Grande Ronde Basalt across the Kamiak Gap: the Gravity Model Revisited using Constraints from the DOE Butte Gap Monitoring Well.[1]

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Abstract

The primary aquifer for storage and transport of groundwater in the Palouse groundwater basin is the Grande Ronde basalt. Within the Palouse basin the northern community of Palouse is connected to the southern cities of Pullman and Moscow through the Kamiak Gap, a topographic opening between Kamiak Butte on the west and the Ringo and Angel Buttes on the east. Uncertainty in the hydrologic connection of the Grande Ronde basalt through the Kamiak Gap has adversely affected efforts to manage the regional groundwater system. Holom (2006) conducted gravity measurements across the Kamiak Gap and presented a geophysical model concluding that the Grande Ronde basalt is not continuous through the Kamiak Gap. However, Conrey et al. (2013) has published new test well data that we use to impose constraints on the interpretation of the gravity data published in Holom (2006). We propose a new geophysical model suggesting that the Grande Ronde basalts are indeed continuous through the Kamiak Gap with a net thickness in excess of 100 m. Thus, Kamiak Gap should not create a hydraulic barrier to north-south groundwater flow. However, we note that the surface drainage divide actually lies between Kamiak Gap and Palouse, in an area north of the gravity control of Holom (2006). If a basement uplift is associated with this steam divide, the Grande Ronde basalt might thin at that

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location, creating a hydraulic barrier. More gravity stations north of Kamiak gap are needed to resolve that question.

Introduction

The Palouse groundwater basin (Figure 1) is approximately 1500 km^2 in extent and serves as the main water supply for Washington communities of Pullman, Colfax, and Palouse and their environs as well as Moscow, Idaho and its environs (Holom, 2006). The primary aquifer is the Grande Ronde basalt and recent studies suggest that its water level has been declining at a rate of approximately 30 to 45 cm/annum for the last four decades (Owsley, 2003). To be successful, future aquifer recharge strategies will require knowledge of the extent and hydrologic continuity of the Grande Ronde basalts throughout the Palouse groundwater basin. To this end, Holom (2006) conducted a gravity survey (Figure 2) to ascertain the continuity of the Grande Ronde basalt through the Kamiak Gap between the cities of Palouse in the north and Pullman/Moscow to the south. The subsequent model produced by Holom (2006) suggested that the Grande Ronde is not continuous through the Kamiak Gap.

The stratigraphy of the Kamiak Gap (Figure 3) consists of a surface covering of loess and Bovill clays of the Latah Formation underlain by approximately 50 meter thick basalts of the Priest Rapids Member of the Wanapum Basalt (Holom, 2006; Conrey et al., 2013). Below the Wanapum basalts are approximately 40 meter thick sedimentary interbeds of the Latah Formation consisting of variable extents of clay, sand, and gravel; this formation is considered to be equivalent to the Vantage Member of the Ellensburg Formation located in central Washington (Holom, 2006; Conrey et al., 2013). Sandwiched between the Latah (Vantage) sedimentary interbed above, and the crystalline igneous granites and metamorphic quartzite basement rocks below, is a variable thickness of Grande Ronde basalt consisting of, at least, the R2 units of Meyer Ridge and Grouse Creek (Holom, 2006; Conrey et al., 2013).

Recently Conrey et al. (2013) has published data for a Department of Ecology (DOE) test well drilled in the Kamiak gap (Figure 3) that provides constraints for the thicknesses and elevations of the stratigraphic units in the Kamiak Gap. The stratigraphy of the DOE Butte Gap well, drilled at the latitude of the southernmost east-west transect of the Holom (2006) study, is remarkably similar to the stratigraphy of the Palouse City #3 well drilled to the north of the Kamiak Gap (Conrey et al., 2013). This suggests that the tops of the Wanapum, Latah (Vantage) interbed, and Grande Ronde stratigraphic layers may be flat through the Kamiak Gap which leads to simplifying assumptions in a gravity model for the gap. The Holom (2006) gravity model interpretation relied upon seemingly random undulations in the tops of the Wanapum, Latah (Vantage) interbed, and Grande Ronde tops without supporting geologic evidence. We present a gravity model using the gravity survey data of Holom (2006) with geology constrained by the DOE Butte Gap and the Palouse City #3 wells.

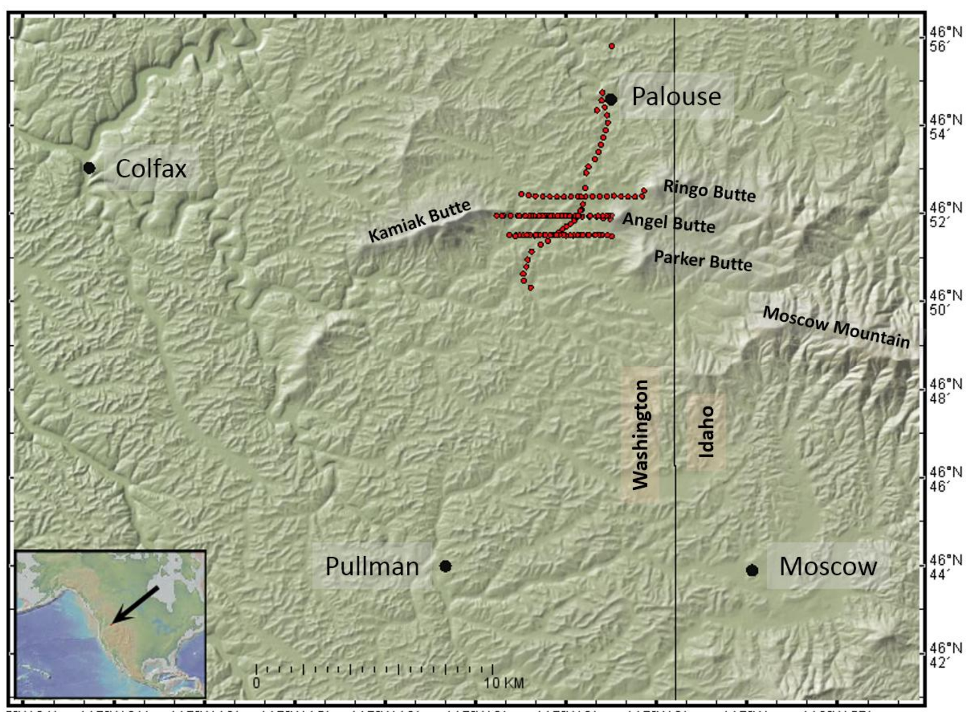

Figure 1. Area map of the Palouse groundwater basin. The red dots are the gravity survey points of Holom (2006) in the Kamiak Gap. Figure generated with GeoMapApp (Ryan et al., 2009).

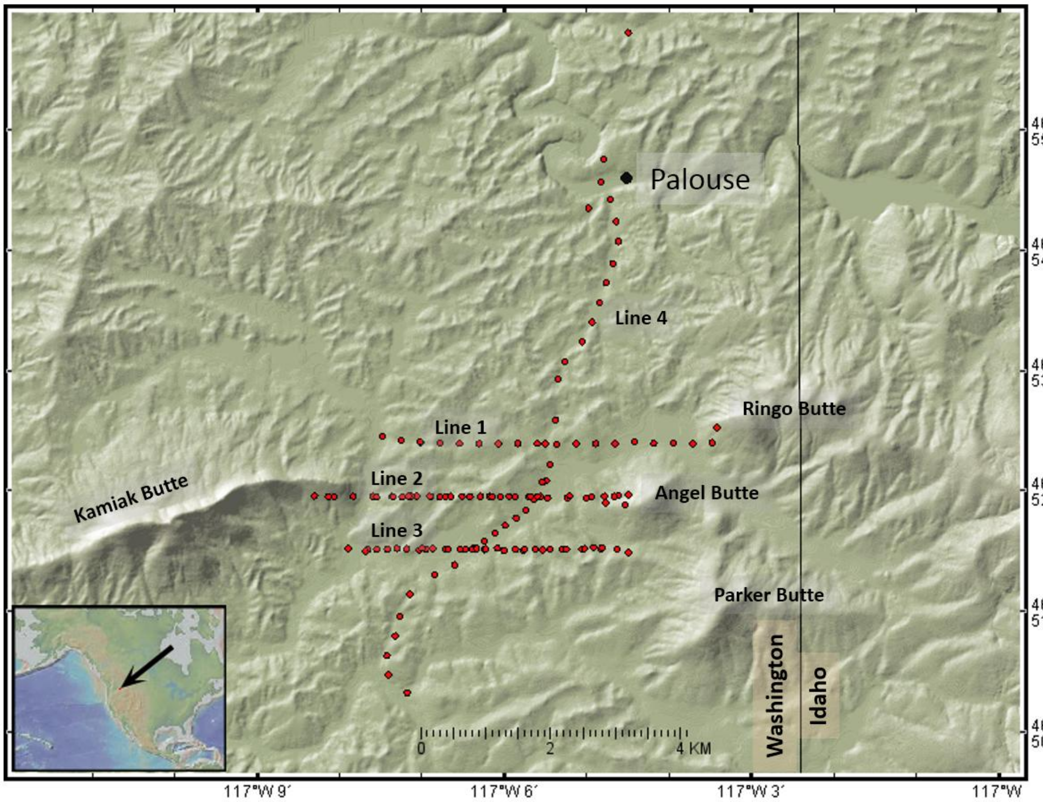

Figure 2. Blowup of gravity survey area in the Kamiak Gap. Lines 1, 2, and 3 are east-west transects across the gap and Line 4 meanders approximately north-south crossing the other three lines. The east end of Line 1 terminates in the bedrock of Ringo Butte. The western terminus of Line 2 is in the bedrock of Kamiak Butte whilst the eastern terminus is in the bedrock of Angel Butte. None of the other line termini are in bedrock. Figure generated with GeoMapApp (Ryan et al., 2009).

Methodology

Introduction

Holom (2006) conducted a gravity survey of 133 points in the Kamiak Gap (Figure 2). This included three east- west transects across the valley, designated Lines 1, 2, and 3 from north to south respectively, and one long meandering north-south transect, designated Line 4, crossing the three east-west transects. To avoid introducing new variables, our study presumes that the Holom (2006) procedures, from collection of raw data to removal of regional trend, are correct. We also use the same values for bulk densities of the various units present. However, we use stratigraphy from the recently drilled DOE Butte Gap monitoring well, located in the Kamiak Gap at the latitude of Holom's (2006) Line 3, along with the stratigraphy of Palouse City #3 well to produce a new geophysical model, constraining the thicknesses of the subsurface beds above the Grande Ronde to be consistent with the two wells (Conrey et al., 2013). This last step, the simplest method of correlating the two wells, is in sharp contrast to the interpretation of Holom (2006) who invoked arbitrary and random variations in the Wanapum, Latah (Vantage) and soil thicknesses above the Grande Ronde, unsupported by any geological evidence, to force a fit between the gravity data and their interpretation of Grande Ronde thickness through the gap.

Figure 3 depicts the stratigraphy at two well sites; Pa #3 is Palouse City #3 well near the city of Palouse north of the Kamiak Gap, and Butte Gap is the DOE test well at the intersection of Line 3 and Line 4 in the Kamiak Gap (Conrey et al., 2013). The elevations of the respective beds is remarkably similar with the top of the Wanapum basalt at approximately 754 m MSL, the top of the Latah (Vantage) sediments at approximately 704 m MSL, and the top of the Grande Ronde basalt at approximately 662 m MSL. These elevations are used as simplifying constraints on the geophysical model throughout the Kamiak Gap and, barring more detailed knowledge of the regional geology, they are reasonable elevation assumptions. With the thickness of the overlying loess sediments being determined by the difference in the elevation of the top of the Wanapum basalt (754 m MSL) and the measured surface elevation at each gravity survey point, the only remaining variable in the gravity model is the thickness of the Grande Ronde basalt down to basement. Our models use the same density values for the geologic units as used by Holom (2006).

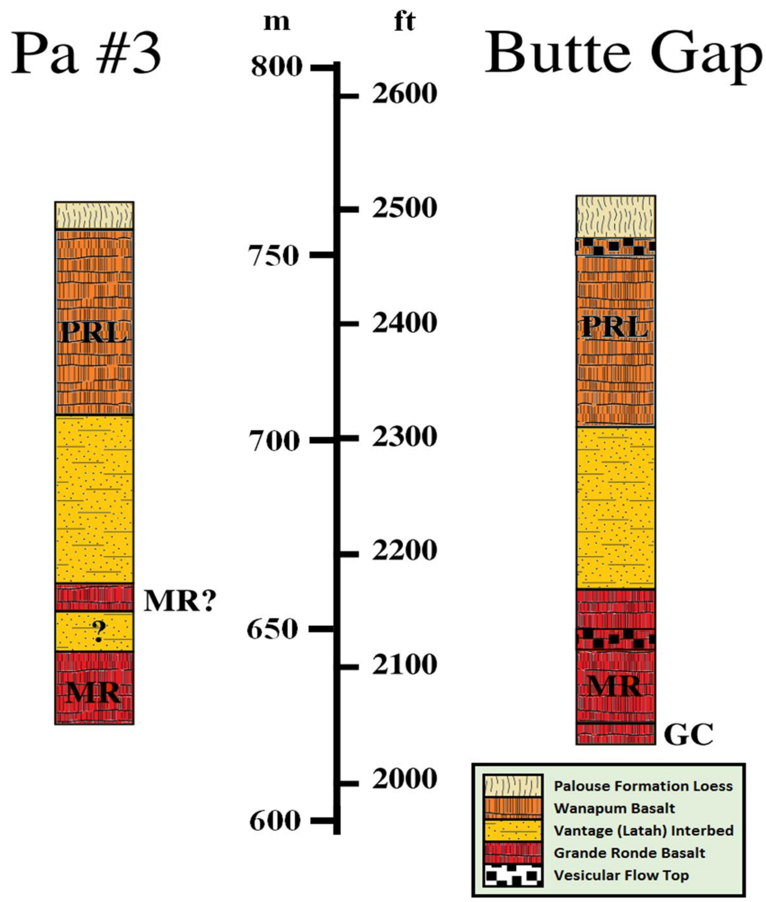

Figure 3 (modified from Conrey et al., 2013). Pa #3 is the Palouse City #3 well. Note its similarity to the DOE Butte Gap well as noted by Conrey et al. (2013). The top tan unit is soil (loess and Bovill clays). The checkered units are weathered vesicular basalt flow tops in both the Wanapum basalt and Grande Ronde basalt. PRL is the Priest Rapids Member of the Wanapum basalt, the yellow unit is the Latah (Vantage) interbed, mostly sand with variable gravel and clay. The lower red units are the Meyer Ridge and Grouse Creek units of the Grande Ronde R2. In both wells the top of the Wanapum Basalt is at approximately 754 m, the top of the Latah (Vantage) interbed is at approximately 704 m, and the top of the Meyer Ridge unit of the Grande Ronde at approximately 662 m.

Simple Bouguer Slab Model

First we analyze the stratigraphy found in the DOE Butte Gap well in terms of its bulk density and its effect on the gravity field. In this way we can isolate that part of the gravity anomaly that is due only to our target—the thickness of the Grande Ronde unit. We will call this reduced gravity the Grande Ronde anomaly. For example, if no Grande Ronde is present, the Grande Ronde anomaly would be zero. If the Grande Ronde is present, the Grande Ronde anomaly would be negative (because the Grande Ronde has a negative density contrast compared to the surrounding country rock).

The new DOE Butte Gap monitoring well is at the intersection of Holom's Lines 3 and Line 4. This well provided the information we needed to correct the residual gravity for the flows and sediments above the Grande Ronde. The gravity attraction of a wide-spread horizontal geological unit of constant thickness can be calculated by the Bouguer slab formula:

$$\Delta gB = 2\,\pi\, G\rho\, h$$

where G is Newton's constant, ρ is the density contrast with the surrounding country rock, and h is the thickness of the unit. In convenient units this formula is

$$\Delta gB = 0.04189\ \rho\ h$$

where ρ is in g/cc and h is in meters and the result is in mGal. The Bouguer slab formula takes advantage of the fact that most of the gravity effect of an infinitely wide slab is due to the mass relatively close to the gravity measurement.

Next, we apply Holom's densities to the well log of the DOE Butte Gap well (Conrey et al., 2013). The gravity effect of each unit is shown in Figure 4 as calculated by the Bouguer slab formula. The total gravity effect of the units above the GR is -2.06 mGal. However, the residual gravity at this location is about -4.9 mGal, so there is a difference of -2.84 mGal of unexplained gravity anomaly at this location. We call this the Grande Ronde anomaly. Using the Bouguer slab formula, the thickness of the Grande Ronde at this location must be at least 251 m. The well penetrated 43 m of Grande Ronde before drilling stopped.

For our conceptual model and using Holom densities, the Grande Ronde Anomaly at any station is:

$$\Delta g = CBA - RT + 0.0595\ (Elev\ -754) + 0.996$$

where CBA = Complete Bouguer Anomaly (mGal), RT = Regional Trend (mGal), and Elev = Gravity Station Elevation (m AMSL). Where Δg is positive, the Grande Ronde is absent and portions of the units above it have lapped on to crystalline basement rocks. Where Δg is negative, the Grande Ronde may exist.

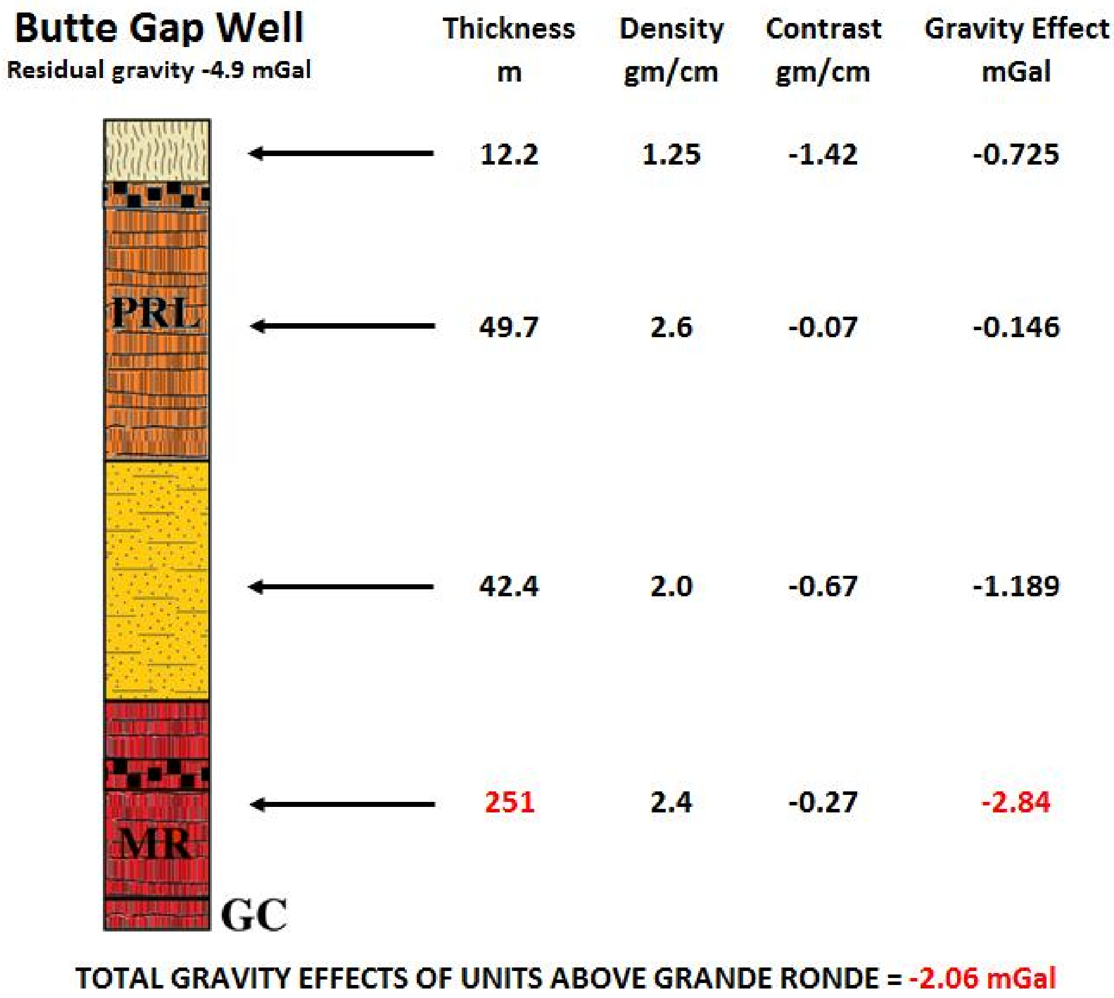

Figure 4. The bulk density, density contrast with respect to country rock, and gravity effect of each unit present in the DOE Butte Gap well. The stratigraphy above the Grande Ronde accounts for a net gravity effect of -2.06 mGal. See Figure 3 for description of units.

The map of the Grande Ronde anomaly (Figure 5) shows the gravity effect of the Grande Ronde unit in the Kamiak Gap, after correction for the thicknesses of loess, Wanapum, and Latah (Vantage) units as observed in the DOE Butte Gap and Palouse City #3 wells. Grande Ronde basalt can exist only within the 0 contours. Outside this boundary, the Grande Ronde anomaly is positive indicating that basement surface has risen above the 662 m AMSL level found in the DOE Butte Gap well. Note that the Grande Ronde anomaly is negative continuously across the gap indicating that the Grande Ronde unit is present. This is in contrast to Holom's interpretation of a barrier at Line 1. The red dots on Figure 5 are the gravity stations observed by Holom (2006). Had another east-west line of gravity observations been made north of Line 1 in the vicinity of the surface drainage divide (dashed line, Figure 5), we would be much more confident of the continuity of the Grande Ronde unit to the north of the Kamiak gap across the drainage divide. The question mark on Figure 5 indicates the area where more gravity station control is needed to resolve this question.

The minimum thickness H of the Grande Ronde unit near the center of the gap can be estimated using the Bouguer slab formula:

$$H = -\Delta g \,/\, 2\,\pi\rho\, G = -88.4\,\Delta g$$

where H is in meters, Δg is the Grande Ronde anomaly in mGal, and ρ is the density contrast between the Grande Ronde unit and the surrounding basement rocks (-0.27 g/cc). A map of this minimum thickness through the Kamiak gap (Figure 6) shows that the Grande Ronde thins across the gap toward the north but remains at least 120 m thick at its thinnest point on Line 1. Once again, this refutes Holom's (2006) interpretation which shows no Grande Ronde at all on Line 1. Thus the gravity data suggests that the Grande Ronde is continuous through the gap with sufficient thickness for groundwater flow. However, Figure 6 clearly shows that considerable uncertainty exists for the continuity of the Grande Ronde across the drainage divide north of the Kamiak gap. As with Figure 5, the question mark on Figure 6 indicates the area where more gravity stations are needed.

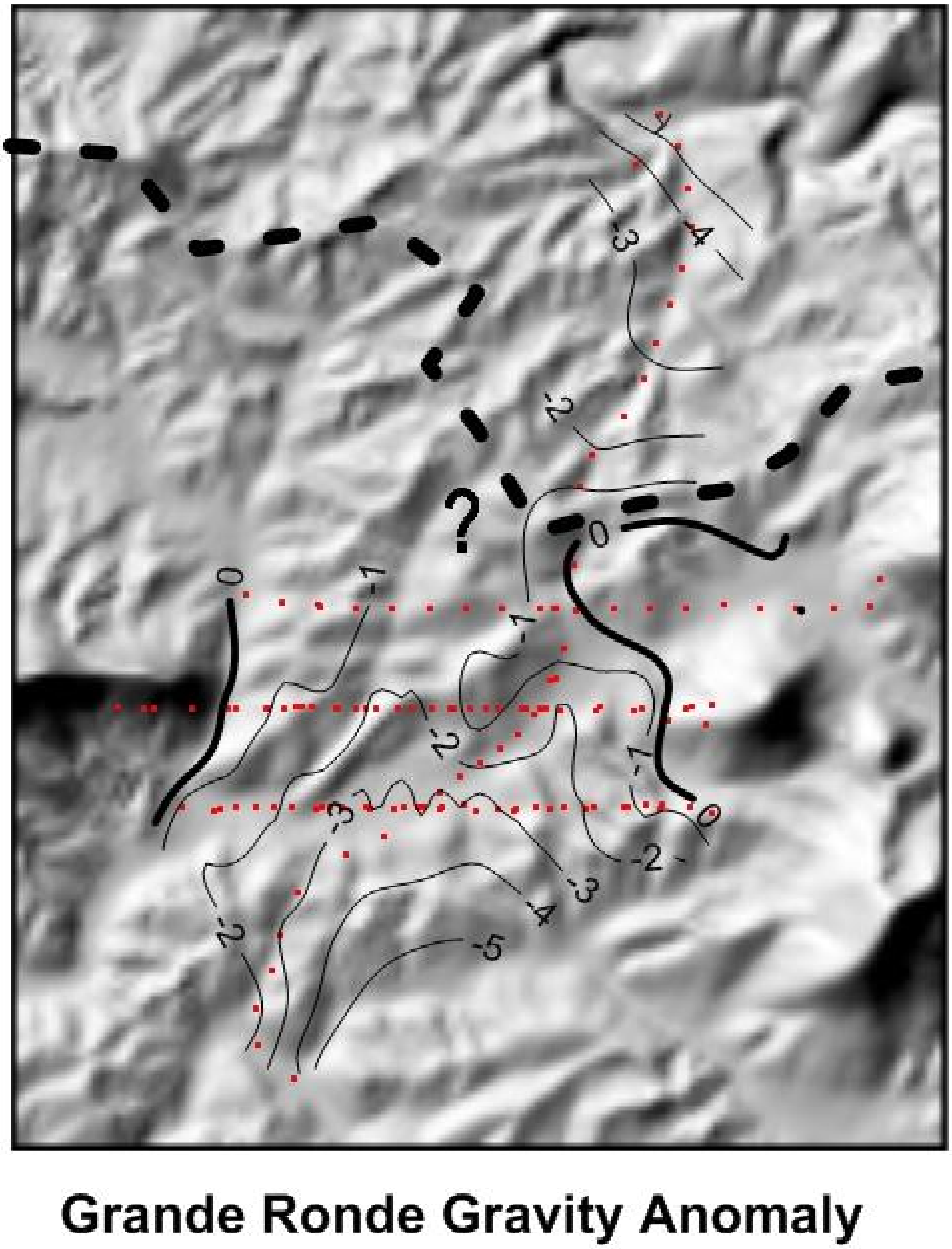

Figure 5. Grande Ronde anomaly in mGals. Contour interval is 1 mGal. This map represents the gravity effect of the Grande Ronde unit in the Kamiak Gap, after correction for the thicknesses of loess, Wanapum, and Latah (Vantage) units as observed in the DOE Butte Gap and Palouse City #3 wells. The Grande Ronde is present if this anomaly is negative. The red dots are gravity stations observed by Holom (2006). The dashed line is the surface drainage divide. The question mark indicates the area where more gravity station control is needed.

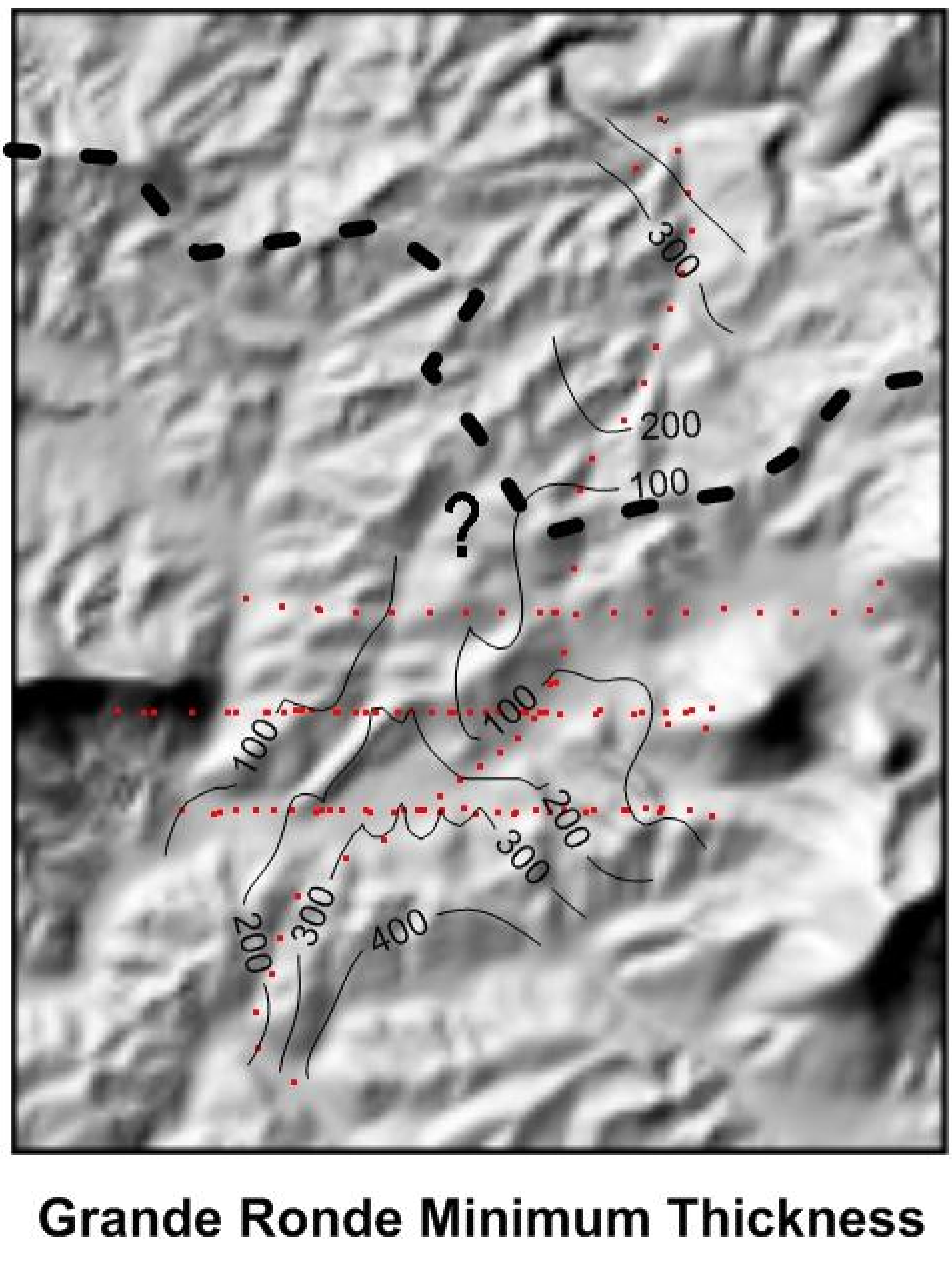

Figure 6. Minimum thickness in meters of the Grande Ronde unit across the Kamiak Gap. Contour interval = 100 m. This map is based on the simple Bouguer slab formula. It provides minimum thicknesses in the center of the gap but overestimates thicknesses near the edges. See the two-dimensional modeling results (Figures 7, 8, 9) for more accurate thickness estimates along the east-west gravity lines. The red dots are gravity stations observed by Holom (2006). The dashed line is the surface drainage divide. The question mark indicates the area where more gravity station control is needed.

Two-Dimensional Gravity Modeling

The Bouguer slab approximation described above is useful only to give a minimum thickness at the center of the gap. A better estimate of the actual Grande Ronde thickness can be obtained by two-dimensional gravity modeling. The three east-west gravity survey lines from Holom (2006) were processed for our model using the GravCad two-dimensional modeling program written by Steven D. Sheriff of the University of Montana. This program allows multiple polygons of designated densities to be depicted. The sinuous north-south Line 4, clearly not in a two-dimensional relationship to the geology, was processed only to ensure reasonable ties between the east-west lines. All lines were modeled using the density estimates of Holom (2006), with overlying loess from 754 m MSL to surface elevation with a density of 1.25 gm/cm^3, Wanapum basalt from 704 – 754 m MSL with a density of 2.60 gm/cm^3, Latah (Vantage) sediments from 662 – 704 m MSL with a density of 2.00 gm/cm^3. The Grande Ronde basalt density was modeled at 2.40 gm/cm^3 and the basement at 2.67 gm/cm^3.

In our modeling, our primary assumption was that the basement topography should change smoothly across the gap resulting in longer wavelength gravity anomalies. Thus we made no attempt to model local short wavelength changes in the gravity measurements from station to station. These local discrepancies are easily explained by nearby changes in soil density, thickness, or water content. Thus our modeled gravity lines are calculated to fit the overall shape of the gravity observations, which in turn, we assume to be representative of the overall basement shape.

Discussion

Line 1

Holom (2006) concluded that Line 1 did not include Grande Ronde basalt and therefore the Grande Ronde aquifer was not continuous through the Kamiak Gap. However, as can be seen in Figure 7, our two-dimensional model suggests there is a significant channel of Grande Ronde basalt up to approximately 125 meters in thickness west of the Line 4 intersection. The westernmost point on Line 1 lies in a valley parallel to and less than 1 km north of the east-west trending ridge of Kamiak Butte. As Line 1 extends east towards the intersection of Line 4 it approaches the northern slopes of Angel Butte and continues on to terminate at the bedrock of Ringo Butte. Apparently, there is shallow crystalline bedrock in the vicinity of these two buttes.

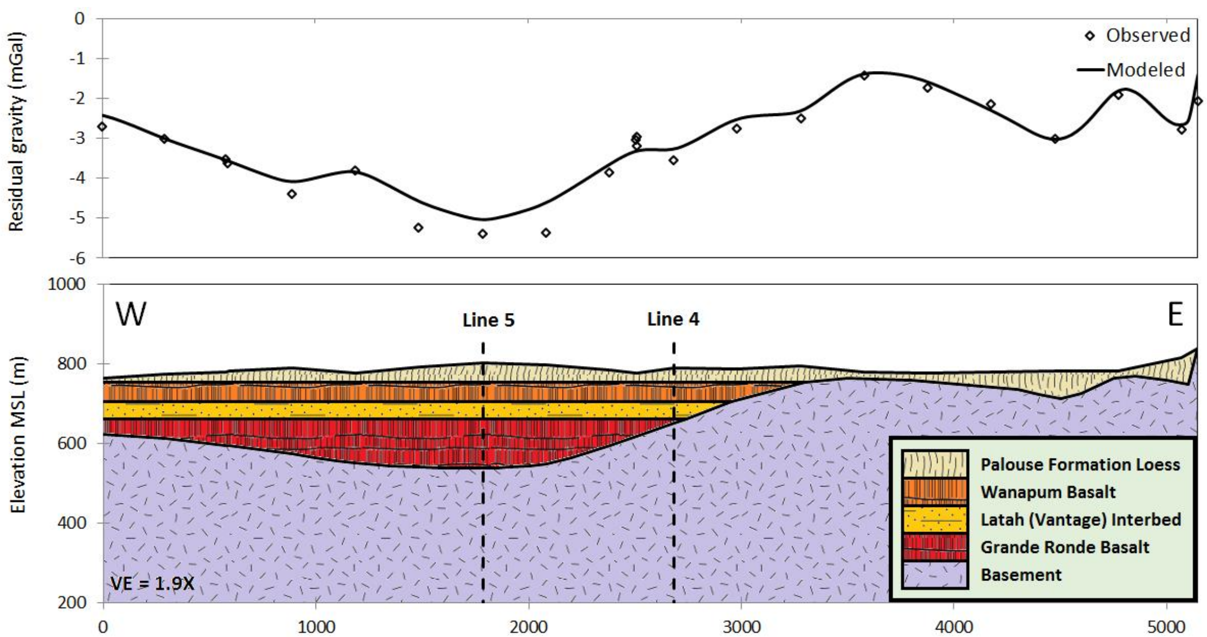

Figure 7. Gravity model of Line 1, see Figure 2 for aerial view. The pattern and colors for stratigraphic units are depicted in legend at lower right; this same legend is used for all modeled lines in Figures 8, 9, 10, and 12. Maximum modeled thickness of Grande Ronde (Line 5) is 125 m; modeled thickness of Grande Ronde at intersection of Line 4 is 10 m.

Line 2

The bedrock of Kamiak Butte on the west and Angel Butte on the east demark the termini of Line 2 (Figure 8). Our model suggests that there is, again, a considerable extent of Grande Ronde basalt in a channel to the west of Line 4 to a thickness of approximately 224 meters at the latitude of Line 2. Line 4 appears to intersect with a shallower extent of Grande Ronde basalt (maximum thickness of approximately 175 m), however, based on the model for Line 1 it does not appear that this basalt extends far to the north but rather rapidly pinches out.

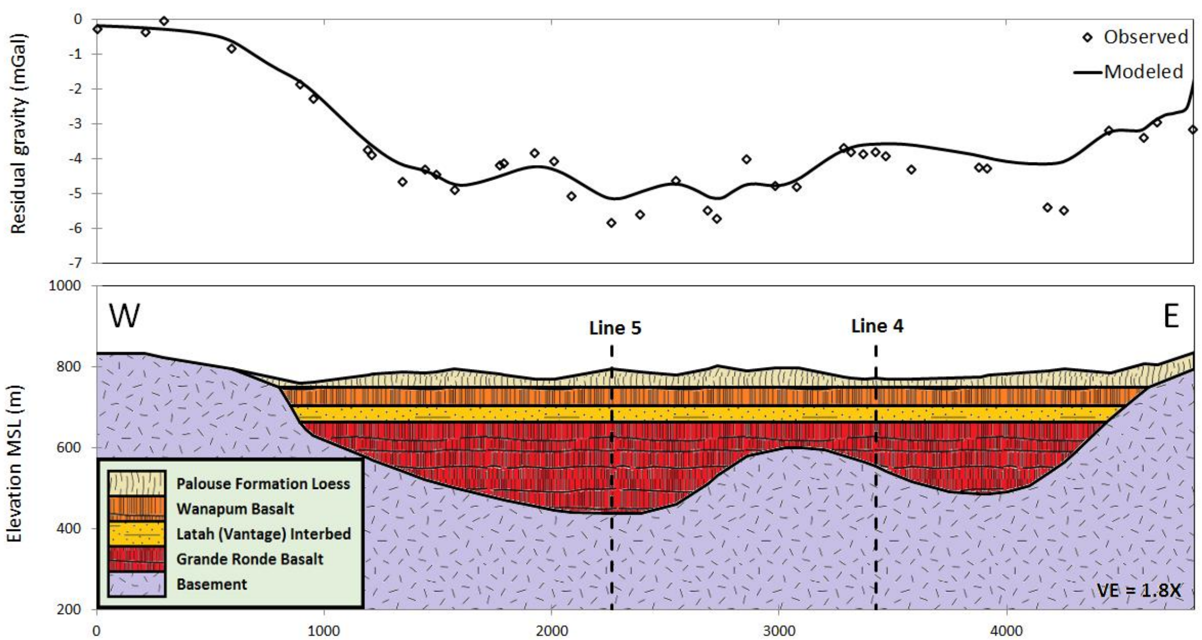

Figure 8. Gravity model of Line 2, see Figure 2 for aerial view. Maximum modeled thickness of Grande Ronde (Line 5) is 224 m; modeled thickness of Grande Ronde at intersection of Line 4 is 107 m.

Line 3

The western terminus of Line 3 is slightly less than 1 km south of Kamiak Butte whilst the eastern terminus is slightly more than a half km south of Angel Butte (Figure 9). The extent of the Grande Ronde basalt channel has broadened and deepened considerably at this latitude with a maximum depth of approximately 316 meters, some 92 meters greater than 224 meter deep western channel modeled in Line 2.

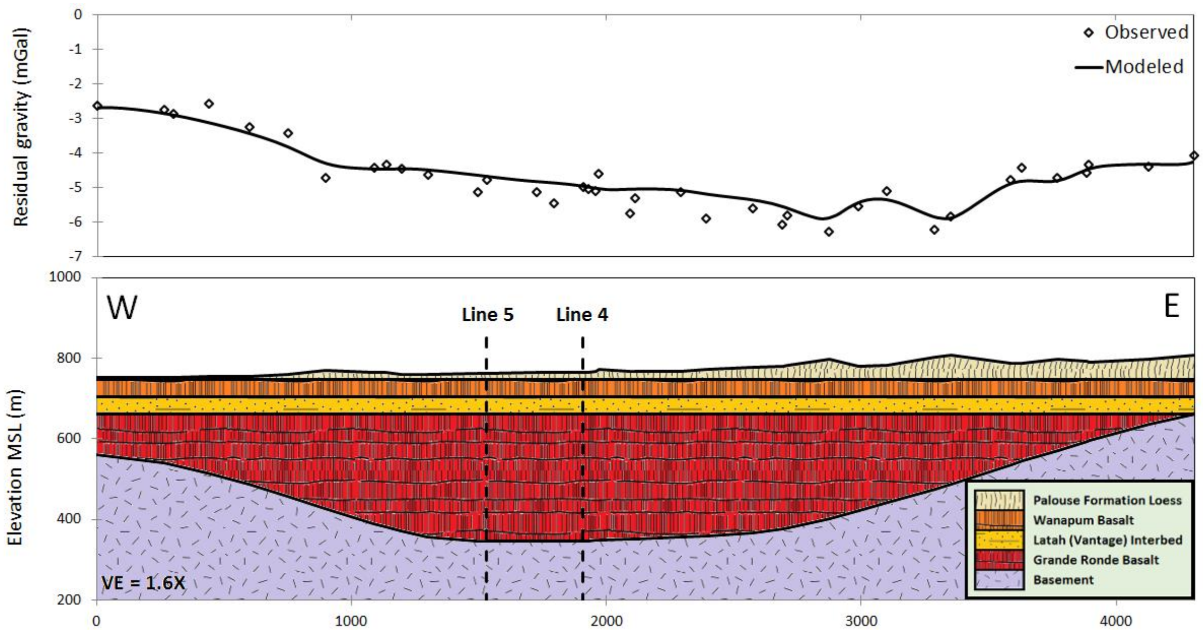

Figure 9. Gravity model of Line 3, see Figure 2 for aerial view. Maximum modeled thickness of Grande Ronde (Line 5) is 316 m; modeled thickness of Grande Ronde at intersection of Line 4 is also 316 m.

Line 4

The model for Line 4 (Figure 10) suggests that the shallowest basement can be found slightly north of Line 1 (Figure 7). However, at the intersection of Line 4 with Lines 1 and 2, Line 4 is quite close to Angel Butte. As the models for Lines 1 and 2 suggest the deepest bedrock is slightly over 1 km west of Line 4 in a channel trending northeast-southwest. To the south at Line 3 the channel has broadened both east and west and Line 4 intersects Line 3 near the deepest bedrock (and thickest Grande Ronde basalt). By approximately a kilometer north of Line 1 the Line 4 model suggests that Grande Ronde basalt channel may also have broadened out east and west through the northern portion of the Kamiak Gap.

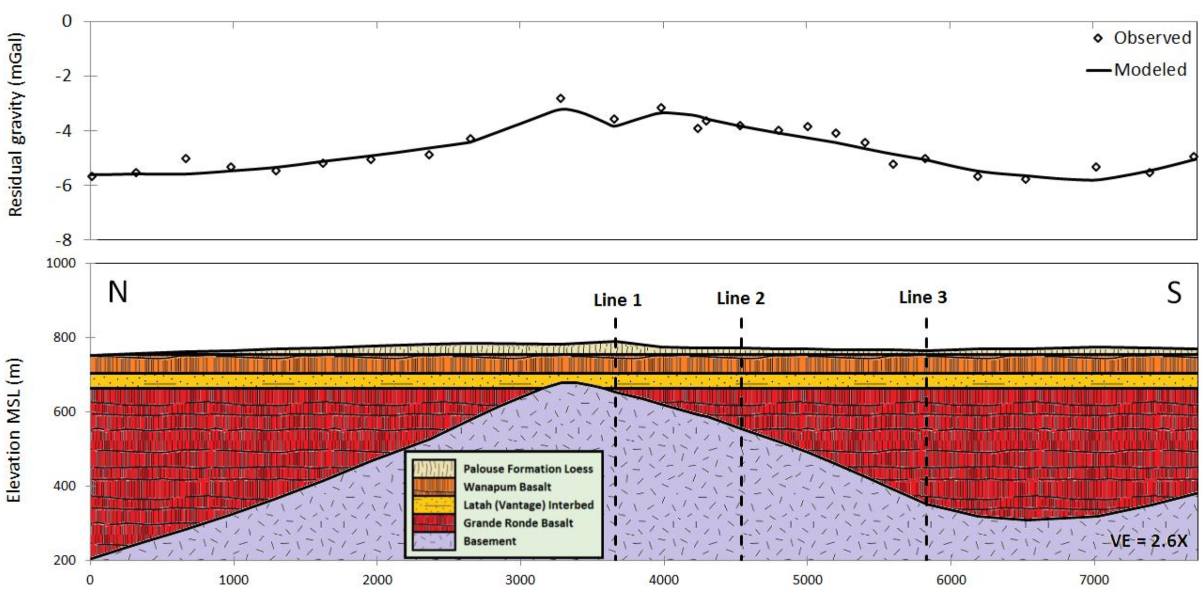

Figure 10. Gravity model of Line 4, see Figure 2 for aerial view. Modeled thickness of Grande Ronde at intersection of Line 1 is 10 m, at intersection of Line 2 is 107 m, and at intersection of Line 3 is 316 m. Note that this line is sinuous and is not representative of the N-S structure of the valley. The basement high in the center of this section is, for example, considerably east of the center of the valley. See Figure 12 for a more representative N-S section.

Line 5

We have taken the northern and southern gravity survey points of Line 4 and extended them through the modeled Grande Ronde channel through the Kamiak Gap to the west of Line 4 (Figure 11) and the subsequent model is depicted in Figure 12. Unfortunately, there is approximately 1.35 km between the point modeled on Line 1 and closest point to the northeast on Line 4 (designated KMK043 and KMK112 respectively in Holom, 2006) leaving some uncertainty in the Grande Ronde thickness in the kilometer north of Line 1. However, our modeling of Lines 1 – 4 strongly suggest that there is a significant thickness of Grande Ronde in the western Kamiak Gap and, at least through the latitudes surveyed by Holom (2006), it is continuous.

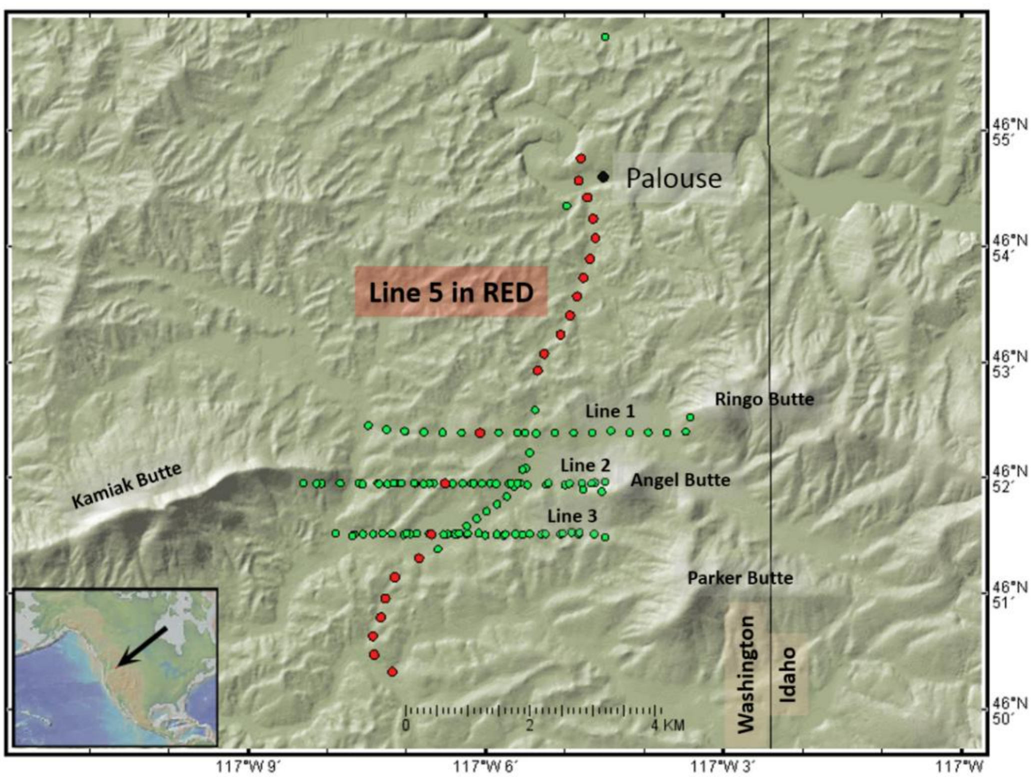

Figure 11. The gravity survey points used to construct Line 5 are delineated in red. The three points in Lines 1, 2, and 3 are the points with the thickest Grande Ronde modeled in Figures 7, 8, and 9 respectively. Figure generated with GeoMapApp (Ryan et al., 2009).

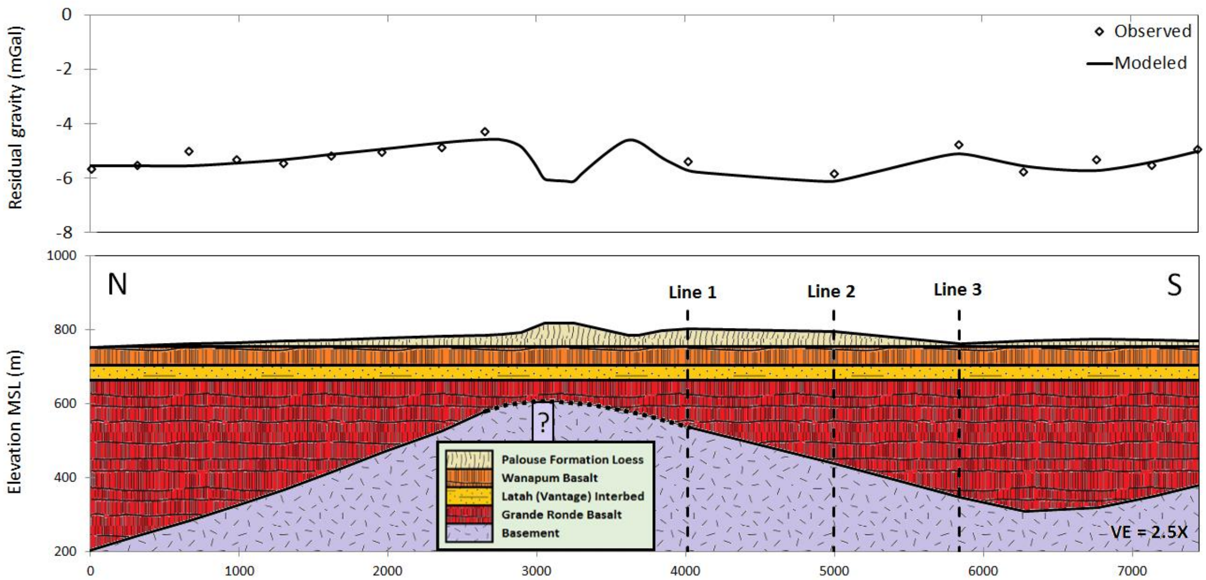

Figure 12. Gravity model of Line 5, see Figure 11 for aerial view. This section is more representative of the N-S structure of the valley than Line 4. Modeled thickness of Grande Ronde at intersection of Line 1 is 125 m, at intersection of Line 2 is 224 m, and at intersection of Line 3 is 316 m. The dashed line between basement and Grande Ronde north of Line 1 below the topographic divide indicates uncertainty in the model as there is approximately 1.35 km between survey point locations.

Conclusion

This new geophysical model, using elevation constraints imposed by Palouse City #3 well and the DOE Butte Gap well, strongly suggests that there is a deep channel of Grande Ronde basalt running continuously north-south through the Kamiak Gap with a minimum thickness of near 125 m (at very least 120 m) at the latitude of Line 1. With this thickness available, it is reasonable to expect that the Grande Ronde aquifer hydrologically connects the north and south portions of the Palouse groundwater basin.

For purposes of discussion we define Kamiak Gap strictly as the area flanked by the Kamiak Butte on the west and the Ringo and Angel Buttes on the east. Unfortunately, Holom (2006) did not adequately survey the slightly higher elevation terrain immediately north of Kamiak Gap along the divide between the Palouse River and Fourmile Creek drainages (Figures 5-6). This surface drainage divide lies between Kamiak Gap and Palouse, in an area north of the east-west gravity control lines of Holom (2006). Accordingly, Line 5 (Figure 12) indicates uncertainty for the Grande Ronde thickness immediately north of the latitude of Line 1 beneath the topographic divide. If a basement uplift is associated with the stream divide, the Grande Ronde might thin at that location, possibly creating a hydraulic barrier. Without further gravity measurements, this possibility cannot be ruled out. Thus, if future groundwater models do require a hydraulic barrier, it should be placed beneath the drainage divide, not in Kamiak Gap.

It is important to reiterate that our conclusions are based on exactly the same gravity observations, regional gravity trend, and bulk densities as used by Holom (2006). Our results are dramatically different because we used a much simpler (and far less subjective) stratigraphic model for the Latah (Vantage), Wanapum, and soil units above the Grande Ronde.

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