INTRODUCTION

The grabens of the Needles District of Canyonlands National Park, Utah, (Fig. 1) are developed in a thick sequence (~500 m) of Pennsylvanian to Permian clastic sedimentary rocks, with movement of the faults and valley floors accommodated by flow in the underlying Pennsylvanian Paradox evaporites. Stresses produced by the Colorado River’s rapid incision through the clastic sequence are thought to be responsible for the development of the graben system over at least the past 60-65 ka (Biggar and Adams, 1987). This actively deforming system of young grabens with its large number of well exposed normal faults makes Canyonlands an almost ideal location to study the relationship between fault trace length and dip-slip displacement for kilometer-scale normal faults. Thus, over the past few decades, Canyonlands has become an important “type area” in such diverse fields as petroleum exploration, where understanding the factors that control graben formation in extensional settings can play a role in predicting the location and size of oil reservoirs, and planetary geology, where grabens are commonly used to calculate regional strain.

Although the faults are well exposed and accessible above the surface, a sequence of alluvial, colluvial, and aeolian sediments obscures the bedrock floor of the hanging wall block in most locations, complicating the measurement of fault displacement. While most previous studies calculate displacement as the sum of the visible scarp topography combined with an estimate for the thickness of
sediment fill, those estimates, averaging between 10 and 15 m, have been widely accepted but poorly substantiated. These estimated sediment thicknesses were based in part on the young age of these grabens, and on a few isolated but direct observations of material interpreted as bedrock in the valley floors. Cartwright et al. (1995) observed blocks of sandstone interpreted as downfaulted caprock in stream sections, fissures and swallow holes. Their measured sedimentary sequence thicknesses varied from 0.5-12 m, with the majority of values falling in the 3-7 m range. Unfortunately, they did not document how these measurements were extrapolated into total sediment thickness.

Structural studies of exposed faulting in the Canyonlands area led Schultz and Moore (1996) to question the commonly accepted estimates of sediment fill and fault displacements. In 1996, a team from Pomona College and the University of Nevada Reno conducted additional structural observations as well as a shallow seismic refraction survey of Devils Lane graben (Bush et al., 1996; Moore and Schultz, 1999). Expecting to image sediment 10 to 15 m thick, they could not detect the bottom of the sediment fill with their seismic survey. Based on their survey geometry, they concluded that the sediment was more than 60 m thick.

Seismic and gravity data from field work in 1999 (Grosfils et al., 2003), showed that the maximum sediment thickness in Devils Lane graben is at least 90 m and typical thicknesses along the length of the graben are on the order of 70 m. Subsequent seismic reconnaissance work (Kroeger et al., 2002) showed that Cyclone graben has similar sediment thickness. Cyclone is longer and wider than Devils Lane and has been assumed to be proportionally older.

The results of these geophysical surveys show that previous estimates of sediment depth are in error by factors of at least 4 to 10, and corresponding estimates of fault offsets are in error by factors of from 1.5 to 2. Thus conclusions drawn using these grabens as mechanical models for other places and planets are in question.

**PROJECT GOALS**

The results of geophysical studies to date have left many questions about fault displacements unanswered and have raised new questions. What is the maximum sediment thickness in these grabens? Limitations of our seismic equipment have prevented us from detecting the maximum depth of sediment in either Devils Lane or Cyclone grabens. Are the graben floors cut by cross-faults and do corresponding segments of the bounding faults move differentially?

The project objective was to literally and figuratively bring bigger guns to bear in a detailed geophysical survey of Cyclone graben. One of these big guns was an accelerated weight drop seismic source (Fig. 2). This battery-powered source is many times more energetic than a sledgehammer, is relatively lightweight (200 lbs), and is safe for both users and the surrounding environment.

![Figure 2. Jennifer Abrahamson and Joshua Michaels fire the Peg 40 accelerated weight drop source.](image-url)
advanced refraction processing techniques including reciprocal methods and tomographic inversion.

FIELD WORK

Participants assembled in mid-July at The Colorado College for a week of preparation. Geophysical, GPS and surveying equipment were assembled and tested. Then, it was off to Moab, Utah, the staging point for two one-week incursions into the backcountry of Canyonlands National Park.

The grabens of Canyonlands National Park are as difficult a place to conduct geophysical surveys in the United States as one could imagine. Vehicle access to the grabens is via one of the most technically difficult 4-wheel drive roads (Elephant Hill) in North America (Fig. 3). Since no power or water is available, all water and batteries (dense and denser) must be transported over these roads. Only primitive camping is allowed, and only in designated campgrounds, which required the equipment and batteries to be moved each day to and from the graben floor. We were also required to use and maintain portable chemical toilets. For these reasons, we used Navtec Expeditions, licensed by the National Park Service (NPS), to transport us into and around the grabens, and to maintain camp and prepare meals in the field.

The daily routine involved transporting vehicles, equipment and people from our campsite into Cyclone graben, a distance of about 2 miles. The seismographs, field computers and batteries were assembled under a portable sunshade that served as temporary “headquarters” for each seismic line. Solar panels erected nearby were used to recharge seismograph and gravity meter batteries.

Working in small teams, students and faculty engaged in a variety of activities often resembling a three-ring circus. Seismic and gravity stations were laid out and flagged. Optical surveying of these stations was one of the most time consuming tasks that had to be completed. Geophones had to be buried and seismic cable rolled out and connected. While all of this was going on, two people were usually off measuring gravity at previously surveyed stations.

Figure 3. A fully loaded Suburban descends the back side of Elephant Hill into the grabens of the Needles District of Canyonlands National Park.

Shooting each seismic line required two or three people to operate the accelerated weight drop source. At each shot point, a 16” square plate of aluminum armor was positioned on leveled ground. A Suburban, with the source attached to its trailer hitch, was backed into place. The elastic bands were installed and tensioned and protective shields attached. A series of shots were fired while two or three seismograph operators configured recording parameters, checked each shot record for data quality, and stacked and saved the data.

In the course of two weeks we acquired a 4.8 km long gravity survey with 49 gravity stations located approximately every 100 m along the axis of the graben. The survey was georeferenced with WAAS corrected GPS measurements. Six p-wave refraction lines ranging from 350 m to 470 m in length with 10 m geophone spacing were shot. Since the source was restricted to the road, lines were only shot where the road was roughly centered in the graben preventing longer continuous seismic lines. In addition to the refraction lines, several shorter reflection lines and a shear wave refraction line were also shot.
The trip back to Colorado Springs included swimming and fly-fishing in lakes in the San Juan Mountains. Once back at Colorado College, the equipment had to be cleaned, rental equipment packed and shipped, and data downloaded and archived. Preliminary reduction of gravity data and picking and modeling of seismic data were carried out.

**STUDENT PROJECTS**

As should be apparent from the description of our field activities, geophysical data acquisition is a group endeavor. Everyone participated in all aspects of the work and focused admirably on the overall task of collecting the best possible data in the time available, often with significant physical exertion and discomfort. Each student had access to all of the resulting data and could freely choose the data he/she wanted to analyze. Despite some overlap, each student ultimately developed a project with a unique focus.

**Jennifer Abrahamson** (Beloit) concentrated on interpreting the seismic and gravity data located midway along the graben near the site of a prominent paleodrainage exposed in the horst blocks.

**Roman DiBiase** (University of California, Berkeley) compared three methods of inverting the seismic refraction data for velocity-depth models. These methods included time-term inversion, a reciprocal or delay-time method, and tomography.

**Tara Gregg** (Whitman College) investigated the use of digital elevation data from the National Elevation Database (NED) for computer generated terrain correction of gravity data.

**Joshua Michaels** (The College of Wooster) focused on interpreting seismic data from the northern half of the graben, where we had parallel seismic lines, to look for evidence of longitudinal faulting in the graben floor.

**Amanda Trenton** (The College of Wooster) interpreted seismic refraction lines from the southern half of Cyclone graben. She investigated the nature of the southern terminus of Cyclone graben and fault displacements and regional extension across the graben system.

**Alice Waldron** (Pomona College) analyzed both seismic and gravity data and concentrated on interpreting the discrepancies between those data as evidence for salt diapirism beneath the floor of Cyclone graben.

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**REFERENCES CITED**


