Preliminary gravity inversion model of Frenchman Flat basin, Nevada Test Site, Nevada

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ABSTRACT

The depth of the basin beneath Frenchman Flat is estimated using a gravity inversion method. Gamma-gamma density logs from two wells in Frenchman Flat constrained the density profiles used to create the gravity inversion model. Three initial models were considered using data from one well, then a final model is proposed based on new information from the second well. The preferred model indicates that a northeast-trending oval-shaped basin underlies Frenchman Flat at least 2,100 m deep, with a maximum depth of 2,400 m at its northeast end. No major horst and graben structures are predicted. Sensitivity analysis of the model indicates that each parameter contributes the same magnitude change to the model, up to 30 meters change in depth for a 1% change in density, but some parameters affect a broader area of the basin. The horizontal resolution of the model was determined by examining the spacing between data stations, and was set to 500 square meters.

INTRODUCTION

Frenchman Flat is a Cenozoic basin located within the southeastern edge of the Nevada Test Site (NTS). The northern part of the basin is bounded by north-trending mountain ranges. The basin is bounded by low ranges comprised mostly of Paleozoic rocks capped locally (to the west and north) by Cenozoic volcanic rocks (fig. 1). Paleozoic rocks exposed in the Buried Hills, Ranger Mountains, Mercury Ridge and Red Mountain bound the eastern and southern edges of the basin. Smaller Paleozoic outcrops occur to the north and west in the CP Hills in southwest Yucca Flat and on the eastern edge of Shoshone Mountain. Tertiary rocks underlie the northern and western edges of the basin, Massachusetts Mountain and the hills around Mount Salyer (fig. 1). The Frenchman Flat basin is filled with Quaternary and Tertiary volcanic and sedimentary deposits that lie unconformably on faulted and folded Paleozoic and pre-Cambrian strata.

The purpose of this study was to estimate the depth to pre-Cenozoic rocks in Frenchman Flat using gravity data from existing surveys and taking into account the information obtained from wells Well ER-5-3#2 and Well ER-5-4. Gravity anomalies indicate deviations in rock density from a reduction density of 2670 kg/m^3. Since pre-Cenozoic rocks are typically denser than overlying, younger deposits, gravity anomalies are inferred to reflect variations in the contact between the two lithologies.

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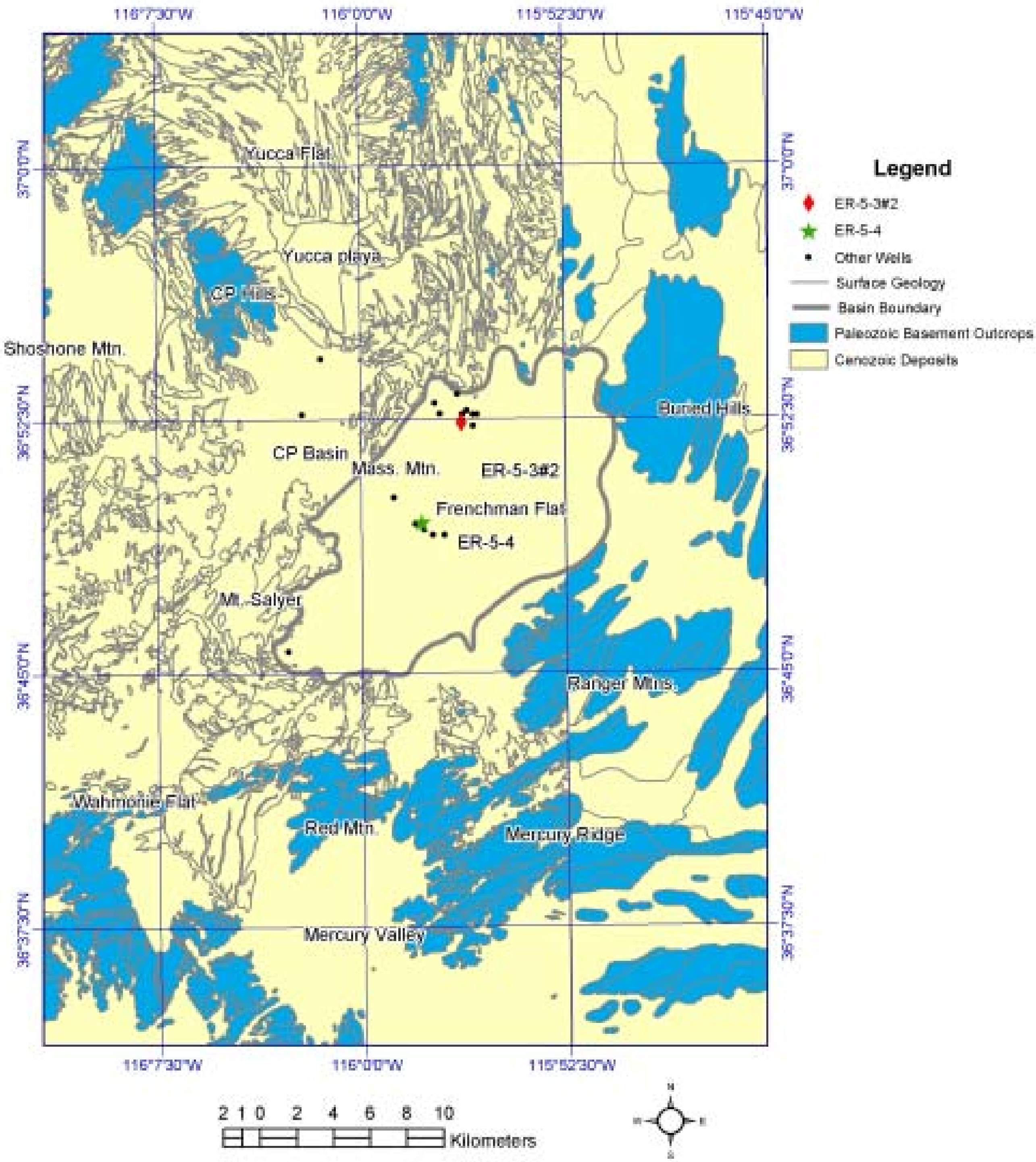

Figure 1. Simplified geologic map of Frenchman Flat and vicinity. The geology is combined from Wahl and others (1997), and Stewart and Carlson (1978). The basin boundary was created by generalizing the topographic break in slope separating Frenchman Flat from the surrounding mountains.

GRAVITY DATA

The isostatic residual gravity anomaly was used as the principle data to model the depth to pre-Cenozoic rocks beneath Frenchman Flat.

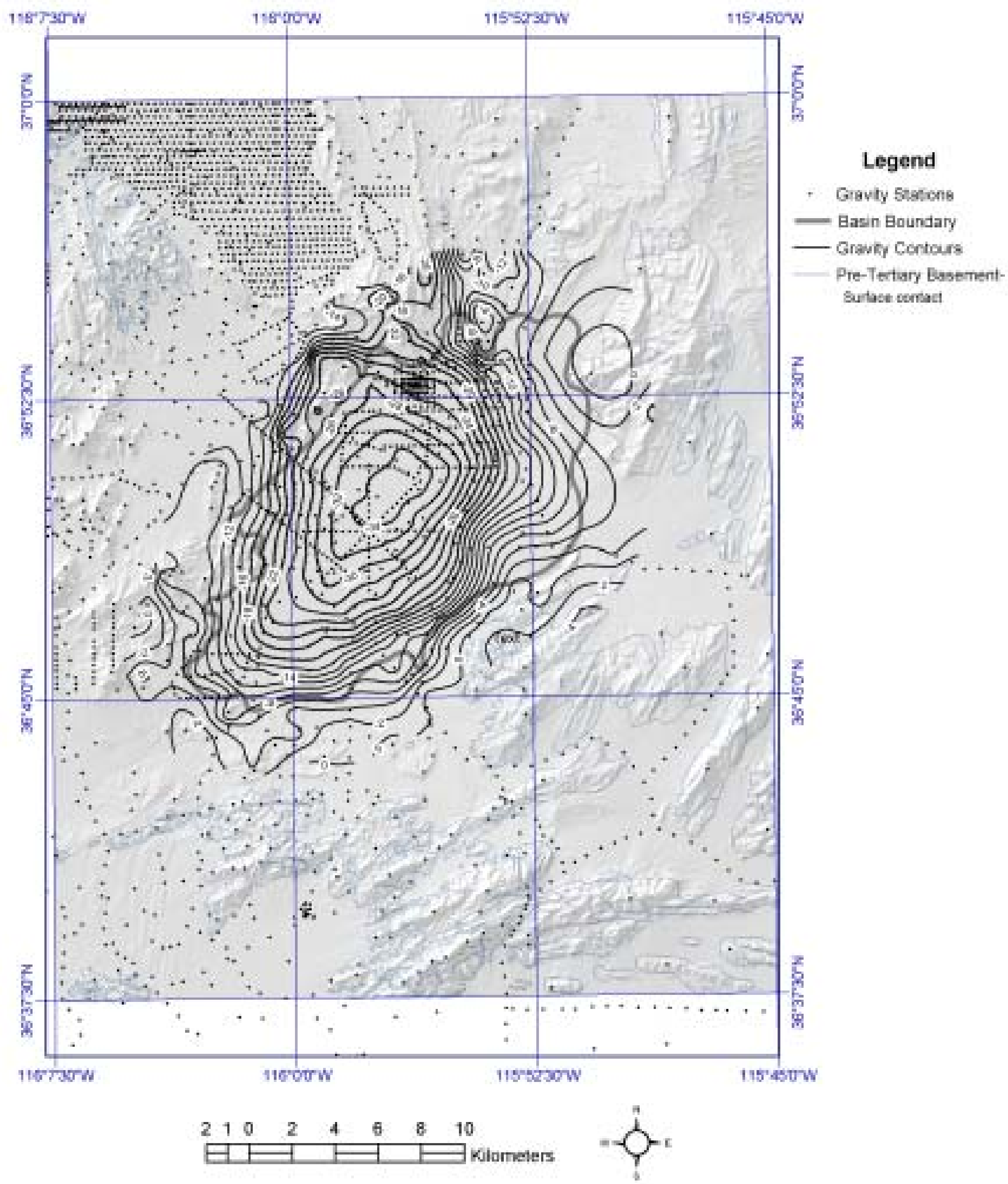

Figure 2. Isostatic gravity anomaly over Frenchman Flat.

Isostatic residual gravity anomalies are inferred to represent the contact between dense pre-Cenozoic rocks and less dense overlying Tertiary and Quaternary deposits. The isostatic residual gravity anomaly was derived from the complete Bouguer anomaly by removing the gravitational component due to isostatic compensation of topography (Jachens and Griscom, 1985). Isostatic residual gravity anomalies reflect density variations in the upper 10 km of the earth's crust. The isostatic gravity anomaly over Frenchman Flat (fig. 2) shows two important points, which are the magnitude of the total anomaly, and the shape of the anomaly, over Frenchman Flat.

The negative gravity anomaly over Frenchman Flat, about -35 mGal, is typical of large basins in the Basin and Range province of the western United States. By comparison, the isostatic gravity anomaly over Yucca Flat, a few miles to the northeast, is –20 mGal where the basin is known to be 1.5 km deep.

The anomaly over Frenchman Flat forms a broad oval with a shallow embayment at the eastern margin. The anomaly reaches its minimum over the center of the basin, is fairly symmetrical along its northeast axis, and lacks obvious internal structures. The anomaly approaches zero near Pre-Tertiary outcrops, which are shown east and south of Frenchman Flat and are just outside the mapped area to the west in Figure 2.

Gravity data were taken from an existing dataset of gravity stations from the Nevada Test Site (Ponce, 1997). A total of 3,746 stations from the nine quadrangles surrounding and including Frenchman Flat were used in the modeling process. 233 gravity stations are located on Paleozoic outcrops in the area surrounding Frenchman Flat and 642 are within the basin as defined by the basin outline (fig. 3). The station spacing in Frenchman Flat is variable, averaging about 300 m, but as large as 2,800 m. Most stations are within 1 km of each other. Gravity data were reduced using the Geodetic Reference System of 1967 (International Union of Geodesy and Geophysics, 1971) and referenced to the International Gravity Standardization Net 1971 gravity datum (Morelli, 1974, p. 18). Gravity data were reduced to complete Bouguer gravity anomalies (Plouff, 1977) with a reduction density of 2670 kg/m^3 by applying earth-tide, instrument drift, free-air, Bouguer, latitude, curvature, and terrain corrections. An isostatic correction, following the method and parameters used by Jachens and Griscom (Jachens and Griscom, 1985), was applied to produce the final isostatic gravity anomaly. Assuming a sea level crustal thickness of 25 km (16 mi) based on seismic profiles, a crustal density above sea level of 2670 kg/m^3, and a mantle-crust density contrast of 400 kg/m^3, the correction removed the long-wavelength gravitational effect caused by isostatic compensation of topography.

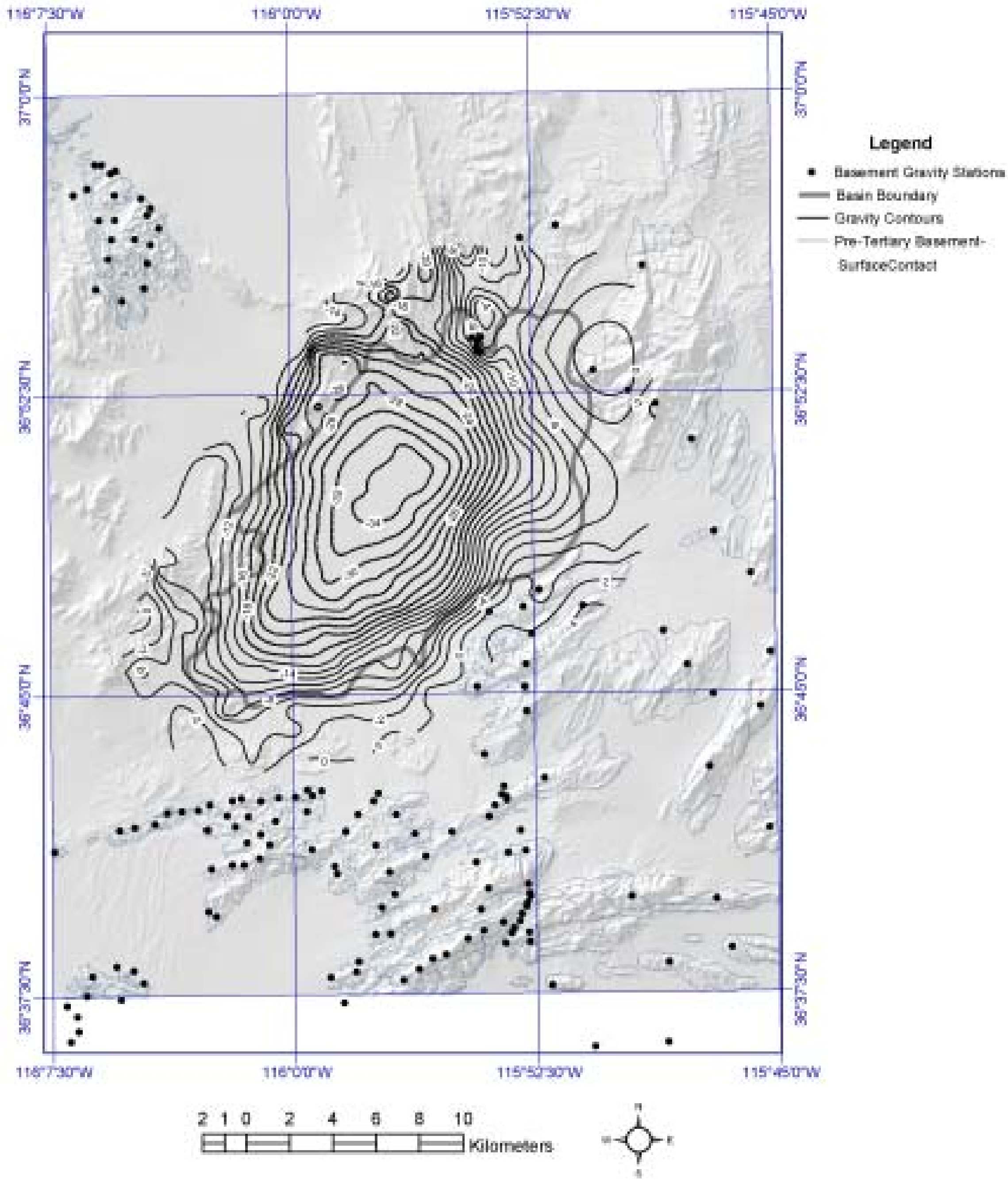

Figure 3. Gravity stations recorded on Paleozoic outcrop.

DENSITY MEASUREMENTS

The inversion process requires a model for the variation in the density of the basin-filling deposits with depth, referred to in this paper as a density profile. The gamma-gamma density log from Well ER-5-3#2 was the primary source of information used to construct the density profiles for the initial set of models. The density profile was updated when new information from Well ER-5-4 became available. The following discussion will describe the logic behind the models based on Well ER-5-3#2 and then use the updated information to propose an improved model.

The initial density profiles were created from the density values derived from the gamma-gamma log for Well ER-5-3#2, as provided by the contractor (fig. 4).

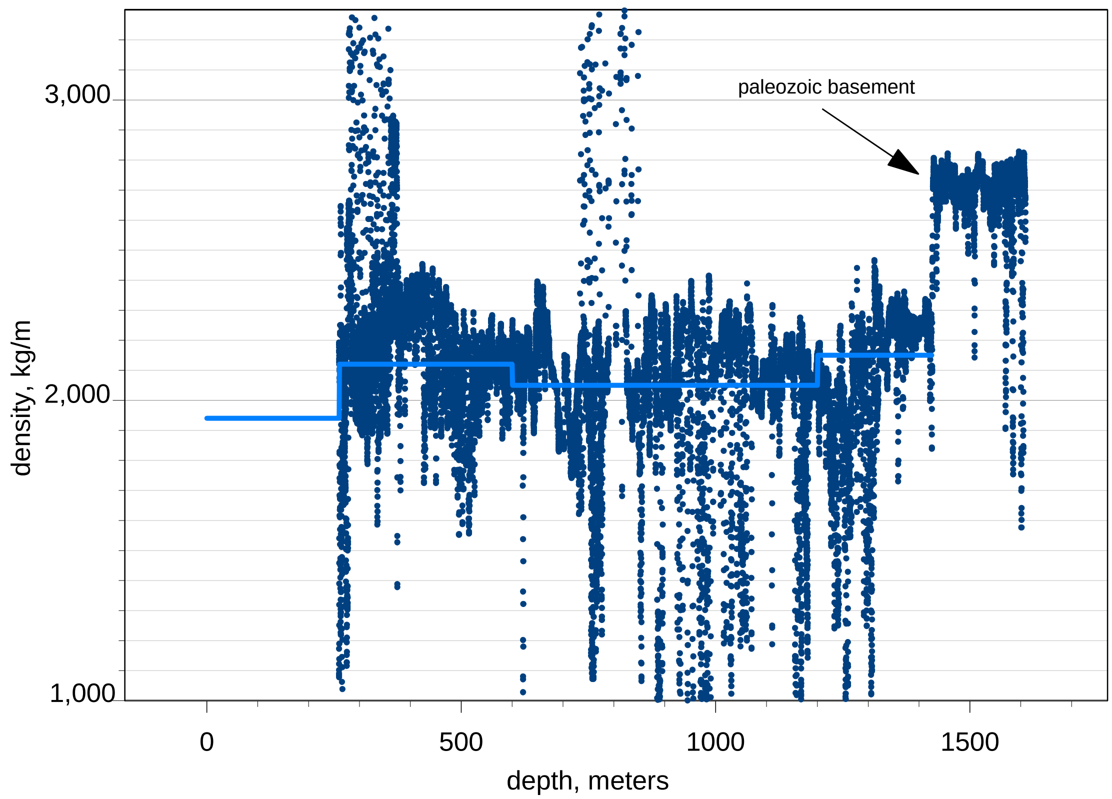

Figure 4. Density vs. depth for the gamma-gamma log from Well ER-5-3#2. Blue circles are the data points from the log and the blue line is the generalized density-depth profile used in model 1. Density log values include only values between 1000 and 3,300 kg/m^3.

The data shown are a subset of the total dataset, including only values above 1000 kg/m^3 and below 3,300 kg/m^3. These numbers are conservative, and values outside this range are extremely unlikely, since 1000 kg/m^3 is the density of water and 3,300 kg/m^3 is the density of gabbro. The true values of the rock densities are probably not even as extreme as this, but the authors feel that discarding data should only be performed when it is clear the values are incorrect: for example, rocks less dense than water occurring below the zone of saturation. Values outside this range were assumed to be anomalous readings that did not measure the density of the wall rock of the well. The density values are most accurate in the zone of saturation, below the water table, because the logging instrument is calibrated using samples of saturated rocks. The water table at Well ER-5-3#2 lies 260 m below the land surface. The median value from borehole gravity data in Frenchman Flat was assigned to depths shallower than 260 m. Using the density information and depth to Paleozoic basement derived from Well ER-5-3#2, three density profiles were created.

The first profile used the gamma-gamma density log information derived from Well ER-5-3#2 (fig. 4). The density values were broken into groups by dividing them at depths that exhibited abrupt changes in density, and a median value was assigned to each group. The number of intervals is a compromise between sufficiently breaking down the density profile into meaningful units while maintaining a relatively simple profile. The gravity inversion modeling process is non-linear and the solution space is complicated, and no method currently exists for optimizing the number of layers used in a given model. However, since the sensitivity of the model to change decreases with decreasing number of layers, the authors prefer simpler models with fewer layers.

Paleozoic bedrock density, according to the log, has a median value of 2710 kg/m^3. This differs from the value of 2670 kg/m^3 typically used in previous gravity inversion models (see, for example, Miller and Healy, 1986, Jachens and Griscom, 1985). Later in this paper we suggest that a pre-Cenozoic rock value of 2670 kg/m^3 might be more representative of the average density of pre-Cenozoic rocks.

The second profile takes into account a possible low-density bias in the gamma-gamma log. Density logs can give erroneously low readings when the logging instrument moves away from the wall of the borehole, due to factors such as well rugosity (Hallenburg, 1998). Because of this, the gamma-gamma log and caliper log were examined for correlation, and a linear relationship was discovered between logged density and caliper width. Logged density decreases with increasing caliper widths for widths greater than about 0.305 m (12 in.). The density data were adjusted to remove this linear trend, normalizing the density values to a caliper width of 0.311 m (12.25 in.), the width of the drill bit during logging, and hence is the minimum width of the hole. Adjusted density values, shown in figure 5, raise the average density of the well 140 kg/m^3, and the pre-Cenozoic rock density 50 kg/m^3, to 2760 kg/m^3. The second density profile was determined from these adjusted density values as before (fig. 5). Values for the density at depths shallower than 400 m were taken from borehole gravity data.

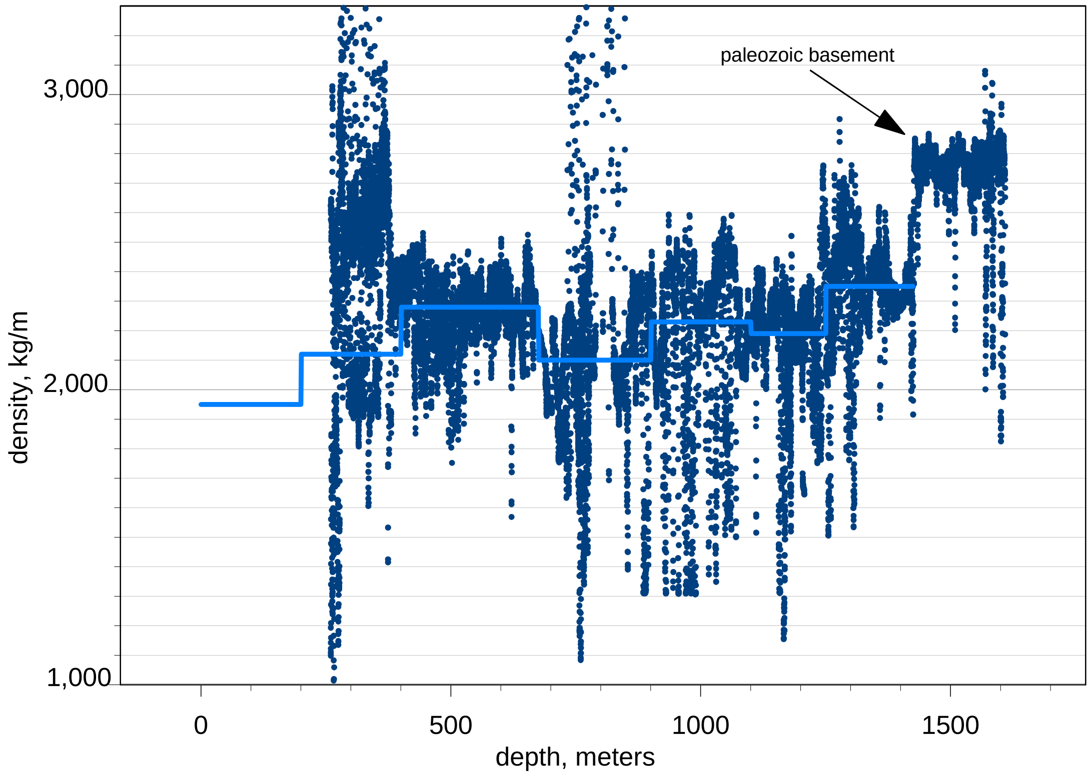

Figure 5. Density vs. depth for the adjusted gamma-gamma log from Well ER-5-3#2. Blue circles are the adjusted data values and the blue line is the generalized density-depth profile used in model 2. Density log values include only values between 1,000 and 3,300 kg/m^3.

For reasons discussed subsequently, the third profile used was identical to profile one (fig. 4), but with the addition of a constant, 200 kg/m^3.

Well ER-5-4 was drilled subsequent to Well ER-5-3#2 over the part of the basin suspected to be deepest. The lithologic record from the well differs greatly from that of Well ER-5-3#2, but the density profile differs less. Well ER-5-4 bottoms at 1,200 m and the entire lithologic section is alluvium. Discrete density profiles were fit to the gamma-gamma density log data using methods described previously. Investigation into the caliper log/density log relationship showed no clear relationship between the two, probably because Well ER-5-4 was not as rugose as Well ER-5-3#2.

The density-depth values from the gamma-gamma log of Well ER-5-4 and the average density profile used for the final model are shown in fig. 6. The portion of the profile that extends below the measured data is based on geologic inference. Using reasoning based on geology it was inferred that at least some volcanic rocks are present at the bottom of the basin below Well ER-5-4. Volcanic rocks are exposed to the north and west of Frenchman Flat. Since no volcanic rocks are exposed south and southeast of Frenchman Flat they must pinch out somewhere beneath Frenchman Flat. Therefore only a moderate section of volcanic rocks would be present. Geologists believe the basin should include an increase in density with depth due to the presence of volcanic rocks and dense sediments (E.H. McKee and L.P. Prothro, personal communication, IT Corporation, 1998). The density profile was modified to account for the presence of deep volcanic rocks by increasing the density profile to 2250 kg/m^3 at 1.22 kilometers (4,000 feet) depth. This profile was used for the final model of Frenchman Flat.

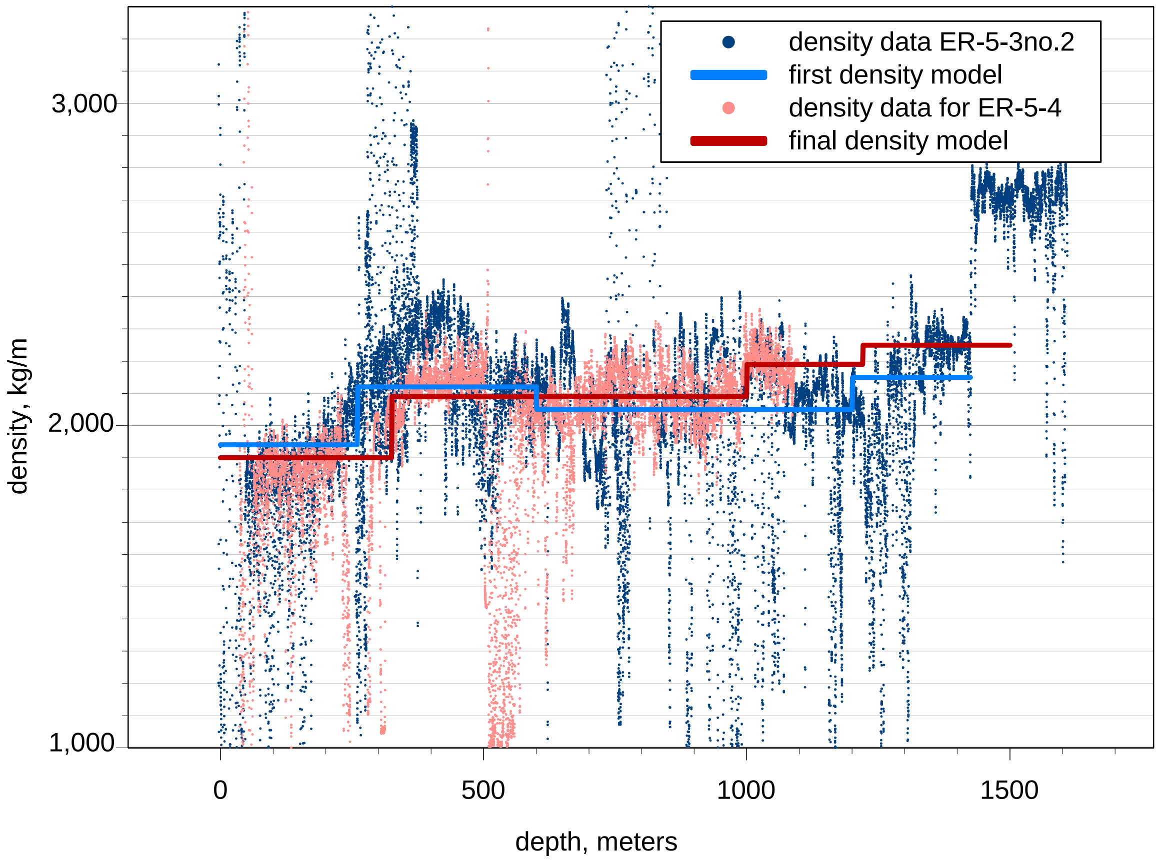

Figure 6. Density-depth profile data and models from Well ER5-3#2 and Well ER-5-4

Three of the layers in the final model derived from the density values recorded in Well ER-5-4 can be tested to determine if the medians of the layers are significantly different. What is important in this particular model is that adjacent layers are different, because it is the change in density with depth that matters in the modeling process. If adjacent layers have the same median then they should be combined into one layer. In the final model demonstrating that the middle layer differs from the layer above and below it is sufficient to demonstrate that the change in density is significant (the fourth layer in the final model is an inferred change and therefore cannot be tested).

There are three issues with performing a valid statistical test between the model layers. The first is that the sampling must be independent. Given that the density measurements were taken from a well log, autocorrelation within the data may violate the assumption of independence. Fortunately, a large number of sample density values exist for each of the three layers. To ensure independence, a random sample consisting of fifteen percent of the total sample for each layer was used for the test.

The second and third issues are normality of the samples taken from a layer and the equivalence of variance of layers. The three layers were non-normally distributed, and did not have equal variances. This ruled out the standard one-way analysis of variance tests and the standard t-test. A Wilcox rank-sum test yielded a rank-sum normal statistic of 24 for layers one and two, and a rank-sum normal statistic of 15 for layers 2 and three, both significant at the 1% level. The layers can be considered to be different from each other and need not be combined.

The density value of the pre-Cenozoic rocks used in the final model was 2670 kg/m^3. The reasoning is presented in the discussion section.

In addition, the density boundaries chosen in the model were compared with the geologic rock units defined independently of the geophysical logs by Warren and others (in press) for Well ER-5-4. The boundaries correspond to the top of the fifth unit and the top of the eleventh unit for the first and second density change, respectively (the third density change is below the T.D. of Well ER-5-4). The correspondence supports the idea of meaningful density boundaries at the depths proposed.

Published information from wells and surface samples in Frenchman Flat and the surrounding area cohere with information from the gamma-gamma density logs of wells Well ER-5-3#2 and Well ER-5-4.

Density data from borehole gravity logs from wells 5a, U5i, UE11a, and UE5n contain density information to a depth no greater than 400 m. Though the gamma-gamma logs are not calibrated for unsaturated rocks, the data are consistent with the borehole gravity data, showing a similar increase in density with depth and a slightly lower median value.

Density values exist for surface samples from the area. Volcanic samples from Massachusetts Mountain and Mount Salyer, west of Frenchman Flat, have densities from 1,550 kg/m^3 to 2,710 kg/m^3, with a mean of 2,220 kg/m^3 (Carr and others, 1975). Paleozoic rock density measurements by Miller and Healy range from 2,480 to 2,840 kg/m^3, with an average of 2,680 kg/m^3 for saturated bulk density, while information from test well F, located in Wahmonie Flat, yields densities between 2,440 and 2,700 kg/m^3 with a mean of 2,550 kg/m^3, for Paleozoic dolomite (Miller and Healy, 1986). Unsaturated bulk densities for Cenozoic volcanic rocks in the vicinity of Frenchman Flat range from 1,350 to 2,550 kg/m^3, with a mean of 2,270 kg/m^3 (Miller and Healy, 1986).

Borehole gravity studies in Yucca Flat are consistent with the above values. Volcanic rock densities ranged from 1,400 kg/m^3 to 2,600 kg/m^3, with a median value of 2,200 kg/m^3, generally increasing in density with depth (Phelps and others, 1999).

This information demonstrates that the density profiles derived from the gamma-gamma logs from Well ER-5-3#2 and Well ER-5-4 represent a typical range of densities for the basin fill, while the basement density, 2,710 kg/m^3, is at the high end of the range of densities for other pre-Cenozoic rocks of the area.

DEPTH TO BASEMENT MODELS

Modeling the depth to basement depends on the density contrast between basement rock and basin fill. A method developed by Jachens and Moring (1990) separates the observed gravity into two components: that produced by dense basement rocks and that produced by less dense overlying basin-filling deposits. The latter component is directly inverted in order to provide the thickness of deposits. The density of basement rocks is allowed to vary horizontally, whereas the density of basin-filling deposits is forced to vary vertically according to the specified density profile. The dense basement rocks are inferred to be pre-Cenozoic rocks, based on the observed density values discussed in the previous section, which are generally about 400 kg/m^3 higher than the overlying Cenozoic deposits. Information on the depth to pre-Cenozoic rocks at known locations, e.g. wells, can either be incorporated into the modeling process to pin the model depth at the location or withheld from the model input and used as an independent check of the model.

For the initial estimate of depth, based on Well ER-5-3#2, three models of depth to pre-Cenozoic rocks were created. In each model the known depth to Paleozoic rock, 1425 m at Well ER-5-3#2, was not incorporated in the calculation, but instead was used as an independent test to estimate the accuracy of the model. In contrast, for the final model the known depth at Well ER-5-3#2 was used to pin the basement at the data point.

The first model used the density profile obtained from Well ER-5-3#2, using median values in four different intervals to approximate the change in density with depth (fig. 4). Though the density profile matched the density data derived from Well ER-5-3#2, the resulting model yields an estimated depth of 900 m, underestimating the recorded depth of the basement at Well ER-5-3#2 by approximately 525 m.

The second model used a modified version of the first model, where the recorded density values were adjusted for possible low readings due to well rugosity, as indicated by caliper widths (fig. 5). These adjusted values resulted in a higher, slightly different density profile. On average, the density values were 140 kg/m^3 higher. The average value for the density of the basement was also increased by 50 kg/m^3, from 2710 kg/m^3 to 2760 kg/m^3. Increasing densities in the basin has the effect of increasing the estimated basin depth, whereas increasing the density of the basement decreases the estimate of the basement depth. The net effect increased the estimated depth at Well ER-5-3#2 by 50 m, for an estimated depth of 950 m. This model underestimated the depth of the basement at Well ER-5-3#2 by approximately 475 m.

The third model was created by increasing the density profile of the Cenozoic deposits (fig. 4) uniformly, until the model gave a predicted depth close to that recorded in Well ER-5-3#2. This back-calculated density profile was 0.20 kg/m^3 higher than recorded by the gamma-gamma log, and gave a predicted depth at Well ER-5-3#2 of 1,440 m, in close agreement with the recorded depth of 1425 m. This model was created assuming that greater opportunity existed for errors in the density profile of the basin filling units and basement density than for error in the geologists' lithologic descriptions and corresponding depth locations recorded at Well ER-5-3#2. The density profile was modified until the model matched the results of the lithologic determination of the depth to pre-Cenozoic rocks at Well ER-5-3#2, rather than adhering strictly to the density profile derived from the gamma-gamma log.

There is a discrepancy between the first two models and the third model. The first two models rely on the measured density profiles, which caused each model to underestimate the depth of the basin at Well ER-5-3#2. The third model relies on the measured depth at Well ER-5-3#2, and requires a density profile well above that which was measured. This discrepancy between the models forces a choice between apparently contradictory information, indicating that the model assumptions have been violated. Without further knowledge of depth or density one relies on expert opinion to choose the most reasonable model.

Well ER-5-4 allows us to examine a second deep density profile and helps us resolve the contradiction posed by the previous models. The final model uses the density profile at Well ER-5-4, and pins the model depth at Well ER-5-3#2. Though the lithologies at the two wells differ, their density profiles are in reasonable agreement, supporting the assumption of a consistent density-depth relationship. The density profile at Well ER-5-4 was used, rather than an average between the two, because Well ER-5-4 is very close to the region of interest, the deepest part of the basin, and is likely to be the best estimate of the density profile for that region. Knowing that this model does not fit the region surrounding Well ER-5-3#2, we can pin the depth at that point to force the model to fit the data point. This has the additional benefit of allowing us to examine the residual gravity at that point, which tells us something about how the local geology deviates from our model assumptions.

RESULTS

The depth to pre-Cenozoic rock is shown in figure 7, and the elevation above sea level for the estimated basement surface is shown in plate 1. Frenchman Flat does not show the complex horst and graben structure of its northerly neighbor, Yucca Flat. This difference is not simply due to the lower number of gravity stations in Frenchman Flat compared to Yucca Flat. While Frenchman Flat does have significantly fewer numbers of gravity stations, several lines of closely spaced stations cross the basin (for example, near Well ER-5-4, densely-spaced gravity stations line up every 45 degrees). If a horst and grabben structure similar to that in Yucca Flat existed beneath the surface of Frenchman Flat it would be seen on at least one of these lines. Instead the model of Frenchman Flat defines a northeast-trending oval basin that deepens to the northeast and narrows to the southwest, with only the suggestion of a possible north-south high between the two deepest parts of the basin.

The deepest part of Frenchman Flat basin is 2.4 km deep and is located south of Well ER-5-3#2 and northeast of Well ER-5-4. Basement is nearly that deep, 2.1 km, at the site of Well ER-5-4.

An unexpected result of the model occurs at the northwest edge of Frenchman Flat over Massachusetts Mountain (fig. 1, 7). The ridge of welded tuffs, primarily the Ammonia Tanks and Rainier Mesa tuffs, form a topographic high extending south into Frenchman Flat but are the site of a local gravity low. The data appear to be correct values, because, though the ridge has few gravity stations, the stations are consistent with each other and surrounding measurements. In addition, since anomalies of this sort can be caused by assuming too high a density value for the Bouguer correction, we examined a re-reduction of the gravity data and it did not significantly reduce the gravity low. The structural high that separates Frenchman Flat from the CP basin is northwest of Massachusetts Mountain under the alluvium of CP basin, not on the mountains themselves. This would indicate that the ridge is underlain by less dense material. One possibility is that the mountain is a very large slide block underlain by low-density basin fill sediments. However where such a slide block would have originated is not clear.

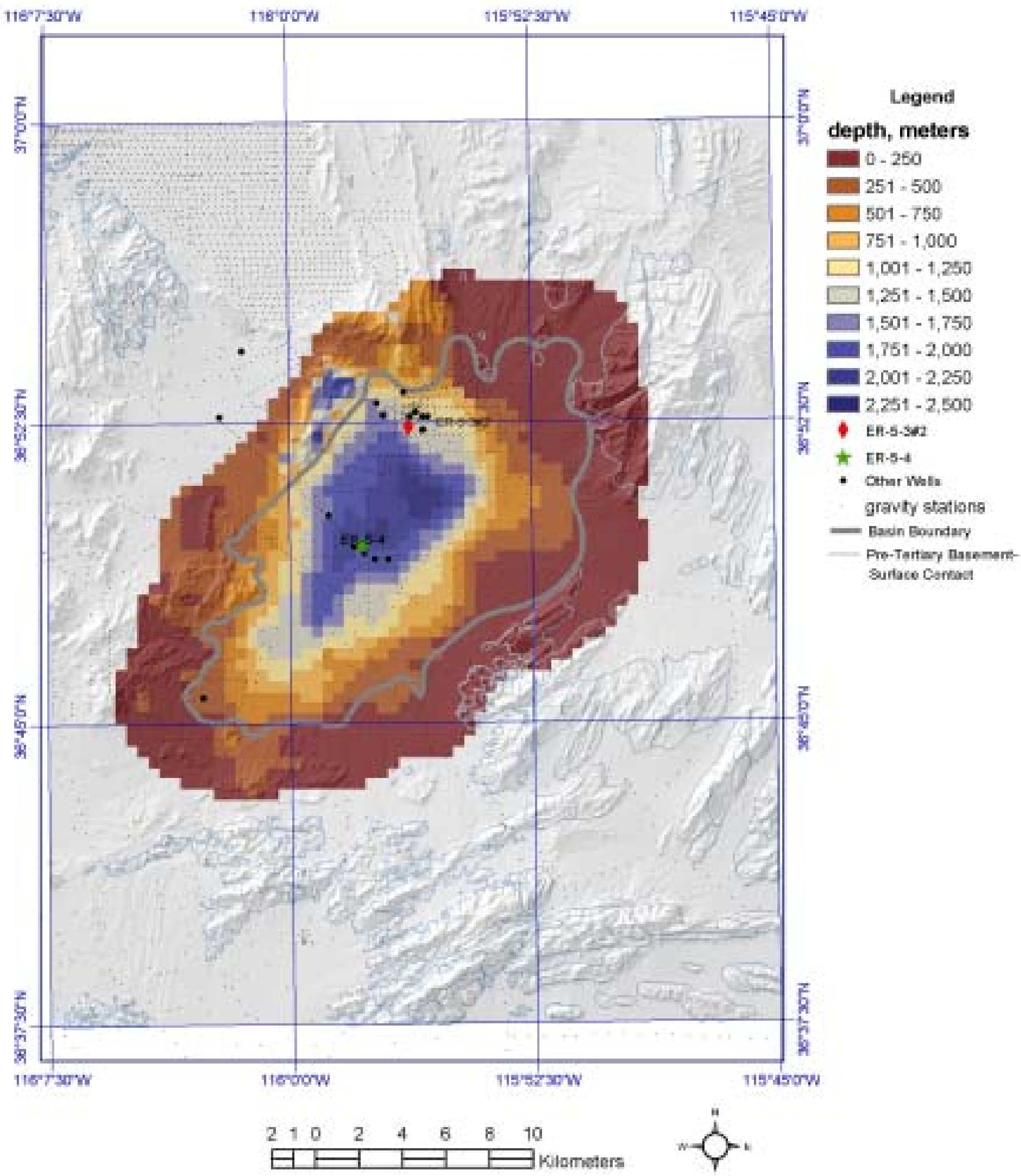

Figure 7. Depth to basement beneath Frenchman Flat.

DISCUSSION

The initial three models demonstrate the complications of the modeling process. Our gravity inversion assumes uniform density over large volumes, and therefore necessarily smoothes the resulting depth estimates. Sharp breaks in actual basement topography cannot be accommodated, and are smoothed into moderate slopes.

At Well ER-5-3#2 the assumptions of reasonably smooth basement topography and density, and laterally homogeneous, vertically stratified sediments, yield discrepant models; matching the recorded sediment density from geophysical log data causes the model to be too shallow, while matching the depth requires density values higher than recorded.

The former model could be the result of a poor estimate of the density of the rocks beneath Frenchman Flat or could occur if the assumption of smoothness is broken. The latter model would occur if the lithologic descriptions and corresponding depth locations in the log of Well ER-5-3#2 were incorrect. The choice of the third model was based upon the idea that an error in the lithologic descriptions and corresponding depth locations was less likely than an error in the density estimates, which could include overestimating the average density of the carbonates beneath Frenchman Flat and overestimating the average density of the basement rocks beneath Frenchman Flat, inability to account for rough basement surface topography, and the inability to account for an abrupt change in density of the basement rocks.

The modeled depth of the basin is affected by the density contrast between basin deposits and basement rocks, which in turn depends on the assumed value for the average pre-Cenozoic rock density. The median density for basement at Well ER-5-3#2 is 2710 kg/m^3 and 2760 kg/m^3 from the gamma-gamma log and the adjusted gamma-gamma log, respectively. While the consequences of such a change in the assumed value of basement density are difficult to predict due to the non-linear nature of the modeling process, the change can be on the order of 100 meters or more. Samples of pre-Cenozoic rocks, predominantly carbonate rocks, collected from outcrops have an average saturated bulk density of 2680 kg/m^3. Samples representative of the lithology of the pre-Cenozoic rocks that included more siliceous sedimentary rocks would likely drop the average density further.

The regional pattern of pre-Cenozoic outcrops suggests an average pre-Cenozoic rock density lower than that of the Paleozoic carbonate rocks. Paleozoic carbonate rocks are common east of Frenchman Flat, but less common west of Frenchman Flat, suggesting that pre-Cenozoic basement rocks change from more dense carbonates to less dense argillites and quartzites progressing westward across the Nevada Test Site (Stewart and Carlson, 1978). This suggests that the average density of rocks lies between that of the Paleozoic carbonate rocks and those of the Paleozoic and pre-Cambrian siliceous rocks.

A pre-Cenozoic rock density value of 2670 kg/m^3, commonly used in other studies in the vicinity of the Nevada Test Site (e.g. Carr and others, 1975; Miller and Healy, 1986), would likely represent the average pre-Cenozoic rock density across Frenchman Flat. It is probable that the single sample location for Paleozoic density beneath Frenchman Flat at Well ER-5-3#2 overestimates the average density for the Pre-Cenozoic basement.

Geologic factors may have contributed to a predicted depth shallower than the actual depth at the well. Well ER-5-3#2 is a single sample point of the depth of the basin in Frenchman Flat. Locally, if the well were drilled adjacent to a topographic offset in the pre-Cenozoic surface, e.g. on the down thrown side of a fault, the depth of the basin seen at the well would be deeper than predicted by the gravity inversion model, which tends to smooth sharp topographic discontinuities.

Based on these factors, the pre-Cenozoic basement density value used in the final model was 2670 kg/m^3. The density log from Well ER-5-4 was similar to that of Well ER-5-3#2, and therefore seemed the best choice for the final model. The model was pinned at Well ER-5-3#2 to force the model to match the data point so that depth estimates in that vicinity were not too shallow. While pinning the model at Well ER-5-3#2 ensures that the depth will be correct at the well, it cannot account properly for roughness in the basement surface. A consequence of this is that the model will not be able to properly account for a possible steep basement surface change and nearby depth estimates on the shallow side of an existing fault may be too deep.

UNCERTAINTY

The accuracy of the calculation of depth to pre-Cenozoic rock is dependent on many factors, including: the accuracy of the gravity measurements, the relative spacing of the measurements on the ground, the accuracy of the constraints and assumptions built into the reduction process (e.g. assuming an average crustal density of 2670 kg/m^3 for complete Bouguer and isostatic corrections), the assumption of uniformly dense, horizontal layers, the density constraints used in the inversion, and the interpolation algorithm used between the data points.

The primary source of uncertainty is the density-depth function used to calculate the thickness of the basin fill. To investigate the variation in the final model a sensitivity analysis (Hill, 1998) was performed. The model was perturbed systematically, and 1% scaled sensitivities were calculated for each model parameter (layer). The sensitivities represent the approximate change in depth resulting from a 1% change in the parameter (density) value. We can use them to gain insight into how the parameters quantitatively contribute to the model. However, the sensitivities do not scale; in other words, multiplying one result by 10 does not yield the exact amount the depth would change given a 10 percent change in density. This is because the model is non-linear, and so the values are valid only within a short range of the solution. Figures 8-11 show the 1% scaled sensitivities for the final model in Frenchman Flat. The largest range in sensitivity, indicating the largest overall influence on the model, occurs in the second layer, while the fourth layer has the greatest influence over the deepest part of the basin. Laterally the shallower layers of the model have a greater affect than the deeper layers. The deeper layers influence the deep part of the basin only; this follows from the simple fact that a layer cannot affect the model if the predicted depth is not deep enough to include the layer.

The general range of the sensitivity values is from a few meters up to 30 meters. This implies the model is fairly sensitive to density changes, since fluctuations of a few percent imply tens of meters fluctuation in the depth estimates.

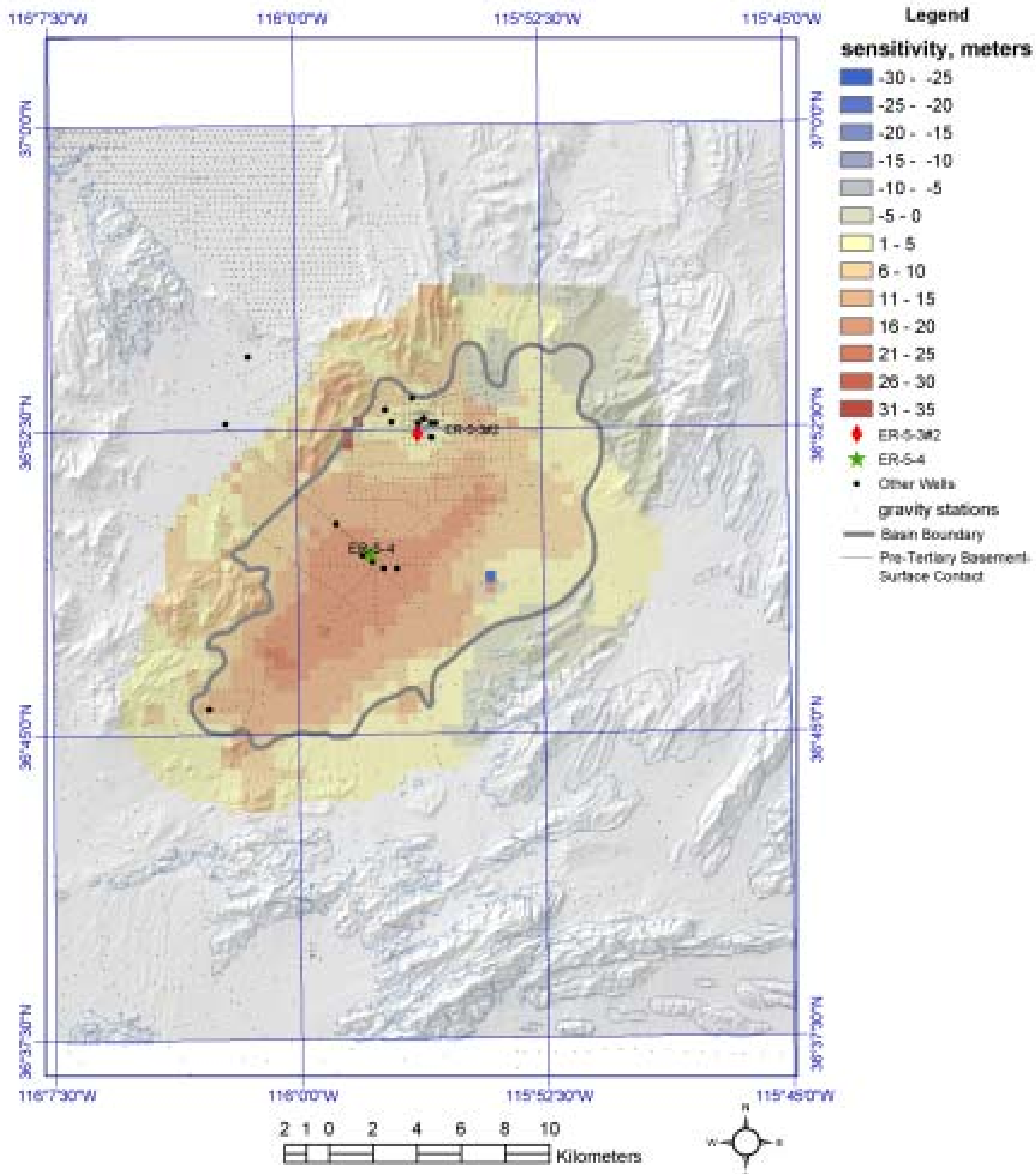

Figure 8a. 1% scaled sensitivity map for layer 1 of the final model. The color scale is the same for figures 8a-8d for ease of comparison. Note that each figure may not show the full range of colors in the legend.

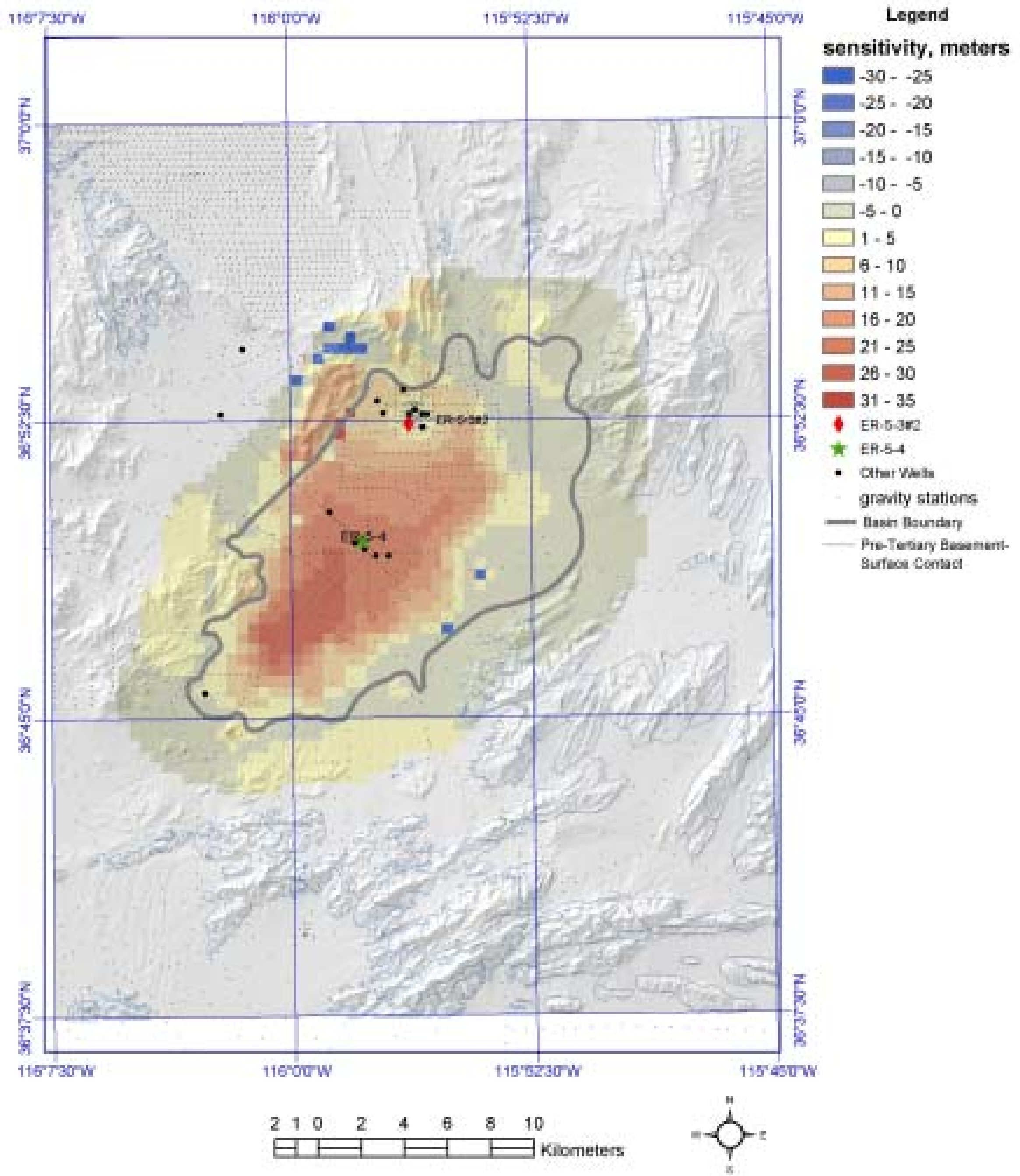

Figure 8b. 1% scaled sensitivity map for layer 2 of the final model.

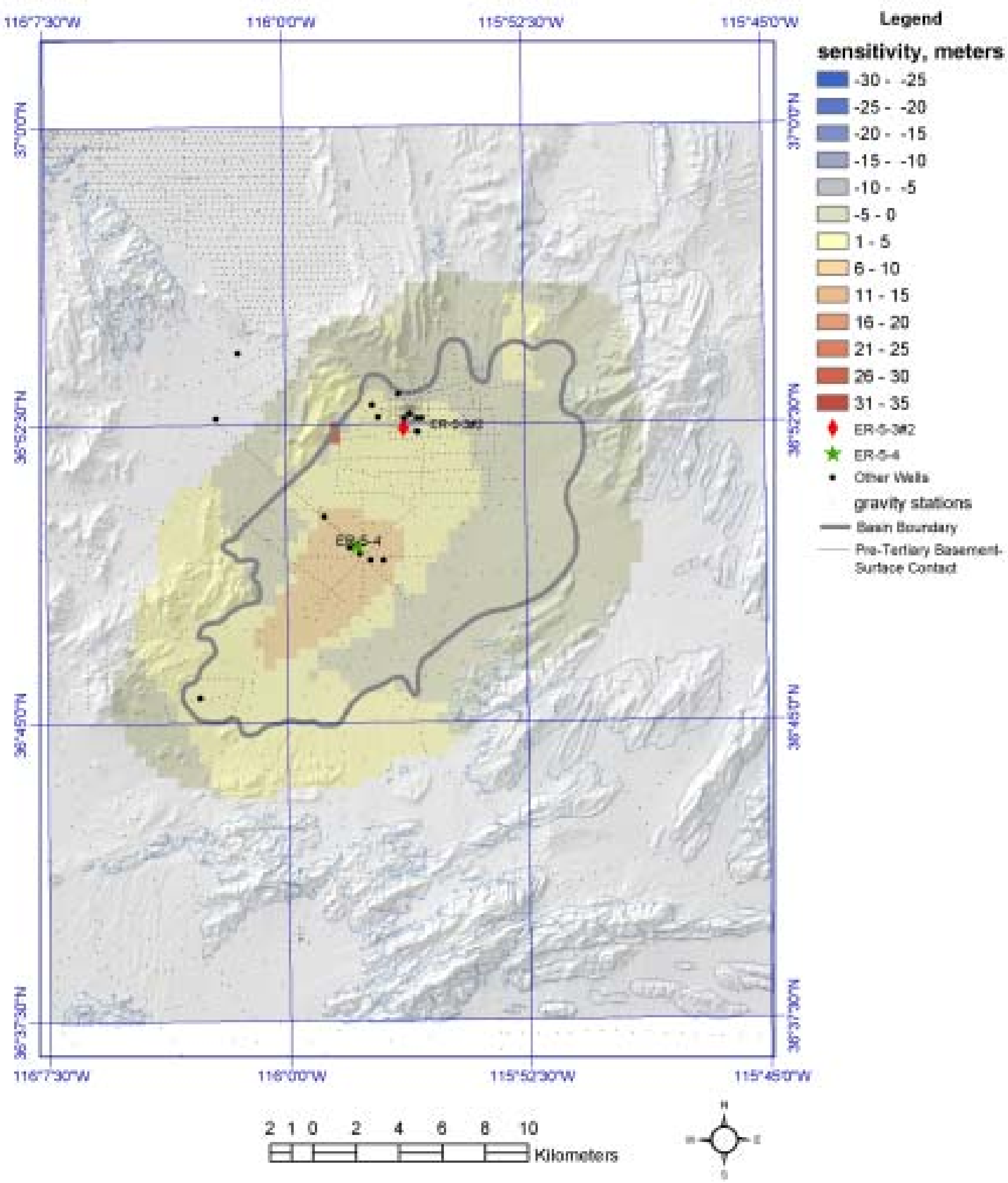

Figure 8c. 1% scaled sensitivity map for layer 3 of the final model.

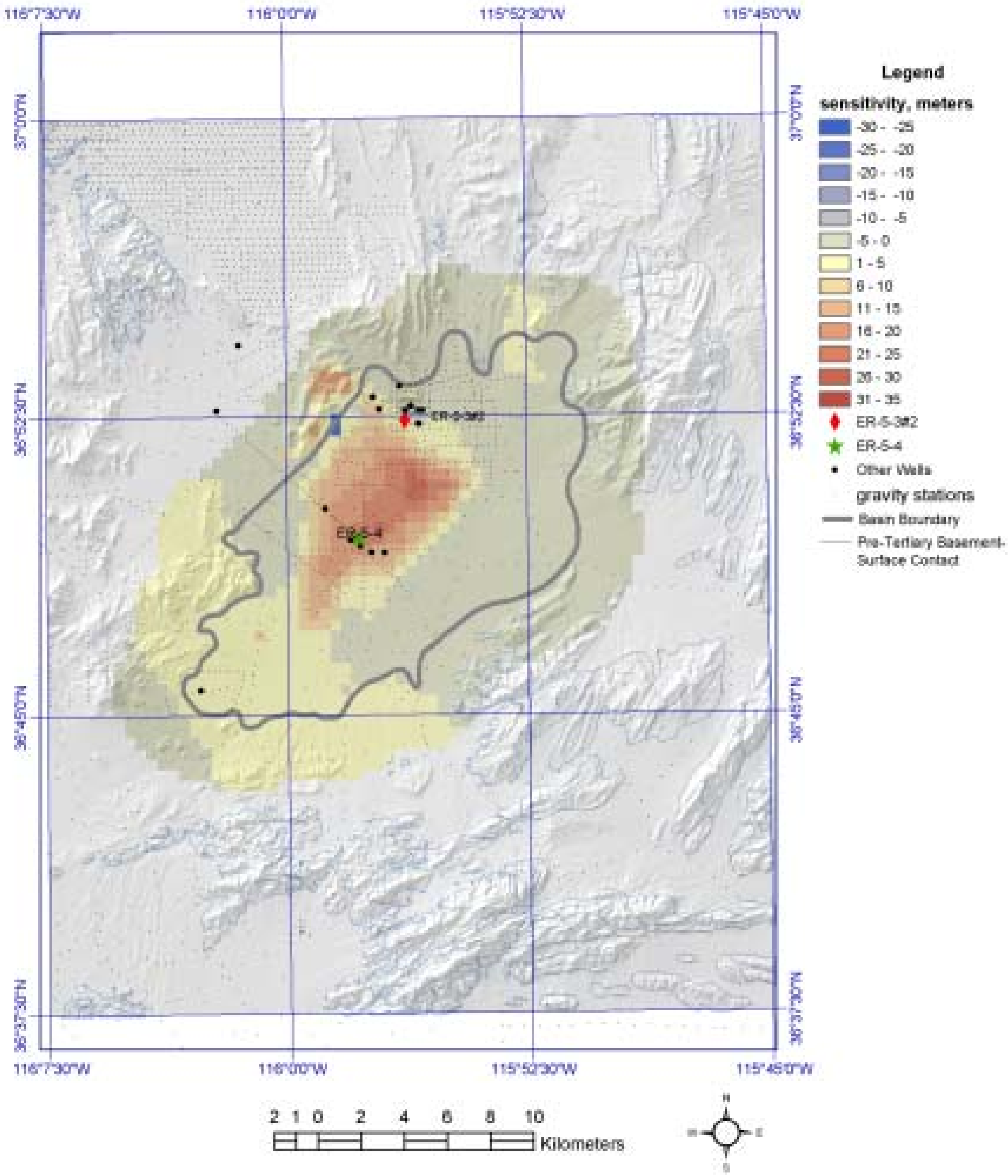

Figure 8d. 1% scaled sensitivity map for layer 4 of the final model.

Another source of uncertainty is the spacing of gravity observations across the area. Wide spacing between observations decreases the resolution of the prediction and increases the influence of anomalous data points. In Frenchman Flat, gravity observations are fairly evenly spaced, but do contain gaps up to 3 km. This spatial scattering was used to determine the resolution of the model. Though no formal method exists to determine the appropriate resolution of a grid based on scattered data (M.F. Goodchild, personal communication, 2000), using a spacing that captures most of the data seems reasonable. In Frenchman Flat a distance of 500 m between grid points allows most of the basin to be gridded with no more than two interpolated values between data points.

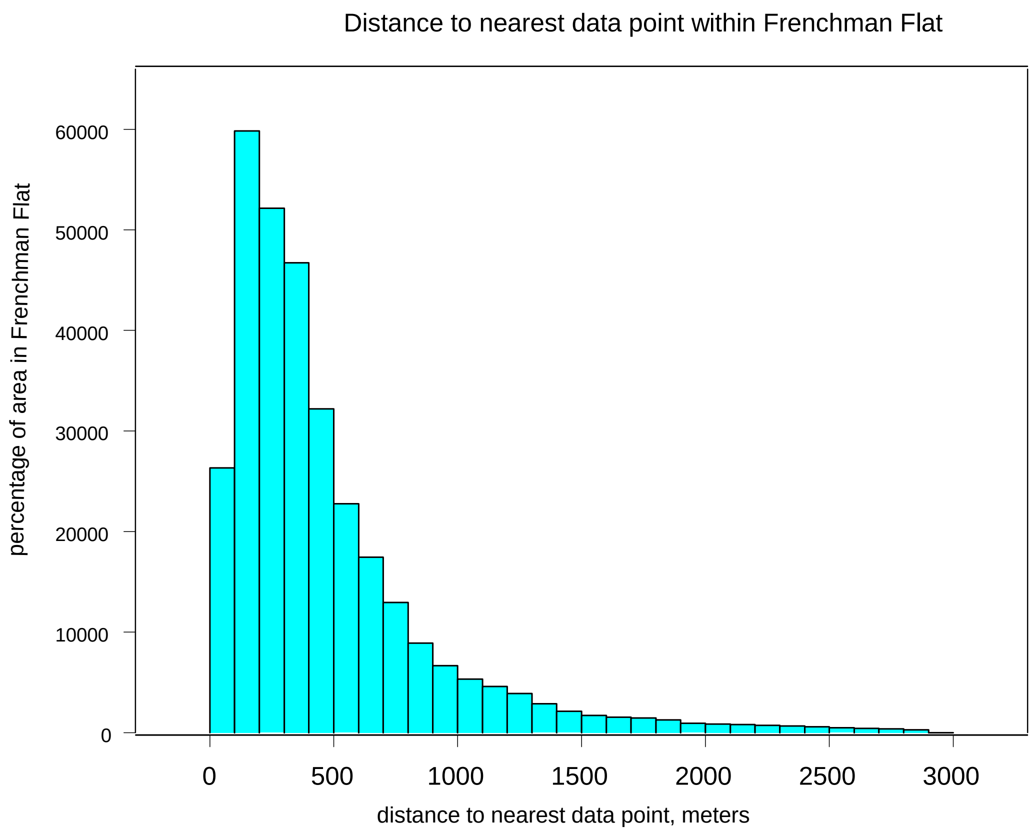

Figure 9. Area within Frenchman Flat that is a given distance from the nearest gravity stations.

This is important, because cells without associated data points rely exclusively on the interpolation algorithm for their value, and different interpolation algorithms can give varying results (see, for example, Phelps and others, 1999). Increasing the resolution of the model (decrease in cell width to less than 500 m) would give increasing influence to the interpolation algorithm. An interpolation algorithm that does not capture the regional or local variation in the data will give a poor estimate of the surface at the regional or local scale. In this investigation we tried to optimize the use of the data, while not pushing it beyond its limits. The distribution of area in Frenchman Flat that is a particular distance from the nearest data point is shown in fig. 9. Ninety percent of the area is within 1 km of the nearest data point.

CONCLUSION

The depth of the basin in Frenchman Flat is estimated using a gravity inversion model. Based on two gamma-gamma density logs, from Well ER-5-3#2 and Well ER-5-4, four different density profiles for overlying basin-fill were used to create four different estimates. The preferred model used a density profile that approximated the density measured in the gamma-gamma logs from Well ER-5-4. The density of the basin-fill was increased near the bottom of the profile so that the model was consistent with regional geologic observations. The model predicts a northeast trending basin with a depth of roughly 2 kilometers, 2.4 kilometers in the deepest part of the basin. The model was pinned at Well ER-5-3#2 so that the estimated depth matched the measured depth at the well. The depth estimate for this model at Well ER-5-4 is 2.1 kilometers. Sensitivity analysis indicates that a 1% change in a model parameter will change the estimated depth by up to 30 meters. 90% of the model output depths are within 1 kilometer of a gravity data point, which justifies a horizontal resolution of 500 meters for the model.

FUTURE WORK

Multiple lines of converging evidence rather than single source investigations better delineate structures such as Tertiary and Quaternary faults. A high-resolution aeromagnetic survey, for example, would delineate subsurface faults that offset magnetic volcanic rocks, where they occur, and show where these volcanic units pinch out below the surface of the basin. In conjunction with this information the gravity and basement gravity could be used as weaker evidence to determine the extent of the faulting. The studies, combined with seismic information, would help identify the amount and location of Tertiary faulting in the basin and would provide information on the accuracy of the assumption of smoothly varying basement topography. A 3D seismic survey was recently conducted over part of the basin. This report, in progress, will help delineate the local structure of the basin over a 40 square km area in the north and central part of the basin.

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