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RESEARCH ARTICLE

Magma at depth: a retrospective analysis of the 1975 unrest at Mount Baker, Washington, USA

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Abstract Mount Baker volcano displayed a short interval of seismically-quiescent thermal unrest in 1975, with high emissions of magmatic gas that slowly waned during the following three decades. The area of snow-free ground in the active crater has not returned to pre-unrest levels, and fumarole gas geochemistry shows a decreasing magmatic signature over that same interval. A relative microgravity survey revealed a substantial gravity increase in the ~30 years since the unrest, while deformation measurements suggest slight deflation of the edifice between 1981–83 and 2006–07. The volcano remains seismically quiet with regard to impulsive volcano-tectonic events, but experiences shallow (<3 km) low-frequency events likely related to glacier activity, as well as deep (>10 km) long-period earthquakes. Reviewing the observations from the 1975 unrest in combination with geophysical and geochemical data collected in the decades that followed, we infer that elevated gas and thermal emissions at Mount Baker in 1975 resulted from magmatic activity beneath the volcano: either the emplacement of magma at mid-crustal levels, or opening of a conduit to a deep existing source of magmatic volatiles. Decadal-timescale, multi-parameter observations were essential to this assessment of magmatic activity.

Keywords Quiescent degassing · Thermal unrest · Microgravity · Volcano deformation · Stalled intrusion · Cascade Range

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Introduction

How is it possible to know whether a restless volcano will erupt? Can we assess the presence of magma in the absence of eruptive material? These are critical questions in volcanology, since the response to unrest must be commensurate with the likelihood and probable impact of an eruption. Addressing the probability of eruption (or an impending eruption's size and influence) is complicated by the fact that relatively few episodes of non-eruptive unrest have been the subject of intensive study. Attention is most commonly paid to volcanoes with persistent or recent eruptive activity; consequently, the scientific record of volcanic unrest is skewed towards those cases that have resulted in eruption. Additional focus is clearly needed on volcanoes that threatened to, but ultimately did not, experience magmatic eruptions; otherwise, evaluations of volcanic unrest will remain equivocal.

Mount Baker, an andesitic stratovolcano in the Cascade Range of northwest Washington (Fig. 1) experienced an enigmatic episode of unrest in 1975. Few monitoring instruments or baseline measurements were in place prior to the activity, and results from investigations conducted during and immediately following the unrest failed to identify a causal mechanism (Frank et al. 1977; Malone 1979). Here, we review gas flux, gas geochemistry, heat flow and geodetic observations from the period of unrest at Mount Baker, as well as deformation, gravity, seismic, and geochemical data collected in the decades that followed and especially during the mid-2000s. Few previous studies have examined such a broad suite of observations over decadal timescales. Integrated interpretation of the geochemical and geophysical data allows us to distinguish among several hypotheses for the source of unrest, yielding a retrospective interpretation connecting the 1975 activity to a magmatic source. We are hopeful that insights from Mount Baker, combined with studies of unrest at other volcanoes, will ultimately lead to timely and accurate assessments of the likely outcome of unrest during a volcanic crisis.

Setting and background

Mount Baker is the youngest stratocone in a Quaternary volcanic field that has been continuously active for the past 1.3 million years (Hildreth et al. 2003). The volcano, visible from the metropolitan centers of Seattle, Washington, and Vancouver, British Columbia, is located about 50 km east of Bellingham, Washington (Fig. 1). The summit of the volcano reaches an elevation of 3286 m, and the edifice has extensive glacial cover. Geologic mapping and geochronology by

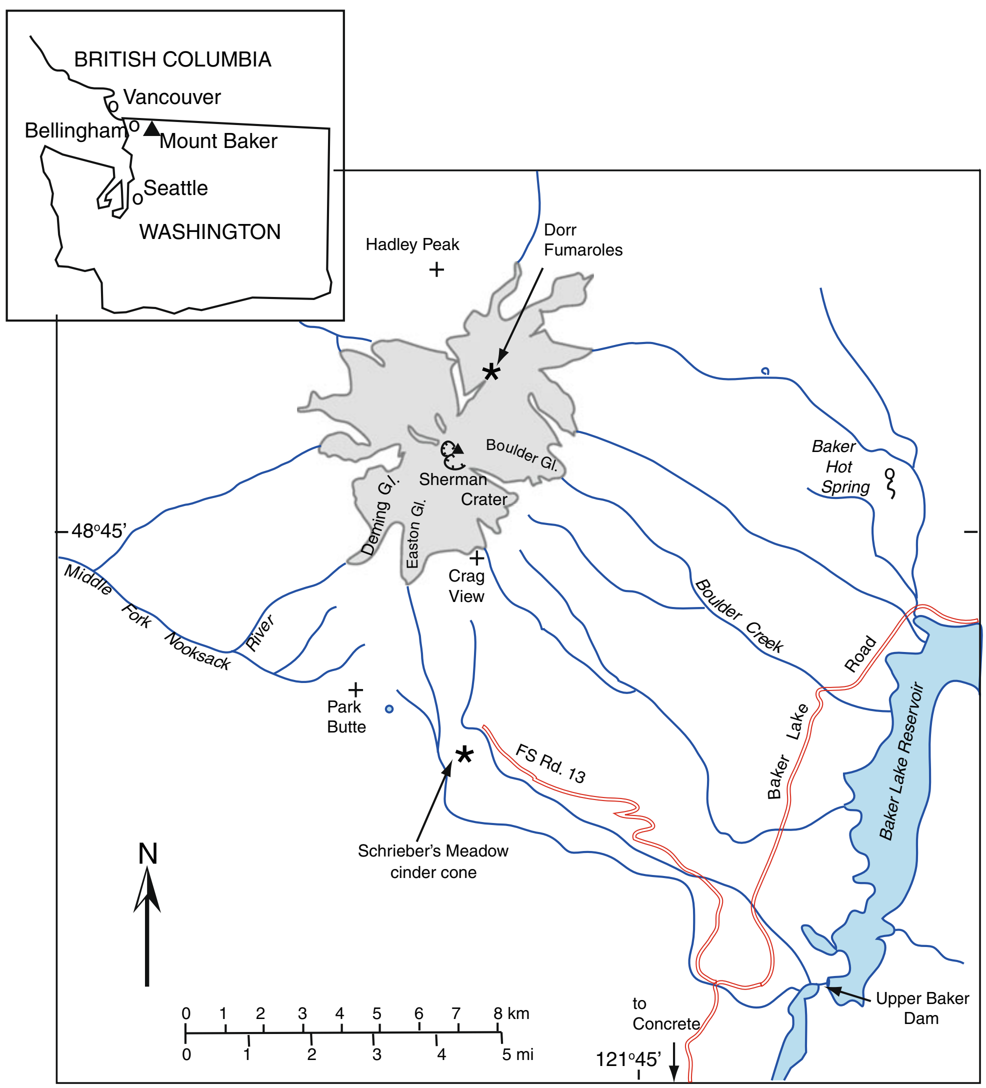

Fig. 1 Key geographic features of Mount Baker volcano. Grey shading shows present glacier cover; small black triangle indicates the volcano summit. Inset shows location. Adapted from Tucker et al. 2007

Hildreth et al. (2003) reveal that Mount Baker is one of the youngest of the Cascade edifices: much of the present cone was built since 40 ka and most of the upper cone since 20 ka.

Tucker and colleagues (2007) recognize four distinct eruptive periods at Mount Baker in the past 15,000 years: The Carmelo Crater eruptive period (~15-12.2 ka B.P.) produced assemblages of lava flows sourced from the summit crater, block and ash flows, and lahars preserved in radial valleys around the volcano. The Schreibers Meadow eruptive period (8850–8500 yr. B.P.) produced tephra and lava flows, flank collapse, and built a basaltic cinder cone on the south flank of the volcano. The mid-Holocene Mazama Park eruptive period (5930–5740 yr. B.P.) is preserved in two tephras and flank-collapse lahars. Historic activity includes a phreatic eruption in 1843 and subsequent lahars originating from Sherman Crater.

The volcano hosts two active fumarole fields: one in Sherman Crater, a glacier-clad bowl south of the volcano's summit (Figs. 1, 2), and the Dorr Fumarole Field, high on the north flank, about 2 km north of Sherman Crater (Fig. 1). Just prior to 1975, Sherman Crater contained an energetic fumarole field with clusters of boiling-point fumaroles along its west and northwest margin and in ice pits within the southwest, northwest, and east parts of the crater glacier. Acidic meltwater drained through the crater's East Breach and under Boulder Glacier into Boulder Creek and then into Baker Lake, a hydroelectric reservoir 13 km distant (Fig. 1). The Dorr Fumarole Field had an area of heated ground about one third that of pre-1975 Sherman Crater. Baseline observations included U.S. Geological Survey photographs of Mount Baker acquired over several decades for glacier studies, intermittent thermal IR surveys begun in the early 1970s, and gas and water chemistry from 1974. Seismic monitoring relied on a single seismic station (MBW) on the west flank of the volcano, 6 km from the crater. MBW, operated since 1972, was the only permanent monitoring instrument of any type on Mount Baker, until a second seismometer was installed in September 2009.

1975 unrest and subsequent observations

Onset

In 1975, Mount Baker underwent the largest observed change in thermal activity since the phreatic episodes of the mid-19th century (Malone and Frank 1975). The unrest occurred at Sherman Crater. The first manifestations of volcanic unrest consisted of increased heat discharge, nonjuvenile lithic and mineral ejecta from fumaroles, and geochemical changes in fumarole emissions and surface water. On March 10, 1975, staff at the Upper Baker hydroelectric dam reported unusually large and dark vapor plumes from Sherman Crater, also visible from the surrounding communities (as compiled by Juday 2006). These initial reports were followed by multiple airborne observations by the U.S. Geological Survey and others of increased steam emission from the crater, increased melting of snow and ice, newly developed crevasses in the crater glaciers, and thin swaths of newly deposited dust adjacent to the crater.

Over the next few weeks, the area of newly exposed heated ground continued to increase. Intermittent snowfall, followed by new dust deposits, revealed continued production of airborne particulates, dominantly from a particularly large 1×5 m fumarole in the East Breach area of the crater (Fig. 2). By mid-April 1975, a 40-m-thick plug of ice melted out of the central part of the crater glacier, exposing

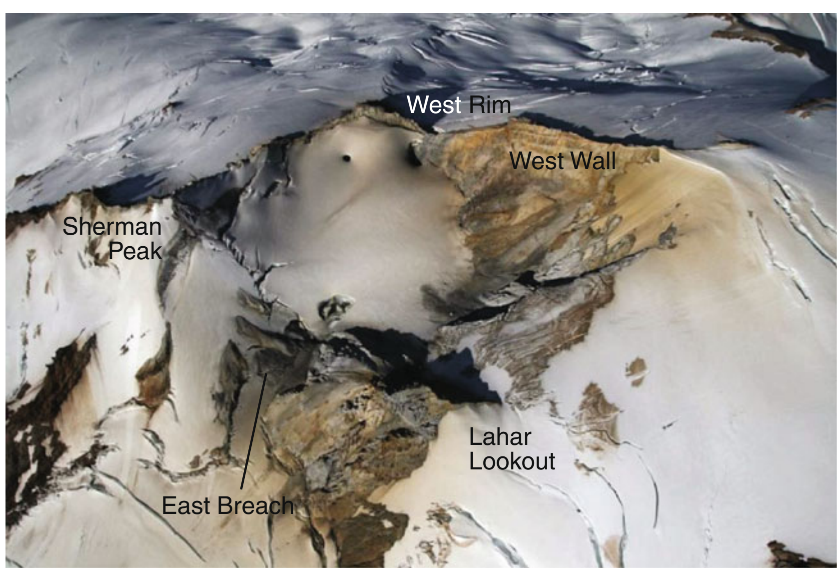

Fig. 2 Oblique aerial view of Sherman Crater, with geographic features noted. Crater diameter is approximately half a kilometer. Photo by John Scurlock, August 2007. View to southwest

a shallow lake. Increased acidic runoff from the lake and fumarole clusters spilled through the East Breach, acidifying Boulder Creek downstream.

Continued melting of snow and ice during the summer of 1975 revealed previously unobserved fumaroles (Fig. 3; Malone and Frank 1975). By September 1975, the snow-free thermal area in Sherman Crater had increased from a typical pre-1975 late-season exposure of 9–10,000 m^2 to almost 30,000 m^2 (Frank et al. 1977). The Dorr Fumarole Field showed no change in thermal activity during the 1975 unrest, and sporadic observations since 1975 have not documented any significant change in this field over the following decades.

Response and observations

Mobilization of multidisciplinary investigations by several institutions followed the onset of unrest on March 10, 1975, and they are described by Malone and Frank (1975). Papers describing these first investigations were given in a special session on volcanology at the October 1975 Pacific Northwest Regional Meeting of the American Geophysical Union (Malone 1976).

Poor weather conditions during the first four weeks of unrest limited initial observations to aerial overflights, seismic monitoring, and lowland stream sampling. The first field team flew into the crater on March 31 to make initial observations, sample ashfall deposits incorporated in the snowpack and install a seismic station on the crater rim (Malone and Frank 1975). Subsequent investigations of unrest throughout spring and summer of 1975 contributed gravity measurements, tilt monitoring, temperature measurements, and sampling of gas, particulates, and crater meltwater. Some investigations continued during and following the 1975–76 winter and, on a less intensive basis, into the 1980s. The volcano was revisited sporadically in the 1990s and more regularly in the 2000s, yielding a sparse record of observations and data for more than three decades after initial unrest.

Heat discharge

Observations from numerous overflights made by multiple parties provided a detailed visual record of changes in activity compared to earlier observations. The U.S. Geological Survey began repeat aerial photography at Sherman Crater on 24 March 1975 and continued for many years thereafter. Photographic surveys were supplemented by thermal-infrared overflights to aid interpretation of visually observed effects of heat emission. An initial thermal-infrared survey (26 March 1975) documented a 50% increase in the area of heated ground compared to previous observations during the same season (Malone and Frank 1975). Additional aerial thermal-infrared data were acquired in April 1975 by Eichelberger and others (1976), and in May another team began a cooperative program of repeat remote sensing (Rosenfeld 1977). More recent unpublished surveys were conducted during the following two decades.

Snow-free thermal areas were mapped with aerial photographs and thermal IR observations, to make calorimetric estimates of that part of the total increase in heat flux required to melt snow and ice: from 2 MW at heat-flux density of 10 W/m^2 averaged over Sherman Crater before 1975, to about 30 MW at 180 W/m^2 during 1975, or roughly an order of magnitude increase in heat discharge (Frank et al. 1977). The snow-free area in the crater has remained high since 1975 (Fig. 3). Aerial thermal-infrared data were further analyzed by Friedman and Frank (1980) to calculate the radiant flux from the crater and, combined with evaluation of all other components of heat flow, were used to estimate the increase in total heat discharge of about 11 MW in 1972 to 80 MW in 1975. Without necessarily endorsing a magmatic source for the thermal increase, Friedman and Frank (1980) cast the net increase in energy yield (2.2×10^{15} J/yr) in terms of a corresponding magma mass of 1.6×10^9 kg, with a volume of 0.008 km^3, or, in its most compact form, a sphere of magma with a radius of 124 m.

Typical fumaroles in Sherman Crater prior to 1975 had openings ranging mostly from a few centimeters to as large as 50 cm and maximum temperatures of about 90°C, the boiling point of water at the crater altitude (Fig. 4). The first fumarole measurements after the onset of unrest (31 March 1975) were limited to the west rim of the crater. These observations found temperatures of 90–91°C (Malone and Frank 1975). Clearly, however, a major locus of new activity was in the East Breach area with a new main fumarole that developed into a 1×5 m fissure. By the time field crews were able to access the East Breach area in September 1975, several superheated fumaroles were measured, with a maximum temperature of 131°C; the west rim fumaroles remained near the boiling point (Frank et al. 1977). A superheated fumarole was eventually found on the west rim in July 1976, with a temperature of 98°C.

Fumarole temperatures have remained high in the decades since 1975. Coinciding with further expansion of snow-free thermal area, additional superheated fumaroles were measured in the west and north part of the crater with a maximum temperature of 150°C in the north wall area in 1994 (Fig. 4; Symonds et al. 2003). Despite several attempts, the new main fumarole remained inaccessible to deep in-throat temperature measurements or sampling. Visual observations of the new main fumarole over the next several years showed waning vapor discharge and accumulation of debris on the lower lip. By the time of a field visit in 1994, the fumarole was completely plugged with debris, although the ground was still warm. The most

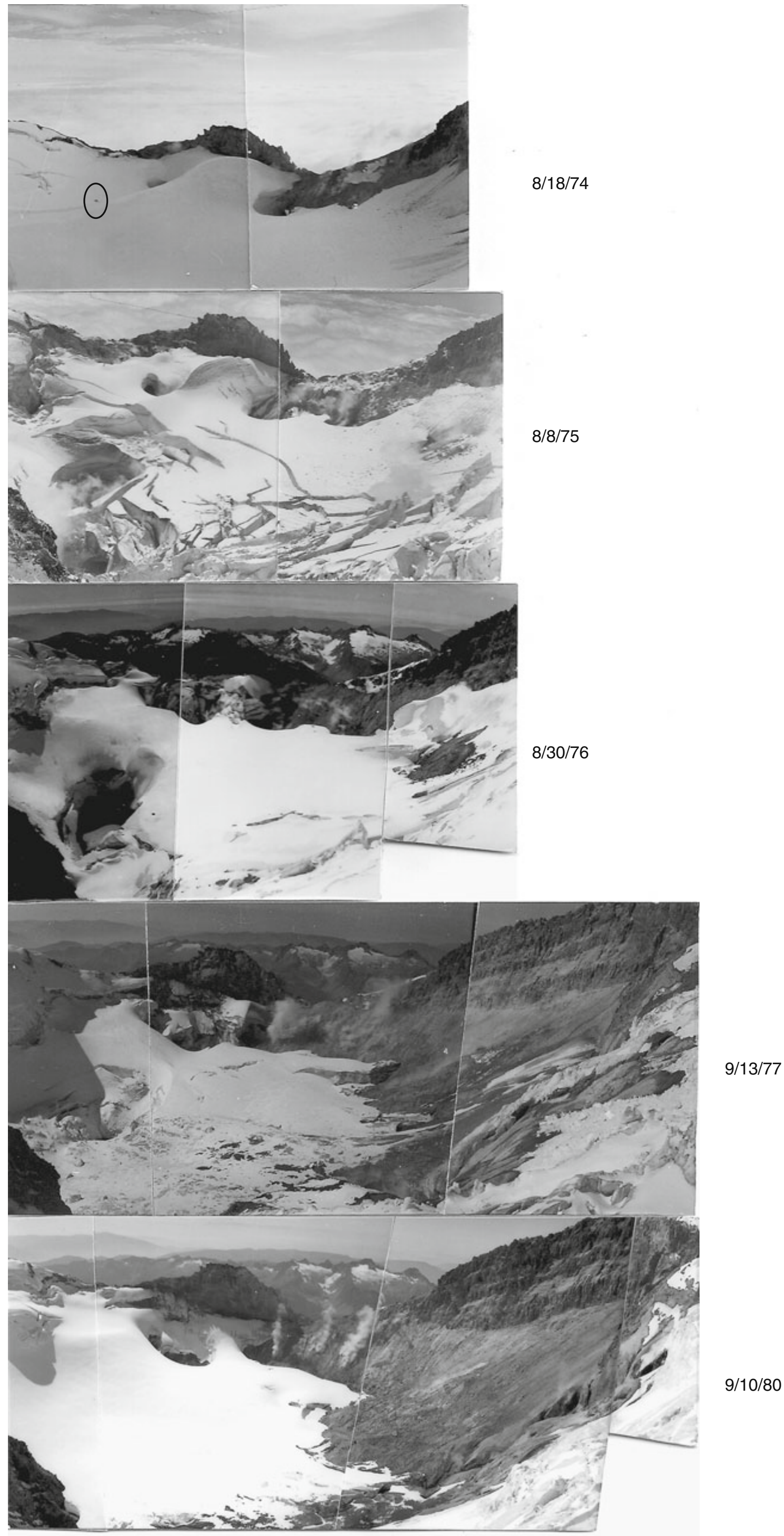

Fig. 3 Development of ice-free thermal area in Sherman Crater from 1974 to 1980. View is toward the west rim of Sherman Crater from a photo point on Lahar Lookout. The photo sequence was taken by DF with the same focal length camera during late summer at approximately the same period of seasonal snowmelt. A tent and standing figure in the upper image provides scale (circled). 8/18/74: Stable thermal conditions six months before onset of unrest. 8/8/75: Glacier breakup following onset of unrest. A large 40-m deep ice pit at the lower left of the image contains a shallow crater lake. 8/30/76: Continued glacial adjustment to increased thermal activity. 9/13/77: Expansion of thermal area following collapse of crater glacier. 9/10/80: Glacier in equilibrium with the new thermal condition, similar to 2007 conditions. Three plumes from fumarole clusters used for gas sampling are visible on the west wall of the crater. About one quarter of the newly exposed ice-free ground in the right part of the image is hydrothermally heated and perforated by small fumaroles

recent observations from 2006 show temperatures of fumaroles in the west part of the crater at pre-unrest levels (90°C; Werner et al. 2009). East Breach fumaroles have not been measured since the mid-1980s.

Fumarole ejecta

Ash production, apparent in the darkened plume from Sherman Crater, was the most obvious indication of unrest in 1975. Examination of particulate-laden snow stratigraphy in Sherman Crater on March 31, 1975, allowed identification of the fall material deposited at the time of the first reports of unrest. All mineral constituents in these initial samples as well as subsequent samples of ashfall and stream sediment collected into September 1975 could be explained as debris originating in fumaroles (Babcock and Wilcox 1977). The material consisted of greater than 10% by volume of opaline silica minerals (including tridymite and cristobalite), large amounts of opaque sulfides (pyrite), lithic and scoriaceous fragments, and a number of minor constituents. Four samples analyzed for a clay-size fraction had greater than 10% by weight of clay minerals. A unique feature of the coarser samples were spheroids of pyrite, opal, and sulfur 0.07–0.5 mm in diameter. Some spheroids were composite, with a thin rind of pyrite that coated a core of opal or sulfur (see McLane et al. 1976). None of the analyses showed evidence of juvenile magma. In particular, scoria fragments and glass shards were encrusted in opaline silica, indicating an origin predating the most recent activity (Babcock and Wilcox 1977). The lack of a magmatic component led to the use of the term *fumarole ejecta* to describe the 1975 ashfall material, although it could also be considered a lithic ash.

Through summer 1975 into September, the densest ash plume originated at the 'new main fumarole' near the East Breach at the base of Lahar Lookout (Fig. 2), although ejecta were also observed from other fumaroles during at least one other period (July 10–11, 1975; Frank et al. 1977). By August–September 1975, mud streams were observed to be discharging from the lower lip of the new main fumarole at the same time as airborne ejecta, so by that time at least part of the fumarole vent had developed into a mudpot. Ejecta production appeared to be continuous over a 6-month period from March to September 1975.

Gas flux and chemistry

The first gas measurement following onset of unrest was an aerial survey using a flame sulfur analyzer on 27 March 1975 that measured 30 t/d of gaseous sulfur in the fumarole plume and a 10 ppb contour that extended as far as 90 km downwind (Radke et al. 1976). The sulfur species is assumed to have been H_2S (Werner et al. 2009). Subsequent measurements on 30 June 1975 found 112 t/d (Fig. 4). The first gas measurements on the ground were limited to the use of colorimetric tubes at west rim fumaroles on 31 March 1975, yielding 27% CO_2 and 0.15% H_2S, compared to 19% CO_2 and 0.0074% H_2S in August 1974. In gas samples from August 1975, the values increased to 36% CO_2 and 7.4% H_2S (Kiver and Steele 1976). Both airborne and ground sampling suggested increasing gas emissions through summer 1975.

The morphology of the crater allowed surface water and shallow ground water to act as a condenser of gas emissions. The condensate, also influenced by geochemical interaction with crater rock and hydrothermally altered debris, and highly diluted by snow and ice meltwater, drained through the East Breach of the crater to eventually influence the composition of Boulder Creek. The first water measurement following the onset of unrest, was a sulfate-laden (264 mg/L) sample on March 11 in Boulder Creek (Fig. 1), 11 km downstream of the crater. Repetitive sampling through 1975 recorded continued production of acidic drainage at that distance from the crater, with the most extreme values from samples collected in March, April, and early May of 1975 (Bortleson et al. 1977).

Water samples from the crater lake and from the creek in the East Breach (the "crater creek") during June–September 1975 had temperatures of 15–34°C, pH values of 2.4–3.0, 850–1300 mg/L sulfate, and 4.2–28 mg/L chloride with the most extreme values occurring in the crater lake in June 1975. In comparison, values of 7–8°C, 2.8–3.2 pH, 450–510 mg/L sulfate, and 0.9–1.6 mg/L chloride were measured in the crater creek in May and August 1974, indicating development of a dilute acid sulfate-chloride composition for shallow hydrothermal solutions during 1975 (Frank 1983).

Subsequent sampling of the crater creek in 1976–1981 yielded pH values of 2.6–2.9, 660–1500 mg/L sulfate, and 4.5–21 mg/L chloride, indicating continued production of sulfate-chloride solutions during that period. At the Boulder Creek bridge, 11 km downstream, seasonal influence of rainfall and snowmelt are apparent in timeseries of pH (Frank, unpublished data). For 1976–1981, late season (August–October) samples collected to avoid peak snowmelt runoff were in the ranges of 3.7–4.2 pH, 38–80 mg/L sulfate, and 0.5–1.5 mg/L chloride. Comparable samples in 1993–94 yielded 3.8–3.9 pH, 69–70 mg/L sulfate, and 0.4–0.7 mg/L chloride. These data are consistent with a relatively long-term influx of acidic fluids into Boulder Creek from Sherman Crater for many years following the 1975 unrest.

Fumarole geochemistry and gas emissions have been measured episodically since 1975 (see Werner et al. 2009, for description of methods). Total gas emissions have waned with time (Fig. 4), with H_2S declining from 112 t/

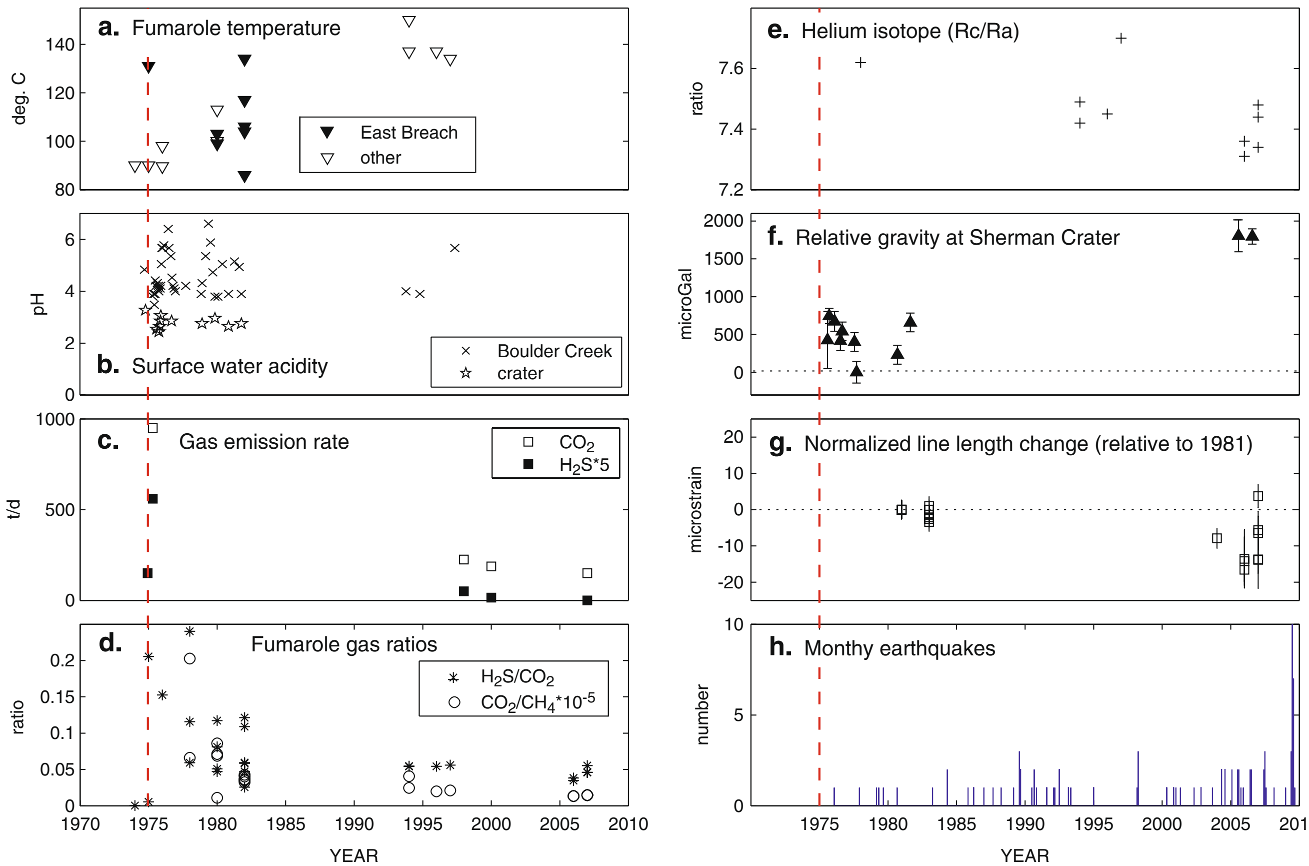

Fig. 4 Thirty-five years of geochemical and geophysical observations of Mount Baker, 1974–2009. Vertical dashed lines indicate the onset of unrest. Data sources as follows: **a, c, d, e**) Werner et al. 2009 and references therein; **b**) Bortleson et al. 1977; Frank 1983 and unpublished data; **f**) Crider et al. 2008 and references therein; **g**) Lines 4, 6, 7, 8, 9, 10, 11 and 16 of Chadwick et al. 1985 showing significant change in 2004–2007 (Hodge and Crider 2010); **h**) Time series for PNSN catalog events shown in Fig. 6. About half of the earthquakes are low-frequency events, including the anomalous swarm in 2009. Time series does not include DLPs

d in 1975 to <1 t/d in 2007, and CO_2 declining from an estimated 950 t/d in 1975–76 to 150 t/d in 2007. Because no measurements were made in the 1980s or early 1990s, it is unknown how the emissions decreased with time. Gas geochemistry of fumaroles, however, showed a fairly rapid change in chemical composition in the few years following 1975; thus, emission rates might also have dropped substantially between 1975 and 1982 (Werner et al. 2009). The emissions of CO_2 and H_2S both declined gradually between 1998 and 2007 (Fig. 4).

Large changes occurred in chemistry of fumaroles from Sherman Crater during and following the unrest. The only chemical constituents measured during the unrest episode were H_2S and CO_2 (Kiver and Steele 1976). Between August 1974 and March 1975, the H_2S/CO_2 ratio in fumarole samples was fairly stable, but the ratio increased by a factor of 20 between March and August of 1975 (Fig. 4). By 1976, the H_2S/CO_2 ratios had dropped back to 0.15 from a maximum of 0.2, and in the years since, the H_2S/CO_2 ratio decreased steadily to near ~ 0.05 by 2007 (Werner et al. 2009). Also noteworthy is that the CO_2/CH_4 ratio was very high in 1976, indicating an enrichment in CO_2 coincident with the unrest (Werner et al. 2009). Since ~ 1978, however, there has been a steady increase in CH_4 relative to CO_2 (Werner et al. 2009).

Finally, carbon and helium isotopic signatures have also changed over time. The carbon isotopic signature of the CO_2 decreased slightly from the late 1990s to the late 2000s ($\delta^{13}C_{CO2}$=-5.9‰ in 1997, −6.7 in 2006, and −7.3 in 2007; Werner et al. 2009). Average He isotopic ratios (R_c/R_a) fell from ~ 7.6 to 7.4 between 1978 and 2007 (Fig. 4). The helium isotopic signature measured at Mount Baker in 1978 (R_c/R_a=7.62) was one of the highest in all of the Cascade Range, exceeded only in spring waters near Three Sisters, Oregon, (R_c/R_a=7.8; Evans et al. 2004).

Gravity

Two gravity stations were established on the rim of Sherman Crater in May 1975, along with a control station at the Concrete, Washington, airport 25 km to the south (Malone and Frank 1975). Results from reoccupying the stations seven times over the next four months showed a gravity decrease of 550 μGal at Sherman Crater relative to Concrete (Fig. 4). Four additional measurements during 1976, when corrected for seasonal snow and ice loads, suggest little gravity change. Subsequent measurements in 1977–78 indicated a slight increase at the crater rim stations compared to 1976, but of the same order as the expected error (Malone 1979).

Hill (2007) reoccupied Malone's (1979) gravity stations at Sherman Crater (SHRM) and on the south flank of the volcano (CGVW) in 2005 and 2006 (Fig. 5). The repeat, relative microgravity survey used the same instrument as the original survey and shared a common base station at the Concrete airport. These microgravity measurements show an 1800 ± 300 μGal gravity increase between 1977 and 2005 (Fig. 4; Crider et al. 2008). Possible variation in ground water levels beneath the base station, and large closure errors due to long distance transport and large elevation changes, contributed to the large uncertainty in the measurement. Crider and others (2008) model variations in snow pack and glacier cover to evaluate the influence of these environmental factors on the observed gravity change. Observations of decreased late-summer snowpack and decreased glacial thickness between 1977 and 2005 reduce the mass on the volcano; this non-volcanic mass change may mask as much as 100% additional gravity increase from changes within the volcano. Thus, the reported 1800 μGal increase is a minimum estimate of the gravity change.

Surface deformation

No strong signal of surface deformation was immediately associated with the 1975 unrest. Sylvester-model 1.2-m-long tilt-bar stations were installed at six sites around Mount Baker by May 1975 and re-leveled at intervals of 10–60 days (Nolf 1976). Three spirit-level tilt stations using fixed points 20–40 m apart were installed by the U.S. Geological Survey on the flank of Mount Baker in July 1975 and resurveyed twice during the summer (Frank et al. 1977). Continuously recording, telemetered tiltmeters were also installed in September 1975 in 1.5-m-deep boreholes near two of the spirit-level sites.

The net tilt from July to September at two of the three spirit-level stations was 7–7.5 μrad directed away from the cone, but was not considered to be significantly greater than the expected error (Frank et al. 1977). Data from the two borehole tiltmeters showed a cumulative tilt of 50–100 μrad through the fall and early winter of 1975, leveling off from December to March 1976. Although the tiltmeter data could be interpreted to be due to withdrawal of magma from beneath the north flank during fall 1975, inconsistencies with spirit-level data, uncertainties due to environmental effects, and concern over the stability of the measurement sites argued against a magmatic source. Results reported by Nolf (1976) for the tilt-bar stations were inconclusive.

The U.S. Geological Survey installed fourteen geodetic benchmarks around Mount Baker in summer 1981, establishing a network of 19 trilateration lines (Fig. 5) to monitor surface deformation (Chadwick et al. 1985) . Electronic distance measurement (EDM) surveys conducted in 1981 and 1983 did not resolve any surface deformation (Chadwick et al. 1985).

In 2006 and 2007, Hodge (2008) reoccupied Chadwick and colleagues' (1985) EDM sites with GPS, completing a mountaineering resurvey of the entire network. Shortly after the initial EDM surveys, most of the volcano was declared a federally-protected wilderness area, and helicopters were no longer permitted. Hodge and Crider (2010) report the subsequent analysis and modeling of the GPS resurvey, reviewed here: Two of the initial 14 benchmarks were disrupted by shallow mass wasting, reducing the network from 19 to 15 lines. Of these fifteen, nine lines showed length changes greater than uncertainty. Eight of the nine lines with significant change shortened (Figs. 4 and 5). Average change per unit length across the network over the period 1981–2007 is −6.7 ppm, with greater change per length observed on the northern flank of the volcano, at about −15 ppm. Estimates of two-dimensional surface strain rate indicate that, during the period of observation, areal dilatation accumulated at a rate of −417±141 nanostrain/yr, with shortening on both principal strain axes. This value is two orders of magnitude greater than the background tectonic strain rate, estimated from permanent GPS stations to be -3 nanostrain/yr, and ten times greater than the maximum expected interseismic elastic strain rate due to locked subduction of the Juan de Fuca plate beneath the forearc west of the volcano.

Surface deformation data were inverted to determine the best fit point source beneath an elastic half space (Mogi 1958). Hodge and Crider (2010) found the source location to be between 1000 and 1800 m north and 0 to 800 m east of the summit of Mount Baker, at 4 to 6 km depth, using a bootstrap method to determine these 95% confidence ranges. The optimal point source is 1360 m north, 285 m east of the summit at a depth of 5.8 km, beneath the Dorr Fumaroles. Hodge and Crider (2010) estimated the volume change of that source to be -2 to -16×10^6 m^3 (varying with source depth), with a best-fit value of -11×10^6 m^3 at the optimal location. This model yields ~10 cm of subsidence (over 1981–1983 to 2007–2008) centered above the source. Line–length changes calculated from the best-fit model show a strong correspondence to the observed line-length changes of the EDM-GPS comparison (R^2=0.91). Hodge and Crider (2010) concede that, given uncertainties in the EDM-GPS comparison, it is possible to find an acceptable fit to the data using a wide range of parameters, and this model solution is not unique. Special care is warranted when interpreting the volume-change estimate: the nature of the EDM data precludes inversion for variation in source geometry, and volume change estimates are variable for different source shapes.

Seismicity

In contrast to typical seismicity at other Cascade volcanoes, few earthquakes have been detected at Mount Baker. Of particular note is the lack of seismicity associated with the 1975 unrest, but Mount Baker's seismic quiescence appears long-lived: fewer than 90 earthquakes have been cataloged in the Mount Baker region in 38 years (1972–2010) by the regional Pacific Northwest Seismic Network (PNSN; Figs. 4, 6). This is partly due to the sparse seismic network: other than MBW, the closest permanent stations were more than 30 km away; thus, only large earthquakes (>M1.7; Moran 2005) were reliably detected by the regional network.

A temporary station (SCW) was installed on 31 March 1975 on the south crater rim, lowering the event detection threshold to less than 0 for events directly under the crater. By the end of summer in 1975, five additional short period stations were installed within 8 km of Sherman Crater, including two additional instruments on the crater rim. Four stations survived the ensuing winter, providing an excellent record of seismicity for the first year following the onset of unrest (Frank et al. 1977). Despite the enhanced network, only one earthquake was located beneath the volcano during that year: a M_L=1 earthquake located about 1.5 km east of Sherman Crater at 3–6 km depth on

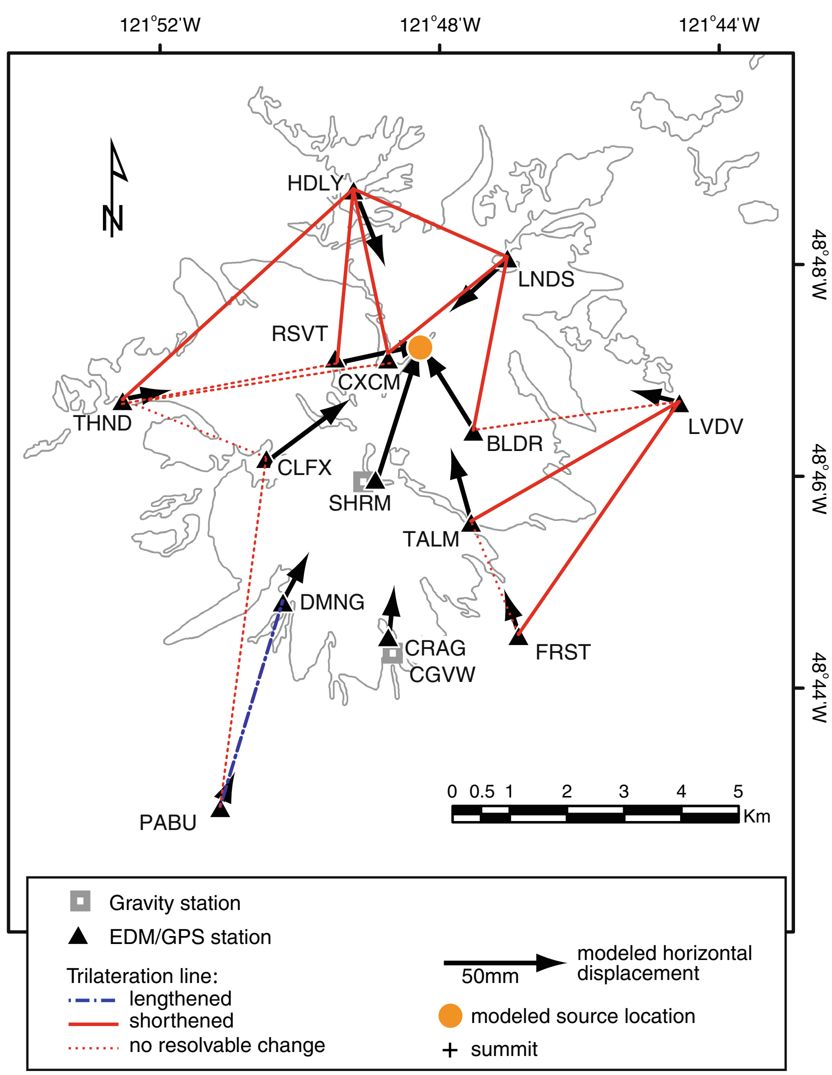

Fig. 5 Deformation and gravity stations on Mount Baker, also showing observed (*lines*) and modeled (*vectors*) deformation of the volcanic edifice, 1981–2007. Outline shows ice extent on the volcano. Modified from Hodge and Crider (2010)

February 27, 1976, almost one year after the onset of unrest (Malone 1977, 1979).

The seismic background noise during most of April 1975 was moderate at SCW, which was located at 3130 m on a mountain subject to frequent storms and strong winds. On April 27, 1975, a dramatic increase in the background noise was observed for several hours. This noise recurred sporadically over the next few weeks and was interpreted as variation in the fumarole's venting mechanism. Wind effects were ruled out based on a lack of correlation between observed weather in the Mount Baker area and seismic noise levels. Large changes in the pressure and volume of vapor coming from the fumaroles were observed from time to time, but these observations were not sufficiently quantitative to make rigorous comparisons with the seismic noise level changes (Malone and Frank 1975).

While unambiguous earthquakes are rare at Mount Baker, there have been many transient events attributed to glacier sources. About half the seismic events in the PNSN catalog are characterized by low frequencies. Studies at Mount Rainier and Mount St. Helens in the early 1970s indicated that similar, low-frequency events were largely, if not entirely, due to the movement of glaciers (Weaver and Malone 1979). Transient low-frequency events were recorded at station SCW in 1975 and to a lesser degree at MBW; they have identical characteristics to ice events and seem to be seasonal in their occurrence (Frank et al. 1977).

During the summers of 2007 and 2008, four broadband seismometers were temporarily deployed on the volcano for periods ranging between 4 and 8 weeks (Caplan-Auerbach et al. 2007; Caplan-Auerbach et al. 2009). During these deployments, several dozen locatable earthquakes were recorded by the network; none of these events was detected by the regional PNSN network. Most of these events were small, and locations are poorly constrained; hypocenters scatter around the volcano, with no clear clustering. Instruments located near glaciers recorded a markedly higher rate of seismicity than other stations, supporting the argument that most activity on Mount Baker is related to glacial processes such as basal slip and crevassing. In the summer of 2009, both the PNSN and temporary network on the volcano detected an unprecedented swarm of shallow, low frequency events (Fig. 4; Moran et al. 2009; Caplan-Auerbach et al. 2009). The swarm occurred during the melt season of a year in which ice on the volcano reached an exceptionally low volume, and may therefore be connected to unusually-high rates of melt-related basal slip or ice deformation. However, no correlation was observed between the increased rate of seismicity and air surface temperatures or stream flow on Nooksack River, into which many of Mount Baker's glaciers drain (Moran et al. 2009). Thus, although glacial activity is a likely source of the low-frequency earthquakes, hydrothermal sources cannot be ruled out (e.g., Chouet 1996).

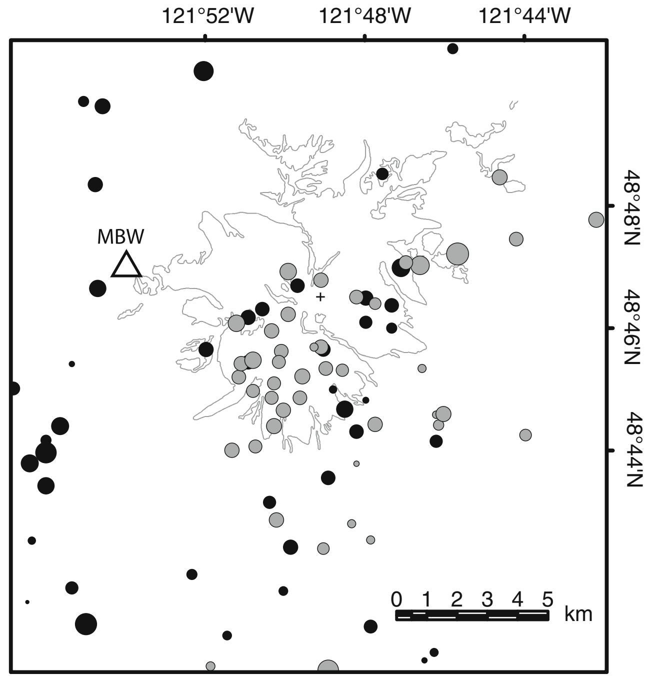

Fig. 6 Epicenters of earthquakes in the vicinity of Mount Baker, 1972–2009 from the Pacific Northwest Seismograph Network catalog. Circle size is proportional to magnitude, with a range of M 0.4 to M 2.7. The gray circles identify low frequency events. These data do not include observations from temporary arrays or DLP events. The white triangle shows the location of permanent short period station MBW, in operation since 1972. Outline shows ice cover. Cross marks summit

In addition to the shallow (<3 km) low-frequency events described above, Mount Baker is host to deep (>10 km) long period (DLP) earthquakes. Nichols and colleagues (in review 2010) identify more than 30 DLPs during 1980–2009 not included in the PNSN catalog, including the deepest and the largest DLP events in the Cascades (Nichols et al. 2009). DLPs are substantially more common at Mount Baker than at other, more seismically and magmatically active Cascade volcanoes (Nichols et al. in press 2010). This type of activity has been associated with deep magma recharge and/or migration of volatiles, and DLPs are known to precede some eruptions (e.g., White 1996; Power et al. 2004).

Discussion

Initial interpretations

In 1975, based primarily on the absence of any significant earthquakes before or following the increased fumarolic activity, the chances of a magmatic eruption at Mount Baker in the near future were thought to be very low. The lack of earthquakes and insignificant edifice-wide deformation suggested that strain rates were low and, therefore, movement of magma to shallow depths was deemed unlikely. Instead, the favored interpretation for the unrest was that increased heat emission was due to a relatively minor change in the deep part of the Sherman Crater hydrothermal system. This change in plumbing allowed for meteoric water to more easily access a deep heat source and/or take easier paths to the surface. The slight reduction in gravity and the higher concentrations of volcanic gasses (CO_2 and H_2S), however, suggested the possibility of magmatic processes at work (Fig. 4).

The increased fumarolic activity was recognized as generating a potential hazard in itself. The new main fumarole was at the base of a steep part of the north-east crater rim called Lahar Lookout, just above the Boulder Creek drainage (Figs. 1, 2). Accelerated hydrothermal alteration of this already highly altered structure could cause slope failure, generating a high-speed debris flow or lahar down Boulder Creek and into Baker Lake. Prior observations had shown that this area was already prone to frequent failures (Frank et al. 1975). If a large enough volume entered the lake at high speed, a wave could be generated that would overtop the dam, possibly causing it to fail (Gardner et al. 1995). In recognition of this hazard, the reservoir was maintained at a lower level by the dam operators during 1975 and early 1976 to accommodate the estimated debris flow volume.

Retrospective interpretations

Although a change in the hydrothermal system was the preferred explanation of the observed unrest in 1975, persistent high temperatures and magmatic helium isotope ratios suggest the presence of magma. Individual data sets (gas, deformation, gravity) collected in the succeeding decades each show signs of a gradual decay in magmatic signatures since the period of unrest and tend to support the interpretation of active magmatism at Mount Baker. At least four hypotheses invoking magmatism can explain the sudden increase in temperatures and gas flux in 1975, the post-unrest persistent high temperatures, and the magmatic helium ratios: (1) constant resupply of magma into the edifice, (2) a single intrusion of magma that stalled beneath the edifice in 1975 or earlier, (3) opening of a pathway to a deep reservoir of magmatic volatiles, and (4) opening of a pathway to a convecting magma source. Although individual data sets cannot distinguish among these hypotheses, each hypothesis is characterized by a unique combination of gas composition, gas emissions, temperature, gravity, deformation, and seismicity timeseries (Fig. 7).

Werner and others (2009) discuss changes in gas geochemistry and emissions at Mount Baker since the 1975 unrest. Their preferred explanation of the data was that a magmatic intrusion occurred in 1975, and, since that time, the volcano and its hydrothermal system have been recovering from this perturbation. The initial increases in CO_2 and H_2S were thought to be directly related to the high content of these species in the magmatic gases. Rapid decreases in CO_2/CH_4 (2 orders of magnitude between 1976 and 1978) likely resulted from the passing of a pulse of magmatic gas in which CH_4 is a minor constituent, whereas the slow decrease in CO_2/CH_4 observed since 1979 most likely indicates more CO_2 reacting to CH_4 as equilibrium between the two species was gradually established over time. Similarly, decline in the δ^{13} C of CO_2 (~−5.9 in 1994 to −7.3 in 2007) is consistent with gradual CO_2 loss from a cooling intrusion, as discussed by Gerlach and Taylor (1990), and is similar in magnitude to the decline in δ^{13} C that has occurred at Mount St. Helens since the 1980 eruption (Bergfeld et al. 2008). Also, the progression of the isotopic signature of He at Mount Baker over time suggests that the mantle-derived magmatic component of He declined slightly over the 30 years since the mid-1970s. Similar decreases have been observed at other Cascade Range volcanoes over similar timeframes (e.g., Mount Shasta decreased by 0.7 Rc/Ra units over 24 years, Symonds et al. 2003).

The level of gas emissions over time is consistent with changes in gas geochemistry, and the levels reached in 1975 (112t/d H_2S and 950t/d CO_2) are similar to those of other hypothesized ‘stalled intrusions’ in Alaska (Roman et al. 2004; Werner et al. 2011), but low compared to eruptive emission rates. Emissions during eruptions at ice-clad andesitic volcanoes similar to Mount Baker typically reach levels in excess of 2000t/d CO_2, commonly exceeding 10,000t/d (Doukas and Gerlach 1995; Hobbs et al. 1991). SO_2 emission rates can also exceed 1000t/d. H_2S emission has not been measured extensively during eruptive activity at such volcanoes, but the measurements that do exist suggest very low H_2S relative to SO_2 emission (Doukas and McGee 2007; Werner et al. 2011). No SO_2 has been detected at Mount Baker, which is expected considering that the maximum sampling and equilibrium temperatures are quite low (150°C and 242°C, respectively; Werner et al. 2009). In most cases of unrest (with or without eruption) at Alaskan Cook Inlet volcanoes, emissions of CO_2 and H_2S decline rapidly during the first year following the unrest and are below detection limits after a few years (Casadevall et al. 1994; Roman et al. 2004). This rapid decline to background levels differs from the long-term nature of the decline of gas emissions at Mount Baker, suggesting that there could be connectivity to a deep magma source, as also discussed by Werner and others (2009).

Although changing climactic conditions may make a small contribution to the persistence and enlargement of snow-free areas in Sherman Crater, high fumarole temperatures through the mid-1990s support the inference of

	PREDICTED POST-EVENT PHENOMENA (years to decades)						
HYPOTHESIS	**Gas chemistry**	**Gas emissions**	**Temperature**	**Residual Gravity**	**Deformation**	**Seismicity**	***Example***
Constant resupply of magma	*Persistent magmatic signature*	*High*	*Persistently high*	*Increase*	*Inflation*	*Abundant VTs and LPs*	Kilauea[1]
Shallow stalled intrusion	*Waning magmatic signature*	*Decreasing to background in a few years*	*Decreasing*	*Increase*	*Deflation*	*Waning VTs*	Iliamna[2], Akutan[3]
Conduit opened to deep volatiles	*Persistent or waning* magmatic signature*	*High or waning**	*Persistently high or waning**	*Decrease or increase**	*Deflation*	*Few VTs; LP events*	Mammoth[4]
Overturning magma	*Persistent magmatic signature*	*Persistent, cyclic*	*Cyclic***	*Cyclic***	*Cyclic***	*Varying; LP events*	Masaya[5], Poas[6]
Mount Baker Observations	*Waning magmatic signature*	*Persistent; slowly waning*	*Persistent snow-free areas; variable fumarole temps*	*Increase*	*Deflation*	*Deep and shallow LP events; few VTs*	

Fig. 7 Hypotheses for the cause of the 1975 unrest at Mount Baker and associated predictions. "Residual gravity" is corrected for free air effects of deformation, and so reflects mass or density changes only. VT: volcano-tectonic earthquakes (shallow, impulsive onset); LP: long period earthquakes. *Waning gas and temperature signatures are predicted if open conduit is resealed over time; gravity may increase due to redistribution of mass in shallow hydrothermal minerals. **Depending on the rate of overturning relative to sampling rates, these phenomena could also appear steady. [1]Dzurisin et al. 1984. [2]Roman et al. 2004; [3]Lu et al. 2000; [4]Farrar et al. 1995; [5]Williams-Jones et al. 2003; [6]Rymer et al. 2000, 2009

continued high heat flux due to the proximity of magma or a persistent volatile source. Water geochemistry from the crater creek and Boulder Creek show constant acidification and elevated sulfate, consistent with continued gas output and active rock alteration.

The relative gravity surveys at Mount Baker show post-unrest recovery and mass redistribution. Crider and others (2008) argue that magma densification and shallow mineral precipitation are the most likely sources of gravity increase, and that hydrothermal recharge may make only a minor contribution. The observed surface deformation alone could produce only a 30 μGal gravity increase, or less 2% of the observed gravity change. Although continued magmatic intrusion would also lead to a gravity increase, this mechanism is inconsistent with observed shortening of EDM line lengths and declining magmatic gas components during the same interval.

Deformation data suggest that the volcano has experienced deflation and mass loss. Hodge and Crider (2010) reject thermal contraction as a primary mechanism for deflation of Mount Baker, because the magma volume required to produce the observed line length shortening is unreasonably large. They also reject deformation from a shallow hydrothermal source because inversion of the deformation data gives an optimal source depth greater than 2 km. Using CO_2 flux values of Werner and colleagues (2009), they estimate that only 10%–20% of the observed deformation can be due to CO_2 loss; however, significant additional volume loss and densification by H_2O degassing from a magma body could plausibly account for the remaining deformation. Similar volume change could be achieved by breaching of, and vapor loss from, a deeper hydrothermal source.

Observations from seismicity show abundant low frequency and long-period sources and relatively few volcano-tectonic (short period) events. Although the possibility of magmatic intrusion at Mount Baker was initially dismissed due to the absence of short period seismicity, aseismic intrusion to the mid-crust (6–10 km) has since been documented elsewhere (e.g., Lu et al. 2000; Dzurisin et al., 2006); therefore, the paucity of earthquakes does not preclude magmatic activity at those depths. The source of shallow (<3 km) low frequency events is very likely related to glacial processes. The high number of deep (>10 km), long-period events is intriguing and may indicate the presence or movement of deep magma and associated volatiles. It is not evident whether the DLP activity suggests recovery from magma redistribution in 1975, indicates the possibility of future unrest, or is unrelated to the surface manifestations of volcanism at Mount Baker.

The combination of observations does not support the hypotheses of constant shallow intrusion. In particular, observed EDM line-length shortening across the edifice is inconsistent with increasing magma volume since 1975, and abundant shallow seismicity is expected to accompany the migration of magma into the upper few kilometers of the edifice. Nor can we support the hypothesis of convective overturning of a deeper magma source on a decadal timescale; although most of the time series are sparse, we see little evidence of cyclic behavior in any of the magmatic indicators in three decades. These observations cannot identify magmatic overturning at longer intervals, and the sparseness of the timeseries precludes detection of rapid overturning.

Many of the observations are consistent with a magmatic intrusion to the mid crust, emplaced in 1975 or earlier. Increases in CO_2 emissions are consistent with the arrival and subsequent degassing of magma at mid-crustal depths (Gerlach et al. 2002). The composition and isotopic ratios of gases during 1975 and shortly thereafter were indicative of intrusion of fresh magma beneath the volcano, and declines in those parameters suggest a transition to a hydrothermal source (Werner et al. 2009). Deflation is consistent with volume loss due to degassing, and gravity increase could be attributed to densification of the cooling and degassing magma body.

We also find strong support for the opening of a conduit to a deep volatile source in 1975, accompanied by a pulse of magmatic gases. As suggested by Hodge and Crider (2010), the 1975 unrest may represent the surface manifestation of the release of volatiles from a deep magma source. Prolonged degassing also suggests connection to a deep magma source rather than a stalled, shallow intrusion (Werner et al. 2009). Slowly waning gas emissions could be attributed to resealing of this new conduit, with the observed gravity increase due to precipitation of shallow hydrothermal minerals (Crider et al. 2008). Observations of deep, long period earthquakes also support the presence of deep magmatic fluids.

Conclusions

In some cases of non-eruptive volcanic unrest, there can be no doubt that rising magma drove the observed activity: intense seismicity and ground deformation in 1996 at Akutan, Alaska, was obviously a result of magma that ascended to within 1 km of the surface (Lu et al. 2000). Often, however, unrest at volcanoes is less intense and the source mechanisms are more ambiguous, as was the case in 1975 at Mount Baker. Our analysis of 30+ years of geophysical and geochemical data from Mount Baker suggests the presence of an active magmatic source beneath the volcano that may have been emplaced or had pathways to the overlying hydrothermal system disturbed in 1975, causing the observed thermal and gas emissions. The 1975 unrest, combined with longer-term geophysical and geochemical datasets, is an indicator that magma is present beneath the edifice, and establishes the potential for future eruptive activity at Mount Baker.

Examples of volcanoes that have displayed signs of magmatic presence, such as Mount Baker, provide a blueprint for interpreting ambiguous manifestations of unrest at other volcanoes. Deformation and seismicity at the typically-quiescent Eyjafjallajökull volcano in Iceland indicated the intrusion of a sill at ~ 6 km depth in 1999 (Pedersen and Sigmundsson 2006), ultimately leading to its eruption in 2010. Seismicity and temperature changes at the Martin-Mageik volcanic complex in Alaska mid-1990s suggested the presence of a degassing, mid-crustal intrusion (Jolly and McNutt 1999), and persistently high helium isotope ratios there are indicative of a magmatic source at depth (Symonds et al. 2003). Increases in heat flux, seismicity, and gas emissions accompanied the formation of a meltwater lake and the disruption of summit glaciers during 2004–2006 at Mount Spurr, Alaska. Other than the increased seismicity, the activity was similar to Mount Baker's 1975 unrest, and Coombs and others (2006) infer that intrusion of magma drove the unrest at Mount Spurr.

Importantly, shallow seismicity is not a strong indicator of magmatic activity at Mount Baker, underscoring the value of a diverse suite of monitoring observations. In this case, gas emissions and chemistry, particularly the observation of high CO_2 emissions, provide the strongest evidence for magmatic activity at depth.

The decadal timescale of observations is key to our interpretation of deep magmatic activity at Mount Baker. The deformation and gravity change, and the slowly waning magmatic signatures of the fumarole gases, could not be identified without solid baseline observations and sufficient elapsed time. Intermediate-term (decadal-scale) indicators of potential volcanism are elusive in volcanology (Dzurisin 2003), yet are critically important for anticipating activity far enough in advance to facilitate intermediate-term mitigation measures, such as relocating critical facilities, implementing a comprehensive emergency response plan, and establishing a reliable short-term warning system. Eyjafjallajökull's stalled intrusion in 1999 and subsequent eruption 11 years later provides further motivation for long-time series datasets. For this reason, it is important to identify volcanoes like Mount Baker that are underlain by active magma bodies, and to observe and understand the surface manifestations of magma deep beneath the surface.

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