Photographic Documentation of the Evolution of Crater Glacier, Mount St. Helens, Washington, September 2006—November 2009

By Joseph S. Walder, Steven P. Schilling, David R. Sherrod, and James W. Vallance

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Abstract

Lava-dome emplacement through a glacier was observed for the first time during the 2004–08 eruption of Mount St. Helens and documented using photography, photogrammetry, and geodetic measurements. Previously published reports present such documentation through September 2006; this report extends that documentation until November 2009.

Introduction

The cataclysmic eruption of Mount St. Helens on May 18, 1980 created a north-facing, amphitheater-like crater. Over time, rock debris and snow shed from both the crater walls and a lava dome that grew within the crater (Swanson and others, 1987; Mills, 1992; Schilling and others, 2004). The rate of accumulation was exceptionally high, and by September 1996 it was reasonably clear from photographs that a crater glacier had come into existence: photographs showed crevasses (Fig. 1), which reflect flow (Paterson, 1994). At the time that the volcano began to erupt again in October 2004, the crater glacier—at that time not yet formally named—had grown into a horseshoe-shaped feature that wrapped around the 1980–86 lava dome. In the early phases of the 2004 eruptive activity, a lava dome punched through the crater glacier and cut it in half. Walder and others (2007, 2008) and Vallance and others (2008) described how glacier deformation subsequently unfolded, and the reader is referred to those reports for details. To summarize, as dome growth progressed, first the east arm of the glacier (informally, east Crater Glacier), then the west arm of the glacier (informally, west Crater Glacier) were squeezed between the growing lava dome and the crater walls. Glacier deformation associated with the squeezing, as documented by photography, photogrammetry, and geodetic measurements, was extreme, with strain rates of extraordinary magnitude as compared to normal temperate alpine glaciers. East Crater Glacier and west Crater Glacier were locally halved in width and doubled in thickness. No more than about 10 per cent of the glacier mass was lost to melting (Walder and others, 2008).

The accounts of Walder and others (2007, 2008) cover the period from the beginning of dome growth in October 2004 through September 2006, by which time the rate of dome growth had fallen off to a few percent of the value at the start of the eruption (Major and others, 2009; Mastin and others, 2009). By January 2008, monitoring parameters, including seismicity, volcanic-gas emissions, and ground deformation, had returned to pre-eruptive background levels, and it appeared that dome growth had stopped. After monitoring parameters had stayed at background levels for another six months, staff of the U.S. Geological Survey Cascades Volcano Observatory (CVO) issued a statement (dated July 10, 2008) declaring the eruption had ended. East Crater Glacier and west Crater Glacier continued to advance, however, while the surface altitude of the thickest ice domains slowly subsided from heights reached during the period of rapid dome growth. This behavior is unsurprising when we consider that the timescale for glacier response to dynamic- and mass-balance perturbations commonly is on the order of decades (Paterson, 1994).

This report provides documentation, primarily in the form of photographs, of glacier evolution from September 2006 to November 2009. We do not comment on glacier dynamics after 2006 because measurements of glacier-surface speed (Walder and others, 2007, 2008), which relied on helicopter-deployed GPS spiders (LaHusen and others, 2008), were discontinued owing to severe crevassing of the ice surface.

Field Setting—Birth of Crater Glacier and Its Condition in September 2006

The cataclysmic eruption of May 18, 1980 beheaded and largely destroyed the glaciers that had existed on the flanks of Mount St. Helens (Brugman and Meier, 1981) and it created a large crater breached to the north. The crater floor, at an average elevation of approximately 2,000 m, would in other circumstances be far below the elevation at which perennial snowpacks or glaciers could form in the Cascades. For example, measurements on Eliot Glacier, Mount Hood, Oregon, about 90 km south of Mount St. Helens, show thinning at a rate of about 1 m/yr at an elevation of 2,000 m (Jackson and Fountain, 2007). The situation at Mount St. Helens is, however, atypical. The crater floor rapidly accumulated rock-avalanche debris from both the crater walls and the growing lava dome. Snow (mostly from avalanches) also accumulated, primarily in the almost perennially shaded area between the growing lava dome and the south crater wall (Mills, 1992; Schilling and others, 2004). When Mount St. Helens awoke in September 2004, the combined thickness of rock debris plus glacier accumulated on the 1980 crater floor was more than 200 m locally (Schilling and others, 2008). Walder and others (2008) discussed the difficulty of deciding which part of the material accumulated on the crater floor after the 1980 eruption—about one-third of which is rock debris—should be deemed part of the glacier from a mechanical (as opposed to morphological) perspective. They decided to pick the surface defined by a digital elevation model for November 12, 1986, as an approximate glacier bed. The reader should bear that context in mind where, in the present report, we report syneruptive glacier thickening as a fraction of original glacier thickness.

The part of the crater glacier overlapping the south flank of the 1980–86 lava dome cracked and bulged during the last few days of September 2004, and was then punctured by a explosion on October 1, 2004 (Scott and others, 2008; fig. 2). Within about two weeks, a lava spine had emerged through the ice. That spine became a small part of the overall lava dome, which grew by formation of a succession of rock spines (Vallance and others, 2008). One of those spines ran into the south crater wall in mid-November 2004 and split the crater glacier into two parts (fig. 3). Ironically, by June 6, 2006, the date on which the U.S. Board on Geographic Names officially gave the name “Crater Glacier” to the crater glacier, there were, for all practical purposes, *two* glaciers in the crater of Mount St. Helens. Fortunately, nature has alleviated the clash between official nomenclature and reality on the ground; the two glacier arms merged on the north side of the 1980–86 lava dome in approximately late March 2008. In discussing Crater Glacier evolution we follow the nomenclature of Walder and others (2008) and adopt the informal names east Crater Glacier and west Crater Glacier to refer to the two separate ice masses that existed in the crater during the period of time from mid-November 2004 until late March 2008. For the period after late March 2008, we use the official name Crater Glacier and refer to the glacier’s two branches as the east arm and west arm. Changes in glacier width and thickness for both periods of time are referenced to the cross sections shown in figure 4.

From mid-November 2004 until mid-April 2005, the erupting lava dome expanded to the east. East Crater Glacier effectively was caught in a vise formed by the dome and the east crater wall. The surface of east Crater Glacier buckled, with east-west-trending crevasses forming parallel to the direction of dome spreading (fig. 5). Between mid-November 2004 and mid-April 2005, the contact between east Crater Glacier and the lava dome shifted eastward by as much as 250 m (fig. 6), and the glacier doubled in thickness locally (fig. 7).

Beginning about mid-July 2005 (Vallance and others, 2008), dome growth migrated westward and began squeezing west Crater Glacier, which bulged and fractured in much the same way as east Crater Glacier had done earlier. The contact between west Crater Glacier and the lava dome shifted westward by >200 m (fig. 8), and the glacier doubled in thickness locally (fig. 9). A distinct bulge in the west Crater Glacier surface propagated downglacier (fig. 9*A*) and impinged upon the gently sloping, mostly rock-covered terminus region, which had originated chiefly as a separate mass shed from the west crater wall. By summer 2006, the bulge was accommodated by development of a shear zone within the flat terminus region (fig. 10).

Change in Crater Glacier September 2006–November 2009

West Crater Glacier and east Crater Glacier showed similar behavior after the squeeze exerted by the expanding lava dome finally stopped; ice from the thickened reaches of the glacier began to be redistributed farther downglacier. Terminus regions of both arms of the glacier became thicker and also advanced. A qualitatively similar pattern of ice redistribution occurs during a glacier surge, with massive, rapid transfer of ice from upglacier to downglacier, although we emphasize that the similarity does not extend to the dynamics: glacier surging is a quasi-periodic oscillation between two modes of flow and is thought to involve an unstable switch in the boundary conditions at the base of a glacier such that the sliding speed of the glacier over its bed first increases and then decreases radically (Raymond, 1987). By this definition, the Mount St. Helens crater glacier did not surge.

The shear zone in the west Crater Glacier terminus region evolved but was recognizable, even under winter snowpack, until about summer 2007 (figs. 11 and 12). Advance of the west Crater Glacier terminus necessitated removal of the Yellow Rock (YEL) seismic station—a station that had been in operation since 1991—on August 29, 2007, at which time the glacier terminus was within 40 m of YEL. By winter of 2008, the gap between east Crater Glacier and west Crater Glacier had narrowed to only a few tens of meters (fig. 13). An overflight by personnel of the Jet Propulsion Laboratory on about March 25 found that the east and west arms of Crater Glacier had merged or were nearly touching just north of the 1980s lava dome (Cascades Volcano Observatory, 2008). This timing is reasonable, given that by May 30, the continued downslope advance of the east and west arms had them abutting along a contact about 120-m long (fig. 14). A photograph taken October 22, 2008, shows how Crater Glacier had encroached upon the ravine marking the head of Loowit Creek (fig. 15). The photograph also shows two other lobate bodies of rock, snow, and ice(?) that had advanced down the east wall of the crater toward the crater floor. The lobate body closest to the east arm of Crater Glacier has a steep snout suggestive of a mass containing glacier ice (Martin and Whalley, 1987), and a thickness perhaps one-third to one-half that of the east Crater Glacier snout (fig. 16). Its distinctive red-brown color reflects the source of its rock fragments (andesitic and basaltic deposits exposed in the east crater wall). This lobate body was overrun by the east arm of Crater Glacier by November 1, 2009 (figs. 17 and 18), by which time the glacier had begun to spill into the Loowit channel.

Runoff from the crater occurs primarily through springs and seeps in the heads of Loowit and Step channels (Fig. 1) rather than in streams emanating directly from the glacier. This hydrological oddity has consequences for glacier dynamics, as discussed at length by Walder and others (2007, 2008). The paucity of stream runoff from the glacier is illustrated by photographs taken in the summer of 2007, as the termini of west Crater Glacier and east Crater Glacier grew closer together (figs. 19 and

20). Again, in summer 2008, there was little surface runoff from the glacier during the ablation season (fig. 21).

Glacier-terminus position was measured at various times by CVO staff working in the crater. The method involved using a handheld GPS unit and traversing along the glacier terminus. As the GPS operator had to stay far enough from the terminus to avoid injury in the event of rock fall, there is a small systematic error—an offset of a few meters—in mapped glacier-terminus position as compared to the true glacier-terminus position. There is also a random error of about 5 m associated with the GPS measurement itself, because the group of satellites used for determining position varied from day to day. We used these measured terminus positions (fig. 22) to calculate the amount and rate of glacier advance along a line roughly normal to the terminus and extending into the head of Loowit channel. Results are shown graphically in fig. 23. The glacier terminus advanced 330 m between July 27, 2006 and June 16, 2009, for an average rate of advance of 116 m/yr.

An overall sense of how Crater Glacier has evolved, and in particular how its terminus has advanced, is illustrated by an animation (Appendix 1) that shows a series of oblique views of the crater of Mount St. Helens for the period September 2003 to June 2009. In the animation, images for September 2003 through September 2007 are derived from DEMs; the glacier terminus for June 2009 comes from visual inspection of an aerial photograph.

The Future of Crater Glacier

Crater Glacier was growing and advancing when lava-dome emplacement began in October 2004 because accumulation greatly exceeded ablation. Had an eruption not begun in fall 2004, the glacier would surely have continued to grow and advance. Lava-dome emplacement strongly perturbed Crater Glacier's approach to a steady state. We may plausibly expect the glacier to approach a steady state only after at least a few more decades (Paterson, 1994). It seems likely that Crater Glacier will develop a steeply sloping tongue as it advances down the Loowit channel, and that this tongue will become largely free of rock-debris cover.

Acknowledgments

We thank CVO colleagues for use of their photographs.

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Figures

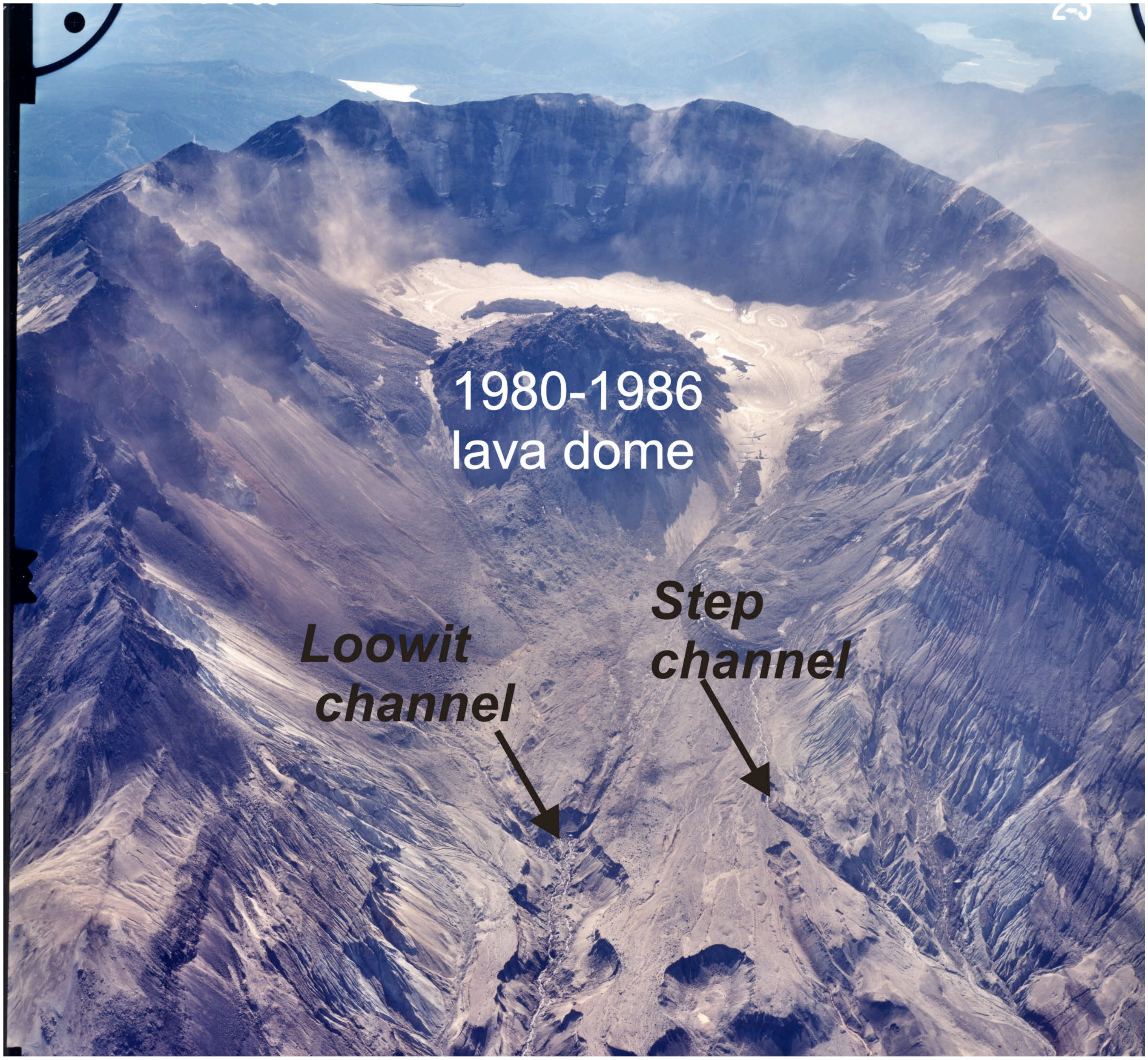

Figure 1. Oblique view south into the crater of Mount St. Helens on October 5, 2000. Glacier wraps around 1980–86 lava dome. East (left) arm of glacier is obscured by rock-avalanche debris; west (right) arm merges to the north of the lava dome with a rock-covered icy mass shed off the west crater wall. Crater width from east rim to west rim is about 2 km. USGS photograph by Bergman Photographic Services, Portland, Oregon.

Figure 2. Beginning of Mount St. Helens eruption through Crater Glacier on October 1, 2004. USGS photograph by J.S. Pallister.

Figure 3. The Mount St. Helens crater glacier as seen on November 20, 2004. View to southwest. The “whaleback” shaped lava dome had grown southward and run into the south wall of the crater by this date, splitting the glacier in two. USGS photograph by D. Dzurisin.

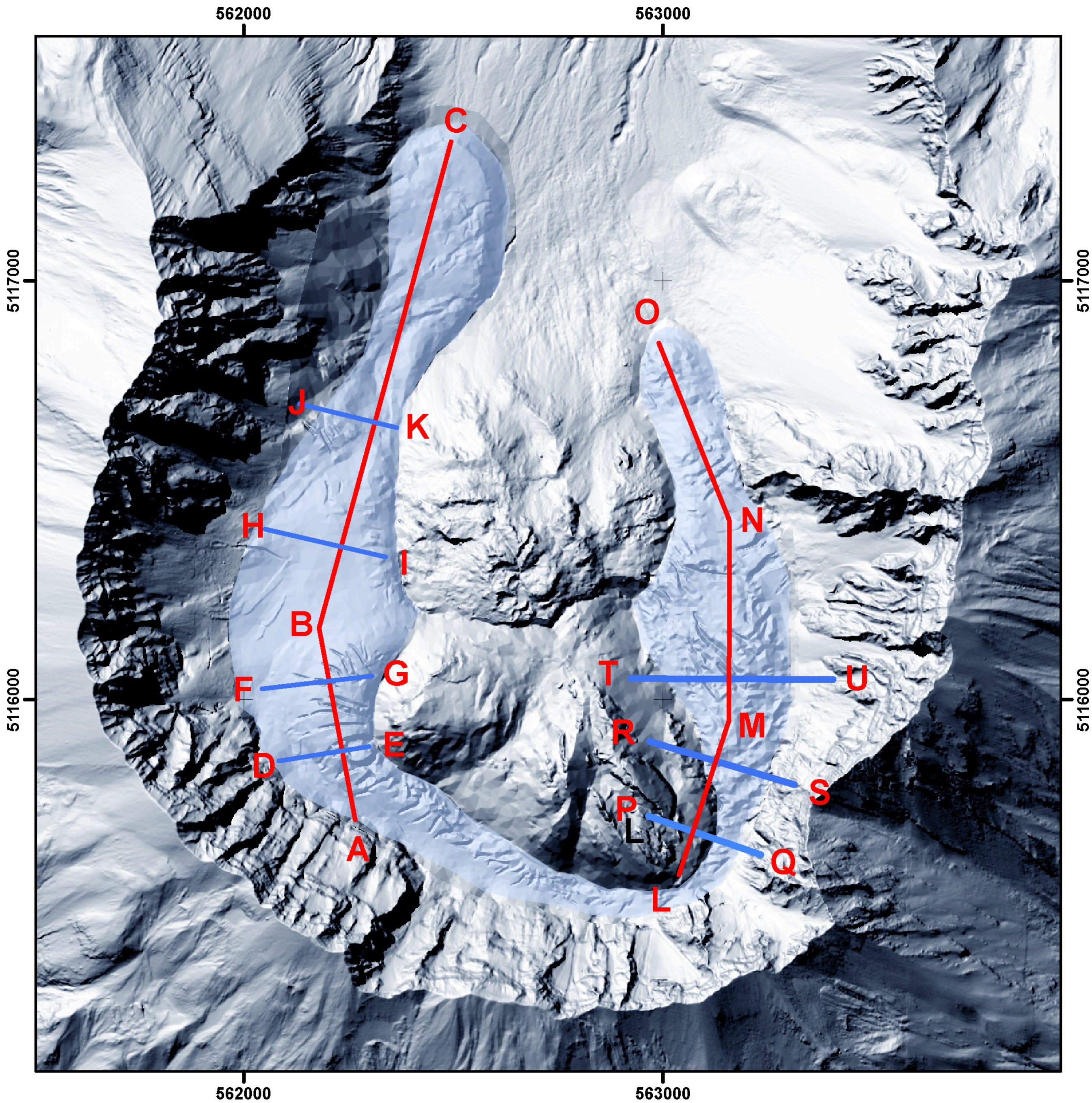

Figure 4. Hillshade-relief map of Mount St. Helens crater constructed from photogrammetric analysis of an aerial photograph dated October 24, 2005. The east and west arms of the glacier are indicated by lines of section LMNO and ABC, respectively, for which changes in glacier-surface altitude were calculated.

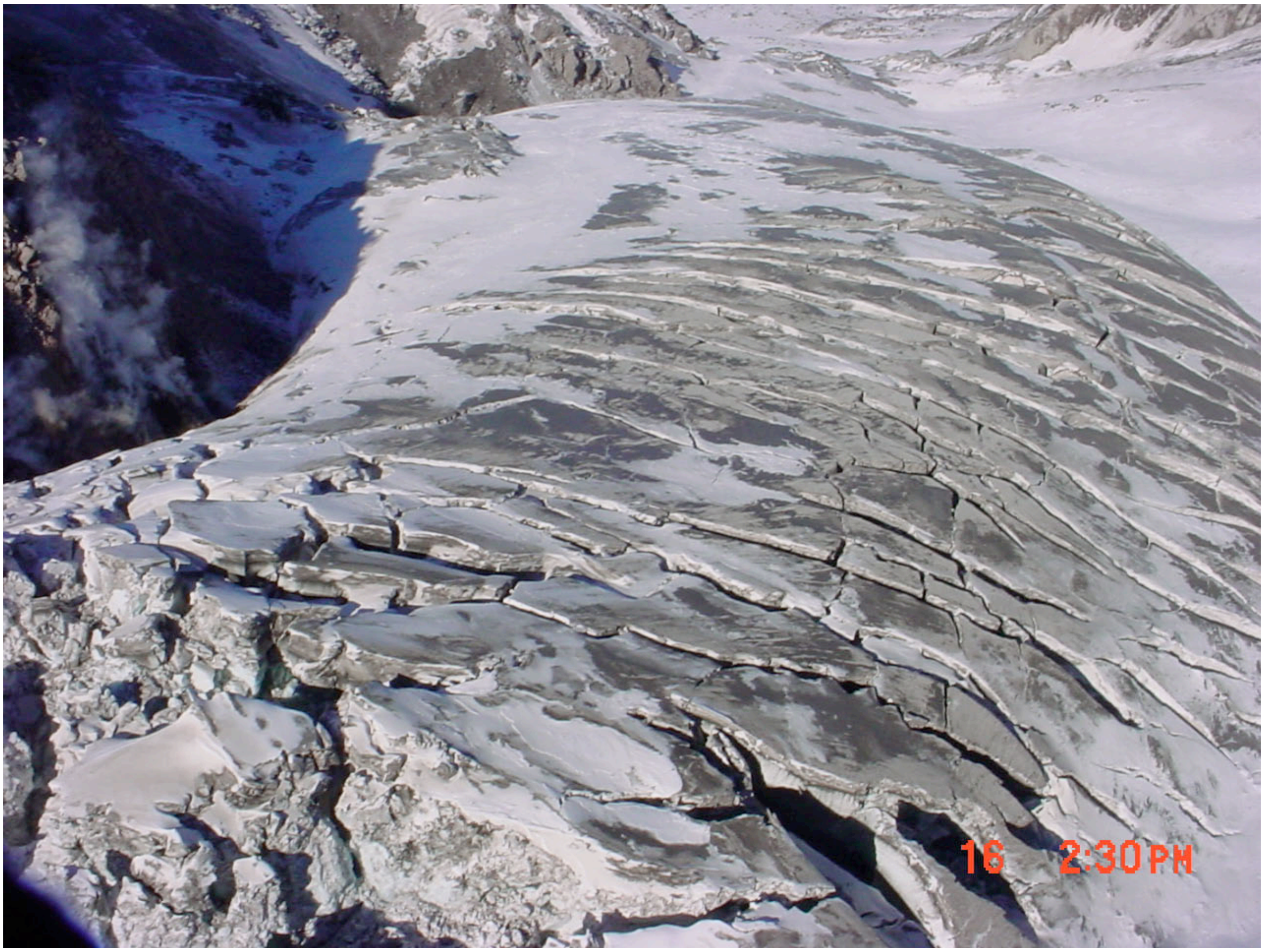

Figure 5. Upwarped surface of east Crater Glacier on February 16, 2005. This photograph (view to the north) was taken from a helicopter flying close to the glacier surface. The width of the upwarped glacier is approximately 250 m. Crevasses are oriented roughly east-west, paralleling direction of squeeze by new lava dome (at left). The 1980s dome is in the left-center distance. USGS photograph by J.S. Walder.

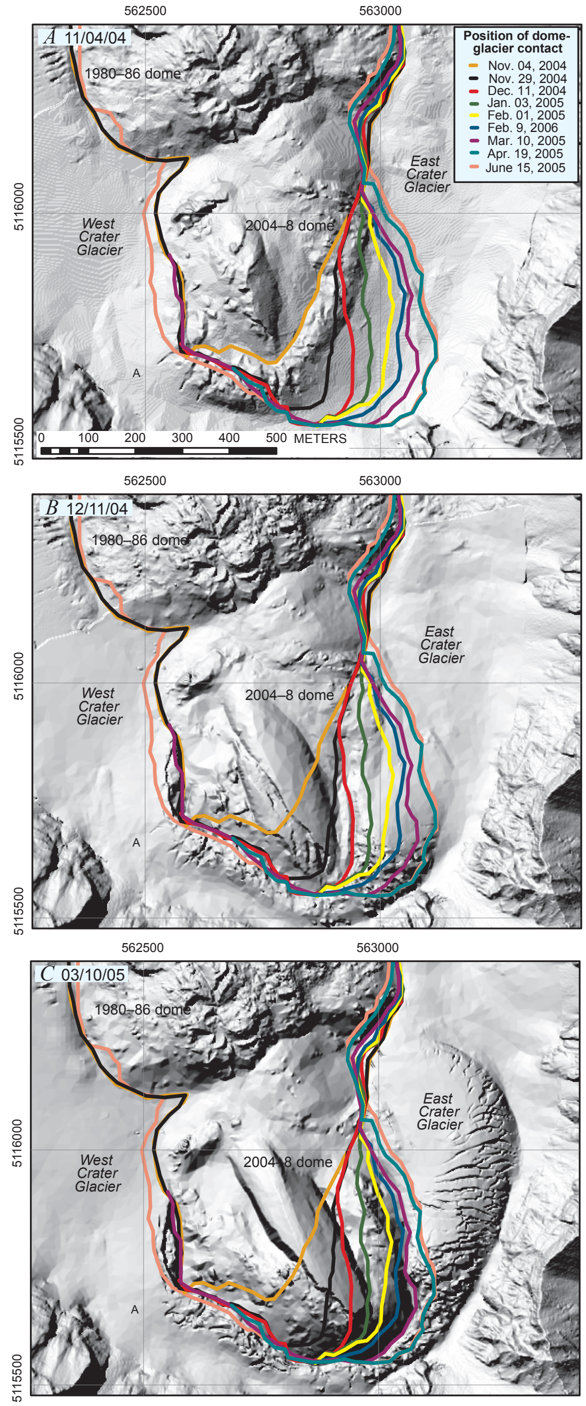

Figure 6. Migration of contact between the new lava dome and east Crater Glacier from November 29, 2004, to April 19, 2005. Contact position was determined from DEMs, with a probable error of about 5 m. Coordinates are UTM zone 10 easting and northing, North American datum 1983. Modified from Walder and others (2008) to include trace of June 15, 2005. *A*, Background image is hillshade-relief map for November 4, 2004. *B*, Background image is a hillshade-relief map for December 11, 2004. *C*, Background image is a hillshade-relief map for March 10, 2005.

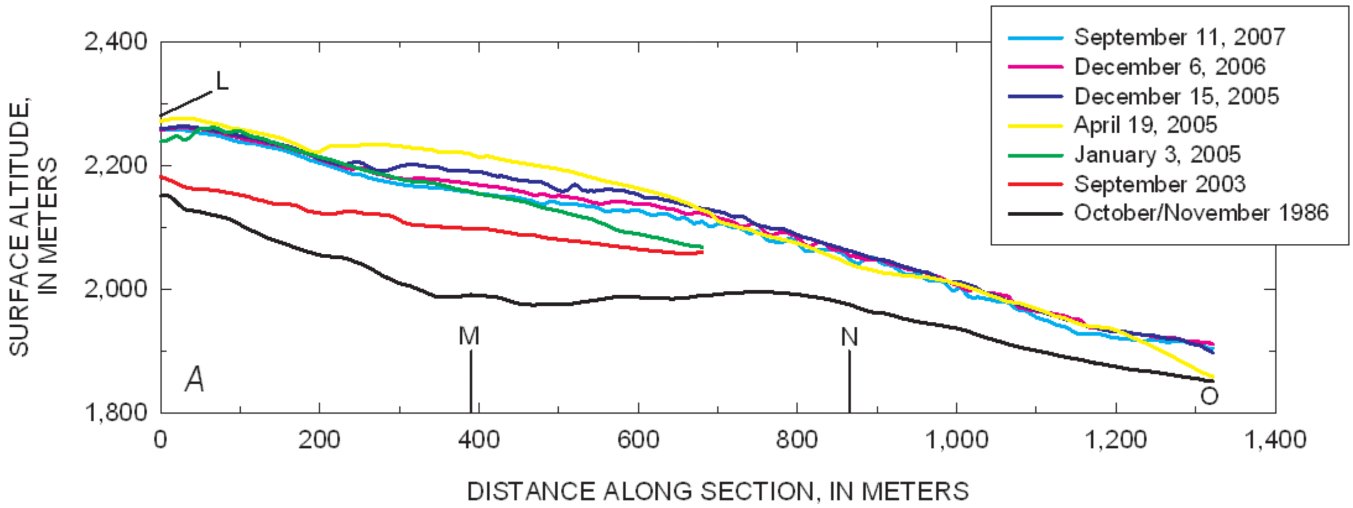

Figure 7. Cross sections showing the change in surface altitude of east Crater Glacier during the course of the 2004–08 eruption, based on sequential DEMs. Modified from Walder and others (2008) to include data from December. 6, 2006 and September 11, 2007. Lines of section are shown in figure 3. The 1986 profile represents the ground surface at the end of the 1980–86 dome-building episode and approximates the glacier bed. The 2003 profile should be within a few meters altitude of the glacier surface at beginning of the 2004 eruption. Not all DEM coverages extend to glacier terminus. *A*, Longitudinal section L–M–N–O approximately parallel to ice flow.

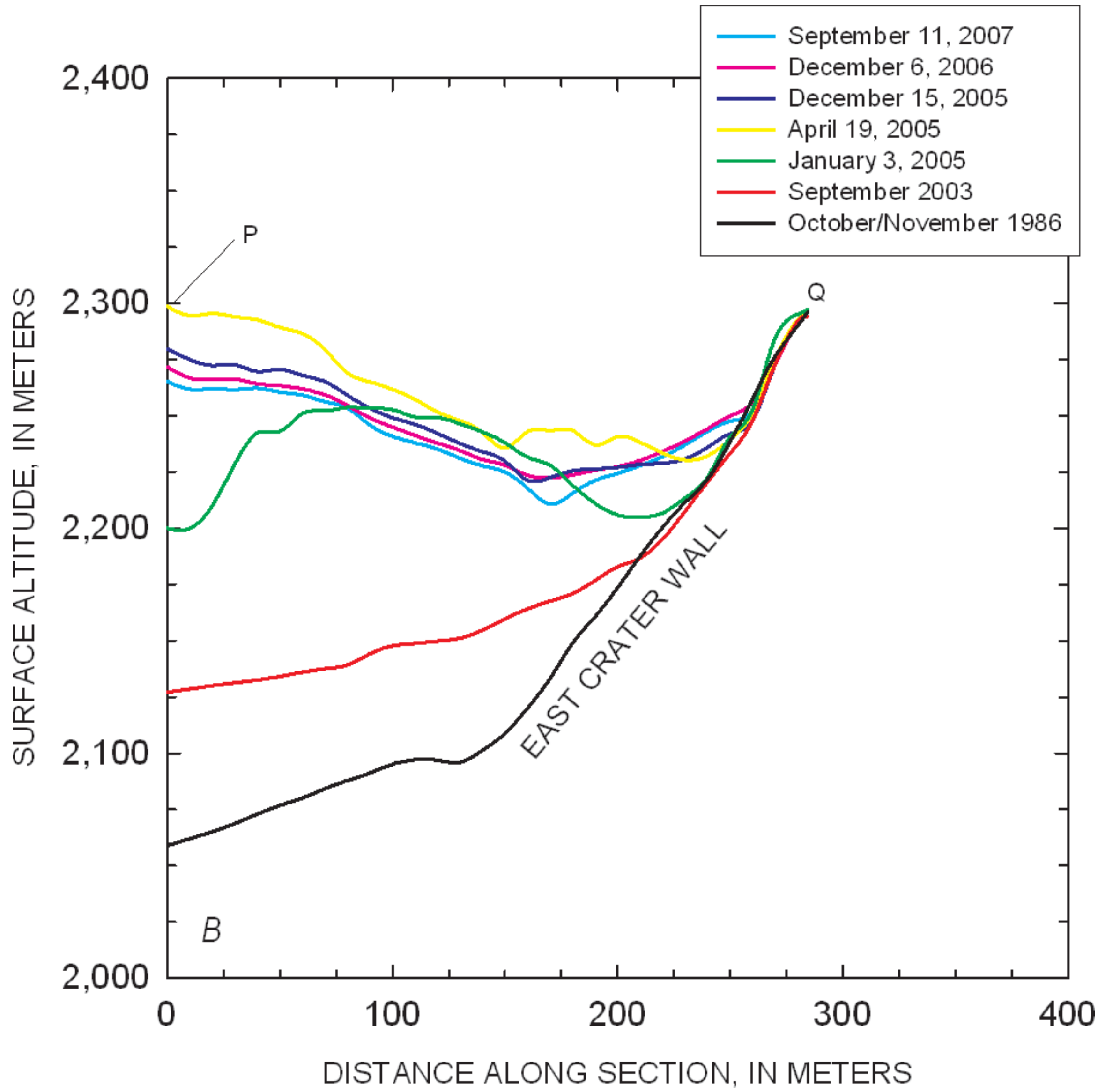

Figure 7 (cont.). *B*, Transverse section P–Q. *C*, Transverse section R–S. *D*, Transverse section T–U.

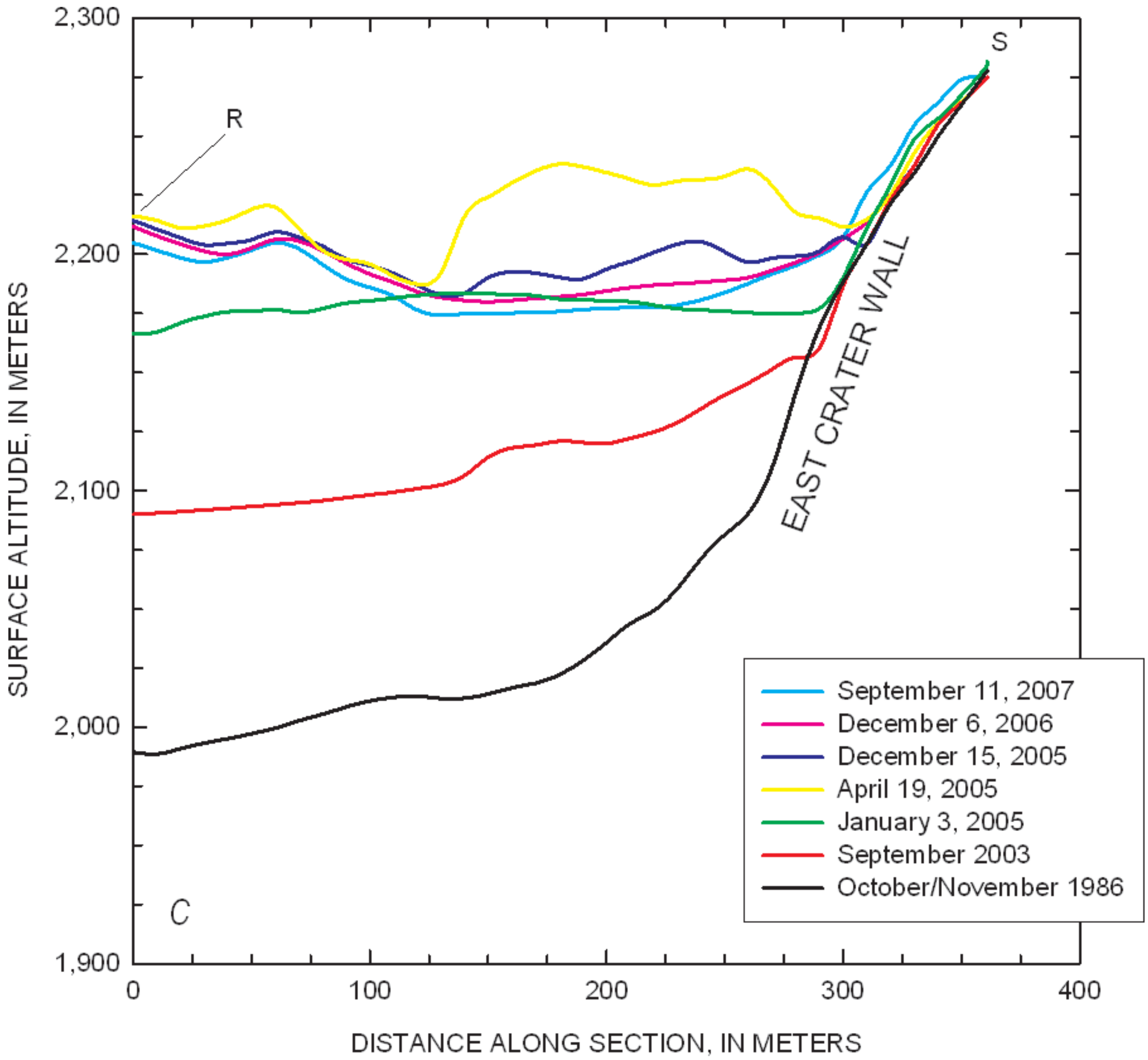

Figure 7 (cont.). *C*, Transverse section R–S. *D*, Transverse section T–U.

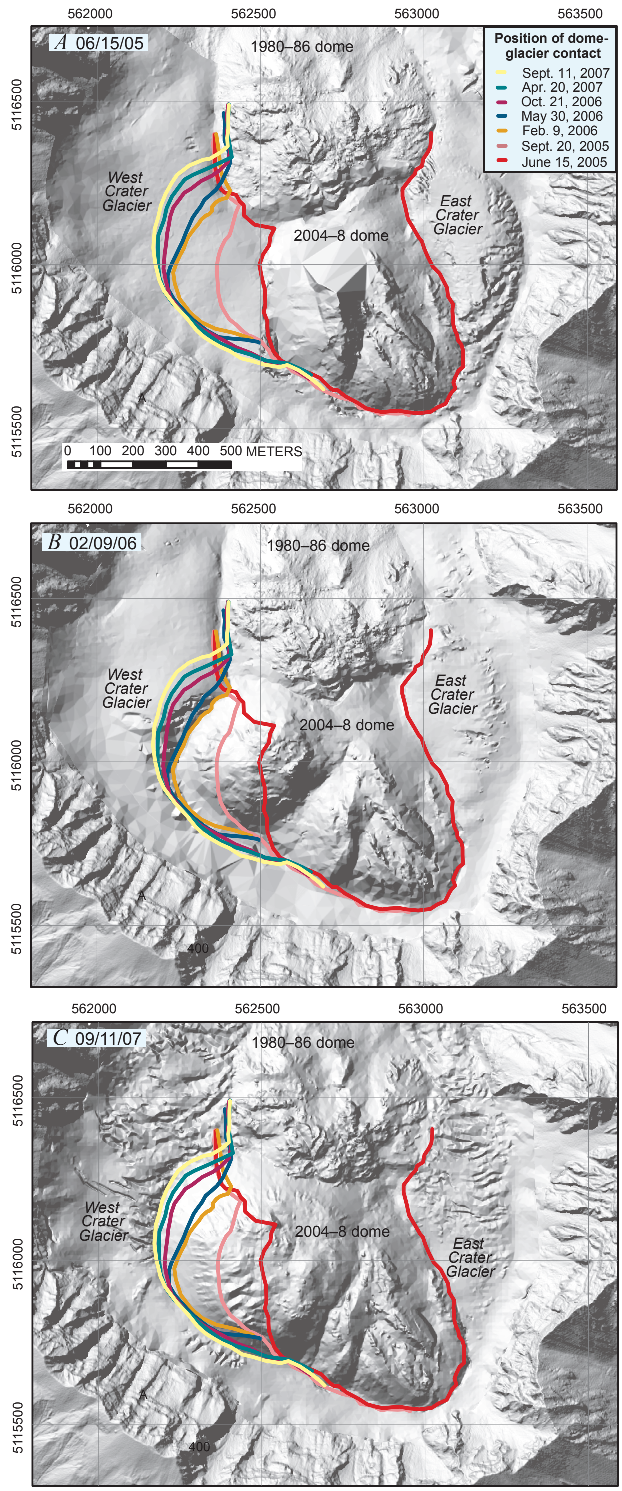

Figure 8. Migration of contact between the new lava dome and west Crater Glacier from June 15, 2005, to September 11, 2007. Contact position was determined from DEMs, with a probable error of about 5 m. Coordinates are UTM zone 10 easting and northing, North American datum 1983. *A*, Background image is hillshade-relief map for June 15, 2005. *B*, Background image is hillshade-relief map for February 9, 2006. *C*, Background image is hillshade-relief map for September 11, 2007.

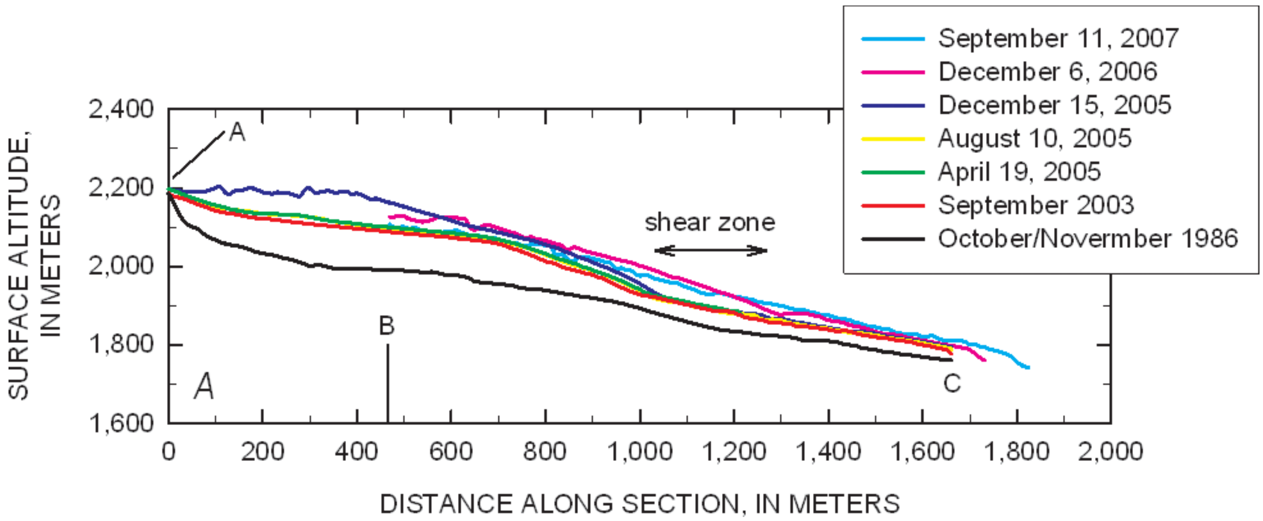

Figure 9. Change in surface altitude of west Crater Glacier during the 2004-08 eruption, based on sequential DEMs. This figure is modified from Walder and others (2008) to show data from December 6, 2006 and September 11, 2007. Lines of sections are shown in figure 3. The 1986 profile represents the ground surface at end of the 1980–86 dome-building episode and is approximately the glacier bed. The 2003 profile should be within a few meters altitude of glacier surface at beginning of 2004–08 eruption. *A*, Longitudinal section A–B–C, approximately following the thickest ice. The points labeled A, B, and C correspond to identically named points in figure 13*B*. The part of the section between points A and B is not shown for the two latest sections because the glacier was almost entirely pushed aside by the lava dome. Approximate location of the shear zone is indicated.

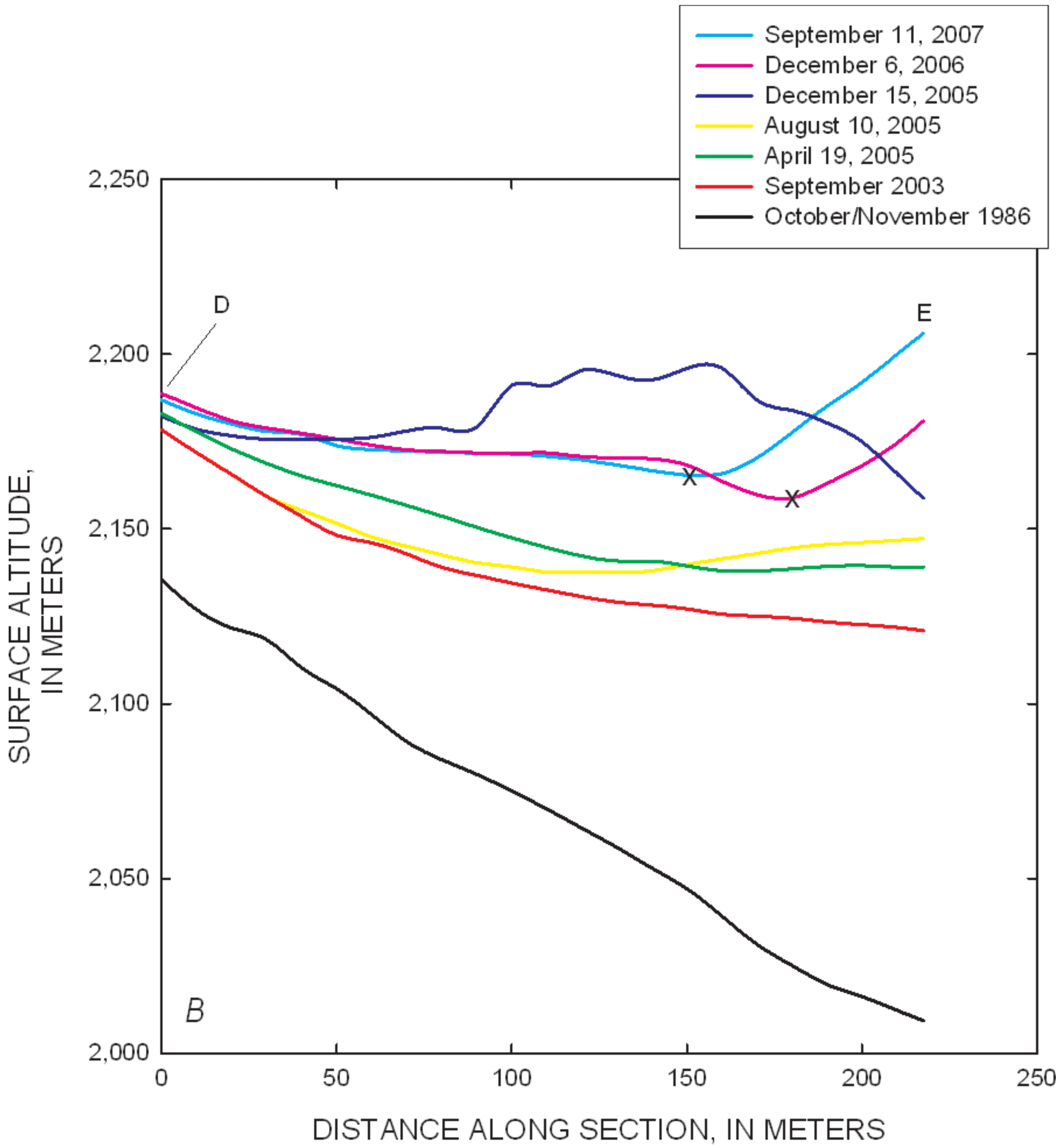

Figure 9 (cont.). *B*, Transverse section D–E. The Xs indicate the edge of the lava dome.

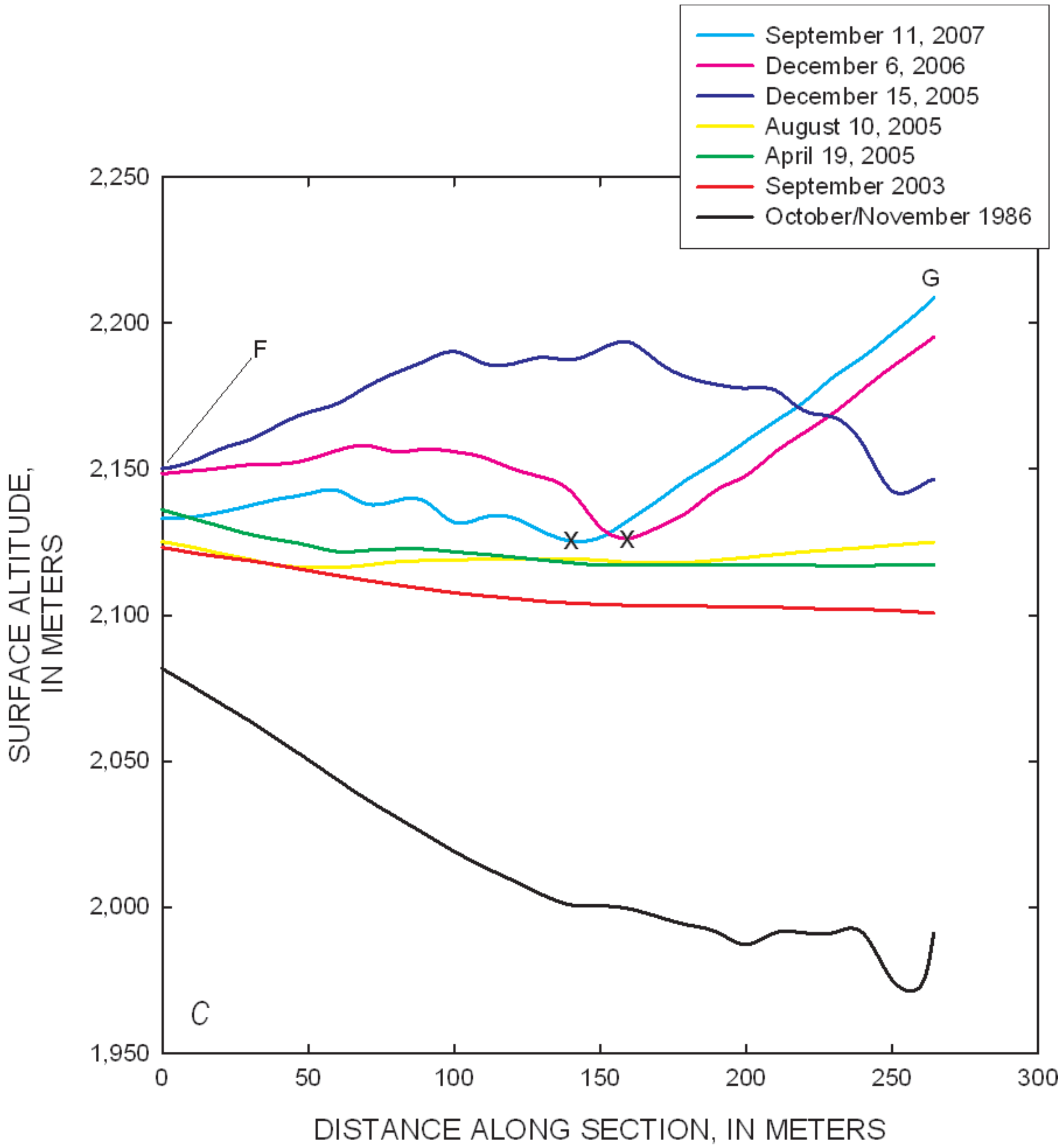

Figure 9 (cont.). *C*, Transverse section F–G. The Xs indicate the edge of the lava dome.

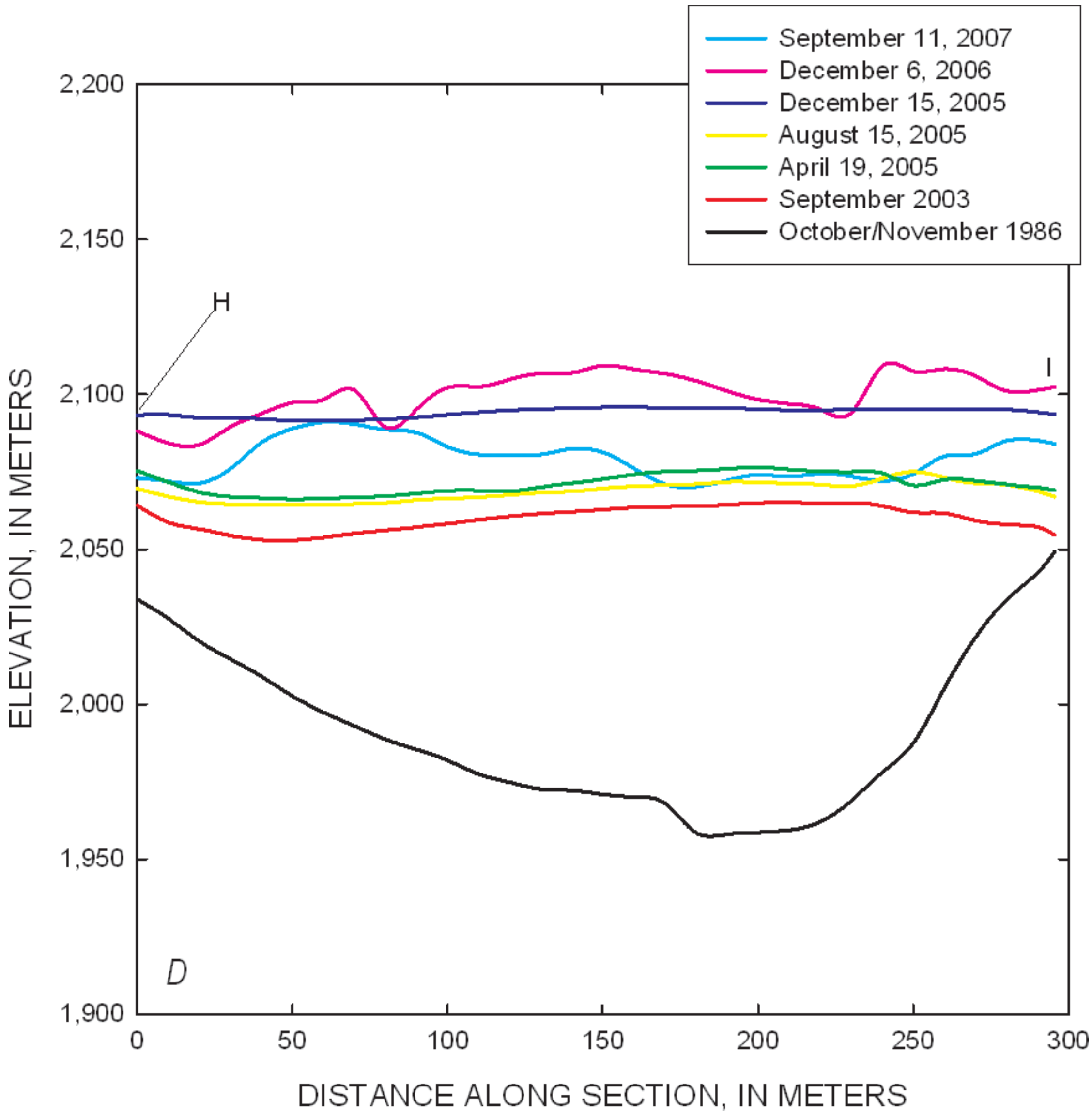

Figure 9 (cont.). *D*, Transverse section H–I.

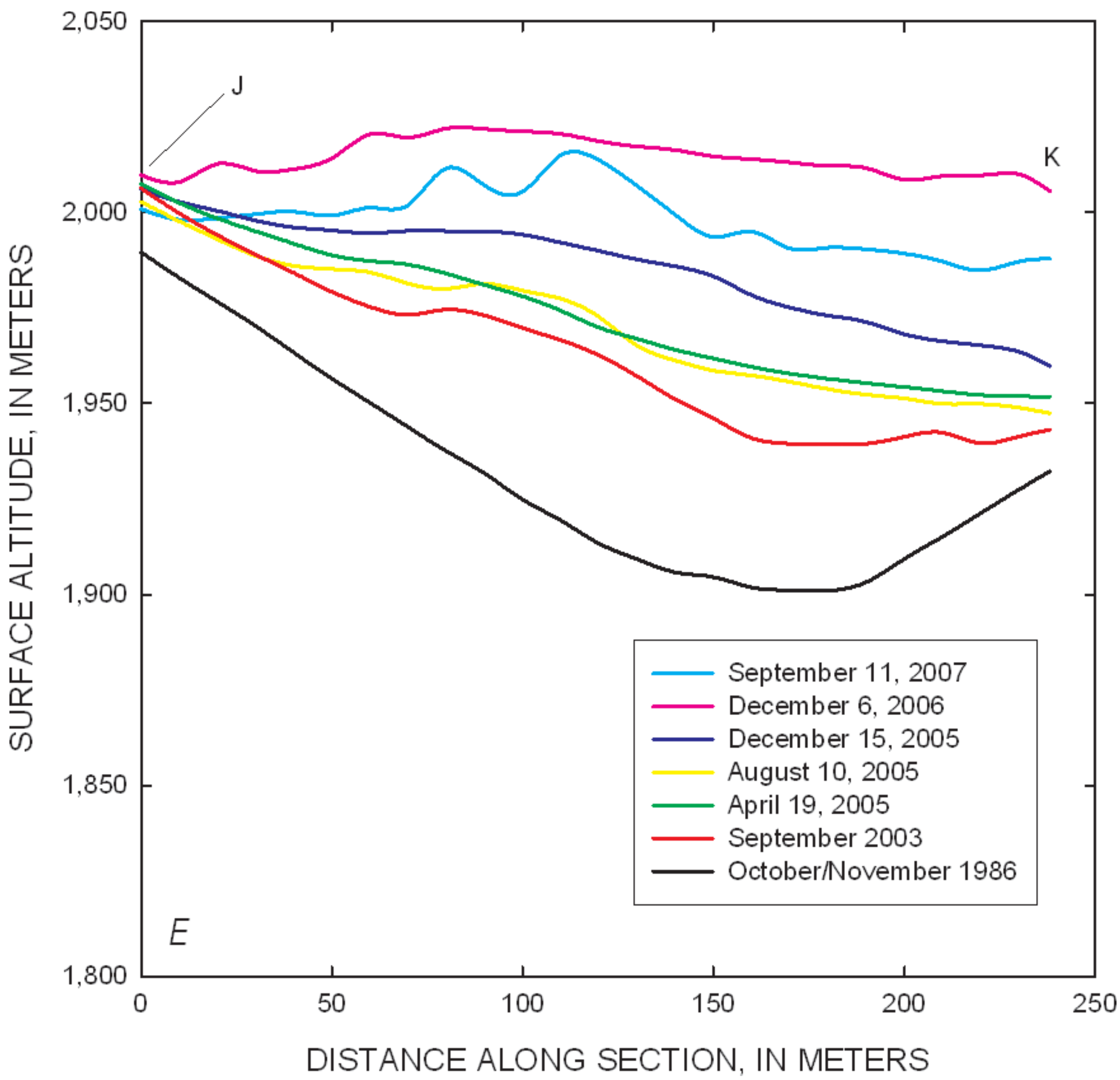

Figure 9 (cont.). *E*, Transverse section J–K.

Figure 10. The Mount St. Helens crater glacier as seen on September 12, 2006, view to the northeast. Distance from east crater rim to west crater rim is about 2 km. As the bulge on west Crater Glacier advanced and impinged on the relatively flat terminus area, a shear zone delineated by echelon fractures developed (dashed curve). USGS photograph by W.E. Scott.

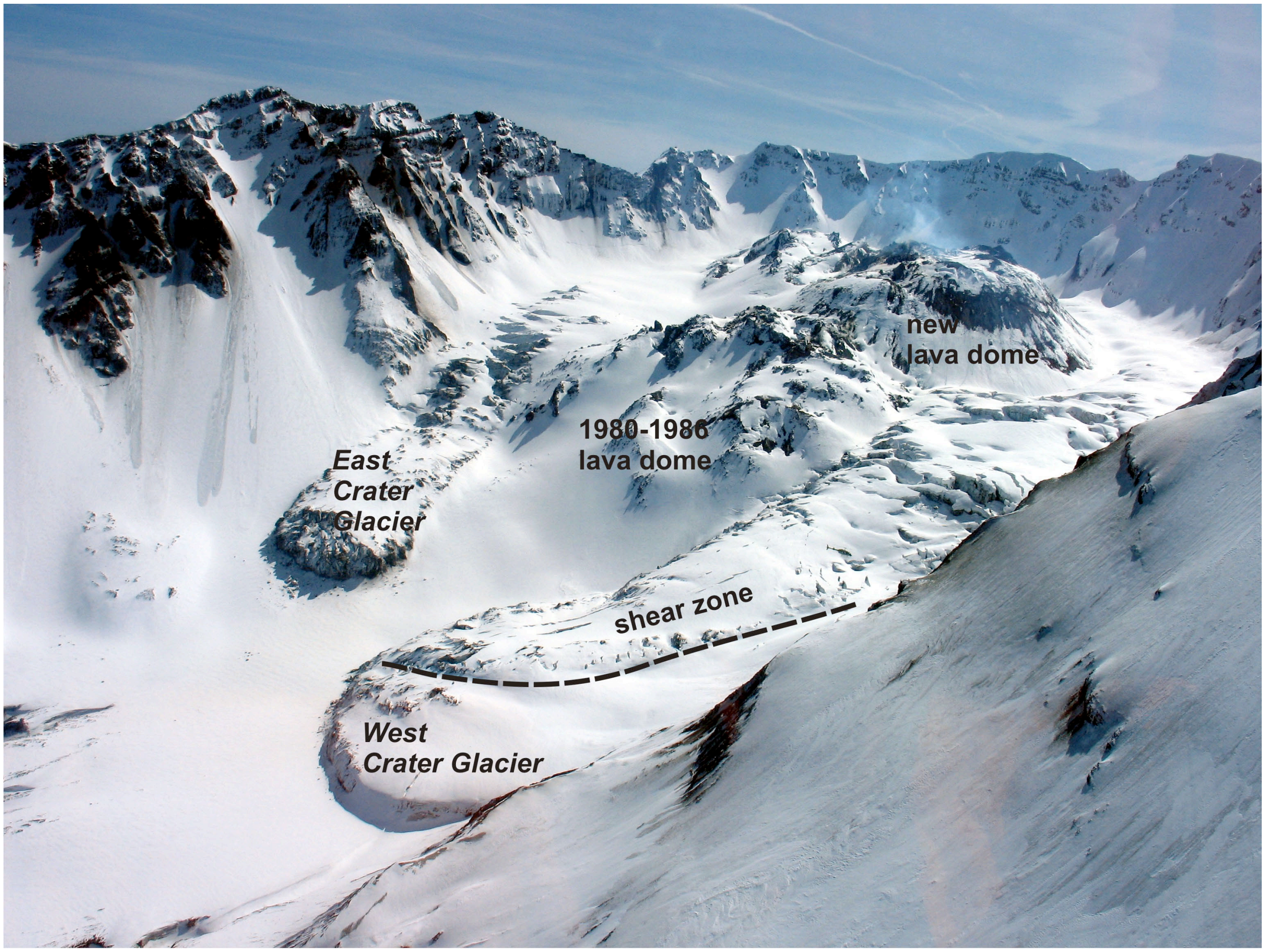

Figure 11. The Mount St. Helens crater glacier as seen on March 29, 2007, view to the southeast. The shear zone in west Crater Glacier first noticed in summer 2006 (fig. 10), is marked by a bulge in the ice surface (dashed curve). USGS photograph by C. Werner.

Figure 12. The Mount St. Helens crater glacier as seen on May 25, 2007, view to the southeast. The shear zone in west Crater Glacier, first noticed in summer 2006 (fig. 10), is indicated by a ridge with alternate snow-covered and debris-covered patches (dashed curve). USGS photograph by S.C. Moran.

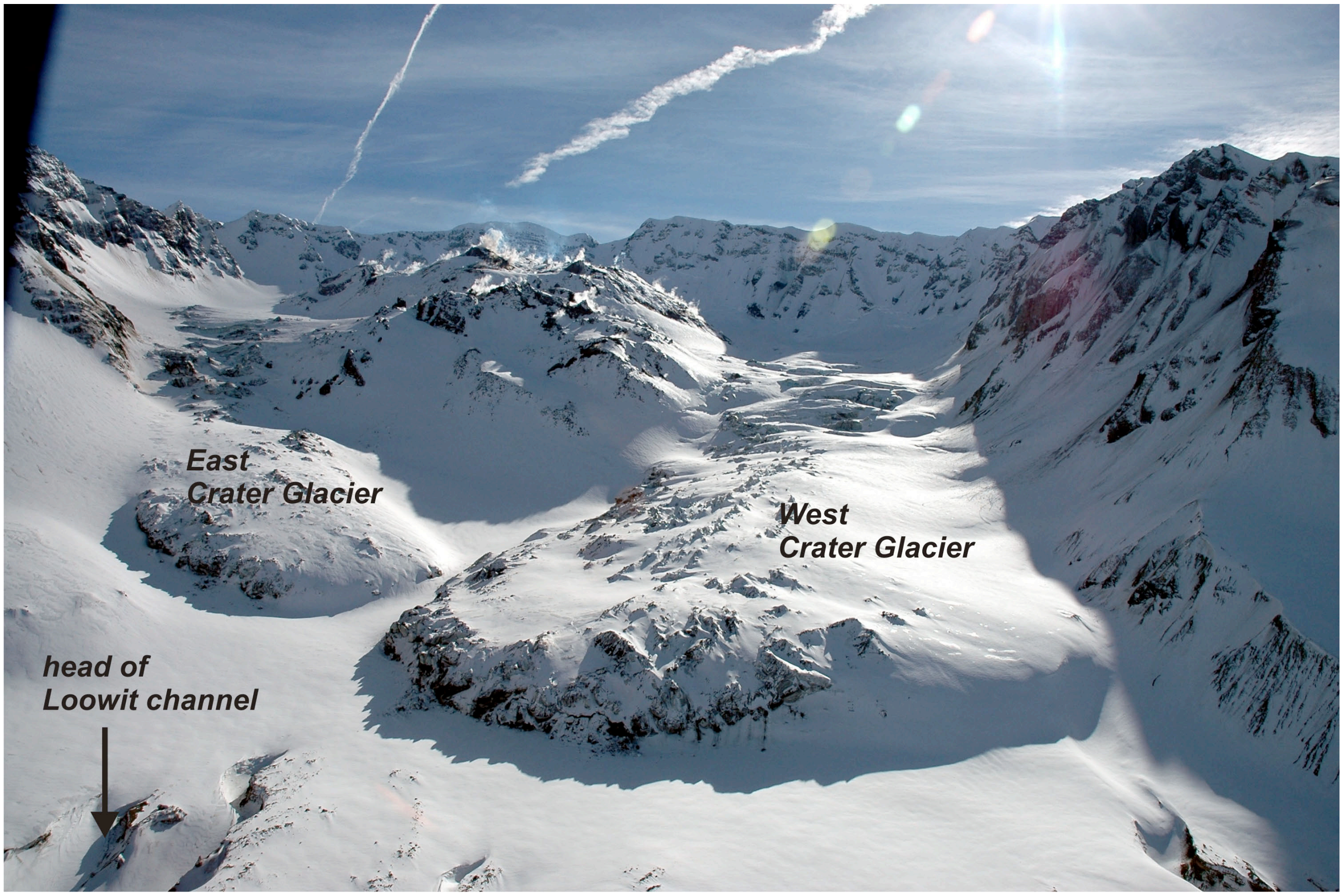

Figure 13. The Mount St. Helens crater glacier as seen on February 26, 2008, view to the south. Snouts of east Crater Glacier and west Crater Glacier are narrowly separated. USGS photograph by E. Iwatsubo.

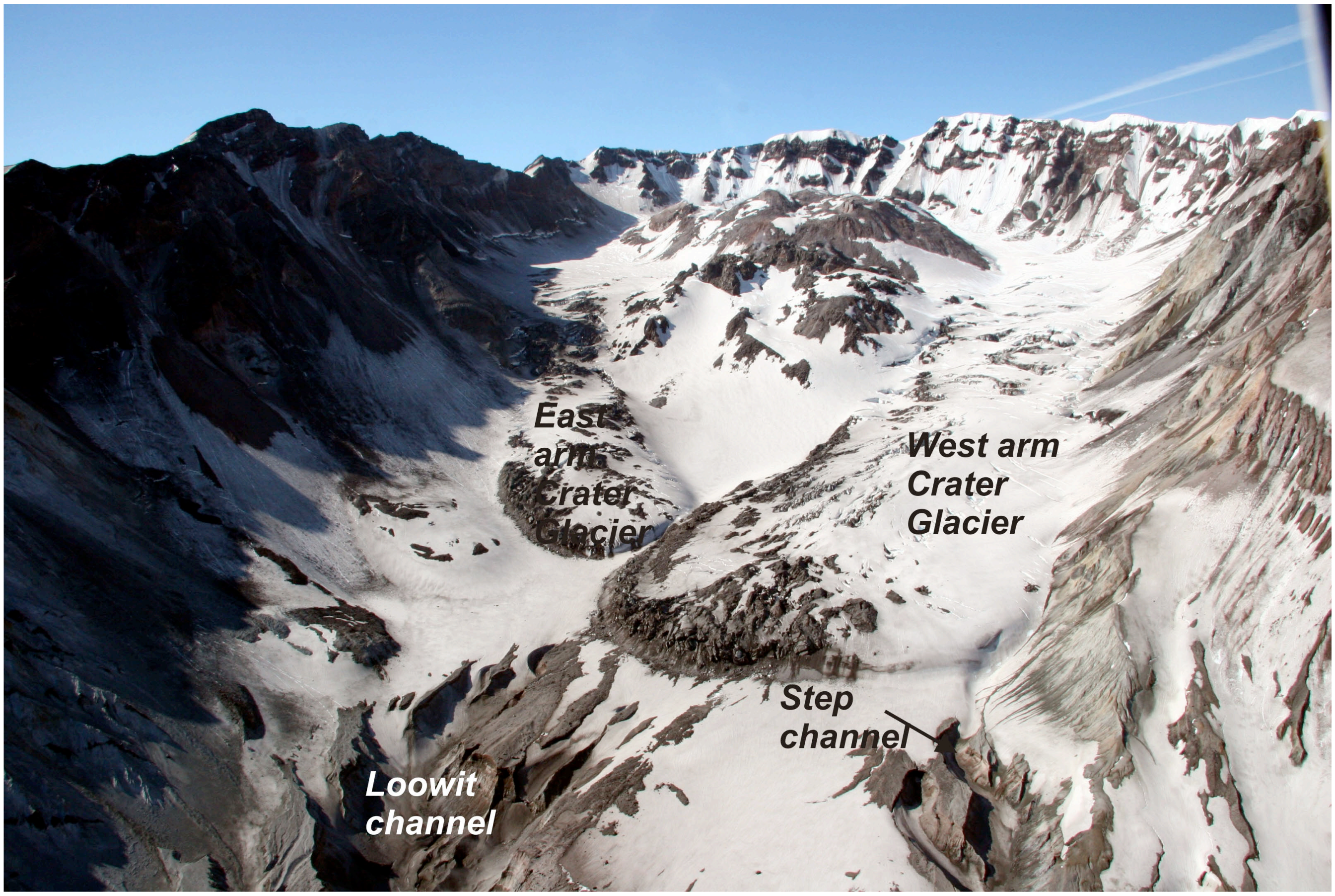

Figure 14. Crater Glacier as seen on May 30, 2008, view to the southeast. East Crater Glacier and west Crater Glacier had touched by this date. USGS photograph by A. Diefenbach.

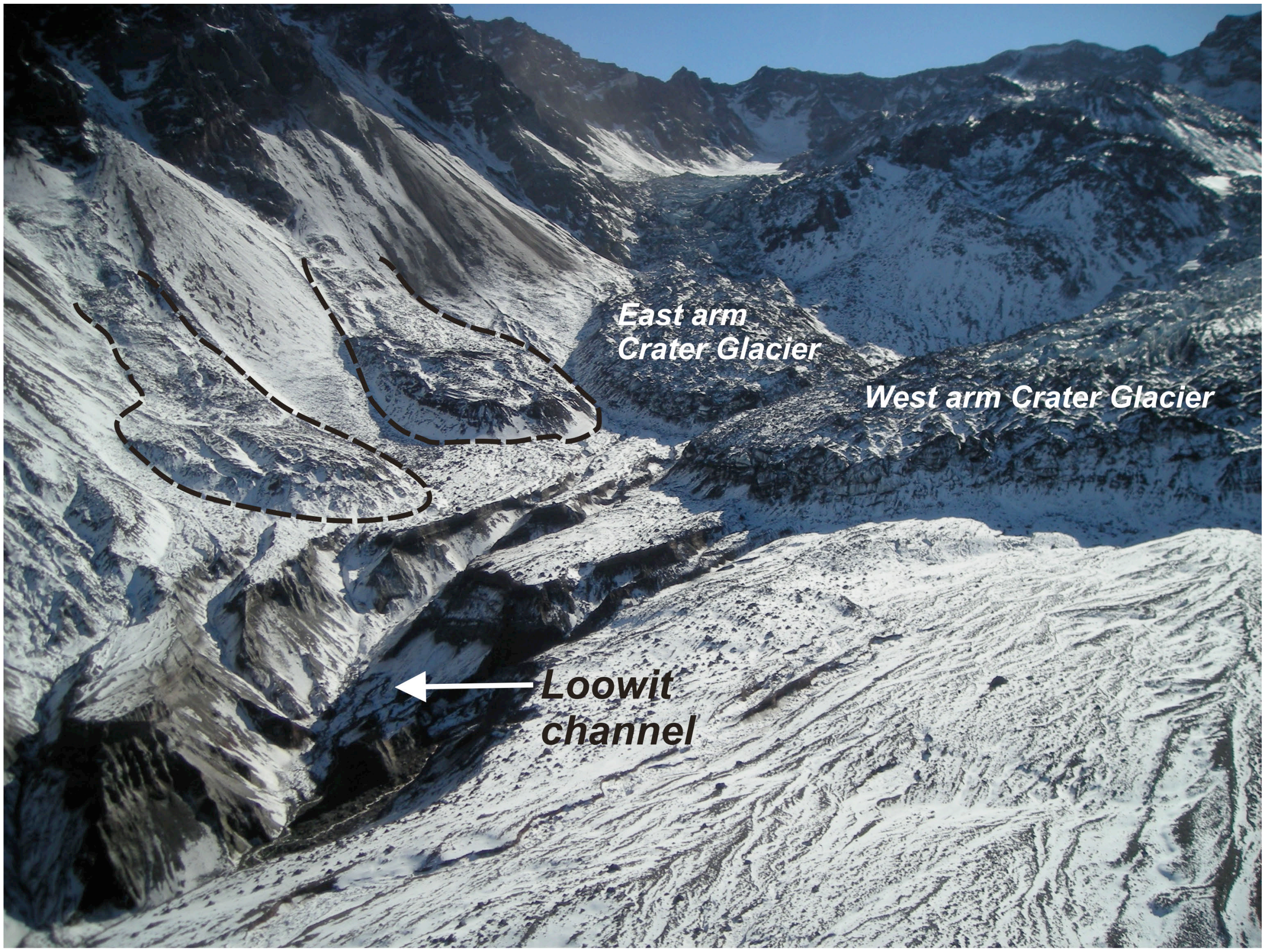

Figure 15. Crater Glacier as seen on October 22, 2008, view to the southeast. East Crater Glacier and west Crater Glacier had merged by this date. Dashed lines indicate lobes of material shed from the east crater wall. USGS photograph by D.R. Sherrod.

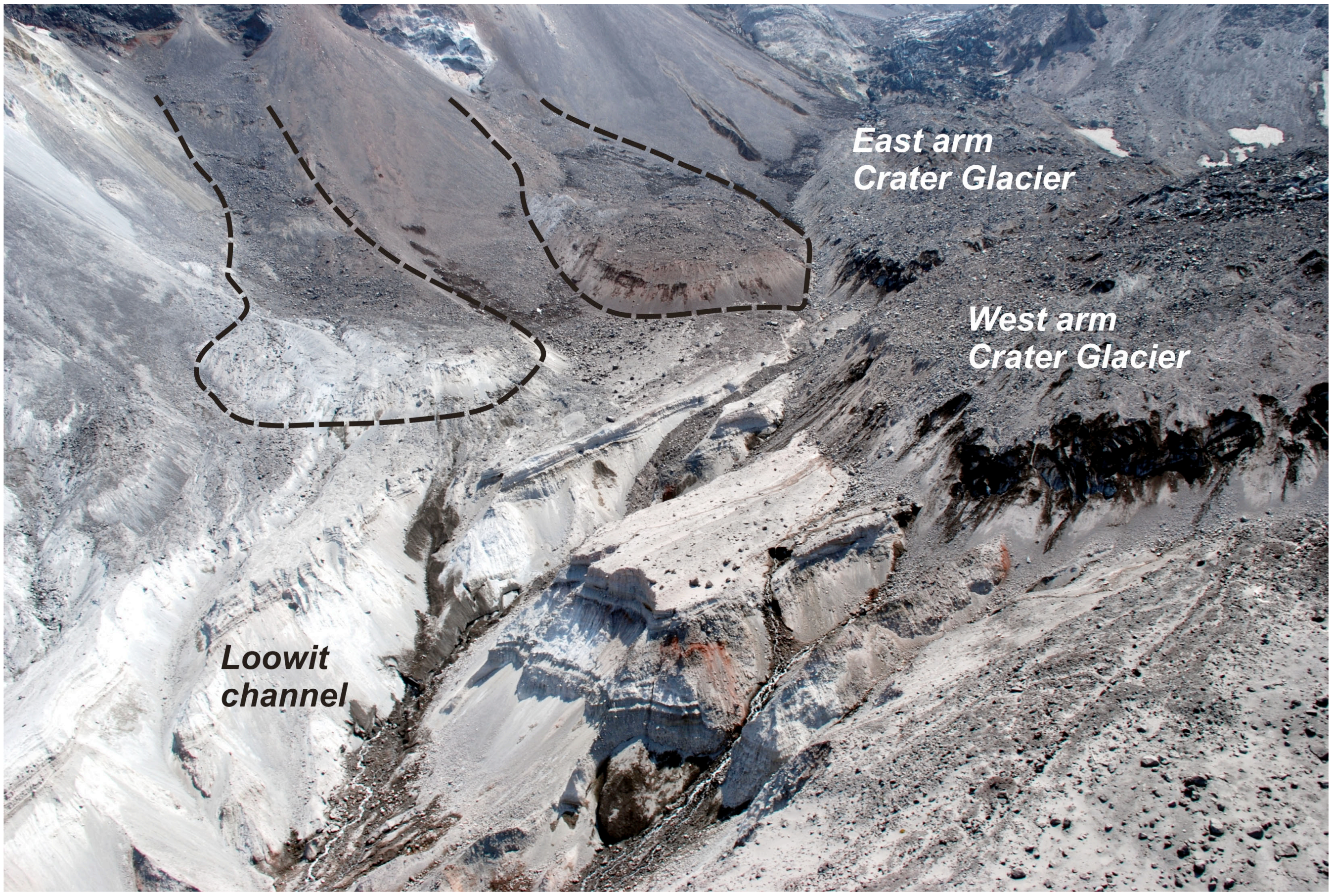

Figure 16. Terminus region of Crater Glacier as seen on August 5, 2009, view to the southeast. Dashed lines indicate lobes of material shed from the east crater wall. By this date, the advancing glacier had abutted the reddish-brown lobe of material shed from the east crater wall. USGS photograph by S.P. Schilling.

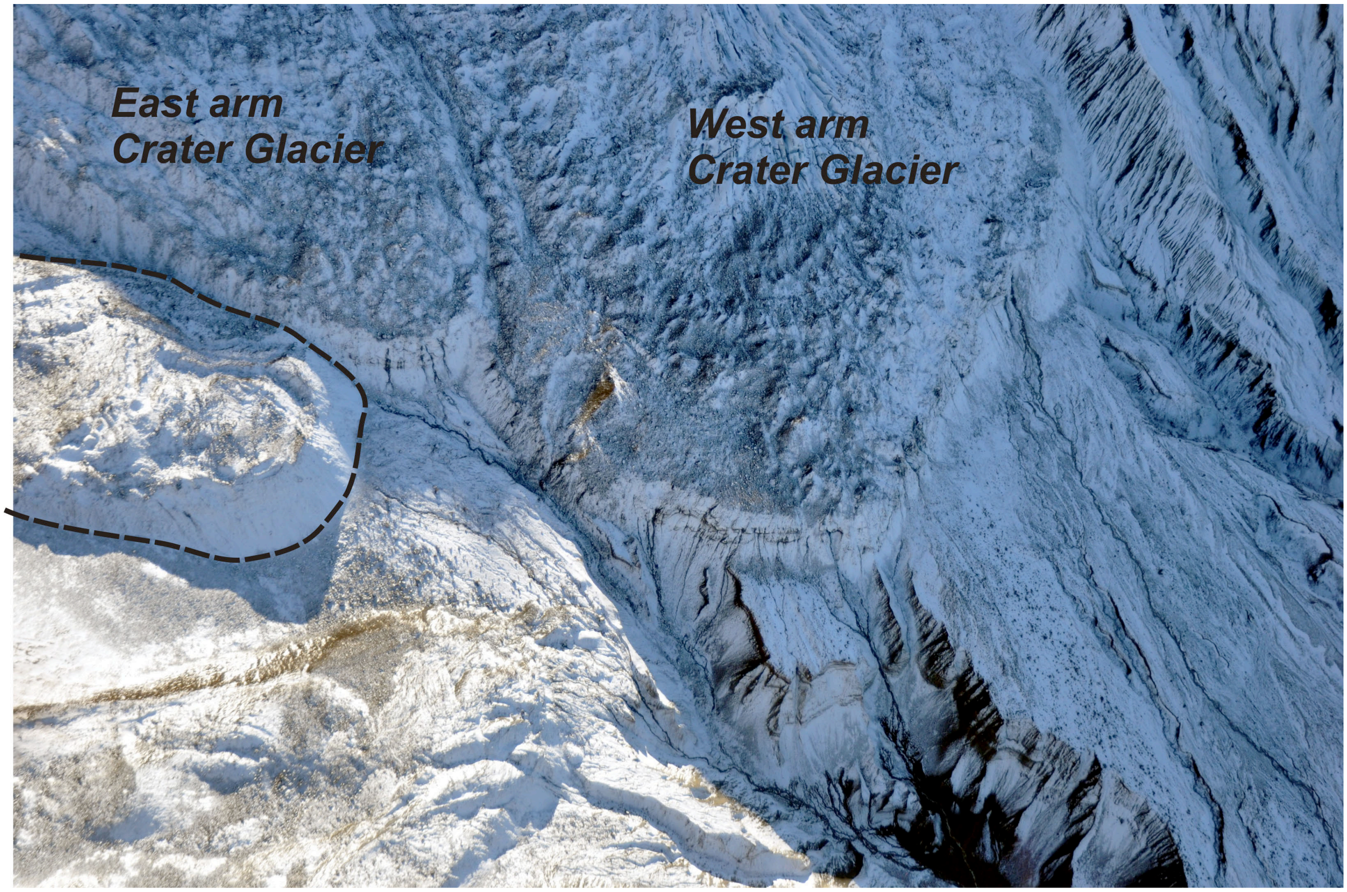

Figure 17. Terminus region of Crater Glacier as seen on November 1, 2009, view to the south. By this date, the advancing glacier was overrunning the reddish-brown debris lobes (dashed line) and had entered the heat of Loowit channel. USGS photograph by J.S. Pallister.

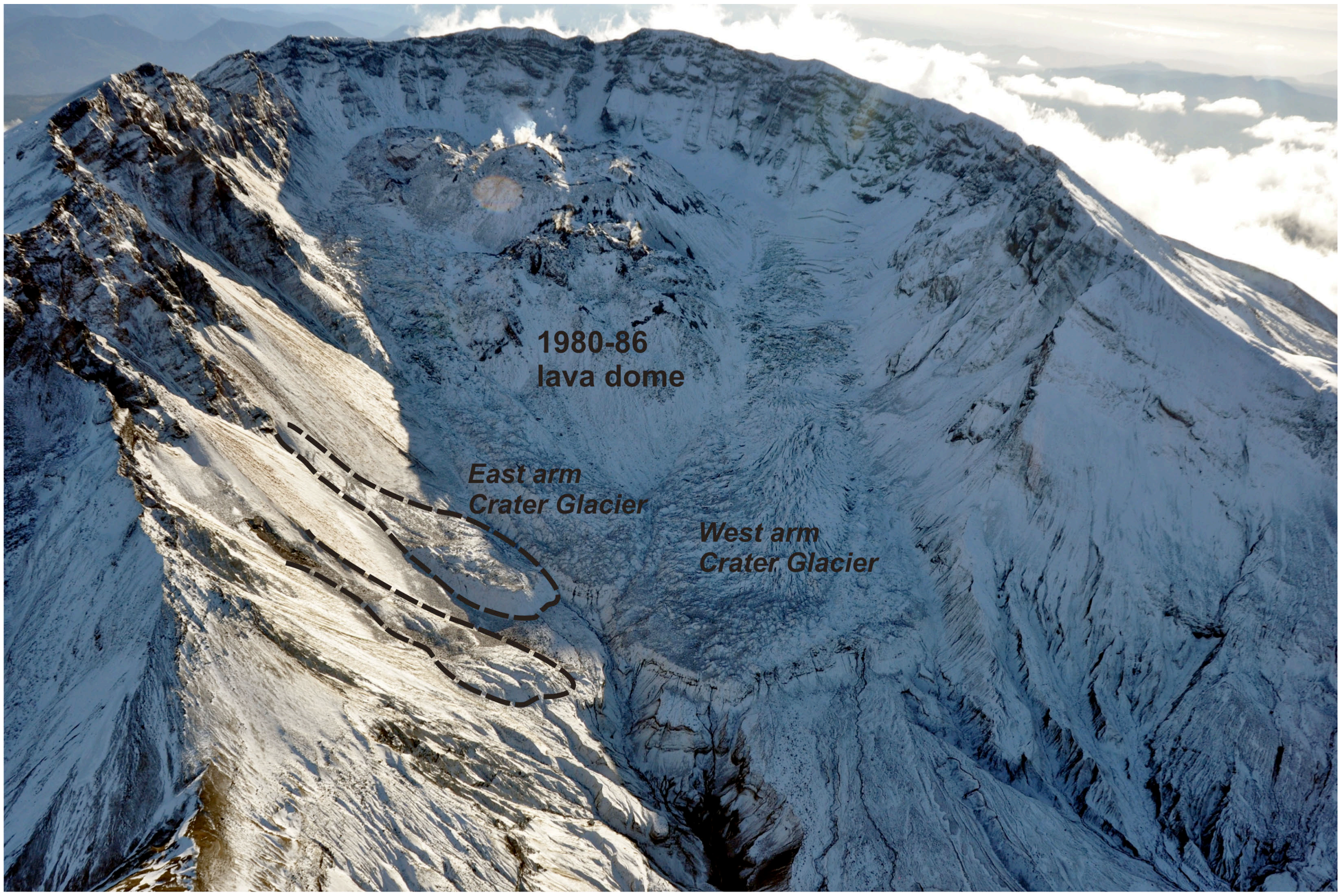

Figure 18. Terminus region of Crater Glacier as seen on November 1, 2009, view to the south. Dashed lines indicate lobes of material shed from the east crater wall, one of which is bordered by the advancing glacier by this date. Note the glacier has reached the head of Loowit channel. USGS photograph by J.S. Pallister.

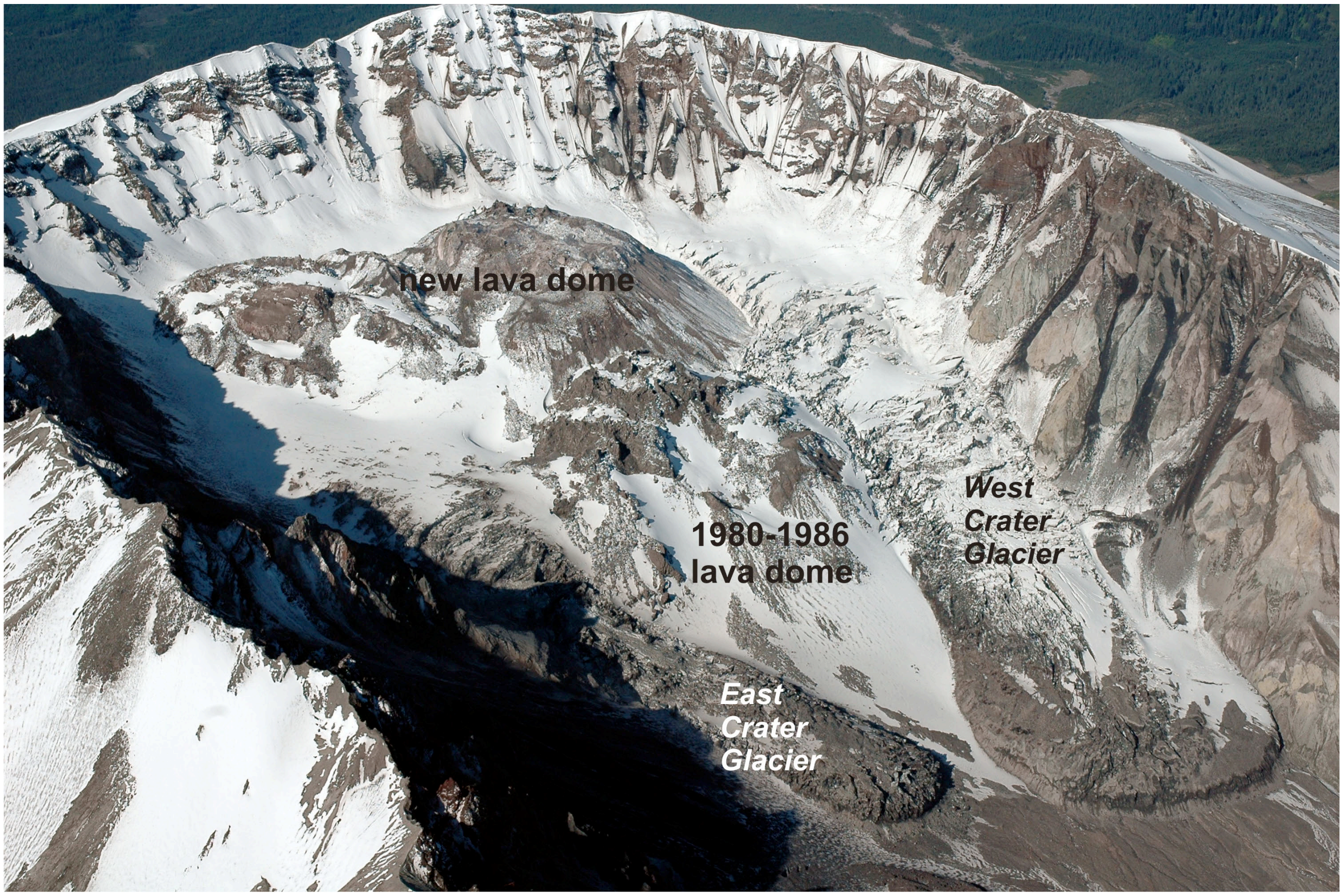

Figure 19. The glacier in Mount St. Helens crater as seen on June 26, 2007, view to the southwest. Note the near absence of surface runoff from the glacier termini. USGS photograph by M. Logan.

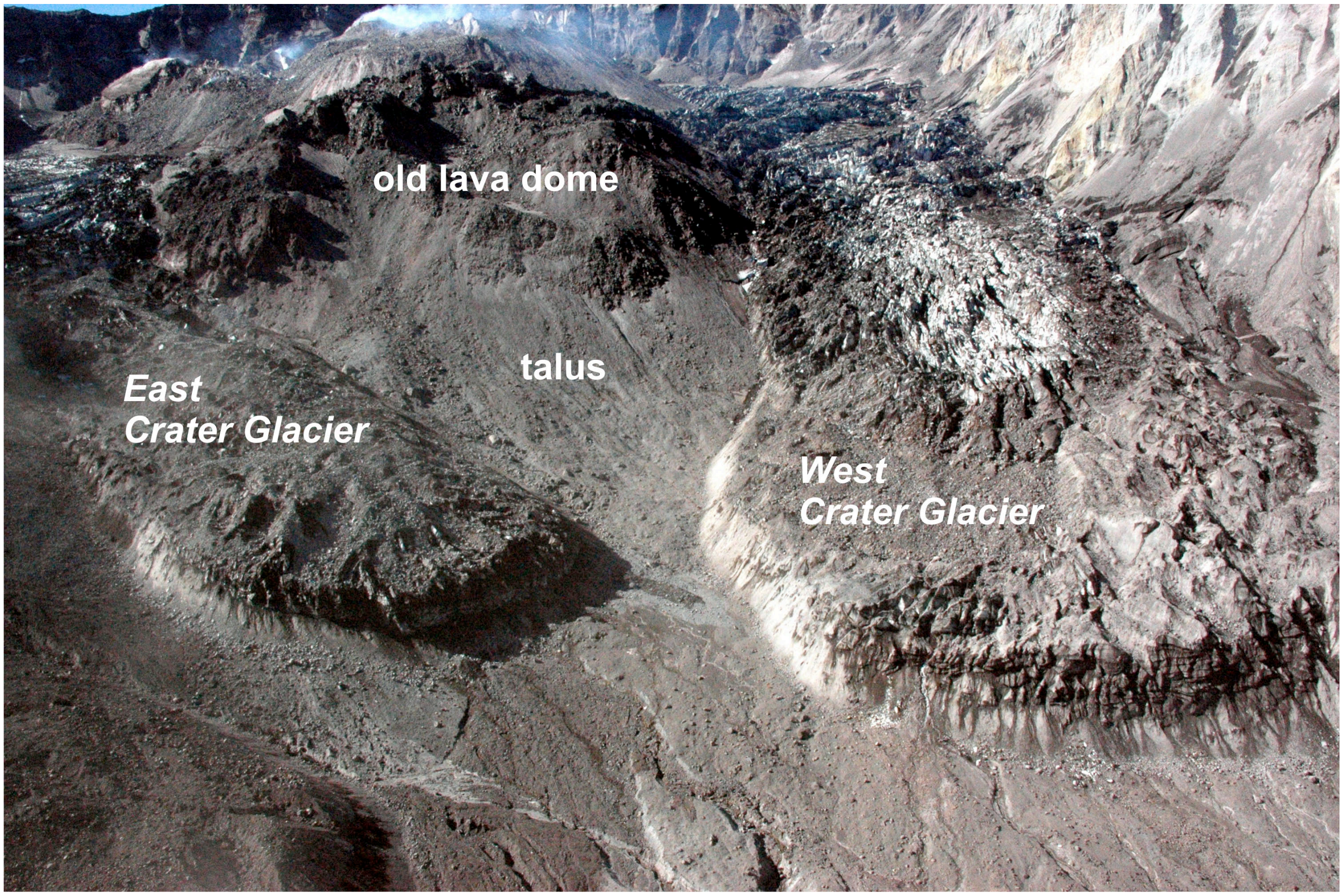

Figure 20. Terminus region of the glacier in Mount St. Helens crater as seen on August 29, 2007, view to the south. Note that east Crater Glacier and west Crater Glacier are both heavily crevassed. As earlier in summer 2007 (fig. 12), there is practically no surface runoff from the glacier termini. USGS photograph by S.P. Schilling.

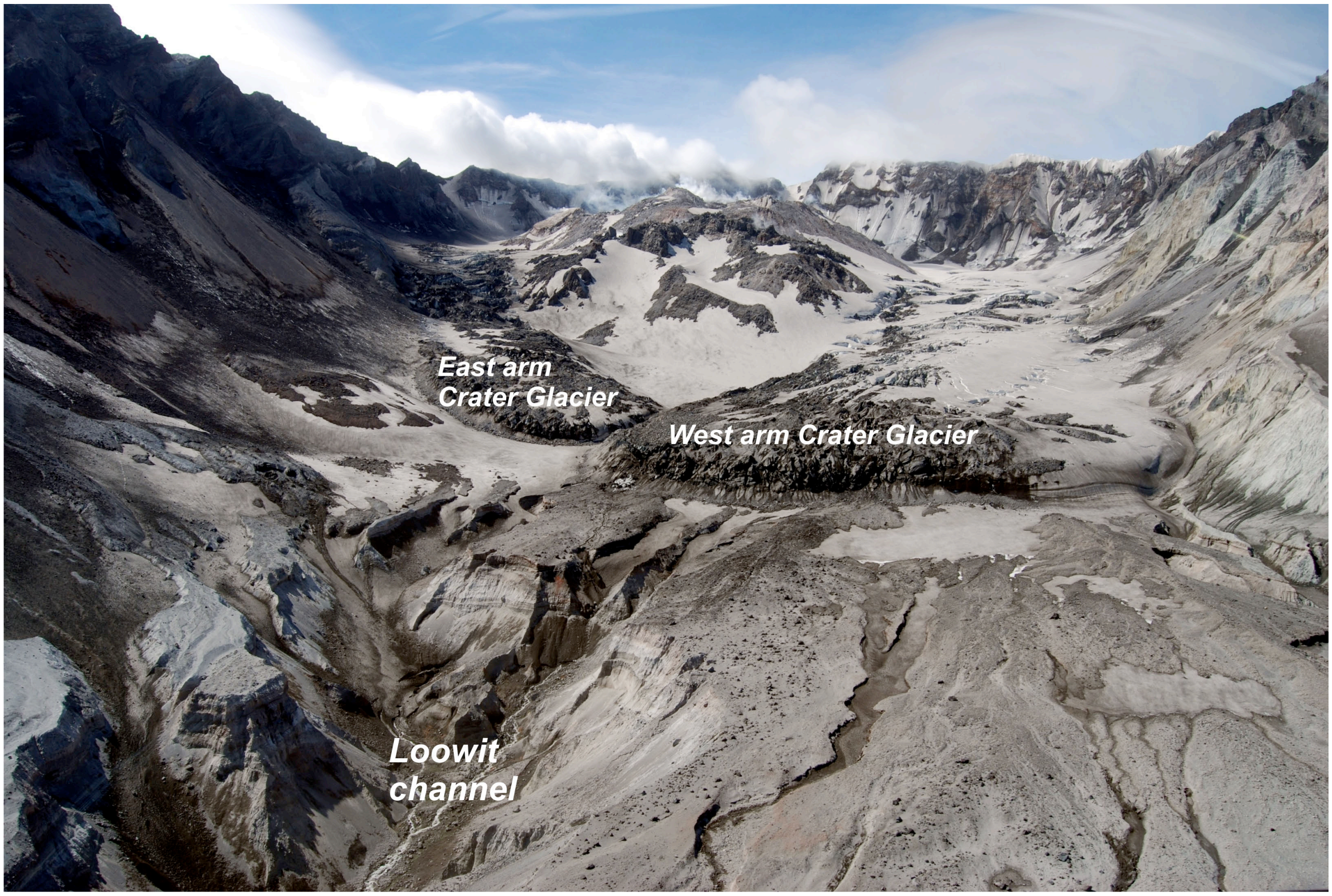

Figure 21. Crater Glacier as seen on June 26, 2008, view to the southeast. East Crater Glacier and west Crater Glacier had touched by this date. Note the lack of surface runoff in this summertime photograph. USGS photograph by J.J. Major.

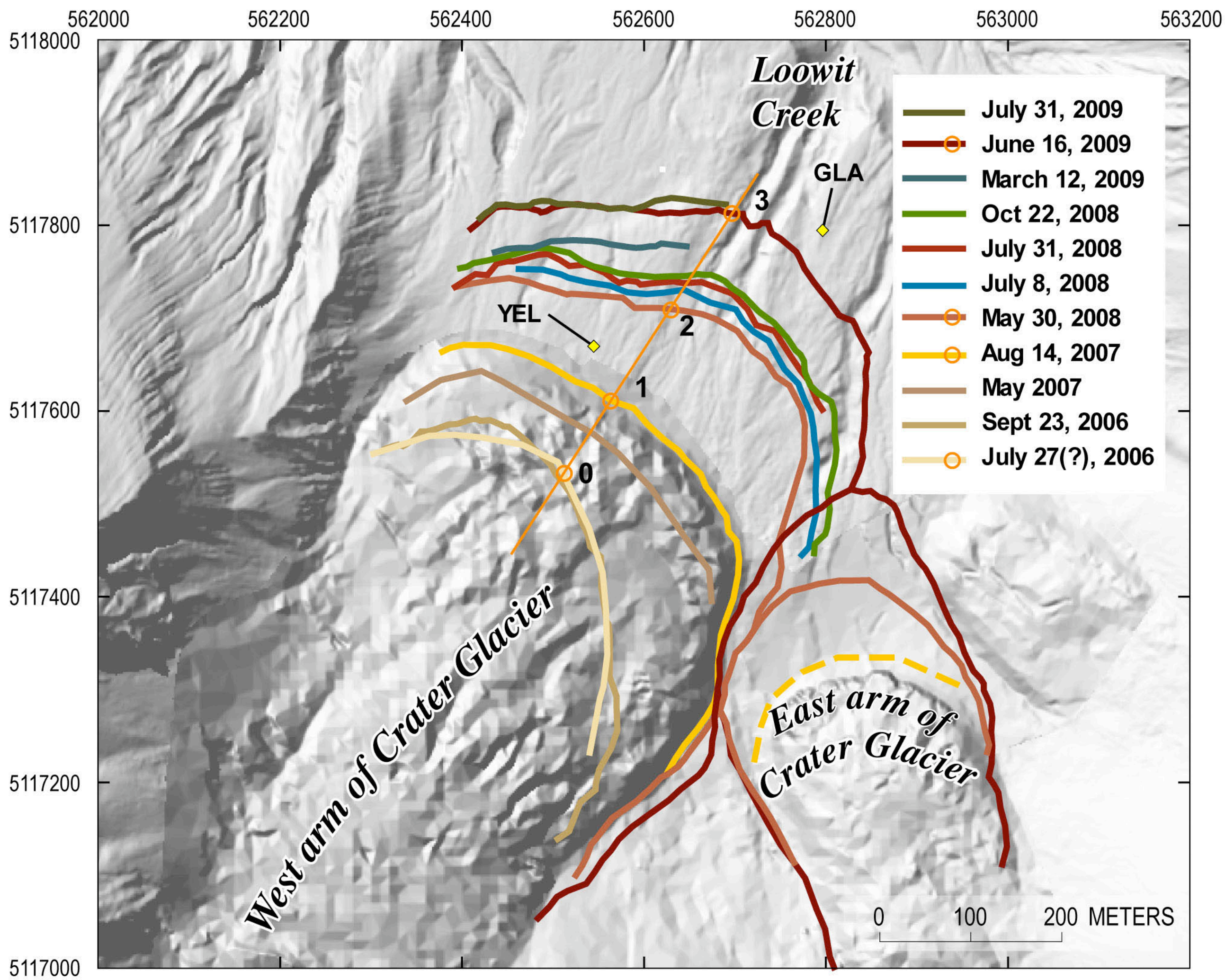

Figure 22. Successive terminus positions of Crater Glacier for dates shown. Mapped using handheld GPS units except trace of Aug. 14, 2007 (dashed), which is from an aerial photograph. Seismic station YEL was abandoned prior to being overrun by the glacier in late 2007. Tiltmeter site GLA had been abandoned but remained accessible as of September 2009. Background image is hillshade-relief map for Sept. 11, 2007. Datum and projection WGS84, UTM zone 10. The line along the glacier axis defines crossing points for terminus-advance calculations. Distances between successive points (0–1, 1–2, 2–3) are 92, 115, and 123 m, respectively.

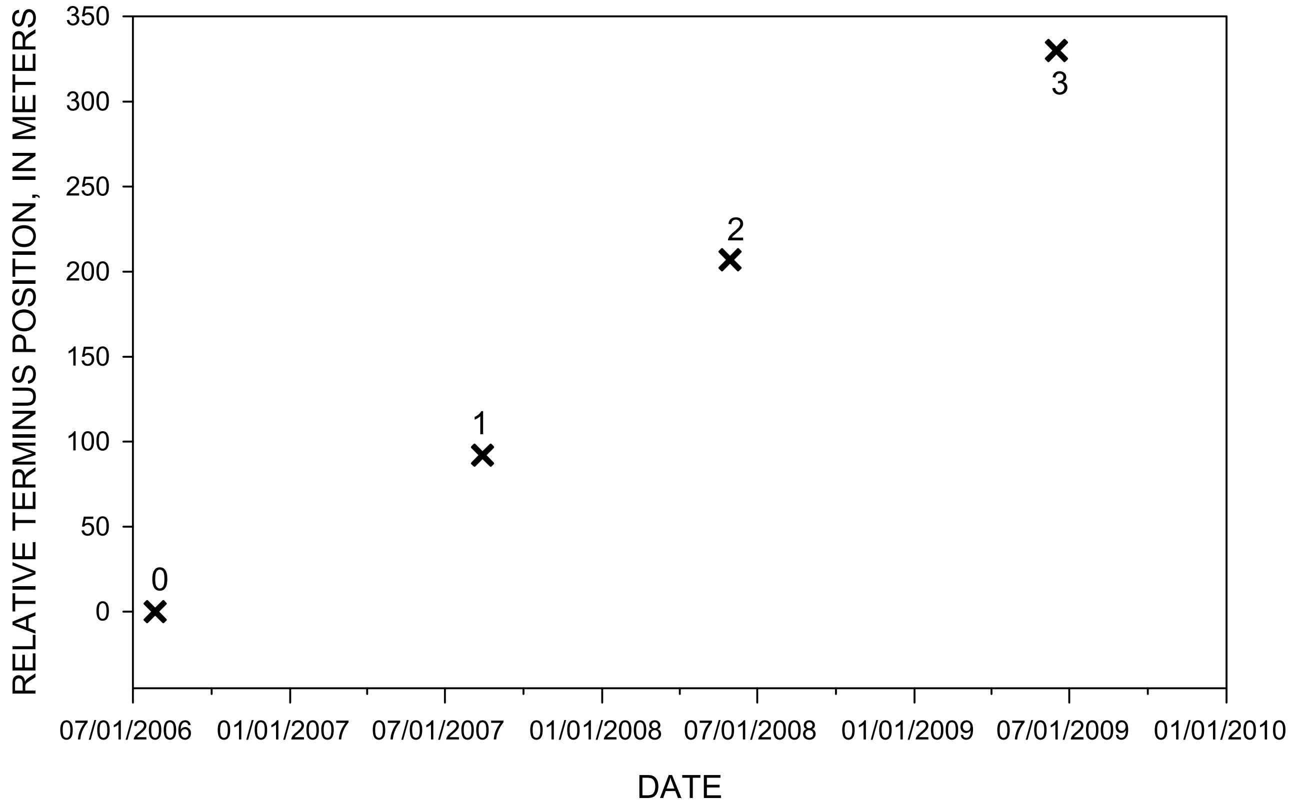

Figure 23. Advance of the terminus of Crater Glacier, calculated for the azimuth of the line indicated in figure 21. Data points are numbered to correspond to similarly numbered points in figure 22. Error is approximately 5 m. The average rate of advance is 116 m/yr.