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Five Tectonic Settings in Five National Parks and Forests: A Field Camp Experience

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ABSTRACT

In summer 2014, Southern Utah University's field camp visited five national parks and forests to study five different tectonic settings in five weeks. These included: thick-skinned contraction of the Laramide Orogeny at Capitol Reef National Park; normal faulting due to salt tectonics of the Paradox Formation at Arches National Park; thin-skinned folding and thrusting of the Sevier Orogeny at Fish Lake National Forest and Kolob Canyon of Zion National Park; foreland sedimentary transitions in the Book's Cliffs areas of Utah; thrusting and conjugate fracture development due to the gravitational collapse of the Marysvale volcanic field at Bryce Canyon National Park; and a metamorphic core complex at Great Basin National Park and Hendry's Creek in the Northern Snake Range of Nevada. This article provides a brief summary and photographic tour of the students' experiences studying each tectonic environment, and it highlights wonderful geological features exposed in our national parks.

KEY WORDS: Laramide Orogeny, Capitol Reef National Park, Waterpocket Fold, Paradox Formation, salt tectonics, Arches National Park, Sevier Orogeny, Fish Lake National Forest, Kolob Canyon, Marysvale volcanics, Marysvale volcanic field, Bryce Canyon National Park, Great Basin National Park.

INTRODUCTION

Southern Utah University's close proximity to unique surroundings enables the university's geology field camp students to examine five different tectonic settings in a relatively short period of time. During the 5-week course in 2014, the students mapped and evaluated the Waterpocket Fold in Capitol Reef National Park, the Delicate Arch Trail in Arches National Park, the Sevier Orogeny structures and resulting sedimentation in the Fillmore and Book Cliffs areas that are similar to those seen in Kolob Canyon region of Zion National Park, the fractured and faulted hoodoos in and around Bryce Canyon National Park, and the extensional features in and around Great Basin National Park. These five areas gave students from around the country a close look at five different and unique tectonic settings.

Tectonic settings included thick-skinned deformation during the Tertiary Laramide Orogeny, salt tectonics caused by the movement of salt from the Pennsylvanian Paradox Formation, thin-skinned deformation during the Cretaceous Sevier Orogeny, gravitational collapse of the Oligocene-to-Miocene Marysvale volcanic field that caused the Rubys Inn thrust fault, and Tertiary to Recent Basin and Range extension. Evaluating these excellently exposed features in our national parks gave students insight into the evolution of western geology. The photographs presented in this article capture the students' experiences.

WEEK ONE: CAPITOL REEF

Capitol Reef National Park is named for its reef, or "barrier-like," appearance and its tall, white, rounded Navajo Sandstone cliffs that reminded onlookers of the U.S. Capitol Building in Washington, D.C. The park was established in 1971 and encompasses a 100-mile-long, fairly narrow area in south-central Utah. The geology is well exposed due to weathering and erosion across the famous Waterpocket Fold. Such exposure provides an excellent area to examine and map the geologic features of the park.

The first week of the course focused on the Laramide Orogeny, which resulted in the asymmetric anticline of the Waterpocket Fold due to subduction of the Farallon Plate beneath the North American Plate (Decelles, 2004). The Waterpocket Fold is a nearly 100-mile long, north-south trending warp in the Earth's crust. The rock layers on the west side of the Waterpocket Fold have been lifted more than 7,000 feet (2,134 m) higher than the layers on the east. This subduction resulted in thick- and thin-skinned deformation of the continental crust (DeCelles, 2004). The thick-skinned deformation, which involves basement-cored uplift and deformation of overlying strata, likely resulted from a reduced subduction angle of the Farallon Plate (Russo and Silver, 1996).

Weathering and erosion exposed Permian through Cretaceous geological units. We produced a stratigraphic section of three sandstones from three distinct depositional environments, and we created a geologic map along a transect in the Burr Trail area from the Triassic Chinle Formation to the Cretaceous Muley Canyon Member. Results from the west-to-east transect exhibited decreasing dip angles and consistent northwest strikes, which resulted from the flattening limb of the asymmetric anticline (fig. 1). Students focused on changes in depositional environments, such as the Kayenta and the Navajo Sandstone contact that shows the transition from the Kayenta's fluvial environment to a possible lake environment at the top of the Kayenta to the eolian environment of the Navajo Sandstone (fig. 2). Also, looking west toward the Navajo Sandstone from Notom Road allowed a view of how the weathering of layers down catchments resulted in a teeth-like appearance of the overlying Carmel Formation (fig. 3). The teeth-like pattern provided a large-scale example of the Rule of V's, a fundamental concept for undergraduate geology majors.

Figure 1. View is to the south along the axis of the Waterpocket Fold showing the broad view of the monocline in Capitol Reef National Park. If the monocline had experienced no erosion, layers in the area fold follow the trend of the dashed red and green line. This is one of the challenges the students face in interpreting and making their maps and cross sections of the area. (Photo by John S. MacLean)

Figure 2. Contact between Kayenta Formation and Navajo Sandstone along the Burr Trail in Capitol Reef National Park. Yellow circle highlights deep mud cracks indicating the transition of the fluvial environment of the Kayenta to a lower energy system of lake deposits. Red circle highlights the change of the red sandstone of the Kayenta into the highly friable red and grey sand and clay, again indicating the change of the Kayenta from a fluvial depositional environment to a lower energy system before moving to the eolian dune depositional environment of the Navajo. Photo credit: John S. MacLean.

Figure 3. Interaction of tilted bedding with the erosional surface results in the Carmel Formation's teeth-like appearance in Capitol Reef National Park. Navajo Sandstone also shows increased weathering and erosion along the catchment, but the Carmel Formation's red contrast on the white Navajo peaks is more visually pronounced. This feature was used to show the students the Rule of V's through a mapping exercise in the area. Photo also shows the steeply dipping limb of the Waterpocket Fold. Photo credit: John S. MacLean.

WEEK TWO: ARCHES

Arches National Park is known for its varied and numerous sandstone arches. It was made a national park in 1971. The park covers 76,359 acres and contains over 2000 natural sandstone arches. The park on average only receives 10 inches of rain each year. The arches were formed in part due to the rise of salt diapirs.

The salt bed is thousands of feet thick in some sections of the park and was deposited in the Pennsylvanian Paradox Basin of the Colorado Plateau. The salt bed was then covered by sediments from the Uncompahgre Uplift and the massive eolian deposits of the Navajo Sandstone. The fluvial and eolian deposits of the Entrada Sandstone were then deposited on top of the previous salt bed and sediment layers.

The weight of the sediments on top of the salt beds caused the salt to flow up into the overlying layers of rock creating salt plumes. This movement of the salt beneath the layers caused extensional faulting above the plumes, which led to normal faulting throughout the area. One particularly photogenic example of normal faulting is the Moab Fault (fig. 4). Weathering and erosion then exposed the features seen throughout the park through the action of wind and water.

Figure 4. Photo showing the Moab Fault zone. The fault zone is a result of the flow of salt beneath the more competent sediments, which caused salt diapirs to uplift the overlying layers. Normal faulting clearly indicates extension. Photo credit: John S. MacLean.

We focused on the trail leading to Delicate Arch (fig. 5). The trail lies on a relay ramp between two normal faults (fig. 6). Deformation bands occur in higher frequency near the faults (fig. 7) (Rotevatn, *et al.*, 2007). Students produced detailed maps and cross sections of these features and several other normal faults exposed in the area that also resulted from salt tectonics. Students then determined the frequency of the deformation bands across the relay ramp and the orientations of major deformation bands. With these data, they predicted how fluids would flow along and across the relay ramp.

Figure 5. Salt diapirs caused fracturing in overlying sediments. Physical weathering processes of wind and water have eroded along fractures to create arches, such as Delicate Arch, as viewed above to the east. The La Sal Mountains, a large laccolith, are visible in the background. Photo credit: John S. MacLean.

Figure 6. In the photo above, one can view the relay ramp leading to Delicate Arch. The normal faults are shown by red lines. The exposed porous sandstone could serve as an analog for reservoirs. Fluid is able to flow around the tips of the normal faults in a relay ramp setting. However, fluid flow across the ramp may be impeded by deformation bands because deformation bands decrease the porosity and permeability of porous sandstone. Photo credit: John S. MacLean.

Figure 7. Photograph of a deformation band in sandstone as seen on the relay ramp leading to Delicate Arch. This particular deformation band shows displacement. Pen for scale. Photo credit: John S. MacLean.

WEEK THREE: THE SEVIER OROGENY

The Sevier Orogeny resulted in faulting and folding across the state of Utah, including in the Kolob Canon area of Zion National Park. Other parts of the state also contain excellent examples of such deformation. The third week was an examination of the Sevier Orogeny deformation and subsequent sedimentation in Fish Lake National Forest and the Books Cliffs region.

The students began the week by mapping a transect along the Chalk Creek Trail east of Fillmore, Utah. The area exhibits a succession of overturned beds of the Triassic Moenkopi Formation, the Triassic Chinle Formation, and the Jurassic Navajo Sandstone that are structurally overlain by the Cambrian Tintic Quartzite (fig. 8).

Next, we traveled to the Books Cliffs area where the students examined a foreland basin sedimentary transition from close to the Sevier highlands to the distal Inner Cretaceous Seaway, including an alluvium fan deposit, a braided stream, a meandering stream, and a deltaic depositional section (fig. 9). The braided stream setting in the area resulted in thin lenses of coal, whereas the meandering stream flood plains exhibit large coal seams as shown in figure 9. Students then measured a stratigraphic section of the Panther Tongue of the Star Point Sandstone and evaluated behind-the-outcrop core samples from the area to get a sedimentological picture of how the Sevier Orogeny affected deposition (fig. 10). The core we examined is 1350 feet in depth and transitions from the Star Point Sandstone at its base through the Blackhawk Formation and the Castlegate Sandstone. The Star Point Sandstone's bay fill depositional setting changes to a fluvial setting in the Blackhawk Formation. Coal is widespread through the Blackhawk Formation, indicating the transition to a low energy floodplain environment. As the core enters the Castlegate Sandstone, the layers indicate a higher energy and an absence of thick layers of coal, indicating a change to primarily channel fill and proximal levee environments.

Figure 8. Photo showing Sevier Orogeny folding and thrusting in the Cambrian Tintic Quartzite adjacent to the Chalk Creek Trail near Fillmore, Utah. Photo credit: John S. MacLean.

Figure 9. Section of the Blackhawk Formation that was deposited by a meandering stream. Layers directly above students show migration of a stream's meander. Coal in the section was likely deposited in the flood plains of the stream before the stream migrated across the basin floor. Photo credit: John S. MacLean.

Figure 10. Photo of students evaluating the cores taken from the Books Cliffs area. The cores show the transitions of the layers from the Starpoint Sandstone through to the Castlegate Sandstone. These cores show a changing depositional setting from bay fill, near shore environments to more fluvial and lower energy settings. The Castlegate Sandstone shows the transition from fluvial and lower energy setting to a channel fill setting. Photo credit: John S. MacLean.

WEEK 4: BRYCE CANYON

Bryce Canyon was settled by Mormon pioneers in the 1850s, and was named for Ebenezer Bryce who was the first person to homestead the area in 1874. Bryce Canyon became a National Monument in 1923, and a National Park in 1928. Unlike its name, Bryce Canyon is not actually a canyon, but a collection of natural amphitheaters. Some of the most distinct geological features found in Bryce Canyon National Park are the "hoodoos." The hoodoos are pillars of rock that have been created through frost wedging of water in vertical fractures.

Week four was an examination of Bryce Canyon National Park and the Ruby's Inn thrust fault. The Ruby's Inn thrust fault resulted from the gravitational collapse of the Marysvale volcanic field (Lundin, 1989; Merle *et al*., 1993; Davis, 1997; May *et al.*, 2012) (fig. 11). The students were first tasked with examining the stratigraphic section at Sunset Point in Bryce Canyon to interpret how the hoodoos formed. Some students made keen observations of sparse conjugate fractures present through the area.

Students then went to the Fairyland portion of the park to view beautifully exposed conjugate fractures across the hoodoos (fig. 12). Students interpreted the orientations of maximum compressional stress (σ_1), which bisects the acute angle of the conjugate fractures. The conjugate fractures seen here are present throughout the area, and their σ_1 matches that of the Ruby's Inn thrust fault.

Figure 11. Photo of the Ruby's Inn thrust fault. Slickenlines are apparent on the underside of the outcrop as a result of the thrust faulting, illustrating a literal hanging wall. The stratigraphic layer in the photo is the Claron Formation. Photo credit: John S. MacLean.

Figure 12. Hoodoos at Fairyland in Bryce Canyon National Park. Blue circle indicates one of many conjugate fractures found in the area. These sets are used to structurally interpret the direction of maximum compression. Photo credit: John S. MacLean.

Expanding on the effects of the thrust faulting in the area, the students were taken to Badger Creek, which lies immediately west of the park boundary, to examine slickenlines in the Claron Formation (fig.13). The Badger Creek outcrops display a complicated arrangement of faults with multiple orientations. Slickenlines on these fault planes show primarily normal displacement as indicated by the structural steps (fig. 14) (MacLean, 2014). Students measured the pitch of the slickenlines, plotted the faults and slickenlines on stereonets, and interpreted the σ_1 associated with the faulting. One interpretation of the data suggests contractile movement during Ruby's Inn thrust faulting that created conjugate fractures, followed by extension during Basin and Range faulting that utilized the pre-existing weaknesses in the conjugate fractures (MacLean, 2014).

WEEK FIVE: GREAT BASIN NATIONAL PARK

Great Basin National Park was established in 1986, and is located in east-central Nevada near the Utah border. The park is part of the Basin and Range province of North America, and as its name suggests, it is part of a large basin. The park is home to groves of ancient bristlecone pines, which are the oldest non-clonal organisms. The bristlecone pines do not exhibit a life cycle as most organisms. When the trees fall down or die due to lack of nutrients the collection of sap and growth on the bristlecone often weathers in features similar to rocks in the area. The park is also home to the limestone Lehman Caves at the base of Wheeler Peak and a large debris glacier just below the peak that is covered by quartzite talus and till of varying size from rubble to boulders.

Figure 13. Slickenlines at Badger Creek. Multiple faults with multiple orientations exhibit beautiful structural features such as these. Photo credit: John S. MacLean.

Figure 14. Structural steps in slickenlines at Badger Creek. As the rock layers pull away they can leave behind steps where the layers break apart. These steps give an indication of the fault's sense of slip. Photo credit: John S. MacLean.

During week five the students focused on the Neoproterozoic and Cambrian depositional environments, Basin and Range extension producing a metamorphic core complex that exhibits plastically deformed mylonites that were then subsequently deformed brittlely during exhumation, and Pleistocene to Recent geomorphologic events that resulted in the glacial features and cave features seen in the park.

First students observed the Prospect Mountain Quartzite in the South Snake Range to get an idea of its thickness in relation to the North Snake Range. In this area the Quartzite is a massive layer extending to all the way to the top of Wheeler Peak. The massive quartzite is the result of deposition of passive margin sediments during Neoproterozoic and Cambrian off the coast of western Laurentia.

Next the students examined and mapped the Northern Snake Range from Hendry's Creek Trail. This area shows structural attenuation of the Prospect Mountain Quartzite and Pole Canyon Limestone due to extensional forces of the Basin and Range. Mylonitic type stretching and large-scale boudins are present throughout the area by the trail. The stretching is the result of a detachment fault or décollement that produced a metamorphic core complex that deformed the layers plastically. Mylonites are pervasive in the area and show subsequent brittle deformation during exhumation after the initial plastic strain. Figure 15 shows conjugate sets of fractures that resulted from the brittle deformation.

Figure 15. Conjugate fractures seen from Hendry's Creek Trail in the Northern Snake Range. Note the bisector of the acute angle is vertical, indicating a vertical orientation of the maximum compressive stress, which is consistent with normal faulting. Photo credit: John S. MacLean.

Finally the students were taken to Wheeler Peak and Lehman Caves to determine how, during the Pleistocene to Recent time periods, geomorphologic events have affected the area. Wheeler Peak shows a cirque (fig. 16) created by a southern glacier that is still present today underneath layers of rubble that protect it from melting completely. The glacier was deposited during the Pleistocene Ice Ages. Water melting from the glacier can be seen in natural glacier lakes around the park.

After Wheeler Peak the students were taken through Lehman's Caves (fig. 17). The limestone cave is unique and large with many distinct features such as cave bacon and sideways straws that resulted from water under pressure and highly saturated in $CaCO_3$ spraying or moving across the cave walls and ceiling. Students were tasked with tying the entire picture of the North and South Snake Ranges with the glaciation and limestone caves to create a complete geological history of the area.

Figure 16. Wheeler Peak is shown in the upper right of this photo. Observable glacial features include the cirque, arête, and horn. Water produced from the melting glacier contributes largely to the formation of Lehman Caves as it infiltrates through the ground and then dissolves the Pole Canyon Limestone forming the caves. Photo credit: John S. MacLean.

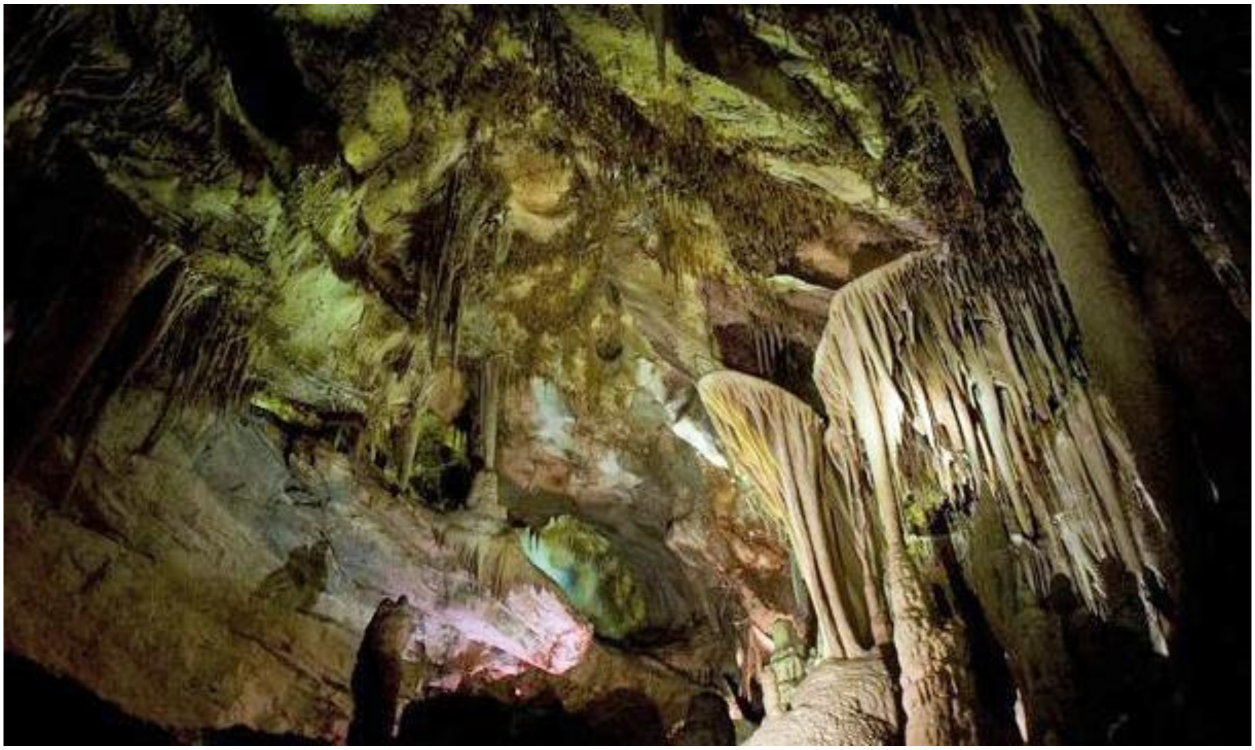

Figure 17. Lehman Cave's Pole Canyon Limestone exhibits unique features such as shown in the photo. On the right are two limestone "shields" formed by $CaCO_3$-saturated water precipitating as it passes across the plates. Photo credit: Todd Peterson.

SUMMARY

Southern Utah University's field camp gave students a rare look at diverse tectonic environments in a 5-week time span during summer 2014. The photos in this paper illustrate the students' experience during the 5-week experience. From the Waterpocket Fold in Capitol Reef National Park, the Delicate Arch Trail in Arches National Park, the Sevier Orogeny structures and resulting sedimentation in the Fillmore and Book Cliffs areas that are similar to those seen in Kolob Canyon region of Zion National Park, the fractured and faulted hoodoos in and around Bryce Canyon National Park, and the extensional features in and around Great Basin National Park showed students how diverse the geology of the western United States is. It allowed them to get a broad range of experience with varied settings as a capstone course before either going into a professional environment or moving on to graduate school. Regardless of where the students are headed, this field camp prepared them to handle many different geological environments and tectonic settings.

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