Case History

Depth to bedrock using gravimetry in the Reno and Carson City, Nevada, area basins

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ABSTRACT

Sedimentary basins can trap earthquake surface waves and amplify the magnitude and lengthen the duration of seismic shaking at the surface. Poor existing gravity and well-data coverage of the basins below the rapidly growing Reno and Carson City urban areas of western Nevada prompted us to collect 200 new gravity measurements. By classifying all new and existing gravity locations as on seismic bedrock or in a basin, we separate the basins' gravity signature from variable background bedrock gravity fields. We find an unexpected 1.2-km maximum depth trough below the western side of Reno; basin enhancement of the seismic shaking hazard would be greatest in this area. Depths throughout most of the rest of the Truckee Meadows basin below Reno are less than 0.5 km. The Eagle Valley basin below Carson City has a 0.53-km maximum depth. Basin depth estimates in Reno are consistent with depths to bedrock in the few available records of geothermal wells and in one wildcat oil well. Depths in Carson City are consistent with depths from existing seismic reflection soundings. The well and seismic correlations allow us to refine our assumed density contrasts. The basin to bedrock density contrast in Reno and Carson City may be as low as -0.33 g/cm^3. The log of the oil well, on the deepest Reno subbasin, indicates that Quaternary deposits are not unusually thick there and suggests that the subbasin formed entirely before the middle Pliocene. Thickness of Quaternary fill, also of importance for determining seismic hazard below Reno and Carson City may only rarely exceed 200 m.

INTRODUCTION

Alluvial basins can amplify the magnitude and lengthen the duration of seismic waves. In Mexico City, for example, "basin site effects" due to waves trapped in the low-velocity basin are cited as a primary reason for disastrously high ground motion in the great 1985 Michoacan earthquake (Campillo et al., 1989; Sanchez-Sesma et al., 1989). Kawase and Aki (1989) showed that both basin shape (i.e., depth to bedrock) and velocity contrasts within the alluvium were essential parameters needed to model ground motion in the Mexico City basin. Frankel and Vidale (1992) used water well depth-to-bedrock data to create a 3-D simulation of seismic waves in the Santa Clara, California, basin. Efforts to predict ground motions in basins in the Salt Lake City, Utah, and Los Angeles, California, areas have required knowledge of sediment thickness as well as bedrock topography (Frankel, 1993; Olsen et al., 1995). The highest ground-motion amplification in Olsen et al.'s (1995) simulations of Salt Lake City occurred near the edges of the deepest portions of the basin (rather than directly over the deepest portion), where the depth gradient was steepest. In these areas, Olsen et al. state that particle motion can be up to 2.9 times greater than in bedrock stations. In addition, the duration of the seismic signal is up to 40 times longer (Olsen et al., 1995). Although many additional factors must be considered to estimate seismic hazard, to model wave propagation in western Nevada population centers, accurate basin models are essential. It is with this in mind that we undertook a detailed gravity survey of the urban centers of Reno and Carson City, Nevada.

The density contrast between bedrock and unconsolidated or poorly consolidated sedimentary rocks allows the study of bedrock structures underlying sedimentary basins. With good gravity data coverage, only changes in rock density affect the shape of any gravity anomaly. Basin shape and depth can be inferred from the spatial distribution of the anomaly. Examples of this general technique can be found in West (1992, pp. 200–209).

Schaefer (1983) modeled the Dixie Valley, Nevada, basin using a similar technique; many researchers have used this method for hydrologic, geothermal, mineral, and oil exploration. Jachens and Moring (1990) mapped Cenozoic thickness across Nevada with this principle.

Geologic setting

Our study area is situated along the western edge of the Basin and Range geologic province in the western United States. The cities of Reno and Carson City lie within the fault-bounded basins of the Truckee Meadows and Eagle Valley, respectively (Figure 1). The two basins are bordered on the west by the Carson Range of the Sierra Nevada Mountains and on the east by parts of the Pah Rah and Virginia ranges, and the Pine Nut Mountains. The Carson Range is predominantly Mesozoic granite with older metamorphic rocks, and the other ranges generally consist of Tertiary volcanic rocks. The basin fill consists of Quaternary and Tertiary alluvial and lacustrine deposits, and outwash from the most recent glacial epochs (Bell et al., 1989). A significant portion of the Truckee Meadows basin is underlain by low-density diatomaceous sediments.

The subsurface geology in this region is poorly understood. Existing gravity coverage, as compiled from the 1994 National

FIG. 1. Landsat thematic mapper over shaded-relief image showing Reno and Carson City area basins, and surrounding mountains.

Oceanographic and Atmospheric Administration gravity CD-ROM (Hittelman et al., 1994), is too sparse to adequately resolve basin structure. Thompson and Sandberg (1958) conducted a gravity survey of the Virginia City, Nevada, and Mt. Rose, Nevada, quadrangles in 1952. However the average station spacing of one station per 2 mi^2 (5 km^2) was inadequate to characterize the basins. Very few of the existing gravity measurements were made over the basins. As a result, basin details are not revealed in the Bouguer anomaly gravity maps of Plouff (1992) and Saltus and Jachens (1995).

Hess (1996), Garside and Schilling (1979), and associated, recently updated databases of geothermal and oil wells present some information on 56 boreholes that are more than 150 m deep in the Reno basin. Table 1 summarizes data from those that we use to constrain our basin models. We selected the 26 wells for Table 1 because we could find some minimal location and total depth information for them. In those cases where a group of wells are on the same property or in very close proximity to one another, we only list the deepest well and/or the well with the best logs of the group. All but a few are clumped in the 5 km^2 "Moana Hot Springs" area on the southwest side of the basin. Four deep geothermal wells there logged bedrock at more than 300 m depth. The bedrock there is the Tertiary Kate Peak formation andesite (part of "Consolidated Basement Rocks" on Figure 2.) Garside and Schilling (1979) report a single wildcat oil well in the Reno–Truckee Meadows basin. The well was drilled in 1908 on the western side of the basin; its log was interpreted by Anderson (1910). The 1890-ft (576-m) hole encountered only sedimentary rocks, giving a minimum basin thickness in that area. The other wells outside these limited areas are domestic water wells with only total depths known. These provide some corroborating minimum basin depth constraints. Seismic studies of Reno basin velocities are underway, but will not be adequate for describing bedrock geometry.

Arteaga (1986) mapped depth-to-bedrock in Eagle Valley using a combination of seismic reflection, seismic refraction, and gravity techniques. Arteaga's gravity results provide independent corroboration of our technique, and his seismic depth soundings allow for more accurate density calibration.

Seismic hazard

The seismic hazard of western Nevada is high, with many faults capable of producing magnitude 7 and greater earthquakes (dePolo et al., 1996). US Geological Survey seismic hazard maps (Frankel et al., 1996) do not include any evaluation of basin amplification effects. They show both Reno and Carson City with a 2% probability of ground motions exceeding 0.6 g in the next 50 years.

As of 1995, approximately 400,000 people live in the Reno, Carson City, and surrounding areas. A hypothetical magnitude 7+ earthquake would represent a tremendous potential for loss of life and property. Identifying those areas susceptible to greatest ground movement would be of use to emergency planning personnel.

METHODS

We made approximately 200 gravity measurements with a LaCoste and Romberg model G gravity meter. The measurements generally follow north-south or east-west roads in
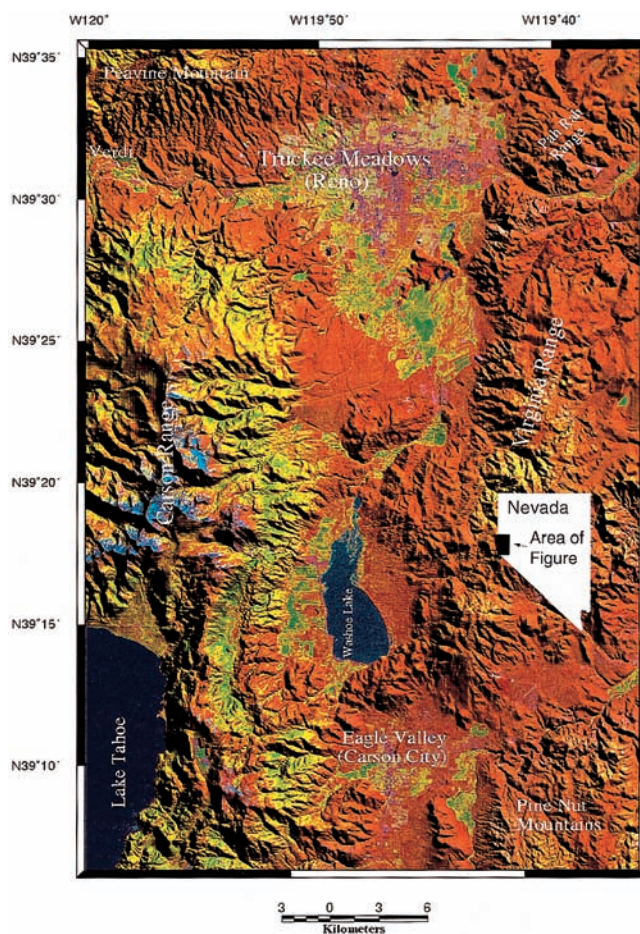
the urban Reno and Carson City, Nevada, areas (Figure 2). In Reno, vertical control was provided by a geodetic-quality Global Positioning System (GPS). In Carson City, an electronic distance-measuring (EDM) theodolite was used for vertical control. The surveys were tied to international gravity (IGSN 1971) at a gravity base station in Reno (ACIC 0454-1). Local base stations were reoccupied on a regular basis to monitor tidal variations to gravity as well as instrument-related drift. Terrain corrections (using 2.67 g/cm^3) were estimated by eye in the field from 1 m to 54 m horizontally (Hammer zones B–C) and computed by algorithm from 54 m to 167 km, using 90-m digital elevation models. The data were reduced to complete Bouguer anomaly using a reduction density of 2.67 g/cm^3. The curvature correction to the Bouguer slab equation was applied when calculating terrain corrections beyond 18 km.

Existing gravity coverage (Hittelman et al., 1994) was merged into the dataset to complete our coverage because we took fewer measurements outside the basins. The terrain corrections from 54 m to 167 km were recomputed and reapplied to the existing data, along with the curvature correction. The total coverage included 600 points.

To differentiate gravity effects due to small-scale basins from broader, regional anomalies, a "bedrock gravity" value was removed from the data set. Following Jachens and Moring (1990),

all gravity stations are classified as "bedrock" or "basin" stations through the use of geologic maps (Bonham and Bingler, 1973; Trexler, 1977; Bonham and Rogers, 1983; Bell and Garside, 1987). We considered measurements on or near Tertiary Kate Peak formation andesitic rocks (part of "Consolidated Basement Rocks" in Figure 2) to be on bedrock for our purpose of differentiating low-seismic-velocity sedimentary fill from relatively high-velocity seismic bedrock. Similarly, points on or near Tertiary Hunter Creek formation sandstones (Figure 2) were considered to be on basin fill. Density measurements by Thompson and Sandberg (1958) indicate that the density of the Kate Peak formation averages around 2.61 g/cm^3. A single density measurement on the Hunter Creek formation [Truckee formation of Thompson and Sandberg (1958)] indicates a density of 1.76 g/cm^3, although there is evidence from well-log data (Anderson, 1910) and this study to indicate that the density of this formation varies widely.

Bedrock gravity values were computed by kriging the complete Bouguer anomaly of those gravity stations known to be in areas where basin fill is minimal or nonexistent. The bedrock gravity is subtracted from the complete Bouguer anomaly of all measurement points. By removing the perturbations to gravity caused by bedrock density contrasts, basin structure is emphasized and the gravity effect of deep density variations below the

Table 1.   Selected well data from the Reno area basin.

No. on Figure 7	Number and Name*	Total Depth (m)	Depth to Bedrock (m)	Top Hunter Creek Sandstone (m)	Reference
1	05000 Washoe Oil Dev. 1	576	>576	3	Anderson (1910)
2	277-1 "Date 9Aug60"	177	≥177 ?	no log	Garside and Schilling (1979)
3	277-2 Sierra Pacific	239	≥239 ?	no log	Garside and Schilling (1979)
4	277-6 Al Koenig 20Jan59	152	≥152 ?	no log	Garside and Schilling (1979)
5	277-84 "Date 12Oct68"	168	≥168 ?	no log	Garside and Schilling (1979)
6	277-85 "Date 24Jul59"	229	≥229 ?	no log	Garside and Schilling (1979)
7	277-86 "Date 21Nov66"	189	≥189 ?	no log	Garside and Schilling (1979)
8	277-87 "Date 4Aug59"	312	≥312 ?	no log	Garside and Schilling (1979)
9	277-88 "Date 22May59"**	201	≥201 ?	no log	Garside and Schilling (1979)
10	277-89 "Date 27Aug60"	209	≥209 ?	no log	Garside and Schilling (1979)
11	277-90 "Date 13Jan58"	198	≥198 ?	no log	Garside and Schilling (1979)
12	90967 Bradley domestic	335	>335	not in log	NBMG[†] database and files
13	90078 Bussa domestic	88	70	not in log	NBMG database and files
14	90072 Pine domestic	96	72	not in log	NBMG database and files
15	90107 Peppermill Inject. 4	1008	344	<274[††]	NBMG database and files
16	NV35815 Kohlenberg Inject. 1	368	310	not in log	NBMG database and files
17	NV5 Manville domestic	238	>238	not in log	NBMG database and files
18	90028 Peterson domestic	107	91	not in log	NBMG database and files
19	90038 Pennington domestic	283	283	not in log	NBMG database and files
20	90047 Talsma domestic	96	49	not in log	NBMG database and files
21	90071 Salem Plaza Inject. 1	491	418	165	NBMG database and files
22	90159 Virginia Lk. Apts. 2	307	≥307	not in log	NBMG database and files
23	DWR49057 Warren Est. 2	209	183	30	NBMG database and files
24	NV30013 Warren Est. 3	450	317	30	NBMG database and files
25	DWR40310 Warren Est. 1	254	192	38	NBMG database and files
26	90108 Lakeview Apts. domestic	381	280	61	NBMG database and files

*Numbers beginning 277 are the order in the Moana Hot Springs listing in Garside and Schilling (1979), pp. 134–138. Other numbers are the final five digits of the American Petroleum Institute (API) well number (which would be preceded by 27-031); Nevada State Department of Mineral Resources permit numbers, starting with NV; and Nevada State Department of Water Resources permit numbers, starting with DWR.
**May be the active Sierra Pacific Power Co. municipal water supply well at Harvard Way and Marker Street, Reno.
[†]NBMG = Nevada Bureau of Mines and Geology.
[††]Authors' reinterpretation of driller's log puts the top of the Hunter Creek Sandstone at 168-m depth.

surrounding mountain ranges is attenuated. The gravity effect of a basin extends beyond the basin boundaries, however, and these are subtracted as part of our "bedrock gravity" estimate. Thus, basin depths subsequently estimated will be minima.

Initial basin depth estimates were accomplished using the infinite slab approximation. We simply scale the basin gravity anomaly value at each measurement point by a factor that assumes the anomaly results from one or more slabs of constant density contrast and infinite lateral extent to find the total sediment thickness. This estimate is similar to reversing the Bouguer slab calculation, and produces a smoothed basin-depth profile, with the deepest depths being underestimated.

We initially used the sediment compaction model given in Table 2 to find the alluvium-basement density contrast. The sediment compaction model is the same used by Blakely et al. (1998) and Jachens and Moring (1990), and represents a regional average for basins within the Basin and Range province.

Table 2. Density contrast versus depth for use in depth-to-bedrock calculations (from Blakely et al., 1999, and Jachens and Moring, 1990).

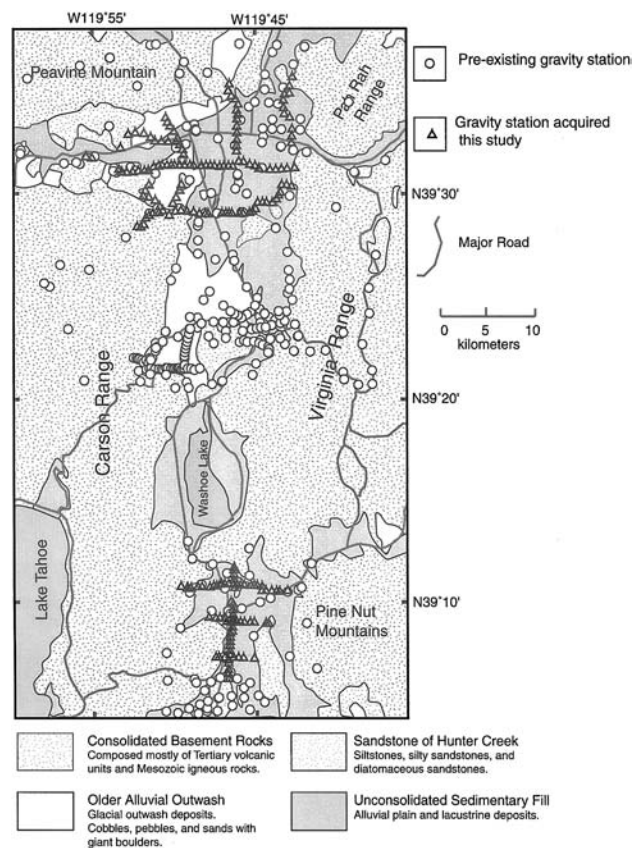| Depth Range (m)	Basin Density Contrast (g/cm^3)
0–200	−0.65
200–600	−0.55
600–1200	−0.35
1200+	−0.25

FIG. 2. Generalized geologic map after Stewart and Carlson (1978). Triangles are new gravity measuring stations, circles represent existing gravity coverage.

Depth was calculated by applying the slab approximation for the shallowest (−0.65 g/cm^3, 200 m) slab. If the gravity anomaly caused by this slab is less than the observed anomaly, deeper layers were taken into account. It should be noted that the infinite slab approximation works best when the slab thickness is much less than the lateral extent of the basin. Errors in depth calculations can occur when nearing the basin edge, where this approximation fails. We subsequently refine the initial density scheme so that depth-to-bedrock matches with seismic depth soundings and well logs.

We also forward modeled 2.5-D selected linear transects in Reno and Carson City using the GM-SYS software package, developed by Northwest Geophysical Associates (Figures 8 and 13). Sediment "blocks" were modeled as extending 3.5 km north and south of the Truckee River east-west transect in Reno (Figure 8). In Carson City, sediment blocks extend 2 km north and 6 km south of the 5th Street east-west transect (Figure 13). Care was taken that the transects followed the trend of the measuring stations as closely as possible. Information from well data (in Reno) and seismic data (in Carson City) were used to constrain parameters in basin modeling. In Carson City, due to the complete lack of local density and lithology information, we made use of average regional density contrasts (Table 2).

Discussion on error

The repeat error of LaCoste and Romberg gravity measurements is estimated to be 0.03 mGal. This is higher than would be expected if the measurements were taken in a quiet environment under controlled conditions. However, most measurements were taken along busy urban streets where traffic and other urban vibrations caused measurement errors. Base stations were carefully chosen to be in quiet, controlled environments. For those measurements, a repeat error of 0.01 mGal is estimated. GPS and EDM theodolite locations, accurate to ±1 m, allow us to neglect latitude correction errors. Vertical position is accurate to within 0.3 m, as confirmed by GPS or EDM theodolite reoccupations of sites. Inner-ring terrain corrections, estimated by eye, rarely approached 0.1 mGal and were 0.01 mGal on average. Still, in areas of high relief, a 20% error in estimating inner-ring terrain effects is possible. In these rare instances, an error of 0.02 mGal could have been introduced. All considered, an error in observed gravity of ±0.08 mGal is possible. Measurements of repeated points from different surveys in the existing data (Hittelman et al., 1994) exhibit a maximum error of ±0.5 mGal. This is the limiting factor in the dataset. Given the magnitude of the anomaly in Reno (15–20 mGal) and the coarse contour interval, we view this as an acceptable amount of error and that the benefits of its inclusion outweigh the problems caused by decrease in accuracy. The depth error in the infinite slab approximation caused by a 0.5 mGal error is 36 m using a −0.33 g/cm^3 bedrock-alluvium density contrast. In the forward models, our tolerance fit levels mean that the 0.5 mGal error between measurement campaigns is essentially invisible.

Our density approximations are the principal source of error in our analysis. The well logs available in Reno lack density measurements or analyses. This lack of density data leads to highly speculative density values. With upper and lower limits for basin-bedrock density contrast set at 0.65 g/cm^3 and 0.30 g/cm^3, a 50% depth error is conceivable.

RESULTS

Several products result from our data analysis: (1) complete Bouguer anomaly maps derived from all stations, (2) complete Bouguer anomaly maps derived from bedrock stations, (3) basin anomaly gravity maps, (4) basin depth maps derived from the infinite slab approximation, and (5) 2.5-D forward models of selected linear transects.
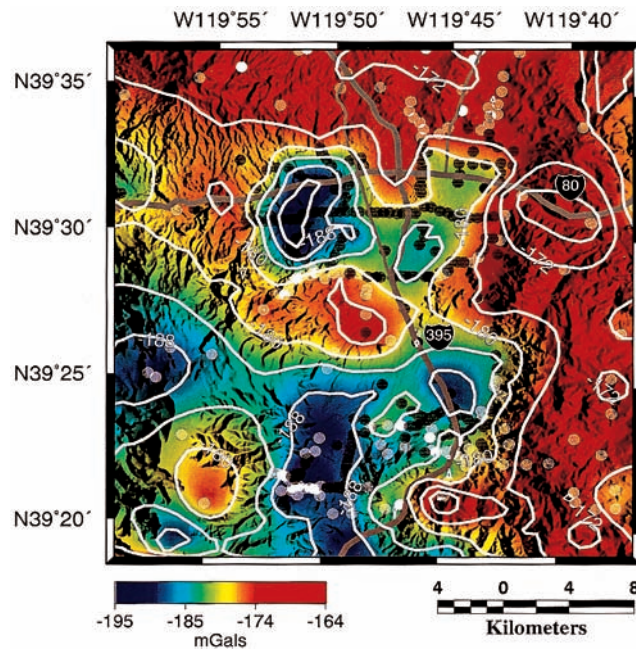
The anomaly maps of Reno (Figures 3–5) show an extended, asymmetrical gravity low over the Truckee Meadows. The gravity low represents the density contrast of bedrock and sediments. The western side of the basin shows the steepest gravity gradients and the most negative anomaly. The maximum local anomaly of −16 mGal yields a basin depth of 1160 m using the infinite slab approximation (Figure 6) if we assume an

FIG. 3. Reno–Truckee Meadows complete Bouguer gravity map. White circles are stations defined as on bedrock, black circles are stations defined as on basin fill. Contour interval is 4 mGal.
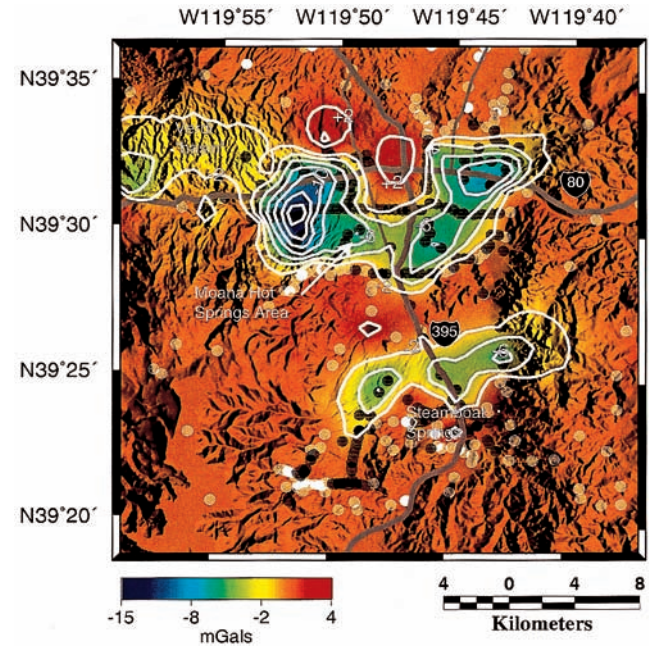

FIG. 5. Reno–Truckee Meadows residual basin gravity. White circles are stations defined as on bedrock, black circles are stations defined as on basin fill. Contour interval is 2 mGal.
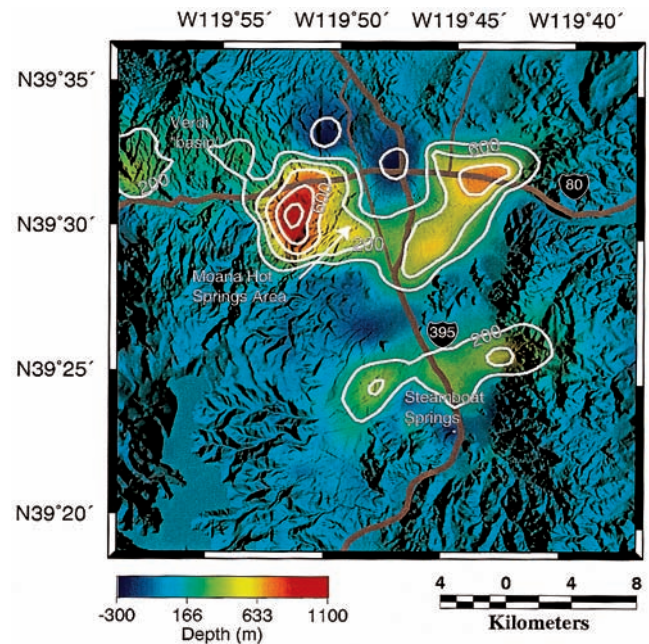

FIG. 4. Reno–Truckee Meadows bedrock gravity. White circles are stations defined as on bedrock. Contour interval is 4 mGal.

FIG. 6. Depth-to-bedrock in Reno–Truckee Meadows as computed with the infinite slab approximation, assuming average basin density contrast of −0.33 g/cm^3. Contour interval is 200 m.

alluvium-bedrock density contrast of -0.33 g/cm^3. A constant average density contrast of -0.33 g/cm^3 produced results most consistent with previous well and seismic data for both Reno and Carson City. There is evidence that the residual gravity separation may not have completely succeeded near this sub-basin. Figure 4, the bedrock gravity grid, also shows a gravity low over this area. Note that the infinite slab approximation underestimates basin depth for a given density contrast. Because we used well-log information to calibrate depth at certain areas, the density contrast required in the infinite slab approximation was underestimated to compensate. Sediment density is likely to be less than the 2.34 g/cm^3 we used.

The westernmost elongation of the basin represents the east-west trending Tertiary Verdi basin. This basin is underlain by the Miocene-Pliocene Hunter Creek sandstone formation. The sandstone has a lower average density than the alluvium of the Truckee Meadows. As such, the depth of the basin may be slightly shallower than indicated on the depth-to-bedrock maps (Figures 6 and 7). A subbasin in the Steamboat Springs area is represented by another gravity low to the southwest, with -6 mGal local anomaly, corresponding to a depth of approximately 430 m.

The east-west cross-section along the Truckee River in Reno (Figure 8) yields a maximum basin depth of 1000 m. This profile shows a striking structural trough in the western portion of the basin. The maximum basin depth in this model is under West McCarran Boulevard. A second trough in the eastern portion

of the basin is separated from the western trough by a bedrock ridge that comes within 200 m of the basin surface near the Reno/Tahoe International Airport.

The anomaly maps of Carson City (Figures 9–11) show an elongate north-south gravity low over Eagle Valley. The anomaly closely approximates the anomaly shape of Arteaga (1986), which he mapped using a combination of gravity and seismic techniques. The magnitude of the local anomaly, -7 mGal, is much smaller than in the Truckee Meadows, suggesting a shallower basin depth. This corresponds to a 520-m depth with the infinite slab approximation (Figure 12, assuming a -0.33 g/cm^3 density contrast). The northeast-trending contours in the northern part of the basin are poorly constrained and may be an artifact of the poor data coverage in the area. A subbasin to the northwest is separated from the main basin by the subsurface expression of a northwest-southeast trending ridge of Triassic metavolcanic rocks. This formation outcrops at Lone Mountain in northern Carson City (Trexler, 1977).

An east-west cross-section along 5th Street in Carson City (Figure 13) yields a maximum basin depth of 530 m. The 5th Street transect shows Eagle Valley to be a more symmetrical basin in which the depth increases fairly smoothly to 0.53 km before returning to bedrock on either side of the basin. The density scheme used is from Table 2. The maximum basin depth along this transect is located 1.5 km east of US Highway 395 (Figure 13).
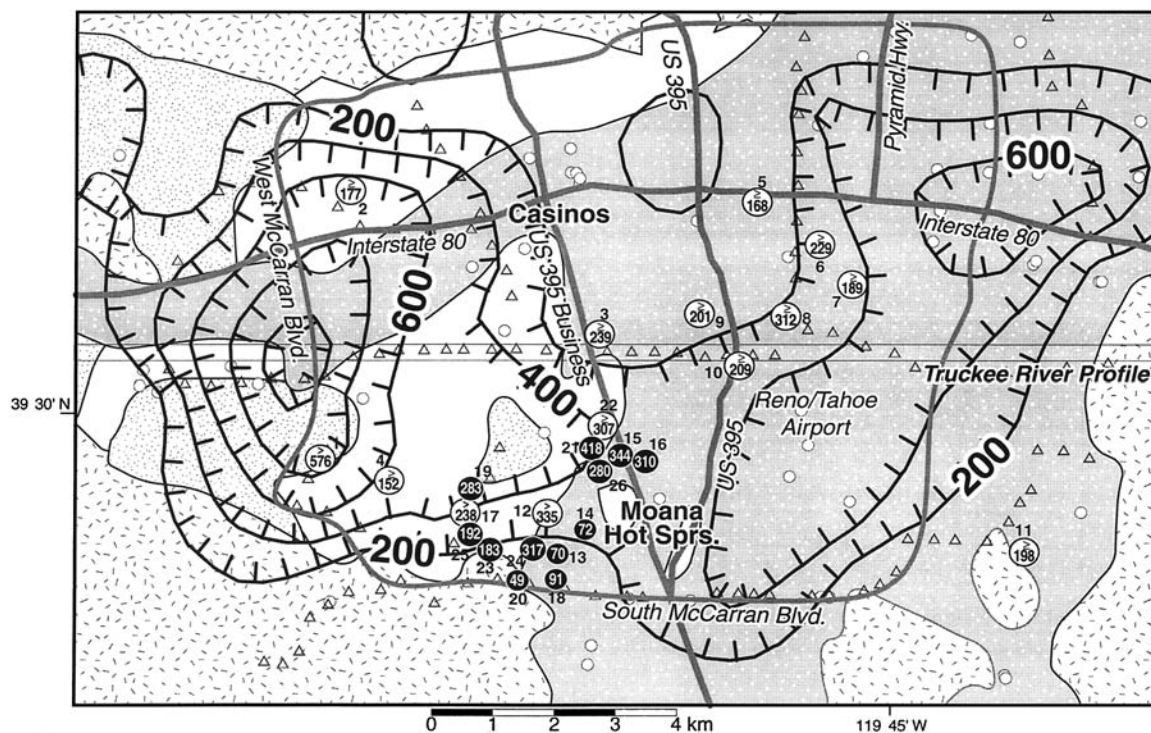

FIG. 7. Depth-to-bedrock in Reno–Truckee Meadows as computed with the infinite slab approximation, assuming average basin density contrast of -0.33 g/cm^3. Geologic units are as in Figure 2. Depths are in meters, contour interval is 200 m; new measuring stations are triangles, existing coverage are white circles. Wells with logged Kate Peak andesite bedrock depths show white numbers in black circles. Logged wells that did not reach bedrock show their total depth in black numbers with a ">" (greater than) in white circles. Wells without logs have their total depths in black numbers with "$\geq$" (greater than or equal to) symbol, also in white circles. Numbers outside circles refer to the list in Table 1. Major roads are labeled.

DISCUSSION AND CONCLUSIONS

Contours indicating negative bedrock depths outside basins allow the estimation of errors in depth-to-bedrock calculations caused by shallower bedrock density contrasts. The +2 mGal contour on the western margin of Eagle Valley (Figure 10) would correspond to a −140 m depth-to-bedrock with the infinite slab calculation (Figure 11), where negative depth would mean bedrock above actual elevation. Therefore, our estimates of bedrock gravity (Figures 3 and 9) may be in error by 2 mGal, and depth to bedrock in the basins cannot be considered more accurate than ±140 m. The cause for this is unclear, but the poor coverage of bedrock gravity measurements, isolated bedrock density variations such as hidden intrusions, measurement errors, or isostatic effects near the Sierra Nevada Mountains are possible. Based on our Reno bedrock gravity estimate (Figure 4), our basin gravity difference (Figure 5), and basin depth (Figures 6 and 7) maps, we estimate a depth uncertainty of 250 m for the Truckee Meadows.

To constrain absolute depths, accurate density measurements need to be obtained. Specific knowledge of how density increases with depth, especially from outside the geothermal fields, would be particularly useful. We can only use the depth to bedrock logged in a few of the wells to check our overall density assumptions. In particular, the thickness of low-density diatomaceous deposits in the Hunter Creek formation varies widely from location to location. Currently, density uncertainty is the overriding cause of depth uncertainty. Using our reasonable end-member values for density contrasts, 50% error in depth calculation is possible, if no other factors, such as seismic depth soundings, were taken into account. The error in our analysis is probably significantly less than this maximum value, however.

Constraints from a previous Carson City study

Arteaga's (1986) hydrological study of Eagle Valley included some depth-to-bedrock calculations based mostly on seismic depth soundings, supplemented by gravity measurements. Absolute comparison of gravity values is impossible because the study did not publish complete Bouguer values. The only published result was the gravity residual, obtained by subtracting out the regional gradient. The shape of gravity residual obtained by Arteaga matched extremely well with our basin anomaly residual.
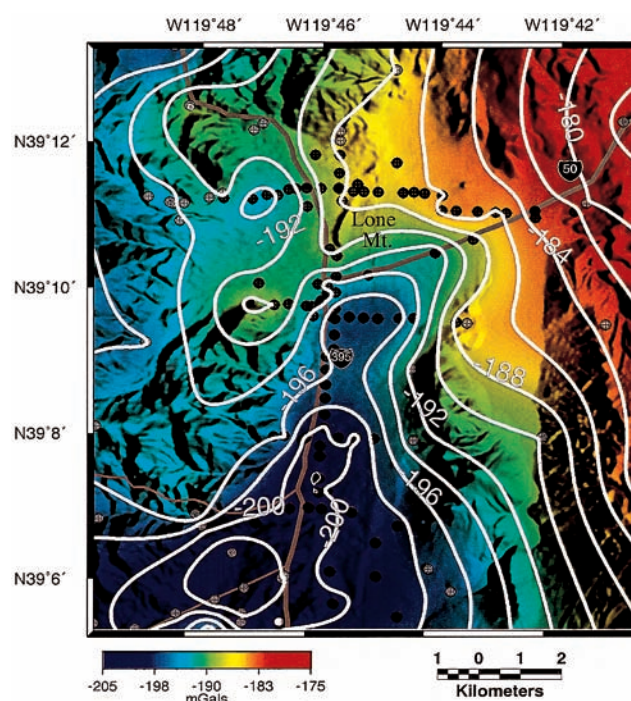

FIG. 9. Carson City–Eagle Valley complete Bouguer gravity. Gray circles are stations defined as on bedrock, black circles are stations defined as on basin fill. Contour interval is 2 mGal.
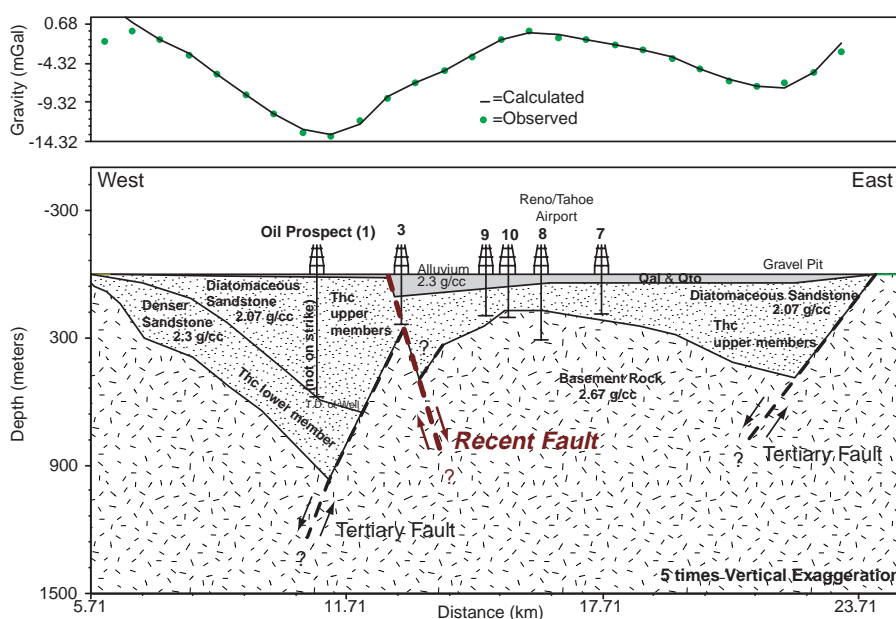

FIG. 8. Reno–Truckee Meadows Truckee River gravity (location given in Figure 7) cross-section as computed by 2.5-D forward modeling. Wells with numbers refer to Figure 7 and Table 1. Vertical exaggeration is 5 times.

Arteaga's (1986) seismic depth soundings predicted a 620-m maximum basin depth, compared to our 530-m maximum. The data quality of the seismic depth soundings were characterized as only being "fair" in Arteaga's study. Overall agreement in
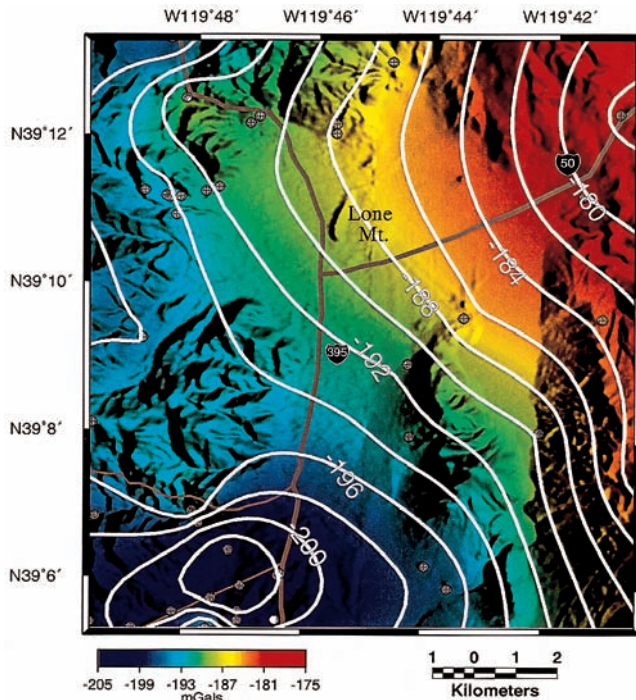

FIG. 10. Carson City–Eagle Valley bedrock gravity. Gray circles are stations defined as on bedrock. Contour interval is 2 mGal.
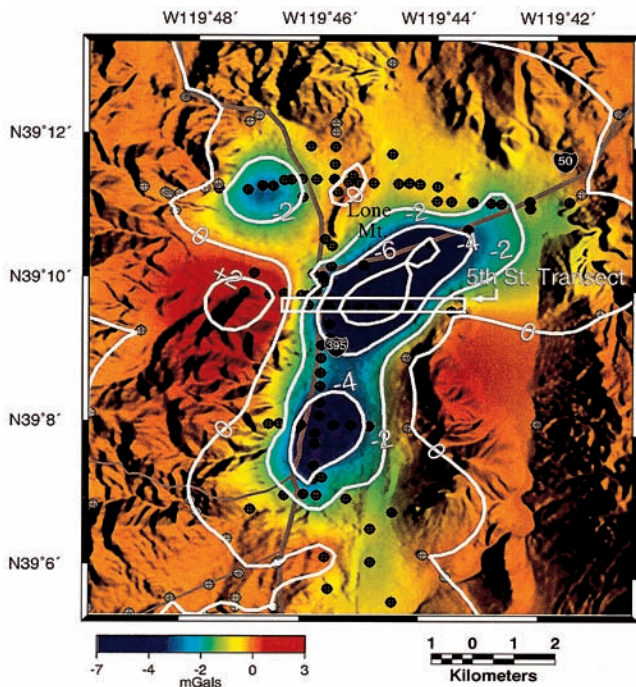

FIG. 11. Carson City–Eagle Valley residual basin gravity. Gray circles are stations defined as on bedrock, black circles are stations defined as on basin fill. Location of 5th street transect is shown. Contour interval is 2 mGal.

depth-to-bedrock is generally within approximately 25%. The location of the three measurements closest to the deeper subbasins is plotted on Figure 12, along with the associated depths in meters.

Constraints from well data

Garside and Schilling (1979) and more recent associated databases (e.g., Hess, 1996) provide some well data that corroborate our basin depths for Reno (Figures 6–8, Table 1). Neither of these latest databases show any boreholes of record in Carson City–Eagle Valley. The well casing from the 1908 deep oil prospect (Anderson, 1910) was located by the Nevada Bureau of Mines and Geology before housing development overtook the site. The location is thus known to within 30 m and appears near the 800-m basin thickness contour from the slab calculations on Figure 7 (labeled 1). Anderson (1910) interpreted all but the top few meters of the 576-m total depth drilled as partly penetrating the middle Tertiary "Truckee formation" of sands, shales, and diatomites. The formation is equivalent to the Miocene-Pliocene "sandstone of Hunter Creek" mapped in the area by Bonham and Rogers (1983). This deepest boring into basin deposits in Reno is only 1.5 km south of our lowest basin gravity anomaly.

Garside and Schilling (1979) and the more recent records show an additional 55 wells drilled to depths greater than 150 m in the Reno basin. Table 1 lists the 26 of these that provide the best constraints throughout the basin. Locations of most of these wells are given by partial sections or permittee addresses,
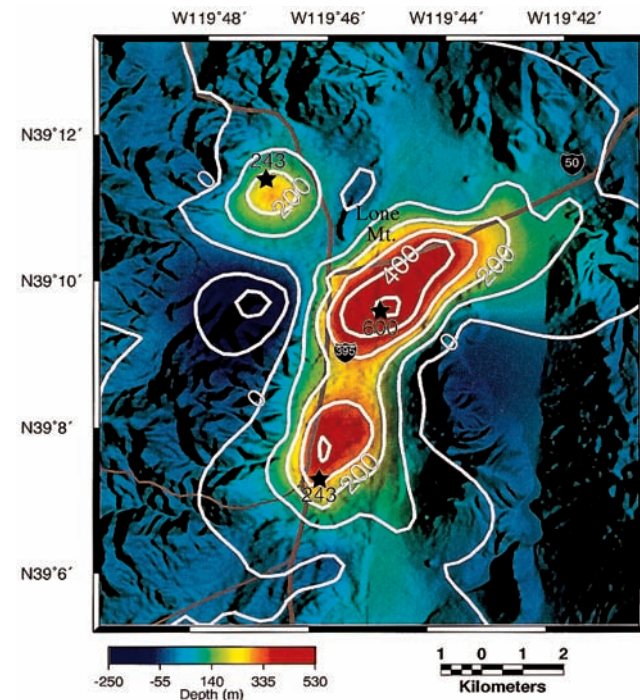

FIG. 12. Carson City–Eagle Valley depth-to-bedrock as computed with the infinite slab approximation, assuming an average basin density contrast of −0.33 g/cm^3. Depths are in meters; contour interval is 100 m. Black stars show locations of three seismic depth soundings (Arteaga, 1986) closest to the deeper subbasins. Black numbers are depth-to-bedrock associated with the three seismic soundings.

and could easily be 300 m in error. The 30 wells not in Table 1 either lacked any reliable depth or location information, or were not as deep or as well logged as another well on the same property or very nearby. Of the 55 wells, only twelve are outside the immediate area of the Moana Hot Springs geothermal district (the concentration of well locations at the lower center of Figure 7). Eleven of these appear on Figure 7; the twelfth lies off the map to the south.

South of the 200-m depth contour, along South McCarran Boulevard, Figure 7 shows basin thicknesses of 100 m or less, corroborated by domestic wells such as the Talsma and the Peterson (labeled 20 and 18 on Figure 7), which logged Kate Peak volcanic bedrock at 49 m and 91 m, respectively. Depths increase rapidly to the north and to the northwest, in concert with the depth contours derived from gravity. The Pennington domestic and Warren Estate geothermal well 3 (labeled 19 and 24 on Figure 7) logged Kate Peak at 283 and 317 m, respectively. The Pennington well is located near the 400-m depth contour on Figure 7. The Warren Estate 3 is located by partial sections, where the first quarter section may be stated in error in the database; its location on Figure 7 may be 1 km southeast of the true location.

At the north end of the Moana Hot Springs area, the deep Kohlenberg Domestic injection well 1, Peppermill well 4, and Salem Plaza injection well 1 (labeled 16, 15, and 21, respectively, on Figure 7) log Kate Peak depths increasing from 310 to 344 to 418 m, respectively, from east to west over a 1-km distance across US 395 Business. The Peppermill 4 well is the deepest hole in the region, with logs to 1008 m (logged lateral deviation of the hole is less than 100 m). These bedrock depths closely approximate the depth contours on Figure 7.

Every logged well in Reno shows Hunter Creek sandstones and diatomites extending through 20–90% of the section above the Kate Peak bedrock, averaging about 80% (Table 1). Anderson (1910) summarized observations of similar diatomites throughout the Great Basin, and proposed that every Miocene basin in the region might host them. The diatomites consist of an open network of silica microfossils having porosities as high as 70%, and air-filled samples from the surface near the oil well (labeled 1 on Figure 7) will float on water (mentioned by Anderson, 1910). These diatomites, with pores filled with water, would have a maximum density of 1.7 g/cm^3. It is likely that the diatomites have less porosity at depth and/or have pore spaces filled with mineralization, thus increasing the formation's density.

In Reno outside the Moana Hot Springs district, the twelve deeper wells listed by Garside and Schilling (1979) have total depths but no logs on file. Figure 7 locates them with white circles with "$\geq$" marked above their total depths. Given that these are all domestic water sources, it seems unlikely that they would have been drilled far into any bedrock formations, although that possibility cannot be ruled out. Assuming that these wells provide minimum basin thicknesses from their total depths, one of them (labeled 3 on Figure 7) does not match the slab gravity–derived depth contours. The other water wells for which there are no logs are all shallower than or close to the infinite-slab depth contours. The "negative depth" contours on Figure 7 surrounding the interchange suggest bedrock density contrasts that are not constrained by the bedrock data, and have artificially pushed the depths to more shallow levels. A 198-m well drilled in 1958 (labeled 11 on Figure 7) in a subbasin to the southeast is very close to bedrock outcrops and may have been drilled partially into bedrock.

Origin of the deep subbasin

A novel result of our work is our definition of the 16 mGal gravity low on the west side of Reno. This anomaly, about 7 km in diameter, had not been sampled by the previously very sparse gravity coverage of the basin. Within the limits of our data coverage, Figures 5–7 show that this low defines a north-south trending trough about 5 km long and 3 km wide, and up to 1.2 km deep, that we call the West McCarran subbasin. It should be noted that the extent of the subbasin is poorly constrained to the southwest. The subbasin is twice as deep as any other subbasin below Reno or Carson City, and identifies the location of what could be the largest basin effects on earthquake ground motion in the western Nevada urban areas.

The 576-m well drilled in 1908 shows that this deep subbasin was formed entirely in the Miocene and Pliocene. The well
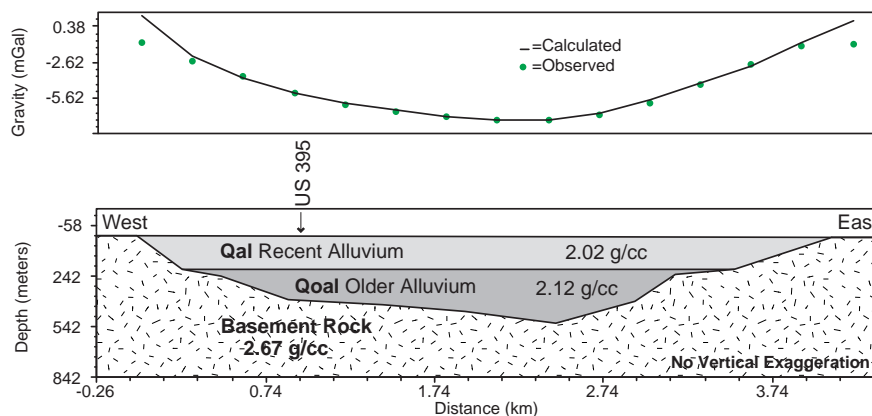

FIG. 13. Carson City–Eagle Valley 5th street gravity cross-section (location given in Figure 11) computed by 2.5-D forward modeling. Layering in basin sediments follow scheme in Table 2. No vertical exaggeration.

sits nearly atop the deepest part of the basin (labeled 1 in Figure 7), only 1.5 km south of the line of depth section modeled in Figure 8. Anderson (1910) mapped the fully exposed Truckee formation (Hunter Creek) section, inspected the well during drilling, and interpreted the driller's log. He proposed that the entire borehole had penetrated just the middle diatomite-dominated member of the Hunter Creek sandstones, perhaps with some sampling of the lower sandy member. Given the exposed 200-m thickness of each of these members in sections compiled throughout the region, and the lesser thicknesses in the Moana Hot Springs well logs (Garside and Schilling, 1979, and recent associated databases), the Hunter Creek sandstones appear to be thickened in the deep subbasin by a factor of two or three. This thickening suggests the subbasin was actively subsiding during deposition of the diatomite member near the Miocene-Pliocene boundary (age taken from Bonham and Rogers, 1983), and probably initiated during deposition of Hunter Creek basal members or earlier.

Since the entire 1.2-km-deep subbasin is filled by lower Pliocene and older sediments, all of the related, basin-forming vertical deformation must have occurred by the early Pliocene. Thus the existence of the West McCarran subbasin requires no Quaternary deformation. The 274-m thickness of Quaternary deposits logged by the driller in the Peppermill well 4 (Table 1, number 15) may be overstated. Reinterpretation of this log, and comparison to nearby logs by the authors suggest only 168 m of Quaternary fill above the Hunter Creek sands. This depth thus represents the maximum observed Quaternary vertical deformation in the Reno basin. All other logged wells in Table 1 show less, between 30 and 165 m. While the total thickness of low-velocity Miocene through Quaternary sediment varies greatly among the Reno subbasins, the maximum thicknesses of Quaternary deposits in these basins may well be less than 200 m.

Seismic hazard estimates

Our less than 30% error in depth calculation (based on negative depth contours) should have little effect on seismic modeling, except possibly in one key area. Currently, modeling of seismic waves in basins is rarely done for frequencies greater than 1 Hz. Any change in depth equal to or less than one-quarter seismic wavelength may be undetectable. Work in progress, not presented here, by the University of Nevada Reno Seismological Laboratory, Kyoto University, and the Shimizu Corporation of Japan is employing the microtremor analysis of Horike (1985). Shear wave velocities for depths below 100 m at a test site near the Reno/Tahoe Airport (Figure 7) are on the order of 2 km/s. At 1 Hz, this would correspond to a 2-km seismic wavelength. Therefore 500-m resolution is required for seismic hazard modeling. Only in the deepest section of the Truckee Meadows would a 30% maximum error in depth even approach this limit. In the shallower sections of both basins, even 30% depth error will be much less than 500 m, and will have a smaller effect on a smaller seismic hazard. Therefore, the depth error in the shallow sections may be insignificant. It is the deepest, most poorly-characterized subbasin that has the most seismic hazard potential, and this is the area with the most error.

Depth gradient maps, not presented here, suggest in the manner of Olsen et al. (1995) that the areas that could most experience basin effects might be near the north and south corners of West McCarran Boulevard (Figure 7). In these areas over the western subbasin, the combination of a deep basin and high gradients may produce the ground motions most amplified by surface waves trapped in the basin. High gradients also exist at the eastern edge of the Truckee Meadows. However, the basin is not as deep in this area, and therefore ground motion amplification may be less. Eagle Valley, with a very muted basin structure as compared to the Truckee Meadows, should show less ground amplification due to basin site effects. The difference in site effects might be of significant amplitude; seismic hazard maps may have to be reevaluated for these two areas. The seismic hazard for Reno may increase with respect to the seismic hazard of Carson City.

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