TEXAS TECH UNIVERSITY
College of Arts & Sciences

Department of Geosciences

Department of Geosciences
Texas Tech University
Research Day 2010

Welcome everyone, to the Department of Geosciences 2010 Research Day. The version of this event, now in its second year continues to expand. Besides contributions from TTU undergraduates, graduate students and faculty, we welcome participants from our colleagues in Geography, the Center for Geospatial Technology, a group from San Angelo State, the USGS, and alumni!

All contributions are greatly valued and it is great to see the full spectrum of research activities in the Department on display. Nevertheless, the principle reason behind the event continues to be the celebration of research accomplishments by our graduating students. Their contributions will be shown in and around room 230 (the same place as the coffee and cookies); abstracts are marked by a † in this volume. A quick note on the vibrancy of undergraduate research – I believe we will have >10 posters from such students this year.

I would like to thank the Geoscience Society who will once again host a BBQ lunch in Room 201 (Structure Lab) from 12:15 onwards, and Prof. Barnes and the Department for supporting this whole enterprise.

Finally, thank you to everyone, presenters and viewers, for coming along to participate in the event. I hope that everyone enjoys the morning and is inspired for their upcoming summer of research.

Callum J Hetherington

The Sensitivity of Adjoint Sensitivity

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Adjoint sensitivity is calculated with the adjoint of a numerical weather prediction model and reveals areas in the initial conditions of a weather forecast to which a chosen forecast aspect is sensitive. Adjoint sensitivity analysis can be a valuable tool because 1) it reveals where initial-condition error is important to a forecast, and 2) it can be used to understand the important dynamical processes involved with various atmospheric phenomena. However, there are issues with adjoint sensitivity analysis that have not been addressed in previous literature. In particular, adjoint sensitivities vary significantly with respect to model resolution, model physics, and the forecast trajectory about which the adjoint sensitivity is produced. The purpose of this study is to understand the sensitivity of adjoint sensitivity with regard to these parameters.

The forecast aspect used here is the 24-hr forecast average surface pressure surrounding a land falling cyclone in the Pacific Northwest U.S. In this case, sensitive regions typically exhibit localized, mesoscale (a few hundred kilometers) structure, and it is found here that horizontal grid spacing has a strong influence on the spatial scale of adjoint sensitivity patterns. Finer grid spacing significantly reduces the size of regions of large sensitivity, indicating the importance of high-resolution models in adjoint applications. A strong variability in sensitivity is also found when using different forecast trajectories or model physics in the adjoint model. This suggests that adjoint sensitivity, like different forecasts within an ensemble forecasting system, should be viewed as equally-likely scenarios. In turn, an ensemble of high-resolution, adjoint sensitivity model runs appears to be the most appropriate way to perform adjoint sensitivity analysis.

Using L-moments with R.

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Estimation of sample distributions is a complex subject, which is simultaneously influenced by, and has influence in, many branches of earth sciences. The literature of distributions is extensive and encompasses many disciplines. In particular, the study of magnitude and frequency of environmental phenomena can be researched and defined using special types of statistical ``moments'' known as L-moments. This poster provides a quick introduction to distributional analysis with L-moment statistics using the R environment for statistical computing (www.r-project.org) and the lmomco package [1]. The package can be obtained from the Comprehensive R Archive Network at www.cran.r-project.org/package=lmomco.

What are L-moments? L-moments are defined through linear combinations of the expected values of order statistics (the statistics of ordered samples). The minimum, maximum, and median are the most familiar order statistics. L-moments are direct analogs, but not numerically equivalent, to the well-known product moments (mean, standard deviation, ...). As a result, L-moments have similar interpretations and applications as the product moments.

L-moments have many advantages over the product moments including natural unbiasedness, robustness, and often smaller sampling variances. These advantages are particularly acute with data having large range or variation, skew, and heavy tails---just the type of data endemic in the earth sciences. The sampling properties of L-moments make them attractive and especially for analysis of non-normally distributed data and hence applications to asymmetrical distributions. L-moments are complementary, as well as alternative, to product moments.

The lmomco package provides for L-moment estimation, parameter estimation for numerous familiar and not-so-familiar distributions, and L-moment estimation for the same distributions from the parameters. The supported distributions include: Cauchy, Exponential, Gamma, Generalized Extreme Value, Generalized Lambda, Generalized Logistic, Generalized Normal, Generalized Pareto, Gumbel, Normal, Kappa, Pearson Type III, Reverse Gumbel, Wakeby, and Weibull..

[1] Asquith, W.H. (2009) lmomco---L-moments, Trimmed L-moments, L-comoments, and Many Distributions: R package version 0.97.4.

Kinematic analysis of surface ice structures on Saturn's Moon Enceladus

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Based on interpretations of crustal features on Enceladus, we developed a global kinematic map of the satellite and suggest a series of events that define its crustal evolution. Features associated with Enceladus' South Polar Terrane (SPT) are indicative of diapirism based on interpretations and kinematic analysis of structures similar to those observed overlying terrestrial salt diapirs. Based on observations of previously modeled diapir evolution and cross-cutting relationships of features on Enceladus, we propose an order of structure formation leading to the current configuration found in the southern hemisphere.

At the SPT, extensional fracturing of four parallel features termed 'tiger stripes', coupled with tidal heating in the icy crust, resulted in reactive diapirism as relatively warm and therefore less dense ice ascended to the surface. As diapirism became active, uplift of the crust overlying the crest occurred creating a series of concentric extensional fractures. Radial extensional fault zones initiated over the crest and continued to lengthen away from the SPT, producing grabens. Features comparable to ogives, found in terrestrial valley glaciers, developed as overlying ice flowed into these grabens. The initiation of a less prominent contractional belt located to the north in the trailing hemisphere occurred by foreland thrusting due to ongoing contractional forces from the SPT.

Structures in the equatorial regions of Enceladus' leading and trailing hemispheres suggest that similar but older events occurred in these locations. The orientation of ridges and grooves and characteristics of features, including structures analogous to ice rises on earth, also suggest rotational displacement of crustal blocks over time in the southern, trailing, and leading hemispheres. Features analogous to terrestrial pressure ridges indicate that localized patches of subsurface water were once present in the equatorial region of the trailing hemisphere, possibly during a paleo diapir event. To further support these interpretations, hypsometry data as well as calculations of ice creep in environments of low gravity and temperature should be analyzed.

Gamma Ray Spectrometry and Lithofacies Assiocation of the Elm Creek Limestone.

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The Elm Creek Limestone is the lowest formation of the Lower Permian Albany Group of North Central Texas. At the study site on US 180 approximately 1 mile west of Albany Texas, the Elm Creek is an approximately 30 meter thick carbonate platform succession deposited on the Eastern Shelf of the Midland Basin. The Elm Creek outcrop has a north/south trending strike and a westward dip of less than1 degree toward the outer shelf and basin. The outcrop exhibits a transition of terrestrial facies in the north-northeast to a marine facies to the south-southwest.

The outcrop lithologies of the Elm Creek are dominated by mud- to grain- dominated skeletal packstones with thick to thin beds of siliciclastic mudstone and lime mudstone.16 rock samples were taken from selected limestone units and cut for thin sections. The dominant carbonate components were Mollusks (bivalves), and smaller benthic foraminifera. Other important skeletal groups include bryozoans, echinoid, sperulids worm tubes, and ostracodes. Gamma ray spectrometry was used to investigate the amount of potassium (K), uranium (U) and thorium (Th) present in the various lithologies, and to generate API GR curves to determine trends of siliciclastic input and U enrichment.

The Elm Creek Limestone represents the development of a set of shallow marine carbonate environments during a regionally extensive transgressive- regressive episode. The harsh nearshore conditions are recorded during the initial transgression and later regression by very shallow marine lime and siliciclastic mudstones. The higher energy carbonate environments are recorded by the grain-dominated skeletal limestones, while deeper water open platform conditions are recorded by the nodular, muddy skeletal packstones. Deeper open platform conditions are also recorded by the very low compensated gamma ray values, indicating little input of nearshore muds.

Fossil Vertebrate Fauna of the Lower Aguja Formation, Big Bend National Park, Texas: A Progress Report

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The upper part of the Aguja Formation in Big Bend National Park has yielded a diverse fossil vertebrate fauna. Virtually all that is known of the fossil fauna of the Aguja (including such well-known creatures as the giant crocodilian *Deinosuchus*, horned dinosaur *Chasmosaurus*, and duck-billed dinosaur *Kritosaurus*) is based on the study of the upper shale member. The lower shale member of the Aguja Formation in Big Bend National Park is poorly fossiliferous, and only a few specimens have been found there. However, as sparse as it is, the vertebrate fauna of the lower shale member is of greater interest and importance than previously recognized. Recent evidence indicates that the lower shale member is older than previously thought (84-80 million years, or "Aquilan" in age), and there are only a few vertebrate faunas of that age found anywhere in North America (e.g., the Milk River Formation in Alberta/Montana and the Wahweap Formation in Utah). Recent field surveys of all the vertebrate fossil material found in the lower shale member of the Aguja Formation in the park has yielded over 300 individual elements, including teeth and bones from turtles, sharks, crocodiles and dinosaurs. The most significant of these is the partial skeleton (~60 elements) of a goniopholid crocodyliform, including osteoderms, teeth, and skull/jaw elements.

Receiver function study of the rifted margin of the Gulf Coast Plain: A Pilot Project

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The Gulf Coast Plain (GCP) is one of the deepest sedimentary basins in the world; as a result little is known about the basement structure beneath this region. The few refraction seismic investigations of the GCP found sediment depths of 15 to 20 km, underlain by severely attenuated continental or transitional crust. A 2-D refraction investigation along the Texas-Louisiana Border, found the crystalline continental crust to be as little as 10 km thick, underlain by an anomalous lower crust/upper mantle body interpreted to be depleted mantle; a "rift pillow" developed during the Late Paleozoic through Early Mesozoic rifting. This rift pillow coincides with the magnetic high that parallels the coast line along the entire Texas GCP. This poster will present new receiver functions (RF) results using data from stations of the EarthScope Backbone array throughout the GCP and a temporary pilot deployment of five broadband instruments between Junction, TX and San Antonio, TX that took place in 2008. The stations at Kingsville, TX (KVTX) and Hockley, TX (HKT) are close to the coast. Receiver functions for KVTX have a very strong P20s phase that is likely from the sediment-basement contact and a Moho Ps phase at about 45 km deep. This depth to the Moho is greater than might be expected for a coastal setting. The 45 km depth is, however, similar to that found for the base of the "rift pillow" observed in the Northern GCP. KVTX is located in the magnetic high anomaly that was associated with the rift pillow in the Northern GCP. The station at Junction (JCT) appears to have about a 42 km depth to the Moho which is typical of a station from the stable continental (cratonic) setting. The station at Nacogdoches, TX (NATX) is situated in older Gulf Coast sediments in a similar position relative to GCP rifting as would be expected a few km outboard of San Antonio. The 36 km depth to the Moho estimated for KVTX appears shallower than those Moho depths estimated for JCT and KVTX which could be the result of attenuated, rifted continental crust that is inboard of the anomalous "rift pillow". Receiver functions (RFs) computed for the temporary deployment between JCT and San Antonio appear to have a uniform depth to Moho of about 45 km. These stations probably did not reach the point at which rifting thinned the crust.

Refraction results from a line shot by Cram (1962) found about a 34 km depth to the Moho at a point about half way between San Antonio and the coastline. So the severe crustal attenuation appears to be outboard of San Antonio.

Middle and Upper Pennsylvanian Glacial-Eustacic Sea Level Changes of the East Mountain Shale.

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The Pennsylvanian was a time of "icehouse" global climate and development of ice sheets across Gondwana. This caused high-frequency glacial-eustatic sea level changes that are recorded across sedimentary basins around the world, including Mid-continent North America. It is believed that during times of maximum transgression fresh surface water and oxygen-depleted deep marine water produced a thermocline, promoting anoxic conditions at the sea floor resulting in the deposition of black shale. The stratigraphic interval of interest is the Middle and Upper Pennsylvanian East Mountain Shale exposed in Mineral Wells, Texas. This shale is thought to contain a black shale unit resulting from deep, anoxic marine deposition as noted above. The goal of this study was to determine the history of sea-level change through this interval.

To determine if the East Mountain Shale is in fact a deep-water shale, gamma ray spectrometry, lithofacies, and conodont faunal data were used. Data from a gamma ray spectrometer has determined the environment in which each layer of rock was deposited. The construction of a measured section with lithofacies, and a conodont frequency curve has also helped to further determine the depositional environment. Elevated uranium (U) values indicate high organic carbon content and reducing depositional conditions characteristic of deep water, anoxic conditions. Lithofacies descriptions and the vertical association of lithofacies provide information of specific environments of deposition and their migration through time. Conodont abundance and diversity is highest in deep, offshore environments and decrease in high sedimentation, nearshore environments.

Results from this study reveal that the East Mountain Shale contains a black shale unit similar to that reported from the Pennsylvanian of the Mid-continent. Conodont data and bulk gamma ray, compensated gamma ray, and uranium curves show that there are actually three cycles of glacial-eustatic sea level change recorded within this section of the East Mountain Shale. The deepest of these resulted in conditions that were deep and reducing enough to result in black shale deposition. This black shale had high gamma ray and uranium readings that suggest reducing or anoxic environments. Also on the conodont frequency curve there was a drastic spike in conodonts in the black shale unit.

Timing and style of emplacement of the Wooley Creek batholith, Klamath Mountains, California, using zircon U-Pb SHRIMP data

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The Wooley Creek batholith is a tilted intrusion that was emplaced between 156 and 159 Ma ago through three different host rock terranes: the eastern Hayfork terrane, an argillite matrix mélange; the Rattlesnake Creek terrane, a serpentine matrix mélange and the western Hayfork terrane, volcanoclastic deposits. The eastern Hayfork terrane contains blocks with detrital Proterozoic zircon (Ernst *et al*., 2008), however, no Mesozoic zircons have been found. The composition of the intrusion ranges from structurally low pyroxene gabbro to structurally higher granodiorite. Zircon crystals were separated from the intrusive rocks, xenoliths, host terranes and were dated by U-Pb at the Stanford SHRIMP-RG. Several zircon populations were characterized in the intrusive rocks, however, only rare inherited cores were found. Igneous ages range from 160.1 +/-1.6 Ma for the lower part of the intrusion to 154.2 +/- 2.1 Ma for the late granite and upper granodiorite. Zircons core from the granodiorite and late granite, dated at 160-163 Ma, are either xenocrysts or antecrysts. Zircons from the lower part of the intrusion have REE patterns that differ from those of the upper part of the intrusion, suggesting a different magmatic history. The lack of HREE depletion agrees with the absence of garnet in the system. Two metasedimentary xenoliths show ages ranging from 156 to 2,400 Ma with a peak around 400 Ma. The Paleozoic ages are similar to the ages of formation of the eastern Klamath province (Ernst *et al*, 2008). The connection between xenolith and host terranes is still unclear since it is the first report of such a wide range of zircon ages in the host metasediments.

[1] Ernst et al. (2008) GSA Bull. **120**, 179-194

A Reinterpretation of the 1970 Hales Onshore-Offshore Refraction Line in the Northern Gulf of Mexico

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This project is a re-interpretation of seismic refraction data from the Northern Gulf of Mexico and the Gulf coast Plain that was originally collected and analyzed by Hales (1970) and then reinterpreted Gurrola (1985). The data set is a north-south trending line extending 350 km along the Texas Louisiana border and to about 400 km offshore to the Sigsbee Escarpment. All the shots were offshore and included 21 one ton shots and almost a hundred small 100 to 150 pound shots. The smaller shots were only recorded to distance of up to 90 km but the larger shots were recorded to 600 km offset. The technology available to Hales in 1970 enabled a 2-D model to be developed by connecting a series of traditional 1-D models. Gurrola later used 2-D tracing to re-interpret these data. The older raytracing program was limited in its ability to include velocity gradients. We will be reinterpreting this data set using modern raytracing and finite element modeling (forward and inverse) that allows 2-D velocity gradients.

Our current model found the basement to be only about 3 km deep above the Sabine Uplift sloping to a depth of 13 km just past the coast line and continues to deepen only slightly more southward. The continental crust basement is thinned to about 16 km beneath the continental shelf. The Moho beneath the continental shelf has a velocity of 7.4 km/sec at a depth of about

30 km. A deeper mantle boundary beneath the continental shelf, with seismic velocity of 8.2 km/sec, is at a depth of 42 km. The Moho beneath the Sabine Uplift is 40 km deep and has a velocity of 8.0 km/sec. The seismic data indicated that the 6 km per second layer shallowed to about 8 km toward the Sigsbee Escarpment. Gurrola interpreted this as a continental fragment. Since basement is denser than sediment, it was necessary to deepen the Moho to 40 km to model the gravity data. More recent models of the Gulf of Mexico have found the salt to be much thicker near the Sigsbee Escarpment than assumed in our previous model. It is, therefore, likely that the shallowing high velocities in the refraction data are due to a salt body. The low density of the salt would not require a deep crustal root. We are modifying the old model using modern forward and inverse seismic modeling techniques to incorporate information from other newer models of the region. Reworking of first arrival data is under way with second arrival data to be interpreted soon. Early reworking of the data indicates a velocity jump between layers that seems to skip 6 km/sec, indicating an absence of a crustal layer within the failed rift zone.

Adult Dorsal Vertebrae of the Titanosaurian Sauropod *Alamosaurus sanjuanensis*, Big Bend National Park, Texas.

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The titanosaurian sauropod *Alamosaurus sanjuanensis* (Gilmore) is North America's only known Late Cretaceous sauropod. Despite the steady recovery of *Alamosaurus* material from sites around the southwestern United States, the phylogenetic position and geographic origin of the species are controversial. Previous authors have suggested a North American, South American, or Asian origin for the taxon, and cladograms exist to support each hypothesis. Attempts to discriminate among competing hypotheses have been hindered by the lack of diagnostic elements, especially dorsal vertebrae. The only dorsal vertebrae of *Alamosaurus* described to date came from a juvenile specimen; ontogenetic factors therefore limit their utility for phylogenetic analysis.

A new specimen of *Alamosaurus sanjuanensis* collected from the latest Maastrichtian Black Peaks Formation at the "Rough Run Amphitheater" locality in Big Bend National Park includes the first complete adult dorsal vertebrae to be described, consisting of three anterior dorsal vertebrae and one posterior dorsal vertebra. These specimens provide insight into the morphology of dorsal vertebrae in the species, and reveal the distribution of vertebral laminae and pneumatic fossae, patterns of variation within the dorsal series, ontogenetic variation from the known juvenile specimen, and patterns of pneumaticity within the vertebrae. These characteristics allow for a more thorough understanding of the skeletal morphology of *Alamosaurus* that may ultimately contribute to the resolution of its relationships and, consequently, its geographic origin.

Fabric Development in a Tilted Pluton, Klamath Mountains, California

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The occurrence of magmatic fabrics within plutons has been used extensively as an indicator of a number of physical processes active within a magma body during emplacement and crystallization. Typically, the presence of a magmatic fabric is attributed to either the effects of some internal strain field (e.g., convection, magma flow, and emplacement), a regional tectonic strain field, or, as is likely in many cases, a complex combination of the two [Zak *et al.*, 2007]. For this reason, fabric development has important implications not only for the mechanisms accommodating magma emplacement, but also for tracking changes in regional strain fields within active volcanic arcs and orogens [Zak *et al.*, 2007; Zak & Klominsky, 2007].

Host-rock metamorphic assemblages indicate that the Wooley Creek Batholith has been tilted approximately 30° W along a NNW – SSE axis [1]. As a result of this tilting and subsequent erosion, the Wooley Creek Batholith exposes roughly 12 km of structural relief, and if the comagmatic Slinkard Pluton is also taken into account, the entire Wooley Creek – Slinkard system exposes nearly 15 km of structural relief [1]. The Wooley Creek Batholith, therefore, provides a rare opportunity to observe gradients in the strength and orientation of magmatic fabrics with depth within a large magma body in the middle to shallow crust, and study the processes responsible for fabric development.

[1] Barnes, C.G., Rice, J.M., & Gribble, R.F. (1986). Tilted plutons in the Klamath Mountains of California and Oregon. Journal of Geophysical Research 91(B6): 6059-6071.
[2] Zak, J., Paterson, S. R., & Memeti, V. (2007). Four magmatic fabrics in the Tuolumne batholith, central Sierra Nevada, California (USA): Implications for interpreting fabric patterns in plutons and evolution of magma chambers in the upper crust. GSA Bulletin, v. 119, no. 1-2: p. 184-201.
[3] Zak, J., & Klominsky, J. (2007). Magmatic structures in the Krkonose-Jizera Plutonic Complex, Bohemian Massif : evidence for localized multiphase flow and small-scale thermal-mechanical instabilities in a granitic magma chamber. Journal of volcanology and geothermal research, v. 164, no. 4: 254-267.

Comparisons Between Isotropic and Anisotropic Reverse Time Migration

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Reverse time migration (RTM) has been successfully applied to production imaging processing in recent years. It propagates source wavefield forward in time and the receiver wavefield backward in time to image the subsurface reflector (Baysal et al, 1983; McMechan, 1983; Whitmore, 1983). By using the two-way acoustic wave equation, RTM has no dip limitation. Also, it naturally takes into account both down-going and up-going waves and thus enables imaging of the turning waves and prism waves that are able to enhance the image of steep salt flank and other steeply dipping events with complex structures.

Conventional isotropic RTM produces erroneous images and misposition of the dipping events in TI media. When multi-component data are available, the elastic RTM seems to be a proper treatment in anisotropic media. However, separating anisotropic wavefield into different wave modes for imaging is difficult in terms of accuracy and efficiency. Rather than solving the complicated anisotropic elastic wave equation, many researchers focus on developing simple two-way wave equation to perform acoustic anisotropic RTM of pressure data.

In this paper, the pseudo-acoustic two-way wave equation in TTI media has been discussed. Because RTM require forward wave propagation from source and backward wave propagation from receiver, the developed TTI wave equation can be directly used for anisotropic prestack RTM algorithms. In this paper, prestack RTM in TTI media will be introduced and comparisons between isotropic, VTI and TTI RTM on BP TTI benchmark dataset are presented to validate the algorithm and show its capacity to adapt to lateral variable velocities and anisotropic parameters.

Evidence of Dinosaur Herbivory in the Aguja Formation of Big Bend National Park, TX

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The Upper Shale Member of the Aguja Formation, in the Gano Springs area of Big Bend National Park, TX, yields abundant dicotyledonous wood of the types Baileyan Big Bend Wood type I, and Platanoid/Icacinoid wood of Wheeler and Lehman (2000)[1]. These wood types occur in only one horizon in the Aguja Formation, which, coincidently, also yields the greatest abundance of hadrosaurid and ceratopsian dinosaur remains, suggesting a possible ecological connection. Paleopalynomorph analysis indicates that this area was also characterized (dominantly) by conifers and (rarer) magnoliopsid-type plants. Analysis of the lithology from field observations and petrographic analysis indicates a moist floodplain environment with minor marine tidal inundations and occasional areas of stagnant water. Thus far I have investigated signs of herbivory on the Baileyan Big Bend Wood type I, and Platanoid/Icacinoid wood types primarily through use of thin section/microscopy and visual inspection of pollarded areas of the fossil wood specimens themselves. Most significantly, thin sections of wood show clear evidence of 1) extensive mechanical damage, and 2) extensive removal of stems in juvenile regions of the aforementioned wood types, with prolonged growth after the events (i.e., - not synchronous with the death of the plant). Visual inspection of pollarded regions of the fossil wood specimens themselves is most consistent with shearing of branches, although much more work and experimentation must be done to confirm this. The above two lines of evidence are significant in light of the lack of apparent environmental mechanical causes of branch-removal (i.e., - flooding events capable of producing such damage). Although thin sections of coniferous wood from the locality possibly indicate irregular, though somewhat frequent, flooding and water-level-fall cycles, lithological analysis does not indicate that such flooding events were particularly strong or forceful.

[1]Wheeler, E. A., and Lehman, T. M., 2000, Late Cretaceous Woody Dicots from the Aguja and Javelina Formations, Big Bend National Park, Texas, USA: IAWA Journal, v. 21, no. 1, p. 83-120.

Ogallala Silcretes of Garza County, Texas

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Silicified sandstone and caliche beds ("silcretes") are found within the Miocene Ogallala Group at several sites along the Caprock Escarpment in Garza County, Texas**.** The silica occurs as an interstitial cementing agent, as a void filling, and as partial replacement of calcite. Silica phases are opal, opal C-T, and chalcedony. The detrital components of the sandstone beds, particularly the clay and carbonate content, appear to have influenced the silica phase that precipitated. Petrographic investigation indicates that the silcretes formed through groundwater precipitation. Initial precipitation of opal occurred in voids and interstices between framework grains, and later by replacement of carbonate matrix and detrital bioclasts. Early Native American inhabitants of the Southern High Plains exploited and utilized the local abundance, induration, and sharp conchoidal fracture of the Ogallala silcretes for expedient tool production.

Evidence for synmagmatic tilting of an S-type intrusive complex, Norway.

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The Helgeland Nappe Complex (HNC) formed and was intruded by the Bindal Batholith near Laurentia during the Taconian orogeny [e.g. 1]. The HNC was then accreted to Baltica during the Scandian orogeny, but it was not greatly overprinted by Scandian deformation or metamorphism [e.g. 1]. This makes it possible to study Taconian metamorphism and plutonism within the Norwegian Caledonides. Metasedimentary rocks of the HNC and S-type granitic and diatexitic rocks of the Bindal Batholith are exposed on the island of Ylvingen. The contact between the metasedimentary and plutonic rocks is covered but inferred to strike subparallel to metamorphic rock foliation. The contact between the Ylvingen granite and S-type granodiorite, which is exposed mainly on the island of Vega, is oriented subparallel to magmatic foliation. The Ylvingen granite and Vega granodiorite also have overlapping zircon crystallization ages [2]. Magmatic cordierite is present only in the southern and wetern parts of Vega, and kyanite is present only in the eastern part of Vega and on Ylvingen. These observations combined with previously published P-T estimates indicate that the Vega-Ylvingen intrusive complex is tilted.

Maximum pressure estimates obtained by bulk rock thermodynamic modeling range from ~7-8 kbar for the Ylvingen metasedimentary rocks. Peak modeled temperatures range from 560-640 °C for two metapelite samples collected <150 m from the contact with the plutonic rocks, whereas the peak modeled temperature for a metagreywacke sample collected ~500 m from the contact is <550 °C. The inferred pre-melting assemblage of a diatexite sample equilibrated between 6.0 and 8.5 kbar and 450 and 640 °C. Textural observations used in conjunction with the modeled P-T diagrams suggest that the metasedimentary and diatexitic rocks were metamorphosed along clockwise P-T paths.

The modeled thermal gradient in the metasedimentary rocks suggests that the covered pluton–host rock contact is intrusive and that pluton emplacement was coeval with peak metamorphism in the metasedimentary rocks. The modeled P-T path for the diatexite sample suggets that decompression to <5 kbar occurred in the presence of melt. This indicates that the tilting of the Vega–Ylvingen intrusive complex was synmagmatic and occurred during the Taconian orogeny.

[1] Roberts et al. (2007) *GSA Memoir* **200**, 357-377.
[2] Barnes et al. (2007) *Geosphere* **3**, 683-703.

A High-Precision Digital Model of the Grayburg Formation, Last Chance Canyon, Guadalupe Mountains, New Mexico: Interpreting Stratal Architectures and Facies Transitions, Using State of the Art Technology

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Last Chance Canyon is located in southeastern New Mexico, in the Guadalupe Mountains 20 km northwest of the Capitan Escarpment. The Grayburg Formation (Late Permian, Guadalupian) is well exposed on the canyon walls throughout the area. The purpose of this research is to build a three dimensional (3-D) framework model of the Grayburg Formation in order to better understand the sequence stratigraphy, stratal architectures, and facies transitions. Such knowledge is useful in characterization of the subsurface hydrocarbon reservoirs in the Grayburg Formation. I integrated traditional geological methods with non-traditional state of the art technology. This was accomplished by incorporating light detection and ranging (LIDAR), Differential Global Positioning System (DGPS), and three dimensional (3-D) point cloud processing software packages to generate a digital 3-D map of the Grayburg Formation in Last Chance Canyon. In GIS, a digital elevation model (DEM) of the scanned area was generated from the LIDAR scan data. Digital aerial photographs of the study area were draped over the DEM and yielded the 3-D prospective view. Using Cyclone, several photos were draped over a 3-D point cloud of the scanned area and used to make visual interpretations.

Lithofacies Analysis and Sequence Stratigraphy of the Fredricksburg Group (Cretaceous) in the Callahan Divide Region West-Central Texas

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The Early Cretaceous Fredericksburg Group of central Texas is composed of the Antlers Sand and overlying Walnut / Comanche Peak, and Edwards formations; however, these units are not differentiated in the Callahan Divide region. The goal of this study is to examine the lithofacies and interpret the depositional systems and sequence stratigraphic framework of the Fredericksburg Group in the Callahan Divide region since no recent work has examined the evolution of these depositional systems in a sequence stratigraphic framework.

To achieve this goal, measured sections (field descriptions) and spectral gamma ray profiles along selected measured sections will be created across the field area. These measured sections will provide 1) detailed lithofacies descriptions and define the lateral / vertical distribution of these lithofacies across the study area 2) spectral gamma ray profiles will be used to identify geochemical facies that might be useful for identifying particular depositional environments or sequence stratigraphic systems tracts. In addition to this, a detailed petrographic analysis will be conducted of all of the various lithofacies of my measured sections to determine the microfacies associated with each lithofacies. Interpretation of the depositional systems will thus be created based upon the field – based lithofacies, petrographic microfacies, and spectral gamma – ray chemofacies distribution. All the work done will be couched within a sequence stratigraphic framework defined by recognized chronostratigraphically significant surfaces such as sequence boundaries and transgressive surfaces.

Local and Regional Crustal Structure: A Beamforming Comparison.

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The method of beamforming is a well known data processing step in reflection seismology to improve signal to noise ratio and remove spurious arrivals, but has rarely been used in receiver function processing. In receiver function analysis, we interpret Ps conversions from broad band recordings of teleseismic events (from 30 to 90 degrees away). These teleseismic events arrive at nearly veritcal raypaths, so the presumtion is that the vertical components contain all P phases and P reverberations. By deconvolving the radial component of the sesimogram by the vertical, the source mechanism is removed, as well as all P reverberations (i.e. PPp). This generally results in a radial receiver functions containing P-to-Sv phases and subsequent reverberations. The transverse components will contain P-to-Sh phases which are generally zero, unless there is significant dip or anisotropy. The vertical component deconvolved by itself is a delta funciton, but can be used to correct the anplitudes on the raidal components. We have found that by beamforming the vertical component using recordings of the same event recorded at stations within 300 km of a central station, we produce a much cleaner estimate of the earthquake source funtion. In most regions there are enough variations in the depth to the Moho or crustal velocities that the reverberations (PPdp phases, d indicating depth of the final reflecting interface) in the beamed vertical component are removed. As a result, we can deconvolve the local veritcal component by the beamed vertical component and recover the PPdp reverberations. This results in a three component receiver function with one component independent of the Vp/Vs ratio. To try and futher improve receiver functions, we are producing beamed seismograms using local stations spread over no more than 20 to 40 km and deconvolving them by vertical component beamed over 300 km (radius). Examples will be shown using data from the southern California Anza array and the transportable array in areas with deep sediment cover.

Review and revision of Late Silurian Spathognathodontid conodont taxa of the south-central United States.

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The Spathognathodontid family of conodonts produced several groups during the Late Silurian and Early Devonian with relatively conservative, carminate P1 elements. Because these forms tend to develop intergrading morphologies, they have resisted resolution into convenient, reliable taxonomic divisions. Study of collections from the south-central United States (Henryhouse and Haragan Formations, south-central Oklahoma; Frame Formation, west Texas; Bainbridge Formation, south-eastern Missouri; Decatur and Ross Formations, western Tennessee) has provided additional data to help both in the resolution of taxa and in the establishment of geographic and biostratigraphic ranges. At least four morphotypes of the complex *remscheidensis/eosteinhornensis* group have been identified, including the first recorded occurrence of "Ozarkodina" (New Genus W of Murphy et al.) *eosteinhornensis* in Oklahoma. P1 elements with incipient terraces on the basal cavity grade into forms that can possibly be assigned to "Ozarkodina" *planilingua*. Variation in P1 element denticle morphology within the *remscheidensis/eosteinhornensis* group ranges from fine, needle-like denticulation, through the majority of specimens with uniformly sized, triangular or palisade-like denticles, into specimens with extremely irregular denticulation that resemble, but differ from the P1 elements of the much younger species *Zieglerodina remscheidensis*. Other Spathognathodontids include *Ozarkodina martinssoni auriformis* in Ludfordian strata and the *Oz. snajdri-crispa* transition crossing the Ludlow-Pridoli boundary interval. Preliminary comparisons with collections and published descriptions from Europe, Australia, and elsewhere in North America suggest that the Silurian and Devonian Spathognathodontidae may have some unutilized potential for correlation worldwide.

An Examination of a West Texas Playa Lake by Geophysical Means.

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Frequently it is difficult, impracticle and/or undesirable to physically sample soil and rock underlying a specific location, due to cost limitations or difficulty obtaining samples. Various electrical, magnetic, and seismic methods have been developed to non-invasively investigate the subsurface. When subsurface sampling is possible geophysical tools make it possible to intrepolate extrpolate geological observations away from the hole. This study is an investigation of a West Texas playa lake using electromagnetic, seismic, electroseismic, and physical sampling. There are several goals for this study. First is to map the playa lake substructure. Of special interest will be to determine if the caliche layer known to be regionally present at approximately two meters depth has become reduced in integrity or removed through solution due to the infiltration of acidic water. Second, models will be developed that explain the variations in seismic/electrical velocity due to changes in porosity and bulk density. Third, three-dimensional models will be developed to explain variations in electrical/magnetic conductance. The models will be compared to and constrained by physical sampling.

Structural Analysis of the Late Paleozoic Fresnal Fault, Sacramento Mountains, NM

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The Sacramento Mountains of south-central New Mexico are a north trending, east tilted fault block range which marks the eastern boundary of the Basin and Range extensional province. Cenozoic uplift of the range exposed late Paleozoic folds and faults, which are the focus of this study. The main fault within this study area is the Fresnal Fault. . The Fresnal Fault is a major, north-south tending high angle fault of the Virgilian and early Wolfcampian. The initial displacement is evident by the uplift and erosion of the Holder Formation into deposition of the Permian Laborcita and Abo Formations to the north of the field area. Many workers have interpreted the Fresnal Fault as being a compressional failure resulting in recumbent drag folding. This is evident because axial planes of local folds are sub-parallel to the trend of the fault. This fault is interpreted to be a product of inversion tectonics, in which the fault is a reactivation of extensional faults during Proterozoic rifting of cratonic crust [4]. Reactivation occurred by the stresses produced from the Ancestral Rocky Mountain contractional event. As of now, it is not quite understood what the kinematics of the fault are in relation to the Dry Canyon Syncline to the west and the Caballero Anticline in the south-east portion of the study area. Observations indicate that structures along the Fresnal Fault suggest fault propagation folding of the hanging wall of the fault.

Only a few have published their hypothesis regarding the kinematics of the Ancestral Rocky Mountain orogeny. Kluth and Coney (1981) [1], propose that intracratonic uplifts that formed during late Pennsylvanian are related to the collision of North America and South America-Africa which produced the Ouachita-Marathon orogeny. Ye et al. (1996) [2] interprets the deformational event as being a Andean style deformation associated with north-east south-west crustal contraction due to shallow dipping subduction of oceanic crust. Folds adjacent to the Fresnal Fault exhibit a shortening direction that are directly associated with Ye at al. (1996) model of north-east to south-west crustal contraction. This paleo-tectonic model seems to be more consistent with the deformation in the area, although there are still many questions left to be answered.

[1] Kluth, C.F., and Coney, P.J. (1981) *Geology*, v. 9, p. 10-15
[2] Ye et al. (1996) *AAPG Bulletin*, v. 80, no. 9, p. 1397-1432
[3] Marshak et al. (2000) *Geology*, v. 28, no. 8, p. 735-738

Why is the Late Ordovician Hirnantian δ^3C Excursion (HICE) Missing Across the North America Midcontinent Region?

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A major positive $\delta^{13}C$ excursion (+3‰ to +6‰) is documented during the Late-Ordovician Hirnantian strata in North Africa, China, Europe, and Canada that correlates with eustatic sea-level changes throughout a major Gondwanan glacial episode [1]. Although the Hirnantian isotope event (HICE) is recently reported to be in carbonate mudstone facies at one section of southern Missouri, it is absent in the supposedly coeval oolitic facies in Missouri. In this study, Hirnantian oolitic limestones from ten different localities extending from west Texas to western Tennessee are analyzed for carbon isotopes in search of the HICE. The widespread North American Midcontinent Hirnantian oolite facies represents a regressive phase that relates to changes in sea level caused by global cooling and glaciation during the Hirnantian [2]. The $\delta^{13}C$ carbonate signature of strata from each locality lies between -1‰ and +2‰, except for samples in the basal Fusselman oolite from the West Texas subsurface and samples of the Noix Oolite from Missouri. Samples of the Fusselman oolite range between +2‰ and +3.18‰, whereas the Noix samples are about -2‰. The major peak in $\delta^{13}C$ characteristic of the HICE appears to be absent in all sections examined. The absence of the HICE peak may be a result of regional post-depositional diagenesis. This could result in a local $\delta^{13}C$ overprint that represents a local shallow marine paleoenvironment rather than glacial melting on a global scale [3]. A second possibility for the absence of the HICE peak may be due to the biological aspects regarding the formation of ooids. There is a possibility that the ooids themselves have a $\delta^{13}C$ signature that may have altered results in each area studied. Lastly, it is possible that strata coeval with the HICE is absent across the North American Midcontinent region.

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[2] Bergstrom, Stig M., Saltzman, Matthew M., Schmitz, Birger.2006. First Record of the Hirnantian (Upper Ordovician) $\delta^{13}C$ excursion in the North American Midcontinent and its regional implications. Cambridge University Press 143, 657-678.
[3] Amsden, Thomas W., Barrick, James E. 1986. Late Ordovician-Early Silurian Strata in the Central United States and the Hirnantian Stage. Oklahoma Geological Survey, 139.

Geothermometry of Pelitic Gneiss in the Little San Bernardino Mountains, Southern California

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Quartzofeldspathic and biotite gneisses, locally containing abundant garnet, are exposed between Mesozoic plutonic rock bodies in the Quail Mountain area of the Little San Bernardino Mountains. Garnet-bearing gneisses were collected with the objective to analyze the Fe-Mg distribution between garnets and biotites in metapelitic rocks in order to obtain temperature estimates and determine metamorphic conditions. Mineral phases present in metapelitic rocks include quartz + plagioclase + garnet + biotite + fibrolite + prismatic sillimanite + cordierite + zircon. Quartzofeldspathic rocks have the assemblage amphibole + quartz + biotite + plagioclase. These two mineral assemblages are consistent with the upper amphibolite to granulite facies. Mineral chemistry was determined through electron microprobe (EMP) analysis. For garnets, the almandine end-member composed 79 to 86% of the analyzed garnets. The pyrope end-member made up 8 to 15 % of the overall composition of the garnets. Diffusion zoning is present around the edges of the garnets. In biotite, total Fe and Mg concentrations range from 2.4 to 3.4 % and from 1.6 to 2.3 %, respectively. Several garnet-biotite geothermometers were applied to these compositions to determine the temperature conditions of metamorphism. The maximum temperature determined was 670^o C $\pm$ 30^o C. Lower edge temperatures, which are 590^o C $\pm$ 25^oC, are inferred to represent continued diffusion during retrograde cooling and exhumation of these gneisses. Because of the mineral assemblages include the key phases cordierite, plagioclase, garnet, and zircon, it will be possible to determine the age and the pressure during metamorphism. If these gneisses were metamorphosed due to the intrusion of the Mesozoic plutonic rock bodies, this would predict a Jurassic to Cretaceous metamorphic age at pressures equivalent to those determined using hornblende + plagioclase assemblages in the plutons.

Polyphase Structures and Passively Emplaced Plutons in Northern Sierra Del Carmen, Big Bend Region, Texas.

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Geologic mapping at 1:10,000 scale of a 60 km^2 area on and near Dagger Mountain in Sierra del Carmen within northern Big Bend National Park and adjacent Black Gap Wildlife Management Area reveals four deformation phases (D1 – D4) in Cretaceous rocks, as well as diverse passively emplaced intrusions. D1 folds are outcrop-scale penecontemporaneous folds in the Boquillas Formation. NNW-striking upright and overturned D2 folds and coeval thrust faults correlate with the primary Laramide deformation phase throughout the Big Bend region. The Dagger Mountain doubly plunging anticline and an adjacent doubly plunging syncline cored by a mafic sill are D2 Laramide structures within a Type 1 interference figure [1]. Previously little-recognized gentle, map-scale, upright NE-trending D3 folds refolded map-scale D2 folds. Abundant mafic sills and other intrusions did not reorient adjacent outcrop-scale

D2 folds. To the west the South Persimmon Gap "laccolith" is a stack of felsic sills that inflated the overall thickness of the Aguja Formation but do not produce outcrop-scale or map-scale folds or faults. In contrast, forcefully emplaced laccoliths are scattered throughout the Big Bend region, including the Iron Mountain pluton, McKinney Hills laccolith, Aguachile fluorspar district plutons, Packsaddle Mountain laccolith, and Christmas Mountains dome. Late Cenozoic D4 NNW- and NW-striking high-angle faults offset felsic and mafic sills. D4 drag folds are localized near D4 faults. A grid of five cross-sections across Dagger Mountain shows that the Dagger Mountain D2 anticline is allowably a fault-propagation fold above a blind thrust.

[1] Ramsay (1967) *Folding and Fracturing of Rocks*, 568p.

Elasmobranch and Osteichthyan Fauna of the Rattlesnake Mountain Sandstone, Aguja Formation (Upper Cretaceous, Campanian), West Texas.

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Fossil remains of sharks and bony fishes are relatively common in Upper Cretaceous marine strata throughout western North America. Although similar remains have been reported from the Aguja Formation in West Texas, only a few specimens from the upper part of the formation have been illustrated and no thorough account of the Aguja shark and bony fish material has been presented. The primary goal of the present research is to provide systematic descriptions and illustrations of a diverse shark and bony fish assemblage recently discovered in the middle part of the Aguja Formation (Rattlesnake Mountain sandstone member).

Tyrannosaurid Bite Marks on an Upper Cretaceous Hadrosaur

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Bones of hadrosaurian ("duck-billed") dinosaurs rarely occur in the Upper Cretaceous Javelina Formation in Big Bend National Park. One specimen comprises parts of a lower leg, ankle, and both feet of a single large hadrosaur. This specimen is particularly interesting because the surfaces of the bones have bite marks attributable to a large scavenger or predator. Based on the size and shape of the bite marks, and preservation of a broken tyrannosaurid tooth among the hadrosaur bones, most of the 104 marks were made by a large tyrannosaurid dinosaur. The size distribution of the bite marks suggests that some were made by smaller animals. The most intensely bitten elements are the tibia, a left proximal phalanx of digit IV, left metatarsal III, and right metatarsal IV. Puncture marks are concentrated on the distal ends of these elements. There is debate regarding whether tyrannosaurid dinosaurs were scavengers or active predators. However, of the many hundreds of bones collected from the Javelina Formation these are the only examples with bite marks thus far reported. A few tyrannosaurid bite marks have been documented on hadrosaurian and ceratopsian dinosaur bones from other strata, but none of these are as intensely bitten as the specimen described here.

Analysis of Precipitation and Saturated Thickness in the Texas Ogallala Aquifer

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The Ogallala Aquifer is a major source of groundwater on the Texas High Plains. Water drawn from the aquifer is widely used to support irrigated agriculture. The aquifer serves as a major source for both domestic and municipal water supplies. Although it is widely recognized that water levels in the aquifer are declining at an average rate of about one foot per year, this average value masks considerable variability in rates of water level decline. To better understand the spatial variability in groundwater depletion, tabular data from the state well-monitoring network were geocoded and used to map the saturated thickness of the aquifer for each year from 1990 to 2009.

This project was undertaken to map changes in the saturated thickness of the aquifer in comparison to precipitation rates. To map the saturated thickness, a layer representing the elevation of the base of the aquifer was subtracted from water level elevation surfaces for each year from 1990 to 2009. The results from this analysis show a strong spatial correlation between the saturated thickness of the aquifer and rates of aquifer decline. Those rates of decline were compared with seasonal variation in precipitation rates. In areas where saturated thickness is greatest, water level elevations are dropping at a much higher rate. Conversely, where saturated thickness of the aquifer is thin, water level elevations tend to be more stable. However, the amount and time of year of precipitation had a minimal effect on the rate of decline for water level elevations.

Field Relationships and Zircon Constrain Relative Timing of Peraluminous Magmatism and Metamorphism in the Ruby Mountains, Nevada.

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The Ruby Mountain-East Humboldt Range metamorphic core complex (northeast Nevada) experienced multiple periods of protracted peraluminous magmatism between 160 and 29 Ma. Zircons from many of the granitic rocks have discordant ages leading to conflicting models for magma generation and the magnitude and duration of partial melting events. A detailed map of a complex polylithological outcrop with clearly defined crosscutting relationships located near Liberty Pass was prepared to better constrain the relative timing relationships between different magmatic events. Accessory minerals from pegmatitic muscovite granite gneiss were characterized using back scatter electron (BSE) and cathodoluminescence (CL) imaging. The pegmatitic granite gneiss represents the geochronologically most complex lithology in the core complex and is an important key to establishing the nature, duration and timing of magmatism between ~90 and ~40 Ma. The complexity is reflected in zircon separated from the granite. Based on morphology and BSE and CL imaging, there are at least three populations: euhedral prismatic zircon characteristic of igneous crystallization; a rounded morphology that has been surrounded by an overgrowth and an elongate population that has been altered. All three populations share similar chemical characteristics, which may be the result of spot size resolution. However, inherited cores and alteration do account for some variation in the chemical signature, especially the U, Th, and Pb concentrations. Clearly defined cross cutting relationships and intra grain heterogeneity of zircon favors a model of distinct and separate geologic events, rather than a period of (40-50 Ma) of prolonged melting and magmatism.

Taphonomy of Hadrosaurid Skeletal Elements in the Aguja Formation in Big Bend National Park: Preservation Bias due to the Effects of Spongiosa versus Compacta Ratio.

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Isolated hadrosaur skeletal elements are the most common large vertebrate remains found in the Aguja Formation of West Texas. Published itemized specimen data and material recently collected (252 specimens total) provide the basis for a taphonomic assessment of relative preservation and transport potential of hadrosaur skeletal elements. There is a predictable preservational bias favoring larger hind limb bones. These large elements (femora, tibiae, metatarsals) also tend to have relatively greater volume of compact bone tissue compared to spongiosa than many of the less well-represented elements. Although vertebrae (particularly mid-caudal and dorsal centra) have a high volume of spongiosa, and are well represented (about 40% of specimens), their abundance likely reflects the large number possessed by each individual and not their great durability. Observed bone macro assemblages probably reflect distinct hydraulic dispersal categories, or 'Voorhies Groups.' Group I assemblages are those readily removed by low-velocity currents, and include bones with high spongiosa to compact bone ratio (S/C ratio), high surface area to volume ratio (SA/V ratio), and low nominal diameter (Dn). Vertebrae, skull material and other highly cancellous and rare elements comprise Group I (e.g., dorsal vertebrae with S/C ratio >10, SA/V ratio >1, Dn < 6 cm). Group II elements comprise those transported by moderate currents and have intermediate S/C and SA/V ratios and Dn values. Group III elements comprise 'lag' assemblages moved only by high-velocity currents and have low S/C and SA/V ratios, and high Dn values (e.g., femora with S/C <1, SA/V <1, and Dn > 20 cm). As with sedimentary particles, the skeletal elements with higher Dn require higher critical shear velocity for transport, so some small elements (e.g., metacarpals) with Dn values < 10 are found in Group I or Group II although both S/C and SA/V may be <1. In the Aguja Formation the most commonly preserved hadrosaur skeletal elements (excluding vertebrae) represent Groups II and III.

Quartermaster Tephera depostited in a Dissolution Basins

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Tephras (volcanic ash deposits) appear intermittently in the late Permian, early Triassic Quartermaster formation of West Texas. The tephras were most likely produced from the western Pangean arcs of eastern Mexico. The purpose of this research is to examine a thick tephra at Dickens, Texas and then characterize its spectral gamma ray signature and lateral variability.

Four sections were measured over an area .5 miles to determine the change of the tephras. Gamma ray spectrometry was taken in tephras and surrounding clay layers. To determine if the Quartermaster tephras were deposited in a dissolution basin, strike and dip was taken throughout the section.

Results indicated that the main Quartermaster tephra in the Dickens area was deposited in a small syncline and was formed from salt dissolution that occurred in the lower lying Permian beds. The tephra thins and becomes more clay rich along the edges of the syncline. The thickest part of the tephra exhibited high API GR values due to high concentration of thorium (Th) and potassium (K). The potassium levels in the tephra decreased in the outer limbs of the syncline. Thus, preservation of the Quartermaster tephra was preserved in the dissolution basin.

Sequential Extraction and Microscope Study of Contaminated Soils at the Anaconda Smelter Site, Montana, USA

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The Anaconda Copper Smelter site in Montana, USA, is an Environmental Protection Agency (EPA) superfund site. Smelter waste, comprising high metal concentrations, was disposed of at the site over a nine decade period. Copper porphyry ore was the primary material processed at the smelter, and included chalcocite (Cu_2S), bornite (Cu_5FeS_4), and enargite (Cu_3AsS_4). The primary metal phases at the Anaconda Smelting site are metal-sulfides.

Two sequential extraction leaching procedures, the Tessier method[1] and EPA Method 3050B, were performed to determine the distribution of metals in a suite of soil samples collected from the smelter site. Five metals, including As, Cd, Cu, Pb and Zn, were of particular interest. In addition, soil samples and residues from the extraction analyses were characterized by thin-section microscopy and Scanning Electron Microscopy (SEM).

The Tessier sequential extraction technique defines metal fractions (adsorbed or bounded to specific minerals) by four leaching steps. For the three contaminated undisturbed soil columns, soil samples show variation in major metal reside fraction between the topsoil and subsoil samples. Total extractable content for each metals peaks at the subsoil samples. This indicates metal vertical migration as a result of percolation.

The SEM imaging showed clear variations in grain morphology between sieved un-reacted soil samples and the soil residual that resulted from each sequential extraction step. The sieved soil samples (grain size of ≤ 0.250 mm) comprised large framework grains, which were fully or partially coated with micro-crystalline particles (possibly iron-oxides, sulfides or clay phases). Following the extraction step for "bound to sulfide fraction metals", most sub-micron particles were absent from the surfaces of the framework grains.

[1] Tessier et al. (1979) *Anal. Chem.* **51**, 844–851.

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