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Gravity Study through the Tualatin Mountains, Oregon: Understanding Crustal Structure and Earthquake Hazards in the Portland Urban Area

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Abstract A high-resolution gravity survey through the Tualatin Mountains (Portland Hills) west of downtown Portland exhibits evidence of faults previously identified from surface geologic and aeromagnetic mapping. The gravity survey was conducted in 1996 along the 4.5-km length of a twin-bore tunnel, then under construction and now providing light-rail service between downtown Portland and communities west of the Portland Hills. Gravitational attraction gradually increases from west to east inside the tunnel, which reflects the tunnel's location between low-density sedimentary deposits of the Tualatin basin to the west and high-density, mostly concealed Eocene basalt to the east. Superimposed on this gradient are several steplike anomalies that we interpret as evidence for faulted contacts between rocks of contrasting density. The largest of these anomalies occurs beneath Sylvan Creek, where a fault had previously been mapped inside the tunnel. Another occurs 1200 m from the west portal, at the approximate intersection of the tunnel with an aeromagnetic anomaly associated with the Sylvan fault (formerly called the Oatfield fault). Lithologic cross sections based on these gravity data show that the steplike anomalies are consistent with steeply dipping reverse faults, although strike-slip displacements also may be important. Three gravity lows correspond with topographic lows directly overhead and may reflect zones of shearing. Several moderate earthquakes ($M \geq 3.5$) occurred near the present-day location of the tunnel in 1991, suggesting that some of these faults or other faults in the Portland Hills fault zone are seismically active.

Introduction

Construction of a light-rail tunnel through the Tualatin Mountains (Portland Hills) west of downtown Portland, Oregon, afforded a unique opportunity to conduct detailed geologic and geophysical investigations through the interior of the Earth in a tectonically active area. The tunnel extends east–west for a distance of 4.5 km, obliquely crossing the Portland Hills. The tunnel has twin tubes, each 6.4 m in construction diameter (5.8 m after completion). Construction began in 1993 and was completed in 1998. The tunnel is a key element in light-rail service between downtown Portland and Beaverton, Hillsboro, and other communities west of the Portland Hills.

The tunnel intersects several faults indicated by surface geologic and aeromagnetic mapping. Nearby earthquakes of moderate magnitude suggest that one or more of these faults may be active. This article describes a high-resolution gravity study conducted through the length of the tunnel and implications for the geologic and tectonic structure of the Portland Hills.

Geologic and Tectonic Setting

The northwest-trending Portland Hills separate the Portland basin to the northeast from the Tualatin basin to the southwest (Fig. 1). The Portland Hills are a late Cenozoic anticline faulted along its northeastern limb by the northwest-trending Portland Hills fault (Beeson *et al.*, 1976, 1985) and along its southwestern limb by the Oatfield fault, Sylvania fault, and several other unnamed faults (Fig. 2a). These faults are structural elements of the Portland Hills fault zone, which in turn comprises part of the Portland Hills–Clackamas River structural zone (Beeson *et al.*, 1985; Blakely *et al.*, 1995). This complex zone of deformation has experienced folding and normal, thrust, and dextral strike-slip faulting since the middle Miocene (Beeson *et al.*, 1985). It is one of several northwest-striking structural zones in northwestern Oregon that accommodate north–south shortening and clockwise rotation of the Oregon Coast Range (Beeson *et al.*, 1985; Wells *et al.*, 1998; Blakely *et al.*, 2000).

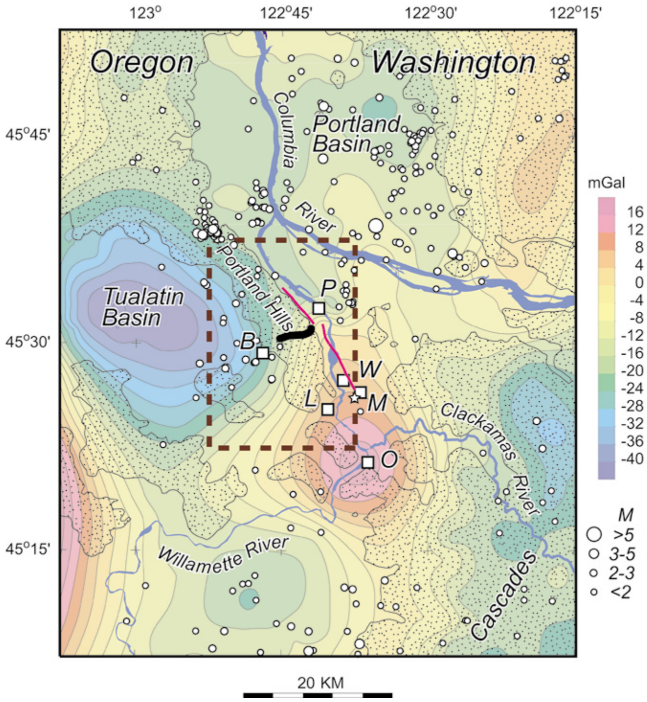

Figure 1. Map showing isostatic residual gravity anomalies, earthquake epicenters, and other features discussed in text. Epicenters (white circles) include all $M > 0$ earthquakes occurring since January 1981, plus the M 5.2 earthquake that occurred in Vancouver in 1962 (Yelin and Patton, 1991). Stipple pattern indicates terrain higher than 100 m. Red line is mapped portion of Portland Hills fault (Beeson *et al.*, 1989, 1991). White star is location of detailed geologic and geophysical studies by Madin and Hemphill-Haley (2001) and Liberty *et al.* (2003). Bold black line is tunnel position. Brown dashed rectangle outlines areas shown in Figure 2. P, downtown Portland; B, Beaverton; O, Oregon City; L, Lake Oswego; M, Milwaukie; W, Waverly Heights.

The southern part of the Portland Hills is underlain by Eocene basalt of Waverly Heights and associated sedimentary rocks (Beeson *et al.*, 1989). The basalt of Waverly Heights is overlain unconformably by various units of the Columbia River Basalt Group of middle-Miocene age. The Columbia River basalts in this area include Grande Ronde Basalt and several flows of the Frenchman Springs Member of the Wanapum Basalt (Beeson *et al.*, 1989, 1991). The Columbia River Basalt Group is overlain by younger sedimentary rocks, including the Troutdale Formation of Miocene to Pliocene age. In Pleistocene time, local vents within the Portland metropolitan area erupted basalt and basaltic andesite, known locally as the Boring Lava (e.g., Conrey *et al.*, 1996; Fleck *et al.*, 2002). Quaternary and younger sedimentary deposits, including catastrophic flood deposits of the Columbia River and loess deposits, mantle the ridges and valleys.

An aeromagnetic lineation extends 40 km along the western flank of the Portland Hills (AA′ in Fig. 2b). The orientation of the lineation parallel to the Portland Hills fault zone, its close spatial association with mapped faults in the area, and the linearity and sharp gradient of its separate anomalies led Blakely *et al.* (1995) to interpret the lineation as being caused by a fault or narrow zone of faults at least 40 km in length. One element of lineation AA′ is in close proximity to the mostly concealed Oatfield fault (Fig. 2b; Beeson *et al.*, 1989, 1991). Based on this spatial association, Blakely *et al.* (1995) interpreted lineation AA′ in its entirety as reflecting the subsurface continuation of the Oatfield fault along the southwestern slope of the Portland Hills. Closer examination of Figure 2, however, shows that the part of lineation AA′ associated with the Oatfield fault is a splay of the main fault zone, and, thus, "Oatfield fault" may not be an appropriate name for lineation AA′. In this article we refer to lineation AA′ as the Sylvan fault, so named because it passes through the community of Sylvan (Fig. 2a).

All faults in the Portland Hills mapped beneath exposures of Boring Lava are concealed by these basaltic rocks (Beeson *et al.*, 1989, 1991), implying that the faults are older than these Pleistocene extrusive events. A cross-sectional model based on the aeromagnetic data (Blakely *et al.*, 1995), however, suggests that the Sylvan fault 8 km northwest of the tunnel has a significant reverse component, placing middle Miocene Columbia River basalt structurally above Boring Lava.

Three $M \geq 3.5$ earthquakes and numerous smaller earthquakes occurred about 20 km northwest of the tunnel in 1991 (Fig. 1), possibly suggesting that the Portland Hills fault zone is seismically active (Blakely *et al.*, 1995). Several recent discoveries appear to support this observation: First, Madin and Hemphill-Haley (2001) noted folded Missoula flood deposits in an excavation site located on the mapped trace of the Portland Hills fault near Milwaukie, Oregon. They interpreted the folds to be the result of slip on a subsurface structure, presumably the Portland Hills fault, subsequent to deposition of the flood deposits 15 to 12.8 k.y. ago. The amount of deformation is consistent with two large earthquakes since 12.8 k.y. ago (Madin and Hemphill-Haley, 2001). Second, Liberty *et al.* (2003) conducted a variety of high-resolution geophysical surveys, including seismic-reflection, ground penetrating radar, and ground magnetic measurements, near the same excavation site and confirmed similar amounts and rates of deformation. Third, Pratt *et al.* (2001) identified several important strands of the Portland Hills fault zone in high-resolution seismic-reflection profiles. Specifically, they found evidence consistent with Pleistocene or Holocene faulting on the East Bank and Portland Hills faults east of the Willamette River in downtown Portland.

The tunnel penetrates many of the lithologic units of the Portland Hills, including Columbia River basalt, Troutdale Formation, Boring Lava, and younger sedimentary deposits. It also lies below aeromagnetic anomaly AA′ and various faults mapped along the western flank of the Portland Hills (Fig. 2). Detailed geologic investigations were conducted inside and surrounding the tunnel as part of the construction

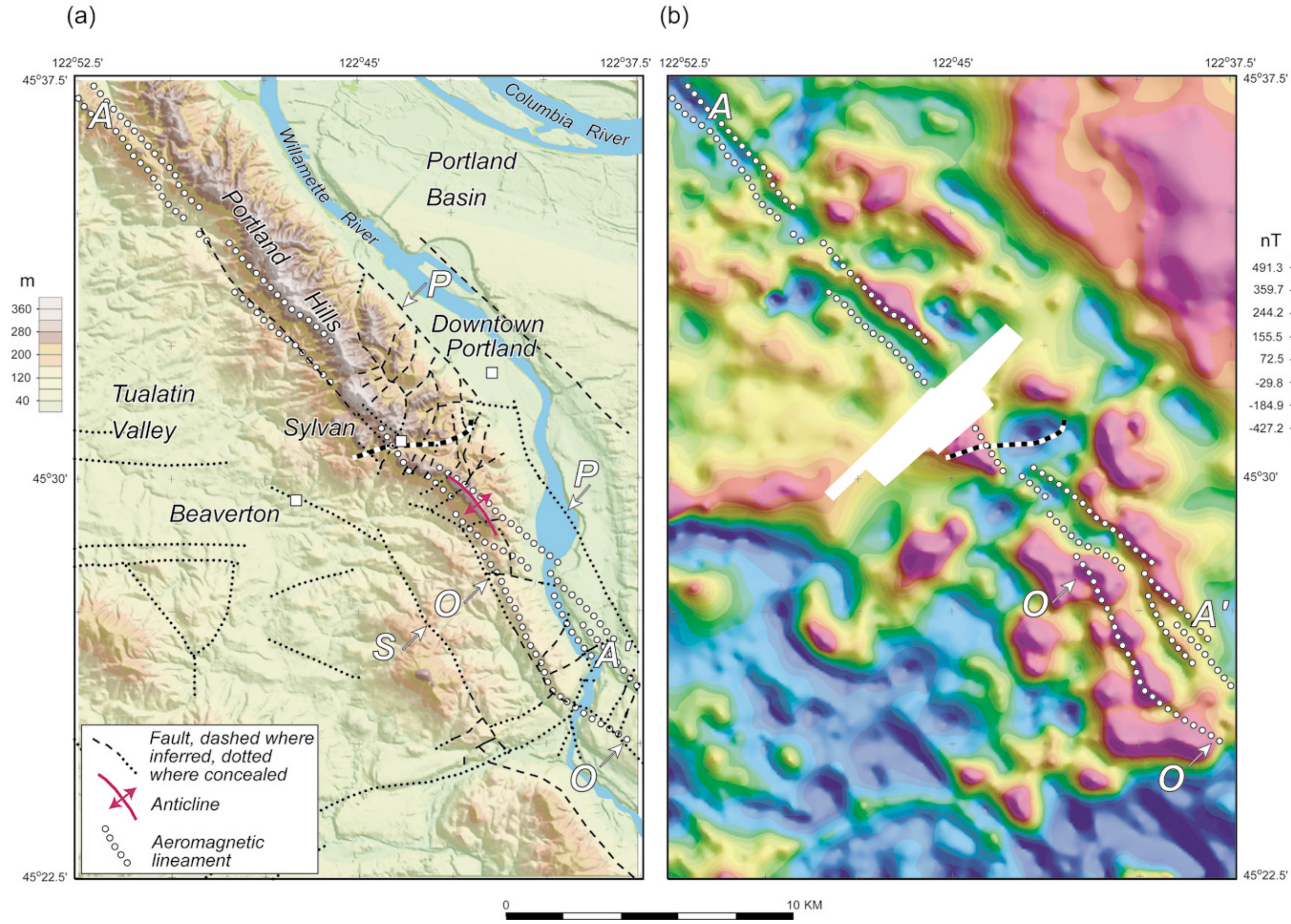

Figure 2. (a) Topography of the Portland area, Oregon. Bold black-and-white dashed line indicates the Portland light-rail tunnel, extending through the Portland Hills. Light black lines indicate mapped faults (Beeson *et al.*, 1989, 1991; Madin, 1990; Yeats *et al.* 1996) and are dashed where inferred and dotted where concealed. White dotted lines AA′ comprise the aeromagnetic lineation taken from Figure 2b and discussed in text. O, Oatfield fault; S, Sylvania fault; P, Portland Hills fault. (b) Aeromagnetic anomalies of the Portland area. White dotted lines AA′ indicate a northwest-striking lineation discussed in text.

project. These included numerous cores drilled above the tunnel and large-scale geologic mapping inside the tunnel prior to concealment beneath construction materials (K. Walsh, unpublished report, Parsons Brinckerhoff Construction, 1993). Our interpretation of gravity measurements relies heavily on these detailed investigations.

Gravity and Leveling Measurements and Reduction

Gravity measurements inside the Earth are not commonly made, and measurements inside tunnels require special considerations. The gravitational attraction observed far from a mass of finite dimensions is inversely proportional to the square of the distance to the mass. It might seem, therefore, that the gravity function would behave poorly as the observation point moves near and inside the mass, as would happen when making gravity measurements into and through a tunnel. To the contrary, it can be shown that the gravitational potential $U(P)$ at point P satisfies Poisson's equation,

$$\nabla^2 U(P) = -4\pi\gamma\rho(P),$$

for P both inside and outside any continuous mass, where $\rho(P)$ is the density of the mass and γ is Newton's gravitational constant (Blakely, 1995). Gravitational acceleration is the gradient of its potential,

$$\mathbf{g}(P) = \nabla U(P),$$

and substitution yields

$$\nabla \cdot \mathbf{g}(P) = -4\pi\gamma\rho(P). \tag{1}$$

Thus the three-dimensional variation of gravitational acceleration at any point is proportional to and thus bounded by the density of the mass at that point.

Consider, for example, the gravitational acceleration inside and outside an infinitely extended slab of uniform density ρ_0 and thickness t. Let the origin be at the top of the slab and direct the z axis downward. Because of symmetry, equation (1) simplifies to

$$\frac{d}{dz} g_z(P) = \begin{cases} -4\pi\gamma\rho_0 & \text{for } P \text{ inside slab,} \\ 0 & \text{for } P \text{ outside slab.} \end{cases} \quad (2)$$

The vertical acceleration of gravity above the slab (i.e., $z < 0$) is the familiar Bouguer slab formula,

$$g_z = 2\pi\gamma\rho t, \quad z < 0$$

(e.g., Blakely, 1995), and acceleration below the slab will have the same magnitude but be directed upward,

$$g_z = -2\pi\gamma\rho t, \quad z > t.$$

At a depth z inside the slab, acceleration is the sum of that part of the slab that lies higher than the observation point plus that part that lies below the observation point, and thus we can write, for any z,

$$g_z = \begin{cases} 2\pi\gamma\rho_0 t & z < 0, \\ 2\pi\gamma\rho_0(t - 2z) & 0 \le z \le t, \\ -2\pi\gamma\rho_0 t & z > 0. \end{cases} \quad (3)$$

Taking the vertical derivative of both sides of equation (3) yields

$$\frac{d}{dz} g_z = \begin{cases} 0 & z < 0, \\ -4\pi\gamma\rho_0 t & 0 \le z \le t, \\ 0 & z > t, \end{cases} \quad (4)$$

which has precisely the same form as equation (2). Thus gravitational attraction of the slab (equation 3) is a piecewise-continuous function at all points, both outside and inside the mass.

Although gravitational attraction is well behaved in a theoretical sense, gravity measurements inside masses still require special considerations. Gravity stations were established along the entire length of the Portland Hills tunnel at spacings ranging from 23 to 46 m and with an estimated precision of 0.05 mGal (Fig. 3). The 23-m station spacing was used at various locations to assure that all important anomalies were properly sampled. Precise measurements were required because modeling experiments prior to the fieldwork indicated that the gravitational variations caused by geologic effects inside the tunnel would be on the order of 1 mGal in amplitude (about 0.0001% of the total gravitational attraction of the Earth) with lateral dimensions of 50 to 100 m. The position and altitude of each station relative to construction benchmarks at each portal were surveyed with a total-station capable of 1-sec angular accuracy. The survey was conducted during breaks in tunnel construction, thus eliminating noise from the operation of heavy equipment. However, large construction fans operated continuously during our survey to clear the tunnel of noxious gases, and these motors probably introduced small measurement errors. Additional small errors were probably introduced by the nonuniform dimensions of the tunnel cavity in some locations, caused by construction stoping of unconsolidated rock.

Special data processing was required to account for the gravity effects caused by the hills and valleys above the tunnel, which are typically much larger than the effects of lithologic variations surrounding the tunnel. The gravitational effects of overburden and terrain were investigated using a 30-m digital elevation model and assuming various uniform densities for the overburden. Unlike conventional gravity surveys conducted on the ground surface, the gravitational effect of terrain is inverted for measurements made on a smooth surface beneath terrain. That is, the vertical force of gravity is higher beneath valleys and lower beneath hills, so that terrain corrections serve to lower anomalies observed beneath valleys and increase anomalies observed beneath hills. As will be discussed in the next section, some anomalies observed in the tunnel do correlate with terrain, but that correlation is positive; that is, positive anomalies are observed beneath hills and negative anomalies beneath valleys. Thus, these anomalies cannot be accounted for with any uniform terrain density. We settled on 2.67 g/cm^3 in our data processing and interpretation, but our conclusions are not greatly influenced by this choice.

The effect of the tunnel cavity itself was also modeled and subtracted. Residual values represent complete Bouguer anomalies through the interior of the mountain range, reflecting density contrasts in and around the tunnel (Fig. 3).

Discussion

The first-order feature of the terrain-corrected Bouguer anomaly profile is a gradual increase from -28.5 mGal at the west portal to a maximum of -15.4 mGal at about 3.3 km from the west portal (Fig. 3). This west–east gradient is due to the tunnel's location (Fig. 1) between a broad gravity low over the Tualatin basin to the west and a gravity high to the southeast presumably caused by mostly concealed Eocene basalt (basalt of Waverly Heights).

Superimposed on this broad gradient are a number of steplike anomalies (Fig. 3) with magnitudes of 1 to 3 mGal and characteristic widths of 100 to 300 m. The amplitudes of these anomalies exceed those expected from measurement error, and we believe they reflect lithologic variations along the tunnel walls. Several correlations with tunnel geology suggest that the anomalies are related to faults that intersect the tunnel. The most pronounced of these anomalies occurs beneath Sylvan Creek, where a fault was previously identi-

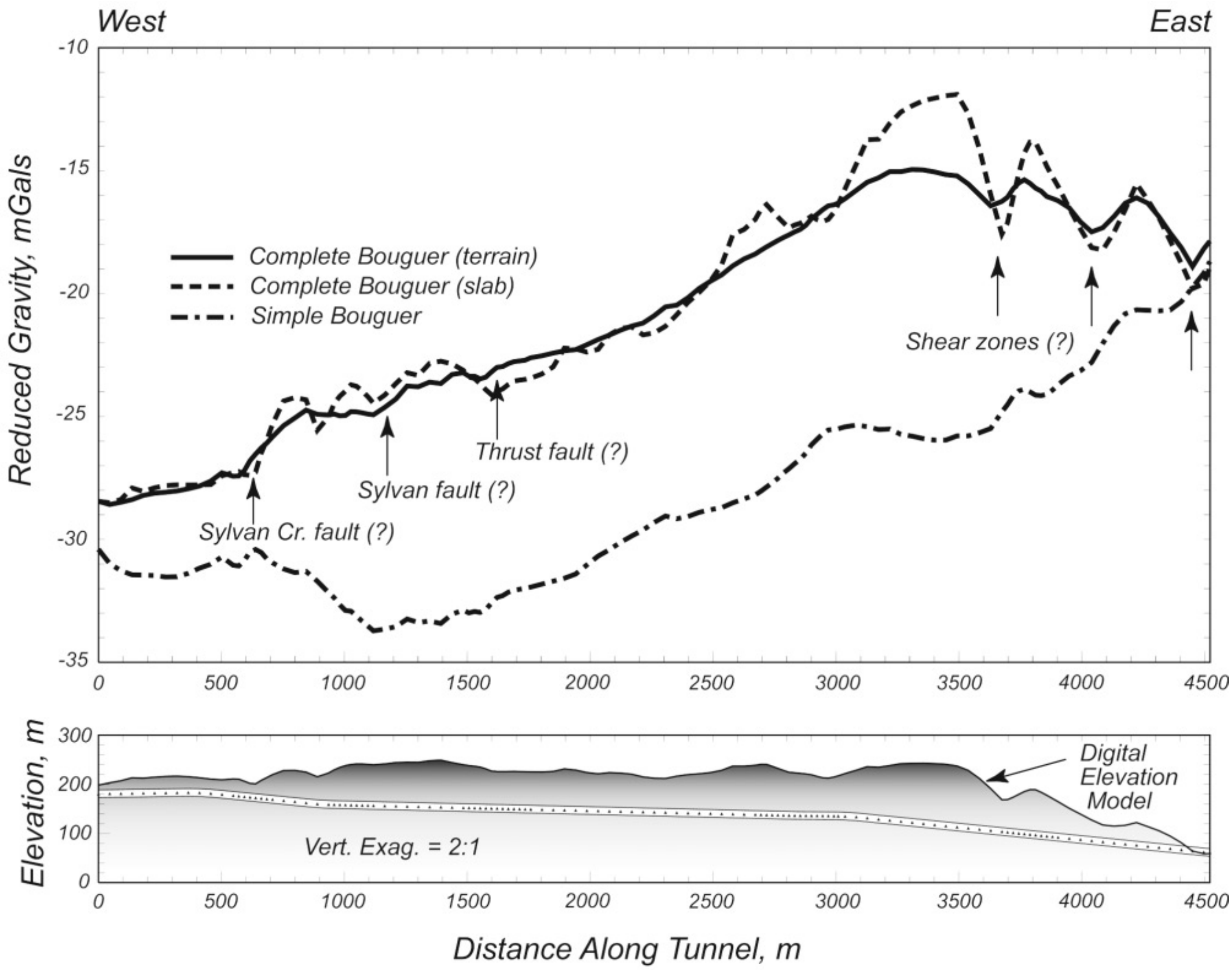

Figure 3. Gravity anomalies inside the Portland Hills. Various gravity anomalies were computed from the gravity measurements: dashed-dotted, simple Bouguer anomaly; dashed, complete Bouguer anomaly, where the terrain effect at each station was approximated by an infinite slab; solid, complete Bouguer anomaly, where the terrain effect was approximated with a digital terrain model.

fied and mapped inside the tunnel (K. Walsh, unpublished report, Parsons Brinckerhoff Construction, 1993). Another gravity anomaly occurs 1200 m from the west portal at the intersection of the tunnel and the surface trace of the Sylvan fault, as interpreted from aeromagnetic anomaly AA′ (Fig. 2b). A complex fault zone was identified inside the tunnel at this same location. Figure 4 shows a low-angle thrust fault within this fault zone. Immediately to the left of the photograph (Fig. 4), a steeply dipping fault has placed 15-Ma Columbia River basalt 20 m above Boring Lava. The fault is thus younger than eruption of the Boring Lava in this location. Ages of Boring Lava taken from tunnel boreholes range in age from 100 to 125 k.y. at the west portal to about 1 Ma in the central and eastern parts of the tunnel (Fleck *et al.*, 2002; Conrey *et al.*, 1996).

The Sylvan fault lies on the steep gradient of an aeromagnetic anomaly, positive to the southwest and negative to the northeast (Fig. 2). The northeast-side-up sense of the Sylvan fault shown in Figure 5 implies that either Boring Lava is reversely magnetized in this location or, more likely, the aeromagnetic anomaly is dominated by offsets on the fault that lie deeper than the tunnel and Boring Lava.

Figure 5 shows a cross-sectional model for part of the Portland Hills tunnel profile based on detailed geologic mapping (K. Walsh, unpublished report, Parsons Brinckerhoff Construction, 1993) and gravity measurements from inside the tunnel. Residual gravity in Figure 5 was computed by subtracting a second-order polynomial from the complete Bouguer anomaly (western part of profile only). Density values are consistent with published values (e.g., Telford *et al.*, 1990, p. 16). The small basaltic dike was considered denser than surrounding basalt flows under the assumption that the dike will have smaller proportions of vesicles, fractures, and interbeds. Gravity models are not unique; for any measured

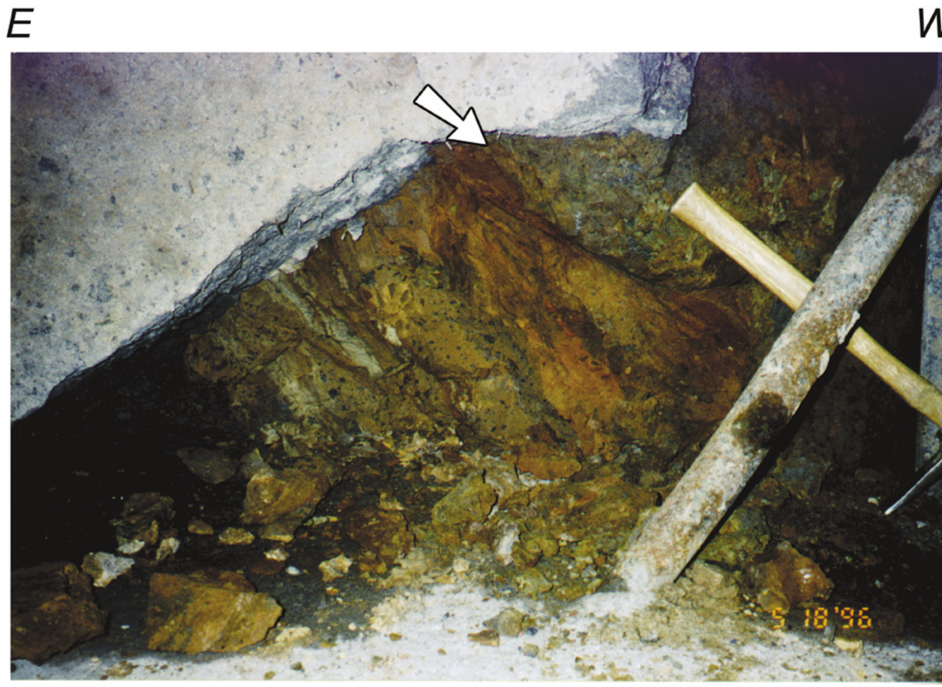

Figure 4. Fault contact inside tunnel. Photograph is of the south wall of the tunnel, approximately 1200 m from the west portal. Arrow indicates a low-angle thrust fault located at the approximate intersection of the tunnel with the mapped trace of the Sylvan fault. Immediately east of photograph, a steeply dipping fault has placed 15-Ma Columbia River Basalt Group above 1-Ma Boring Lava. Gray block in the upper-left corner is construction material.

anomaly there are an infinite variety of mathematically acceptable geologic models. The model shown in Figure 5, of course, suffers from the same nonuniqueness. In one sense, this model is more problematic because, in a tunnel, sources are both above and below the measurement location. However, the model is exceptionally well constrained by drill information from above the tunnel and large-scale geologic mapping inside the tunnel.

The small-amplitude anomalies at the western end of the tunnel are modeled as faults with reverse components of motion and about 100 m of vertical throw across Columbia River basalt (Fig. 5). This does not preclude the possibility of additional strike-slip motion, which is difficult to observe in the tunnel walls. Indeed it is likely that overall motion on the Portland Hills fault zone has been oblique (Beeson *et al.*, 1985). As modeled, the thickness of Columbia River basalt remains approximately uniform across each fault, implying that fault displacement postdates emplacement of Columbia River basalt. The model extends only to depths of a few hundred meters below sea level, and it is quite possible that these faults merge into a single fault at deeper levels (Wong *et al.*, 2001). The model also includes a dike of Boring Lava and a low-angle thrust fault, consistent with geologic mapping of the tunnel walls (K. Walsh, unpublished report, Parsons Brinckerhoff Construction, 1993).

Three pronounced gravity lows at the eastern end of the profile correspond to topographic depressions overhead (Fig. 3). As discussed in the previous section, terrain and gravity anomalies should be inversely correlated when gravity measurements are made beneath the terrain. An overlying valley, for example, will produce a positive anomaly, whereas an overlying hill will produce a negative anomaly. Figure 3, however, indicates a generally positive correlation between anomalies and terrain, with positive anomalies beneath hills and negative anomalies beneath valleys. Simple topographic effects cannot cause these anomalies. One of the gravity lows, at 3700 m from the west portal, occurs where the tunnel passes through a pronounced 40-m-wide zone of fractured Columbia River basalt observed in the tunnel walls. Fault breccias are typically low in density, and thus the gravity lows and corresponding topographic depressions at the eastern end of the profile may be related to shear zones underlying this part of the Portland Hills. Model calculations indicate that the three gravity lows, each about 1 to 2 mGal peak-to-trough amplitude, can be explained by three low-density zones extending perpendicular to the tunnel walls, each 200 m wide with density contrast of -0.25 g/cm^3. With this interpretation, the reduction in density due to shearing is approximately 13% relative to surrounding Columbia River basalt.

The ages of latest movement on the various faults are difficult to evaluate. The Sylvan fault has placed 15-Ma Columbia River basalt structurally above 1-Ma Boring Lava (Conrey *et al.*, 1996; Fleck *et al.*, 2002), indicating slip at

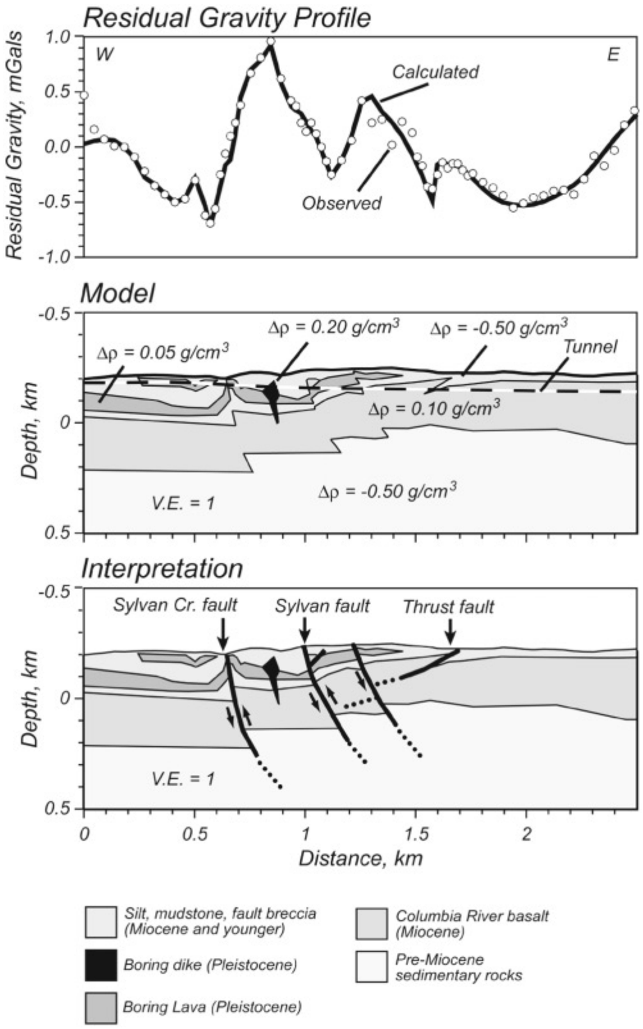

Figure 5. Interpretation of tunnel gravity anomalies. Residual gravity was computed by subtracting a second-order polynomial from the complete Bouguer anomaly (western part of profile only). Model is constrained by wells above the tunnel and geologic mapping inside the tunnel. Densities are relative to 2.67 g/cm^3.

least as recent as Pleistocene time. Although this fault extends upward into younger, overlying sediments, we do not know the age of these sediments. As noted previously, three $M \geq 3.5$ earthquakes occurred in 1991 about 20 km northwest of the tunnel. The epicenter locations fall very near the aeromagnetic trace of the Sylvan fault, and it is tempting to associate these earthquakes with a fault that intersects the tunnel. The earthquakes occurred at moderate depth (15 to 20 km), however, and associating them with any specific strand of the Portland Hills fault zone is problematic. For example, assuming the faults continue at depth with dips as shown in Figure 5, earthquakes at 15- to 20-km depth would have epicenters far removed from the surface trace of the faults. It is quite possible, moreover, that the Sylvan fault merges at depth with the Portland Hills fault (Wong *et al.*, 2001), and that the 1991 earthquakes occurred on a deeper master fault.

Conclusions

In comparison to ground-based gravity measurements, the tunnel transect provides a more detailed view of density variations at tunnel depths. However, such interpretations are complicated by ambiguities posed by having mass both above and below each measurement.

We believe that steplike gravity anomalies observed beneath the west side of the Portland Hills are caused by the Sylvan, Sylvan Creek, and other subparallel faults. These faults are part of a system of faults that have been mapped along the western margin of the Portland Hills uplift and are recognized in aeromagnetic anomalies as regionally significant structures. Although these faults are shown in Figure 5 with reverse displacement, they probably have significant strike-slip components as well.

Three gravity lows in the east side of the Portland Hills are associated with topographic lows but probably are not caused solely by topographic effects. One of these anomalies occurs within a zone of fractured Columbia River basalt, and we believe all three anomalies (and the topographic expression above them) are the result of shear zones in this part of the Portland Hills.

One of the faults observed in the tunnel has placed Columbia River basalt structurally above Boring Lava, which erupted in this location about 1 Ma (Conrey *et al.*, 1996; Fleck *et al.*, 2002). Thus, latest displacement on this fault occurred in Pleistocene or later time, but the question remains whether faults observed in the tunnel are active today. In 1991 moderate earthquakes ($M \geq 3.5$) occurred 20 km from the tunnel and near the trace of the Sylvan fault, but it is unlikely that these earthquakes occurred directly on faults observed in the tunnel, given the likely dip of these faults and the depth of the earthquakes. It is more likely that the Sylvan fault and faults observed in the tunnel are part of a master fault system (Wong *et al.*, 2001) possibly responsible for the 1991 earthquakes.

Acknowledgments

We are saddened by the passing of two of our coauthors. After our study was largely completed, Ken Walsh passed away after a difficult battle with cancer. Ken's geologic expertise and knowledge of tunnel construction were instrumental in our efforts. Then, after our report had been accepted for publication by BSSA, Marvin Beeson died unexpectedly of a heart attack. Marv was a good friend, an outstanding scientist, a mentor to many, and an acknowledged expert on Oregon geology. We dedicate this work to the memory of both Ken and Marv.

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