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Satellite Radar Interferometry Measures Deformation at Okmok Volcano

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The center of the Okmok caldera in Alaska subsided 140 cm as a result of its February-April 1997 eruption, according to satellite data from ERS-1 and ERS-2 synthetic aperture radar (SAR) interferometry. The inferred deflationary source was located 2.7 km beneath the approximate center of the caldera using a point source deflation model. Researchers believe this source is a magma chamber about 5 km from the eruptive source vent. During the 3 years before the eruption, the center of the caldera uplifted by about 23 cm, which researchers believe was a pre-eruptive inflation of the magma chamber. Scientists say such measurements demonstrate that radar interferometry is a promising spaceborne technique for monitoring remote volcanoes. Frequent, routine acquisition of images with SAR interferometry could make near real-time monitoring at such volcanoes the rule, aiding in eruption forecasting.

The Okmok Volcano

Okmok Volcano (Figure 1) is a 10-km-wide caldera that occupies most of the northeastern end of Umnak Island, in the Aleutian Islands. It erupted extrusively in 1945, 1958, and 1997, and explosively in 1986 and 1988. All historic eruptions of Okmok originated from Cone A, which is located on the southern edge of the caldera floor, and produced abundant ash emissions and mafic lava flows that crossed the caldera floor. Voluminous rhyodacitic caldera-forming eruptions occurred 8000 and 2400 years ago.

The latest eruption of Okmok Volcano began in mid-February 1997 and lasted for 2 months. Ash and lava were vented from Cone A, eventually covering an area of about 15 km^2. The red line in Figure 1 shows the extent of the lava flows. Satellite thermal imagery and inspection from the air indicated that eruptive activity had ended by late April 1997.

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Satellite Radar Interferometry

To measure the deformation associated with the 1997 eruption, interferograms were constructed from the phase difference of pairs of SAR images recorded by ERS-1 and ERS-2 satellites. The two satellites have C-band microwave radars with a 5.66 cm wavelength. The phase difference between two images taken on different satellite passes corresponds to the change in the round-trip path length of radar waves to ground targets.

Essentially, an interferogram is a contour map of the change in distance to the ground surface along the look direction of the satellite. In the case of ERS-1 and ERS-2, the look direction is inclined 23° from the vertical. As a result, interferograms constructed from ERS data are more sensitive to vertical displacements in the target area than to horizontal displacements. Path length changes are related to topography, the difference in the satellite positions between the two passes, ground deformation occurring between the times of the two passes, and noise. Each cycle of the interferometric phase, or fringe, is represented by a series of colors on the interferogram (Figures 2a-c).

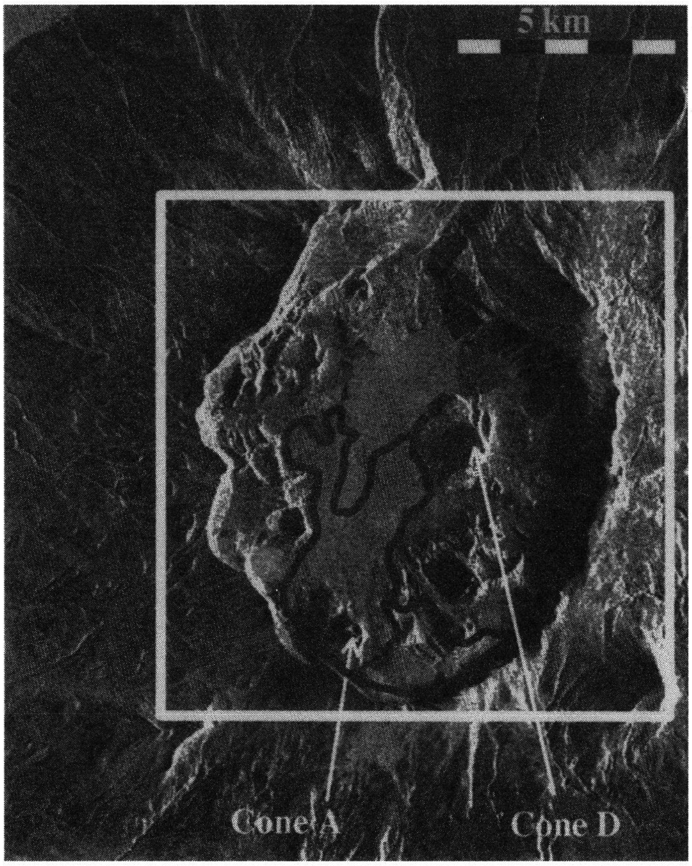


Fig. 1. SAR amplitude image of Okmok volcano, 16 x 20 km in dimension. Floor of the caldera is filled by lavas and ash from eruptions in 1945, 1958, 1986, 1988, and 1997. The extent of lava from the latest 1997 eruption is outlined by red line. The solid white rectangle indicates the position of Figures 3a and 3b. Original color image appears at the back of this volume.

An interferogram is usable only in those areas where the radar returns in both images are coherent. The degree of coherent interference of SAR images depends on the changes of the backscattering characteristics of the ground surface between the two radar acquisitions. Reduction of coherence can be caused by surface alterations such as growth of vegetation, changes in snow or ice cover, or the covering of the old surface with new volcanic ash or lavas [*Zebker et al.*, 1996].

On Alaskan volcanoes, coherence can be maintained over a time interval of at least 2 years if images are acquired during subarctic summer and fall, July to November [*Lu and Freymueller*, 1998]. The deformation associated with the 1997 eruption was analyzed using images acquired during the summer and fall of 1992, 1993, 1995, and 1997. No data were recorded between March and November of 1996. All of the images were acquired in the descending mode of the ERS-1 and ERS-2 orbits, where the satellites travel approximately from north to south, and look to the west, inclined 23° down from vertical. No Global Positioning System or other geodetic data are available for Okmok Volcano.

The component of the phase change contributed by ground surface deformation can be obtained by removing the topographic component of an interferogram using a digital elevation model or another interferogram [e.g., *Massonnet et al.*, 1995; *Peltzer and Rosen*, 1995]. The effect of topography was removed using a digital elevation model and the known satellite geometry, leaving only the contributions of ground deformation and noise (Figure 2a). The existing elevation model for Okmok Volcano was interpolated from 90 m spacing to 20 m (the dimensions of each pixel), and was improved using an interferogram derived from ERS-1 and ERS-2 tandem images acquired 1 day apart. The topography of the caldera floor, where most of the coherent signal is observed, is relatively flat, with less than 270 m relief.

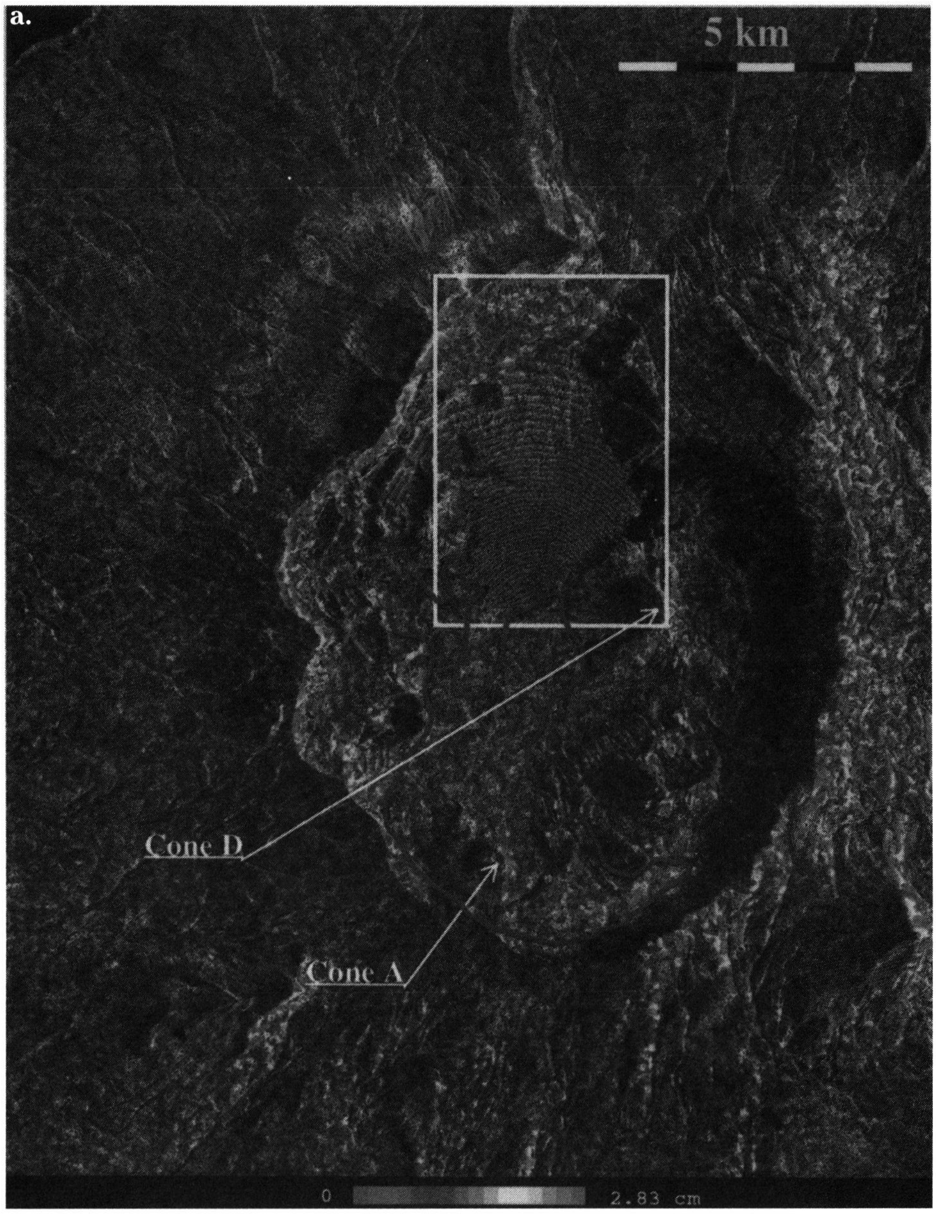
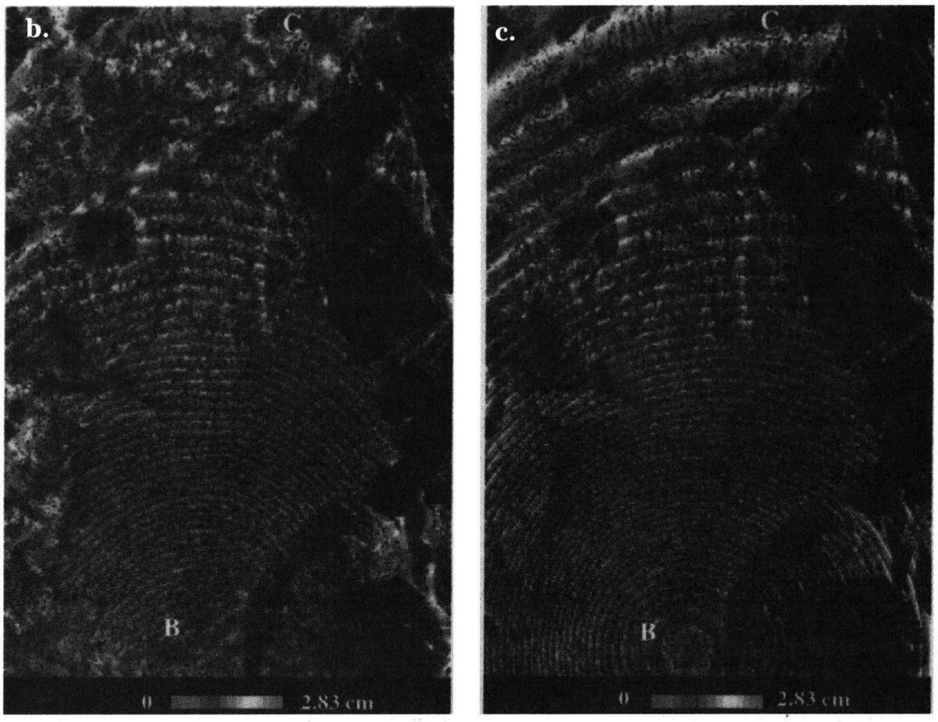


Figure 2. see next page

Deflation of Okmok Caldera

Figure 2a shows an interferogram with topography removed for a 16 x 20 km area of Okmok Volcano, showing ground deformation between October 9, 1995, and September 9, 1997. Each fringe caused by ground deformation corresponds to a 2.83 cm change in the distance from satellite to ground between two radar acquisitions and is represented by a complete color cycle in an interferogram. Phase signals are coherent in the northern portions of the image, both within and outside of the caldera, as well as in the western and southeastern parts of the image. The area of loss of signal coherence within the caldera corresponds mostly to regions covered by loose materials or by new lava and ash of the 1997 eruption.

An enlargement of the main area of coherence is shown in Figure 2b. Both in the main coherent region and the small coherent region east of the caldera, the elliptical fringes and the order of colors (repetitions of blue-yellow-magenta from the caldera outward) show that the deformation field is consistent with a deflation source located in roughly the center of the caldera. The three fringes in the southeastern part of the image are important because they show the same sense of motion as the other fringes, down toward the center of the caldera, and rule out the possibility that the fringes observed in the northern part of the image are erroneous "junk fringes" caused by poor orbital control. The altitude of ambiguity (the amount of topographic change required to generate one interferometric fringe) of this interferogram is 950 m; so 950 m of topography would contribute only one fringe to the image, and the expected topographic error amounts to no more than 0.04 fringes.



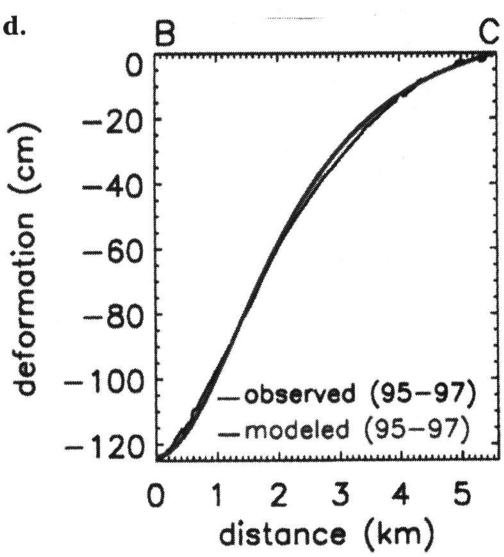


Fig. 2. a) Deformation interferogram spanning October 1995 to September 1997, which brackets the February 1997 eruption of Okmok Volcano. Each fringe represents a 2.83-cm change in distance along the satellite look direction. The image covers the same area as Figure 1; b) Portion of the interferogram of Figure 2a, outlined by the white box in Figure 2a. There are 44 fringes along a profile from B to C of 5.5 km; c) A modeled interferogram using the best-fit point deflation model and covering the same region as Figure 2a; d) The observed (Figure 2b) and the modeled (Figure 2c) deformation along the satellite look direction on the profile from B to C. Original color image appears at the back of this volume.

The maximum topographic relief over the entire image is about 800 m. Atmospheric delays can cause up to two or three fringes of systematic, spatially correlated error in an interferogram (see, e.g., *Massonnet and Feigl* [1995]). Therefore systematic biases can account for no more than a few percent of the observed volcanic inflation. There are 44 fringes along a distance of 5.5 km from B to C (Figure 2b) and two or three more outside the caldera, each fringe representing 2.83 cm of ground surface motion in the satellite's look direction. Point B moved away from the satellite more than point C, corresponding to subsidence at the center of Okmok caldera (Figure 2d). The center of subsidence is offset by about 5 km from the eruptive vent, which implies that significant lateral magma transport may have occurred during eruption. The observed deformation was modeled using a spherical point deflationary pressure source in an elastic half-space [*Mogi*, 1958].

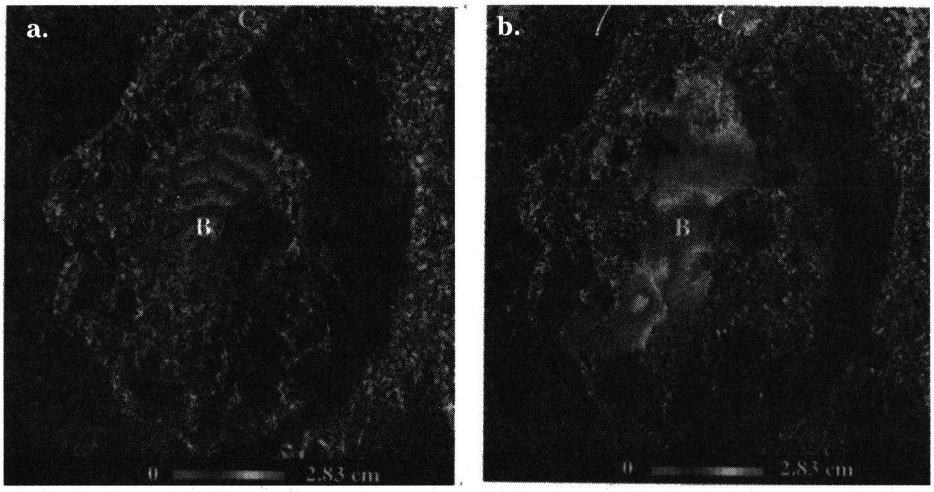
The deflationary source is inferred to be a shallow magma chamber—the source of the 1997 lavas. Synthetic interferometric fringes were generated from a variety of models, varying the location and depth of a single point source deflation. The approximate horizontal coordinates of the model deflation source were chosen to match the concentric appearance of the fringes. The source depth and scale of the pressure source were varied to match the observed fringe spacing and total number of fringes.

The best-fitting model matches the fringe spacing and shape within the caldera, the total observed deformation, and profile B-C. Based on this model, the 2.7 km source depth (Figure 2c) and a volume change in the magma chamber of 0.048 km^3 (see *Anderson* [1936]) were inferred. The maximum subsidence in this model is 140 cm, directly above the deflationary source. A modeled interferogram is shown in Figure 2c, which covers the same region as Figure 2b. The volume change estimate assumes that no inflation or deflation occurred between October 1995 and the beginning of the eruption. The lava covered an area of 15 km^2, so assuming the volume of lava is the same as the volume removed from the magma chamber, the average flow thickness would be 3.2 m.

The spherical point source model used suffers from two potential drawbacks: the source could be aspherical and the point source approximation may be invalid (see, e.g., *McTigue* [1987]). One or both of these possibilities is suggested by the poor fit of the model fringes to those observed in the vicinity of point B and the middle between B and C (Figures 2b, 2c, and 2d). The location of the deflation source in the approximate center of the caldera and the inference that the source is shallow are conclusions that do not require investigation of more complex models, but the estimated eruptive volume could depend on the source model chosen.

Inflation of Okmok Caldera

Interferograms were formed for time periods spanning October 31, 1992 to November 20, 1993 (Figure 3a), and November 1, 1993 to October 25, 1995 (Figure 3b) to measure how much inflation may have preceded the eruption. In general, pre-eruptive inflation is expected and the inferred pre-eruptive inflation source should be located in the same



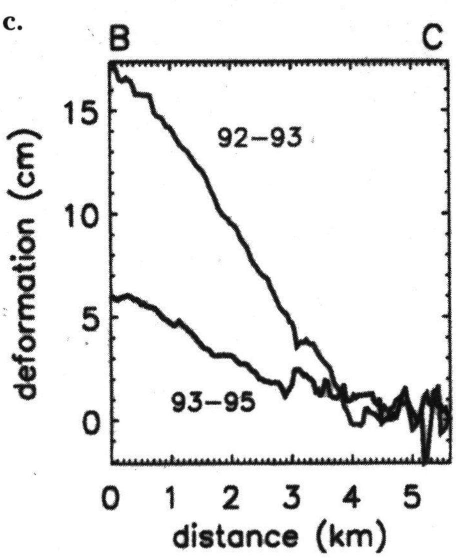


Fig. 3. a) Deformation interferogram spanning 1992-1993. The location of the image is outlined by the solid white rectangle in Figure 1. A total of 17 cm of uplift was observed along the profile from B to C; b) Deformation spanning 1993 to 1995. A total of 6 cm of uplift occurred along the profile from B to C during 1993-1995; c) Deformation along the satellite look direction on the profile from B to C for 1992-1993 and 1993-1995. Original color image appears at the back of this volume.

place as the coeruptive deflation source [*Dvorak and Dzurisin*, 1997]. More than four fringes were observed, corresponding to about 17 cm uplift of the center of the caldera from 1992 to 1993 (Figures 3a, 3c) and about two fringes corresponding to about 6 cm uplift from 1993 to 1995 (Figures 3b-c). Within these interferograms, the magnitudes of possible systematic biases from atmospheric delays or other sources are a larger fraction of the inferred signal. However, because the inferred uplift is generally consistent in time, it is unlikely that the apparent 23-cm uplift above the magma chamber from 1992 to 1995 is entirely the result of such errors.

It is less clear that the apparent reduction in the inflation rate from 1992-1993 to 1993-1995 is significant. The center of 1993-1995 uplift (Figure 3b) correlates well with the center of 1995-1997 subsidence in the model (Figure 2c). The observation of pre-eruptive inflation of Okmok caldera could mean that a minimum of 0.05 km^3 of magma was emplaced in a shallow magma chamber in the 3 years prior to the eruption, or that pressure increased without additional magma input by development of a vapor phase, perhaps by second boiling during crystallization.

Because no images were recorded in the summer of 1996, and no usable images were recorded immediately prior to the eruption in 1997, it is unknown how much inflation occurred between October 1995 and the beginning of the eruption. If pre-eruptive inflation continued at a rate similar to that for 1992-1995, the 1995-1997 inflation would be fairly small and the model would give a reasonable estimate of the coeruptive deflation. However, if Okmok caldera inflated rapidly in the year, months, or days prior to the eruption, then the coeruptive deflation would have been significantly underestimated. Observations at several volcanoes suggest that both cases are possible (see, e.g., *Newhall and Dzurisin* [1988]).

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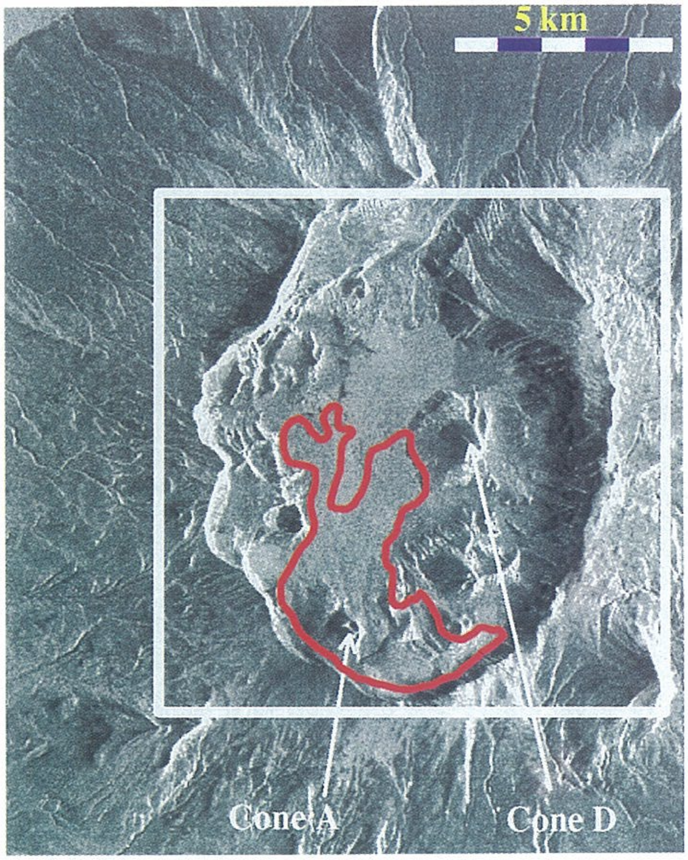

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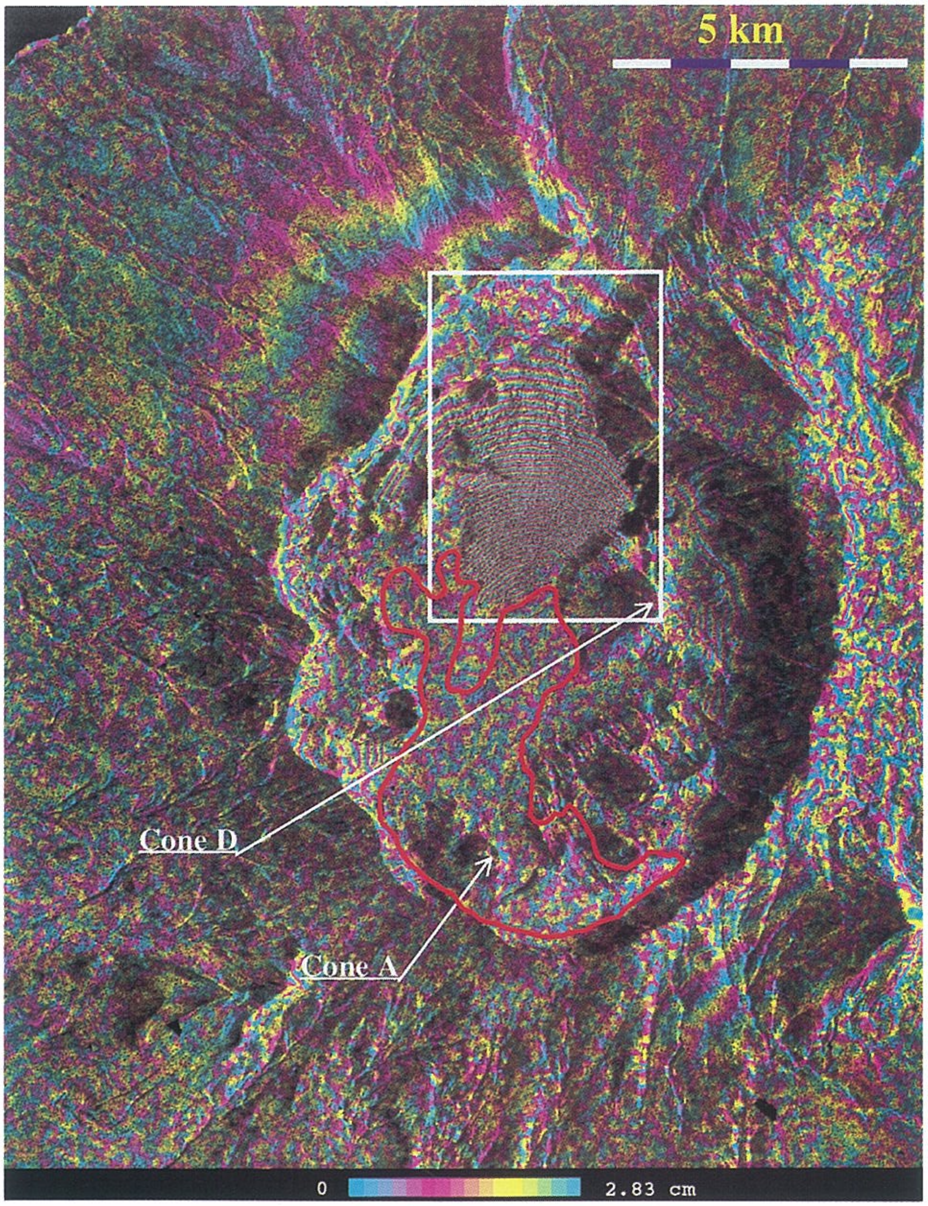
a.



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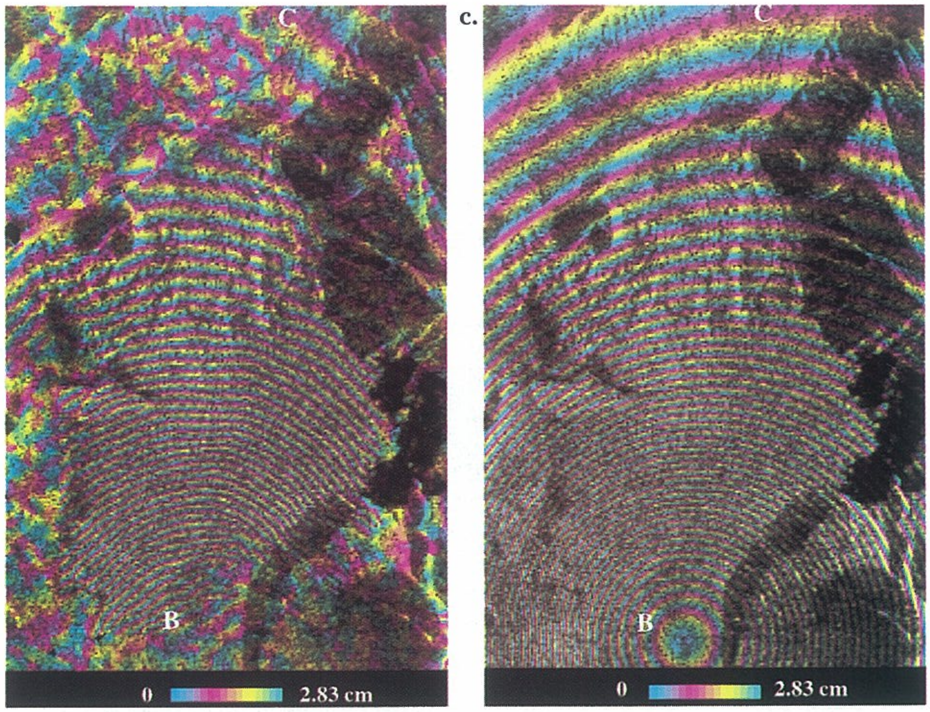
b. c.



d.

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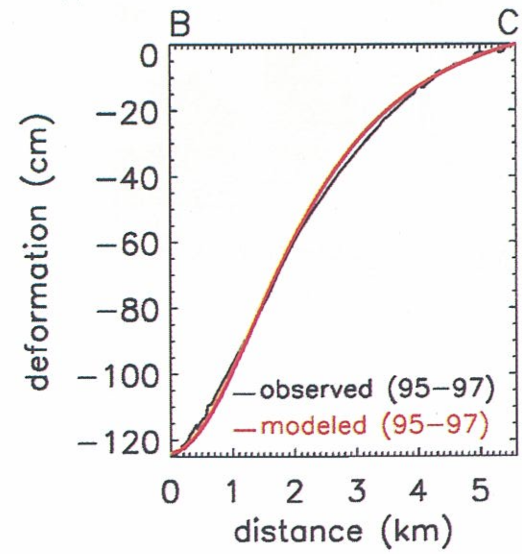

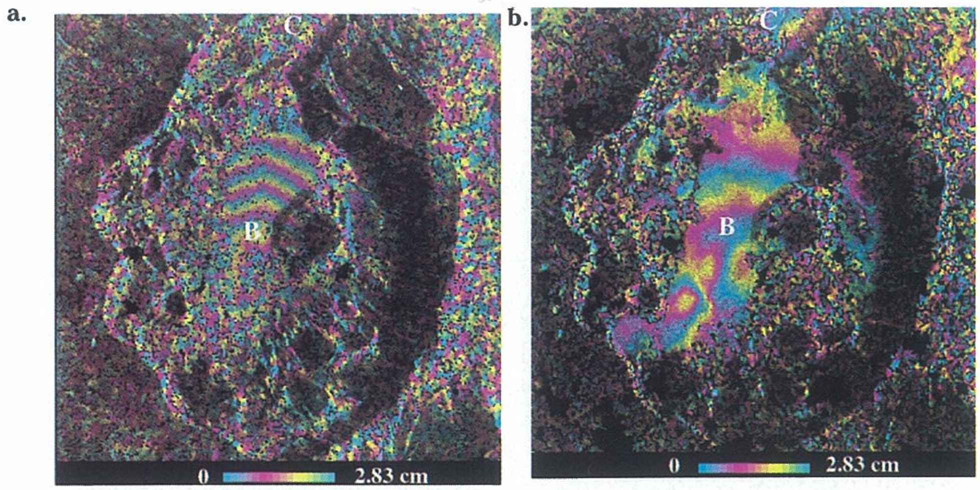

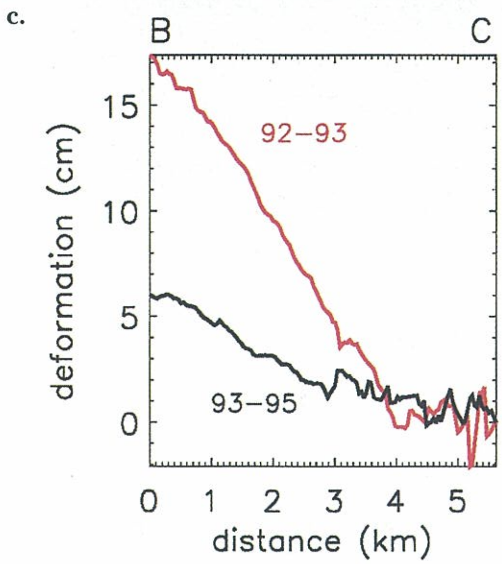

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