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Thirty-year gravity change at Mount Baker Volcano, Washington, USA: Extracting the signal from under the ice

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[1] Mount Baker in the Cascade Volcanic Arc displayed an unexplained period of increased fumarolic activity in 1975 and has since been quiescently degassing. We reoccupied gravity stations near the active crater and on the south flank of the volcano, initially measured in 1975–1981. We observe 1800 ± 300 μGal gravity increase at the crater since 1977. Estimates of snow and ice volume change suggest these environmental factors significantly mask gravity change due to magmatic and hydrothermal sources; correcting for environmental factors could double the observed gravity increase. Hydrothermal recharge, magma intrusion, and significant deflation are rejected as explanations for the source of the gravity change. Densification of a magma body emplaced in 1975 is consistent with our gravity observations and with deformation and degassing data. Shallow pyrite precipitation may also contribute to the gravity increase. **Citation:** Crider, J. G., K. Hill Johnsen, and G. Williams-Jones (2008), Thirty-year gravity change at Mount Baker Volcano, Washington, USA: Extracting the signal from under the ice, *Geophys. Res. Lett.*, *35*, L20304, doi:10.1029/2008GL034921.

1. Introduction

[2] Many stratovolcanoes are steep, remote, and ice-covered; due to their intermittent explosive nature, routine monitoring is important. These logistical difficulties and the volcanoes' long periods of quiescence mean that few time series of microgravity measurements have been produced from active stratovolcanoes. Furthermore, volcanogenic signals may be masked by mass changes related to environmental factors. Here we present a method to estimate the environmental noise in gravity observations due to ice and snow.

[3] The ice-covered, andesitic Mount Baker is the northern-most Cascade Arc volcano in Washington (USA) (Figure 1). Only one notable magmatic eruption at Mount Baker has been recorded for the Holocene (6.5 ka), and the last interval of major activity was ~12 ka [*Hildreth et al.*, 2003]. Reported historical activity includes a hydrovolcanic explosion and subsequent smaller phreatomagmatic eruptions between 1843 and 1891, and increased thermal activity beginning in the 1930s [*Scott and Tucker*, 2003].

[4] In March 1975, geothermal activity at Mount Baker increased suddenly, releasing large vapor plumes from summit fumaroles. Several gravity stations were established in response to this activity [*Malone*, 1979], including one on the south rim of Sherman Crater (SHRM), one on the south flank of the volcano at Crag View (CGVW) (Figure 1), and a base station at the Concrete town airport (CNCR), 25 km south of the volcano. Additional gravity measurements were collected episodically at those stations between 1975–1981 [*Malone*, 1979, also unpublished data, 2006]; none of these surveys included elevation control. Between 1981 and our study, no gravity surveys were conducted at Mount Baker.

[5] Five seismic stations were established at Mount Baker in 1975; they detected very few local earthquakes over the next four years, with the largest event $M_L = 1$ [*Malone*, 1979]. Since then, Mount Baker has continued to be seismically quiet [*Moran*, 2004]. Fumarolic emissions increased 5–10 times above background in 1975, and fumarole temperatures increased by as much as 40 °C [*Frank et al.*, 1977]. Since 1975, quiescent degassing has continued. In September 2000, emission rates were 187 ± 26 tonnes/day t/d of CO_2 [*McGee et al.*, 2001], and observations in summer 2007 indicate that CO_2 emissions remain above 150 t/d (C. Werner, personal communication, 2007).

[6] Three spirit-level tilt stations were established and reoccupied twice on the flanks of the volcano in 1975, but yielded conflicting results [*Frank et al.*, 1977]. Trilateration networks were installed at Mount Baker in 1981 and reoccupied in 1983; no deformation was detected [*Chadwick et al.*, 1985]. Recent reoccupation of the EDM network with GPS reveals 10 cm of deflation between 1981 and 2006 at SHRM [*Hodge*, 2008].

2. Methods and Observations

[7] In the summers of 2005 and 2006, we reoccupied *Malone*'s [1979] gravity stations using the same LaCoste and Romberg gravimeter used in the 1975–1981 surveys (G-213). The stations are not monumented but are located on distinctive rock outcroppings and documented with field descriptions and photographs (S. Malone, personal communication, 2005); we are confident that we recovered the original locations to better than a few decimeters. We made repeat measurements at CNCR, CGVW, and SHRM, in a modified closed-loop survey [*Hill*, 2007]. We applied standard instrument and earth tide corrections to both the new data and to the raw data from the 1975–1981 surveys. All observations were normalized to the common base station, CNCR. The terrain at Mount Baker is very steep, and the gravimeter was carried over bare rock, fallen trees, snow and ice, with elevation changes of >2100 m, resulting in closure errors of 187 and 6 μGal for the 2005 and 2006 surveys, respectively. Gravity change, Δg, is presented relative to 1977 values (see auxiliary material).[1] In summer

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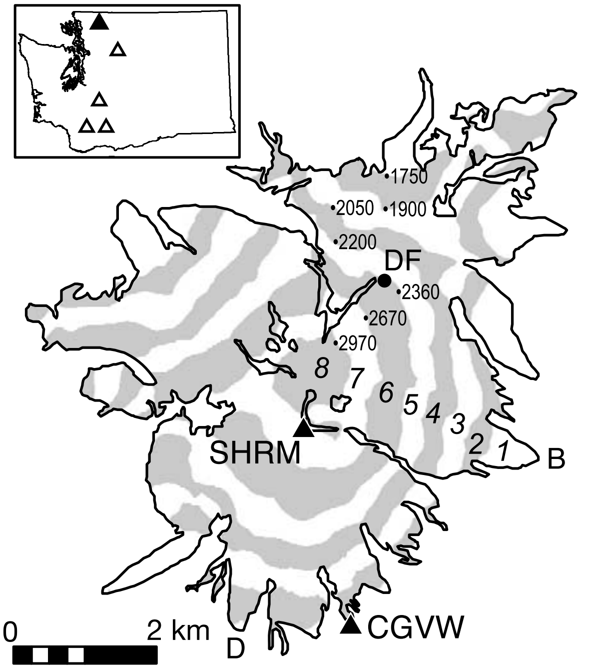

Figure 1. Ice cover on Mount Baker with numbered rings used to estimate the effect of snow and ice on Δg. Elevation of the contours separating each ring is given in m. Gravity stations at the crater (SHRM) and flank (CGVW) are shown by black triangles. Base station CNCR is 25 km to the south. DF, Dorr Fumaroles; B, Boulder Glacier; and D, Deming Glacier. Inset shows location of Mount Baker (filled triangle) relative to other Cascade stratovolcanoes in Washington State.

2005, we found that gravity at SHRM increased by 1804 ± 211 μGal since 1977. This difference is substantial, and significant even with the large closure uncertainty. The measurement was repeated and confirmed in 2006 (1796 ± 101 μGal). The time series (Figure 2) shows an initial decrease in gravity, which *Malone* [1979] attributed to mass loss from fumerolic degassing. Here we consider the 1977–2006 gravity increase.

3. Addressing Environmental Factors

[8] The largest source of uncertainty in Δg is the contribution of non-volcanic factors such as snow accumulation and ablation, variations in glacial mass, and groundwater fluctuations. We estimate the contribution to Δg from each of these factors, considering both the magnitude and sign of the gravity signal.

[9] We begin by assessing the effects of snow cover. Mapped glacier extent was used as a proxy for maximum area of late summer snow cover. Based on records for the past 79 years at the nearest site with long-term records (Mount Baker ski area)(A. Andalkar, Historical Northwest Weather and Avalanche Center snowdepth data and plots, 2006, available at http://www.skimountaineer.com/CascadeSki/CascadeSnowNWAC.php), the 1990s average snow accumulation is a reasonable representation for historical average snowfall. We fit a curve to direct measurements of late summer snow depth at 1680–2450 m elevation (M. S. Pelto, North Cascade Glacier Climate Project, 2005, available at http://www.nichols.edu/departments/glacier/), averaged for the years 1990–1999, to construct an empirical relationship and estimate snow depths at all elevations [*Hill*, 2007].

[10] We divide the resulting snow volume into eight annular rings (rings 1–7 below SHRM and ring 8 above, Figure 1). The expected gravity signal from snow at SHRM (g_{snow}) is thus [e.g., *Tipler*, 1991]:

$$g_{snow} = G\rho_{snow}\left(\sum_{i=1}^{7}\frac{A_i d_{(i)snow} z_i}{\left(z_i^2+r_i^2\right)^{3/2}} - \frac{A_8 d_{(8)snow} z_8}{\left(z_8^2+r_8^2\right)^{3/2}}\right) \qquad (1)$$

where G is the universal gravitation constant (6.67×10^{-11} m^{3}kg^{-1}s^{-2}), ρ_{snow} is snow density (600 kg m^{-3}) [*Benn and Evans*, 1998], $d_{(i)snow}$ is the snow depth in the ring, A_i is the surface area of the ring, z_i is the vertical distance from the crater to the center of the ring, r_i is the radius of the ring, and the subscripts indicate the ring number. To estimate the maximum value of g_{snow}, we choose the shortest radius from the crater that includes all rings (down Boulder Glacier, Figure 1). For an average snowfall year at Mount Baker, the gravity signal due to snow in mid-summer is 640 μGal. To correct the observed gravity measurements for snow mass, we subtract g_{snow} from the observed gravity, equivalent to stripping away all of the snow.

[11] Because there is substantial annual variation in snowpack, further insight into the size and sign of this correction may be gained using snowfall records. The 1976–1977 snow season was dry, with a maximum recorded snow depth 62% of average. The 2004–2005 snow season was even drier, with a maximum recorded snow depth 42% of average (http://www.skimountaineer.com/CascadeSki/CascadeSnowNWAC.php). Since there was less snow mass in 2005, we would expect a gravity decrease of −130 μGal due to snow-mass change.

[12] The ice mass at Mount Baker is considerable, and ice-mass changes could also result in measurable gravity differences. Although the glaciers show evidence for both advance and retreat during the past 30 years [*Harper*, 1993], all glaciers on Mount Baker have presently retreated from

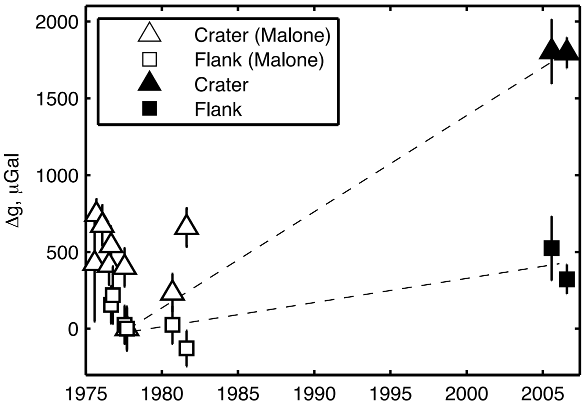

Figure 2. Gravity timeseries for the crater (SHRM) and flank (CGVW) stations relative to CNCR. Error bars include closure and RMS errors. (See auxiliary material.)

their 1977 positions [*Pelto*, 2006]. Thinning of ice is likely an even more important contributor to mass loss than terminus retreat at Mount Baker. Using the annular ring divisions shown in Figure 1, we estimate initial ice thickness within each ring as [*Benn and Evans*, 1998]:

$$d_{(i)ice} = \frac{\tau}{g_{ave}\rho_{ice}\sin\alpha_i} \tag{2}$$

where τ is shear stress at the base of the glacier, ρ_{ice} is the ice density (900 kg m^{-3}), g is the average acceleration due to gravity (9.81 m s^{-2}), and α_i is the average slope of each ring. We assume that the glaciers behave as typical alpine valley glaciers, and for high and low estimates of ice thickness apply end member shear stress values of 1.5×10^5 and 5×10^4 Pa [*Benn and Evans*, 1998]. We find the ice thickness to be between 18 and 55 m (averaged values), consistent with other estimates for the volcano as a whole [*Harper*, 1993].

[13] With mapped ice extent in 1979, when most glaciers were at their recent maximum [*Harper*, 1993], and using the same approach as for snow, we calculate the gravity signal due to glacier ice in 1977 to be between 510 and 1700 μGal at SHRM. *Pelto* [2006] estimates 18–32% ice loss between 1984 and 2004. Projecting these same volume losses back to 1979 gives a range of maximum volume losses, as a few glaciers were static or advancing in the interval 1979–1984 [*Harper*, 1993]. Assuming the ice on Mount Baker in 1977 was thick and underwent a 32% volume loss, the change in gravity signal due to ice load (Δg_{ice}) could be as much as -1600 μGal. If the glaciers in 1977 were thin and experienced only 18% volume loss since that time, $\Delta g_{ice} = -300$ μGal. Although the magnitude range is large, the sign is certain: to restore the 2005–2006 ice to estimated 1977 values, we must add 300 to 1600 μGal to the observed Δg.

[14] Seasonal or interannual variations in the shallow groundwater system can influence gravity measurements [e.g., *Rymer and Brown*, 1987]. These are very difficult to constrain at volcanoes even in the best-monitored cases [*Hurwitz et al.*, 2003; *Battaglia et al.*, 2003]. With the absence of wells or systematic surface water measurements on the volcano, we have no constraints for Mount Baker. The SHRM and CGVW stations are located on bedrock, and we compare gravity observations collected in the same season each year; both of these factors should minimize the influence of groundwater variations. Observed interannual variation at SHRM and CGVW for 2005–2006 shows differences well within uncertainty (Figure 2), suggesting that the influence of shallow groundwater is small at these stations.

[15] We consider the possibility that groundwater fluctuations at base station CNCR have influenced the observed Δg. CNCR is a small concrete pad in the flood plain of the Skagit River. While there are no local water well data covering the period of gravity observations, there is a 75-year monthly precipitation record from the Concrete PPL Fish Station, a few km away (Western Regional Climate Center, Washington climate summaries, accessed 2008, available at http://www.wrcc.dri.edu/summary/climsmwa.html). We assume that relative water table heights in mid-to-late summer in any unconfined aquifer beneath CNCR will correlate with the relative cumulative precipitation for a given water year. (A water year begins in October). For a water year with high cumulative precipitation at late summer, we expect the water table to be high, thus a greater mass of water in the subsurface. During these years, gravity at CNCR will be greater, increasing the difference relative to stations on the volcano. For a water year with low cumulative precipitation, there will be less subsurface water mass, thus lower base values and a smaller gravity difference relative to base. When we track a gravity change from a dry year to a wet year, if we assume that the change is due entirely to groundwater changes at the base station, we expect a gravity increase ($\Delta g > 0$). If we compare wet year to dry, we expect $\Delta g < 0$. In all cases, the 1975–1980 gravity values are lower than the 2005–06 values *(*$\Delta g > 0$*)*. Water year 1976 was extremely wet (9-month cumulative precipitation = 144% of mean), and water year 1977 was uncommonly dry (9-month cumulative precipitation = 69% of mean). When the CNCR observations are normalized to the prime base station at the University of Washington, the observed change from late summer 1976–1977 (two extreme water years) is $\sim$200 μGal, about twice the closure error. This should represent the maximum possible contribution to Δg from groundwater variations at CNCR. Water year 2005 (9-month cumulative precipitation = 88%) was somewhat less dry than 1977; thus groundwater variation at CNCR might contribute to the observed gravity increase at SHRM, but the contribution is at most tens of μGal.

[16] In summary, correcting for known snow and ice variations from 1977–2005 could add between 430 and 1730 μGal to the observed gravity change at SHRM, possibly doubling Δg. Shallow groundwater variations are not well constrained, but observations suggest that these are likely small compared to the observed Δg. To be conservative, we include an additional 100 μGal uncertainty. Station CGVW is at an elevation below the glaciers, and snow or ice-loss could yield apparent gravity increase there; thus, the source of the observed gravity increase at CGVW may be wholly or partly environmental. Due to this uncertainty, we omit CGVW from our interpretation of Δg.

4. Interpreting the Gravity Increase

[17] Disregarding gravity increase that might be masked by a decrease in snow and ice volume, the observed Δg at SHRM 1977–2006 is at least 1800 ± 300 μGal. This increase could be due to elevation decrease, mass increase, and/or density increase in the volcano.

[18] The 1975–1981 gravity surveys at Mount Baker had no elevation control, and therefore any observed gravity change since the earlier surveys will include some elevation change uncertainty. The elevation change required to fully account for the observed Δg at SHRM is -4.7 to -7.0 m, assuming a Free Air Correction of -308.6 μGal m^{-1}. A recent deformation study of Mount Baker, however, finds a deflation of only 10 cm at SHRM during the interval 1981–2007 [*Hodge*, 2008], and *Frank et al.* [1977] report no significant deformation 1975–1977. While it is possible that there was significant, rapid subsidence during the period 1977–1981, we consider it unlikely, given the absence of notable seismicity [*Weaver and Baker*, 1988].

It is therefore unlikely that elevation change alone is responsible for the observed Δg at SHRM.

[19] We use a point source to model the mass increase that would be necessary to produce the observed gravity change [e.g., *Dzurisin et al.*, 1980]. A shallow source beneath SHRM requires a mass increase of 10^{11}–10^{12} kg, while a deeper source at the distance of the Dorr Fumaroles (Figure 1) requires more than 10^{13} kg (Figure S1). This increase must be in addition to the estimated 3.8×10^9 kg lost over the last 30 years from CO_2 degassing [*Werner et al.*, 2007]. Mass increase at Mount Baker could be due to magma influx or hydrothermal recharge. While a magma accumulation at Mount Baker of 10^{11} to 10^{13} kg over 30 years is plausible, it is not compatible with the observed deflation of the edifice [*Hodge*, 2008] and lack of seismicity.

[20] The active hydrothermal system beneath Mount Baker is expressed at the surface by steaming ground and boiling fumaroles in Sherman Crater and the Dorr Fumarole field, and by hot springs low on the southwest flank. Large volumes of steam were emitted from the volcano shortly before the initial gravity observations, and some of the gravity signal could be due to water recharge. We consider two possibilities: shallow recharge at Sherman Crater, and deep recharge beneath the entire edifice. Average total annual precipitation at the summit of Mount Baker for the period 1975–2005 is 3.5–4.0 m of water (PRISM Group, Gridded precipitation data, accessed 2008, available at http://www.prismclimate.org), most of which is expected to run off, either immediately or as snowmelt, due to extensive ice cover and steep slopes. Precipitation is likely to be captured, however, in the closed depression of Sherman Crater, $\sim$0.25 km^2. Thirty-year accumulation through the crater is $\sim 10^7$ kg water (assuming 100% recharge and none re-emitted as steam), and is insufficient to explain the observed gravity change. If we assume the deep recharge area for the hydrothermal system is the entire volcanic edifice at elevation above the lowest known hot spring (390 m), omitting the area covered by ice, the 30-year water accumulation could be on the order of 10^{10} kg. From previous studies in the Cascades, we expect $\sim$50–70% infiltration [*Manga*, 1997], with most of this feeding shallow aquifers [*Jefferson et al.*, 2006]; thus, the deep recharge is likely to be at least an order of magnitude less than the precipitation (consistent with simulations by *Hurwitz et al.* [2003]), or 10^9 kg. This deep recharge must be at or below the elevation of the lowest point in the recharge area (z = 2500 m). Assuming the increase in mass can be described as a point source at that depth, this yields an insignificant increase in Δg at SHRM due to deep hydrothermal recharge.

[21] Changes in gravity could also result from internal density changes due to 1) densification of a magma source due to degassing and vesicle collapse, and 2) densification of the shallow subsurface due to pyrite precipitation. We assume a spherical magma source to model the range of density variations [e.g., *Sharma*, 1986] (Figure S2). *Wallace* [2001] argues that shallow, unerupted magma may contain as much as 30 vol.% exsolved gas. Complete devesiculation of andesite magma could thus produce a maximum density increase of 700–800 kg m^{-3}. A 700 kg m^{-3} density increase in a shallow magma source (z = 1 km) with a small radius (r = 450 m) directly beneath Sherman Crater (x = 0) could produce the observed gravity change. More plausibly, a deeper source (z = 5 km) with a larger radius (r = 1.6 km) can produce the same gravity change with 50% devesiculation ($\Delta\rho = 400$ kg m^{-3}). Observed contraction of the edifice is small [*Hodge*, 2008], suggesting that internal voids created by this process may be filled with fluid.

[22] Finally, near-surface precipitation of dense hydrothermal minerals such as pyrite could also influence the gravity signal. Degassing and cooling with meteoric water are conditions favorable for pyrite precipitation [*Reed and Palandri*, 2006], and pyrite has been observed in Sherman Crater (D. Frank, oral communication, 2007). Pyrite appears in drill cores in the conduits of Unzen volcano, active in 1991–1995 [*Almberg et al.*, 2008] and is an early stage hydrothermal mineral observed in rock cores from Newberry Caldera [*Bargar and Keith*, 1999]. Thus, it is plausible that a detectable mass of pyrite may have precipitated at Mount Baker in the 30 years between gravity surveys. Assume that pyrite precipitates at <350°C, that the top of the magma source is at 5 km [*Hodge*, 2008] and 800°C, that the surface temperature is 100°C (from measured fumarole temperatures). We posit a cylindrical zone, r = 1 km, extending from the surface down to 350°C (2500 m) that is a region of pyrite precipitation. If the volume of pyrite increases to 1%, the density in this cylinder increases 23 kg m^{-3}. The resulting Δg over the center of the cylinder is nearly 800 μGal, a significant fraction of the anomaly we observe.

5. Conclusion

[23] Microgravity surveys at Mount Baker volcano indicate that gravity at Sherman Crater has increased by 1800 ± 300 μGal between 1977 and 2005. Large closure errors reflect environmental noise and long-distance transport of the gravimeter on foot over rugged terrain. The effects of shallow water table variation high on the edifice are assumed to be small and on the order of $\sim$100 μGal at the base station. Environmental factors likely mask some of the volcanogenic gravity change: correcting for variations in snow and ice could increase the observed gravity change (Δg) by 430–1730 μGal, possibly doubling the observed magnitude of Δg.

[24] The observed gravity increase can possibly be explained by magma intrusion, hydrothermal recharge, densification of magma due to degassing, and shallow pyrite precipitation. Magma intrusion scenarios are plausible, but inconsistent with recent geodetic work that shows deflation of the edifice. Hydrothermal recharge alone is not sufficient to explain the observed gravity increase. Densification of a magma body emplaced in 1975 (or earlier), augmented by shallow pyrite precipitation, is consistent with the gravity, geodetic, and degassing observations.

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References

Almberg, L. D., J. F. Larsen, J. C. Eichelberger, T. A. Vogel, and L. C. Patino (2008), Comparison of eruptive and intrusive samples from Unzen Volcano, Japan: Effects of contrasting pressure-temperature-time paths, *J. Volcanol. Geotherm. Res.*, *175*, 60–70, doi:10.1016/j.jvolgeores.2008.03.020.

Bargar, K. E., and T. E. C. Keith (1999), Hydrothermal mineralogy of core from geothermal drill holes at Newberry volcano, Oregon, *U.S. Geol. Surv. Prof. Pap.*, *578*, 92 pp.

Battaglia, M., P. Segall, and C. Roberts (2003), The mechanics of unrest at Long Valley Caldera, California, *J. Volcanol. Geotherm. Res.*, *127*, 195–217.

Benn, D. I., and D. J. A. Evans (1998), *Glaciers and Glaciation*, Oxford Univ. Press, New York.

Chadwick, W., E. Iwatsubo, D. Swanson, and J. Ewert (1985), Measurements of slope distances and vertical angles at Mount Baker and Mount Rainier, Washington, Mount Hood and Crater Lake, Oregon, and Mount Shasta and Lassen Peak, California, 1980–1984, *U.S. Geol. Surv. Open File Rep., 85-0205,* 96 pp.

Dzurisin, D., L. Anderson, G. Eaton, R. Koyanagi, P. Lipman, J. Lockwood, R. Okamura, G. Puniwai, M. Sako, and K. Yamashita (1980), Geophysical observations of Kilauea Volcano Hawaii, 2. Constraints on the magma supply during November 1975–September 1977, *J. Volcanol. Geotherm. Res.*, *7*, 241–269.

Frank, D., M. Meier, and D. Swanson (1977), Assessment of increased thermal activity at Mount Baker, Washington, March 1975–March 1976, *U.S. Geol. Surv. Prof. Pap.*, 1022A.

Harper, J. T. (1993), Glacier terminus fluctuations on Mount Baker, Washington, U.S.A., 1940–1990, and climatic variations, *Arct. Antarct. Alp. Res.*, *25*, 332–340.

Hildreth, W., J. Fierstein, and M. Lanphere (2003), Eruptive history and geochronology of the Mount Baker volcanic field, Washington, *GSA Bull.*, *115*(6), 729–764.

Hill, K. S. (2007), Microgravity survey of Mount Baker, Washington, M.S. thesis, 128 pp., West. Wash. Univ., Bellingham.

Hodge, B. E. (2008), Characterizing surface deformation from 1981 to 2007 on Mount Baker, Washington, with campaign GPS resurvey of trilateration network, M.S. thesis, 147 pp., West. Wash. Univ., Bellingham.

Hurwitz, S., K. L. Kipp, S. E. Ingebritsen, and M. E. Reid (2003), Groundwater flow, heat transport, and water table position within volcanic edifices: Implications for volcanic processes in the Cascade Range, *J. Geophys. Res.*, *108*(B12), 2557, doi:10.1029/2003JB002565.

Jefferson, A., G. Grant, and T. Rose (2006), Influence of volcanic history on groundwater patterns on the west slope of the Oregon High Cascades, *Water Resour. Res.*, *42*, W12411, doi:10.1029/2005WR004812.

Malone, S. D. (1979), Gravity changes accompanying increased heat emission at Mount Baker, Washington, *J. Volcanol. Geotherm. Res.*, *6*, 241–256.

Manga, M. (1997), A model for discharge in spring-dominated streams and implications for the transmissivity and recharge of quaternary volcanics in the Oregon Cascades, *Water Resour. Res.*, *33*, 1813–1822.

McGee, K. A., M. P. Doukas, and T. M. Gerlach (2001), Quiescent hydrogen sulfide and carbon dioxide degassing from Mount Baker, Washington, *Geophys. Res. Lett.*, *28*, 4479–4482.

Moran, S. C. (2004), Seismic monitoring at Cascade volcanic centers, 2004—Status and recommendations, *U.S. Geol. Surv. Invest. Rep.*, *2004-5211*.

Pelto, M. S. (2006), The current disequilibrium of North Cascade glaciers, *Hydrol. Processes*, *20*, 769–779.

Reed, M. H., and J. Palandri (2006), Sulfide mineral precipitation from hydrothermal fluids, *Rev. Mineral. Geochem.*, *61*, 609–631.

Rymer, H., and G. Brown (1987), Causes of microgravity change at Poas volcano, Costa Rica: An active but non-erupting system, *Bull. Volcanol.*, *49*, 389–398.

Scott, K. M., and D. S. Tucker (2003), The Sherman Crater eruptive period at Mount Baker, North Cascades, 1843 to present: Implications for reservoirs at the base of the volcano, *GSA Abstr. Programs*, *35*(6), 321.

Sharma, P. V. (1986), *Geophysical Methods in Geology*, 2nd ed., 442 pp., Elsevier Sci., New York.

Tipler, P. A. (1991), *Physics for Scientists and Engineers*, Worth, New York.

Wallace, P. J. (2001), Volcanic SO_2 emissions and the abundance and distribution of exsolved gas in magma bodies, *J. Volcanol. Geotherm. Res.*, *108*, 85–106.

Weaver, C., and G. Baker (1988), Geometry of the Juan de Fuca plate beneath Washington and northern Oregon from seismicity, *Bull. Seismol. Soc. Am.*, *78*, 264–275.

Werner, C., W. C. Evans, K. A. McGee, M. P. Doukas, D. S. Tucker, D. Bergfeld, M. P. Poland, and J. G. Crider (2007), Quiescent degassing of Mount Baker volcano, Washington, USA, *GSA Abstr. Programs*, *39*(4), 65.

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