GEOPHYSICAL STUDY OF NORTHERN CYCLONE CANYON GRABEN, CANYONLANDS NATIONAL PARK, UTAH: SEDIMENT DEPTH AND IMPLICATIONS FOR CROSS-SECTIONAL MODELS

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INTRODUCTION

The arcuate graben area of the Needles fault zone in Canyonlands National Park, Utah, was the location of the Keck Canyonlands 2004 project, which employed exploration geophysical techniques to determine the Quaternary sediment fill depth in a graben called Cyclone Canyon. The extensional structure of the Needles fault zone can be explained as a block of brittle sedimentary rock extending above the ductile Pennsylvanian Paradox Formation (predominantly evaporite formation) into the void created by the Quaternary downcutting of the Colorado River (Cataract Canyon). This extension creates regularly spaced grabens on the eastern side of the Colorado River, where there is a regional 2-4° dip towards the river.

Numerous previous studies of these grabens have assumed a Quaternary sediment depth of less than 25 m for any graben. However, Grosfils et al. (2003) published an exploration geophysical study of Devils Lane graben (graben east of Cyclone Canyon) concluding that the maximum sediment depth was about 80-90 m.

METHODS

Six seismic refraction lines were shot in Cyclone Canyon. Gravimetry was taken every 100 m along the graben. Only results from the northern four refraction lines are described here (Fig. 1).

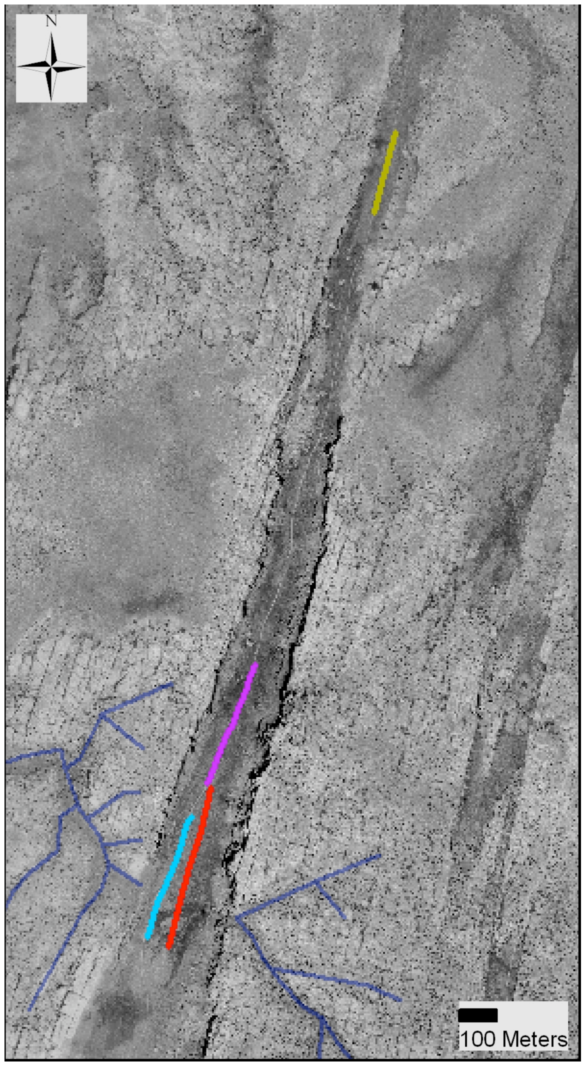

Figure 1. Northern Cyclone Canyon digital orthophoto quadrangles, showing line 3 (light blue), line 4 (purple), line 5 (yellow), and line 6 (red). Paleodrainage shown in blue.

The program SeisImager™ (version 3.0) was used to analyze the seismic refraction lines. SeisImager™ comprises two modules: Pickwin™ (version 3.02), for analysis of the raw data, and PlotRefa™ (version 2.68), for the analysis of a whole refraction line using the output of Pickwin™.

I used the Pickwin™ module to begin seismic refraction analysis. First breaks (a first break is the point in time where the P-wave is received by a given geophone) were chosen using the inflection point of the first polarity change instead of the first instance of the signal as is conventionally used. This technique induces a known error that may produce inaccurate sediment depths up to five m, but should more precisely define the structure.

I used two methodologies to choose first-breaks: all refraction including weak refraction (WR) and strong refraction only (SR). The WR method employs the concept that any refraction, no matter how weak or out of place, is real and not anomalous. My SR method assumes that weak refraction may just be caused by large but non-continuous blocks or other such means, which are unimportant for our purposes in this study. Consequently the SR method "reads through" weak refraction to a strong refraction signal that is continuous for the entire length of the refraction line. The SR method was always produced the preferred velocity model.

Travel-time curves (connecting together first breaks from each shot) are corrected and modelled in PlotRefa™. The first correction was to remove first breaks that caused "kinks" in the travel-time curve. This is a subjective correction, but I tried to minimize the number of deleted points and try to make the travel-time curves look like an ideal model. This correction has the greatest overall effect on the velocity model.

The second correction dealt with the reciprocity of travel-time curves. Theoretically, switching the receiver and source will result in exactly the same travel-time curve, but that is rarely the case. This correction has the greatest effect on the sides of the velocity model where the data does not constrain the depth as well. All velocity models were created using the time-term inversion function.

In selecting a preferred velocity model, three factors were considered: the accuracy of first-break choices in raw data, the selection of layers, the comparability of travel-time curves to the ideal model, and the velocity value for layer 2 (sandstone of the graben block) of the velocity model (layer 1, or sediment, produces a consistent value of ~0.5 km/s for all velocity models). All my final models have undergone extensive rechecking and verification.

RESULTS

Line 6 is the southernmost refraction line in this study and is centered between the graben walls (Fig. 1). I have dismissed the WR method model as imaging irregularities of the graben block surface since the WR method model conformed to the general topography of the SR method models but was at a shallower depth. The SR method produced an acceptable 2.97 km/s for layer 2. The sediment depth of line 6 is ranges from 70-78 m, due to the edges of the preferred model are not as well defined as near the center. A large 10 m bedrock bulge occurs under the surface expression of the paleodrainage, a drainage system that predated graben development that crosses Cyclone Canyon at the southern end of line 6.

Line 3 is parallel to line 6 but about 60 m to the west and closer to the graben wall. The SR method produced a velocity model with layer 2 values of 2.95 km/s. The maximum sediment depth of line 3 is 40 m at the northern end. A large 17 m bulge occurs at the paleodrainage, similar to line 6. The significance of lines 3 and 6 will be discussed later.

Line 4 is immediately north of line 6 and is centered in between the graben walls. The WR method velocity model was dismissed as imaging a buried erosional remnant pillar near the center of line 4. Exposed erosional pillars are seen on the east graben wall east of line 4. The SR method velocity model produced layer

2 velocity of 2.87 km/s. The maximum sediment depth of line 4 is 60 m at the southern end. The preferred velocity model has two undulations, but the general northward-shallowing trend is most important.

Line 5 is the northernmost of the refraction lines. Line 5 had generally poor and noisy refractor arrival, but should have had excellent data due to the shallow refractor, complications of the data were caused by a complex surface topography of the graben block. The SR method velocity model produced a layer 2 velocity of 2.81 km/s. Due to the poor nature of the refraction data and difficulty with analysis, the sediment depth was generalized to be about 30 m.

DISCUSSION

I estimate the precision of the seismic refraction resultant depths to be about ±10 m, inherent from the subjectivity of analyzing the seismic refraction data. However, ±10 m precision allows for the general depth of Cyclone Canyon to be determined reasonably well and higher resolution is not needed.

Longitudinal Profile

The complete longitudinal profile of Cyclone Canyon (Fig. 2) illustrates the expected lenticular profile with a maximum depth of about 75 m (lines 1, 2, and 3 analyzed by Amanda Trenton, cf. this volume). Propagation of graben bounding-fault tips theoretically dictates that the widest and deepest portion of the graben represents the oldest faulting. Therefore, the theoretical profile should be lenticular with the fault becoming younger, thereby shallower, toward the fault tips and should be symmetrical about the center of the graben (Cartwright and Mansfield, 1998).

Cross-Sectional Model

From our results and from data and observations from numerous published studies about the graben area, constraints on a cross-sectional model for Cyclone Canyon graben can be stated as follows:

1. The bounding faults of the graben are asymmetric (having a master and antithetic fault).
2. Due to the vertical joints, the bounding faults (both master and antithetic) are near vertical in approximately the upper 100 m; the bounding faults become dipping at depth (observed at outcrop) and possibly converge near or at the evaporate layer (but this has not been observed in outcrop).
3. Seismic refraction results from Cyclone Canyon indicate a maximum sediment depth of approximately 75 m.
4. Two parallel refraction lines provide a glimpse of the cross-sectional graben structure: line 6 is 75 m deep and line 3 abruptly shallows to 40 m. Line 3 is 50-60 m toward the westward graben wall from line 6, which is centered in Cyclone Canyon.
5. Graben width does not imply a deeper maximum sediment depth when assuming equal initial graben width for all grabens.
6. Gravity results from Cyclone Canyon suggest sediment depths of 200-300 meters (cf. A. Waldron and T. Gregg, this volume).

My preferred cross-sectional model for Cyclone Canyon is the "step model" (Fig. 3). This model was first suggested by Moore and

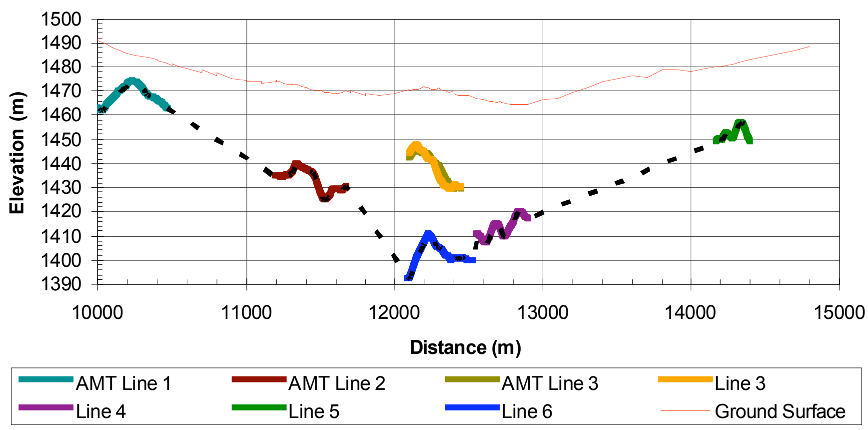

Figure 2. Northern Cyclone Canyon profile from all seismic refraction lines. AMT lines were analyzed by Amanda Trenton. Line 3 was analyzed by me and Amanda Trenton.

Schultz (1999) and 2D numerical modeling of the entire graben system created a similar cross-section (Schultz-Ela and Walsh, 2002). This model fulfills the model parameters set above. With this model, the graben can be asymmetric and have vertical surface faults that become dipping at depth (suggesting some form of listric normal fault). Due to internal faulting of the graben block, the surface of the graben block will form "steps," which is illustrated by the difference between

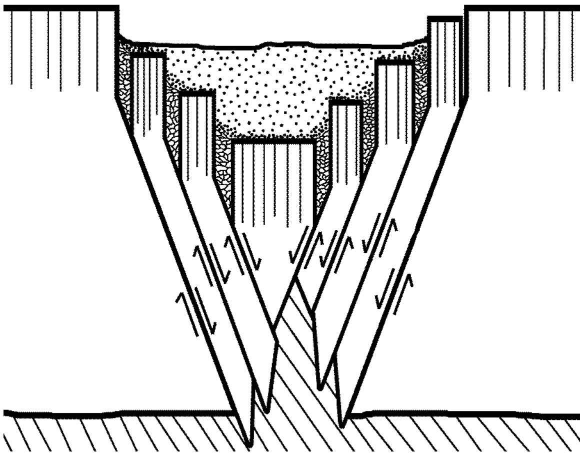

Figure 3. Schematically balanced cross-section of Cyclone Canyon and other wide complex grabens (not to scale). Note the vertical jointing at the surface that affects the shape of the graben blocks and the reactive (possibly active) salt diapir. Faults at depth may be listric and not linear as is shown.

the sediment depths of lines 3 and 6. The maximum sediment depth of only 75 m for Cyclone Canyon, when compared to Devils Lane and its maximum sediment depth of about 80-90 m (Grosfils, 2003), indicates that sediment depth is not a linear function of width (Cyclone Canyon is twice as wide as Devils Lane) if it assumed that the grabens were initially a similar width. The gravity results indicate a sediment depth of 200-300 m and are believed to be accurate (cf. A. Waldron and T. Gregg, this volume). However, if a large salt diapir caused by the thinning of the overlying sedimentary rock was to be included, the gravity results could possibly be explained since salt is about the same density as the sediment. The salt diapir would produce an apparent sediment depth much deeper than the true sediment depth.

Other field and remote observations provide circumstantial evidence in support of the step model. A swallow hole, about 10 m east of the west graben wall, was found just north of the paleodrainage which appears to show in situ bedrock covered with ~1 m of sediment. In the southern portion of the graben, the digital elevation model and digital orthophoto quadrangles show a large longitudinal block on the east graben wall. This block appears to be a forming step, with only about 20 m of displacement from the east horst surface. Two other large potential steps can be seen in the orthrophoto quadrangles, but no available digital elevation models have sufficient vertical resolution to resolve the potential steps.

The Moore and Schultz (1999) step model was not a balanced cross-section and was strictly schematic. Since there is no ductile deformation of the brittle sedimentary rock block, I constructed a simple paper cutout to determine the plausibility of a salt diapir in a balanced step model. The paper model demonstrated that a void can be formed using the step model to accommodate a salt diapir. If the salt diapir were large enough, it could be considered an active salt diapir and could oppose the downward faulting of the center of the graben block, supporting it at a shallower depth than a non-diapiric step model.

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