New Mexico Institute of Mining and Technology


The 20th century shrub invasion of semiarid grasslands in New Mexico is one example of the transition of a semiarid herbaceous to woody plant ecosystem. A key factor controlling plant productivity and reproduction in semiarid environments is water availability in the soil. We characterize the hydrologic changes resulting from the shrub invasion, specifically the hydrologic advantage that shrubs hold over grasses, to pinpoint the primary factor(s) that contribute to the invasion. Observations are based on measurements of near surface soil moisture and soil-water potential availability in the soil. We focus on the differences between the grass and shrub environments. Our previous research has shown that in both environments, maximum spatial soil moisture variations exist at the plant-to-interspace scale, on the order of meters. Therefore, we now focus on individual plant canopy and interspace patches. We hypothesize that the critical hydrologic difference(s) contributing to the shrub invasion exist at this scale.

During the 2001 summer monsoon season, we used the TDR (time domain reflectometry) method to measure soil water potential in both environments. TDR probe arrays are installed laterally covering the surface of eight plant canopies in total and their adjacent interspaces, using 128 probes. One array in each environment contains TDR probes inserted both at the surface and at depths. In addition, soil matric potential is measured adjacent to selected TDR probes. Soil-water potential is measured using a total of 64 heat dissipation sensors. The measurements are designed to observe spatial, temporal, and axial variation in soil moisture. In both environments, TDR probe arrays are installed laterally covering the surface of eight plant canopies in total and their adjacent interspaces, using 128 probes. One array in each environment contains TDR probes inserted both at the surface and at depths. In addition, soil matric potential is measured adjacent to selected TDR probes. Soil-water potential is measured using a total of 64 heat dissipation sensors. The measurements are designed to observe spatial, temporal, and axial variation in soil moisture.


Recent geologic mapping in the northern Albuquerque Basin near Albuquerque, Rio Rancho, Zia Pueblo, and San Felipe Pueblo, New Mexico, suggests that facies of the upper Santa Fe Group are locally differentiable. Integration of these maps with paleocurrent data and studies of sand and gravel petrography supports the differentiation of these facies. Previous petrographic studies of these deposits are focused on sand petrography. However, this study shows that gravel petrography is key to differentiating the facies of the upper Santa Fe Group.

Stratigraphic sections were measured in Pliocene and early Pleistocene deposits, and sand and gravel samples were collected at different locations in the northern Albuquerque Basin in order to understand the lithologic character of the Arroyo Ojito and Sierra Ladrones Formations. Deposits of the Arroyo Ojito Formation constitute the fluvial facies of the ancestral Rio Jemez/Guadalupe, Rio Puerco, and Rio San Jose that drained sedimentary, crystalline, and volcanic rocks exposed along the western and northwestern margins of the basin. Deposits of the Sierra Ladrones Formation are divided into axial fluvial (ancestral Rio Grande) deposits and piedmont deposits derived from basin margin uplifts. The ancestral Rio Grande drainages are dominated by crystalline and volcanic rocks. Piedmont streams drained crystalline and sedimentary rocks.

Arroyo Ojito Formation gravel samples are typically moderately to poorly sorted, occur in horizontally stratified, laterally discontinuous beds and are primarily composed of volcanic tuff and fine-grained red granite with subordinate Pedernal chert, sandstone, and basalt. Ancestral Rio Grande gravels are generally moderately to well sorted, occur in thin, planar to cross-stratified beds, and are composed of rounded to well-rounded matrix-supported and contorted clasts. Granite and sedimentary clasts are relatively sparse. Piedmont gravels contain abundant sedimentary clasts, especially limestone, and coarse-grained, pink porphyritic granite deposited in horizontally stratified, clast- and matrix-supported beds.

Sand and gravel samples of all lithofacies ranges from subarkose and arkose to feldspathic litharenite. Arroyo Ojito Formation sands are subarkose to lithic arkose and occur in planar stratified to low-angle cross-stratified beds. Arroyo Ojito Formation sands contain more chert and granite clasts than the ancestral Rio Grande deposits. Ancestral Rio Grande sands were deposited in planar stratified to trough cross-stratified beds and contain abundant volcanic grains. Volcanic grains are rare to nonexistent in piedmont sands in the study area. Piedmont sands were deposited in planar stratified to low-angle and trough cross-stratified beds. Paleocurrents for the ancestral Rio Grande deposits are dominantly to the south. Paleoflow in the Arroyo Ojito Formation was south-southwest to southwest and piedmont paleoflow was generally to the west.

The results of this study show that the three lithofacies assemblages in the northern Albuquerque Basin can be confidently differentiated by integrating studies of stratigraphy, gravel and sand petrography, and paleocurrents.


The Victorio mining district, southwestern New Mexico, hosts different types of mineral deposits that are spatially related (from the central zone to outer zone): porphyry molybdenum, W-Be-Mo skarn/vein, and carbonate-hosted Pb-Zn replacement deposits. Through geochronology, fluid inclusion microthermometry and gas analysis, and stable isotope analysis a genetic model was developed showing the genetic relationships between the three types of mineral deposits.

The fluid inclusions from the porphyry deposit have a homogenization temperature range of 208°–315°C and salinities between 2.0 and 11.9 eq. wt% NaCl. The fluid inclusions from the skarn deposits have a range of homogenization temperatures from 180° to 350°C and have salinities 2–22.5 eq. wt% NaCl. The carbonate-hosted replacement deposits are slightly lower in temperature and salinity than the skarn and porphyry deposits. The homogenization temperatures of 105–289°C and salinities <2–5 eq. wt% NaCl. The fluid inclusion and stable isotope analyses indicate an alteration continuum between the porphyry molybdenum, skarn, and carbonate-hosted replacement deposits. The sulfur and oxygen isotope data from sulfide and silicate samples and fluid inclusion gas analyses point to a probable magmatic source for the skarn and porphyry mineralization. The sulfide ore data from the carbonate-hosted replacement deposits also suggest a magmatic component. The carbon and oxygen values from carbonate and silicate samples for the carbonate-hosted replacement deposits indicate a moderate to high degree of interaction between the mineralizing fluid and the host rock.

The mechanisms responsible for the shift in mineralization style between high-temperature porphyry and skarn deposits and low-temperature carbonate-hosted replacement deposits are most likely boiling and mixing of meteoric and magmatic waters. There is evidence for boiling and fluid mixing in all three mineral deposits, which caused a decrease in temperature and salinity, an increase in pH, and an increase in oxidation state of the mineralizing fluids.
The geochronological results for the Victorio Granite and the skarn alteration minerals indicate that all three mineral deposits formed from one magmatic source at about 34.9 Ma. However, there is no direct evidence that the mineralization of the three deposits was one continuous event. It is more likely that mineralization took place over an extended period of time with episodic events of brecciation, boiling, fluid mixing, and mineral precipitation as a result of the intrusion of the Victorio Granite.


To improve our ability to measure and predict quantities such as moisture content and soil-water conductivity in the unsaturated or vadose zone, an infiltration experiment was monitored with a dense array of geophysical and hydrological instrumentation. The geology of the site, as described from four continuous core samples, is fairly continuous layers of unconsolidated alluvial deposits, consisting primarily of fine sands but also containing a significant cobbly clay layer at 4–6-m depth. The infiltrometer consisted of a finely controlled irrigation system, which delivered local tap water to the surface at a flux of 2.7 cm d−1 over a 3-m by 3-m area. After approximately 1,100 days of regular infiltration events, a 6.9 g L−1 concentration of NaCl was added to the water, increasing the irrigation water conductivity from 80 mS m−1 to 1,300 mS m−1.

The focus of this thesis was subsurface soil conductivity measurements, collected weekly during the infiltration of the salt pulse with an EM39 probe (Geonics LTD., Mississauga, ON, Canada). Data was collected in a 16-m by 16-m area surrounding the infiltrometer, in 13 boreholes reaching an average depth of 12 m. 3D images created from these measurements showed structures of salt distribution related to the stratigraphy of the field site and to the shape of the wetty spot created under the infiltrometer. To quantify how well the EM39 was capturing the extent of the salt plume, a mass balance approach was used to compare a calculated soil-water salt mass to the known mass of salt infiltrated at the surface. Following models designed primarily for agricultural soils, the measured bulk soil conductivity (ECw) was converted to soil-water conductivity (ECw) using estimates of the volumetric water content (θw) from monthly neutron probe measurements, and the percent clay of the soil as determined by lab analysis of the continuous core samples. The result of these calculations was a close fit (r2 = 0.98) between the calculated mass of salt in the soil-water and the known mass of salt infiltrated at the surface.

The low water content (<<15% by volume) and low bulk soil conductivity (<100 mS m−1) measured at the test site present more resistive conditions than previous studies of this type and were a cause for uncertainty in the calculated ECw results. Sensitivity analysis results show that due to the low measured water content at the site, the calculated ECw is strongly dependent on the chosen limit between immobile and mobile water content, or threshold water content, but determination of the value was possible through lab analysis of soils from the site. Errors in the calculated soil conductivity profile from ECw measure the overall ECw, such as during the initial stages of the salt pulse infiltration and during a tap water flush following the end of the salt pulse. Calculations were shown to be less sensitive to soil temperature and percent clay estimates. The results of this study indicate that downscaling methods show much promise for characterizing water and solute distribution in the vadose zone.


Soil salinity is a common problem in arid riparian areas of the arid Southwest, but the dynamics of soil salinity in these areas are not well understood. The main causes of soil salinity in non-flooded riparian areas are generally known as low precipitation, high evapotranspiration, and capillary flux from saline shallow ground water. However, some riparian areas maintain relatively low soil salinity for a long period of time with thriving salt-sensitive vegetation such as cottonwoods, whereas other areas are completely salinized and covered by salt-tolerant vegetation such as salt cedars. This difference in soil salinity caused by a small amount of deep infiltration sufficient to leach salts back to the ground water or by ground water dynamics that “wash” the soil profile from below? The results of this study, using the modeling program HYDRUS-1D, indicate that soil salinity is a complex process affected by a number of factors such as soil profile texture, ground water table depth and its fluctuation, ground water quality, and time period of simulation. First, a validation of the HYDRUS-1D model demonstrated that predicted apparent soil electrical conductivities of six representative soil profiles show a good correlation with the apparent soil electrical conductivities measured in the field with the Geonics EM38 ground conductivity meter. A sensitivity analysis was conducted to analyze which factors determine soil salinity under the riparian conditions of my study area. Soil texture— which determines capillary rise—is the most important predictor variable for long-term soil salinity; generally finer soil texture leads to more saline soils in this environment because of higher capillary rise. The effect of deep infiltration on soil salinity was examined. Differences in soil salinity levels among different riparian areas are not caused by a small amount of deep infiltration but by ground water fluctuations that “wash” the soil profile from below. Although evapotranspiration affects the rate of soil salinization over time, the basic processes of soil salinity have not been changed.


Evidence of the most recent highstand cycle of Lake Lahontan and associated paleolakes persists throughout the western Great Basin and has been studied intensively for over 100 years. In contrast, little is known about the longer-term history of the basin. Many workers agree that lake filling events were somehow related to glacial periods, when amounts of precipitation and stream runoff into lakes were higher. Two competing hypotheses have been put forth to explain the response of the western Great Basin to the forcing of Pleistocene climate changes. One is that there were large basin-filling events during oxygen isotope stages (OIS) 16, 6, and 2 with a long period of aridity after OIS 16. The second is that the basin responded in a predictable manner to global glacial filling during these glacially as well as the other glacial periods in the sequence. This study tests these hypotheses by dating paleoshorelines in the western Great Basin.

Dating ancient shorelines in the western Great Basin allows for a better understanding of both the timing and the magnitudes of lake-filling events. Geomorphic and soil properties suggest that the ages of several shorelines above the latest Pleistocene level increase as a function of elevation. Shoreline deposits at three sites in western Nevada were sampled for cosmogenic nuclides (10Be) dating to global lake filling during these glacially as well as the other glacial periods in the sequence. These results suggest that Lake Lahontan filled to nearly the same level during OIS 2 and 4; the results also suggest large filling events occurred during OIS 6, 8, and possibly 12 or 16. From these results, we can conclude that the Lahontan Basin filled more frequently and to higher levels than previously thought and that preserved shorelines show an apparent decrease in maximum lake levels with time.


Gas permeameters are widely used in the fields of hydrology, soil science, and petroleum engineering to characterize the spatial heterogeneity of hydraulic properties, in particular permeability. The spatial distribution of permeability governs fluid flow and transport, affecting such processes as contaminant migration, groundwater recharge, and petroleum recovery. Laboratory scale and field-portable permeameters, based on steady or transient gas flow, are used to map the distribution of permeability. Most permeameters are optimized for use on a particular type of material (lithified rock or unconsolidated sediments) with a certain permeability range. A good field permeometer must be highly portable and allow for rapid measurement of permeability across a wide range of materials. Many outcrop studies have been performed on high-permeability, poorly consolidated sand bodies dissected by nearly vertical zones of lower permeability material (small-displacement faults or clastic dikes). The lightweight syringe-based air-minipermeameter (LSAMP) designed by Davis et al. (1994) and modified LSAMP II (Suboor and Wilson, pers. comm.) were the primary permeameters used in many
of these studies. Difficulty was encountered when attempting measurements on low-permeability rocks with these devices; the measurement duration was too long.

Three studies were performed to better understand and improve permeability estimation with gas permeameters, with particular focus on increasing the amount of data that can be collected in the field (making measurements faster) with the use of a new field-portable transient pressure decay permeameter to allow for rapid estimation of permeability across a wide range of materials. Over 1,000 permeability measurements were collected to inform the operational characteristics of the LSAMP and LSAMP II as they apply to measurement repeatability (measurement variance at a point). The major operational differences are: (1) the LSAMP uses a hand-held tip seal, whereas the LSAMP II has a pistol grip-mounted tip seal with a gage to monitor application force, and (2) the LSAMP's tip seal must be removed to measure pressures in a tank with a syringe, whereas the LSAMP II has a 3-way solenoid valve and air pump that automatically removes the tip seal, eliminating the need to remove the tip seal between measurements. Results suggest removing the tip seal when making multiple measurements at a point produces a significantly higher variance than not removing it, whereas the amount variability attributed to applying the tip seal by hand or with the pistol grip-mounted tip seal (monitoring application force) is relatively the same. Instrument error was also quantified and found to account for less than 2% of the total measurement variability for all materials tested, but results indicate it could be an issue at the high end of the instrument’s measurement range.

Two modifications were tested to decrease the required measurement duration of the LSAMP II: (1) changing tip seal inner radius and geometric factor and (2) increasing the gas injection pressure by adding weight. Thirty measurements were made at relatively the same location on an aluminum oxide sharpening block using three different tip seal geometries (inner radii and/or geometric factor). Measurements were made on different lengths of POREX® porous plastic standards with no weight, 1 lb, and 2.5 lbs added weight. Increasing the tip seal radius (geometric factor) for a given tip seal inner radius did not prove to have a significant effect on measurement duration. Increasing the tip seal inner radius, for a given geometric factor, significantly decreases the measurement duration, though application of this modification is limited due to practical considerations. The addition of weight proved to significantly decrease measurement duration: 5 times faster than the un-weighted duration for 1 lb, and 10 times faster than the un-weighted duration for 2.5 lb. Reduction of the measurement duration by a factor of 10 (for 2.5 lb added weight) effectively adds an order of magnitude permeability to the low end of the measurement range.

A mathematical model was developed and a prototype device was built to test the range and corresponding measurement duration of a transient pressure decay permeameter. Experiments were performed on multiple sample materials, at a range of initial tank pressures, using two different volume tanks (with and without a heat capacitor in the tank). Results suggest use of a heat capacitor in the tank is essential to dampen thermodynamic effects resulting from rapidly decaying pressure at the onset of a measurement. Derivative plots and steady-flow measurements indicate the presence of nonlinear effects, occurring at the transition to turbulent flow, in high-permeability materials at higher pressure. For data in which thermodynamic and nonlinear effects were unnoticeable, pressure decay permeability estimates agree fairly well with steady-flow measurements, but are consistently higher. Though gases tested in the laboratory, the pressure decay permeameter could significantly improve data collection in the field, allowing for rapid ($\Delta$permeability $< 26$s$^{-1}$) permeability measurement across at least four orders of magnitude permeability (from $1 \times 10^{-12}$ to $3 \times 10^{-15}$m$^2$) using a single permeameter.

### CONTROLS ON THE ACCUMULATION OF HYDROCARBONS IN THE LOWER BRUSHY CANYON FORMATION, SOUTHEASTERN NEW MEXICO


The Lower Brushy Canyon Formation (LBC) of southeastern New Mexico consists of fine-grained clastic material deposited by turbidity currents during sea level lowstands in the Delaware Basin. Hydrocarbon production from the LBC is often unpredictable and well logs offer little assurance of pay.

Detailed descriptions of several cores taken from the LBC show a very fine-grained siltstone, which is dominated by finely interbedded organic shaley turbidities. The producing intervals are generally thicker, cleaner siltstones. Non-producing siltstones are generally darker in color indicating a high clay content. Further petrographic analysis of both producing and non-producing sandstones confirm observations from the field. The non-producing siltstones are enriched in clay and calcite cement. These components fill pore space and increase pore entry pressures, thereby reducing the ability of the rock to transmit hydrocarbons. The producing siltstones are generally clean with very low amounts of clay or calcite cement. Porosity in these productive rocks is very high, and pores are interconnected. Further research shows that it is possible to calculate the amount of clay in a siltstone from the LBC based on its gamma ray curve. Clay content of sandstones can then be quantitatively mapped at the reservoir level and at the basinal level. This technique will help identify unproduced reservoirs as well as better explain current reservoirs and traps.

### RADAR DETECTION OF BURIED LANDMINES IN FIELD SOILS


The contrast in the dielectric constant between a landmine and the surrounding soil is one of the most important parameters to be considered when using ground penetrating radar (GPR) for landmine detection. For most geologic materials, the dielectric constant (relative permittivity) lies within a range of 3–30, with dry sand at the lower end of this range at about 3–5. Nonmetal-

Information about Quaternary paleoclimatology has been dominated by marine and ice core records, but these data do not provide direct information on mid-latitude continental paleoclimate. However, one source of continental records is sediments deposited in closed-basin lakes. Data δ 13C and δ 18O measured in calcite from closed-basin lake sediments suggest a relationship, or covariance between these isotopes. As the δ 18O decreases so does the δ 13C during the hydrologically closed periods of the lake's history. Covariation of δ 13C and δ 18O has been considered diagnostic of closed-basin lacustrine sediments, but the mechanism of this covariation remains controversial. The main factors that affect δ 18O in a closed-basin lake are vapor exchange and hydrologic balance. On the other hand, the mechanisms for δ 13C variation in closed lacustrine basins are not clearly understood. Several hypotheses, including vapor exchange, hydrologic balance, lake productivity, and CO2 degassing have been put forward to explain δ 13C variation, but none have been tested experimentally.

This work involves experimentally determining the effects of CO2 degassing on carbon isotope evolution. The hypothesis is that in alkaline lakes, the exchange with the atmosphere, as a function of lake volume, dominates the carbon isotope dynamics. Verification of this hypothesis will allow the carbon isotope history of such lakes to be modeled, thereby enhancing the value of the paleoenvironmental records obtained from lacustrine carbonates.

In a series of simple experiments, we approximated a closed-basin lake using three chemically different solutions: a deionized water control, a Na-HCO3 solution, and a Ca-Na-HCO3-Cl solution. The solutions were allowed to evaporate in three large tanks. Once the final evaporation point was reached, deionized water was added in a series of five steps until returning to the original volume.

The dissolved inorganic carbon δ 13C and δ 18O measurement was done in both the Na-HCO3 and Ca-Na-HCO3-Cl solutions indicated different covariant trends during different stages of the experiment. The calcite that precipitated in the Ca-Na-HCO3-Cl solution also showed a covariant trend for these isotopes. The final δ 13C values in both solutions confirmed the absence of biological productivity. The δ 18O in both solutions was a direct result of the geochemical evolution of the solution. The δ 18O isotopes showed an evolution consistent with Rayleigh distillation. The δ 13C isotopes, however, appeared to be driven mostly by CO2 exchange with the atmosphere, which could be calculated with a carbon exchange and degassing model rather than with Rayleigh distillation.


Late Pleistocene glacial and lacustrine fluctuations preserved strong and most dramatic evidence of climate change on the continent. Unfortunately, paleoclimatic interpretation of those records has long been hampered by the mutual dependence of both hydrologic systems on temperature and precipitation, that is—glaciers and closed-basin lakes increase in size in response to decreased temperature as well as increased precipitation. Researchers have therefore relied on uncertain assumptions about one of these variables in order to infer changes in the other. In this study, we show that reconciliation of glacial and lacustrine records by itself provides on some, but not all, temperature and precipitation. This is possible because each system has different relative sensitivity to those primary climatic variables. To convert the geologic record of changes in the glacial and lacustrine records to paleoclimatic constraints, we used physically based models of the glacial and lacustrine systems to identify combinations of climatic conditions that could reproduce the changes preserved in the geologic record. The glacier model is a spatially distributed snow- and energy-balance model loosely coupled to a vertically integrated 2-D glacier flow model. It specifically addresses the need for a model that can reproduce not only the larger, easily estimated shapes of the last glacial maximum, but also the much more complex ice distributions of the latest Pleistocene. We used a Thornthwaite water balance model to estimate the sensitivity of the lacustrine system to climate change, as it is dominated by climatically induced changes in evapotranspiration and runoff. Applying this dual-system modeling approach to the glacial-pluvial record in the Owens Valley, we find that temperatures were ~6°C colder during the last glacial maximum (LGM) but had warmed by about 4°C from that low by ~13 ka, well before the onset of the Holocene. More significantly, we conclude that LGM precipitation was at least 25 to 50% greater than today and that the increased precipitation continued, with intermittent dry periods, until the end of the Pleistocene.


After observing that studies involving filtration effects on natural water samples yielded results similar to those of geological membrane experiments, we conducted a series of laboratory and field experiments to examine this similarity. During the lab phase, we synthesized dilute sodium chloride and multi-component aqueous solutions mixed with variously sized sodium-saturated bentonite to simulate natural water samples with low concentrations of total dissolved solids (TDS) and high levels of total suspended sediment (TSS). We subjected these synthetic solutions to filtration, centrifugation, and dialysis before chemical analysis. We observed a decrease of as much as 24% in major ion concentrations after filtration. We also noted that TDS concentrations for samples subjected to dialysis and centrifugation were within 2–8% of their actual concentrations. During the field phase, we obtained water samples from the Rio Puerco and Rio Grande following large runoff events. We examined the effect of different solid-liquid separation methods on the concentration of dissolved species in the samples. We filtered the field samples collected and analyzed major ion concentrations in the filtrate. We observed that the concentrations of chemical species in the filtrate as a function of volume filtered varied by as much as 8%. We concluded that, under certain circumstances, hyperfiltration might be occurring during the filtration of natural water samples. We believe this phenomena may be caused by the rapid accretion of sediment onto a 0.45 μm filter, and, although much more prevalent for trace metals, can occur for some major cations and anions. We also concluded that the solid-liquid separation techniques of centrifugation and dialysis show promise for the treatment of aqueous sample before chemical analysis.

In addition to examining chemical variations of aqueous solutions as a function of filtered volume and as a function of liquid-solid separation method, we measured and analyzed filtration rates for each experiment using the filter cake model developed by chemical engineers during the early 1900s. We noted that plotting inverse flow rates versus cumulative volume filtered for each experiment yielded a linear relationship, just as described by the filter cake model. We were also able to calculate values for the resistance of the filter medium used (Rm), as well as the resistance from the accretion of sediment onto the filter (α). Although we noted some problems associated with using the filter cake model to predict the behavior of natural water samples subject to filtration, we concluded that it may be possible to extend the filter cake model to adequately describe and predict clogging rates associated with filtering natural water samples.
emissions from energy injection in some geologic media may contribute to global warming. Of the greenhouse gases, CO$_2$ plays a significant role in trapping heat near the surface of the earth. Technology is available to capture CO$_2$ emissions from energy plants, and these captured emissions can be sequestered in deep basin repositories. However, determining the viability, risks, and optimal locations of sequestering CO$_2$ in geologic media requires modeling the complex interactions between the injected CO$_2$ matrix, and pore fluid under site specific pressure and temperature conditions. Previous studies consisted mainly of simulating fluid and transport of CO$_2$ in subsurface environments. Realizing the importance of chemical processes, we assembled the TR-T reactive transport model, in which in addition to flow and transport simulates the impact of fluid-mineral interactions on CO$_2$ mobility. The TR-T simulator is an assemblage of the CO$_2$ flow and transport module TOUGH2-EOSCO2 and TRANS, a multicomponent geochemistry module. Where the main goal of this project was to create the base version of the TR-T simulator, we have begun comparing TR-T predictions to results from laboratory experiments. Comparisons to laboratory experiments provide a means to assess the accuracy of the TR-T simulator. The experiments also offer information to parameterize the TR-T model for specific media. Model predictions show excellent agreement to results from the first completed experiment. Awaiting additional results, we performed a suite of bench-scale sensitivity simulations to determine the effects of varying brine pH and alkalinity, and rock type. Our analysis indicated that varying brine pH and alkalinity resulted in a 0–5 % difference in mineral volume fraction at 1.25 x 10$^9$ seconds, depending upon the mineral assemblage. However, we found that variability among rock type was extreme; suggesting that CO$_2$ injection in some geologic media may induce significant dissolution and dramatically increase CO$_2$ mobility. As an introduction to larger-scale simulations, we simulated CO$_2$ injection at the reservoir scale. Contrary to the bench-scale results, the TR-T simulator predicted negligible changes to the matrix. We hypothesize the displacement of brine by the expanding supercritical CO$_2$ plume may limit brine reactivity with the geologic media. However, we employed a smaller ratio of injected CO$_2$ to calculate volume in our reservoir-scale simulation, which may account for the discrepancy between the simulated matrix change at the bench and reservoir scales. These introductory simulations were used to quantify fluid-mineral interactions, compare simulations to experimental data, and to demonstrate the ability of the TR-T simulator. The ultimate goal will be to employ the TR-T simulator to identify ideal CO$_2$ repositories and to assess the effectiveness and environmental implications of sequestering CO$_2$ in deep basin environments.

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Synogenic Cretaceous strata exposed in La Popa Basin, northeastern Mexico, record the development of local salt structures, Sierra Madre Oriental fold and thrust belt, and the resultant sedimentary systems. Detailed sedimentologic and stratigraphic analysis of the synogenic Upper Cretaceous to lower Tertiary Delgado Sandstone Tongue reveals complex sedimentation patterns that delineate the impact of regional tectonics, local salt stock growth, and eustasy on stratigraphic development.

Fourteen lithofacies observed in the Delgado Sandstone Tongue are interpreted as outer shelf and inner shelf depositional environments that form a geometrically complex shoreline assemblage. Three parasequence types are observed and stack as two parasequence sets, a lower, progradational parasequence set and an upper, retrogradational parasequence set. A sequence boundary is interpreted between the two sets, thus defining a highstand and transgressive systems tract as part of two partial sequences in the Delgado Sandstone Tongue.

Regional thickness trends show thinning both toward and away from the paleocoastline. Thinning away from the coastline reflects the non-deposition of sandstone. In contrast, thickness toward the paleocoastline reflects erosional removal of strata resulting from transgressive reevinment. Localized thinning trends are observed adjacent to all salt stocks as well as La Popa weld. Stratigraphic thinning begins at a greater distance from El Gordo diapir than La Popa weld and El Papalote diapir. This suggests that El Gordo diapir had a higher bathymetry than El Papalote and La Popa weld.

Lithofacies, thickness, and percent sandstone data show that Delgado Sandstone sands were deposited as part of a wave- and storm-dominated delta system or sinuous coastline. Sandstone provenance analysis suggests that the Sierra Madre Oriental fold and thrust belt, Alisitos magmatic arc, and intrabasinal limestone lentils contributed detritus to the Delgado Sandstone Tongue; this suggests that detritus was derived from the west/northwest. Additionally, lithofacies data, percent sandstone data, and thickness trends suggest that the orientation of the paleoshoreline was roughly northwest/southwest; this is consistent with sandstone source regions in the west/northwest and sparse paleocurrent data. Sandstone bodies were generally controlled by the overall depositional system and were influenced by salt diapirism within 2 km of the salt.


The La Popa Basin in northeast Mexico contains thick sections of Cretaceous through Tertiary strata disrupted by several salt diapirs and one salt weld. The salt weld structure forms a thin diapiric salt structure trending east-southeast 12 km from its western end to a bend, and another 12 km southeast to its tip in the study area.

Shallow marine siliciclastic strata of the Parras Shale (Campanian), Muerto Formation, and lower members of the Potrerrillos Formation (Lower Maastrichtian) fill the salt weld, indicating syndepositional topographic expression of a salt wall. The strata are composed mainly of siltstone, shale, sandstone, and uncommon limestone. These units represent deposition at the distal parts of a deltaic system. Petrography and stratigraphic position of a thin limestone unit suggest that it is a calcite-turbidite deposited at the southeast tip of the salt wall.

Muerto Formation sandstones are feldspathic litharenites originating from a recycled orogen or magmatic arc. The composition of the Muerto Formation varies within the basin. Petrographic analysis of samples from throughout the basin shows that the salt wall blocked the dispersal of sediment in the La Popa Basin.

Structural features in the study area include three distinct fault sets and a fold set. Faults within the study area trend north-northwest. Post-depositional folds also trend northwest. Sub-parallel trends of the weld trace, folds, and faults suggest a kinematic link between shortening and salt evacuation.

A four-phase weld history consisting of diapirism, welding, shortening, and fault displacement due to continued salt flow is inferred. Normal faulting and diapir-flank folding accompanied the rise of an elongate diapir during sediment deposition. The welding phase was nearly synchronous with diapirism. The Hidalgoan orogeny initiated southwest-north-east shortening oblique to the trend of the salt weld. Detachment folds formed adjacent to the weld where salt was more abundant. Right-lateral, transpressional slip occurred along the salt weld, causing increased vertical displacement to the northwest. Transpression along the salt weld forced the evacuation of remnant diapiric salt. Combined salt flow toward the remaining diapirs in the basin caused the formation of two southwest-dipping normal faults.


Lateral variability of the distribution of pebble sand channels, floodplain fine-grained sand, silt, and mudstone, and of authigenic carbonate is evident in axial-fluvial strata of the late Pliocene to early Pleistocene Camp Rice Formation in the Hatch–Rincon graben, southern Rio Grande rift, New Mexico. Five stratigraphic sections, averaging 35 m thick and spaced approximately 1.5 km apart, were measured along the northern flank of Rincon Arroyo, which bisects the northern half of the graben. The sections were correlated utilizing (1) a lower carbonate bed of probable geothermal origin (white bed) that is traceable between the middle three sections, (2) a 1.6 Ma pumice-clast conglomerate.
that is present at all five sections, and (3) the constructional top of the formation, the La Mesa surface, where the sections of reverse magneetostratigraphy at one of the sections establishes an age range from the Reunion subchron (2.15 Ma) to near the Matuyama–Brunhes chron boundary (0.78 Ma).

The relative abundance of multistory channel sands increases toward the basin center, where as channel sands are relict to isolated ribbons near the basin edge. Channel recurrence interval is 152 kyrs in the basin center and 685 kyrs near the edge. The ratio of floodplain mudstone to fine-grained sand and silt increases toward the basin edge, as do the number of calcilutic paleosol surfaces. The abundance of soil welding, and the maturity of the paleosols expressed as a greater number of K horizons. Assuming an average time of development of 10 kyrs for stage II and 100 kyrs for stage III calcic horizons, approximately half of the stratigraphic history near the edge of the basin was taken up in soil formation. The number of ground water carbonates and paleosols with gleyed horizons also increases toward the basin edge.

A see-saw-like motion of the basin related to independent histories of movement of the border faults best explains the channel facies distribution. Southward flow of shallow ground water into the basin from northern recharge areas best explains an increase in ground water carbonates and gleyed horizons near the basin edge.

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This study includes geologic mapping of the 7.5min Tesuque quadrangle at 1:24,000 scale and a ground water study covering 40 km² within the quadrangle to determine what geologic features of control ground water flow in the Tesuque aquifer. Geologic mapping substantiates early workers’ choice of including the volcaniclastic strata of the Bishop’s Lodge Member within the Tesuque Formation, because the volcaniclastic layers are interbedded with and conformably overlie characteristic arkosic strata of the Nambe Member of the Tesuque Formation. Major-element glass geochemistry of the tephras within the Nambe and the Skull Ridge Members aided in stratigraphic correlation across faults and between discontinuous outcrop exposures. Deposition of the Nambe Member began before Bishop’s Lodge Member, which confirms that subsidence of the Española Basin was underway before 31 Ma. Previous restriction of the age of the Nambe Member to the middle Miocene overlooked the presence of diagnostic fossils only in the upper part of the member. Many late Pliocene to early Pleistocene-age deposits (QTg and QTg±c) form stream channel and surface strata which are likely remnants of fluvial systems emerging from the foothills. Multiple terrace deposits, commonly inset into existing stream valleys, show an overall 80-m lowering of base level during the Quaternary. Mapped units are tentatively correlated to units from other studies within the Basin and Range province based on stratigraphic correlation of volcanic sediment, soil studies, or elevation above base level. Only two Pliocene and Quaternary terrace deposits close to the mountain front have been offset by faults, precluding significant Quaternary fault movement. The contact between the Tesuque Formation and the mostly Proterozoic rocks of the Sangre de Cristo Mountains is both structural and depositional.

The ground water elevation data measured in 1998 for this study provide a degree of accuracy for interpolation of the ground water flow geometry not provided by the existing NMOSE WATERS data. The ground water elevation map interpolated from the 1998 data delineates a gaining reach along the Rio Tesuque and establishes that the regional aquifer is hydrologically interconnected paleo-basin(s) of relatively small to large size aquifers. Anomalous ground water elevations, which do not conform to the interpolated water-table surface, are likely the result of local gradients and variability in permeability. The map does not reveal barriers to ground water flow such as faults. The density of the 1998 well data alone cannot resolve geologic controls that act on a hundreds-of-meters scale, such as the heterogeneity of permeability in the Tesuque aquifer. Additional insight into the geologic controls on ground water flow was gained by combining the measured 1998 data with adjusted daily data from the NMOSE WATERS database to achieve greater data density. This prevented interpretation methods from smoothing over variability and reveals that arroyos and valleys are recharge zones.


Beach ridge and lacustrine deposits from Laguna El Fresnal and Laguna Santa Maria in the Chihuahuan Desert, Mexico, reveal episodic Holocene lake highstands and long-term climate changes in currently dry basins. Situated approximately 70 km south of the U.S.–Mexico border, lakes occupying these currently arid basins combined during episodes of wetter than modern climatic conditions to form pluvial Lake Palomas.

Constructional beach ridges dated at 221 ± 33 and 435 ± 39 14C years before present (14C yr B.P.) (Little Ice Age), 3,815 ± 52 to 4,251 ± 59 14C yr B.P. (early Neoglacial), 6,110 ± 80 to 6,721 ± 68 14C yr B.P. (middle Holocene), and 8,269 ± 64 and 8,456 ± 97 14C yr B.P. (early Holocene) provide the first detailed Holocene lake-level chronology for this region. The depositional environment of the Tesuque Formation was an alluvial slope, which is an streamflow-dominated piedmont setting that is similar to many Basin-and-Range basins. The depositional processes were channelized ephemeral streams, overbank floods, and wind. Lithofacies shapes are both ribbon-and bell, and the sediment is poorly lithified mostly silt and sand, but also clay and gravel. The outcrop is a 30-m-think stratigraphic panel ca 370 m long.

I tested the hypothesis that the permeability frequency distributions of the different lithofacies are distinct. Inferred to be driven by a greater frequency of winter storms, and reduced temperatures and evaporation rates over the southwestern U.S. and northern Mexico.

An ~17-m-long sediment core from the center of Laguna El Fresnal reveals climate-driven changes in sedimentology, magnetic susceptibility (MS), total organic carbon, and total inorganic carbon that delineate episodes of wet and dry conditions for the last 50,000 years (390 cal yr). Colder than modern climate conditions coupled with low-energy lacustrine deposition before 30,000 cal yr B.P. are marked by low total organic carbon and a gradual increase in clay-dominated sediments. Maximum pluvial conditions ca 20,000 cal yr B.P. are characterized by peaks in sand-size sediment, high MS, and low organic productivity within El Fresnal Basin. The transition to relatively drier, warmer climate ca 10,500 cal yr B.P. is shown by a marked decrease in MS, increased organic and inorganic carbon concentrations, and pulses of fine sand. These results are consistent with other regional paleoecological evidence of late Quaternary climate change, and represent the first detailed chronology of glacial to interglacial changes in climate from the pluvial Lake Palomas system.


Aquifer heterogeneity at small scales (meters to tens of meters) can be characterized by investigating outcrops that are geologically analogous to aquifers. To evaluate and contribute to techniques in outcrop-analogue studies, I defined and mapped lithofacies, and measured permeability in situ, at an outcrop of the Tesuque Formation (Miocene) near Española, New Mexico. The depositional environment of the Tesuque Formation was an alluvial slope, which is an streamflow-dominated piedmont setting that is similar to many Basin-and-Range basins. The depositional processes were channelized ephemeral streams, overbank floods, and wind. Lithofacies shapes are both ribbon- and bell, and the sediment is poorly lithified mostly silt and sand, but also clay and gravel. The outcrop is a 30-m-think stratigraphic panel ca 370 m long.
studies, furthermore, the spatial distribution of lithofacies must also be quantifiable. Toward this end, I calculated relative proportions of the lithofacies, measured thicknesses and widths of channel lithofacies, attempted Markov chain analysis on a vertical transition matrix, and calculated horizontal and vertical indicator variograms for the different lithofacies. The indicator variograms are perhaps the most sophisticated of these methods to quantify spatial distributions of lithofacies. Indicator variograms permit quantification of traditionally descriptive geologic data, and can incorporate the spatial, temporal, and process-based knowledge of the geologist.


Fernley is located in west-central Nevada, at the point where the Truckee River is diverted by the Truckee Canal. The ground water shows isotopic signatures of the Truckee Canal water, indicating that the aquifer gets its recharge mainly from Truckee Canal leakage and irrigation return flow. The ground water chemistry in this area is highly mineralized compared to the dilute Truckee Canal water. It is high in arsenic; 97% of the wells sampled have concentrations above the current United State Environmental Protection Agency–maximum contaminant level (US EPA–MCL) in drinking water of 10 µg/L. This study used mass balance calculations to describe how the Truckee Canal water evolves to the ground water chemistry observed in wells. It evaluated the correlation of different chemical constituents with arsenic and the temporal variability of arsenic to predict the sources and processes causing high arsenic in the ground water. The dissolution and precipitation of the minerals plagioclase, muscovite, halite, mirabilite, magnesite, kaolinite, illite, and chlorite control the major ion chemistry in the area. The source of arsenic in the area is natural, mainly associated with iron oxide coatings in the lake sediments. The main process that controls arsenic concentration in the area is adsorption/desorption from oxide surfaces, and changes in pH play a major role in this process. This is shown by the increase in arsenic concentration with pH. The negative correlation between arsenic and sulfate and calcium show that pyrite and calcium arsenates are not important sources of arsenic in the ground water of Fernley area. The role of evaporation in concentrating dissolved ions in the ground water of Fernley is much less than the addition and removal of these ions by dissolution/precipitation and adsorption/desorption.


The dominant orogenic fabric in Proterozoic rocks of the southwestern U.S. includes a series of northeast-striking shear zones that are commonly interpreted as suture zones across which blocks of juvenile crust were assembled to the southern margin of Laurentia. New structural and geochronological data from southwestern Colorado suggest that fabrics related to assembly of tectonomagmatic terranes in this area strike northwest. The northwest-striking foliation in the rocks across this zone is caused by progressive shortening in the prominent northeast strike of this zone. For example, the Yavapaip province may have involved a complex arcuate subduction system, with multiple arcs, analogous to that of the modern Banda Sea in the Indonesia region.

A detailed structural analysis combined with new U/Pb zircon/titanite geochronology, in situ monazite geochronology, Ar/Ar thermochronology, and geothermobarometry constrains a six-stage tectonic history of the Proterozoic rocks in the Black Canyon of the Gunnison and region. 1) The island-arc stage (ca 1.79–1.73 Ga) involved deposition of submarine bimodal volcanic rocks of the Dubois and Cochetopa successions in arc-related settings and the emplacement of coeval calc-alkaline granites. 2) The outboard assembly of island arcs (ca 1.73–1.70 Ga) and the creation of isoclinal F1 folds and northwest-southeast shortening. 3) The Yavapaip orogeny progressed into the assembly of the composite arc terrane to Laurentia (ca 1.70–1.68 Ga) and the formation of various northeast-striking faults and southeast-northeast shortening. 4) Quartzite deposition in syn-tectonic basins (ca 1.70–1.68 Ga) that separate orogenic pulses. 5) The Mazatzal orogeny (ca 1.65 Ga) involved continued northwest-southeast shortening. 6) Intracontinental magmatism and tectonism (ca 1.43–1.39 Ga) reactivated the Black Canyon shear zone, further enhancing the northeast-southwest grain of the Proterozoic orogen. The results of this investigation are presented as two looping pressure/temperature/time/deformation (P/T/t/D) paths that add to models for the evolution of Proterozoic rocks exposed in the southwestern United States.


The northeast-trending Virgin Mountain anticline (VMA) of the North Virgin Mountains straddles the boundary between the unextended Colorado Plateau and the highly extended crust of the central Basin and Range province. The anticline is 50 km long and 8 km wide, is doubly plunging, and has overturned Paleozoic beds on both limbs. The crystalline core of the VMA is composed of Paleoproterozoic supracrustal and interlayered ophiolites that were accreted from ca 1,740 Ma to 1,550 Ma (D1–D2) characterized by distinct structural fabrics and associated metamorphic assemblages and microstructures. The most prominent Proterozoic structure is the Virgin Mountains shear zone (VMSZ), which was initially defined by retrograde recrystallizing D3 northeast-southwest contraction and may represent an important crustal suture, as it contains “exotic lithologies” commonly associated with ophiolites. A clockwise-rotating strain field during progressive east-west (D2) and north-west-southeast (D1) contractual events resulted in the prominent northeast strike of this zone. Late Paleoproterozoic, east-west contraction across this zone (D2) resulted in a complex array of linked, dextral transpressional shear zones that partitioned strain into strike-slip, pure-shear, reverse, and normal sense deformation zones. Deformation within the VMA continued to 1,600 and 1,550 Ma based on syn-tectonic monazite rim ages that are associated with sub 500°C (greenschist facies) metamorphic assemblages and textures, and sub 500°C deformational microstructures. Development of these highly fossil shear zones later controlled the geometry of Laramide and Miocene brittle deformation.

The Proterozoic basement in the core of the VMA now resides at elevations of more than 2 km above sea level, roughly 2.5 km higher than the elevation of basement in the adjacent Colorado Plateau. The northeast trend and vertical uplift of the anticline is a result of Miocene east-west extensional deformation superimposed on the pre-existing northeast- and north-trending structural grains created during Paleoproterozoic (D2, D3, D4) and Laramide contractual tectonic events. Outward-vergence monoclinal reverse faults similar in style to Laramide-age reverse faults in the Colorado Plateau are present on the east and west limbs of the VMA, and we propose that much of the vertical uplift of the anticline occurred during this time. The geometry of Miocene deformation was both strongly partitioned and directed by these pre-existing structures, and also manifest as steeply dipping conjugate normal faults in the Mesozoic and Paleozoic section that solided into basal deformations in the Cambrian Bright Angel shale and at the Great Unconformity. Apatite-fission track (AF) dates range from 21.7 to 2.3 Ma directly below the Cambrian–Precambrian unconformity to 14.0 < 2.5 Ma in the core of the VMA, and indicate that the anticline was unroofed in Miocene time. Short AF lengths (<13µm) with large standard deviations (>2.5) from the 22–20 Ma AF ages suggest that Proterozoic rocks of the VMA cooled slowly through the AF partial annealing zone at the end of the extension, whereas longer AFTs suggest rapid cooling and syn-extensional exhumation from 16–14 Ma. We interpret the former ages to represent pre-extensional erosional cooling of a regionally elevated terrain, contrary to most models that assume a peneplain pre-extensional surface. Our model is consistent with geophysical, sedimentological, and tectonic studies of the region.

MODIS/ASTER Airborne Simulator (MAS-
Paleomagnetic data, combined with high-precision $^{40}\text{Ar}/^{39}\text{Ar}$ age determinations, show that Cripple Creek diatremes, Front Range of Colorado, experienced modest amounts of deformation since mid-Tertiary time. Overall, the demagnetization response, based on both alternating field and thermal methods, and directional data and field tests, are interpreted to indicate that most rocks in the Cripple Creek district carry geologically stable magnetizations. Site mean directions are of both normal (D = 358.3°, I = 63.0°, $\alpha_0 = 4.4$, $k = 27.5$, N = 39 sites) and reverse (D = 172.1°, I = -62.2°, $\alpha_0 = 4.1$, $k = 32.7$, N = 49) polarity. Notably, the site mean directions of both polarities are steeper than expected mid-Tertiary field directions. An analysis of the overall distribution of the site mean data with respect to different parts of the district suggests that slight north-side-down tilting affected the entire district. Detailed analyses distinguish declination as well as inclination discrepancies within the south and east subbasins. Such deformation could have been accommodated by motion along faults active in a structurally complex area. These data proved invaluable in producing more than 60 km$^2$ of new geologic mapping for the first author, and recognizing many of the key structures that led to our Proterozoic, Laramide, and Miocene tectonic interpretations.


The mechanisms by which juvenile Paleoproterozoic continental crust was derived from the mantle, accreted to southwestern Laurentia ca. 1.79–1.68 Ga, and stabilized as new continental lithospheres have been much debated. This study addresses the problem by assessing the proposed Paleoproterozoic “Farwell Mountain–Lester Mountain suture zone,” a broad, complex zone of deformation that may contain the oldest accretionary structures within Paleoproterozoic crust south of the Cheyenne belt.

One of the major contributions of this study is the correlation of metamorphic and deformational fabrics among four field subareas (Farwell Mountain, Lester Mountain, Mica Basin, and the Soda Creek–Fish Creek shear zone), in an attempt to investigate the history and character of the proposed “suture zone.” Steepening and overprinting by an east-west-striking, subvertical fabric is attributed to post-accretionary shortening ca. 1.68 Ga. Also documented is an earlier Paleoproterozoic dike fabric (“$S_2/F_2$”), which may preserve evidence of a north-vergent fold and thrust system. This is consistent with the hypothesis that the region has a collisional accretional history.

Seismic data from the CD-ROM experiment reveal north-dipping reflections that are tentatively associated with a 3–5-km offset of the Moho and a north-dipping, high-velocity body and are together referred to as the Farwell Mountain backthrust. Another set of reflections dip southward and project to the surface near Lester Mountain; these are tentatively correlated with the “$S_2$” fabric. Together, these features may record the juxtaposition of two tectonic blocks along south-dipping structures in the proposed suture zone ca. 1.74 Ga.

A tectonic model is proposed to explain the geometries outlined by combined surface geologic and seismic data from the Cheyenne belt and Farwell Mountain–Lester Mountain “suture zone,” allowing some investigation of the early tectonic history of the region despite overprinting by subsequent tectonism.


The Rio Grande in central New Mexico flows through a semi-arid, historically aggrading Quaternary rift basin. Flow regulation measures include dams, irrigation diversions, levees, and bank stabilization. These have caused severe impairment including incision, lowered water tables, and less overbank flooding; disrupted ground water-surface water interactions; altered seasonal organic carbon dynamics; and declining native biota. Previously dynamic flowpaths in the shallow alluvial aquifer (hyporheic corridor) have become less reversible due to parallel drain ditches with beds lower than the river. These ditches impose relatively static hydraulic gradients on the alluvial aquifer, which force water to flow from the river to the drains. A water sampling campaign from May 2001 through April 2002 established seasonal major element and redox chemistry using dialysis multi-level samplers, wells, and surface water sampling. Sediment extractions quantified and characterized authigenic Fe/Mn oxyhydroxides, as well as solid phase P, all of which were more widespread in intermently wetted sediments near the water table. Filter papers were incubated in the aquifer to grow seasonal precipitates and examined by scanning electron microscopy with chemical characterization by energy-dispersive X-ray spectroscopy.

Oxygen is rapidly depleted from Rio Grande water shortly after it enters hyporheic corridor sediments. A series of terminal electron-accepting processes, including denitrification, manganese reduction, iron reduction, and sulfate reduction, occurs under anoxic conditions as microorganisms metabolize organic carbon. These reactions occur downflow from the Rio Grande through the alluvial aquifer toward the drainage ditch system. These redox processes depend on changes in hydraulic head driven by diel, seasonal, interannual, and irregular (anthropogenic) variations in river stage. Oxidanoxic cycling produces Fe/Mn oxyhydroxide and Fe sulfide minerals near the water table. Stalky, helical, and spherical oxide morphologies and cubic sulfide morphologies were observed. These phases grow on the scale of weeks, probably as microbial respiration products. Seasonal mineralogy and organic carbon dynamics may affect water quality and the success of potential restoration efforts. Restoration should include geochemical and hydrologic monitoring of ground water-surface water interactions.