the displacement of oil by water in a conventional waterflood. Although most reservoir minerals are intrinsically water-wet, their wetting properties can be altered by complex interactions among crude oil components, brine, and reservoir minerals. Most studies of crude oil/brine/rock (COBR) interactions have relied upon measurements that quantify the end result of exposure of high-energy surfaces to brine and oil including measurements of contact angles on smooth mineral surfaces and imbibition phenomena in porous media. Less work has focused on chemical analysis of minerals because of the difficulties posed by complex mixtures of organic compounds and small amounts of material. Reducing complexity by eliminating water or substituting model organic compounds for crude oils has failed to reproduce wettability conditions that represent those that result from COBR interactions.

Acidic and/or basic species in crude oils are expected to display the greatest tendency to interact with mineral surfaces and alter wetting. In this work, the use of an ATR-FTIR technique has been evaluated, as a potential tool, for quantifying the adsorption of species from polar functional substituents from the oil onto mineral surfaces. Six crude oils with varying chemical properties, including a wide range of acid and base numbers, were analyzed by ATR-FTIR using a ZnSe prism. Oil selection was guided by the results of earlier studies that used traditional methods to assess wettability-altering potential. Oil spectra by the ATR technique adequately reproduced those obtained with standard sample preparation methods, although absorbance levels were weaker. Spectra of all the oils were dominated by C–H stretching and bending of aliphatic groups with only minor differences between oils.

**ARSENIC GEOCHEMISTRY OF STREAM SEDIMENTS ASSOCIATED WITH GEO- THERMAL WATERS AT LA PRIMAVERA GEOTHERMAL FIELD, MEXICO,** by David Welch, 1999, MS thesis, Department of Earth and Environmental Science, New Mexico Institute of Mining and Technology, Socorro, NM 87801, 91 pp.

The purpose of this study is to determine factors controlling the mobility of arsenic under natural conditions and is part of a reconnaissance study on arsenic speciation of geothermally impacted stream waters. Stream sediments and algae were collected at 20 sample locations along the Rio Salado watershed and its tributaries at La Primavera geothermal field near Guadalajara, Mexico. Sediments were analyzed by several partial extractions to determine: (1) the amount of arsenic available to the environment and its partitioning into different size fractions, (2) the species of arsenic present in sediments, (3) the sedimentary phases that are associated with arsenic, and (4) the relationship between arsenic sediment chemistry and water chemistry. In addition, Rio Grande sediments, collected near Socorro, New Mexico, were analyzed for As, Mn, Fe, and percent total organic carbon (%TOC) for comparison with La Primavera sediments. In carrying out these objectives, a modified method of ion-exchange chromatography is used for speciation of As(III), As(V), monomethylarsonate (MMA), and dimethylarsinate (DMA) in sediment extracts.

Total arsenic in sediments available to the environment ranges between 3 and 16 ppm and is largely present as arsenic oxides and hydroxides of iron and manganese and organic carbon. Arsenic concentrations are positively correlated with manganese and %TOC and show no direct correlation with Fe; however, evidence suggests that iron oxides are also enriched in arsenic. The positive correlation between arsenic and %TOC suggests that plants and algae may represent a significant sink in some natural settings.

Sediment arsenic concentrations showed no correlation with surface water concentrations. Though sediment-water heterogeneity may account for this lack of correlation, evidence indicates that sediment arsenic concentrations are determined by the amount of organic matter, iron and manganese oxides and hydroxides present, not the concentration of arsenic in surface waters.

Comparison of sediment-water data from the Rio Grande to that of La Primavera showed arsenic to be more mobile in La Primavera waters with relatively less being retained in the sediments. This is most likely due to lower concentrations of iron, occurring as iron oxides and hydroxides in La Primavera sediments, but could also occur if the capacity of the sediments to take up arsenic has been exceeded.

**SOLUTE MIXING IN A FRACTURE JUNCTI- ON UNDER EQUAL AND UNEQUAL FLOW CONDITIONS,** by J Sidney Wise, 1999, MS thesis, Department of Earth and Environmental Science, New Mexico Institute of Mining and Technology, Socorro, NM 87801, 84 pp.

I conducted a series of experiments using a physical model of a fracture junction with simple geometry. The flow conditions in the experiments included equal flow, where the flow rates in all four fracture branches were identical; unequal flow, where the flow rates in the two inflow fractures were different but the flow rates in adjacent inflow and outflow branches were identical; and forced mixing (a type of unequal flow), where water from one of the inflow branches was forced to the junction and mixed with water from the other inflow branch. Forced mixing occurred because the flow rate in one inflow branch was greater than the flow rate in the adjacent outflow branch, resulting in overflow to the opposite outflow branch. The goal of the experiments was to determine how the mixing behavior of a solute would be affected by the Peclet number at the junction in each of these flow conditions.

In the case of equal flow, the present work verifies the findings of Li (1995), showing that partial mixing occurs at Peclet numbers between approximately 1 and 2. Complete mixing occurs below this range, and streamline routing occurs above this range. Photomicrographs of the equal flow case illustrate the three types of mixing behavior and show that upstream diffusion occurs at low Peclet numbers. In the case of unequal flow without forced mixing, where the water from each inflow branch exited through the adjacent outflow branch, the transition between mixing states occurs at a lower range of Peclet numbers than in equal-flow conditions, so that complete mixing was not observed at a Peclet number of 1. In the case of forced mixing, the transition occurs at even lower Peclet numbers, too low to be observed in the present work.

**WHOLE-ROCK OXYGEN ISOTOPE TRA- VERSES ACROSS GOLD-BEARING AND BARREN STRUCTURES, LONE TREE COMPLEX, NEVADA,** by Christopher M. Young, 1999, MS thesis, Department of Earth and Environmental Science, New Mexico Institute of Mining and Technology, Socorro, NM 87801, 104 pp.

The Lone Tree Complex includes the Lone Tree, North Peak, and Trenton Canyon deposits. These fine-grained gold deposits, hosted in Paleozoic sediments, are variations of Carlin-type deposits with one zone being structurally controlled. Both gold-bearing and barren structures have hydrothermal alteration centered along faults that is indicated by an increase in modal percent of alteration minerals towards the structure. The alteration mineral assemblage is dominated by quartz, fine-grained white phyllosilicates (sericite), oxidized sulfide (mainly pyrite), and locally, clays and chlorite.

Whole-rock oxygen isotope traverses across gold-bearing and barren structures record isotopic alteration resulting from deposition of alteration minerals and water-rock exchange. On a district-scale, oxygen isotopes are inconclusive at detecting ore zones. All gold-bearing traverses have depletions at the fault zone relative to background values, whereas barren traverses produced either an enrichment (North Peak) and a depletion (Lone Tree) at the fault zone. On a deposit-scale, correlation of oxygen...
isotope composition and ore zones can be made. Gold-bearing structures are associated with more oxygen isotope alteration (change relative to background values) than the barren structures. At Lone Tree, North Peak, and Trenton Canyon gold-bearing quartz was isotopically lighter than the barren quartz, respectively, by 8.8%, 4.1%, and 9.9%.

Calculated oxygen isotope composition and fluid inclusion data indicate multiple sources of fluid for deposits of the Lone Tree Complex. A regional, barren formation water is documented by temperature and salinity measurements in inclusions and calculated oxygen isotope compositions from the three deposit areas. This formation water ranges in both salinity and oxygen isotope composition respectively, from 0.0 to 18.0 eq. wt.% NaCl and from 8.5 to 13.1‰, and ranges in homogenization temperature from 170° to 310°C, with the upper range resulting from mixing with a higher temperature magmatic fluid at Lone Tree.

At Lone Tree, a magmatic source for gold-bearing fluid is suggested by the range in homogenization temperatures from 280° to 400°C and salinity from 12.0 to 39.0 eq. wt.% NaCl (Kamali, 1996). Calculated oxygen isotope composition of gold-bearing fluid (6.5%) supports this conclusion. Ranges in salinity and homogenization temperature for gold-bearing and barren sample suggest mixing between the gold-bearing and barren fluids. Trenton Canyon gold-bearing fluids had calculated δ18O of 0.0‰, indicating an evolved meteoric fluid. This meteoric fluid, ranging in homogenization temperature from 210° to 350°C and salinity from 2.6 to 5.7 eq. wt.% NaCl, can be approximated by mixing the Lone Tree magmatic fluid and a local meteoric water (from -6.0 to -9.0‰) established at Twin Creeks and Getchell deposits (Groff, 1996). Further mixing of this fluid with the barren formation water lowers salinity and homogenization temperatures from values expected by a true meteoric-magmatic mixing trend. Gold-bearing fluid at North Peak had calculated δ18O value of 8.5‰. Mixing between meteoric water and regional barren formation water produces the oxygen isotope composition, along with ranges in homogenization temperature (170°–270°C) and salinity (5.7–14.0 eq. wt.% NaCl). As with the Lone Tree and Trenton Canyon deposits, salinity and homogenization temperatures at North Peak from gold-bearing and barren samples indicate mixing between the barren and gold-bearing fluids.

New Mexico State University


The Cordilleran foreland basin formed in Aptian through Campanian time. Clastics deposited in the basin were sourced by erosion unroofing of the Sevier orogenic belt to the west. The Sevier orogenic belt includes folded synorogenic deposits that include the Indianola Group, of which the Reddick Canyon conglomerate is part. The Reddick Canyon conglomerate is composed dominantly of large cobble to boulder-size quartzite clasts.

The Reddick Canyon conglomerate is divided into three units, 1, 2, and 3, which are defined in the stratigraphic section studied. Unit 1 is interpreted to have been deposited in a fan-delta environment. Unit 2 developed on the proximal to upper mid-fan environment. Unit 3 contains deposits that are indicative of mid-fan to distal-fan environments.

Three major controls influenced deposition of the Reddick Canyon conglomerate. The first control was lithology of source bedrock. Widely exposed Precambrian and Cambrian quartzite strata provided large resistant clasts to the depositional site. These strata are presently exposed in the upper plate of the Canyon Range thrust currently located 40 km west of the Reddick Canyon conglomerate. The second control is the tectonic evolution of thrust belt. The clasts found in the Reddick Canyon conglomerate are very large, well rounded, and as much as 1 m in diameter suggesting that 40 km of transport is unlikely. Distance from the source, overall rounding of clasts, and clast size suggest repeated recycling of clasts from the thrust belt to the basin. It is therefore likely that other as yet unknown thrusts located between the Canyon Range and the Gunnison Plateau contributed to deposition of the Reddick Canyon conglomerate. The third control was the evolution of the foreland-basin system. Decreasing stratigraphic dips upsection in a single measured section in the northern part of the study area suggest that the Reddick Canyon conglomerate records foredeep disruption and subse-quent deposition in a wedge-top depocenter. Disruption had not yet begun in the southern part of the study area, because no significant change in stratigraphic dips is observed there. Thus, the southern part of the study area was located in the foredeep depocenter throughout deposition of Reddick Canyon conglomerate.


In the southern part of the Cordilleran foreland basin, a Middle Cretaceous alluvial plain was developed. Along the flanks of the southern High Plateaus and Kaiparowits Plateau of southern Utah, the Wahweap Formation consists of four informal members. The lower and middle members were deposited by north- and northeast-flowing meandering and anastomosing rivers that transported fluvial deposits and volcaniclastic sediments. The upper member was deposited by northeast-flowing alluvial fans that transported sedimentary lithic detritus from Paleozoic sedimentary rocks uplifted in the Sevier thrust belt in southern Nevada. The uppermost capping sandstone member was deposited by east- and southeast-flowing braided rivers that transported quartzose detritus derived from Paleozoic and Mesozoic sedimen-

tary rocks of the Sevier orogenic belt. Although not directly dated, the Wahweap Formation overlies the Santonian Straight Cliffs Formation and underlies the middle-late Campanian Kaiparowits Formation.

The lower, middle, and upper members were deposited in an actively subsiding foreland setting with abundant accommodation space. The capping sandstone member was deposited in wedge-top basins that were carried by eastward advancing thrust sheets of the Sevier thrust belt. Thickness trends of the Wahweap Formation and stratigraphically adjacent units indicate that the foreland basin was partitioned during or after Wahweap deposition. The capping sand- stone member thins in a down-dip direction from 150 m in the Henrieville Basin to 30 m in the Kaiparowits Basin. In the updip direction it is present locally as paleovalley deposits in the Paunsaugunt Basin beneath the Eocene Clarion Formation west of the Paunsaugunt fault and thicker quartzose units in the Markagunt Basin. I infer that the Paunsaugunt fault, most recently with Neogene normal offset, and other associated Neogene and Late Tertiary faults are invert- ed Campanian thrust faults. Uplift along thrust- tip anticlines resulted in the formation of wedge-top basins and concomitant erosion of and partitioning of the foreland basin.


This study has focused on the delineation of intramound sequence stratigraphy in order to understand vertical and lateral mound growth patterns. Because other phylloid algal mound complexes hold million to billion barrel fields within the mid continent and southwestern U.S. and the former U.S.S.R., it is important to under- stand how phylloid algal mound growth is affected by change in accommodation.

Fourteen lithofacies and 10 depositional se-quences were recognized and correlated within the Upper Pennsylvanian Lower Holder Formation phylloid algal bioherms of the Sacramento Mountains, New Mexico. These facies include mound core phylloid algal bioherms, mound flank skeletal wackestones and packstones, and off-mound conglomerate, sandstone, siltstone, shale, and algal-peloid-rich wackestone and packstone. Detailed sequence stratigraphic correlation of 10 depositional sequences within Yucca and Dry Canyons reveals that sequence thickness and vertical facies successions vary relative to biohermal buildups. Variation in facies patterns, both laterally and vertically, has been attributed to the variable growth of mound core boundstones in response to generation and destruction of short-term accommodation space. Vertical development of abnor- mal subaerial exposure surfaces developed on top of individual phylloid algal mounds indi- cates potential sea-level fluctuations of 54 m and possibly as high as 100 m. Furthermore, esti-mates of sequence durations for Late Pennsyl- vanian time suggest that these fluctuations occurred for a period of 400,000 yrs. Therefore, lower Holder bioherm complexes experienced changes in accommodation of at least 54 m that...
were glacioeustatically controlled and short term. Bioherm accretion varied as a function of both spatial (lateral) location relative to mound core buildups, and evolutionary (nucleation, acme, and mature phases) positions. Sequences accumulated during the nucleation stage of mound growth developed during late stages of falling sea level (LHST to VLHST) and display a “catch-down” character. These sequences developed during sea level rise (TST to EHST) and display a “keep-up” phase of deposition followed by a “catch-down” phase of deposition. Sequences developed during the acme evolutionary phase are characterized by (1) vertical aggradation of mound core boundstone, (2) abrupt vertical and lateral facies transitions ("Non-Waltherian”), and (3) significant syndepositional topography. Marine stage sequences grew atop significant bathymetric relief and are characterized by deposition of late highstand rise to early fall, “catch-down” sequences.

DEPOSITIONAL ENVIRONMENTS AND PROVENANCE OF THE CENOZOIC GILA CONGLOMERATE OF THE DURANCE AND CANADOR PEAK QUADRANGLES, SOUTHWESTERN NEW MEXICO, by Shane V. Smith, 1999, MS thesis, Department of Geological Sciences, New Mexico State University, Las Cruces, NM 88033, 103 pp. Lithofacies discriminant and provenance data are used to define the evolution of the Cenozoic Gila Conglomerate in the Basin and Range tectonic province of the Duncan and Canador Peak quadrangles, southwestern New Mexico. Crustal extension in this part of the Basin and Range resulted in fault-block mountains and complementary basins filled with up to 315 m of conglomerate, sandstone, siltstone, and mudstone of the Gila Conglomerate. The Gila Conglomerate is divided into upper and lower stratigraphic units that are separated by an angular unconformity. The lower unit consists of strongly consolidated conglomerate, sandstone, and mudstone, and the upper unit consists of unconsolidated to poorly consolidated siltstone, mudstone, and sandstone with uncommon conglomerate. Three mappable members were identified in these two units including the Wilson Mine and Nichols Canyon members of the lower Gila Conglomerate and the Pearson Mesa member of the upper Gila Conglomerate.

The Gila Conglomerate of the Duncan and Canador Peak quadrangles shows a two-stage evolution. The initial stage was the deposition of the late Oligocene(?) to early Miocene Wilson Mine and Nichols Canyon members, which consist of 240 m of sediment deposited in distal alluvial-fan, alluvial-flat, and lacustrine environments. Clast composition and paleodrainage directions indicate a provenance for both members to the southeast in the southern Big Burro Mountains. This initial stage was followed by uplift and tilting of the strata of these two members. The second stage was the deposition of the Pliocene to Pleistocene(?) Pearson Mesa member, which consists of 75 m of alluvial-flat and distal to mid alluvial-fan lithofacies, in a northwest-trending, northeast-tilted, internally drained half graben. Clast composition and paleocurrent directions indicate a provenance for this member to the north in the Rileyes Peak area. There is no evidence of an ancestral Gila River during the time of deposition of the Gila Conglomerate.

FIELD, PETROGRAPHIC, AND ISOTOPIC DISCRIMINATION OF SHALLOW, AUTHIGENIC CARBONATE OF THE PLIO–PLEISTOCENE PALOMAS BASIN OF SOUTHERN NEW MEXICO, by Leandro Trelitho, Jr., 1999, MS thesis, Department of Geological Sciences, New Mexico State University, Las Cruces, NM 88033, 78 pp. In the Plio–Pleistocene Palomas basin, half-graben of southern New Mexico, shallow authigenic carbonate is commonly found in both the footwall-derived and hanging wall-derived facies of the Palomas basin. Site investigation and sample collection on a basin-wide scale has resulted in the identification of nine types of shallow, authigenic carbonate that can be classified into four categories. Pedogenic or soil carbonate is found on the hanging wall- and footwall-derived alluvial fans. Carbonate that precipitates at or near the water table consists of nodular mudstones found in the hanging wall-derived alluvial fan and the axial fluvial system; nodules and tubes in eolian sand and gully bed cementation are common to the hanging wall- and footwall-derived alluvial fan. Carbonate precipitating at or near the land surface produces groundwater carbonate with capillary fringe restricted to the hanging wall- and footwall-derived alluvial fans; thick shallow ground-water carbonate and calcareous root mats are found only in the hanging wall-derived alluvial fan. Concretions, found only in the axial fluvial system, and sparry cement, found in all environments within the basin, develop below the water table.

Subtle but discernible changes in the vertical fabric, presence or absence of peds, root traces, and bounding surfaces help differentiate among different forms of carbonate. In the case of non-pedogenic carbonates, the base of the indurated carbonate bedding is sharply defined and parallel to the overall bedding, resulting in a laterally extensive sheet-like deposit. In contrast, pedogenic carbonate is bounded on a pedological horizon with gradational bases. Unless eroded before burial, pedogenic carbonate is overlain by an argillie B horizon characterized petrographically by clay coatings (argillans) around grains and/or peds.

Stable carbon isotopes further differentiate carbonate in footwall-derived alluvial fan strata and associated axial-fluvial fan strata from that in hanging wall-derived strata. This is likely the result of vegetation differences or the presence of Paleozoic carbonate rocks in the catchment and as clasts in the footwall-derived detritus. Stable oxygen isotopes help differentiate among different forms of carbonate on the footwall fan.

EVALUATION OF AQUIFER RECHARGE USING A MASS-BALANCE MODEL AND CONSERVATIVE TRACERS, SANDIA NATIONAL LABORATORIES/KIRTLAND AIR FORCE BASE, ALBUQUERQUE, NEW MEXICO, by Jerry K. Bird, 1998, MS thesis, Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, NM 87131, 115 pp. Recharge in arid and semi-arid climates is diffi-
cult to evaluate with traditional soil-physics and water-budget calculations that can provide estimates off by as much as an order of magnitude. The use of conservative tracers is an accepted method of evaluating mixing processes, residence time, recharge source, and recharge volume. This study uses the mass-balance model NETPATH and the conservative tracers Cl-, Br-, and H2 to investigate potential recharge at Sandia National Laboratories/Kirtland Air Force Base

University of New Mexico

The 1.65 Ga Manzanita pluton and its aureole record an interaction of Paleoproterozoic plutonism, deformation, and metamorphism in New Mexico. Field observations and microscop- ic analysis indicate that the pluton was emplaced during regional northwest-southeast shortening. Synchronous plutonism and contact metamorphism are indicated by an increase in temperature from regional metamorphic greenschist grade rocks to contact metamorphic amphibolite grade rocks. Peak contact metamor- phic temperatures and pressures of 600°–620°C and 2–3 kbar are shown by assemblages with Fe-rich andalusite + K-feldspar + biotite + quartz + white mica + oxides. Synchronous deformation and metamorphism are indicated by contact metamorphism–mineral-matrix relationships including the growth of garnet before, during, and after development of the regional S2 folia- tion, sillimanite that is both randomly oriented and aligned along S2, and hornblende that is dynamically recrystallized along S1. Synchronous plutonism and regional deformation are indicated by parallel magmatic and solid-state fabrics; dynamic recrystallization of feldspar indicating high-T solid-state deformation; vari- ably deformed dikes and veins that cross-cut and are also folded by regional foliation; and dike orientations consistent with a regional kinematic framework of northwest-southeast shortening.


Zircon, ZrSiO₄, has been proposed as a host for the forward dissolution rate for crystalline zircon at 90°C. Using the Arrhenius rela- tion for zircon dissolution, the forward rate of zircon dissolution at temper- atures in the range of 120°–250°C. The forward dissolution rates for zircon based on the Si release rates are: 4.1 × 10⁻¹² m² d⁻¹ at 250°C, 1.7 × 10⁻¹² m² d⁻¹ at 200°C, and 7.1 × 10⁻¹² m² d⁻¹ at 120°C. The Arhenius activation energy for the zircon dissolution reaction is 23 kJ/mol. The dissolution of amphibolous, hydrous “gel-zircon” was measured using a static test method. The forward dissolution rate for “gel-zircon” based on the U release profile is 8.5 × 10⁻¹⁰ m² d⁻¹ at 90°C. Using the Arhenius rela- tion, the forward dissolution rate for crys- talline zircon was extrapolated to 90°C from the data collected in this study. The forward disso- lution rate for crystalline zircon at 90°C, 4.6 × 10⁻¹⁰ m² d⁻¹, is two orders of magnitude lower than the forward rate for “gel-zircon.” Based on these data, it is suggested that zircon would make a chem- ically unrealistic contribution to the discharge and slope to incision. Five versions of the stream power law, with different m and n values and/or slight modifications to the gener- al law, are tested. This study presents one of the first rigorous tests of the stream power law with field-measured discharge and slope data. Stream power models generally reproduce field-measured incision rates within ±10–20%. No single version of the stream power law consistently outperforms other models, although tributary junction analysis suggests an m/n ratio of 0.4, similar to the ratio of 0.5 for a unit stream power (n=0.5, m=1) or shear stress (n=0.33, m=0.66) model. Stream power models calculated using map-measured data match known incision rates as well as field-parameterized stream power models. Thus, substituting drainage area for discharge, a common technique of the map-based metric approach, may be valid because drainage area may represent the cumulative effects of many discharge events over geologic time. Stream power models reproduce incision rates measured over hundred-thousand-year time scales better than incision records from shorter or longer time scales. Shorter-term records (10⁴–10⁵ yr) are sensitive to local vari- abilities such as migrating knickpoints, whereas drainage-basin characteristics likely have changed for longer-term (10⁸ yr) records.

Proterozoic multistage (~1.1 and 1.1 Ga during northeast-southwest extension on domino-style normal faults during Gneville northwest-directed contraction. The Neoproterozoic Chuar Group was deposited in a north-south rift basin, synchronous with movement on the Butte fault during east-west extension. Synclinal structures of the Chuar Group are documented by sedimentary patterns and sedimentary structures, including growth syncline and intraformational faults, within the Chuar Group. Neoproterozoic faults locally reactivate and cross-cut older Mesoproterozoic faults. Laramide monoclinal movements have northwest and north-northeast segments that cross-cut Unkar- and Chuar-age structures and are used to infer the drive extent of each extensional event. We suggest that 1.1 Ga northwest structures and 0.8 Ga north-south structures have persisted into the Phanerozoic as important regional grains that influenced subsequent tectonism.


The validity of modeling fluvial bedrock incision rates with the stream power law is evaluat- ed on five northern New Mexico streams: the Rio Pueblo de Taos, Rio Hondo, Red River, Comanche Creek, and Jemez River. Fluvial ter- races within these basins provide an excellent spatial and temporal record of fluvial bedrock incision. The stream power law follows the gen- eral form Q = kA, where Q is the incision rate, k is a constant that incorporates bedrock erodibility, A is drainage area (a proxy for discharge), S is channel gradient, and m and n are exponents that scale the relative importance of discharge and slope to incision. Five versions of the stream power law, with different m and n values and/or slight modifications to the gener- al law, are tested. This study represents one of the first rigorous tests of the stream power law with field-measured discharge and slope data. Stream power models generally reproduce field-measured incision rates within ±10–20%. No single version of the stream power law consistently outperforms other models, although tributary junction analysis suggests an m/n ratio of 0.4, similar to the ratio of 0.5 for a unit stream power (n=0.5, m=1) or shear stress (n=0.33, m=0.66) model. Stream power models calculated using map-measured data match known incision rates as well as field-parameterized stream power models. Thus, substituting drainage area for discharge, a common technique of the map-based metric approach, may be valid because drainage area may represent the cumulative effects of many discharge events over geologic time. Stream power models reproduce incision rates measured over hundred-thousand-year time scales better than incision records from shorter or longer time scales. Shorter-term records (10⁴–10⁵ yr) are sensitive to local vari- abilities such as migrating knickpoints, whereas drainage-basin characteristics likely have changed for longer-term (10⁸ yr) records.

Channel widths, valley-bottom widths, and controls on channel gradient and discharge gen- eration are examined in the context of the para- meters of the stream power law. Channel widths vary nearly as a function of the square root of
discharge. This relationship is similar to the relationship known for purely alluvial streams and those used in bedrock stream power models. Discharge-area relationships show that local geologic controls on discharge can cause significant differences in discharge production between adjacent basins. A comparison of New Mexico gage data with Washington State gage data shows that local geologic controls on discharge generation are more significant in semi-arid New Mexico.

A discharge threshold that controls the effect of rock type on channel gradients is quantified. Above this threshold sufficient discharge is generated to maintain incision in the face of base-level fall, regardless of rock type. The discharge of threshold sediment eroded from different formations is difficult in calibrating the proportionality constant, which likely varies spatially in response to rock-type changes and temporally in response to changes in discharge generation.

A combination of field and laboratory geomorphic, sedimentologic, and sedimentary petrographic methods are employed to document the sources of basin-fill sediment, the character and relative amount of sediment produced on local hillslopes through time, the hillslope weathering and transport processes occurring through time, and the role that rock type has played in influencing the evolution of basins. Results of these studies indicate rock type is the dominant control on sediment yield and landscape development in tectonically inactive, dry landscapes. Hillslope processes and products in the study area have been consistent through time, but process rates have varied greatly, indicating that orbital-scale climate cyclicity can be, but is not always, well expressed in the stratigraphy of continental basins.


Rare exposures of buried hillslopes and colluvium are found in the upper Miocene and Pliocene basin-fill records of two extensional basins in southeastern Nevada. Study of the stratigraphy, sedimentology, and petrology of these hillslopes through time and evolution. Results of these studies indicate rock type is the dominant control on sediment yield and landscape development in tectonically inactive, dry landscapes. Hillslope processes and products in the study area have been consistent through time, but process rates have varied greatly, indicating that orbital-scale climate cyclicity can be, but is not always, well expressed in the stratigraphy of continental basins.

A combination of field and laboratory geomorphic, sedimentologic, and sedimentary petrographic methods are employed to document the sources of basin-fill sediment, the character and relative amount of sediment produced on local hillslopes through time, the hillslope weathering and transport processes occurring through time, and the role that rock type has played in influencing the evolution of basins. Results of these studies indicate rock type is the dominant control on sediment yield and landscape development in tectonically inactive, dry landscapes. Hillslope processes and products in the study area have been consistent through time, but process rates have varied greatly, indicating that orbital-scale climate cyclicity can be, but is not always, well expressed in the stratigraphy of continental basins.


The Middle Cambrian Marjum Formation (~400 m thick) in the House Range of western Utah is composed of deep-water carbonates, which were deposited in the axis of the House Range embayment. Within the Marjum Formation, there are three scales of cyclicity recognized, including (1) limestone-marl rhythms (~5 cm thick), (2) rhythm-mound cycles (~3–30 m thick), and (3) large-scale sequences (145–190 m thick).

Rhythmites are composed of thin rhythmically interbedded, laterally continuous, limestone and marl layers. Limestone layers are composed of dark, laminated pelletal lime mudstone (~3 cm thick), and marl layers (~2 cm thick) are composed of laminated, argillaceous, dolomized, pelletal lime mudstone; both lithologies contain rare agnostid trilobites and sponge spicules. Fine-grained carbonate and siliciclastic material in rhythmites is detrital in origin and was deposited in quiet, dyserobic waters, below storm-wave base. Alternations of limestone and marl layers are interpreted as the result of millennial-scale paleoclimatic fluctuations, which influenced changes in fluvial/olian influx and/or changes in the location or intensity of storms.

Rhythmite-mound cycles (3–30 m thick) are composed of limestone-marl rhythms overlain by stromatolite-bearing carbonate mud mounds (0.5–1.5 m thick at crest). Mud mounds are composed of bioturbated peloidal lime mud and are composed of dark, laminated mudstone with sparse trilobite wacke and some detrital carbonate lenses and abundant spar-filled stromatolite-like structures. Mud mounds were precipitated in situ in deeper waters with some contribution from detrital carbonate and terrigenous sediment. Lime mud and pelletoids precipitated from highly alkaline waters produced by bacterial decay of siliceous sponges and microbial mats. The mud mounds are interpreted to have developed during a 10^10–10^13 year sea-level rise when the carbonate “factory” retrograded and the supply of fine, detrital carbonate material to the basinal regions decreased. During sea-level fall/lowstand, an increase in detrital carbonate influx due to carbonate factory precipitation resulted in deposition of limestone-marl rhythms.

Three large-scale siliciclastic-carbonate sequences (145–190 m thick) are recognized in the Wheeler Shale and Marjum Formations and are composed of shale and marl-dominated rhythmites facies grading into carbonate-dominated intervals. These sequences correlate to time-equivalent shallow-water carbonates that exhibit similar scale sequences interpreted to have formed in response to 3rd-order (1-3 m.y.)
Dextral Transcurrent Deformation of the Eastern Margin of the Colorado Plateau (USA) and the Mechanics of Football Uplift Along the Simplon Normal Fault (Switzerland/Italy), by Timothy W. Waarsvandege, 1999, PhD dissertation, Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, NM 87131.

Two independent studies employ kinematic analysis of minor-fault populations to address large-scale tectonic problems. The first addresses the nature of transcurrent deformation along the eastern margin of the Colorado Plateau. The work is based on a combined fault kinematic and paleomagnetic investigation of rocks affected by faulting during the Laramide orogeny and younger Rio Grande rifting. The second evaluates the mechanics of football uplift along the Simplon low-angle normal fault in the Alps, by combining a fault kinematic study with fluid inclusion analysis of kinematically referenced fluid inclusion arrays.

Chapters 2 and 3 address the nature of transcurrent deformation and the transition from ductile to brittle deformation during the exhumation of mid-crustal rocks in part influenced by the composition of syn-kinematic fluids. Structural and fluid-inclusion analysis indicates that the eastern margin of the plateau has experienced an elongated history of dextral transpression followed by dextral transtension. Chapters 2 and 3 address the nature of extension along the Simplon low-angle normal fault (southern Switzerland and northern Italy). Structural and fluid-inclusion analysis indicates that the eastern margin of the plateau has experienced an elongated history of dextral transpression followed by dextral transtension.


Post-Laramide rock uplift in the western United States has been the subject of a long-standing debate, fueled in part by deep fluvial incision into the world’s second largest carbonate platform. Studies of late Cenozoic landscape evolution in the Rocky Mountains have focused on deeply incised fluvial systems, which have been touted as critical evidence for post-Laramide epeirogeny. Debate persists about whether this plateau achieved its current elevation during the Laramide orogeny or more recently in the late Cenozoic. The models can not resolve the implications for the mechanisms that uplift rocks after compression and crustal thickening has ceased. Efforts to elucidate a rock uplift signal from fluvial systems are complicated by numerous non-tectonic mechanisms, such as climate change, that also drive river incision and have typically contributed little to our understanding of post-Laramide rock-uplift processes.

This study presents new incision data from a well-constrained reach of a Rocky Mountain front—Great Plains river that is uniquely situated to isolate the effects of post-Laramide rock uplift. The Canadian River of northeastern New Mexico is one of many Great Plains rivers draining the eastern slope of the Rocky Mountain front. This river has carved a deep (300 m), narrow canyon through Mesozoic strata at a location where its profile is broadly convex and crosses the Jemez lineament, a well-known, northeast-trending line of late Cenozoic volcanism. The numerically dated (14C and 40Ar/39Ar) fluvial terrace and volcanic stratigraphy in this canyon reach constrain rates of fluvial bedrock incision. Incision is maximized in the canyon reach where it has been relatively steady at ~0.06 mm/yr (60 m/m.y.) over the past 4.5 Ma. Canyon reach terraces are correlated to produce paleo-long profiles that are increasingly convex with profile age and converge to the modern channel profile both upstream and downstream of the canyon reach. Similar terrace profiles are commonly seen for well-studied streams in the adjacent Rio Grande rift where rates of incision can be greater by a factor of three. These observations of the Jemez lineament are best explained by invoking a slow but steady rate of rock uplift during the late Cenozoic beneath the Canadian River along a northeast-trending axis coincident with the Jemez lineament. Recently acquired geophysical data, including upper mantle velocity structure, suggest that hot asthenospheric mantle is rising diapirically beneath the southern Rockies and is subsequently funneled along compositional and structural heterogeneities at the base of the lithosphere. The Jemez lineament has long been recognized as one of these heterogeneities, and the Canadian River likely indicates rates of rock uplift for the mantle processes acting at its base. If rates of incision and rock uplift for the Canadian River are representative for the southern Rockies in general, then they place constraints on the timing and degree of high-standing topography for the western Cordillera.

MULTIPHASE THERMAL MODELING IN VOLCANIC AND CONTACT METAMORPHIC TERRAIN, by Gordon N. Keating, 2000, PhD dissertation, Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, NM 87131.

This dissertation presents the results of unique numerical models of heat transfer in systems in unsaturated pyroclastic systems. A simple one-dimensional, radial conductive finite-difference heat-flow model is demonstrated to be an adequate tool for investigating possible thermal conditions in a limited contact metamorphic aureole that developed around a large mafic intrusion in the Canadian Shield. The model is applied to the metavolcanic aureole at Grants Ridge, New Mexico. A modified version of the Los Alamos National Laboratory code, FEHM, is presented that has the unique capability of simulating multiphase (melt + H2O) flow under the high-temperature conditions near intrusive

The modified equations of state (EOS) for water and air are valid in the ranges 10^6 < T < 10^8 K, 0.001 < P < 1000 MPa, 10^2 < T < 10^10 K, 0.00123 < P < 22 MPa, respectively.

Two applications of the FEHM code are presented. A two-dimensional model of multiphase flow near a magmatic intrusion was constructed to characterize the cooling history of part of a late-Miocene mafic intrusive complex at Pauite Ridge, Nevada, USA. The results of the model were compared with age data to estimate that the rate of change of the transitional part of the geomagnetic field during a reversal was 0.06–0.13 degrees/year.

Multiphase cooling processes in cooling ash-flow tuffs (ignimbrites) were investigated using a set of FEHM models. The results of these models identify important factors in the cooling history, including the presence of a saturated zone in the shallow subaerial geometry, the substrate-ignimbrite interface (e.g., buried valleys), and young zonation and funnel structures within the ignimbrite. In addition, the models show that conditions under which any give rise to the development of secondary explosions in ignimbrites. Finally, the model results indicate that superheated vapor from the boiling zone at the base of the ignimbrite, flowing upward through the core, may provide the necessary water mass in the upper zones of the ignimbrite to account for reported oxygen exchange in the Bishop and Chegoghi Tuff, rather than requiring high meteoric infiltration on the surface of the ignimbrite, as previously proposed.

Geographic Names

Cañada del Agua—arroyo, 0.8 km (0.5 mi) long, heads 3.5 km (2.2 mi) southwest of Rainville at 35°58′S, 105°44′W, trends southwest 1.6 km (1 mi) before joining Cañon del Agua, 1.6 km (1 mi) north-northwest of the community of La Cueva; Spanish name meaning “little valley of water”; Mora County, NM; T20N R16E, NMPM; 35°57′21″N, 105°15′16″W; USGS map, Mora 1:24,000 (mound of feature).

Montoya Pasture—flat, 4.8 km (3 mi) by 4 km (2.5 mi) elevation 2,057 m (6749 ft), in Gila National Forest/Gila Wilderness, located southeast of the confluence of Diamond Creek and the East Fork Gila River, 8 km (5 mi) east of the Gila Cliffs Dwellings National Monument; named for Donaciano Montoya, who homesteaded and ranched in the area in the early 20th century; Catron County, NM; T12S R13W, NMPM; 33°14′30″N, 108°09′05″W; USGS map, Gila Hot Springs 1:24,000 (central point); not Montoya Ranch.

Perra Peak—summit, 3,586 m (11,765 ft), in Carson National Forest, 1.6 km (1 mi) south-southwest of Lobo Peak, 2.3 km (1.4 mi) north of Gallina Peak, 4.5 km (2.8 mi) east-northeast of Kiowa Village; Spanish name meaning “female dog”; Taos County, NM; sec. 4 T27N R13E, NMPM; 36°35′54″N, 105°33′03″W; USGS map, Arroyo Seco 1:24,000.

Puerto del Venado Alazán—gap, 0.8 km (0.5 mi) west of State Route 21, 2.5 km (1.6 mi) west of Rainville, 4.2 km (2.6 mi) northeast of La Cueva; Spanish name meaning “port of the red elk”; Mora County, NM; T20N R16E, NMPM; 35°58′43″N, 105°14′14″W; USGS map, Rainville 1:24,000.