A Mini-Surge on the Ryder Glacier, Greenland Observed via Satellite Radar Interferometry

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A dramatic short term speed up of the Ryder glacier has been detected using satellite radar interferometry. The accelerated flow represents a substantial, though short-lived, change in the ice discharge from this basin. We believe that meltwater was involved in this event, either as an active or passive participant, as meltwater-filled lakes on the surface of the glacier drained during the period of rapid motion. There are too few measurements of other large outlet glaciers to determine whether this type of event is a wide-spread phenomenon in Greenland, but because most other outlet glaciers are at lower latitude, they should experience *much* **more extensive melting.**

Discharge of ice through outlet glaciers represents a substantial portion of the mass loss of the Greenland and Antarctic ice sheets. Variations in discharge, if they are long-lived, can have a major impact on an ice sheet's mass balance. The difficulty and expense associated with *in situ* measurements of ice velocity means that few observations have been made with which to assess the variability of outlet glacier flow (1). Recently, satellite radar interferometry has provided an important new means for measuring ice velocity (2-4). We have used this technique to document a radical pulse in the speed of the Ryder Glacier, an outlet glacier at the northern edge of the Greenland ice sheet. This flow pulse represents a substantial, though short term, change in discharge from the ice sheet. We have used the term "mini-surge"(5) in the title to highlight the rapid ice motion and short duration that characterized this event. There are only a few outlet glaciers from the large ice sheets on which substantial speed variations have been observed (6). None have exhibited a similar short pulse of enhanced motion as we have observed on the Ryder. Short pulses in speed have been documented on several valley glaciers, such as a large tidewater glacier in Alaska (7), and on a glacier during an extended surge (8). Our observation on the Ryder opens a new set of questions regarding the variable flow of outlet glaciers and the potential consequences for the ice sheet.

The Ryder Glacier (Fig. 1) drains a basin of 2.8,300 km^2, which is roughly 1.7% of the inland ice area. Based on the accumulation rate data of Ohmura and Reeh (12), the total accumulation for the basin is 5.0 km^3/yr water equivalent, making the Ryder a moderately-sized outlet glacier by Greenland standards. The Ryder has two branches, which converge at 1000 m elevation and then flow out through the Sherard Osborn Fjord where the ice eventually goes afloat. At the. head of the fjord, a prominent ice ridge is oblique to the fjord axis (Fig. 1). This feature is likely generated by ice flow over a ridge in the glacier bed. The ridge shifts ice flow to the western side of the fjord. Ice backed up behind this ridge forms an ice plain (slope of c. 0.002) covered by several large lakes (Fig. 1).

We have created several interferograms of the Ryder Glacier using images from the ERS-1 and ERS-2 synthetic aperture radar (SAR). Figure 2 shows interferograms of the Ryder from September and October of 1995. There are striking differences between the interferograms for the fast moving portion of the glacier below about 1100 m. The density of fringes (color cycles) in the October interferogram (Fig. 2B) is much greater than in the September interferogram (Fig. 2A), indicating more rapid flow in October. The magnitude of the. differences are well in excess of what could be caused by differential propagation delays due to atmospheric effects (15), and the patterns of enhanced fringes are clearly related to ice flow. Further down-glacier the. pattern of fringes is lost completely in the October interferogram, while prominent fringes are still visible over this part of the September interferogram. The loss, which occurs on the fastest moving part of the glacier, is due to gradients in velocity beyond the rate that can be measured with a 1-day separation of images. In the region where there is a rapid increase in the flow speed in October (white box Fig. 2A, B), the pattern of fringes is clearly more complex (Fig. 2C) than it had been prior to the speedup.

We have used the interferograms to map the across-track component of velocity. The velocity map for the September observation is shown in Fig. 3A. This map agrees well with another velocity map (not shown) made from images acquired in March 1992 and appears to represent velocity in the normal flow mode. Figure 3B shows the difference between the September and October velocity maps. The difference map exhibits a steady increase in the change in speed from 20 m/yr up to about 150 m/yr (16), at which point the flow speed increases rapidly in the October interferogram. Noisy fringes and areas of complete-fringe loss prevented us from making quantitative comparisons of the velocity on the faster moving portions of the glacier (17) in October. In these areas, visual comparison of the noisy fringe patterns in the October interferogram with those in a 3-day interferogram from March 1992 (not shown) indicates that over large parts of the active area ice flow was in excess of 3 times its normal rate when the October data were acquired (18).

We also created an interferogram using images from 8-9 November 1995. These images were acquired from a satellite track that is nearly orthogonal to that of the other interferograms. Because different horizontal components of motion were measured by these interferograms, we cannot make direct comparisons of horizontal velocities. Sensitivity to vertical displacement of the ice as it flows over bumps, however, is independent of look direction. Comparison of the highfrequency "bull's eye" patterns in the interferograms indicates that the November data is consistent with the September observation (19), indicating that by 8 November flow on the Ryder had returned to close to its normal mode. Thus, the interferometric data indicates that the. Ryder glacier experienced a relatively short speedup (less than 7 weeks, and possibly as short as a few days), during which velocity increased by a factor of 3 or more as compared to the normal velocity of 50-300 m/yr for most of the glacier

We believe that in both the normal and mini-surge modes much of the. glacier motion is due to sliding. The low surface slope over much of the glacier makes it unlikely that the high velocities arise from ice deformation alone. Fluctuations in sliding velocities are commonly related to changes in subglacial water pressure due to variable input of surface water or rearrangements in the basal water system (20). The mini-surge of the Ryder glacier may have been caused by drainage of surface lakes, which could have elevated subglacial water pressure. in the September image (Fig. 2) several lakes show up as small dark areas, while the same lakes appear as very bright features in the October image. The change in signature indicates that the lakes may have drained over the period from September to October, causing the ice on the surface to collapse. The lake basins are regions of low correlation (13) in the October interferogram (Fig. 2C), indicating they are areas which are undergoing substantial surface change during the one day period, such as would be caused by drainage-induced fracturing of the ice on the lake surface. This suggests that the probable drainage of the lakes was related in some way to the rapid increase in velocity.

In the area near Jakobshavns Isbrae, several lakes have been observed to drain periodically through large moulins (21). These moulins close off during the winter, when there is no melt water input from the surface. Sometime after a lake forms in the summer, melting and water pressure reopen the moulin, allowing drainage. Some similar process, such as high basal water pressure opening or enlarging connections to the surface, may allow the lakes to drain on the Ryder glacier near the end of the melt season. The increase in meltwater access to the bed might play a role in greater sliding and faster velocities.

Alternatively, the increase in velocity could have opened crevasses, allowing the lakes to drain. In this case, lake drainage is an effect rather than a cause of the rapid flow and the flow instability could be caused by changes in basal water system alone. One possible scenario is that the presumed bedrock ridge could cause pending of subglacial water beneath the ice plain. This may take place if the upstream side of the bedrock ridge is 10 times steeper than the relatively low ice surface slope driving basal water downstream (22). Basal water pressure may increase to the point when stable sliding is no longer possible and a mini-surge begins.

Our interferometric data documents a dramatic increase in the speed of the Ryder outlet glacier. The mini-surge caused a temporary fewfold increase in ice velocity and discharge. The exact mechanism behind the increase is difficult to determine from the remotely-sensed data alone. The Ryder glacier, however, must have been responding to changes in basal hydrology, be it drainage of surface meltwater to the bed or internal changes in the basal water system. We do not know if this sort of event is common (perhaps seasonal) on the Ryder or on other outlet glaciers. We also do not know if this is an indication of potential for a more profound flow instability, such as a surge, which could produce a substantial change in ice flux. Surging glaciers are known to shut down and restart (8). Perhaps what we observed on the Ryder was a surge that didn't quite succeed. The Ryder mini-surge indicates that a program of satellite monitoring of the behavior of such glaciers combined with *in situ* observation is needed to improve our understanding of the role that variable discharge plays in determining the mass balance of the Greenland Ice Sheet.

REFERENCES AND NOTES

1. K. Echelmeyer, W. Harrison [*J. Glacial.*, **36**, 82 **(1990)]** looked for variations in the speed of Jakobshavns Isbrae, the fastest glacier in Greenland. Although they believe that there is a large seasonal input of meltwater to the bed, their measurements exhibited no significant seasonal variation. Due to the limited number of observations, they may have missed an episodic short term acceleration such as the one we discuss in this paper.

2. **R.** M. Goldstein, H. Engelhardt, B. Kamb, R. M. Frolich, *Science*, **262, 1525 (1993).**

3. I. Joughin, D. Winebrenner, M. Fahnestock, *Geophys. Res. Letters*, 22, 571 (1995).

4. E. Rignot, K. Jezek, H. Sohn, *Geophys. Res. Letters*, 22, 575 (1995).

5. The term "mini-surge" was used by C.F. Raymond and S. Malone [*J. Glaciol.*, 32, 178 (1986)] and B. Kamb and H. Engelhardt [*J. Glacial.*, **33**, 27 (1987)], to describe pulses of high flow speed related to high basal water pressure, which propagated down a 1 km wide valley glacier at a rate of a few hundred meters per hour. The event that we see is occurring on a larger glacier, and we do not have evidence for the propagation of the velocity pulse along the glacier. The event is short-lived, however, and the change in velocity large, thus matching several of the important characteristics they observed, The changes on the Ryder could be likened to a surge, but the duration of the speedup was too short to develop the large changes in ice distribution seen during **such** an **event.**

6. J. G. Ferrigno, B. K, Lucchitta, K. F. Mullins, A. L. Allison, R. J. Allen, W. G. Gould, *Annals of Glaciology*, *17*, 239(1993).

7. M. Meier, S. Lundstrom, D. Stone, B. Kamb, H. Engelhardt, N. Humphrey, W.W. Dunlap, M. Fahnestock, R.M. Krimmel, R Walters, *J. of Geophys. Res.*, 99, 15219 (1994).

8. B. Kamb, C.F. Raymond, W. D. Harrison, H. Engelhardt, K.A. Echelmeyer, N. Humphrey, M.M. Brugman, T. Pfeffer, *Science*, 262,469 (1985).

9. M. Fahnestock, R. Bindschadler, R. Kwok, K. Jezek *Science*, **262**, 1530 (1993).

10. Kwok R. & M. Fahnestock, *IEEE Trans. Geosci. Remote Sensing*, **34,** 189 **(1996).**

11. I. Joughin, D. Winebrenner, M. Fahnestock, R. Kwok, W. Krabill, *J. Glaciol.*, 42, 10 (1996).

12. A. Ohmura, N. Reeh, *J. Glaciol.*, 37, 140(1991).

13. Temporal decorrelation is caused by shifts in the relative positions of sub-pixel sized scatterers between acquisition of the images used to form an interferogram. Such shifts can be caused by rapid ice motion or collapse of lake ice.

14. I. Joughin, R. Kwok, M. Fahnestock, *J. Glaciol.*, accepted June 5, 1996.

15. R. Goldstein, *Geophys. Res. Letters*, 22,2517 (1995).

16. Velocity differences below 150 m/yr are accurate to within about 10 m/yr. For the small area where we measured larger differences, the error may be much greater as this region borders the area where we were unable to unwrap the phase (i. e., to remove the modulo-2π ambiguity, which is necessary for estimating velocity).

17. Over *large* parts of the fast moving areas fringes remain visible but are too noisy to unwrap.

18. For equal flow rates the pattern of fringes is three times as dense for a 3-day verses a 1-day interferogram, since three times the displacement is observed. The fact that over some. of the fast moving area, where we could not directly estimate velocity, the noisy fringe patterns for the 1 -day October interferogram are visually denser than for the 3-day interferogram (acquired March 1992 and representative of the normal flow mode) suggests that the October 1995 ice-flow velocity is in excess of three times its normal rate.

19. The effect of vertical displacement, which is proportional to horizontal flow speed, dominates the phase at length-scales of less than few ice thicknesses (3) (i.e., less than a few kilometers). Comparison of the short-scale phase variation in the November interferogram with that observed in the other interferograms indicates that similar vertical displacements occurred in September and that significantly larger vertical displacements took place in October. While not as accurate as direct comparison of horizontal velocities, the results indicate that the November velocity is close to the September velocity.

20. B. Kamb, H. Engelhardt, M.A. Fahnestock, N. Humphrey, M. Meier, D. Stone, *J. of Geophys. Res.*, **99**, 15231 (1994).

21. H. Thomsen, L. Thorning, R. Braithewaite, The Geological Survey of Greenland, Nr. 138, (1985).

22. W. S. B. Paterson, *The Physics of Glaciers.* Second Edition, Pergammon Press, Oxford (1994).

23. We thank B. Bindschadler for his many helpful comments on the manuscript. I. Joughin and R. Kwok performed this work at the Jet Propulsion Laboratory, California Institute of Technology, under contract with NASA, S. Tulaczyk acknowledges support from the Henry and Grazyna Bauer fellowship. Mark Fahnestock was supported under NASA NMTPE grant NAGW4285.

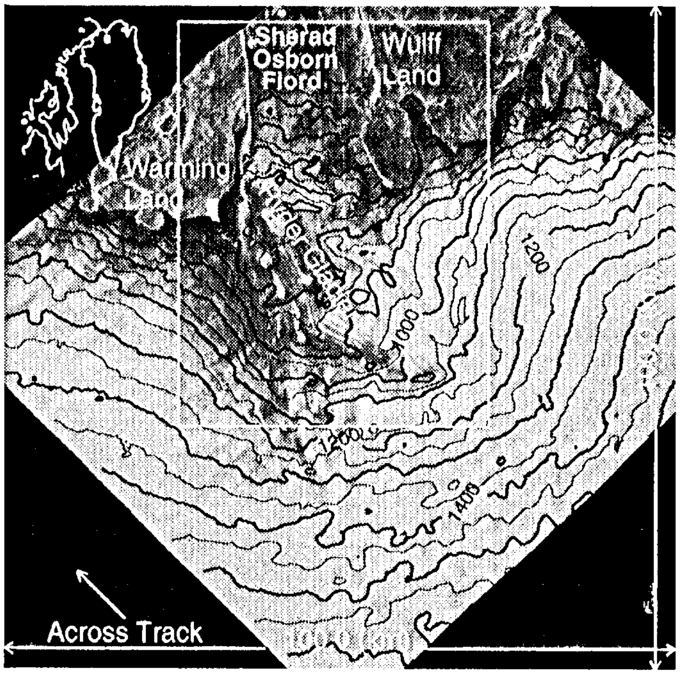

Fig. 1. ERS-1 SAR amplitude image of the Ryder Glacier, Greenland acquired 18 March 1992 at the location indicated by a solid-white box in the inset map. Several smaller glaciers along the ice margin extend into Wulff Land. The pattern of low backscatter at the ice margin increasing to bright backscatter further inland is due to the different scattering properties of the bare-ice, wet-snow and percolation facies (9). The locations where lakes existed during the previous melt season show up as bright spots of a few kilometers in diameter. Elevation contours at 50- (thin) and 100-m (thick) intervals are plotted over ice-covered portions of the scene. To create this high resolution DEM we difference pairs of interferograms to remove the displacement effect (10,11). The relative accuracy of the resulting DEM is on the order of a few meters, while there may be long wavelength errors of up to several ten's of meters.

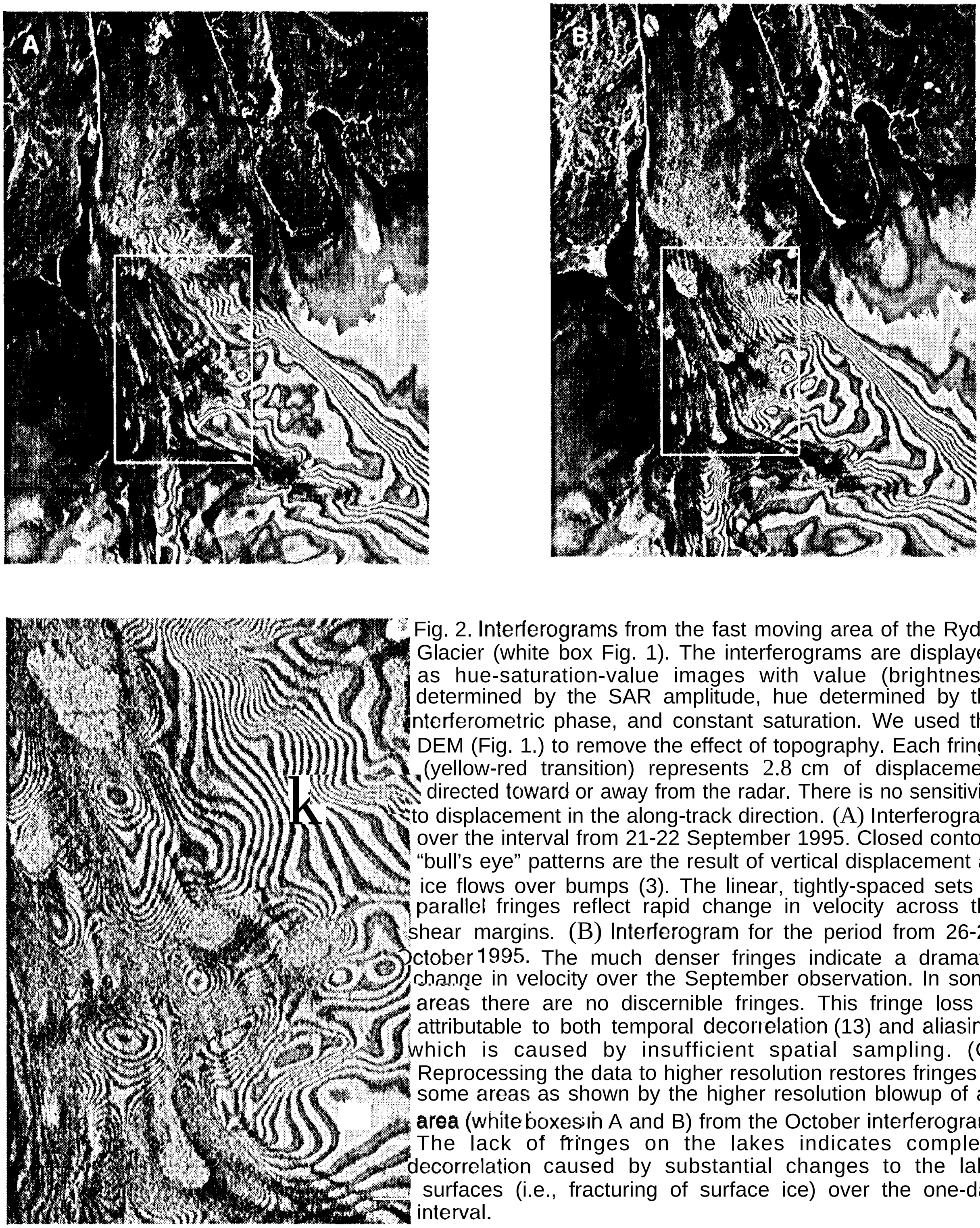

Fig. 2. Interferograms from the fast moving area of the Ryder Glacier (white box Fig. 1). The interferograms are displayed as hue-saturation-value images with value (brightness) determined by the SAR amplitude, hue determined by the interferometric phase, and constant saturation. We used the DEM (Fig. 1.) to remove the effect of topography. Each fringe (yellow-red transition) represents 2.8 cm of displacement directed toward or away from the radar. There is no sensitivity to displacement in the along-track direction. (A) Interferogram over the interval from 21-22 September 1995. Closed contour "bull's eye" patterns are the result of vertical displacement as ice flows over bumps (3). The linear, tightly-spaced sets of parallel fringes reflect rapid change in velocity across the shear margins. (B) Interferogram for the period from 26-27 October 1995. The much denser fringes indicate a dramatic change in velocity over the September observation. In some areas there are no discernible fringes. This fringe loss is attributable to both temporal decorrelation (13) and aliasing, which is caused by insufficient spatial sampling. (C) Reprocessing the data to higher resolution restores fringes in some areas as shown by the higher resolution blowup of an area (white boxes in A and B) from the October interferogram. The lack of fringes on the lakes indicates complete decorrelation caused by substantial changes to the lake surfaces (i.e., fracturing of surface ice) over the one-day interval.

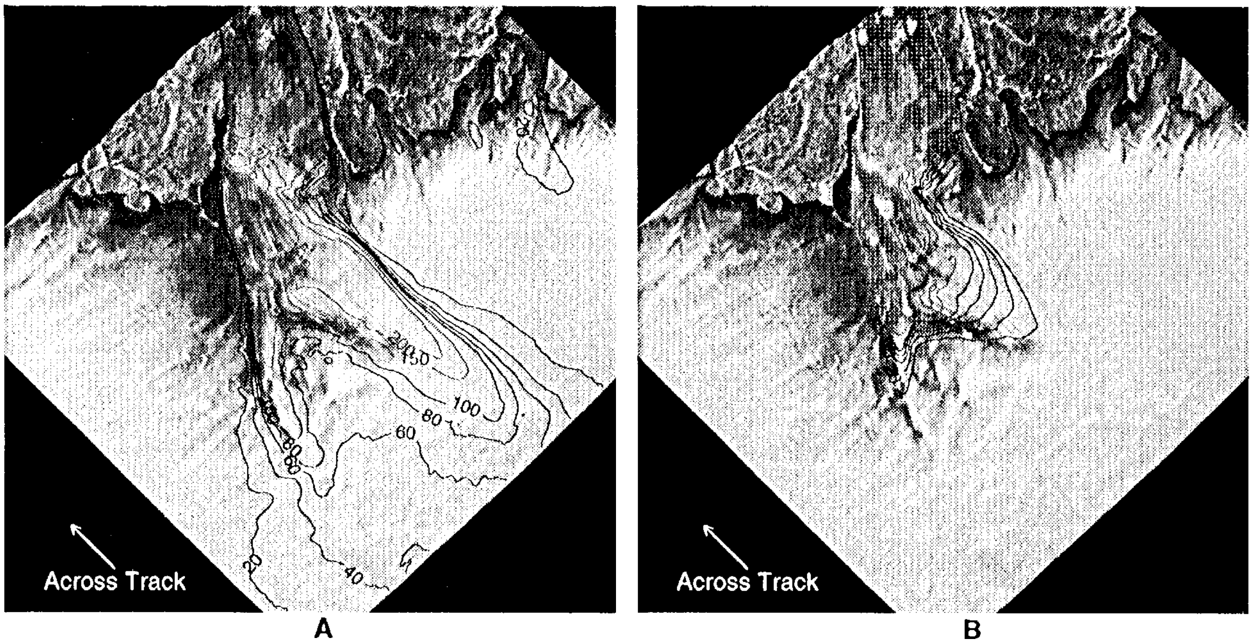

Fig. 3. (A) Contours of September across-track velocity plotted over the SAR image acquired 21 September, 1995. Blue contours at 20 m/yr intervals are used for velocity up to 100 m/yr and 50 m/yr red contours are used for velocity greater than 100 m/yr. In estimating the horizontal velocity field, slope information was used to help reduce the effect of vertical displacement (14). (B) Difference between the October and September velocity estimates plotted over the 26 October 1995 image. Green stippled areas indicate where October velocity could not be estimated (17).