INFLUENCE OF PROTEROZOIC AND LARAMIDE STRUCTURES ON THE MIOCENE EXTENSIONAL STRAIN FIELD, NORTH VIRGIN MOUNTAINS, NEVADA / ARIZONA

2002 Geological Society of America Rocky Mountain Section Annual Meeting
Cedar City, Utah
May 4 to 6, 2002

Examining deformed North Virgin Mountain pillow basalts at the peak of Mount Bangs, 2.5 kilometers above sea level. Six kilometers to the west, equivalent Proterozoic rocks lie 5-6 kilometers below sea level in the Mesquite Basin of the Basin and Range Province. Two kilometers to the east, Proterozoic rocks lie one kilometer below sea level in the Colorado Plateau province. Development of this dramatic structural topography is one of the focuses of this trip.

Mark C. Quigley, University of New Mexico
Karl E. Karlstrom, University of New Mexico
Sue Beard, USGS Flagstaff
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INTRODUCTION

This two-day field trip begins on the evening of May 4 and ends on the evening of May 6, 2002, in Cedar City, Utah. We will investigate the long-lived tectonic evolution of the North Virgin Mountains (NVM), approximately 5 kilometers east of Mesquite, Nevada, a northeast-trending basement-cored uplift straddling the Colorado Plateau – Basin and Range margin (figure 1). This trip will present the results of detailed structural mapping, U-Pb zircon and monazite geochronology, and Ar-Ar thermochronology, and examine how Proterozoic (circa 1,750 – 1,600 Ma) and Laramide (circa 70-55 Ma) – aged structures influenced the geometry of Miocene-aged extension and rapid exhumation of the North Virgin Mountains. We will examine a wide spectrum of rocks ranging from circa 1,700 Ma tectonic "mélanges" to middle Miocene conglomerates, in order to evaluate various aspects of the tectonic evolution of this region. We will spend two nights in Mesquite, Nevada, discussing the regional geologic and geochronologic context for the trip.

Figure 1. Location of the North Virgin Mountains, straddling the Arizona – Nevada border, and surrounding Proterozoic exposures (black) in the Beaverdam, Mormon, and South Virgin Mountains (Gold Butte Block).

The first day of the trip will begin in Cabin Canyon, in the core of a late Paleoproterozoic dextral-transpressive ductile shear zone. Here, we will investigate the complexly partitioned strain patterns in the context of regional Proterozoic tectonics. We will traverse the zone, discussing the shear sense and U-Pb monazite dating of the deformation events, and examine how the shear zone has been brittlely reactivated during Miocene deformation. We will conclude the morning with a brief look at syn-extensional Miocene conglomerates on the north flank of Bunkerville Ridge, and discuss how they provide time constraints on the exhumation of the Proterozoic core of the North Virgin Mountains (NVM), i.e. the Virgin Mountain anticline (VMA). This will be complemented by discussion of the apatite fission-track study conducted in the NVM in February 2001.

In the afternoon, we will drive to the north end of the NVM to examine Laramide contractional structures and various types of Miocene extensional structures. We will discuss the differences between "uplift" and "exhumation" of the VMA in terms of our structural, sedimentological, and thermochronological data, and look at how extensional deformation is partitioned throughout the Cambrian section. We will discuss the idea that the steep normal faults that sole into basal detachments in the Bright Angel Shale and at the Great Unconformity provide a small-scale analogue for a regional subhorizontal detachment at the Proterozoic – Phanerozoic interface. This concept of extensional slip along the Great Unconformity is important regionally for understanding Miocene extensional processes.

The second day of the trip will begin with a brief stop at the mouth of Elbow Canyon, where we will examine the Proterozoic ductile deformation history, especially the structural transition from high-temperature, syn-magmatic deformation to lower-temperature, mylonitic deformation. We will then drive west to begin our traverse through Paleoproterozoic "exotic" mélanges, including 2-pyroxene ultramafic rocks, calc-amphibolite gneisses, garnet-sillimanite paragneisses, and diopside-bearing marbles. We will discuss the petrologic and structural significance of these units in the context of the Paleoproterozoic tectonics of the region. We will also examine the structural overprinting of these units during Mesoproterozoic ductile shearing. At the 8,021 foot summit of Mount Bangs, we will discuss our findings within the Proterozoic rocks, than jump to a discussion of the Miocene extensional strain field over a spectacular panoramic view of the NVM, with the deepest basin in the Basin and Range (> 10 km) immediately juxtaposed with the highest peak on the western edge of the Colorado Plateau. We will present gravity and aeromagnetic data for the Mesquite Basin and discuss the tectonic development of this key region.

Major issues to be addressed by the field trip

1) **Proterozoic deformation and tectonic history – importance of late Paleoproterozoic ductile shear zones, and the question of whether they record a progressive deformation continuum or separate deformation events partitioned in time and space**
2) **The importance of a Laramide ancestry in forming the Virgin Mountain anticline – When did this structure form (Laramide, Miocene, or both) and when were the Proterozoic rocks unroofed?**
3) **How did older structural features affect the geometry of Laramide and Miocene deformation in the North Virgin Mountains?**
4) **What were the dominant processes during Miocene deformation: strike-slip faulting? Isostatic uplift? N-S shortening? Lower-crustal flow? Low-angle normal faulting?**
5) **What thermochronologic constraints can we place on deformation events, cooling events, and exhumation events? How robust are our interpretations?**

FIRST DAY ROAD LOG

Cabin Canyon, Bunkerville Ridge, and Hendricks Canyon, North Virgin Mountains

The first day will be divided into three parts: 1) structural analysis of a Proterozoic shear zone, 2) discussion of the tectonic significance of Miocene conglomerates, and 3) examination of the detachment at the Great Unconformity. We will examine structures ranging in age from circa 1,700 Ma to < 13 Ma, conceptually linked by our evidence that Proterozoic deformation fabrics were pervasively reactivated during Laramide and Miocene deformational events.

ROAD LOG

Increment Mileage	***Cumulative Mileage***	***Description***
91.0	91.0	Saturday, May 4: Drive from Cedar City, Utah to Casablanca Hotel, 950 W Mesquite Boulevard, Mesquite, Nevada via Interstate 15 S.

Increment Mileage	*Cumulative Mileage*	*Description*
0.0	0.0	Sunday, May 5: Casablanca Hotel, 950 W Mesquite Boulevard, Mesquite, Nevada. Assemble at front lobby by 7:45 am and depart for the Cabin Canyon shear zone at 8:00 am sharp. Proceed E on Mesquite Boulevard to Riverside Road. Head south on Riverside Road, take first left on dirt road immediately across bridge. Take this dirt road for 8 miles, bearing right at Y-junction at 2.5 miles. Park at entrance to Cabin Canyon, where we will be spending the entire morning.
9.5	9.5	Stop 1: The Cabin Canyon shear zone Stop 2: Miocene conglomeritic outcrops
25.5	35.5	Return to Mesquite via dirt road, go left on Mesquite Boulevard for roughly 0.5 miles, take Interstate 15 N on-ramp. Take Interstate N 12 miles to Farm Road exit, past Littlefield, Arizona. Take Farm Road south for 3 miles to Hendricks Canyon. Stop 3: Hendricks Canyon unconformity.
16.0	51.0	Return to Casablanca Hotel

Stop 1: The Cabin Canyon shear zone

Main points: 1) The Cabin Canyon shear zone segment forms part of the late Paleoproterozoic Virgin Mountains shear zone, a NE-trending dextral-transpressive deformation zone that is exposed throughout most of the length of the North Virgin Mountains
2) Deformation within this zone is strongly partitioned into pure shear dominated, simple shear dominated, and general shear dominated strain domains that operated synchronously during transpressional deformation (the space-time partitioning problem)
3) The strongly fissile mylonitic foliation that developed was brittlely reactivated during Miocene extension, and most likely during Laramide contraction, and thus helped control the uplift and current geometry of the Virgin Mountain anticline

Background Geology

The crystalline core of the NVM consists of Paleoproterozoic (circa 1,700 Ma) rocks that are part of the Mojave Precambrian province, an isotopically enriched, upper-amphibolite to granulite facies metamorphic terrain extending from west-central Arizona westward into the Basin and Range (figure 2). The proposed boundary between the Mojave and the juvenile Yavapai province (Karlstrom and Bowring, 1988) is at least 40 kilometers east of the NVM at the Gneiss Canyon shear zone, or perhaps lies farther east at the Crystal shear zone of the Grand Canyon.

The early tectonic history of the Virgin Mountain crystalline terrain (VMCT) likely involved burial to depths of 20-25 kilometers and complex bedding sub-parallel thrusting and contraction (S_1). This first-generation fabric has been intensely overprinted, with the only remaining structural evidence being northwest-trending inclusion trails in pre-D_2 porphyroblasts and weak fabrics in low strain domains south of the Big Springs

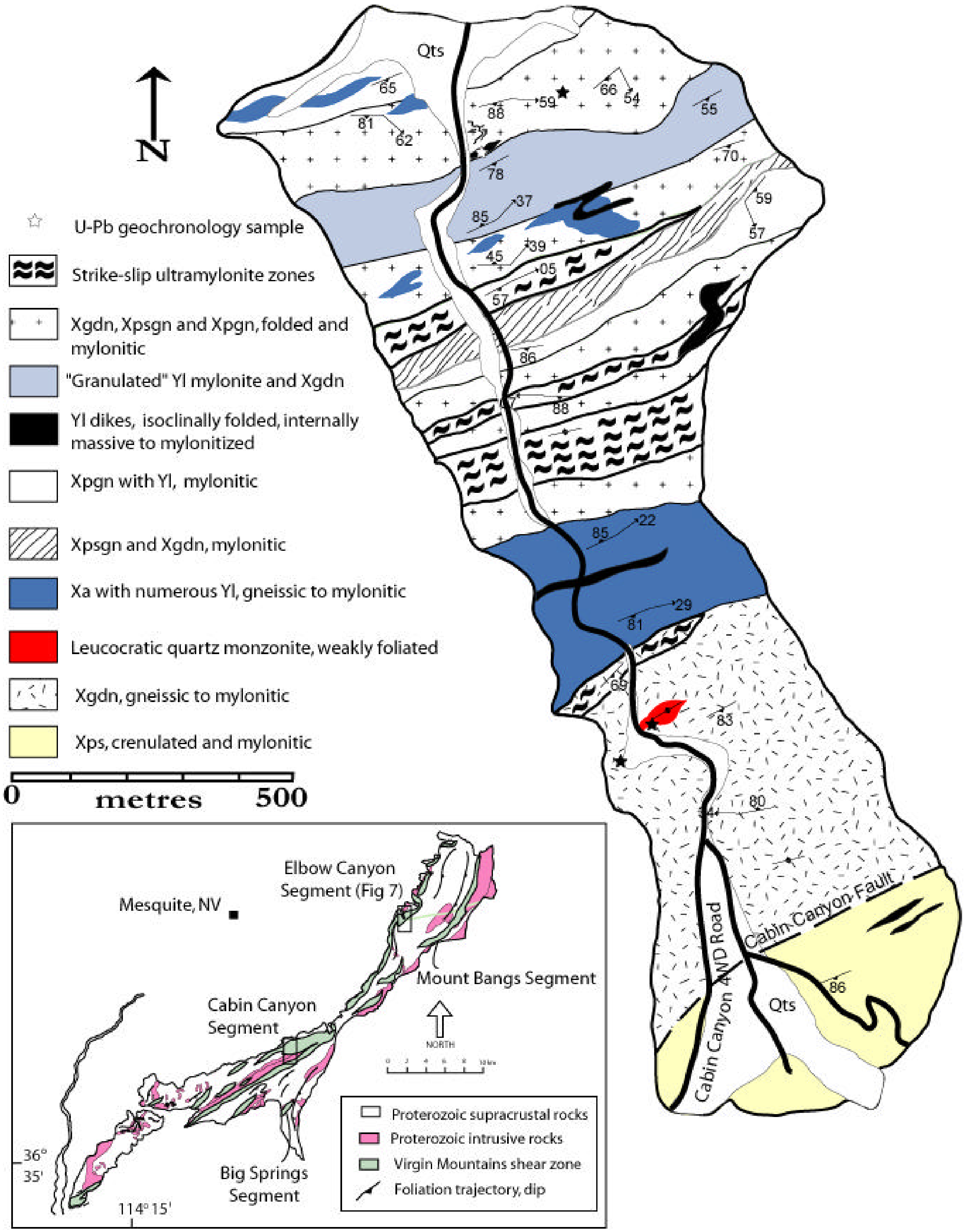

Figure 2. Geologic map of the Cabin Canyon segment, with location of U/Pb monazite and zircon samples. Inset. Virgin Mountain shear zone network, with location of Cabin Canyon segment (box)

segment (figure 2 inset). Throughout the rest of the VMCT, intense E-W contraction resulted in formation of a penetrative N-S fabric (S_{2a}), accompanied by high-temperature metamorphism and localized migmatization. This fabric was progressively reoriented into a NE-trend (S_{2b}) during synchronous NW-side-up thrusting, continuing peak temperature metamorphism (upper amphibolite facies), and granitic magmatism.

This NE-trending fabric was strongly reactivated during continual deformation at shallower crustal levels (D_3), resulting in formation of the Virgin Mountains shear zone network (VMSZ). The VMSZ is composed of structurally linked mylonitic shear zones displaying a wide variety of finite strain state geometries, including: 1) dextral strike-slip zones with spectacular structural asymmetry, 2) oblate (flattening) domains with conjugate shear bands and weakly developed vertical stretching lineations, 3) steeply lineated L>>S prolate (stretching) domains with poor asymmetry, and 4) obliquely lineated reverse and normal sense domains with excellent asymmetry. Deformation is most intense along pre-existing lithologic and structural heterogeneities, although almost all of the Proterozoic rocks have been overprinted by this event.

An overall kinematic analysis of the VMSZ suggests that deformation was primarily dextral-transpressive, with complexities arising due to variations in shear zone orientation and geometry, rheologic heterogeneities, and perhaps, timing of deformation. Regional deformation has been dated at circa 1,650-1,550 Ma using U-Pb monazite geochronology, a broad time range suggesting either multiple movement histories or a protracted deformation continuum lasting over 100 m.y. Seemingly incompatible structures can be easily created during heterogeneously partitioned transpressive deformation, and are correlated based on metamorphic conditions and deformation microstructures. The best-exposed, most intriguing evidence for this style of deformation is in the Cabin Canyon segment of the VMSZ, our first stop on the field trip.

VMSZ - Cabin Canyon Segment

The Cabin Canyon segment (figure 2) provides the best evidence for partitioned dextral-transpressive deformation in the VMSZ. Detailed mapping revealed strain patterns indicative of transpressional deformation; simple-shear dominated, dextral strike-slip domains (Stop 1D), flanked by pure-shear dominated domains (Stop 1B), and LS domains with oblique-reverse sense kinematics.

Stop 1A: Cross-cutting Leucopegmatite Dikes

The first outcrop reveals the complexity of the pre-mylonite, high-temperature S_{2a} and S_{2b} structural fabrics and associated plutonism of the VMCT. This biotite-hornblende granodiorite unit, interlayed with pelitic paragneiss and cross-cut by numerous leucopegmatite dikes and veins, preserves cross-cutting relationships that have been largely obliterated within the higher D_4 strain domains in the core of the Cabin Canyon shear zone. The chronology of events was as follows:

D_{2a}: High temperature metamorphism and development of compositional layering and strong S_2 foliation, defined here by alternating layers of granodiorite and isoclinally folded syn-D_2 migmatitic leucosomes (figure 3). This fabric was weakly crosscut by thicker late syn-D2 leucopegmatites (figure 3) that record slightly lesser degrees of D_2 isoclinal folding (although they are still strongly deformed in this fashion).

D_{2b}: Refolding of D_2 leucopegmatites orthogonal to their axial planes by open F3 folds, associated with the progressive re-orientation of the N-S fabric (S_2) into the NE-SW fabric (S_3) during NW-side-up thrusting. "Syn-D_3 leucopegmatites" (figure3) intruded axial planar to F_3 folds. The late-D2 leucopegmatites locally "bleed-into" the early-D3 pegmatites, and the formation of NW-side up shear fabrics associated with intrusion of these dikes and re-orientation of the S2 fabric. These dikes are relatively straight, although they have been folded locally. It is this generation of dike which we believe we have dated at Stop 1C (see below).

D_3: All fabrics and intrusions are overprinted by a lower temperature mylonitic foliation associated with dextral transpressive deformation in the VMSZ. The mylonitic fabric (S_3) weakly crosscuts the leucopegmatites, and likely records a retightening of the outcrop-scale F_3 open fold, which would account for the slight splaying in the D_{2b} pegmatites.

Stop 1B: Oblate (pure-shear dominated) Mylonites

Pure-shear domains contain mylonitic, conjugate shear planes at roughly 30 degrees from the mylonitic foliation on vertical rock faces. Foliation planes contain large (>12 centimeter) "pancake-like" K-feldspar porphyroclasts, likely derived via the mechanical dismemberment of leucopegmatite dikes during deformation. The same crystals appear as highly flattened and dismembered leucosomes on faces perpendicular to the mylonitic foliation, resulting in aspect ratios of roughly 30:30:1. The combination of these oblate flattening strains, conjugate shear bands recording vertical extension parallel to the foliation planes, and development of a weak, vertical stretching lineation (figure 3) suggest that shortening in these domains was accommodated by intense vertical “extrusion”, similar to that first predicted by the Sanderson and Marchini (1984) transpression model. While grain-sizes are coarser in these domains relative to the ultramylonitic strike-slip domains, the microstructures and metamorphic reactions are suggestive of similar tectonic conditions. The strike-slip domains are thus inferred to have recorded more intense finite strains than the oblate domains, as opposed to recording a different deformation event. Further evidence of increased strain in the strike-slip mylonites is that obliquely plunging fold axes in the wall rocks have been rotated into parallelism with the shallowly plunging lineation in the strike-slip domains.

Stop 1C: Folded Leucopegmatite Dike

This muscovite-biotite leucopegmatite dike is of early D_{2b} generation in that it crosscuts all other intrusions and the strong S_{2a} foliation, locally at high angles, but is tightly folded about an axis sub-parallel with those fabrics. It shows small domains of D_3 mylonitization and associated retrogression, but for the most part is internally unfoliated. This dike is currently being dated at the Massachusetts Institute of Technology (Samuel Bowring, personal communication) to constrain the minimum age of D_{2b} deformation and the maximum age of D_3 mylonitization.

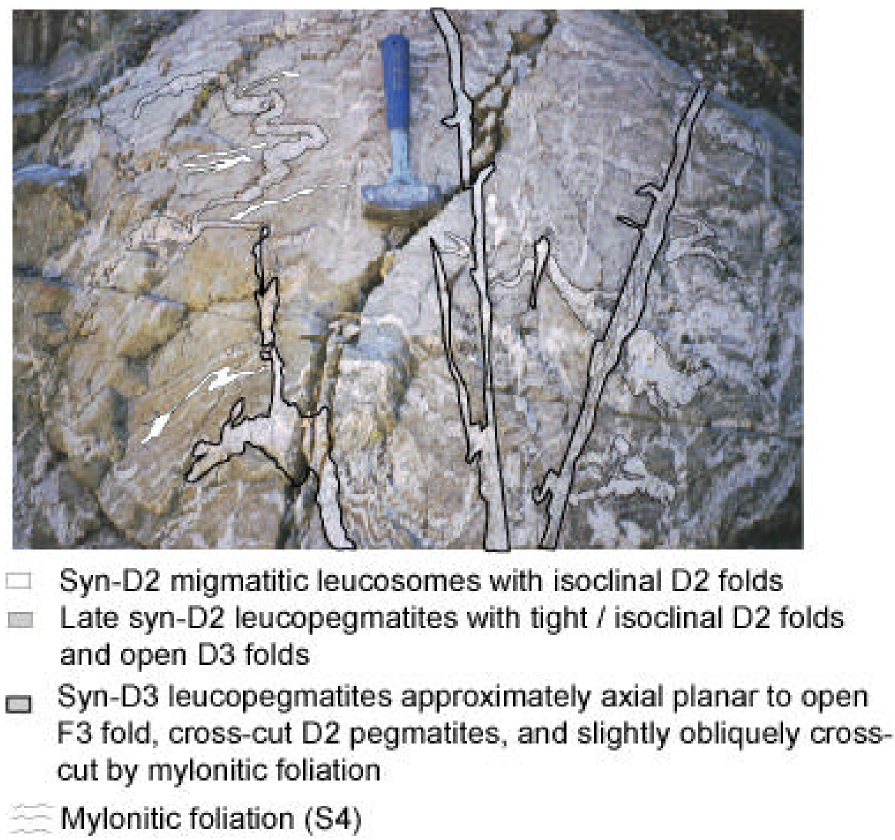

Figure 3. Crosscutting leucopegmatite dikes at the opening to Cabin Canyon. These excellent cross-cutting relationships are obscured in higher strain zones within the Cabin Canyon shear zone, and record the transition from migmatization and foliation development associated with D2 to the reorientation of this fabric into a NE-trend (D3) and synchronous plutonism. Cross sectional view, looking northeast.

Stop 1D: Dextral Strike-Slip Mylonites

The narrow (~15 meters maximum) dextral strike-slip ultramylonite zones contain a variety of shear sense indicators on faces paralleling the lineation, including sigma and delta porphyroclasts (figure 4), antithetic bookshelf-type structures, asymmetric myrmekite fabrics in K-feldspars, C-S fabrics, and shear bands. The sub-horizontal lineation developed in these zones thus appears to represent the movement direction. Quartz microstructures indicate deformation occurred predominantly by subgrain rotation and climb-accommodated dislocation creep, whereas feldspars deformed by internal kinking and development of mechanical twins, brittle fracturing, and recrystallization-accommodated dislocation creep, together are suggestive of lower amphibolite, upper greenschist deformation conditions. Garnet is retrogressed and locally psuedomorphed by plagioclase + epidote +/- actinolite, often resulting in a “disaggregation” of originally euhedral garnet porphyroclasts during progressive strain. Hornblende has broken down to form actinolite. The microstructures and metamorphic relations thus suggest that deformation and metamorphism occurred under upper greenschist facies conditions.

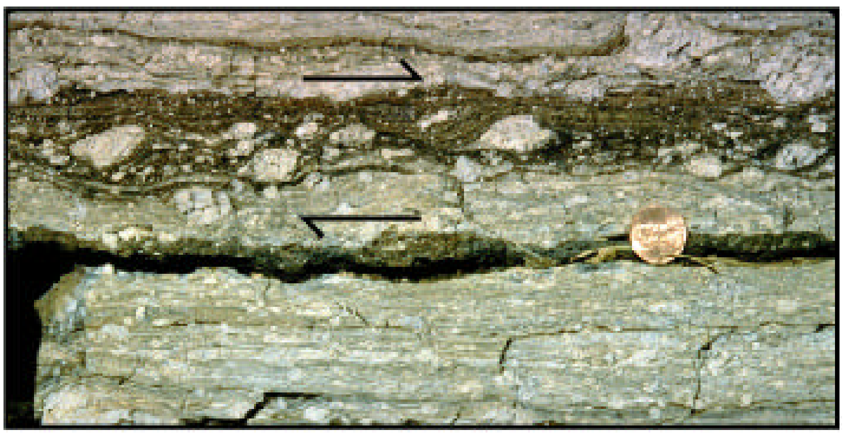

Figure 4. Sigma-porphyroclasts, and shear bands revealing dextral shear sense, ultramylonitic unit, Cabin Canyon shear zone. Plan view, NE is to the right.

As you walk up the canyon….

Interpreting the kinematic history in the strongly lineated, obliquely plunging domains is more complicated. Sinistral N-side-up indicators are present in some of the northern locations, although oblique-dextral deformation still predominates. Lower temperature shear sense indicators such as shear bands and sigma porphyroclasts are present on faces non-parallel to the strong lineation observed in these units. The apparent conflict between opposing senses of shear is reconciled with the interpretation of early, high-temperature NW-side up thrusting (D_{2b}) and development of the stretching lineation, overprinted by the upper greenschist facies dextral transpressive deformation (D_3), with some sinistral faults operating during D_4 shortening to accommodate space problems, structural anisotropies, and heterogeneous transpression. The steeply plunging lineation is interpreted to be the result of the earlier event based on: 1) the differing character between it and the strike-slip and vertical lineations observed in the simple shear and pure shear dominated domains, respectively, 2) the obliquity of lower temperature shear sense indicators to this lineation, and 3) the apparent overprinting and reorientation of this lineation proximal to the strike-slip domains.

To the east of Cabin Canyon in Lime Kiln Canyon, the mylonitic foliation is strongly folded and displays a combination of N and NE-trending, dextral-oblique strike-slip segments and N-trending, W-side-up reverse segments. This is interpreted as a partitioned, syn-mylonitic constraining bend in the Cabin Canyon segment (figure 2 inset), based on the presence of localized parasitic mylonitic folds with the same geometry, and lack of evidence that folding preceded the ductile deformation.

Stop 1E: Cabin Canyon Fault Trace

As you come southward out of Cabin Canyon, the trace of the sub-vertical Cabin Canyon fault is visible in the near saddle to the NE and the prominent valley and far saddle to the southwest. The fault separates granodioritic gneiss and semi-pelitic paragneiss to the north from a relatively thick package of pelitic schist to the south. Kinematic indicators are rare, but where observed, slickenlines plunge shallowly (10-20^o) to the east. This fault zone has had a long movement history, as a high-temperature D_2 deformation zone, a lower-temperature D_3 mylonitic shear zone, and most likely as a brittle Laramide reverse fault and Miocene oblique strike-slip fault.

The nature of basement-penetrating faults is enigmatic because their age (Miocene vs. Laramide) is largely unknown, and they rarely show slickenlines. They are often recognized as continuous chloritic breccia zones along Proterozoic lithologic contacts. Although Miocene left-slip is likely (Williams and others, 1995), reconstructions of fault separation using Proterozoic lithologies are unreliable due to the extremely heterogeneous nature of the Proterozoic basement. Furthermore, it is likely that most basement-penetrating faults had both a Laramide and Miocene component of slip. Aside from the Hen Spring fault, basement-penetrating faults predominantly follow the Proterozoic foliation, striking NE in S_{2b} dominated domains, and striking N-S in S_{2a} dominated domains. An important conclusion of our work is that the orientation of Proterozoic fabrics helped control the geometry of Miocene and Laramide faults, and uplift of the VMA.

Stop 2: Miocene conglomeritic outcrops on north flank of Bunkerville Ridge

Main points: 1) Bunkerville Ridge is a structurally complex package of steeply north-dipping to south-overturned Paleozoic limestones, and was created as a result of Miocene normal faulting modified by later, intense strike-slip deformation.

2) Miocene conglomeritic outcrops on the north flank of Bunkerville Ridge are assigned to the red sandstone unit (10-12 Ma) based on general appearance and presence of Proterozoic clasts. This section records a syn-extension middle Miocene unroofing sequence consistent with apatite-fission track ages of basement rocks ranging between 14-20 Ma.

3) The red sandstone conglomerates are vertical to overturned to the south, suggesting that intense strike-slip faulting occurred sometime during or after the 10-12 Ma deposition of this unit, post-dated uplift and exposure of the Proterozoic rocks, and thus post-dated formation of the VMA.

Geology of Bunkerville Ridge

From our lunch spot we can view the high-standing late Paleozoic limestones of Bunkerville Ridge, Miocene conglomerates at the foot of the ridge, and Pliocene and Quaternary alluvial strata of the Virgin River depression. Bunkerville Ridge is an east-northeast-trending section of Paleozoic strata that strike roughly parallel to the local trend of the physiographic high and dip northerly or are vertical to overturned to the south. The continuity of the ridge is broken by two prominent low areas through which northeast-striking faults pass.

The south side of the ridge is commonly marked by the depositional contact of the Tapeats Sandstone (∈t) on various Proterozoic crystalline rock units or by the two northeast -trending faults that have Paleozoic rocks on their northwest sides and Proterozoic rocks on their southeast sides. South of the ridge the quadrangle is underlain by various Proterozoic crystalline rocks that are faulted by two regionally prominent faults that have northeast trends, the Hen Spring and Cabin Canyon faults. The Hen Spring fault marks the southern edge of Bunkerville Ridge where it separates Paleozoic rocks from crystalline basement, and is one of the few basement-penetrating faults that locally cut the Proterozoic foliation (Beal, 1965).

The basal Cambrian strata that form the southwestern ridge segment have moderate northwest dips. A broad, open fold pair, whose axial plunge parallels the stratal dips, is defined by changes in strike of the beds. The syncline is well displayed, but the anticlinal axis is buried by Quaternary and late Tertiary deposits and is cut by a fault with a northeast trend. This suggests a sequence of events in which a flat section of Cambrian rocks was folded gently, later to be tilted more steeply and cut by faults. Both the large east-bounding fault and the one cutting the anticline exhibit a well-developed left separation of the basal Proterozoic-Cambrian contact. The separation on the fault between the southwestern and central ridge segments is on the order of one kilometer.

The central ridge segment is primarily a moderately northeast-dipping homocline in Lower Cambrian to Mississippian rocks. Intermediate dips are common at high stratigraphic levels and steep dips are common near the base of the homocline. The Proterozoic-Cambrian contact is faulted in places and depositional in others, but it defines large open folds with northeast trends in the Proterozoic-Cambrian contact that are not obvious at higher levels in the homocline. Two large fault blocks rest tectonically above the homoclinal section of rocks. The faults beneath each block form two convex-up, spoon-shaped surfaces, each of which appears to plunge to the southwest, perpendicular to the strikes in the underlying homocline and to the orientation parallel to the basement crenulations. Northeast-dipping homoclines of Cambrian to Pennsylvanian rocks form the hanging-wall blocks of each of the spoon faults. The stratigraphic separations suggest that each spoon was transported to the southwest relative to the underlying homoclinal block. The central part of the footwall homocline is offset with about 0.5 kilometers of left separation by a northeast-trending fault that merges with the fault that forms the west-northwest side of the eastern spoon.

The structural relations surrounding the two spoon-shaped fault surfaces suggest that they developed as a single normal fault surface that cut a flat-lying section of rocks. The original fault surface was probably gently crenulated and had a general northwest strike and a steep to intermediate southwest dip. Subsequent strong northeast-tilting of both the hanging wall and footwall blocks resulted in the gentle southwest dip of the modern spoon-shaped surface. Erosion of much of the hanging wall preserved only the cuspate crenulations in the original surface.

The strata in the eastern ridge segment form a deformed north-dipping homocline. The basement-basal Cambrian contact is depositional and gently dipping all along this part of the ridge. Two small left-separation faults with north-northeast trends cut the contact. Strata in the higher stratigraphic levels in the homocline dip steeply to the north. At no point is there a complete section exposed in this segment of the ridge. A complex pattern of low- to intermediate-angle, north dipping, normal faults disrupts the middle part of the homocline. Each of these faults locally eliminates part of the section, placing younger strata on older. At the eastern boundary of the quadrangle these faults merge into two, which in turn join with the Hen Spring fault to the east of the quadrangle. In map view the nearly continuous Tapeats Sandstone at the base of the homocline converges with Mississippian rocks in the homocline's upper part at the eastern border of the quadrangle, indicating that, at that location, a large amount of section is removed by the two faults.

Significance of the Miocene Conglomeritic Unit

Scattered outcrops of steeply dipping, middle Miocene red sandstone conglomerate cover an area of approximately 300 square meters on the north flank of Bunkerville Ridge, and provide key insights into the pre-tilting topography and structural evolution of the VMA. The conglomeritic unit is 50-100 meters thick, and contains angular clasts ranging in diameter from 1 to 100 centimeters. While the clast assemblage is dominated by middle to late Paleozoic limestones, nearby outcrops contain Proterozoic and lower Cambrian Tapeats clasts up to 5 percent. The presence of coarse clasts of Tapeats Sandstone and Proterozoic granite, amphibolite, biotite-garnet schist, pegmatite, and mylonite in the stratigraphically higher red sandstone units (figure 3), and absence in the stratigraphically lower units, suggests that this red sandstone conglomerate records a Miocene unroofing event, whereby the Proterozoic rocks were fully exhumed sometime during proximal red sandstone conglomerate deposition. This unroofing event was likely synchronous with basement-penetrating strike-slip and normal faulting, and development of the Mesquite Basin, after some structural relief was already present. The farthest west exposures of this unit lie disconformably on 74 degrees north-dipping Triassic Moenkopi Formation, middle-distance exposures dip between 60 degrees to the north and 74 degrees overturned to the south, and the closest outcrop dips 32 degrees to the east, at a high angle to adjacent, intensely overturned, south-dipping Kaibab Formation limestones. These complex geometries are likely a result of the syn-extensional strike-slip faulting that this area underwent probably during deposition of these units.

The Virgin River Depression

The Neogene Virgin River depression has a surface area that exceeds 1,500 square kilometers. The depression formed within the foreland of the Sevier orogenic zone, a region characterized in Paleogene time by a flat-lying section of Cambrian to Cretaceous platform strata about 5 kilometers thick and perhaps a small amplitude Laramide uplift to the east (VMA). Well data from Mobil Virgin 1A on Mormon Mesa reveal 2,000+ meters of Neogene basin fill that consists mostly of the Muddy Creek Formation (4-10 Ma), the red sandstone unit (10-12 Ma) of Bohannon (1984), and the Lovell Wash Member of the Horse Spring Formation (12-13 Ma). Seismic reflection data from six primacord and two vibroseis lines show that the Muddy Creek Formation uniformly fills Virgin River depression to a depth of 1-2 kilometers. Two older and less-extensive basins, the Mormon and Mesquite, lie beneath the Muddy Creek and are separated from one another by a complex buried ridge. The basins are mostly filled with rocks of the red sandstone unit and Lovell Wash Member to depths locally exceeding 6 kilometers. Two older members of the Horse Spring Formation, the Rainbow Gardens and Thumb, also are present in Mormon basin (the western one), where they rest disconformably on the pre-Tertiary strata. The basins are east-tilted half grabens bound on the east and southeast by large listric normal fault systems. The Muddy Creek Formation buries the faults that bound Mormon basin, but the Piedmont fault, on the east side of Mesquite basin, cuts Quaternary alluvium.

The Virgin River depression formed in three stages. The period from 24-13 Ma is characterized by slow subsidence in Mormon basin and little noticeable deformation of the basin substrate. The Mormon and Mesquite basins became fully differentiated during the period from 13-10 Ma. This stage is associated with large displacements on the normal faults bounding both basins and the buried ridge. Proterozoic crystalline rocks were exposed locally, as determined from the unroofing sequence within the red sandstone unit and apatite-fission track data, which suggest rapid cooling through ~100^{o}C between 20-14 Ma. Tectonic denudation during the 13-10 Ma stage locally removed large amounts of the pre-basin section. Pronounced strike-slip deformation affected the west limb of the VMA, and locally overturned red sandstone conglomerates, sometime after 12 Ma. Post 10 Ma, most of the fault activity had ceased, the ridge between the basins was overlapped, and the Virgin River depression began to subside uniformly over a wide area. This stage lasted until the commencement of the modern period of dissection associated with the Colorado River. Structural analysis suggests that upper crustal extension within the basin, mostly during the 13-10 Ma stage, might have exceeded 60 percent. The basin subsidence was partly due to extension in the upper crust and partly due to viscous flow in the deeper crust beneath the basin.

Stop 3: Hendricks Canyon Traverse

Main points: 1) Overturned monoclinal-style geometries in the lower Cambrian section at the NW end of the VMA suggest a component of Laramide deformation

2) Sub-horizontal fault surfaces in the Bright Angel Shale and at the Great Unconformity suggest detachment faulting and tectonic transport of allochtonous, tilted fault blocks above para-autochthonous Proterozoic basement

The Hendricks Canyon Area

Upon arrival at the north end of the NVM, we can view the only location where the Great Unconformity between the Proterozoic crystalline core of the NVM and the overlying Phanerozoic section runs east-west. It is the varying structural-rheological aspects of this Proterozoic-Phanerozoic surface that we will be focusing on during this stop.

The Proterozoic rocks in this area are predominantly garnet-biotite-sillimanite migmatitic paragneiss, pink monzogranitic pegmatite, and a thin (5-10 meters) quartzite layer that is concordant with the paragneiss. The Phanerozoic section north of the Great Unconformity consists of a variably thinned Cambrian section through to the Mississippian Monte Cristo Limestone, which forms the high peaks visible from this location. On the northeast flank of the NVM, not visible from here, the east-tilted section contains Cambrian through Middle Triassic units, capped by flat-lying Quaternary basalts and landslide deposits.

Visible in the section exposed before us is a complex array of east- and west-dipping conjugate normal faults, with offsets ranging from centimeters to >400 meters. We have focused mainly on fault geometry and deformation partitioning in the Cambrian section. The normal faults commonly dip 50-70 degrees in the Muav Limestone, and are associated with strong brecciation and formation of calcareous vein networks. These steep normal faults shallow to 40-50 degrees at the contact with the underlying Bright Angel Shale, resulting in moderately dipping horst and graben structures in the upper Bright Angel Shale. These faults sole out into sub-horizontal geometries throughout the highly fissile Bright Angel Shale, resulting in dramatic changes in stratigraphic thickness. The Tapeats Sandstone is also strongly attenuated due to segmentation by both steep and bedding parallel (basal) normal faults. These normal faults also obtain sub-horizontal geometries along the Great Unconformity, where the flat-lying Tapeats stratigraphy overlying the vertically foliated Proterozoic basement presents a dramatic rheological contrast. The best field example of lateral transport of allochtonous Cambrian section along low angle normal faults at the Great Unconformity in the NVM is at Stop 3B.

The strong rheologic contrasts between the competent overlying Paleozoic Limestones and the incompetent Bright Angel Shale, and the competent underlying Tapeats Sandstone and Bright Angel Shale, resulted in significant structural decoupling within the Phanerozoic section during crustal extension. The strong rheologic contrast between the Tapeats Sandstone and the underlying Proterozoic basement also resulted in this decoupling, suggesting that at least locally, the Phanerozoic cover may have moved independently from its

Proterozoic counterpart. Similar observations from the Gold Butte area in the South Virgin Mountains suggest this was a regionally important detachment surface.

Stop 3A: Evidence for Laramide-Style Deformation in the North Virgin Mountains

We investigated the possibility of a Laramide component to the finite strain field of the NVM based on the following: 1) The position of the VMA just east of the leading edge of the Sevier thrust belt, as documented in the Mormon Mountains (Axen, 1990), and west of the well documented high angle Laramide reverse faults and monoclines of the Grand Canyon (Huntoon, 1990), suggests that the VMA may occupy a “transition zone” between these two structural domains. Beard (1993) mapped Sevier-style thrust faults in the Phanerozoic section south of Virgin Peak, suggesting that contractional deformation did affect parts of the NVM. 2) The Laramide monoclinal uplifts of the Grand Canyon have a systematic spacing in map view, and are generally cored by basement-penetrating reverse faults. Just from the spacing, we suggest there were monoclines at the NVM, roughly 50 kilometers west of the Hurricane fault monocline; 3) Paleocurrent and stratigraphic relationships in the early Miocene (~26 Ma), pre-extensional Rainbow Gardens Member basal conglomerate suggest deposition in overall northest-flowing braided streams, with positive areas south of the Gold Butte block (figure 1) in the N-plunging Kingman highlands, and a “moderate to abrupt relief area” within the NVM, deemed the “Virgin positive area” (Beard, 1996). The shedding of sediments to the southeast off the Virgin positive area suggests some topography existed here before middle Miocene extension began.

Figure 5: Monoclinal west limb of the VMA, with dramatic angular relationships between the Cambrian Muav limestone (60^o W-dipping) and Lower Cambrian Tapeats Sandstone (46^o E-dipping) accommodated by spectacular tectonic thinning and splaying of the Bright Angel Shale. Monoclinal reverse fault dips at most 46 degrees to the E.

The outcrop before us (figure 5) consists of, from west to east, 1) moderately west-dipping Muav Limestone, 2) contact between the Muav and Bright Angel Shale (231/42^o), 3) tectonically thinned Bright Angel Shale, which fans from moderately to steeply W-dipping (235/80^o), 4) vertical contact between Bright Angel Shale and Tapeats Sandstone, and 5) overturned Tapeats Sandstone, which fans from near vertical to moderately E-dipping (240/46^o); extrapolated reverse fault contact between Tapeats Sandstone and Proterozoic paragneiss. While the presence of overturned beds are not explicitly diagnostic of a Laramide structure, the geometry of the structure before us is similar to those commonly observed in the monoclines of the Grand Canyon, and not a feature as commonly observed in extensional or strike-slip faults within the Basin and Range. The lowest dip of the basal Tapeats Sandstone (240/46^o), gives the maximum dip of the reverse fault, which in this case must dip at most 46^o to the east. The inward-verging, basement-penetrating nature of this fault, required to explain the observed geometry, is characteristic of the basement-cored Laramide uplifts of the Colorado Plateau.

As you walk up the arroyo…

Between stops 3A and 3B, examine the Paleozoic section outcropping to the north. Steep conjugate normal faults within the Paleozoic limestones sole into basal detachments within the Bright Angel Shale, Tapeats Sandstone, and at the Great Unconformity. It is the latter variety which we will observe at Stop 3B.

Stop 3B: Basal Detachment Fault at the Great Unconformity

The outcrop before us consists of W-tilted "domino blocks" of Tapeats Sandstone atop Proterozoic mafic schist and monzograntic pegmatite, separated by a chloritic–hematitic zone of fault gouge at the Great Unconformity. The Tapeats Sandstone can be divided into three zones: 1) allochtonous W-tilted blocks separated by 50-60 degrees E-dipping normal faults, 2) quartz-cemented fault breccia, and 3) para-autochthonous fault slivers that appear to have glided along the Great Unconformity fault surface (figure 6). The allochthonous blocks dip roughly 50 degrees towards 335 degrees, and also contain some evidence of fault slip along bedding planes. The proposed extension direction related to tilting of these blocks is approximately 120 degrees, orthogonal to the trend of fault-block corners.

The Great Unconformity fault gouge is dominated by fine-grained, low-grade alteration minerals (chlorite, hematite, clay minerals), and exhibits chaos structure, whereby the fault breccia is thickest beneath the footwall at the normal fault, and thinnest beneath the hanging wall at the normal fault. The fault gouge is strongly layered and exhibits numerous conjugate horst and graben structures with small centimeter scale offsets. Measurements of these conjugate sets approximate 191/61 degrees and 346/49 degrees.

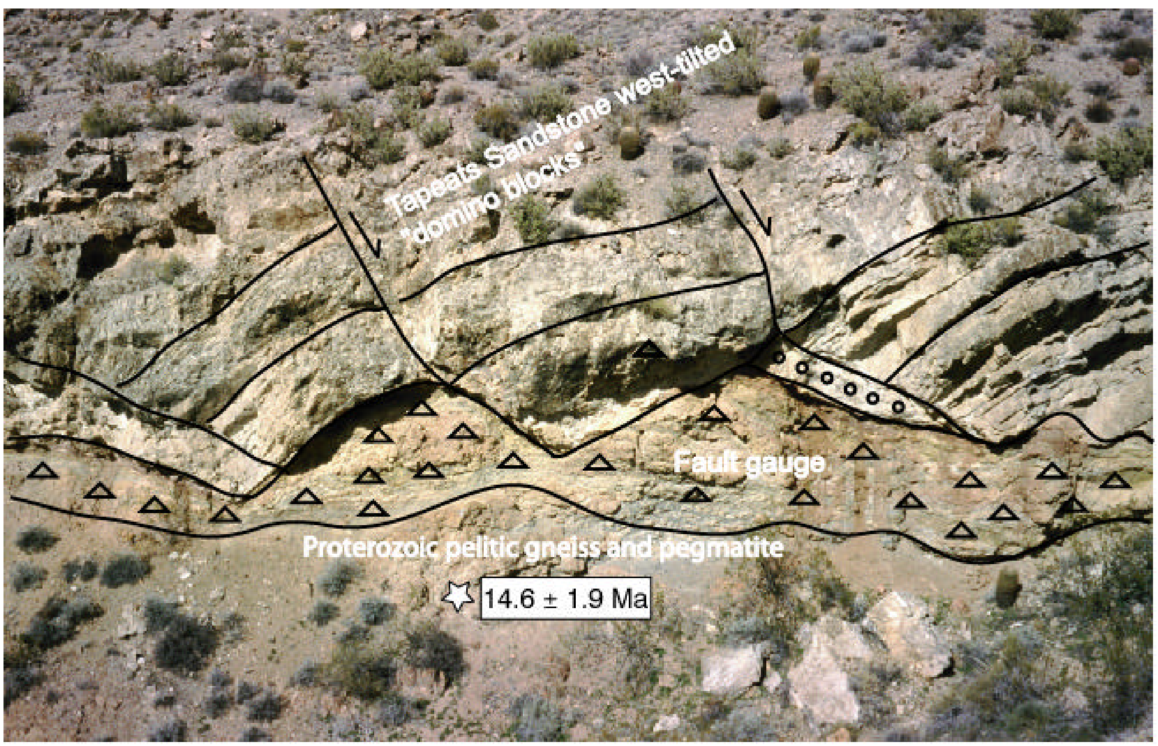

Figure 6: Allochtonous, W-tilted domino blocks of Cambrian Tapeats Sandstone overriding Proterozoic crystalline rocks (the Great Unconformity). The fault zone consists of para-autochtonous silvers of flat-lying Tapeats that have glided along the flat-lying fault zone (open circles), and ultrafine-grained fault gauge dominated by layers of low-grade alteration minerals and conjugate fault sets. Proterozoic pegmatite below the fault gauge yields an apatite fission-track age of 14.6± 1.9 Ma.

The Proterozoic rocks also show signs of localized alteration and faulting; however, they are not penetrated by the normal faults in the Tapeats Sandstone, confirming that these faults sole out into the basal fault zone at the Great Unconformity.

Three conclusions can be drawn from this outcrop; 1) this style of extensional block faulting was associated with extension towards 120^o; 2) Proterozoic basement was structurally decoupled from the Phanerozoic section through soling of normal faults at the Great Unconformity; and 3) this style of deformation was likely early in the period of Miocene extension, and was proceeded by some component of “bowing up” and NW tilting of this once horizontal Great Unconformity fault surface.

SECOND DAY ROAD LOG

Elbow Canyon and Mount Bangs, North Virgin Mountains

On this second day, we will begin looking at the structural interplay between Proterozoic high temperature and lower temperature constriction-dominated strains in Elbow Canyon, and conclude with a traverse through a Paleoproterozoic mélange sequence leading up to the highest ridge in the NVM, Mount Bangs. At the summit, we will conclude the trip with a panoramic view of the NVM and surrounding region, looking east to the Colorado Plateau and west to the Basin and Range.

ROAD LOG

Increment Mileage	*Cumulative Mileage*	*Description*
0.0	0.0	Casablanca Hotel, 950 W. Mesquite Blvd., Mesquite, Nevada. Assemble at front lobby by 7:45 am and depart for the Elbow Canyon saddle at 8:00 am sharp. Proceed E on Mesquite Boulevard to Riverside Road. Head S on Riverside Road, take first left on dirt road immediately across bridge. Take this dirt road for 1 mile, take first left onto Elbow Canyon Road. Continue on Elbow Canyon Road E for 9 miles to opening of Elbow Canyon.
11.0	11.0	Stop 4: Stream wash W of Elbow Canyon Road, roughly 0.5 miles from opening of Elbow Canyon
4.5	15.5	Stop 5: Park at high saddle to execute Mt Bangs traverse.
15.5	31.0	After traverse is completed, return to Casablanca Hotel via Elbow Canyon Road. Pick up luggage at Casablanca Hotel.
91.0	122.0	Return to Cedar City, Utah via Interstate 15.

Stop 4: Mouth of Elbow Canyon

Main points: 1) High-temperature D_{2a}/D_{2b} structures (i.e. sheath folds, lineations, shear sense indicators) are overprinted by lower-temperature D_3 structures (mylonitic lineations, shear sense indicators) with similar lineation plunges and shear sense, suggesting that the Elbow Canyon segment may represent a long-lived northwest-side up contractional shear zone that continued during evolution of the crust from lower- to upper-middle crustal levels.
2) Preliminary U-Pb monazite dating of Elbow Canyon VMSZ tectonites reveals age groupings at ~1,700 Ma and between 1,650-1,550 Ma. These are correlative with tectonic fabrics and are tentatively interpreted to represent the high-temperature and lower

temperature tectonic events, respectively. U-Pb apatite dates of 1420 Ma suggest that the crust was > 450C at this time, and shear zone reactivation is likely, but not documented at this time.

VMSZ - Elbow Canyon Segment

This stop will provide an opportunity for further discussion of the Proterozoic deformational history of the crystalline basement of the VMA. The Proterozoic rocks of the Elbow Canyon area represent an excellent example of high temperature (upper amphibolite facies migmatitization [D_2]) and lower temperature (upper to middle greenschist facies [D_3]) constriction-dominated strains. These strains are interpreted within a tectonic and geochronologic context.

High Temperature Fabrics (S2,S3)

The roughly N-S trending foliation in Elbow Canyon is defined by metamorphically segregated garnet-biotite-sillimanite bearing paragneisses and leucosomes (Xpsgn), monzogranitic (Xmgn) and granodioritic (Xgdn) intrusions, pegmatites (Xl), and amphibolitic gneisses (Xa) (figure 7). Amphibolite pods are highly boudinaged, and wrapped by strongly foliated domains. The strong lineation, best developed in quartzofeldsapthic rocks, plunges dominantly to the NW, and is locally associated with the same NW-side-up shear sense as determined from the syn-pegmatitic shear bands at the mouth of Cabin Canyon.

The chronology of events is similar to Cabin Canyon; a north-striking foliation was variably reoriented into a northeast strike during northwest -side up thrusting and associated plutonism (pegmatites, granites). This event was related to strong constrictional strains, resulting in the strong, steeply plunging lineation and development of sheath folds, as F_1 and F_2 isoclines were variably rotated into the S_3 shear plane. An example of this is present within the exposure before us. This strongly anisotropic fabric was then progressively reactivated during dextral transpressive mylonitic deformation (D_3) at lower crustal levels (see below).

As you walk through the rocks exposed in the arroyo, attempt to differentiate the high-temperature foliation and associated structures (sheath folds, isoclinal folds) from lower-temperature mylonitic fabrics.

Mylonitic Fabrics (S_3)

The Elbow Canyon segment of the VMSZ (4A) contains two types of mylonitic deformation; L-tectonite mylonites with localized northwest-side-up shear sense, and a thin (3 meter) mylonite zone with sinistral E-side-up shear sense (figure 7).

The L-tectonite mylonites display an intense vertical stretching lineation at ~ 48 → 320^o, with localized evidence (bookshelf structures, sigma K-feldspar porphyroclasts) for northwest-side-up (reverse) deformation, although much of the deformation appears to have been symmetric and a result of strongly prolate coaxial strain. This is an excellent location for participants to practice their shear sense interpretative skills. Mylonitic deformation utilizes pre-existing northeast-trending, high-temperature foliation planes (S_{2b}) as zones of weakness, creating complex structural geometries on the faces orthogonal to foliation planes. Intense, chaotic folding on these surfaces is interpreted as a composite fabric of pre-existing F_2 folds, which tightened during the intense vertical stretching (L_3) and northwest-southeast contraction. The mylonitic fabric is poorly developed on these foliation-orthogonal surfaces. The resultant geometry is shown in figure 4B.

The consistent constriction-dominated, northwest -side up kinematics of D_2 and D_3 events in this area suggest that these events may represent a progressive deformation, occurring as the crust cooled from upper amphibolite to greenschist facies conditions during contraction and exhumation.

A small shear zone with left-lateral, E-side-up sigma porphyroclasts wraps around amphibolite boudins to the south of the L-tectonite mylonites. This is interpreted as an accommodation zone enclosing the more competent amphibolite unit, resulting from the combination of heterogeneous mylonitic deformation and rheologic anisotropy.

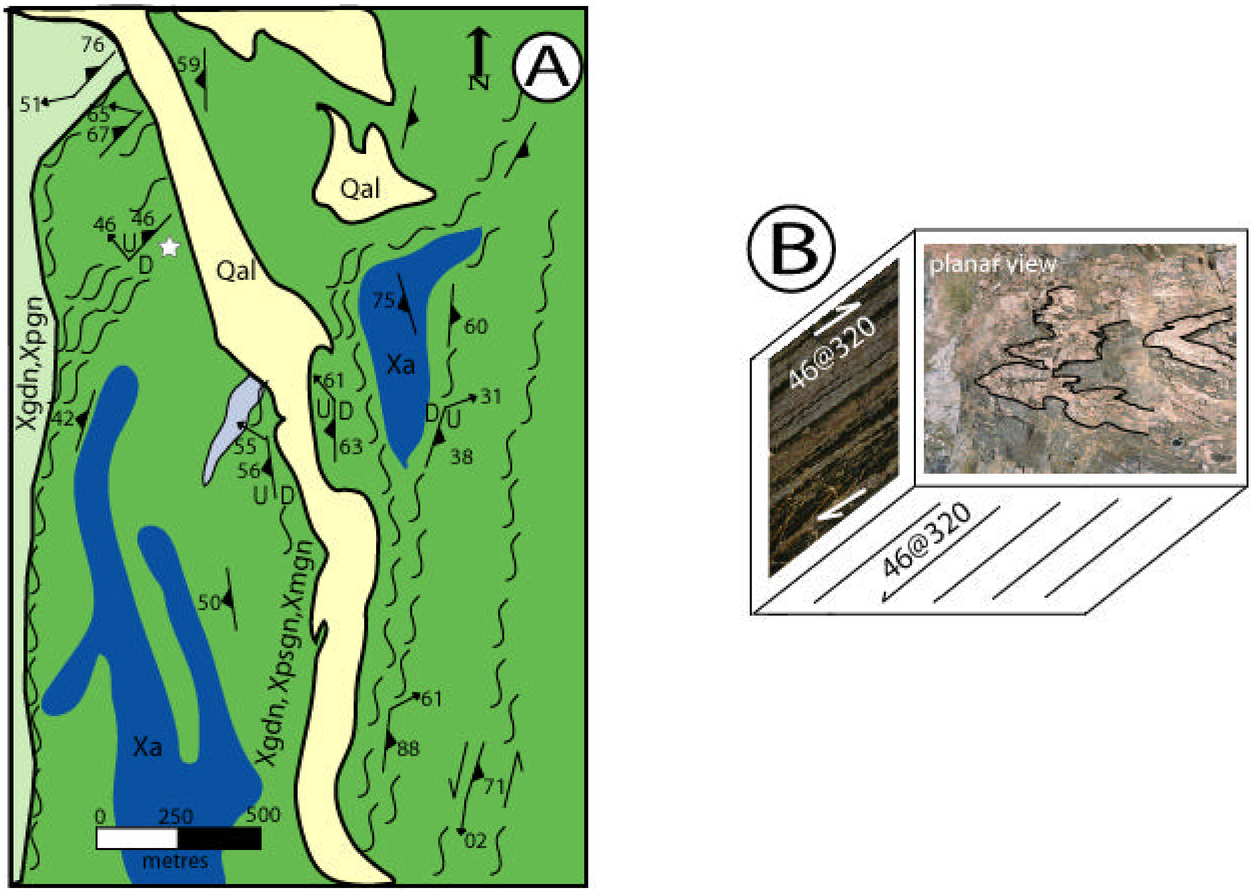

Figure 7: Geology of the Elbow Canyon segment of the Virgin Mountain shear zone. D_3 shear zones (~~) are NE-trending, L>>S constriction-dominated zones with strongly developed down-dip lineations and complexly folded YZ planes, and N-trending sinistral strike-slip zones, which may be weak conjugates to the dextral strike-slip domains in Cabin Canyon. Three-dimensional view of strained pelitic gneiss with monzogranite intrusions (B) shows strongly developed composite L3 / L4 lineation plunging 46^o at 320^o on XZ and XY planes, with strongly folded foliation striking 231^o/46^o in fold limbs (location of sample = star in map A), perpendicular to YZ plane (planar view).

Timing Constraints on Deformation

Preliminary U-Pb monazite ages from the L-tectonite mylonites of Elbow Canyon yield age clusters in at least three distinct intervals, correlative with multiple growth patterns and chemical U-Th-Pb zonations visible in backscatter images and compositional maps of the grains (figure 8). Earliest growth occurred circa 1,695 Ma, determined from core analyses of zoned monazites and consistent with preliminary zircon ages. This time frame appears to represent peak metamorphism (D_2), granitic plutonism, and formation of the penetrative NE-trending tectonic fabric (S_{2b}). This is also the time of peak tectonism (deformation at peak metamorphic grade) in the Lower and Upper Granite Gorge (1,700-1,680 Ma (Ilg and others, 1995), and in the Hualapai and Cerbat Mountains (Duebendorfer et al., 2001).

More puzzling, progressive monazite growth (rims) is recorded at 1,600 and 1,550 Ma. While these dates are preliminary and need to be checked using new methods for calculating background matrix values (Williams pers. comm., 2002) at present, we interpret them to record distinct monazite growth intervals that post-date 1,680 Ma. From regional consideration, we had thought they might be circa 1,400 Ma, but this remains unconstrained. If we interpret them to record distinct or progressive tectonothermal events, the VMSZ may provide evidence of recurrent mobilization of a partitioned, inboard crustal weak zone over a 200 m.y. time interval of tectonic convergence. Monazite structural asymmetry, and evidence that the growth of other

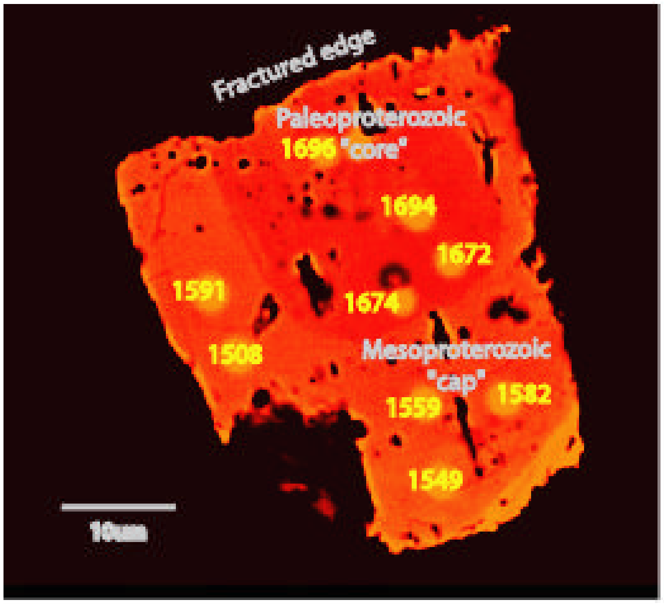

Figure 8: "Blackbody" backscatter image of monazite Q295A from L-tectonite mylonite in Elbow Canyon. U-Pb analysis yields Paleoproterozoic "core" ages (~1,696 Ma, ~1,673 Ma) and Mesoproterozoic "cap" ages (1,591 Ma – 1,508 Ma), suggesting multiple "zonation-type" monazite growth intervals. If these ages are interpreted to be tectonically significant, they may correspond to D_{2a} (1,696 Ma) and D_{2b} (1,675 Ma) high temperature metamorphism, and D_3 (1591 – 1508 Ma?) lower-temperature metamorphism, all of which are linked to tectonic fabric development.

metamorphic minerals was synchronous with the D_3 deformation, suggests that these dates may in fact be representative of the long-lived, complex history of the VMSZ. We note that other areas of 1,500 Ma deformation are known from eastern Australia (Betts and Giles, 2000), which may have been close by based on the Auswus reconstrucutions (Karlstrom et al, 1999). This is an important issue that we are trying to resolve with additional zircon and monazite geochronology.

Stop 5: Mount Bangs Traverse

Main points: 1) The formation of a tectonic mélange of "exotic" Paleoproterozoic lithologies from varying crustal levels suggests that this region may have been part of an accretionary boundary during Paleoproterozoic crustal assembly.
2) This ultramafic- and carbonate-dominated mélange belt has extreme competence contrasts relative to surrounding granitoids and other supracrustal rocks during subsequent deformation, and thus partitioned late Paleoproterozoic ductile shearing (D_3) and Tertiary brittle faulting of unknown age.

Introduction

This traverse has two objectives: 1) continued examination of the Proterozoic history—in this case, evidence for Paleoproterozoic mélange and discussion of the early accretionary history in this zone, and 2) visit a spectacular overlook of the surrounding geologic and physiographic terrain of the Colorado Plateau – Basin and Range transition to synthesize problems and issues surrounding understanding the Phanerozoic history of the VMA itself and the importance of Proterozoic ancestry on present structures. Although the final destination is the Vista Grande, some 1,240 feet above us, participants may progress as they see fit, based on both physical fitness and interest.

Stop 5A: Deformed Leucopegmatites and Pelitic Schists

We begin in a package of strongly foliated Paleoproterozoic garnet–biotite–sillimanite pelitic schist cross cut by a garnet-biotite-muscovite bearing leucopegmatite, of similar generation to the late D_3 leucopegmatites in Cabin Canyon (figure 9). The leucopegmatite here is strongly internally mylonitized, with large K-feldspar porphyroclasts in the dike displaying NW-side-down (normal) shear sense on faces parallel to the down-dip, NW-plunging lineation (practice your shear sense determinations and see if you agree). Shear bands in the pelitic schist record this same normal movement and down-dip lineation. The presence of the same lineation orientation and kinematics in the two lithologies present suggest that D_3 deformation was largely penetrative here, and was likely coeval with D_3 deformation in the Cabin Canyon and Elbow Canyon segments of the VMSZ. This deformation is thus part of the Mount Bangs segment of the VMSZ. Leucopegmatites to the S, outside of this D_3 high strain zone, are internally massive and show few signs of D_3 deformation.

Stop 5B: Ultramafic Pods

After crossing through more deformed leucopegmatites and pelitic schist, we come to a pod of ultramafic rocks cut by leucopegmatites. The rock of interest is a clinopyroxene–orthopyroxene–hornblende ultramafic rock containing serpentinized pits that were formally olivine. This suggests that this rock was likely metamorphosed at granulite facies metamorphic conditions, and then hydrously altered during retrograde metamorphism. The pock-marked appearance is a likely result of the less resilient serpentine–brucite pits. The rock contains the high-temperature S_2 composite foliation, but shows little effect of the lower temperature mylonitic event, and probably remained a physically and chemically competent “lump” during D_3 deformation. We are unsure if these ultramafic rocks represent dismembered mantle rocks from an ophiolite complex or crustal cumulate from deep in an arc sequence, but as we proceed up the hill, think about the importance of juxtaposition of these deep crustal fragments with granitoids, pelitic schists, pillow basalts and marbles, the latter of which will be our last stop of the trip. This association can be thought of as a tectonic “mélange” and we suggest that this mélange represents tectonic mixing early during accretion (we favor the ophiolite idea) and progressive mixing at various crustal conditions (granulite to retrograde shear zone) during a long progressive deformational history.

Stop 5C: Sheared Leucopegmatite

One of the interesting puzzles of Proterozoic terrains throughout the southwestern United States is in unraveling the importance of various plutonic events in the overall crustal evolution. Like the Grand Canyon, the Mojave and adjacent regions (Cerbat Mountains) have evidence for 1,780-1,720 Ma arc (subduction-related) granodiorites, 1,710-1,680 Ma collisional granites and pegmatites that may represent crustal melting, and 1,400 Ma A-type granites. As we walk further up the hill you will see representatives of the first two - a package of granodioritic orthogneiss and pink monzogranite. Further up, we will come across a spectacularly sheared SW-dipping leucopegmatite dike with excellent SW-side-down (normal sense) shear sense indicators. Note that we are likely on the other limb of a NE-trending syncline of unknown generation, and that extensional slip, to this point, has dominated the kinematic analysis. On the underside of the saddle, note the presence of calc-amphibolite gneiss, with the calcareous layers dominated by a calcite-diopside-garnet-hornblende mineralogy (more components of the mélange). Again, the intense D_3 shearing had added an extra component of tectonic mixing of the earlier features, which makes understanding the early history difficult in this area. On our way down from the ridge, we may stop to have a look at an outcrop of tectonic mélange, characterized by a diopside-bearing marble unit juxtaposed with amphibolite layers and fragments of ultramafic rocks.

Stop 5D: Vista Grande

Here we stand along Mount Bangs ridge, with the rocky 8,021 foot summit of Mount Bangs to our immediate northeast; a complexly faulted, SW-dipping section of Cambrian through early Miocene strata to our immediate west and southwest; Sullivans Canyon and Front Faults to our immediate WNW; and the Elbow Canyon fault to our immediate south. Less than 5 kilometers to our west lies the flat-lying Phanerozoic section of the Colorado Plateau Province, capped by the Tertiary basalts of Black Rock Mountain. Less than 5 kilometers to our east lies the Mesquite Basin, one of the deepest basins in the Basin and Range Province, separated from the NVM by the Piedmont Fault. To the north we can view the north plunge of the Proterozoic core of the VMA

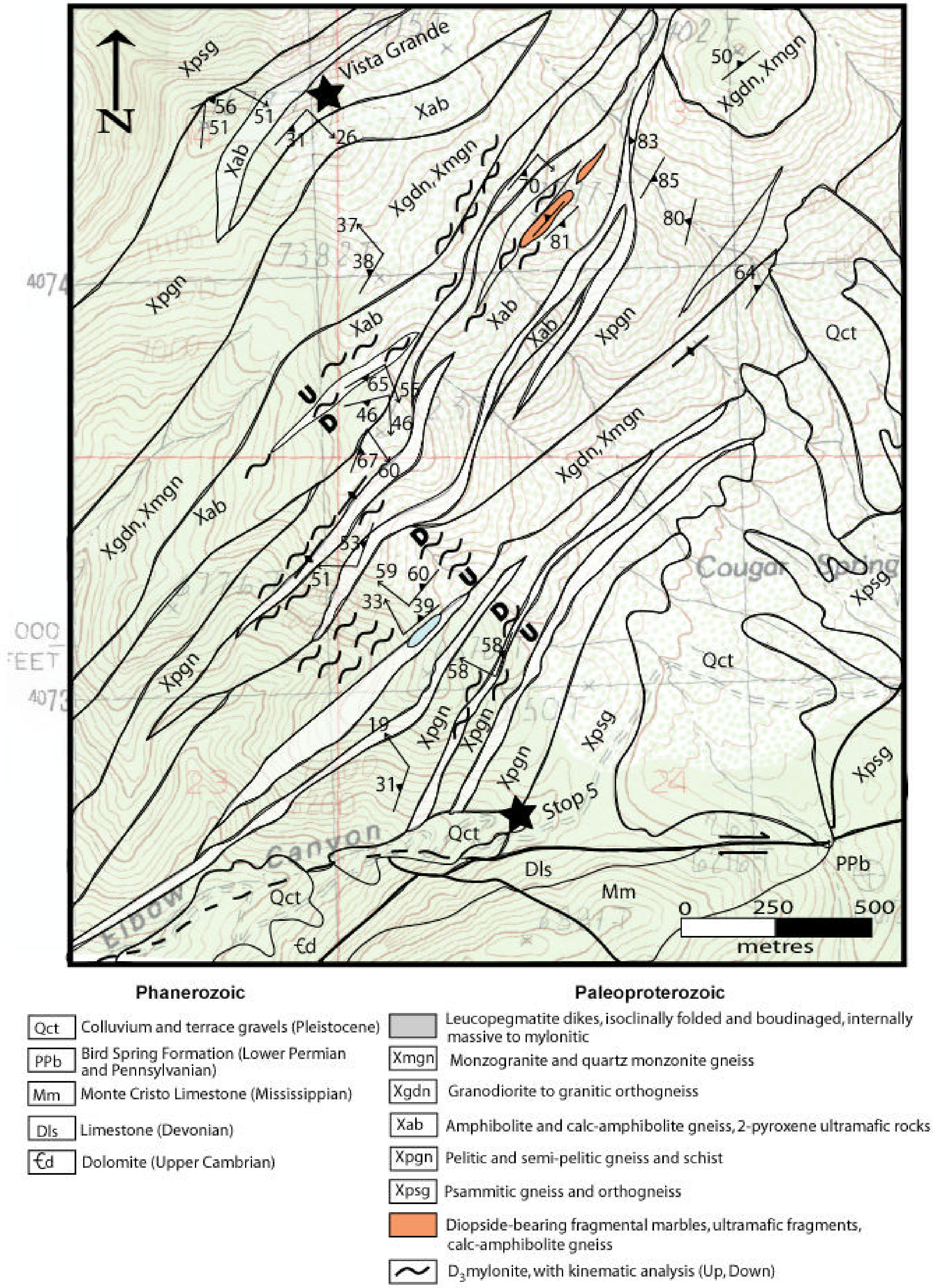

Figure 9. Geologic map of the Mount Bangs region, from "Stop 5" at the top of Elbow Canyon to "Vista Grande" along Mount Bangs ridge. See text for explanation.

beneath N-dipping strata, and to the south we can view the various faults and undulating basement topography, emphasizing the structural complexities of this region. Certainly a breath-taking spot for discussion of this complex structure!

The main ideas that we wish to discuss here are as follows. We present them as our favored interpretations in order to promote discussion and synthesize ideas presented throughout this field trip.

1) The Proterozoic history of the NVM involved an important early accretionary boundary within Mojave province.
2) The intrusive history and $D_{1,}$ D_2 is similar to that documented in Grand Canyon and throughout the region.
3) D_3 shear zones are texturally similar to regional 1400 Ma shear zones, but monazite dates suggest deformation was late Paleoproterozoic and raises the intriguing idea that it is linked to a previously unrecognized 1,600-1,500 Ma event, similar to eastern Australia.
4) Proterozoic shear zones and foliation patterns controlled the geometry of Phanerozoic uplift.
5) The Sevier-Laramide history is more important than usually thought and probably marks the inititiation of a modest-sized VMA structural uplift bound by paired monoclines.
6) Miocene deformation involved slip of cover above para-autochthonous basement.
7) The importance of Miocene isostatic uplift as a driving force remains unresolved.
8) Importance of Miocene strike slip and NS shortening in generating the VMA remains unresolved.
9) By whatever combination of mechanisms, basement rocks were rapidly cooled through 100 degrees Celsius at 14 Ma – they were probable close to this temperature at end of Laramide, however there is no evidence for Laramide cooling here.

After discussion of these topics, please proceed back down to the vehicles for the drive back to Cedar City, Utah.

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