# GEODAZE 2014 ABSTRACTS

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Oral Sessions

Economic Geology

Paleogeographic and paleoclimate reconstructions of iron-oxide copper gold and sediment-hosted copper deposits: implications for ore-forming processes
Ada R. Dominguez, Mark D. Barton

This project examines the paleogeographic (paleoclimate, magmatic) distribution of two major types of ore deposits – sediment-hosted copper (SHCu) and iron-oxide copper gold (IOCG) – to test hypotheses about global-scale controls. Both SHCu and IOCG systems require brines to transport Cu, Co, Ag, Au, and Fe (solubility increases with Cl⁻ and, for Fe and Au, with T). However, the sources, timing, and drives for the ore-forming fluids are controversial. Saline fluids can have magmatic or non-magmatic (typically evaporitic) origins. High T can be achieved by input of magmatic heat, or by rapid flow from mid-crustal levels or below. A key test of alternative models is to see if these deposits correlate with arid climates or older evaporites, and (in the case of the hotter IOCG systems) with magmatism.

In this study, paleogeographic reconstructions (0-600 Ma) incorporating magmatism and paleoclimate were used to plot where deposits formed as a function of time. Location data from 215 IOCG and 522 SHCu deposits were assembled from various sources and their original coordinates were recalculated to obtain their paleocoordinates. The paleogeographic and paleoclimate models were adapted from Scotese (2007, 2008, 2009, 2011, 2013); magmatism was compiled from multiple sources. We find that 73% of SHCu and 90% of IOCG deposits formed in arid settings. The balance formed almost exclusively in either tropical or warm climates.

Although climate and, thus, brine availability are key factors (many rocks are adequate metal sources), igneous influences must be considered. Only 9 out of >500 SHCu deposits (which form at ≤250°C) showed any association with magmatism (5 in arcs, 4 in rifts). Conversely, only 1 out of 211 IOCG systems (which form at 200-600°C), lacks associated magmatism. Of the rest, 113 were associated with arc magmatism, and 97 occur with rift magmatism. The lack of correlation with tectonic regime and magma type, compared to the strong correlation with climate (aridity) implies that evaporitic rather than magmatic brines are key. Magmas provide only the heat and drive for the ore formation. Thus paleoclimate, particularly aridity, is critical in generating SHCu and IOCG ore deposits.
Scale and significance of variability in dolomite alteration at the Tenke-Fungurume Cu-Co district (TFM) of the Central African Copperbelt
Isabel Fay

Ongoing research into the formation and evolution of the Copperbelt’s Cu-Co resource includes the character of altering fluids and the scale of their flow. To estimate these, paragenesis and composition of alteration minerals were examined at 17 rafted fault blocks of ore-hosting strata over 20 km of TFM. Of these, 13 show the same mineral textures and compositions. Following sedimentary dolomite, the earliest alteration phases were pyrite and chalcedony of uncertain relative timing. The next stage brought dolomite in first a blue-gray, then a white form, accompanied by carrollite, bornite, and chalcopyrite; then quartz replaced much of the dolomite. It was overgrown by a second dolomite with the same composition as the first and like it associated with Cu-Co-Fe sulfides. Over the study area, the dolomites are constant in composition and CL signature, although the second is slightly more Fe-rich than the first and luminesces darker than its medium red. However, both are relatively low in Mn and Fe. A third, crosscutting dolomite, intergrown with malachite, has millimeter-scale banding easily visible in CL, and its composition ranges between Ca0.964-0.997Mg0.896-1.031Fe0.002-0.881Mn0.001-0.019(CO3)2. Its sequence of bands and distribution of compositions are erratic. The other 4 blocks examined lack the ore and the white form of the first dolomite, but their minerals’ parageneses and compositions are otherwise the same as in the other 13.

The low Mn and Fe contents of the early dolomites indicate that they formed from relatively oxidizing fluids, like most sediment-hosted Cu deposits; the consistency of their compositions over space suggests that the formative fluid system extended over at least 20 km with remarkably uniform conditions, like MVT systems. This may help establish a lower limit on the size of individual fluid systems in the ore-forming basin. The absence of ore and one of the early dolomites from 4 blocks suggests that they were occluded during one stage, but the presence of the later alteration minerals indicates that they were afterward accessible to fluids. Local effects dominated later, creating supergene dolomites with strong compositional variations erratically distributed. Thus, large fluid systems may have controlled Copperbelt ore distribution, and local ones its redistribution.
The distribution of rhenium concentrations in molybdenite in ore deposits
Christian Rathkopf

Rhenium, though rare in the Earth’s crust (0.4 ppb), is observed in many types of ore deposits at a wide range of concentrations [C(Re)] within the crystal structure of molybdenite—commonly between 0 and 2,000 ppm. It is hypothesized that the distribution and variance of C(Re) in molybdenite may be causally linked, and therefore may correlate, with other geologic traits of ore deposits, including deposit type, metal ratios, alteration, and intrusive lithology. With a greater understanding of such correlations, C(Re) in molybdenite could be used as a tool in mineral exploration. To test this hypothesis, a database of C(Re) values has been compiled from a comprehensive literature review of deposits worldwide as well as from new analyses of molybdenites from the Bagdad porphyry Cu-Mo deposit.

The database of C(Re) in molybdenite is being compiled from a diverse body of published data sets, including many Re-Os geochronology studies. Currently, it includes >615 data, from >26 countries, <52 deposit sub-types, and >220 localities. The lowest average C(Re) values are found in W-Sn deposits (C(Re)=86 ppm; σ=327 ppm; n=102) and the highest average values are found in porphyry Cu-Mo deposits (C(Re)=1,514 ppm; σ=5,260 ppm; n=165). Additionally, the distribution of C(Re) is being examined at the deposit scale with high-precision electron microprobe analyses on molybdenite samples from the Bagdad porphyry Cu-Mo deposit. In combination with published data, microprobe analyses of >6 distinct molybdenite assemblages confirm a similarly large variation in C(Re) at Bagdad (399.2 ppm; σ=336 ppm; n=35). The lowest observed C(Re) is hosted by a porphyritic quartz monzonite, whereas the highest C(Re) is hosted by a porphyritic granite. A wide variation in C(Re) is also observed within individual crystals (ex. C(Re)=183 ppm; σ=166 ppm; n=8).

Although the investigation of C(Re) in molybdenite as a tool for mineral exploration is still in its early stages and many uncertainties remain, preliminary results corroborate that C(Re) can be both highly variable and distinct between deposit types, host lithologies, as well as within individual crystals. The validation that certain geologic traits can be associated with distinctive ranges of C(Re) is promising. Continuing work will be focused on further investigating these correlations as well as correlations with other geologic traits of ore deposits, such as metal ratios and alteration.
Magmatic fluxes in the Andean Coastal Batholith, northern Chile
James D. Girardi

Magmatic fluxes in the Andean Coastal Batholith were determined through the analysis of more than 400 published and 60 unpublished radiometric ages, and spatial analysis between 26° to 28°S for 10, 5, and 3 My average intervals. Magmatic maxima occurred at 240-230 Ma, 200-190 Ma, 160-130 Ma, and 70-60 Ma. Intervening minima are lower by up to a factor of 5. Maximum areal fluxes ranged from 100 to 500 km²/My, which can be recast as 0.5 to 2.4 km²/My per km of strike length, or 13 to 60 km³/My per km of strike if a batholith thickness of 25 km is assumed. Batholith formation occurred mainly during ~200-100 Ma, with initial granodioritic magmas that evolved to overall dioritic compositions with uniformly depleted mantle-like Nd isotopes as magmatic activity increased during high rates of back-arc extension. After 100 Ma the arc became contractional and granodioritic magmas became volumetrically abundant. These results are parallel to data from 15°S to 34°S and are therefore consistent with a similar evolutionary history over >2,000 km of the Mesozoic western South American margin.

By comparison, Mesozoic Cordilleran arcs of North America had granitic-granodioritic and tonalitic peak fluxes that were greater by a factor of ~1.5-2.0; they correlate with contractional tectonism and record considerable reworking of older crustal materials. Comparison with island arcs reveals that episodic 10-40 My duration Cordilleran magmatic peaks are matched in average output by island arcs for timescales that are greater by an order of magnitude or more. Cordilleran “flare-ups” (fluxes >2σ from the average output over the arcs lifespan) occur when large, > 1000 km² exposure, composite plutonic complexes are emplaced at timescales < 5 My. The similarities in magma fluxes but differences in compositions and tectonic setting of Cordilleran magmatic episodes points to the need to consider multiple contributions to Cordilleran magmatic flare-ups, including differences in the crust (thermal structure, bulk composition, state of stress, and thickness) and of the underlying mantle and slab. Maxima in Andean Coastal Batholith magmatism may reflect rapid reworking of juvenile material generated in response to back arc extension operating on a thinning crust whereas maxima in other regions may reflect fundamentally different processes.
Epithermal mineralization associated with diatreme breccia and rhyolitic dome, La Miel, Haiti: preliminary results
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Synthesis of recent geologic work coupled with new mineralogic, petrographic, and geochronologic studies of the La Miel epithermal deposit offer an improved understanding of its genesis and broader geologic setting. La Miel is an early-stage epithermal exploration project in Haiti. It occurs within the Restauración - La Miel epithermal belt, which is located along the border between Haiti and the Dominican Republic and within a Cretaceous island arc. This belt is the second-largest epithermal district in La Hispaniola, after the world-class high-sulfidation deposit Pueblo Viejo in the Dominican Republic.

The geology of the La Miel system is interpreted based on data from surface mapping and logging of the few holes that have been drilled. The host rocks are Cretaceous mafic and felsic volcanic rocks that strike northwest and dip steeply southwest. These are overlain in fault contact by sedimentary rocks. Alteration and mineralization are controlled by northwest striking faults and lithologic contacts. These structures are cut by normal faults that strike northeast, which are interpreted to postdate ore formation. Banded, brecciated epithermal quartz veins were identified with anomalous gold in an area of 1.5 x 2 km. The SLP target contains multigram gold mineralization that crosscuts a blind phreatomagmatic breccia body identified in drill holes.

Diatreme breccias and felsic domes with a close genetic relationship to mineralization and alteration have been described in many epithermal systems. A new U-Pb zircon age of 84.2 ± 1.4 Ma on a post-mineralization rhyolite dome that is interpreted as the last event in the evolution of the epithermal system constrains the age of SLP. Geochemical analyses and mineralogical studies indicate that mineralization is zoned from Au ±Ag – Zn – Cu at shallower levels to predominant copper at depth. Gold is associated with silica –clay ± sericite alteration. Different events of silica deposition have been distinguished with banded chalcedonic and microcrystalline silica veins associated with sulfides, and clay ± sericite at the border of the chalcedonic event. Adularia has not been detected. Spectroscopic analysis detects illite - smectite associated with mineralization; smectite – chlorite halos at the borders of the system. The deposit may be classified as an intermediate sulfidation epithermal system. Areas within the Cretaceous island arc that are covered by late rhyolite flows or domes are prospective for gold.
The Jackson-Lawton-Bowman normal fault system, Eureka district, central Nevada
Aryn K. Hoge

The Eureka district hosts Cretaceous polymetallic carbonate replacement deposits that have subsequently been overprinted by Eocene (?) Carlin-type gold mineralization, including the 5-Moz Archimedes deposit. This study presents new Anaconda-style mapping and structural reconstructions of the Jackson-Lawton-Bowman normal fault system (also known as the Jackson fault), which has been proposed as a structural control for both styles of mineralization. The study evaluates the possible relationship of the fault system to Carlin-type gold mineralization as well as the geometry, displacement, and timing of its various component segments. Stable isotopic analyses and trace element geochemistry were employed in an attempt to differentiate between alteration associated with igneous-related and later Carlin-type hydrothermal systems.

The Jackson fault runs the length of the Eureka district (21 km). For ~3.8 km beginning at the southern edge of the district, the fault zone is composed of a series of overlapping, steeply (~70°) east-dipping, north-trending fault segments. North of this junction, the main branch splits into three closely spaced, roughly parallel faults, which also dip steeply eastward. Evidence from structural reconstructions suggests that the north-trending Jackson branch and north-northwest trending Lawton branch have dismembered a regional-scale fault-propagation fold, known as the Eureka culmination, in the Late Cretaceous Eureka fold and thrust belt. Offset on both the Jackson and Lawton branches exceeds 1.5 km. A third north-trending fault, previously characterized as a thrust of the Ruby Hill thrust zone, cuts down-section and is more likely a normal fault related to the Jackson-Lawton-Bowman normal fault system. Soil analyses in the northern Eureka district show a subtle Au anomaly adjacent to the compound portion of the Jackson fault, and the trace of the fault coincides with a belt of Cretaceous carbonate replacement mineralization mined in the late 1800s. However, mapped alteration patterns in the district (jasperoid, marble, bleaching, and sanding of carbonates) show no spatial relationship to the Jackson fault.
Normal faults in the Yerington district, western Nevada: Reconstructions based on new structural data from the Ann-Mason and Blue Hill areas
Carson Richardson

This ongoing study within a classic area of continental extension examines the structural evolution of a part of the Yerington district around the Ann-Mason porphyry copper system, where there is >30 km of new drilling by Entrée Gold since 2010. This work involves detailed mapping of two major fault traces, logging intervals of drill core containing the fault damage zones, constructing structure contour maps of fault planes, and developing geologic maps of the immediate footwall and hanging wall (fault surface maps) of several faults.

Six normal faults, representing four distinct geometric sets or temporal generations of faults, are examined in this study. Faults of the three youngest generations, all initially roughly north-striking and steeply east-dipping, are well known from previous work, but faults of the oldest generation, first recognized decades ago but little described in the literature, are now better defined. The youngest (fourth) generation consists of Pliocene to Recent faults that presently dip 50-60°E and include the Montana-Yerington fault (~600 m offset) and Sales fault (~900 m offset). The next youngest (third) generation of faults are late Miocene faults that presently dip 15-30°E, and these are represented by the May Queen fault (~450 m offset). The next youngest (second) generation of faults are middle Miocene faults that currently dip gently east, which include the Blue Hill (~2.8 km offset with increasing displacement to the north) and Singatse (~3.7 km offset) faults. Faults of the oldest (first) generation presently strike northwesterly and dip 60-70°SW. The fault with the most offset is known as the 1A fault. Fault surface maps of lithology provide evidence for ~230 m of sinistral slip on the fault in its present orientation, which is supported by maps of copper grade and alteration. Incremental untilting of the three younger generations of faults restores first-generation faults such as the 1A to south-dipping normal faults. These faults clearly cut the Jurassic Ann-Mason deposit and are cut off by the second-generation Singatse fault, but their ages of movement are not well known. The 1A fault appears to connect with a fault mapped at surface that cuts the Weed Heights Member of the Mickey Pass Tuff (27 Ma), suggesting a late Oligocene to middle Miocene age. This generation of faults at Yerington may have counterparts in eastern Nevada, where east-striking normal faults also formed prior to periods of extreme extension.
Georgius Agricola’s contributions to hydrogeology
Isabel Fay

Georgius Agricola (1494-1555) is best known for helping found modern economic geology and mineralogy, but his work in both fields was based on his ideas about the movement and origins of groundwater. His influential writings on the subject, once well known and used by Boyle, Steno, Kircher, and Werner, have fallen into obscurity in the last two centuries.

Agricola’s De Ortu Et Causis Subterraneorum (Of the Sources and Causes of Things Underground, 1546), though keeping close to the medieval tradition in many respects, nevertheless contained many new concepts. Among them are the first known statement of the erosional cycle; advances in the description of mechanisms of fluid storage and transport; the first concept of water-rock interaction; the novel hypothesis that fluid pressure could fracture rocks; and the first hint of the slowness of geological processes. Though Agricola himself did not develop many of them fully, they opened new fields to later work. They led to quantitative evaluations of the hydrologic cycle by Palissy and Perrault; to the principles of sedimentation of Palissy, Peiresc, Gassendi, and Steno; to Steno’s and Kircher’s understanding of the importance of erosion; to Perrault’s concept of magma motion through the earth; and Boyle’s studies of natural solution chemistry.

Besides planting these early seeds of later geological theories, Agricola helped science in general by replacing authority with observation in his procedure. For instance, he showed by water infiltration into the local Saxon mines that water penetrates much farther into the ground than the ten feet Seneca alleged. He reasoned that the giant “receptacula” that Aristotle and his followers believed stored water underground had never been observed, and that water could just as well be stored in pores in the rock. Its interaction with the host rock, he theorized, dissolved and precipitated minerals. This was the concept he later articulated into the theories of mineral and ore deposit formation in his more famous De Re Metallica (posth. 1556) and De Natura Fossilium (1546). Although not correct in all particulars, Agricola’s meticulous empirical studies represented a major advance for hydrogeology, and deserve to be better known by geologists, who daily use the theories he helped to develop.
Climate and Paleoclimate

The context of southwest North American megadrought
Cody Routson, Jonathan Overpeck, Connie Woodhouse

Extreme droughts that persisted for decades have occurred numerous times in the Southwest. Here we present a set of new climate reconstructions including drought, dustiness, and temperature from the south San Juan Mountains in southern Colorado to help characterize these unusual events. The new drought record is from bristlecone tree-rings, spans the last 2000 years, and shows two periods of anomalous aridity and drought. The first period corresponds with well-characterized Medieval (900-1400 AD) aridity in the Southwest. The earlier interval coincides with the Roman Period (1-400 AD). We highlight a severe drought, characterized by nearly 50 consecutive years of below average tree-growth, which occurred in the middle of the Roman Period during the 2nd century AD. We also developed a new dust reconstruction from a lake sediment core to augment the tree-ring drought record. The dust record confirms anomalous dustiness associated with recent human caused land disturbance, but also illustrates that dust has been an important component of Southwestern climate over the past 2940 years. The record shows high dust deposition around 900 BC and during the Medieval Period. High dust deposition before recent land use changes suggests that megadroughts or associated periods of aridity were severe enough to mobilize dust. Finally, we also developed a biomarker based temperature reconstruction from a complementary lake. The reconstruction spans the last 2000 years and shows that the warmest temperatures occurred during the Roman and Medieval Periods. Both periods of warm temperatures coincide with anomalous drought and dustiness, suggesting that temperature and dust may have acted as megadrought enhancing feedbacks. As global and regional temperatures rise and atmospheric dust loading increases, dynamic interactions between drought, temperature, and dust will critically shape future Southwestern climate.
Patterns and processes of drought in the Northeast United States
Connor Nolan

The Northeast United States is generally not considered drought prone, but the region has experienced severe droughts in the last century (as seen in the instrumental record), the last millennium (as reconstructed by tree rings), and last 10,000 years (as recorded in lake level changes). Synoptic and dynamic controls on drought in the region are poorly understood, even for the 1960s drought, the only major drought in the instrumental record period. This knowledge gap creates uncertainty in the interpretation of paleoclimate proxy records of drought and in projection of future drought risk for the region. In this talk I will show attempts to better understand the patterns and processes of drought in the Northeast US using observations, reanalysis data, and networks of paleoclimate proxies.
Influence of Atlantic Ocean circulation on American tropical rainfall and carbon balance
Luke A Parsons, Jianjun Yin, Jonathan T. Overpeck, Ronald J. Stouffer, Sergey Malyshev

We conduct climate modeling experiments with an Earth system model that explicitly simulates the global and regional carbon cycle to examine the effects of changes in Atlantic Meridional Overturning Circulation (AMOC) strength on the American Tropical rainfall and carbon balance. We find that a moderate weakening of the AMOC drives some small but significant drying in the South American monsoon region. By contrast, a complete shutdown of the AMOC shifts the seasonal cycle of precipitation over Amazonia and reduces total precipitation in much of Central America and northern South America. Our results indicate that AMOC weakening can have a significant impact on the terrestrial primary productivity and carbon storage capabilities of the American Tropics.
U.S. Northeast Coast 2009-2010 anomalous sea level rise event
Paul Goddard, Jianjun Yin

By analyzing long-term tide gauge records, we find an anomalous sea level rise (SLR) event during 2009-2010 along the Northeast Coast of North America. During 2009, the coastal sea level jumped by up to 128 mm. Despite significant year-to-year fluctuation, this magnitude of SLR (above the 95th percentile) is unprecedented for the entire history of the tide gauge records north of New York City (NYC). We show that this anomalous SLR event is associated with an observed 30% transport decrease of the Atlantic meridional overturning circulation (AMOC) from April 2009 to March 2010. Regression analysis suggests that for every 1 Sverdrup (1 Sverdrup = 10^6 m^3 s^-1) of AMOC weakening, sea level rises ~13 mm in the region north of NYC. The unique nature of the 2009 SLR event suggests that the 2009-2010 downturn of the AMOC may not have happened during the 20th century, and its magnitude may provide insight into this region’s 21st century SLR.

Unlike previous studies which focus on land subsidence, wind stress forcing, and/or movement of the Gulf Stream to explain the SLR pattern along the coast, our study primarily focuses on the SLR being induced by density changes in the subpolar gyre. Specifically, our research suggests that an anomalous heat flux into the subpolar gyre during 2009 and 2010 initiated a sequence of events slowing the AMOC, resulting in the anomalous SLR event. The warming of the waters in the eastern subpolar gyre creates a SLR due to thermal expansion adjacent to the continental shelf which cannot be sustained by geostrophic currents. This sharp sea level height gradient between the ocean interior and the area above the shelf will dissipate as waters flow onto the shelf region and towards the coastline.

Our analysis of tide gauge records reveals that the 2009 SLR signal is strongest for a composite of tide gauge stations north of NYC. The signal remains robust in the Mid-Atlantic region from Cape Hatteras to NYC, though the magnitude is much less. South of Cape Hatteras the 2009 SLR signal vanishes. This north-high, south-low pattern of SLR differs from previous research that describes the 20th century SLR pattern as a Mid-Atlantic high. Our research shows that SLR will continue to be most prominent in the Northeast region for the 21st century and that SLR events, such as the 2009 event, may occur more often as the AMOC is projected to weaken under climate change.
Rapid sea level rise on the East Coast of the US analyzed via GPS
Alexandria Will-Cole

The Eastern Coast of the United States displays a trend of sea level rise that is estimated to be three times the global mean. There are two probable causes for such significant rise: sea level rise associated with oceanic circulation and/or land subsidence associated with glacial isostatic adjustment (GIA). Distinguishing between these two has important implications for safety because each represents processes acting over different a vastly different time scale. Oceanic circulation would account for a short-term sea level rise, which evolve on time scales of years to decades. In contrast, the land subsidence caused by GIA would cause relative sea level rise into the foreseeable future. We obtained coordinate time series data from 58 Global Positioning System stations located within 100km of the longest running coastal tide gauges. These time series data reveal vertical crustal motions with sufficient precision to reveal the pattern of coastal subsidence associated with GIA and possibly other processes. Our preliminary analysis of the GPS data reveals that this region of coastline is subsiding at rates in the range of -0.70 to -2.50 mm/yr. This subsidence could be a major factor in the increased rate of sea level rise in this coastal region.
The micromorphology of Younger Dryas-aged black mats: a paleoenvironmental and compositional analysis of unusual desert sediments
Erin Harris-Parks

A micromorphological and geochemical analysis of Younger Dryas-aged (12.9-11.6 ka BP) “black mats” from the SW United States was conducted in order to determine the composition and depositional environment in which these desert strata form. Twenty black mat samples were collected from previously documented and radiocarbon dated sites in Arizona, New Mexico, Texas and Nevada. Geochemically, black mats are highly variable and can range from 0.3% to 45.67% CaCO3 and from 0.9-21.8% organic matter. Micromorphological analysis was conducted on 31 thin sections using reflected, polarized and fluorescent light. Differences in features such as void infillings, hypocoatings and b-fabrics show that black mats experienced varying amounts of translocation, moisture and biological input. All samples contained organic materials either in the form of very fine (<20µm) fragments of vascular plants, or as amorphous humified organic remains. None of these forms of organic material showed any fluorescence indicating they were in an advanced state of chemical and biological decomposition. The micromorphological characteristics showed that black mats can form in subaerial, extensively bioturbated settings or calm, subaqueous conditions. Overall, black mats across the SW United States formed on stable landscapes and experienced high amounts of organic input and biological activity. These conditions indicate moister and more productive conditions than the typical desert ecosystem due to environmental changes associated with the Younger Dryas.
Geophysics

Variations in lithospheric structure, slab geometry, and surrounding mantle under the north central Andes from teleseismic tomography
Alissa Scire, C. Berk Biryol, George Zandt, Susan Beck, Lara Wagner, Maureen Long, Estela Minaya, Hernando Tavera

The central Andes in South America are characterized by along-strike variations in magmatism, upper crustal shortening, crustal thickness, and slab geometry that make it an ideal region to study the relationship between the subducting plate, the surrounding mantle including the mantle wedge, and the overriding plate. We use finite frequency teleseismic tomography to image P-wave velocity variations in the mantle under the central Andes between 8°S to 20°S down to a depth of ~700 km. P- and PKIKP-arrivals were picked in three frequency bands for earthquakes at distances from 30° to 90° and from 155° to 180° from the array respectively. Results from the finite frequency tomography inversion show a clear trench-parallel fast velocity anomaly migrating inboard from the trench. This dipping fast anomaly, which penetrates the 410 km discontinuity, is interpreted as the subducting Nazca slab under the central Andes. Although we are unable to directly image the shallow portion of the Peruvian flat slab north of 14°S, the distance between the trench and the slab anomaly at depths greater than 200 km increases and the slab dip becomes almost vertical, showing the effect of flat slab subduction. Our results are consistent with other evidence that the slab may remain flat further inland than has been previously modelled. South of 16°S, the northern Altiplano is consistently underlain by slower P-wave velocities while the upper mantle beneath the Eastern Cordillera and the Subandean Zone is highly variable. Around 20°S a fast anomaly is observed directly above the slab at depths of 150 to 300 km. This anomaly, particularly in conjunction with the observation of slow velocities under the Altiplano, may represent previously removed South American mantle lithosphere resting on top of the subducting slab. Along the entire length of the imaged subduction zone the results reveal a complex deformation of the slab as it interacts with and penetrates the mantle transition zone.
Crustal scale faults above the Peruvian and Argentinian flat slab segments
Brandon T. Bishop, Susan L. Beck, George Zandt, Lara S. Wagner, Maureen D. Long

In both central Peru and the Sierras Pampeanas region of Argentina global and regional seismic studies have identified extremely low angle to flat Wadati-Benioff zones which have been proposed to represent unusually shallowly subducted segments of the oceanic Nazca Plate. Since 2000, three temporary seismic networks using a total of 81 broadband seismometers in the Sierras Pampeanas region and one temporary seismic network using a total of 40 broadband seismometers in central Peru have been deployed to investigate these regions. We have used teleseismic receiver functions calculated using data from these deployments to image features within the overriding South American Plate and the subducted Nazca Plate. In Peru, we have identified signals we interpret as the Moho of the South American continental crust and the Moho of oceanic crust of the subducted Nazca Plate. Complexities in the South American Moho in Peru appear to be spatially correlated to mapped and inferred active fault zones at the surface, suggesting these fault zones or related shear zones penetrate deeply into the South American continental crust. These results have encouraged us to reexamine data from the Sierras Pampeanas using improved shear wave velocity models to investigate previously observed large offsets in the South American continental Moho. Our reexamination of the data indicates offsets in the Sierras Pampeanas Moho are robust features and not artifacts of migration velocities. We suggest these features may correlate to Paleozoic terrane boundaries mapped at the surface. It is unclear whether these are ancient faults preserved from the time of terrane accretion or reactivated faults. However, in both locations there is evidence that lower crustal deformation is part of the crustal thickening process above flat slabs.
Crustal thickness variations in the Central Andean Plateau: Influence of climate induced exhumation?
Jamie Ryan, Susan Beck, George Zandt

The Central Andean Plateau (CAP) is a high plateau in excess of 3 km elevation, and part of the Andean Cordillera that resulted from shortening along the western edge of South America as it was compressed between the subducting Nazca plate and underthrusting Brazilian cratonic lithosphere. We have calculated receiver functions for the Central Andean Uplift and Geodynamics of High Topography (CAUGHT) temporary deployment of broadband seismometers in the Bolivian orocline (12°-20°S) region and combined them with waveforms from 38 other stations in the region to investigate crustal thickness and lithospheric structure. The Moho is well imaged under the Altiplano and the eastern side of the CAP, but becomes complicated underneath the active volcanic arc and virtually transparent in the forearc. Results from all the receiver functions provide a more detailed map of crustal thickness than previously existed; our results indicate 70-75 km thick crust underneath the high elevations of southern Peru, 60-65 km thick crust underneath the Bolivian Altiplano, crust that varies from ~70 km to ~50 km underneath the Eastern Cordillera and Interandean zone, to less than 50 to 40 km in the Subandes and the edge of the foreland. The variable crustal thickness of the Eastern Cordillera and Interandean zone ranges from >70 km associated with the Los Frailes volcanic field at 19°-20°S to <60 km beneath the 6 km peaks of the Cordillera Real at ~16°S. We have compared these observed crustal thicknesses to a simple Airy isostatic model based on the low-pass filtered topography for the region. While the overall mountain belt appears to be close to isostatic equilibrium there are localized zones that are not. Two regions of anomalously thin crust in the Eastern Cordillera and Interandean Zone, where ~50-55 km thick crust underlies the locally high elevations (>4.5 km), correspond to areas of young post-shortening exhumation (<15-11 Ma) and high mean annual rainfall (> ~3 m/yr), suggestive of climate controlled exhumation (Barnes, et al., Geology, 2012). We explore the possibility that these areas of anomalously thin crust are due to localized uplift of the Moho from climate induced exhumation.
Shear wave velocity structure of the Anatolian Plate; implications for pre-collisional tectonics
Jonathan R. Delph, C. Berk Biryol, Susan L. Beck, George Zandt, Kevin M. Ward

The Anatolian Plate consists of various terranes amalgamated during the closure of the Tethys Ocean, and is currently extruding to the west as a response to a combination of the collision of the Arabian plate in the east and the roll back of the Aegean subduction zone in the west. We used Ambient Noise Tomography (ANT) at periods <= 40s to investigate the crust and uppermost mantle structure of the Anatolian Plate. We computed a total of 13,779 unique cross-correlations from 215 stations to compute fundamental-mode Rayleigh wave dispersion curves. We then inverted the dispersion data to calculate phase velocity maps throughout Anatolia and the Aegean regions. These dispersion curves were then inverted using an iterative inversion scheme to produce a 3-D shear-wave velocity model of the crust and uppermost mantle throughout Anatolia and the Aegean.

We find a good correlation between our seismic shear wave velocities and paleostructures (suture zones) and geologic terranes. The most prominent seismic anomaly corresponds to a slow velocity perturbation in the western flank of the Isparta Angle, which separates the actively extending portion of western Anatolia from the plateaus in the east. Thrusting to the east of this anomaly and extension to the west across the Fethiye-Burdur Fault Zone (FBFZ) is leading to the relative uplift of this area as an aseismic block, which we term the Fethiye Lobe. We attribute this relative uplift, along with the shallow dip of the subducting African lithosphere to the underplating of a rigid, buoyant, attenuated continental fragment that detached from the African margin prior to subduction. This fragment was subducted in early to mid-Miocene times, and controlled the location of a Subduction Transform Edge Propagator (STEP) fault in the eastern Aegean during rapid rollback of the Aegean trench. The formation of a STEP fault caused a 30-degree counter-clockwise rotation of the Fethiye Lobe. We hypothesize that hydrated sediments and accretionary material accompanying subduction are introducing fluids into the upper mantle and crust, which may be concentrated and trapped in shear zones that formed during the rotation of the Fethiye Lobe, leading to the slow crustal and upper mantle shear-wave velocities seen in the region today. The subduction of buoyant fragments may play a significant role in the formation of STEP faults, and could help explain the formation of other arcuate shaped mountain belts seen in the world today.
The 2010 April 4 Mw 7.2 El Mayor-Cucapah (EMC) earthquake is the largest event to occur along the southern San Andreas fault system in nearly two decades. We use 161 GPS velocity estimates from regional sites to model the crustal velocity field of southern California, USA, and northern Baja California, Mexico, prior to the EMC earthquake. In the year following the EMC earthquake, the EarthScope Plate Boundary Observatory (PBO) constructed eight new continuous GPS sites in northern Baja California, Mexico. We used our velocity model, which represents the period before the EMC earthquake, to assess postseismic velocity changes at the new PBO sites. Time series from the new PBO sites, which were constructed 4-18 months following the earthquake, do not exhibit obvious exponential or logarithmic decay, showing instead fairly secular trends through the period of our analysis (2011.25-2013.25). The weighted RMS misfit to secular rates, accounting for periodic site motions is 0.6-1.0 mm, indicating high positioning precision and fairly linear site motion. Results of our research include new fault slip rate estimates for the greater San Andreas fault system, generally consistent with previous geodetic studies within the region. Velocity changes at the new PBO sites associated with the EMC earthquake are in the range 0.6±0.1 to 6.8±0.2 mm/yr. Rate changes decay systematically with distance from the EMC epicenter and velocity orientations exhibit a butterfly pattern as expected from a strike slip earthquake. We infer a lower crust that is at least an order of magnitude stronger then the relatively weak uppermost mantle for the study region from post-seismic deformation modeling using a three-layer viscoelastic model.
Seismic imaging of the magmatic underpinnings beneath the Altiplano-Puna Volcanic Complex from the joint inversion of surface wave dispersion and receiver functions

Kevin M. Ward, George Zandt, Susan L. Beck, Douglas H. Christensen, Heather McFarlin

In the central Andes, the Altiplano-Puna Volcanic Complex (APVC) is the location of an 11-1 Ma silicic volcanic field, one of the largest and youngest on Earth, of which the magmatic/plutonic underpinnings have only been geophysically investigated in a few widely spaced locations. Previous studies have identified an extensive (~60,000 km²) low-velocity zone (LVZ) below the APVC referred to as the Altiplano-Puna Magma Body (APMB); however, insufficient seismic constraints have precluded uniquely measuring its thickness, and the volume of the APMB remains mostly constrained by varying estimates of plutonic to volcanic (P:V) ratios. Here we present new 3-D seismic images of the APVC crust based on a joint inversion of Rayleigh-wave dispersion from ambient seismic noise and P-wave receiver functions from broadband seismic stations recently deployed in the area. We identify a large ~200 km diameter and ~11 km thick LVZ that we interpret as the plutonic body that sourced the voluminous APVC volcanics and show that its volume is much larger than previous estimates, perhaps as much as an order of magnitude larger. The large volume (>500,000 km³) and shallow depth (4-25 km) of the LVZ we image is centered on the observed surface uplift below the composite volcano Uturuncu providing strong evidence linking our imaged low-velocity body (APMB) with the presence of an amalgamated plutonic body. We suggest the APMB retains a significant percentage (4-25%) of partial melt, perhaps in a mush state, and represents the source of the continued ground deformation attributed to magma ascent beneath the APVC. Placed in a regional context, the timing of the 11-1 Ma APVC ignimbrite flare-up and the magnitude of surface uplift inferred from the addition of a large plutonic body below the APVC is consistent with the large volume ignimbrite flare-up being the source of the topographic relief recognized by previous workers. The seismic imaging of this plutonic body allows us to make a direct calculation of a ~25:1 Plutonic to Volcanic (P:V) ratio and although there are still some uncertainties in these estimates, an important result is the P:V ratios are high, much higher than the often cited estimates of 3:1, 5:1, or even the extreme, 10:1 ratios for the APVC magmatic system. A much larger P:V ratio documented in the APVC reopens the question of the importance of magmatic addition in the building of the western Central Andean Plateau.
Investigating connections between large-magnitude earthquakes and active aseismic creep on the Alto Tiberina low angle normal fault, Italy
Lily J. Jackson, Richard A. Bennett, David Mencin, Gabriele Casale

The Alto Tiberina Fault (ATF) in the Northern Apennines, Italy, is a low angle normal fault dipping ~20° to the east-northeast. The ATF geometry between 43.2°N and 43.5°N is imaged and constrained by seismic reflection data and microseismicity. The ATF hanging wall is cut by west-dipping, high angle normal faults that produce large-magnitude earthquakes. Although the region where the ATF is imaged has not been associated with large earthquakes, GPS data of crustal motions suggest that the ATF is accommodating extension through aseismic creep at depth. Balanced cross sections suggest that the ATF could have accommodated up to 10km of extension since the late Pliocene. The software TDEFNODE was used to model along-strike variations in creep and extent of the ATF. The model suggests maximum creep of ~2mm/yr between 43.1°N-43.7°N. Areas to the north and south appear locked, corresponding to areas of large-magnitude earthquakes. To explore the relationship between large earthquakes in the hanging wall and variation in creep along the ATF, we used the code PSGRN/PSCMP to model post-seismic deformation and coulomb stress changes associated with several large-magnitude earthquakes in the region bounding the ATF. We hypothesized that correcting geodetically observed crustal motions for post-seismic deformation would cause along-strike variation in fault creep to be less pronounced. However, our model shows that initiating the post-seismic correction causes along-strike variation to be more pronounced, raising the question of whether the large-magnitude earthquakes control the creep variation, or whether creep variations are dictating fault ruptures in the hanging wall.
Tectonics and Geochemistry

Tectonic significance of crystal-fiber quartz veins in Recreation Redbeds (Jurassic), Brown Mountain: expression of caldera collapse in the Tucson Mountains, Arizona
Jean Villena-Celis, Christopher Young, George H. Davis

Mayo and Davis (1976) identified the presence of crystal-fiber quartz veins in the Jurassic Recreation Redbeds of Brown Mountain, but were unable to determine their origin and significance. Patches of crystal fiber veins, appearing white encased in red, are quite visible in the Recreation Redbeds and Brown Mountain of the Tucson Mountains, Arizona. These low-dipping quartz veins, with penetrative crystal-fiber lineation, are proximal to the western fault boundary as mapped by Lipman (1993). The crystal-fiber lineations engraved in the quartz veins establish the slip-line direction. Although the crystal-fiber veins are most abundant in the Jurassic Recreation Redbeds, some occur in the Cretaceous Amole Arkose Formation. At one exposure a 70 Ma Silver Lily Dike appears to cross-cut the crystal-fiber veins and their Amole Arkose host rock, thus tightly constraining the timing of formation of the veins. In this study we attempt to discern the structural and tectonic origin of the crystal-fiber veins.

Our approach was to map the distribution of the crystal-fiber veins and to establish orientations of the veins themselves and the penetrative mineral lineation. We anticipate that determination of the kinematic nature of the crystal-fiber veins will be achieved through study of the microstructures. Fluid inclusion analysis of samples will reconstruct the temperature, pressure and fluid composition when the quartz formed. Mapping has thus far revealed that the crystal-fiber lineation is concentrated around the Museum Embayment Fault, which Lipman interprets to be the western boundary fault of the caldera. Moreover, the crystal-fiber lineation tends to be orthogonal to this fault boundary, regardless of the trend of the boundary. If the quartz-fiber lineation relates to caldera collapse, crystal-fiber quartz lineations function as a reasonable means to define the caldera boundary and track slip-motion at the time of collapse.
Provenance of the Indus-Yarlung Suture Mélange and the onset of Tethyan Himalaya-Asia collision, Southern Tibet
Kathryn Metcalf, Paul Kapp, Drew Laskowski, Devon Orme

The Indus-Yarlung Suture Zone (IYSZ) is the boundary between rocks of Indian and Asian affinity. From north to south in southern Tibet, it exposes the preserved Asian forearc, ophiolitic rocks, tectonic mélanges, and Tethyan Himalayan strata of Indian affinity. Resolving the timing of collision is fundamental to understanding the extent of Greater India and the tectonics of the southern margin of Asia. The mélange formed by subduction accretion associated with the Cordilleran-style southern margin of Asia, prior to India–Asia collision, but its provenance, age, and extent are poorly constrained. We conducted geologic mapping and U/Pb detrital zircon provenance studies of the blocks and matrix of the mélanges and of Tethyan Himalayan units to the south near Lopu Kangri, ~200 km NNW of Kathmandu.

Near Lopu Kangri, the mélange is composed of a mudstone matrix with blocks of basalt, chert, mudstone, metabasite, limestone, and sandstone. The majority of the blocks are deep-water facies or consistent with oceanic crust, supporting the interpretation that the mélange is an accretionary complex formed by oceanic subduction. Over a span of ~10 km to the southwest blocks gradually increase in size to encompass ~2 km x ~10 km areas of measurable section and the component of matrix gradually decreases. Eventually the matrix is absent and strain is apparently taken up in incompetent layers within the stratigraphic sections. Results from U/Pb dating of detrital zircons suggest that the mélange contains Tethyan affinity blocks with early Cretaceous peak ages of ~130 Ma as well as Gondwanan affinity blocks with peak ages of ~500-550 Ma. Two samples show clear similarity to the Asian forearc and have maximum depositional ages of ~58.5 Ma.

Collectively, our preliminary results suggest that most sandstone blocks in the mélange in this locality are of Tethyan affinity, while two Asian-affinity samples represent and overlap assemblage derived from the forearc and deposited on Tethyan strata at ~59 Ma. We propose a tectonic model in which prior to collision the mélange received no sediment from the upper plate, then at the time of collision Asian forearc material was deposited on Tethyan strata, and as collision proceeded the Tethyan strata were broken up into blocks and imbricated.
Early foreland basin depo-systems in the south-central Andes of Argentina, 32°S -35°S
Elizabeth Balgord, Barbara Carrapa

The Andean orogen is the type-example of an active Cordilleran style margin with a retroarc fold-and-thrust belt and foreland basin. Upper plate shortening, crustal thickening, underthrusting, and arc processes related to subduction of the Nazca plate under South America have led to uplift of the Argentinean Andes. Timing of shortening and foreland basin development seem to be diachronous along strike, with ages varying from Paleocene initiation in Bolivia and NW Argentina to Jurassic in the Patagonian Andes. Although much of the early stratigraphy has been eroded or covered the Neuquén basin (32° S to 40° S) contains a thick sedimentary sequence ranging in age from late Triassic to Cenozoic. The Neuquén basin initiated as an east-west trending rift basin in the late Paleozoic-early Mesozoic and then evolved into a foreland basin sometime in the late Cretaceous or Cenozoic. Previous workers in the central Neuquén basin (35° S to 39° S) have used changes in detrital zircon signature between the Rayoso Group (~ 120-100 Ma) and the Neuquén Group (~ 95-80 Ma) as evidence for the initiation of foreland basin sedimentation, but have given little discussion to the spatio-temporal evolution of specific foreland basin depozones.

Correlative stratigraphic sections from the Malargüe and Aconcagua fold and thrust belts (35°S and 32°S respectively) record a facies change between the marine evaporites of the Huitrín Formation (~125 Ma) and the fluvial sandstones and conglomerates of the Diamante Formation (equivalent to the Neuquén Group). A major, 25-30 myr, unconformity between the Huitrín and Diamante formations potentially represents the passage of the flexural forebulge and preliminary detrital apatite fission track data indicate a change in source exhumation signal at that same transition, which is consistent with an actively eroding and deforming hinterland at ~ 95 Ma. However, there is no significant difference in detrital zircon signature. Instead, a change in provenance and paleocurrent direction occurs in the middle Diamante Formation. This new provenance signature along with a change from west directed to east directed paleocurrents within the Diamante Formation may reflect a late Cretaceous transition from forebulge derived sediment in the distal fordeep to sediment derived from the thrust belt to the west deposited in the proximal foredeep.
Two-phase exhumation of subducted Indian passive margin metasedimentary rocks in the Lopu Kangri Range, south-central Tibet
Andrew Laskowski, Paul Kapp

The Lopu Kangri Range transects the India-Asia suture zone near Saga, in south-central Tibet. Rocks exposed along this >100 km, NW-SE oriented range record a rich, semi-continuous history of Cenozoic Himalayan-Tibetan orogenesis. This study presents mapping, igneous U-Pb geochronology, detrital zircon geochronology, zircon (U-Th)/He thermochronology, and electron microprobe geochemical data from the Lopu Kangri Range and the surrounding India-Asia suture zone. Our results indicate that two distinct episodes of tectonic exhumation occurred in this region during the Cenozoic, despite rapid India-Asia convergence. India passive margin (Tethyan) strata were subducted to depths >20 km and experienced lower blueschist facies metamorphism. These rocks were exhumed in the footwall of a north-dipping, normal-sense shear zone that separates Indian and Asian-affinity metasedimentary rocks. Therefore, this structure is the reactivated India-Asia suture. A second episode of tectonic exhumation initiated during the Miocene (by 12 Ma) and culminated in ongoing orogen-parallel extension.

In the northern Lopu Kangri Range, Cretaceous—Eocene Gangdese arc granitoids are unconformably overlain by nonmarine, conglomerate-bearing strata of the Eocene (?)—Miocene Kailas Fm. Gangdese arc and metaconglomerate rocks are confined to the footwall of the north-directed Great Counter Thrust system, which carried Cretaceous-Early Eocene Xigaze forearc, suture zone mélangé, and Tethyan strata northwards across three major NE-SW fault strands during the Miocene. Tethyan strata in the Range consist of phengite-bearing calc-gneiss and schist that display N-S stretching lineations and top-N s-c fabrics.

Six detrital zircon samples from the Xigaze forearc, metaconglomerate and meta-Tethyan strata were analyzed to confirm our fieldwork-based lithologic correlations and provenance interpretations. 12 igneous U-Pb samples were analyzed to characterize granitoids that intrude the Range. They reveal a suite of 50-40 Ma granodiorites that were produced by Gangdese arc magmatism. A separate suite of 42-10 Ma leucogranites contains abundant inherited zircon cores whose age spectra suggest genesis by anatectic melting of crustal rocks. A 42 Ma anatectic melt, which was intruded into the meta-Tethyan blueschist, indicates that the India-Asia collision occurred prior to the mid-Eocene.
Extending for ~2500 km along the Himalayan-Tibetan orogen, the South Tibetan detachment system (STDS) is the best-studied example of an orogen-scale extensional structure formed during collisional orogenesis. The STDS separates Ordovician low-grade metasedimentary rocks of the Tethyan Himalaya in its hanging wall from Neoproterozoic leucogranites, gneisses, and schists of the Greater Himalayan Crystalline series (GHS) in its footwall. Although the structural development of the GHS has been studied extensively along the Himalayan front, constraints on the timing of exhumation of the STDS footwall from thermochronology are limited. This study presents the first low-temperature thermochronologic data from leucogranites in the footwall of the STDS in the Rongbuk Valley, 18 km north of Mt. Everest.

AFT and ZHe analyses were conducted on samples from two vertical transects in the footwall of STDS in order to constrain the timing of cooling through ~90-120 °C and ~140-200 °C, respectively. AFT analyses on six samples yield dates 15-17 Ma, with a weighted mean age of 16 ± 3 Ma. In contrast, ZHe analyses on four of the same samples yield single grain dates 9-13 Ma, with weighted mean ages for each sample 9-11 Ma. The 16 Ma AFT age agrees with previously published data from Th-Pb monazite analyses, suggesting Miocene slip across the STDS. ZHe dates are highly reproducible but systematically younger than the AFT dates thus requiring a thorough investigation of the kinetic behavior of both systems. Detailed SEM examination and laser ablation depth-profiling of these zircons reveals zoned, high [U] rims, causing ages to be artificially young as more He is ejected from the grain than can be accounted for by the standard α-ejection correction. The rim diameters and [U] of these zircons suggests that our ages suffer a ~ 35% younging effect. The presence of 17-22 Ma metamorphic rims on some zircon crystals indicates that metamorphism prior to cooling likely annealed all previously accumulated radiation damage at that time and may have altered the bulk closure temperature for the ZHe system. Therefore, the measured age-[eU] trend likely reflects the past 16 Myr of accumulated damage at low temperatures. The combination of zoned zircon crystals with low, but variable amounts of [eU] identified herein provides a viable explanation for inverted ZHe and AFT ages. This study demonstrates the importance of utilizing multiple thermochronometers to fully understand the timing of tectonically exhumed fault blocks.
The structure and stratigraphy of the Lesser Himalaya of central Nepal
Edward Cross, P.G. DeCelles, Tank Ojha

We present a map and balanced cross section supported by zircon U-Pb age spectra from 15 detrital samples and 2 igneous samples, 8 neodymium isotopic analyses, and 6 zircon (U-Th)/He ages. The map covers the area from the Tansen-Pokhara Highway in the west to the Mugling-Chitwan highway in the east. From north to south, the major structural features in the area are (1) the Lesser Himalayan duplex, consisting of both upper and lower Lesser Himalayan Sequence rocks; (2) the Ramgarh Thrust sheet; (3) a synformal klippe of Greater Himalayan Sequence rocks; (4) a second appearance of the Ramgarh Thrust sheet; and (5) low-grade upper Lesser Himalayan Sequence rocks carried in the hanging wall of the Main Boundary Thrust. The detrital zircon and neodymium analyses, along with field observations, clarify the stratigraphy of central Nepal and reveal the presence throughout the map area of Gondwanan sedimentary rocks. On top of these Gondwanan sediments are thrust a package of Lesser Himalayan rocks including graphitic schists and meta-carbonates that we correlate with the Benighat Slates and Dhading/Malekhu carbonates of the Kathmandu area. These rocks also correlate to similar rocks found in the footwall of the Ramgarh Thrust in the high mountains of central Nepal, which our U-Pb and Neodymium results also support. The zircon (U-Th)/He results constrain the rate of shortening in this area of Nepal from 7-3 Ma to be a minimum of 7 mm/yr.
The 2500-km-long Tian Shan orogenic system constitutes a dominantly Paleozoic amalgamation of Eurasia that has been overprinted by the Cenozoic Indo–Eurasian collision. Separation between the continental Asian orogenic collage’s old (Tian Shan–Altaid) and new (Himalaya–Tibet–Pamir–Karakorum) components is smallest along the Alai intracontinental subduction zone, where the Pamir and southern Tian Shan orogens approach. Although considerable interest has recently developed in the tectonic evolution of the Pamir, the southern Tian Shan in Tajikistan has been comparatively ignored.

The Variscan, late Carboniferous–early Permian Gissar batholith is the southern Tian Shan’s southernmost lithotectonic unit and displays interesting trends along strike from west to east. Zircon U-Pb weighted-mean crystallization ages of Gissar granitoids young from W–E from ~310–280 Ma. Calc-alkaline rocks with minor amounts of mafic phases (amphibole and biotite) are volumetrically dominant. Syenites constitute the youngest batholith rocks but are volumetrically subordinate, indicating a final stage of alkaline magmatism.

The Garm “metamorphic” block occurs in the eastern Gissar batholith and is apparently more deeply derived than the rest of the batholith, as indicated by its defining features: (i) discontinuous outcrops of amphibolite-facies metasedimentary rocks; and (ii) presence of igneous garnet. Zircon U-Pb ages from Garm metasedimentary rocks are Precambrian. Modern river sands and Cretaceous sandstones that unconformably overlie the Garm block produce age spectra consistent with the middle and final stages of Gissar magmatism.

Zircon ϵHf in Gissar granitoids generally decreases with decreasing zircon U-Pb age from +5 to 10. Zircon ϵHf in grains from a Cretaceous sandstone whose U-Pb ages are consistent with the end of Gissar magmatism range from -4 to +12.

Zircon He data from Gissar-batholith rocks show both positive and negative age-εU trends and constrain the batholith’s low-temperature, Cenozoic cooling history.
Latitudinal variations in Andean exhumation reflected in detrital apatite fission record of modern river sands
Andrea Stevens, Barbara Carrapa

The Andes stretch over 4,000 miles along the western coast of South America forming one of the longest mountain chains in the world. Although the subduction of the Nazca plate under the South American plate is continuous along the length of this chain, the deformation and exhumation of the Andes varies along strike, providing a natural laboratory that facilitates the study of regional variations in exhumation patterns. These varying exhumation patterns are influenced by changes in both climate and tectonic patterns along strike. In this study, we use apatite fission track thermochronology (AFT), a method shown to record a Cenozoic exhumation signal in the Andes, to track the change in exhumation signals along strike of the mountain range.

In the Andes, modern river drainages with a large catchment naturally provide sands that record the regional thermal history of that area. By conducting AFT analysis on these sands we can track changes in this exhumation signal from modern river sands draining the Andes at different latitudes. This study focuses on a region of varying deformational styles in northwest Argentina from 23° to 27° S where climate patterns remain constant. To the north the internally drained Puna Plateau records a young exhumation signal. To the south of the plateau towards the basement uplifts of the Sierra Pampeanas, this young exhumation signal has not been recorded. Four modern river samples in this region record this regional change in exhumation signal. The AFT signatures from these modern river sands also suggest changes in the style of regional deformation, with northern exhumation recorded as a late Miocene pulse while samples to the south suggest a protracted exhumation signal that initiated in the early Miocene. Regional exhumation signals recorded in modern river sands provide a valuable perspective on the spatio-temporal evolution of Andean deformation.
Oligocene laccoliths on the Colorado Plateau: a key to understanding Cenozoic cooling and canyon cutting
Kendra E Murray, Peter W Reiners, Stuart N Thomson

The timing, mechanisms, and magnitude of Colorado Plateau uplift and erosion during the Cenozoic have been among the great puzzles of North American geology since the first observations of Powell, Gilbert, and Dutton, and remain controversial today. Erosion of Utah’s iconic canyon country is unconstrained compared to the region along the Colorado River downstream of Lee’s Ferry, Arizona, including the Grand Canyon. In part, this is because many low-temperature thermochronometers in rocks exposed in canyon country were not sufficiently reset during Mesozoic burial to clearly constrain Cenozoic exhumation patterns. Here, we demonstrate that the magmatic history of the Henry, La Sal, and Abajo mountains provides unique constraints on the middle and late Cenozoic cooling and exhumation history across the Colorado Plateau. In these mountains, shallowly intruded Oligocene laccoliths heated late Paleozoic and Mesozoic country rocks ~26 Ma, locally resetting apatite fission track and (U-Th)/He ages so they record Miocene-Quaternary cooling and exhumation. Sandstone samples from within 3 km of laccoliths in each mountain range yield single-grain apatite He ages that vary with the effective uranium concentration (eU). In these key samples, minimum He ages are ~5 Ma in grains with eU < 10 ppm, and maximum ages are ~25-20 Ma with eU > 60 ppm. We model and interpret these apatite He age-eU patterns together with (1) with stratigraphic constraints, (2) the timing of laccolith intrusion determined by zircon U/Pb geochronology, and (3) the extent of resetting temperatures >100 °C by apatite fission track analysis. Results require prolonged sample residence in the apatite He partial retention zone (40-60 °C, ~1-3 km depth) from 25-10 Ma, suggesting there was minimal early and middle Miocene exhumation. Best fit time-temperature solutions show onset of rapid cooling to surface temperatures in the Plio-Pleistocene; this erosional event removed ~1.5 km at time-averaged rates between 0.3 and >1.0 km/Myr. These results agree with previous studies that link regional late Cenozoic exhumation to the ~6 Ma integration of the Colorado River through the western Grand Canyon. More broadly, the Oligocene laccoliths are one expression of a regional thermo-magmatic event that likely transiently raised the Plateau’s geothermal gradient. Therefore, previous interpretations of cooling in the late Oligocene as an erosional event in the Grand Canyon and elsewhere need to be re-evaluated.
Immediately following a wildfire, denudation can dramatically increase, but the importance of this heightened post-wildfire denudation over long-term, geologic time scales is unknown. In this study we calculate the mean denudation rates of watersheds that were recently burned, and watersheds that were not burned, by the 2011 Las Conchas fire in the forested, mountainous landscape of the Valles Caldera, NM, over short (~100 yr) time scales and long (~103-106 yr) time scales. Suspended sediment load, LiDAR, 10Be cosmogenic radionuclides, and paleosurface incision methods were used to quantify mean denudation rates. The results indicate that following the Las Conchas fire, the mean denudation rates of affected watersheds were greater than 1000 μm yr⁻¹, ~103 to 104 times higher than nearby unburned watersheds. Long-term mean denudation rates are on the order of 10-100 μm yr⁻¹ and are a combination of both heightened post-wildfire denudation rates and non-wildfire-affected denudation rates. These long-term DRs are consistent with a period of heightened post-wildfire denudation lasting approximately 1 yr and recurring every 30 to 800 yr. Post-wildfire periods of heightened denudation are responsible for the majority (~99%) of long-term denudation. Both the estimates of recurrence intervals for wildfire occurrence and the estimates of the amount of material associated with post-wildfire denudation agree well with dendrochronological, paleolimnological, and alluvial sediment records in the region. The results of this study show that post-wildfire denudation is the dominant factor in shaping the landscape.
Sediment-hosted copper and Iron-Oxide Copper Gold (IOCG) deposits are two of the most prominent copper-bearing deposits. It is suggested that the presence of evaporites, which tend to occur in arid climates, influences whether these deposits occur due to their ligand capacity to attach to, transport, and concentrate metals. An important component for the formation of these deposits is the existence of a source of metals that can be leached and concentrated. It is generally thought that red bed deposits are good sources of metals for sediment-hosted copper deposits, while igneous material might be the source of metals for IOCGs.

In this study, 215 IOCG and 522 sediment-hosted copper deposits were collected from databases (Cox et al., 2003; Corriveau, 2007). Paleogeographic coordinates of continental reconstructions, up to 600 million years ago, were calculated using PointTracker (Scotese, pers. comm.) software and superimposed on their corresponding continental reconstruction figures using a Mollweide projection on R programming. Paleoclimate data from Scotese (pers. comm.) were added to the reconstructions. Sediment-hosted copper deposits were sorted by Cu grade, tonnage, and deposit type; IOCGs were sorted by igneous host rock and presence of Cu, Au, and Fe. They were then mapped onto continental reconstruction maps for their corresponding ages, which include magmatism and paleoclimate data and completed in Adobe Illustrator.

When studying the association between climate and frequency of these deposits there was significant correlation. 73% of sediment-hosted copper deposits and 90% of IOCG deposits occurred in arid climate, with others being deposited in tropical or warm climates. There were no deposits located in polar environment, further indicating the significance of the role of climate and evaporites in the deposition of these deposits. A histogram analysis of the frequency of deposits with respect to their latitude indicates a bimodal distribution with peaks at latitudes known to be arid. The relationship was stronger between sediment-hosted copper deposits and the presence of red beds (47% of these deposits were red beds). In the case of IOCGs, the relationship between the existence of these deposits and igneous activity is significant. This report is a complement to the oral presentation, where the continental reconstruction maps showing magmatism and paleoclimate data can be shown in detail.
Eleven new U-Pb dates from key igneous units in the Central Mining District (CMD) of New Mexico document a relatively short duration of magmatism related to multiple, distinct types of mineralized systems. The new dates are compatible (within error) with observed crosscutting relations. Most zircons exhibit simple zoning and yielded only Laramide ages; three samples have inherited cores ranging from 1.4 to 1.6 Ga.

Regionally distributed quartz monzodioritic sills formed first at 60.5 ± 1.3 Ma (3 samples). The granodioritic to granitic Santa Rita (59.5 ± 1.5 Ma) and Hanover-Fierro (58.5 ± 0.9 Ma) stocks are associated with the principal porphyry Cu and Fe skarn and replacement deposits. Felsic dikes, including quartz diorite porphyry (58.5 ± 0.7 Ma), granite porphyry (58.3 ± 0.8 Ma), and late granodiorite porphyry (59.0 ± 0.7 Ma) overlap in age but cut earlier intrusions; they are associated with Zn ± Cu skarn and replacement mineralization. The Copper Flat stock formed at 57.5 ± 0.7 Ma and is associated with breccia and skarn Cu ± Fe. An age of 46.6 ± 0.9 Ma on the monzonite plug in the North Star basin suggests an independent, later phase of magmatism. These ages, when combined with relative ages based on crosscutting relationships, constrains the timing of mineralization of porphyry copper in the CMD associated with the Santa Rita stock to between 61.0 and 59.5 Ma. Available K-Ar and Ar-Ar dates are mostly concordant with these results, indicating rapid cooling from magmatic to Ar closure temperatures.

The ages determined here are similar to many other Laramide porphyry copper-related plutons in the Southwest (~55-65 Ma). Unlike some of the other districts, there is no evidence for older mafic to intermediate magmatism that predates mineralized plutons by 5-10 m.y. Indeed, the <2 m.y. time span is considerably less than that observed between mineralized centers in the same area (e.g., Globe-Miami, Ray, and Pima districts). Nevertheless, the span in ages and geologic relationships indicate that the several centers reflect separate magma batches which, if linked at all, would share only a deep crustal origin.
**G03: Fe oxide-Cu mineralization at the Minnesota and Pumpkin Hollow deposits, Yerington district, Nevada**
Simone Runyon, Mark Barton

Petrographic and field studies at the Minnesota and Pumpkin Hollow magnetite-rich skarns (Yerington district, Nevada) show that Mt-rich, Si-poor mineralization formed early in a multi-step hydrothermal history, likely related to Na-Ca alteration and, presumably, from non-magmatic brines. This contrasts with evidence for later formation of porphyry Cu and Mt-poor, Cu skarns associated with release of magmatic fluids (Dilles et al., 2000).

Both Minnesota and Pumpkin Hollow are magnetite-rich, sulfide- and silicate-poor deposits hosted in calcareous Mesozoic sedimentary rocks intruded by the Jurassic Yerington batholith. Hydrothermal alteration consists of endoskarn: deep Na-alteration (Ab-Rut-Chl-Act) at Minnesota, Ca alteration (Grt-Olig-Act±Di±Cc) at Pumpkin Hollow, and Na-Ca (Olig-Act-Sph±Di) at both deposits. Mt-mineralization dominantly occurs in marble, but also replaces more aluminous rocks (intrusions, volcaniclastic rocks). At Minnesota, Fe oxide-mineralization zones from central Mt-replacement to peripheral hornfels-clast Mt-cemented breccia, and distal Mt-clast Mg-silicate-cemented breccias along the marble contact. Magnetite mineralization at Pumpkin Hollow differs in size, in having higher contents of Cu-Fe sulfides.

Field relations suggest that the Mt-rich mineralization may have formed early, with quartz monzodiorite and added comparatively high Fe/Si. In contrast, the Mt-poor Cu-rich skarns in the district have abundant calc silicates, are linked to later granitic phases of the batholith which generated porphyry Cu deposits, and added lower Fe/Si. These suggest that Mt-rich, variably Cu-bearing systems in the Yerington district are related to early circulation of non-magmatic brines, which transport Fe and Cu, make extensive Na-Ca alteration, widespread Fe-oxide mineralization on upwelling, and locally concentrate Cu. These features parallel those seen in IOCG-type systems worldwide.
Climate and Paleoclimate

G04: The seasonality of Coccidioidomycosis: Predicting Valley Fever outbreaks in Arizona
Angelica Alvarez, Eyal Oren, Joellen Russell

Coccidioidomycosis, most commonly referred to as Valley Fever, is endemic to the arid regions of central and southern Arizona where soil fungi Coccidioides spp. flourish most. Previous research has established that life cycles of the fungi correspond to variations in meteorological and climatic conditions which are good indicators of Valley Fever disease trends. Assessing the covariability between various climate variables and AZDHS reporting data, will show which meteorological and environmental conditions correlate with seasonal patterns of Valley Fever incidence. ANOVA tests, regressions and quantitative time series analysis will be used to quantify these correlations. We believe that the historical patterns observed in our analysis will aid in the projection of future disease levels in the state of Arizona.
During the past decade the mean global surface-temperature has shown little to no increase; a phenomenon often referred to as a warming hiatus. There have been several mechanisms proposed to explain the current warming hiatus, including changes in deep ocean heat storage. The Pacific Ocean could be especially important due to the natural variability it experiences on decadal to multi-decadal time scales. Sea-level rise (SLR) provides a tool for studying ocean heat content since water expands as it gains heat. SLR rates in the western Pacific are currently up to five times greater than the global mean, while, the eastern Pacific currently shows little to no SLR. Phase shifts in the Pacific Decadal Oscillation (PDO) have been suggested as a potential cause for the present surface warming hiatus and also have implications for SLR predictions. Predicting when the west-high/east-low SLR pattern in the Pacific may reverse has important implications for people living on the US west coast.

My research uses ocean temperature and sea-level observations along with CMIP5 climate model data to explore the potential link between the warming hiatus and sea-level variability in the Pacific Ocean. The preliminary results from ocean temperature data suggest that distribution of ocean heat content anomalies (OHC) change over time with the possibility for periods of increased OHC in the deep ocean. It also appears that the contribution of each ocean basin towards the total OHC varies by depth and over time. Variability in dynamic sea-level (DSL) from 39 CMIP5 pre-industrial control runs were analysed using DSL as a measure for the PDO Index. Comparing the model data with observations suggests that climate models may be useful for studying the SLR variability in the Pacific Ocean. My research is also exploring the skill of near-term decadal CMIP5 experiments for predicting future SLR changes in the Pacific.
The Indian monsoon is the critical source of freshwater for over one billion people. Variability in monsoon precipitation occurs on all time scales and has severe consequences for the people who depend on monsoon rains. Extreme precipitation events have increased in the 20th century and are predicted to continue to become more frequent with anthropogenic global warming. The most recent models project that both monsoon precipitation and variability of precipitation will increase over the 21st century leading to increased flooding and possibly severe droughts. Although current models are able to capture the risk of relatively short droughts (1-5 years) reasonably well, they tend to underestimate the risk of longer, decadal-multidecadal droughts. I use observational records over the last 100 years in conjunction with cave, tree ring, and lake data from the NOAA paleoclimate database to reconstruct Holocene monsoon variability. I am able to show that the Asian monsoon has more low frequency variability than is projected by current climate models. The growing evidence for this discrepancy in hydroclimate variability between models and observational/paleoclimate records is of grave concern. If these models fail to capture the decadal-multidecadal droughts of the past it is likely they will underestimate the possibility of such droughts in the future.
The “Green Sahara” pluvial phases that alternated with North African hyper-aridity during the Pleistocene are well recognized in tropical and Mediterranean marine records. However, comparatively few studies have investigated the terrestrial expression of these pluvials. In this study, we show that the travertine record of Egypt’s Western Desert constitutes a promising terrestrial proxy for North African paleohydrology. Integrating our reconnaissance sampling of travertine and modern groundwaters from five major oasis areas with previously published data, we combine high-precision U/Th dating, and stable isotope and 87Sr/86Sr geochemistry, and geologic characterization to create a record of Egyptian pluvial periods for the last ~650 ka. We confirm previous findings that large volume deposition occurred across the region at ~125 ka, as well as constraining major deposition from ~450-600 ka. We also show that some lacustrine deposits at Dahkla Oasis associated with paleolithic artifacts are 300-350 ka rather than ~130 ka. A comparison of travertine geochemistry with modern groundwater chemistry suggests that a consistent Nubian groundwater source has fed travertine deposition over the last half million years. These observations lead to a depositional model in which travertine accumulations around paleo-oasis springs reflect episodes of enhanced spring discharge deriving from high hydrologic head in the Nubian aquifer system, which we interpret to be a response to greater precipitation in southern groundwater recharge areas. Importantly, this discharge includes significant upward flux of deeply-derived carbonic fluids through faults. Thus, in our model, large-scale travertine accumulations serve as an archive of wet intervals in the Ethiopian-Sudan recharge region, which are then expressed in oasis springs following the short (<10 ka) lapse time it takes for transmission of high head pressure from the highlands. This idea is supported by the fact that peak times of large volume travertine deposition are associated, roughly, with sapropels, indicating response to major regional pluvial episodes. Subject to further testing, we interpret large volume travertine deposition in Egypt’s Western Desert to be a pluvial indicator ultimately responding to orbital forcing.
The Southern Ocean (SO) plays a large role in the uptake of anthropogenic heat and carbon by the global ocean, ultimately affecting the climate’s transient response to increased greenhouse forcing. We present an assessment of the impact of wind and ice biases on the simulated uptake of heat and carbon by the SO in coupled climate model simulations of the pre-industrial, modern and future climates. For this analysis, modeled winds will be compared to the Climate Forecast System Reanalysis (CFSR) from the National Center for Environmental Prediction (NCEP), and modeled sea ice to data from the Hadley Centre Sea Ice and Sea Surface Temperature (HadISST). Coupled Model Intercomparison Project 5 (CMIP5) and Intergovernmental Panel on Climate Change-AR5 (IPCC-AR5) simulations, obtained from the Program for Climate Model Diagnosis and Intercomparison (PCMDI), are analyzed.
G09: Revisiting the age of Zuni Salt Lake maar in west-central New Mexico
Jill Onken, Steven Forman

Zuni Salt Lake maar is a large volcanic crater created by a Quaternary hydromagmatic eruption along the Jemez Lineament in west-central New Mexico. Prior dating places the eruption at >23 ka (14C) and 86–114 ka (40Ar/39Ar), suggesting a late Pleistocene age seemingly inconsistent with the maar’s relatively uneroded geomorphic appearance and weakly developed soils. The radiocarbon date was on calcareous algae susceptible to reservoir effects, and the two argon-argon ages have very large standard errors, a problem common with volcanics younger than 100 ka. We used small aliquot single aliquot regeneration OSL dating in tandem with AMS 14C dating of organic materials not susceptible to reservoir effects to reevaluate the age and eruption sequence of the Zuni Salt Lake vent. Based on three radiocarbon ages and five OSL ages, we found evidence of two eruptive phases. The first phase consisted of a Strombolian-style eruption of ash, cinders, and basalt during the latest Pleistocene between ~13 and 12.3 ka. This was followed a couple millennia later by a Vulcanian hydromagmatic, maar-forming eruption during the early Holocene between ~10.9 and 9.9 ka. The second, “wet” eruptive phase ended with the formation of three cinder cones on the crater bottom when groundwater depletion caused a return to “dry” Strombolian eruptions. Subsequent groundwater recharge resulted in the formation of a crater lake with a highstand 25 m above the modern lake level that ended by ~9.5 ka.

The paleobotanical phytolith record appears consistent with the eruption sequence, suggesting dry conditions preceding the initial Strombolian eruptive phase and substantially moister conditions preceding the second, hydromagmatic phase. Both eruptive phases coincide with early human occupation of the region and probably left a long-lasting mark on Paleoindian ideology. Besides Zuni Salt Lake, only two other Holocene vents have been identified along the Jemez Lineament. Better dating of recent Jemez Lineament volcanics is important for more realistic recurrence interval estimates and more accurate predictions of future volcanic hazards in the region.
G10: LOI data for total organic and total inorganic carbon in the Tugen Hills and West Turkana regions of Kenya.
Kojo Plange, Kevin Ortiz, Preston Smith, Andrew Cohen

Our goal this project is to improve our understanding of paleoenvironments and paleoclimates in this region during the Plio-Pleistocene with an emphasis on how they relate to early human evolution. Lake sediment from drill cores collected at 2 sites in the Tugen Hills and West Turkana regions of Kenya have been analyzed for total organic (TOC) and inorganic carbon (TIC) using Loss on Ignition methods. These are areas of significance for understanding the environmental context of human origins because they are located close to some of the most important paleoanthropological and archeological sites in the world.

Drill cores were sampled and analyzed for LOI every 64cm throughout the 227m Tugen Hills and 215m West Turkana core records, which respectively cover time intervals of 2.5-3.5Ma and ~1.4-1.9Ma respectively. Looking at the data that we have analyzed thus far, there are a couple of trends that are revealed. In the first 55m meters of the drill core sample there are elevated levels or spikes in organic carbon at depths of 11.4m, 33.57m, and 34.23m. There are also spikes in inorganic carbon at depths of 12.7m, 23.11m, 35.2m, 41.4m, 44.35m, and 45.01m with the largest being at 44.35m. What is also interesting is there are several spikes that seem to coincide with each other where spikes in inorganic carbon seem to occur right after a spike and subsequent drop in organic carbon. This information may indicate possible fluctuations in paleolake depths and also possible fluctuations in precipitation or weather patterns in the area. We will continue to analyze deeper stratigraphic sequences in the drill core samples to see what other trends develop.
Extensive debate over climatic effects of the Mt. Toba super-eruption circa 75ky has been centered around East Africa. It has been hypothesized that the Mt. Toba eruption in Sumatra, Indonesia, caused a volcanic winter that impacted East Africa and dramatically affected the evolution of early hominins. A genetic bottlenecking in hominin evolution is roughly synchronous with the Toba eruption. Cored lake sediment provides an excellent record of local variability in the lake’s watershed that may be linked to specific climatic events. If the Toba super-eruption caused a volcanic winter in East Africa, then we would expect to see a response in Lake Malawi or its watershed. Specifically, cooler temperatures would reduce density contrast between epilimnion and hypolimnion waters, allowing for increased mixing and oxygenation of normally anoxic bottom waters. This mixing would cause noticeable changes on benthic microfaunal communities. We analyzed Lake Malawi core 2A-10H-2 in 2-4 mm (4-6 year) intervals surrounding the Youngest Toba Tephra (YTT) for sediment composition, microfaunal abundance and variability, and evidence of changes in occurrence of fires or watershed precipitation. Our analysis included point counts of siliclastics and micas, algae, charcoal, shallow and deep-water invertebrates, and diatoms. No significant change in microfaunal variability and abundance or sediment composition was found around the YTT in the 2A core. Similarly, charcoal counts do not suggest a change in fire regime. Based on our results it is unlikely that the Mt. Toba eruption caused a volcanic winter that impacted East Africa.
Though rapid and highly influential in Arizona and the American southwest, climate change in such arid environments remains insufficiently understood. Local livelihood relies, to a fundamental extent, on the effectiveness of water management and preparation for future drying, which can be informed by past climate. Speleothems (cave deposits) are an underutilized yet emerging proxy in the world of understanding past climate change, which, as previous research has shown, can provide a record of past climate over time. To improve our understanding of past climate in the area, we analyze trace element (Mg, Sr, Ba, P) abundances in a 7,000 year old speleothem collected from the Cave of the Bells in Tucson, Arizona using laser ablation ICP-MS. Past work on cave paleoclimatology suggests that these elements are particularly useful paleohydrological proxies. Ba and Sr are in phase across all time scales although both show shifts that may be nonclimatic. On the millennial time scale Mg tends to be out of phase with P. Sr and Ba come in and out of phase with Mg on the millennial scale and are generally out of phase with P. On the centennial scale Mg, Ba, and Sr are out of phase with P and mostly in phase with each other. On the decadal scale Mg comes in and out of phase with P, Sr, and Ba. On the interannual scale Mg and P are out of phase, while Sr and Ba come in and out of phase. These elemental data will be complemented by elemental drip water data, which may shed light on how seasonal-interannual climate variations influence elemental concentrations. These elemental data will be used in concert with isotopic data from the speleothem to give a more complete picture of hydroclimatic changes in cave records. We will examine the covariability among these elemental data, along with isotopic variations, to help define the potential climatic and nonclimatic influences on our records.
G13: Power spectral analysis of lake levels: variations in structure and scaling in lake level frequency space.
Zachary C. Williams, Jon D. Pelletier

Lake levels vary from daily to decadal time scales. Power spectra of lake level time series are saturated at low frequencies with log-linear decreasing power with increasing frequency. This power law dependence of the power spectrum on frequency is common to other natural phenomena such as river discharge, atmospheric temperature, and humidity. Given the universality of the scaling exponents describing streamflow and evaporation records, it is reasonable to assume that lake level scaling exponents might also be universal. A simple mass balance model of lakes predicts that power law scaling results from the integration of streamflow inputs and evaporative outputs where both streamflow and evaporation are modeled as fractional Gaussian noises. A preliminary analysis of lake level time series finds that scaling exponents range from -1.5 to -2. Lake level spectra also contain shifts in the scaling exponent at both high and low frequencies. Understanding the complexities that give rise to variations in power law scaling and power spectral structure between lakes can help the institutions that govern lakes make more informed management decisions.
Geophysics

G14: Investigation into the cause of a large magnetic anomaly in southeastern South Dakota
Clinton Koch

Southeastern South Dakota hosts a large circular geophysical anomaly present in both magnetic and gravity data that was investigated as a potential Precambrian bolide event, intrusive body or volcanic feature. The anomaly occurs at the southern end of the Superior Boundary Zone which extends northward into Canada. The objective of the study was to attempt to determine the cause of the anomaly and to further the understanding of the geologic history of this area. Estimation of the depth of the anomaly was constrained through a map of Precambrian surface depth. Petrographic and microscopic analysis on SD Geological Survey core samples from the overlying Sioux Quartzite in Davison County were analyzed in grain samples and thin sections for microstructures and composition relating to a bolide. Initial analysis of the core shows no evidence supporting a bolide or any reason for the anomaly, indicating that the source is deeper than the available core. Geophysical modeling on aeromagnetic and gridded gravity data indicates a large body at approximately 4km depth as the primary cause of the anomaly. ArcMap was utilized in the extraction of the magnetic and gravity data as well as use for comparison to the geology and terrane of the area. ArcMap was additionally used to look at known impact craters and intrusive bodies for comparison. Analysis of the maps produced in ArcMap show similarities between the South Dakota anomaly and other impact features. Future work is needed in order to reach a solid conclusion.
The Joshua Tree Integrative GPS Network (JOIGN) consists of 21 campaign GPS stations as part of a long-term study aimed at understanding strain transfer and accumulation between the eastern California shear zone and the complex southern San Andreas Fault system. The University of Arizona Tectonic Geodesy Laboratory offers hands-on experience to students interested in studying active tectonics using GPS geodesy by operating GPS equipment, and collecting and processing GPS data. The GPS Processing Seminar course (GEOS 596F), consisting of 3 Grads and 3 UnderGrads, carefully planned a GPS campaign to Joshua Tree National Park, southern California, in October, 2013. Over a period of 6 days, we occupied 21 campaign GPS stations located within the park and the immediate surrounding region. Students learned to deploy and operate GPS equipment, which included Trimble Zephyr antennas, Topcon GB-1000 GPS receivers, and both spike and fixed-height mast mounts. We used the GAMIT/GLOBK v.10.4 processing software to process the collected GPS data in the UA Tectonic Geodesy Laboratory. The fall 2013 data was processed along with data previously collected from within the network and southern California region between 1993-2014. We created coordinate time series in a North America fixed reference frame for each site and used the GGMATLAB program TSVIEW to analyze the data. Detailed analysis of the time-series data has improved our understanding of plate boundary deformation in southern California and provided new insights into post-seismic deformation following a M7.2 earthquake that occurred in northern Baja California in April 2010.
We present results from a new continuous GPS network spanning the state of Arizona and the southern portion of Utah. The 33 station continuous GPS network, funded by the NSF EarthScope Program, supplements a sparse distribution of continuous GPS stations that comprise the NSF EarthScope Plate Boundary Observatory (PBO) network. Installation of the sites started in July of 2010 as a collaborative effort between University of Arizona and University of Nevada, Reno. The data from the continuous GPS stations are analyzed independently with the GIPSY and GAMIT/GLOBK software using the NA12 reference frame. As data was collected the observed velocities at the EarthScope sites nearest to Apr 4, 2010 El Mayor-Cucapah (EMC) rupture area appeared to be effected by post-seismic deformation. Modeled post-seismic deformation in the area of these sites indicates it can be significant; approaching and in some cases exceeding 1mm/yr, which is of the same order of magnitude as the expected tectonic signal the network was intended to measure. Correcting for this deformation can give a better picture of the long term velocity field that we seek to understand. Using a slip model for the EMC event and the co-seismic and post-seismic deformation modeling software PSGRN/PSCMP, observed co-seismic and post-seismic deformation at PBO and NGS CORS sites with data preceding the EMC event can be compared with modeled deformation to estimate regional viscosities. These viscosities can then be used to predict post-seismic deformation at the EarthScope sites that were installed after the Apr 4, 2010 EMC event. Best fitting viscosities for the lower crust and upper mantle were sought using all the available observations and a subset that include the southern Basin and Range; the region of the of the EarthScope sites that were most effected by the EMC earthquake. The observed co-seismic displacements over a wide area were well matched using the slip distribution of the EMC earthquake and an elastic crustal thickness of 15km. The corrected velocities are generally in agreement, but more southerly than the pre-EMC velocities for nearby CORS and PBO sites.
G17: Slip on the Suckling Hills splay fault during the 1964 Alaska earthquake
Jay Chapman, Julie Elliott, Diane Doser, Terry Pavlis

The Suckling Hills in southern Alaska experienced localized, anomalously high coseismic uplift in the Mw 9.2, 1964 Alaska earthquake. High uplift at the Suckling Hills can be explained by increased slip, or an asperity, on the Aleutian megathrust, however, new research suggests that increased uplift may be a result of slip on the recently mapped Suckling Hills splay fault. We present a series of models that demonstrate how the inclusion of the Suckling Hills fault improves the fit between modeled vertical displacement and measured coseismic uplift in comparison to slip on the Aleutian megathrust alone. Our results suggest ~3m of slip in the 1964 earthquake on the Suckling Hills fault to explain the high coseismic uplift data. These results are consistent with recent studies indicating Pleistocene slip on the Suckling Hills fault and together highlight the potential seismic and tsunami risk associated with this segment of the Alaskan subduction complex.
G18: New velocity estimates from the Puna Andes GPS Array
Phillip McFarland, Rick Bennett

The Puna Andes GPS Array (PAGA) is a continuous GPS (CGPS) network operating in northwest Argentina located at approximately 24°S latitude. It has been established in an effort to observe ongoing deformation in both the Puna Region of the Central Andes and in the adjacent fold and thrust belt, directly to the East. The PAGA network is composed of 10 stations total that were installed in two phases. Five stations were installed in the first phase in March 2009. These form an East-West transect from roughly 64°W (near the eastern edge of the modern thrust front) to 66°W longitude. The second phase of five stations was installed in August 2013 to expand the latitudinal coverage of the network. We have analyzed nearly 4.5 years of data from PAGA stations (phase 1) along with other existing CGPS networks, totaling more than 100 stations, following standard processing procedures utilizing the GAMIT/GLOBK software package. From the time-series, we infer trench perpendicular velocities, realized in a South America fixed reference frame, ranging from 13.4 mm/yr ± 0.4 mm/yr in the west decreasing to 3.6 mm/yr ± 0.2 mm/yr at the easternmost extent of the array. Two crustal deformational models were used to produce theoretical surface velocities for comparison with the velocity gradient estimated from the PAGA network data. They include: 1.) a single edge dislocation embedded in an elastic half-space intended to model a low angle decollment feeding slip into the fold and thrust belt and 2.) a superposition of edge dislocations embedded in an elastic half-space intended to model deformation from the trench to the thrust front. Here, we present the results of those comparisons. We also present co-seismic station position offsets due to the February 27, 2010 Mw6.3 Salta earthquake calculated from the time-series analysis.
G19: Plate boundary zone deformation associated with Panama-South America collision using GPS
Wadyan O. Ayyad, Rick Bennett

We analyzed coordinate time series from 63 Global Positioning System stations in Central America and northwest South America. We used these data to estimate crustal motions relative to the International Terrestrial Reference Frame (ITRF2008). These data show the relative motions between the Cocos, South America, and Caribbean Plates, as well as plate boundary zone deformation between these plates including the Panama Arc microplate. Velocity estimates for most (>90%) stations have uncertainty less than 1mm/yr. We used these data to investigate plate boundary zone deformation associated with collision of the Panama Arc and northwest South America. These data allow us to infer slip rates on the major faults in the area and assess potential earthquake hazards in Panama, Colombia, and elsewhere in the region.

The deformation of northwestern South America is apparent across much of Colombia and western Venezuela, involving a significant amount of right lateral shear, which is related to escape tectonics. Internal deformation of the Panama Arc microplate is less obvious. We will present our velocity field and discuss its implications for the tectonics and earthquake hazards in the region.
Tectonics and Geochemistry

G20: Timing of exhumation of Laramide ranges in Montana constrained by apatite fission track thermochronology
Mariah C. Romero-Armenta, Barbara Carrapa

The Laramide Orogeny is thought to be related to Late Cretaceous-early Cenozoic shallow slab subduction of the Farallon plate under the North American Plate. Flat slab subduction in turn has been related to subduction of the more buoyant Hess-Shatsky Rise. As the Hess-Shatsky Rise subducted eastward it caused upper plate deformation. Possible slab rollback or delamination following slab subduction has been suggested to have been responsible for a second pulse of exhumation in the Laramide foreland. In order to test these various models of flat-slab subduction it is important to constrain the timing of exhumation of Laramide ranges. As of today it is unclear whether or not exhumation migrated eastward, westward or was concentrated within a certain time frame or instead erratic. In particular, one important limiting factor in our ability to resolve trends in exhumation is the lack of data from the Laramide ranges in Montana. We here apply apatite fission track thermochronology (AFT) to basement samples and modern river sands draining Laramide ranges in southwestern Montana to determine the tectono-thermal histories of these ranges. Fission track dating permits reconstruction of thermal histories and the rates of geological processes such as exhumation of the upper few kilometers (~4-6 Km) of the crust. Fission track ages of detrital apatite grains can provide a more regional signature of the exhumation within the catchment. We hypothesize that AFT analyses will provide a more specific time constraint for when exhumation and deformation occurred in the Laramide ranges of Montana.
G21: Detrital geochemical fingerprints of rivers along the Indus-Yarlung suture zone in Tibet: implications for drainage evolution, timing of arc development and erosion
Mohd Faiz Hassim, Barbara Carrapa, George E Gehrels, Michael A Cosca, Paul A Kapp

The Indus-Yarlung suture zone between India and Asia comprises today a central depression occupied by the Yalu River, flanked to the north and to the south by high-elevation ranges. Rivers along the suture zone are derived from such ranges and drain into the Yalu River, which in turns drains eastward. Modern sands from these rivers provide an opportunity to broadly sample rocks present within the suture zone and study their regional geochemical fingerprints and tectono-erosional implications.

Seven sand samples from rivers along the suture zone in Tibet between Xigatze to the east and Mt. Kailas to the west were collected for detrital zircon U-Pb geochronological analyses and apatite fission track thermochronology. Zircon U-Pb ages for all rivers range between 15 and 3568 Ma. Rivers draining the northern side of the suture zone mainly yield ages between 40 and 60 Ma, similar to the age of the Gangdese arc. Samples draining the southern side of the suture zone record a Tethyan signal characterized by age clusters at 500 Ma and 1050 Ma. A more detailed analysis of the youngest zircon U-Pb age components reveal strong signals between 30 Ma and 100 Ma with significant peaks at 37–40 Ma, 47–50 Ma, 55–58 Ma and 94–97 Ma, recording the activity of the magmatic arc along strike.

Our U-Pb detrital zircon ages are overall in agreement with previous work (Zhang et al., 2012); however, the details of our age spectra show some differences, including an age component at 94–97 Ma which was previously not recognized. Our results also indicate that the ages and proportion of U-Pb zircons ages of downstream samples from tributaries of the Yalu River directly reflect source area ages and degree of source rocks exposure in the catchment area. Detrital thermochronology of the same samples is undergoing and will provide information regarding the timing of erosion of the suture zone and potential along-strike variability.
G22: Zircon ages from the Amole Arkose, Tucson Mountains
Nick Hillemeyer, Eric Alpine, Angela Blanks-Bennett, Marcel Chamberlain, Muhammad Nur Addeen Amran, Anna Loukianova, Felipe Moreno-Monge, Stephen Plunk, Anna Schuh, Carly Stewart, and Rachel Tsong

The Tucson mountains themselves formed approximately 70 Ma sitting atop the now Catalina Mountains system. Beneath the peaks of the rhyolitic Tucson mountains lies a sedimentary unit known as the Amole Arkose. The Amole Arkose was thought to have formed mainly during the Early Cretaceous period. Honors students from the University of Arizona’s GEOS 251 – Physical Geology course (Fall 2013) set out to test that theory by Uranium-Lead dating of detrital zircons from the Amole Arkose using a mass spectrometer. The dates found were mainly Mesozoic (166, 189, and 225 Ma) and Proterozoic (1143, 1412, and 1650-1740 Ma) in age. This suggests that our sample may have been deposited during Jurassic time, and that zircons were also included from many different rock units exposed in southern Arizona. The lack of Cretaceous zircons in the sample is surprising given that the Amole Arkose is thought to be Cretaceous in age (Lipman, 1993). From this unique experience the students were able to learn how to gather specimens from the field and use sophisticated equipment in a professional laboratory setting in order to go through the process of extracting and dating zircon crystals. Students also learned about the geologic history of the Southwestern United States.
G23: Geologic investigation of fracture intensity in the Escabrosa Limestone at Kartchner Caverns State Park, AZ
Wesley Wilkins, Dr. George Davis

The caves and passages of Kartchner Caverns are developed in Mississippian Escabrosa Limestone along the eastern margin of the Whetstone Mountains in southeastern Arizona. The Caverns occur within an isolated fault block less than 1 mi² in area. The fault block lies ~6 kilometers east of the principle outcrop region of Mississippian Escabrosa in the Whetstone Mountains. Here, we examine whether the limestone of Kartchner Caverns is more intensely fractured than normal (due to faulting), thus permitting a higher degree of bulk permeability, conducive to cavern formation. The objective is to compare and contrast fracture intensities in the fault block setting of Kartchner Caverns versus that of the Mississippian Escabrosa Limestone in other parts of the range. The initial approach was to identify a limestone bed lying within the Kartchner Block that is also identifiable elsewhere in the Whetstone Mountains, and then carry out comparative fracture-intensity analyses. Such a bed was indeed identified through reconnaissance tracking of a set of marker beds in the Escabrosa Limestone that were mapped by David Jagnow (1999).

However, for the chosen marker (“Horn Coral Bed”), it became obvious that trace length (< 3 meters) and exposure quality were inadequate. Furthermore, because of limestone’s capacity to accommodate tectonic stresses with mechanisms other then fracturing, the fractures in the bed were not as systematic and well defined as previously imagined.

A breakthrough presented itself through the discovery of pre-tectonic layers and nodules, composed of chert, situated concordantly with the bedding of the limestone.

Using the chert nodules and layers as objects of fracture-intensity analysis has advantages. Silica/chert is, mechanically, extremely stiff, and so it is deformed exclusively by fracturing. Also, because of its resistance to erosion, chert layers commonly display trace lengths that are orders of magnitude greater then thickness, thus are amenable to standard techniques of conducting fracture intensity analyses. These types of chert deposits and layers are commonly found in the Escabrosa Limestone throughout the Whetstone Mountains, and thus it should be possible to determine whether the Kartchner Caverns selectively developed in anomalously highly fractured limestone.