Recent faulting in western Nevada revealed by multi-scale seismic reflection
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SUMMARY

The main goal of this study is to compare different reflection methods used to image subsurface structure within different physical environments in western Nevada. With all the methods employed, the primary goal is fault imaging for structural information toward geothermal exploration and seismic hazard estimation. We use seismic CHIRP (a swept-frequency marine acquisition system), weight drop (an accelerated hammer source), and two different vibroseis systems to characterize fault structure. We focused our efforts in the Reno metropolitan area and the area within and surrounding Pyramid Lake in northern Nevada. These different methods have provided valuable constraints on the fault geometry and activity, as well as associated fluid movement. These are critical in evaluating the potential for large earthquakes in these areas, and geothermal exploration possibilities near these structures.

INTRODUCTION

Our main interest in western Nevada is mapping and determining recent fault history. This is especially important when it comes to seismic hazard estimation. Our focus for this study is the Reno metropolitan area and the region surrounding Pyramid Lake. These two areas lie in the structural domain of the Walker Lane (Figure 1). The Walker Lane region encompasses much of eastern California and western Nevada (Stewart, 1988). This structural domain accommodates about 20-25% of the motion between the North American and Pacific plates (Faulds and Henry, 2008). Due to the northwest motion of the Sierra Nevada microplate, the Walker Lane subject to significant amounts of dextral and normal faulting along this boundary, resulting in earthquakes and other forms of deformation.

A series of fault systems accommodate the strain release within in the Walker Lane, and are delineated by zones of earthquakes in western Nevada and eastern California. Those in the northern Walker Lane are classified as systems of: northwest-striking, left-stepping right-lateral faults; north-striking normal faults; and northeast-striking left-lateral faults (Faulds et al., 2005). The observed deformation on these faults appears to be younger than 22 Ma, although many are younger than 3-12 Ma. It is important to understand the fault distribution, architecture, and kinematics to better assess hazards and geothermal potential.

Geothermal energy production is very prominent in Nevada (see Figure 2). Many of the current geothermal power plants
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in western Nevada are associated with known faults. Fault systems often play a role in creating permeability structures for fluid flow. In western Nevada, often regions of increased fluid flow are structurally controlled (Sibson, 1981), and therefore these areas are logical places to explore for geothermal energy potential. Faulds et al. (2006) has shown that the north- to northeast-striking faults are the primary structural control on fluid pathways in the majority of geothermal fields in Nevada.

Significant earthquake activity is associated with the Walker Lane as well. There have been several moderate-to-large earthquakes on the major faults in the northern Walker Lane. These include about twenty different M4 and greater earthquakes in the Reno-Carson City-Lake Tahoe corridor within the last 150 years, including the large 1954 Dixie Valley Fairview Peak sequence, M7.2 and M6.8, respectively (Ramelli et al., 1999). This distribution in time highlights the need to determine the potential seismic hazard in and around the Reno and Pyramid Lake areas.

Figure 3: Conceptualized Pyramid Lake fault map showing general bathymetry and the locations of CHIRP profiles collected in summer 2010. Labeled profiles are those mentioned in this paper. Also labeled here are the locations of The Needles and Anaho Island, two tufa formations, as well as the location of Astor Pass.

METHODS

Several methods were used in the collection of seismic reflection data. Each of these methods is described below.

Seismic CHIRP (upper 80 m)
We collected more than 500 km of seismic CHIRP data along a grid of lines on Pyramid Lake (Figure 3) in the summer of 2010. The CHIRP data were collected using a single hydrophone with a dual transducer source sweeping between frequencies of 0.7-3 kHz. This method is particularly useful because of the high vertical resolution, which is typically submeter (Dingler et al., 2009), with the capability of imaging down to at least 80 m below the lake floor.

Heavy vibrator (upper 2 km)
About 29 km of 2D vibroseis reflection data were collected in 16 total lines on the north side of Pyramid Lake (Astor Pass) in 2010 and previous years. Unlike the urban surveys in Reno, described below, this campaign used both vibrator and geophone arrays. We used three heavy vibrators, and recorded 6-second records of 8-second, 10-100 Hz linear sweeps. Source and receiver spacing varied from 17-67 m, with up to 240 channels live for maximum offsets varying from 1000-5000 m, depending on the line length. Some receivers were set on steep slopes, inaccessible to the three heavy vibrator trucks. With the large vibrators, we are able to image as deep as 2 km. The resolution is about 10-25 m vertically.

Weight drop (upper 300 m)
In March 2010, we collected 3.5 km of 2D reflection data along 5 profiles using the Boise State University accelerated weight drop source (Liberty, 2011). The weight is 80 kg, and the data were collected using a 120-channel seismograph. Both the source and receiver spacing was 3 m. This method also yields a high vertical resolution (about 1 m), and can image down to at least 300 m depth.

Urban vibroseis (upper 1 km)
About 10.5 km of 2D vibroseis reflection data were collected along 3 separate lines in Reno in June 2009 using the nees@UTexas minivib I vibrator source. We used a 12-second, 15-120 Hz linear sweep. We recorded 2-second records on 144 channels with 5-m geophone intervals. This method has a vertical resolution of about 5-15 m, and can image down to at least 700 m depth.

Figure 4: CHIRP line D02L07, through the Needles on the west side.

PROCESSING AND INTERPRETATIONS

Seismic CHIRP (upper 80 m)
The seismic CHIRP data were processed with the SIOSEIS package developed at the Scripps Institution of Oceanography. The processing included conversion from JSF to SEG-Y formats, correction for the water bottom depth, a trace mix, and amplitude gain. We converted to depth using a nominal water velocity of 1500 m/s.
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Figure 5: CHIRP line D06L12, terminating to the east, just south of Anaho Island.

A tufa formation called The Needles is located at the northern end of Pyramid Lake, and interpretation of the CHIRP data indicates the location is structurally controlled by a small strike-slip fault (see Figure 4). Farther south, a CHIRP profile terminates just south of Anaho Island (see Figure 5). Anaho Island is just south of the largest tufa formation (Pyramid Island) near the south end of the lake. It is clear from Figure 5 that the island is bounded to the west by a west-dipping normal fault and to the east by a strike-slip fault. It is the normal fault on the western side of the island that is likely the fluid path for the vigorous hydrothermal venting near Pyramid Island.

These normal and strike-slip faults beneath Pyramid Lake are imaged near the surface, and in many cases, the sediment fault offsets extend to the lake floor. These faults imaged with the CHIRP have been active within the last 50 ka; most have been active in the last 10-20 ka. The youthfulness of the fault systems here suggests an excellent location for geothermal exploration.

Heavy vibrator (upper 2 km)

The vibrator data from Pyramid Lake were processed using field correlation and stacking, followed by first-arrival time picking and 2D velocity optimization with SeisOpt®, using true 3D source-receiver coordinates instead of elevation corrections. Depth extent of first-arrival velocity control varied from 500-1000 m. Optimized velocity sections were extended in depth via downward extrapolation and lateral smoothing for prestack Kirchhoff-sum depth migration.

All 16 lines were incorporated into a single database in OpendTect for easier viewing (see Figure 6). These sections show strong fault-plane reflections and stratigraphic terminations. It is clear that there are three different sets of faults coming together in the area, (known as Astor Pass). Figure 6 shows these three systems; an east-dipping fault, a north-dipping fault, and a west-dipping fault. The Pyramid Lake Paiute Tribe is using this information to locate and drill test bores for geothermal power exploration.

Figure 6: View from the northwest showing all three fault sets with the east-dipping fault (shown in pink) directly imaged at point A. The north-dipping fault is shown in green, and the west-dipping fault in blue.

Figure 7: Weight-drop profile following the bike path along the Truckee River in downtown Reno. The main west-dipping fault is shown here.
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**Weight drop (upper 300 m)**
The weight drop data were processed using ProMAX, and a post-stack migration was used. The migration was a simple 1D velocity correction, with a replacement velocity of 1100 m/s.

There are many strong reflectors in these sections. There are a few discontinuities in the reflections, which we interpret as faults. This is particularly apparent in the profile along the bike path on the Truckee River (Figure 7). This profile suggests we have an important active west-dipping fault, which appears to cross the river. The river flows west to east (left to right), and the finely-layered horizons along the western end of the profile is interpreted as ponded sediment deposited upstream of the fault scarp.

This fault is likely young, based on near-surface sediment offset. This will have significant implications for seismic hazard in downtown Reno.

**Urban vibroseis (upper 1 km)**
The urban minivib data were processed using ProMAX. The processing included a vibroseis correlation for the wavelet generated by the minivib. We also used automatic gain control (400-ms window) and a bandpass filter (20-140 Hz). The velocity analysis was done two different ways: we did a migration velocity analysis (MVA) as well as used velocities picked from first arrivals using SeisOpt® (details described in following section). It was difficult to get accurate first-arrival times from these data, so it seems the MVA velocities were a bit better. We implemented pre-stack Kirchhoff-sum depth migrations in both cases.

These sections exhibit strong reflections and discontinuities as well. Many of the discontinuities we interpret as faults (see Figure 8). Not all of these faults break the surface, so it is difficult to determine the age of these faults, but we do know that they are relatively young; less than 2.6 Ma based on dates of the Tertiary diatomite in the area (Widmer et al. (2007)). This reinforces the implication for seismic hazard in downtown Reno.

**CONCLUSIONS**
We presented the results of our multi-scale seismic reflection surveys in western Nevada. Specifically, we used seismic CHIRP, heavy vibrator, weight drop, and urban vibroseis methods for our investigations. The seismic CHIRP data were simple to collect and process, however, it requires a marine environment to deploy, which is not always possible. In section, it is easy to see sediment offsets as well as possible fluid flow pathways. The heavy vibroseis gave us greater depth penetration, and perhaps a better clue to the overall structural setting. These methods have important new insights regarding geothermal exploration in Pyramid Lake and the surrounding area. The weight drop data also revealed faults, but provided some stratigraphic information as well. The urban vibroseis data, which were processed two different ways, showed different things in each variation. The velocity analysis from first arrivals showed faulting almost down to the basement, where the MVA analysis was better for stratigraphic information but also showed several discontinuities. These two methods have presented vital information that will influence the seismic hazard study in the Reno metropolitan area. We plan to implement additional 3D processing and interpretations in future analysis.

CHIRP works well in marine environments to image the upper 80 m, and has a very high vertical resolution. Weight drop and minivibroseis methods work well in urban areas and some vegetated areas, where heavy vibrator trucks may not be used. Heavy vibroseis provides information about the deeper subsurface. The combination of two or more of these methods provides a more detailed picture of the structure of a region, rather than defining a smaller area with only one method.

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![Figure 8: Multiple faults are shown in this minivib seismic profile in southern Reno.](image)
EDITED REFERENCES
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REFERENCES


