Short Note
Quaternary Extensional Growth Folding beneath Reno, Nevada, Imaged by Urban Seismic Profiling
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Abstract We characterize shallow subsurface faulting and basin structure along a transect through heavily urbanized Reno, Nevada, with high-resolution seismic reflection imaging. The 6.8 km of $P$-wave data image the subsurface to approximately 800 m depth and delineate two subbasins and basin uplift that are consistent with structure previously inferred from gravity modeling in this region of the northern Walker Lane. We interpret two primary faults that bound the uplift and deform Quaternary deposits. The dip of Quaternary and Tertiary strata in the western subbasin increases with greater depth to the east, suggesting recurrent fault motion across the westernmost of these faults. Deformation in the Quaternary section of the western subbasin is likely evidence of extensional growth folding at the edge of the Truckee River through Reno. This deformation is north of, and on trend with, previously mapped Quaternary fault strands of the Mt. Rose fault zone. In addition to corroborating the existence of previously inferred intrabasin structure, these data provide evidence for an active extensional Quaternary fault at a previously unknown location within the Truckee Meadows basin that furthers our understanding of both the seismotectonic framework and earthquake hazards in this urbanized region.

Introduction

The seismically active Intermountain West (IMW) region, from the Colorado Plateau to the Sierra Nevada range, has experienced remarkable urbanization and a rapid population increase in recent decades, exposing increasingly large communities and infrastructure to seismic hazards in the region. Many IMW urban centers such as Reno, Nevada, sit atop fault-bounded sedimentary basins whose seismic velocity and geologic structures are poorly characterized. Consequently, detailed seismic-hazard assessments, which require realistic velocity structures and basin structural geometry, are often problematic.

In support of efforts to develop the western Basin-and-Range community velocity model and the Reno–Carson City urban seismic-hazards maps, we conducted high-resolution $P$-wave seismic investigations along the Truckee River through downtown Reno, Nevada (Fig. 1). Our goal was to further characterize seismic hazards in an area that is both rapidly urbanizing and where information on subsurface geologic structure is limited. The $P$-wave seismic imaging investigation therefore targeted shallow basin geometry, faulting characteristics, and intrabasin deformation that are critical to assessing potential earthquake sources and ground-motion variability.

Basin Geology and Geologic Structure

Reno is located in the Truckee Meadows basin on the western edge of the IMW and in the dextral transtensional shear zone of the northern Walker Lane (Fig. 1a; see also Stewart, 1988; Wesnousky, 2005). Faults in the Walker Lane, a generally linear north-northwest-trending geologic depression extending for about 800 km, accommodate approximately 20% of the Pacific–North American plate boundary relative motion, with the San Andreas fault system accommodating much of the remainder (e.g., Dokka and Travis, 1990; Dixon et al., 2000; Bennett et al., 2003; Wesnousky, 2005; Hammond et al., 2011). Basins in the Walker Lane along the Sierran range front, including the Truckee Meadows, formed from active extension and dextral shear in roughly the last 12–3 Ma (Trexler et al., 2000).

Recent seismicity (e.g., the 2008 Mogul, Nevada, swarm described by Anderson et al., 2009) is further evidence of the Truckee Meadows basin’s seismic hazard. Additionally, Bonham and Bingler (1973), Bonham and Bell (1983), and Ramelli et al. (2010), among others, have mapped Quaternary-age faults within the basin. The U.S. Geological Survey (USGS) Quaternary fault-and-fold database documents many of these Quaternary faults, the majority of which are associated with the Mt. Rose fault zone (USGS and
Minivib Data Acquisition and Processing

We acquired approximately 6.8 km of P-wave seismic-reflection data through an urbanized area of Reno to define subsurface geologic structure, fault locations, and evidence of possible Quaternary activity in the central Truckee Meadows basin. We acquired these data using the Network for Earthquake Engineering Simulation (NEES) minivib I source vehicle (see Data and Resources), 5 m receiver, and 5 m source–station intervals. We used a 12 s source signal, swept linearly from 15 to 120 Hz, and recorded 144 channels (720 m array maximum aperture) of data per record. Field records suggest that urban noise in the basin, though high, was sufficiently mitigated by use of the minivib source coupled with prestack processing (Fig. 2a). We conducted data acquisition on the existing roadway and bike-path systems of Reno along the Truckee River, thus minimizing impact to the community. Because of dense urbanization that concentrated significant pedestrian and vehicle traffic, and other difficult urban logistical constraints, we were forced to acquire the data as two separate profiles, with approximately 450 m of east–west overlap (Fig. 2b).

We processed each profile independently because there were no common source or receiver locations between them. Processing was generally conventional for each profile, which included gain correction, band-pass filtering, and multiple passes of both residual-statics corrections and reflection-velocity analysis. Additionally, we further mitigated urban ambient noise through precorrelation gain correction, source- and receiver-domain high-pass velocity dip filtering and frequency-offset (FX) deconvolution. Both profiles were prestack Kirchhoff depth migrated prior to merging them into a 3D model for the basin. The results suggest a maximum depth of about 1.1 km for the basin floor. Widmer (2005, see Data and Resources) describes horst-and-graben structure within the basin and infers four separate subbasins with the deepest subbasin being at most 1.3 km deep. Both studies used available borehole information for constraints; however, boreholes in the basin are sparse, and those penetrating crystalline bedrock (Tertiary volcanics) are extremely limited (Abbott and Louie, 2000).

Figure 1. Map of Truckee Meadows basin investigation area. Seismic profiles trk1 and trk2 (heavy green lines) traverse a segment of the Truckee River (blue line) through downtown Reno, Nevada. Main roadways (Interstate 80 is “I-80,” U.S. Highway 395 is “US 395,” and McCarran Boulevard) are shown as heavy black lines. The “s” is the location of seismic profile “stitch line” discussed in text. (a) Tertiary and Mesozoic geologic units (T-Mz) are tan-shaded areas, Quaternary (Q) deposits are gray-shaded areas (geologic boundaries simplified from Hess and Johnson, 2000, see Data and Resources). Green box outlines area of (b). Inset: Generalized regional tectonic setting of Reno, showing approximate area of Walker Lane shaded in gray (adapted from Stewart, 1988). (b) Elevation of bedrock, tectonic setting of Reno, showing approximate area of Walker Lane sources). Green box outlines area of (b). Inset: Generalized regional boundaries simplified from Hess and Johnson, 2000, see Data and Resources). Faults in the Mt. Rose fault zone predominate the predominantly strike-slip Walker Lane system of faults.

The Truckee Meadows basin is bordered on the west by predominantly Mesozoic granitic and older metamorphic rocks of the Sierra Nevada (Bonham and Bingler, 1973; Bell and Garside, 1987). Other ranges surrounding the basin are composed mainly of Tertiary volcanic rocks (Trexler et al., 2000), including flows, breccia, and tuffs (Bonham and Bingler, 1973; Ramelli et al., 2010). The basin fill consists primarily of Quaternary and Tertiary alluvial and lacustrine deposits as well as Quaternary glacioluvial outwash sands and gravels and colluvium (Bell et al., 1989; Ramelli et al., 2010). Diatomaceous sediments probably underlie a significant portion of the basin (Abbott and Louie, 2000).

The subsurface 3D basin geometry, including estimates of basement depth, has been characterized from gravity modeling. Abbott and Louie (2000) developed a 3D sediment-thickness model for Truckee Meadows basin from gravity data using a Bouguer slab approximation matched to 2D modeling. Their results suggest a maximum depth of about 1.1 km for the basin floor. Widmer (2005, see Data and Resources) describes horst-and-graben structure within the basin and infers four separate subbasins with the deepest subbasin being at most 1.3 km deep. Both studies used available borehole information for constraints; however, boreholes in the basin are sparse, and those penetrating crystalline bedrock (Tertiary volcanics) are extremely limited (Abbott and Louie, 2000).
from decreased array aperture and common-midpoint fold coverage were minimized. Although these profiles were processed independently, the depth-converted waveforms qualitatively align across the stitch line. The reflector misalignments and mismatches between profiles across the stitch line are primarily due to 3D subsurface geologic variations not resolved by the 2D seismic reflection method, thus precluding better alignment.

**Shallow Deformation and Active Faulting within Truckee Meadows Basin**

The stitched seismic-reflection image reveals an intriguing and complex subsurface structural geometry (Fig. 3). We interpret uplifted volcanic bedrock throughout the central part of our profile (distances 1700–3700 m), based on borehole data (described in Abbott and Louie, 2000; see Fig. 1b) that roughly constrain the depth to volcanic rocks, and the reflective character of the horizon, and we further interpret this uplifted block as a horst. An uplifted region in the central Truckee Meadows basin was first inferred through gravity modeling by Saltus and Jachens (1995) and subsequently interpreted as a horst by both Widmer (2005, see Data and Resources) and Ramelli et al. (2010). Overlying the inferred volcanic surface we interpret Tertiary and Quaternary basin-fill deposits (Fig. 3). West of this uplift, reflecting horizons within the basin sediments (distances 0–1500 m) generally dip at 6°–8° eastward and either truncate at or warp over the western edge of the interpreted horst. (We note that all dips interpreted from these seismic data are apparent rather

**Figure 2.** (a) Field records (labeled i, ii, and iii) from selected locations along seismic profile after gain correction and filtering. Offsets are distance from source location (arrow) to sensor location. Examples of reflections, surface waves, and traffic noise are shown by arrows. $R_Q$, $R_T$, and $RHV$ denote reflections from the interpreted base of Quaternary sediment, Tertiary sediment, and a prominent Tertiary volcanic horizon, respectively. Records suggest seismic signal is reasonably good across the study area in spite of significant urban noise. (b) 3D view of trk1 and trk2 depth-migrated seismic-reflection profiles acquired along the Truckee River through downtown Reno, Nevada. Locations of Virginia Street (VS), North-South Freeway (NSF), and Rock Boulevard (RB) are shown. Profiles are merged along line of projection (stitch line) for interpretation in Figure 3. Locations of minivib source for records i, ii, and iii shown at arrows. West end of data is at approximately 257415 m east, 4378457 m north; east end is at approximately 262614 m east, 4377983 m north (UTM Zone 11 North).
than true angles.) In the upper 400 m between 0 and 1500 m, the shallowest strata (<300 m) thicken eastward toward the horst. Across the horst, reflectors in the upper 200 m generally are dipping gently (<3°) eastward, with both eastward- and westward-dipping reflective packages below 200 m. East of this horst (between roughly 3400 and 6400 m) the basin reflectors dip to the east between 0° and 6°, and the reflective package thickens eastward to a depth of about 420 m.

We interpret the base of the Quaternary sediments to be a prominent reflector ranging in depth from 20 to 200 m beneath the profile. The depth to the base of Quaternary is not well constrained by existing subsurface information in the basin (e.g., Abbott and Louie, 2000; Widmer, 2005, see Data and Resources; Ramelli et al., 2010); however, we believe that interpreting the shallowest and most continuous reflector that is consistent with this limited information as the base of Quaternary is reasonable given that this horizon is likely an unconformity. As interpreted in Figure 3, the base of the Quaternary is at approximately 190 m depth on the eastern end of the profile and at about 20 m at the western edge of the profile. This westward thinning of the overlying Quaternary deposits is also consistent with mapped surface locations of the Quaternary–Tertiary contact roughly 3 km west of the profile (Ramelli et al., 2010).

There is a lateral discontinuity in reflectors between 1000 and 2000 m, where we interpret a primary fault cutting through the basin (F1 in Fig. 3). The fault-dip angle is not well constrained, but the thinning of basin sediments to the west of this fault favors a westerly dip. As interpreted here, fault F1 passes through the stitch line, which adds uncertainty to the fault location in the upper 200 m. Seismic processing artifacts at the ends of the two separate profiles unfortunately preclude a more accurate extrapolation of the fault even if these profiles were interpreted separately. However, the main deformational characteristics used to define this fault (east-dipping strata to its west, uplifted block to its east) are observable regardless of the stitch-line location. A fault zone has been inferred from surface mapping to the south of fault F1 as a series of fault splays that displace Quaternary deposits (USGS and NBMG, 2006, see Data and Resources; Ramelli et al., 2010). Fault F1 aligns with the northern projection of these mapped surface faults of the Mt. Rose fault zone, although prior to this study no surface fault traces have been documented in this location along the Truckee River.

A series of faults are evident in and east of the horst. Fault F2 displaces the surface of Tertiary volcanic rocks as well as the overlying Tertiary and Quaternary sediments; however, this fault does not have a clear surface expression. Fault F3 bounds the interpreted horst on the east. This inferred east-dipping fault deforms the upper 100 m of sediments but may not displace the youngest (latest Quaternary) basin sediments. A prominent zone of deformation at distances of 4300–4700 m and depths greater than 400 m suggests
another possible fault that deforms but does not displace Tertiary and younger basin sediments (F4 in Fig. 3). The surface projection of F4 does generally align with an inferred fault trending northeast–southwest, as mapped at the surface (Fig. 1b); however, this fault may be predominantly strike slip and may not have sufficient vertical displacement (< ∼6 m) to be resolved in our seismic data. Holocene-age, left-lateral, strike-slip faulting has been mapped on the Olinghouse fault, approximately 20 km east of our seismic profile (Briggs and Wesnousky, 2005), suggesting that a similar style of faulting could be possible in the immediate vicinity of the seismic profile.

Discussion

Recent geodetic and geologic studies provide insight into intrabasin faults in the northern Walker Lane, such as those associated with the Mt. Rose fault zone (Henry et al., 2007; Wesnousky et al., 2012). Northwest-trending faults in Walker Lane accommodate predominantly dextral strike slip, whereas west-trending faults tend to be sinistral strike slip and northerly-trending faults typically have normal displacement. In the Truckee Meadows basin, mapped faults in the Mt. Rose fault zone accommodate primarily normal displacement, consistent with the general Walker Lane fault characteristics. Geodetic studies by Hammond et al. (2011) and Wesnousky et al. (2012) suggest that recent faulting in the Truckee Meadows basin is accommodated by minimal dextral slip and normal slip between 0.4 and 1.5 mm/yr on north-striking faults, with dextral slip accommodated through clockwise block rotation. These geodetic results are consistent with subsurface deformation imaged in our data. The stratigraphic deformation imaged in our seismic-reflection data throughout the central basin further suggests a complex Cenozoic tectonic history dominated by extension since deposition of the interpreted Tertiary volcanic units.

The increase in dip of reflective strata at greater depth and the eastward-thickening sediment package in the upper 300 m are consistent with synextensional deposition as intrabasin faulting evolved. Reflectors (beneath about 1400–1800 m) in the western basin may be caused by drag folding (Fig. 4), which often accompanies fault growth (Schlische, 1995). Drag folds are a common feature observed in extensional tectonic settings like the Rhine graben, East Africa rift, and Gulf of Suez (Schlische, 1995; Morley, 2002). Drag folds are commonly the result of fault propagation or growth folding (e.g., Schlische, 1995), where the deformation may initiate as a monoclinal fold that is eventually displaced by faulting (Sharp et al., 2000). The zone of extensional folding over buried faults results in a wide zone of distributed shearing (Fig. 4a; Withjack et al., 1990).
Bonham and Bingler (1973) mapped two Quaternary faults that define a possible graben at the surface in the vicinity of the seismic profiles, approximately 600 m south of the Truckee River (Fig. 4b). The eastern fault is mapped with a west dip, which is consistent with the dip direction of fault F1 imaged in our data. The western fault dips to the east and is likely a fault antithetic to the west-dipping strand, which is also consistent with the deformation imaged in our data. These faults, when linearly projected northward on trend with their mapped surface traces, cross both seismic profiles. Figure 4c shows an enlarged segment of the seismic profile across the tip of fault F1, which we infer to be a strand of the Mt. Rose fault zone beneath the seismic profile. A clear zone of warping that as yet appears uncut by faulting (within the resolution of these data) is typical of growth folding. By projecting the linear slope of the Quaternary base from distances of 2300–1800 m westward to 100 m, we approximate a net vertical displacement of approximately 90 m across fault F1 at the Quaternary base (Fig. 3).

During the formulation of the interpretation we present in this article, tectonic inversion was proposed as an alternative mechanism to create the complex deformation observed in these seismic-reflection data. Indeed, our seismic image has deformational characteristics that are reminiscent of “positive flower structure” developed through transpression between 1500 and 4000 m at depths below the interpreted Tertiary basin sediments (i.e., horst alternately interpreted as a pop-up; Fig. 3). Though we cannot preclude transpressive (i.e., wrench) faulting as a mode of ancestral structural deformation in the Truckee Meadows basin, it seems unlikely to have occurred since the late Tertiary given the following: (1) the existing pattern of mapped Quaternary faults and their sense of displacements; (2) geologic evidence that dextral transtension has dominated in roughly the last 12–3 Ma (Trexl er et al., 2000); and (3) the extensional deformation imaged in the upper 300 m of the seismic data (Fig. 3).

Data and Resources

The U.S. Geological Survey (USGS) and University of Nevada, Reno (UNR) collected the minivib active seismic imaging data presented in this study. We used the Network for Earthquake Engineering Simulation (NEES) minivib I seismic source truck (http://nees.utexas.edu/Equipment-Thumper.shtml, last accessed 20 May 2013) for data acquisition. The unprocessed version of these data is available online through the NEES data repository (http://nees.org/warehouse/project/870, last accessed 28 March 2013). The data sources used in the development of Figure 1 are as follows: (1) topographic data can be downloaded from http://keck.library.unr.edu/Data/DEM (Fig. 1a is a mosaic of topographic quads 412, 425, 823, 824, 837, and 984; website last accessed 10 February 2011); (2) geologic contact and fault data were obtained in ArcMap format from Chris Henry, Nevada Bureau of Mines and Geology (NBMG; chenry@unr.edu; database received 19 November 2010); (3) gravity-based geological modeling of the central Truckee Meadows data were obtained from Mike Widmer, Washoe County Department of Water Resources (2005; MWidmer@washoeCounty.us; data received 6 December 2010); (4) Quaternary fault data were obtained from USGS and NBMG at http://earthquake.usgs.gov/regional/qfaults (2006; last accessed 8 March 2012); and (5) geologic boundaries were simplified from R. H. Hess and G. Johnson (2000), County Digital Maps of Nevada, Nevada Bureau of Mines and Geology Open-File Rept. 97-1, CD-ROM. Images in Figure 2b were developed using OpendTect open-source software. We used MATLAB by the MathWorks for image analysis and processing. Seismic data processing was performed with ProMAX by Landmark Graphics Corporation.

Acknowledgments

This work was supported with both internal and external funding from the National Earthquake Hazards Reduction Program. Research was partly supported by the USGS, Department of the Interior, under USGS Award Number G09AP00051 to JNL at the University of Nevada, Reno. We thank David Worley for his technical field expertise, Cecil Hoffpuair and Robert Kent of the Network for Earthquake Engineering Simulation (NEES), for expert operation of the minivib, and NEESCOMM for collaborating with USGS through a shared-use agreement. We thank our field crew (M. Conley, Z. Maharrey, M. Messmer, and I. Tomlinson of USGS; E. Littlefield, A. Hughes, S. Jha, K. Kohls, M. S. Dhar, S. Konkol, and A. Wawak of UNR) for their assistance. We thank Mike Widmer for providing gravity modeling results of bedrock elevation, and Chris Henry for providing his ArcMap geologic database. Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. government.

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