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Results of the Basin and Range Geoscientific Experiment (BARGE): A marine-style seismic reflection survey across the eastern boundary of the central Basin and Range Province

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[1] **Abstract:** Approximately 120 km of marine-style deep seismic reflection data were shot during a survey on the waters of Lake Mead in southeastern Nevada. The survey extends from near the abrupt eastern edge of the Basin and Range Province (BRP) to a point ~80 km into the extended domain. Data quality throughout the survey ranged from fair to poor; the recorded data include significant towing noise and occasionally problematic diffractions and sideswipe from canyon walls. The upper 2–4 s of the data shows well-defined reflections from sedimentary fill, but below that point, reflectivity is weak. Lower crustal reflectivity is generally absent under the eastern part of the survey, with a slight increase in reflectivity to the west. The reflection Moho appears as a series of weakly defined, discontinuous reflections, most of which occur at 10–11 s. A particularly interesting feature of the data set is the relative lack of reflectivity from the lower crust, which is a region of strong reflectivity on other seismic reflection data sets from the BRP.

Keywords: Seismic; tectonics; extension; Tertiary; Nevada; Arizona.

Index terms: Marine seismics; continental crust; continental tectonics–extensional; North America.

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1. Introduction

[2] The Basin and Range Geoscientific Experiment (BARGE) recorded over 120 km of marine-style deep seismic reflection data on the waters of Lake Mead, Nevada and Arizona (Figure 1). The profiles cross over part of the Gold Butte breakaway zone (easternmost Lake Mead), which marks a transition at the surface from extended crust of the central Basin and Ridge Province (BRP) into unextended crust of the Colorado Plateau.

[3] The transition from extended to unextended crust is apparently more abrupt here than elsewhere along the eastern edge of the BRP, since Miocene extension of the eastern Lake Mead region exceeded 80% [*Fryxell et al.*, 1992; *Brady*, 1998; *Brady et al.*, 2000], while the adjacent Colorado Plateau remained essentially unextended. In addition, the profiles cross over the transition from the amagmatic eastern Lake Mead region to the magmatic western Lake Mead region, both of which have experienced large-magnitude Tertiary extension [*Anderson*, 1971; *Bohannon*, 1984; *Duebendorfer et al.*, 1990; *Duebendorfer and Simpson*, 1994; *Fitzgerald et al.*, 1991; *Fryxell et al.*, 1992; *Wernicke and Axen*, 1988; *Wernicke et al.*, 1988]. While the geology and physiography of the Lake Mead region is now dominated by Tertiary extensional processes, prior to the Tertiary, the area was part of the foreland to the thin-skinned Sevier thrust belt [*Burchfiel et al.*, 1992], which developed within the sediments of the Paleozoic miogeocline. Given its foreland setting, the eastern Lake Mead region was probably underlain by a very gently west dipping Moho.

[4] Because it is currently the abrupt boundary of a highly extended terrain and was previously underlain by a more or less flat Moho, this area represents a unique opportunity to investigate the deep crustal effects of large-magnitude upper crustal extension. Furthermore, since the BARGE seismic lines cross over both magmatic and amagmatic extended regions in close proximity to unextended continental crust, they seem to be ideally located for evaluation of the roles of magmatism, flow, and brittle failure in the deep crust during extensional deformation.

2. Acquisition and Processing

[5] For the experiment on Lake Mead, a 40′ × 90′ barge (trade name Flexifloat) was built, using sections brought in to Lake Mead Marina on flat bed trucks. The barge was assembled from 10-foot-wide sections that ranged in length from 10 to 40 feet. The completed barge carried a streamer reel, a 3-km-long streamer, 2 Price A-300 compressors, their associated generators and hydraulic drives, two air gun arrays of four guns each (ranging in size from 80 to 750 cubic inches; total volume 2727 cubic inches), a van that housed the DSS-5 recording system, and a small mobile home. The barge was powered by twin diesel props located on the stern corners. Construction of the barge and installation of all the necessary equipment took ~1 week. The streamer, recording systems, compressors, and air guns were equipment that had originally been installed on the R/V *Conrad*.

[6] The 3-km-long streamer was a Digicon 120-channel analog system with 25-m receiver spa-

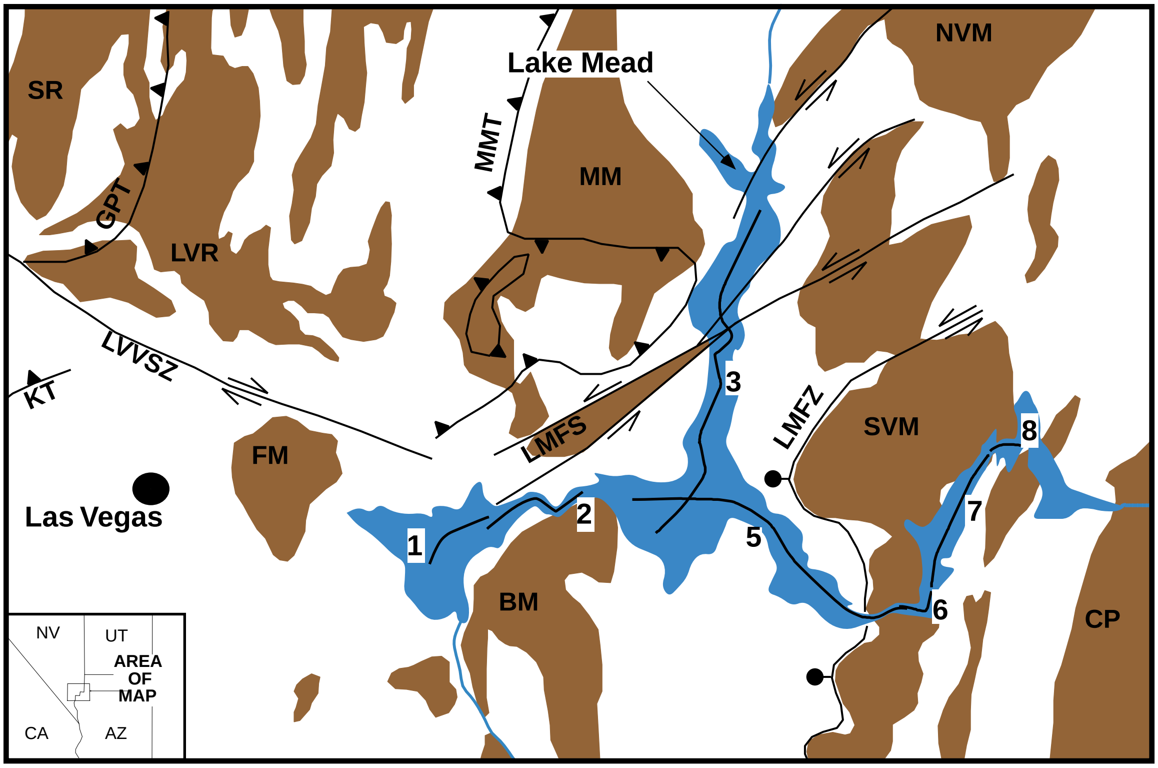

Figure 1. Location map, showing Lake Mead and the surrounding area, as well as major structural features and the locations of Lines 1, 2, 3, 5, 6, 7, and 8. Numbers indicate the line locations. Brown indicates the location of mountainous terrane. BM, Black Mountains; CP, Colorado Plateau; FM, Frenchman Mountain; GPT, Gass Peak Thrust; KT, Keystone Thrust; LMFS, Lake Mead Fault System; LMFZ, Lakeside Mine Fault Zone; LVR, Las Vegas Range; LVVSZ, Las Vegas Valley Shear Zone; MM, Muddy Mountains; MMT, Muddy Mountains Thrust, NVM, North Virgin Mountains; SR, Sheep Range; SVM, South Virgin Mountains.

cing. Owing to the fact that the streamer was designed to be neutrally buoyant in salt water, it was suspended from floats in order to prevent it from sinking in the fresh water of Lake Mead. The floats maintained the deployed streamer at a constant depth of 10 m.

[7] BARGE collected eight deep reflection seismic lines on the waters of Lake Mead (Figures 1, 2, and 3). For lines 1 through 4, which were acquired on Boulder Basin and the Overton Arm of western Lake Mead, the full 3-km streamer was deployed. In the narrow canyons of eastern Lake Mead the streamer was shortened in order to negotiate the relatively tight turns. This was achieved by rolling the unused portion of the cable up onto the drum on deck, which resulted in the trailing portion of the streamer no longer being separated from the barge by an isolation cable. For lines 6 and 7, in Virgin Canyon and Gregg Basin to Iceberg Canyon, the streamer was shortened to ~2 km. For line 8 in northern Iceberg Canyon to Wheeler Ridge it was shortened to ~1 km. Line 4 was shot along the same path as line 3, with the streamer shortened to 20 channels. Line 4 was not processed as part of this study, because it provided the same spatial coverage

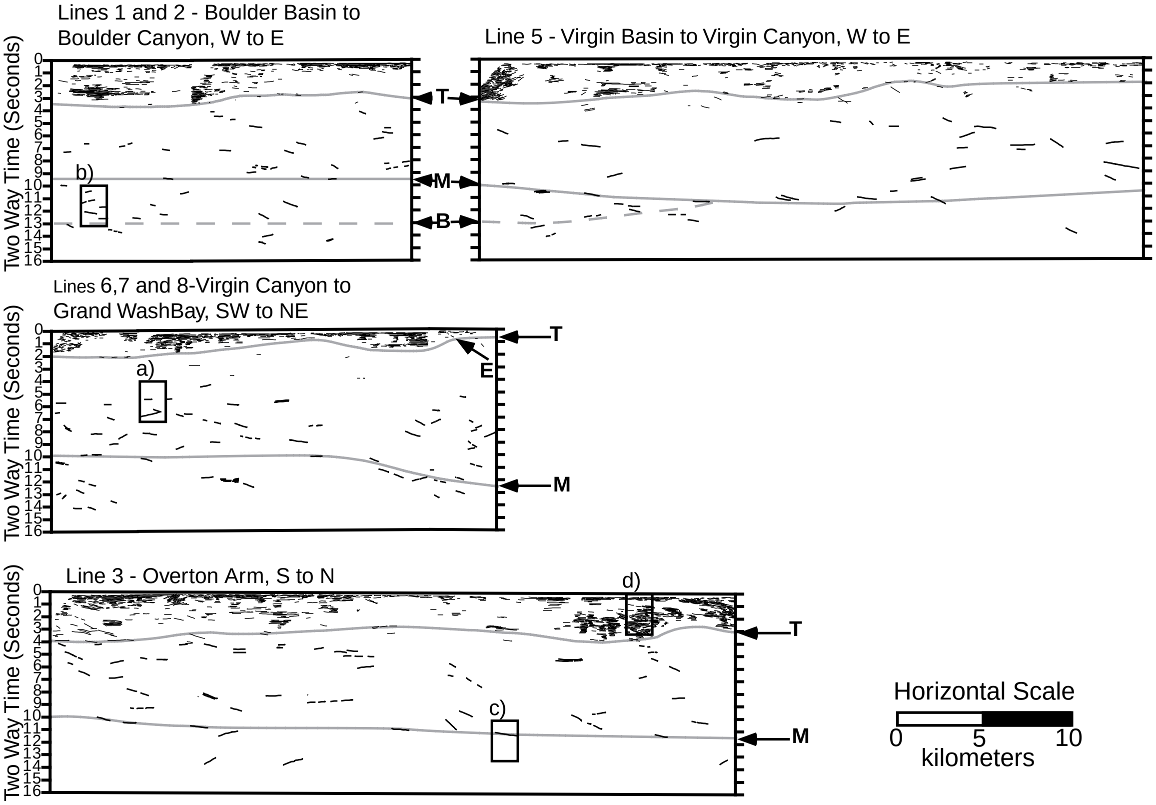

Figure 2. Line drawings of unmigrated BARGE data, showing interpreted base of Tertiary basin fill (T), east-dipping carbonates of Iceberg Ridge (E), Moho (M), and the approximate base of deep reflectivity on lines 1, 2, and 5 (B). Boxes labeled a, b, c, and d show the location of the data panels displayed in Figure 3. Note that all sections are exaggerated horizontally by a factor of 4.

as line 3, but with lower-quality data (lower fold).

[8] During data acquisition the barge traveled at ~3 knots (~5.6 km/h), with both four gun arrays being fired simultaneously every 30 s, resulting in a shot spacing of ~50 m. This provided a maximum coverage of ~30 fold (for lines 1, 2, and 3), with variable lesser coverage on lines 6 and 7 and a minimum coverage of ~10 fold (for line 8). Recording time for all shots was 15.3 s.

[9] The data were processed using Western Geophysical's Omega Seismic Processing System; the same procedure was used for lines 1, 2, 3, 5, and 7. The following procedure was used: editing for bad traces and shots, followed by wave equation multiple attenuation, common midpoint (CMP) gathering, refraction muting, normal moveout (NMO) correction, CMP stacking, spiking deconvolution, time variant band pass filtering, random noise attenuation, and application of automatic gain control. The processing procedure for lines 6 and 8 was nearly the same, except wave equation multiple attenuation was not applied to the final processed version of these lines. It was not applied to the final versions because it was shown to degrade the data in earlier-

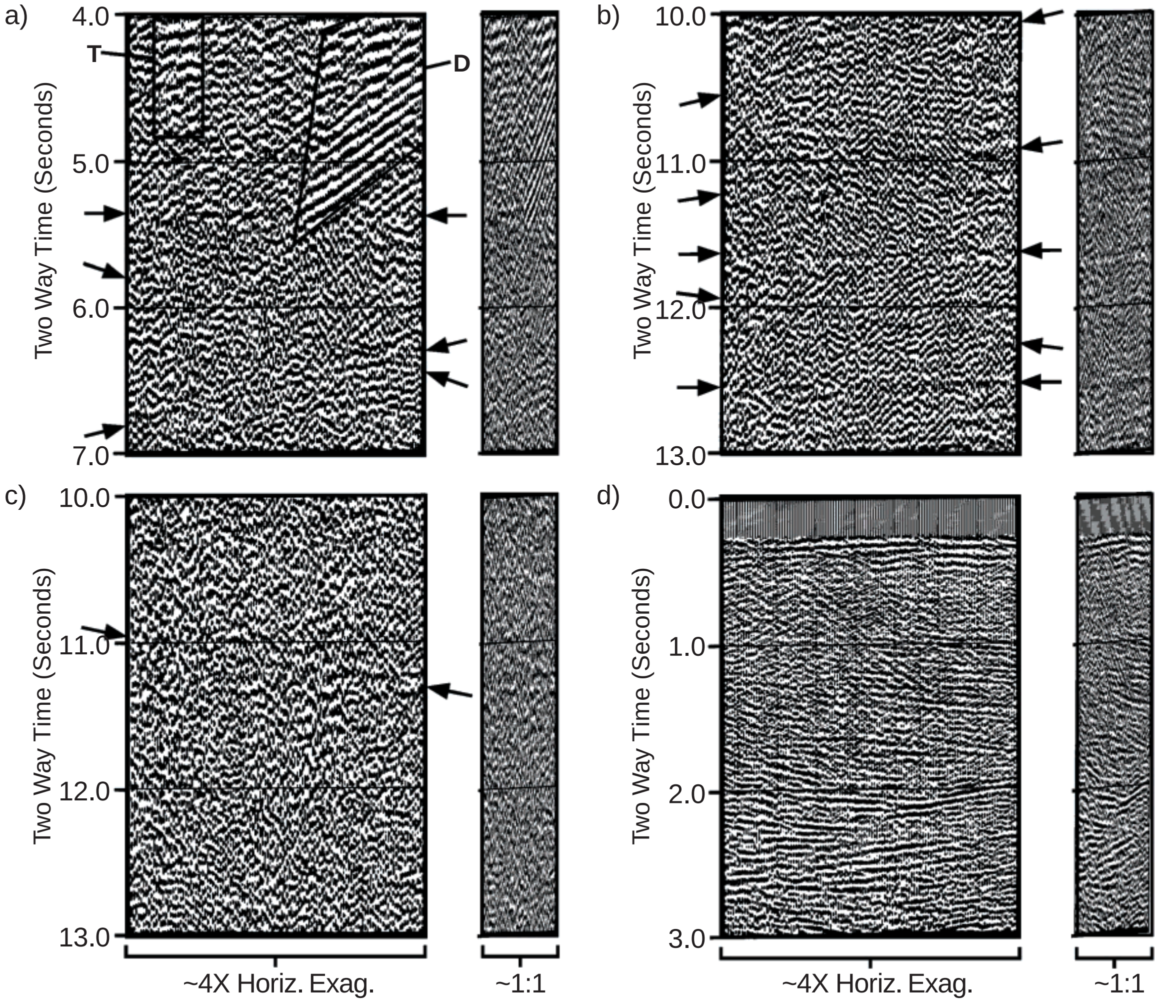

Figure 3. Selected data panels from the processed BARGE data, each displayed both at approximately 4 × horizontal exaggeration and with no horizontal exaggeration. See Figure 2 for locations. Interpreted reflections are indicated by arrows at the panel margins. Note the greater continuity, apparent higher frequency, and different orientations from the strong diffraction pattern (*D*) and semicoherent subhorizontal noise trains (*T*). (a) Typical midcrustal reflections, (b) the apparently reflective deep crust under eastern Lake Mead, and (c) an example of shallow reflections from Tertiary strata.

processed versions of these lines, perhaps owing to the particularly poorly known water depths under lines 6 and 8. Because lines 6, 7, and 8 were collected with the shortened streamer and no isolation cable, the 10 channels closest to the barge were particularly noisy; this problem was easily dealt with by killing the noisy channels.

[10] In addition to the procedure described above, various frequency notch-filters, F-X deconvolution, Kirchoff Migration, trace blending, and a variety of different final display parameters were applied to the data. However, these did not render any noticeable improvement in the image quality and were therefore not applied in the final processing stream.

[11] The quality of the data allowed the velocities to be determined only approximately, and the velocity structure used for processing was the same for all lines (Figure 4). This velocity structure probably overestimates the velocities between 8 s two-way time (TWT) and the Moho (~10 to 12 s TWT). It was applied because the depth (or time) to Moho was not well known and the postprocessing geometry of reflections at depth is relatively insensitive to overestimates of velocity.

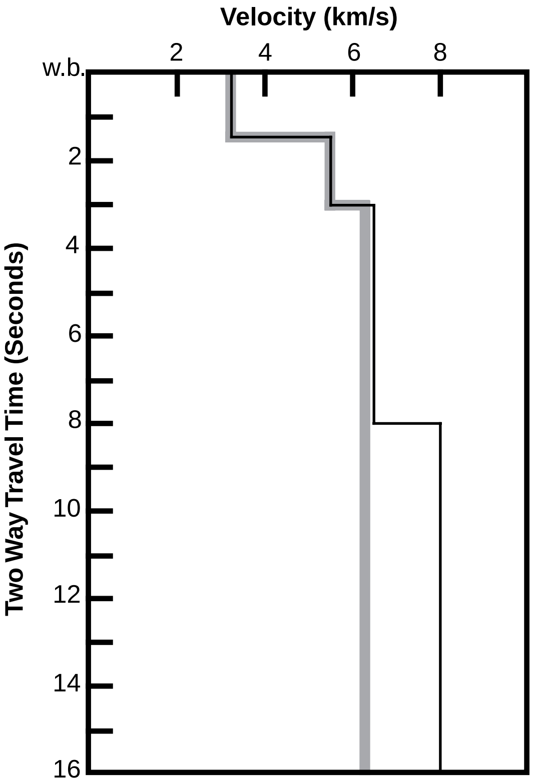

Figure 4. Velocity models used during processing and interpretation of the BARGE seismic reflection data. The black line indicates the velocity structure used during processing of all lines; w.b. indicates water bottom, a velocity of 1.48 km/s was used above the water bottom. The gray line indicates velocity used during conversion of travel times to depths during interpretation; a velocity of 6.3 km/s was applied down to Moho, below which very few reflections were recorded.

[12] The velocity structure used during interpretation is also shown in Figure 4 (gray line). This velocity structure differs from that used during processing in so far as it assumes a lower velocity for that portion of the section that is below 8 s TWT, thereby allowing a more reasonable estimate of depths to various reflectors that lie above the Moho. Reflections from below the Moho would be misplaced in the depth domain using this velocity model; however, there were no clearly identified reflections from below the Moho, so this potential weakness in the velocity model was irrelevant. This model assumes a reasonable average crustal velocity of 6.3 km/s for the dominantly crystalline rock below 3-s TWT [cf. *Valasek et al.*, 1989], and a lower velocity for rock above 3 s TWT, which is dominantly Tertiary basin fill. For purposes of discussion in this paper, calculated depths are reported depths as below lake level (~360 m above sea level) and are rounded to the nearest 0.5 km.

[13] The final processing step was the creation of line drawings (Figure 2). This was done by hand, with reflections being identified as any arrivals that were coherent and linear over significant distances (e.g., reflections shown on Figure 3a, 3b, and 3c). In many cases, the identified reflections differed in frequency and orientation (in distance versus time coordinates) from the surrounding noise patterns (compare reflections on Figure 3a with low-frequency noise *T* and diffractions *D*).

3. Results

[14] All of the lines (Figure 2) show strong horizontal or subhorizontal reflectivity in the upper 1–4 s TWT; below this, the sections are relatively unreflective. In the 6- to 9-s range, several strong reflections occur; these reflections stand out in the data because some of

them are continuous over lengths of 2–4 km. There are also a number of moderately dipping reflections in the ~9- to 13-s range that form a band across the data (most obvious on lines 3 and 5). The deepest reflections (down to ~14 s TWT) are gently dipping reflections clustered near the west end of the survey on lines 1, 2, and 5.

[15] Because the survey was conducted in a relatively shallow (generally <100 m) and narrow body of water, problems with strong water bottom multiples as well as diffractions from irregular canyon walls were expected. Surprisingly, there are relatively few strong diffractions in the shallow part of the data. Diffractions, inferred to be from irregularities in the canyon walls, are only problematic where line 3 passed through the Overton Islands. Water bottom multiples were not particularly pronounced and were effectively suppressed by the wave equation multiple attenuation applied during processing.

[16] One significant problem in the data set is the occurrence of semicoherent noise trains, which form bands down through the entire recorded section. Because the frequencies included in this noise overlap with the most of the frequency range of the useful data, bandpass filtering was of limited use. These noise trains are thought to have resulted from the streamer being coupled to buoys at surface. As the buoys were towed behind the barge, they "fluttered" or "strummed" back and forth in the current. It is speculated that the connection between the buoys and the streamer resulted in this strumming being transmitted to the streamer, moving it up and down in the water. This strumming, as well as surface wave noise, would have been recorded as pressure variations in the hydrophones, thus creating a semicoherent noise pattern in the recorded data.

4. Interpretation of Major Features

[17] A band of moderately dipping reflections, which is visible across much of the data set between ~9.5 and 12 s TWT (~25–33.5 km), is interpreted to be the reflection Moho (line M on Figure 2). There is an abrupt end of reflectivity downward beneath the reflection Moho, as is commonly seen on BRP and Colorado Plateau data sets [e.g., *Klemperer et al.*, 1986; *Hauge et al.*, 1987; *Hauser et al.*, 1987; *Serpa et al.*, 1988; *Hauser and Lundy*, 1989; *McCarthy and Parsons*, 1994]. The Moho under lines 3 and 5 occurs at depths of ~27–32 km (~10–11.5 s TWT). On line 3 the Moho deepens slightly from south to north. The location of the Moho becomes less clear on lines 6, 7, and 8 owing in part to lower-quality data but appears to remain at ~27 km (~10 s TWT) until somewhere near the northeast end of line 7, where it begins to deepen, reaching a depth of ~35 km (~12.5 s TWT) by the east end of line 8. This deepening is not surprising, as the edge of the extended terrain lies immediately to the east of line 8, and crustal thickness must increase eastward beyond this boundary to reach a thickness of 40–50 km under the Colorado Plateau [*Roller*, 1965; *Warren*, 1969; *Prodehl*, 1979; *Hauser and Lundy*, 1989; *Wolf and Cipar*, 1993]. An eastward thickening of the crust is consistent with the results of *Montana et al.* [1995], who reported an eastward thickening of the crust beginning in the vicinity of the Grand Wash Cliffs.

[18] The Moho on lines 1 and 2 is interpreted to lie at a depth of ~25 km (~9.5 s TWT) and deepen to the east, reaching a depth of ~32 km (~11.5 s TWT) under the middle of line 5. This interpretation is based on the occurrence of a band of moderately dipping reflections (line M on Figure 2) that seems to correlate with the interpreted Moho from the rest of the survey. It is possible, however, that the base of the crust is deeper than 25 km, because there are a

significant number of deeper reflections on lines 1 and 2 and on the western end of line 5 (see line B on Figure 2 and deep reflections on Figure 3b). If these reflections are from the deep crust, then the Moho under lines 1, 2, and 5 could be as deep as ~36.5 km (~13 s TWT). However, these reflections are both unusually deep for BRP crustal reflections and are some of the less clearly defined reflections from the data set (compare these deep reflections on Figure 3b with the more distinct reflections on Figure 3a and 3c). Therefore it is likely that this apparent deep reflectivity is due to misinterpretation of unusually coherent noise (see preceding section).

[19] Although the midcrust is generally unreflective, it does show some of the strongest and most continuous individual reflections visible in the data (for example, the lowest reflection on Figure 3a). These reflections are probably from contacts within the complex Precambrian crystalline basement that underlies the area and outcrops in the Gold Butte Block or from younger sills or shear zones within the middle to lower crust (~6–9 s TWT, ~14.5–24 km). Given the available data it is difficult to distinguish between these possibilities.

[20] The numerous subhorizontal to horizontal reflections in the upper 1–4 s TWT (~1.5–8.5 km) of all lines are most likely due to reflectors within the Tertiary basin fill (see Figure 3d and reflections above line T on Figure 2). These reflections are interpreted to be from horizons within the little extended Tertiary Red Sandstone and Muddy Creek Formation. The same units, only mildly faulted, are seen on seismic reflection profiles acquired just to the north of Lake Mead, in the Virgin River Valley, where they extend to depths of ~2.5 s [*Bohannon et al.*, 1993]. Identification of more steeply dipping reflections within the upper ~4 s of the data was generally not possible; however, one dipping reflection seen on line 8 does tie to the east dipping Paleozoic carbonates of Iceberg Ridge (E on Figure 2).

5. Conclusions

[21] The BARGE data set suffers from low signal-to-noise ratio; however, coherent reflections are discernible throughout the recorded sections. Interpretation of the data set shows that the reflection Moho under most of the Lake Mead region, which is defined primarily by a downward end of reflectivity, is at a depth of ~30 km. It begins to deepen near the edge of the Colorado Plateau, reaching ~39 km depth under easternmost Lake Mead, in general accord with previous findings elsewhere in the region [*Braile et al.*, 1989; *Zandt et al.*, 1995]. The data also suggest that the Moho deepens slightly toward the north, across the Lake Mead Fault system.

[22] The middle to lower crust beneath the Lake Mead region is seismically transparent, and Moho reflections are relatively weak and discontinuous. This weakly reflective Moho seems to be characteristic of the Basin and Range to Colorado Plateau transition. Similar weak, discontinuous Moho reflections have been recorded by other seismic lines that cross over the transition north and south of Lake Mead [*Allmendinger et al.*, 1983; *Hauser et al.*, 1987; *McCarthy and Parsons*, 1994].

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