Interferometric Synthetic Aperture Radar Studies of Alaska Volcanoes

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Abstract-Interferometric synthetic aperture radar (InSAR) imaging is a recently developed geodetic technique capable of measuring ground-surface deformation with centimeter to subcentimeter vertical precision and spatial resolution of tens-of-meter over a relatively large region (~10^4 km^2). The spatial distribution of surface deformation data, derived from InSAR images, enables the construction of detailed mechanical models to enhance the study of magmatic and tectonic processes associated with volcanoes. This paper summarizes our recent InSAR studies of several Alaska volcanoes, which include Okmok, Akutan, Kiska, Augustine, Westdahl, and Peulik volcanoes.

I. INTRODUCTION

Study of Alaska volcanoes using interferometric synthetic aperture radar (InSAR) has been motivated by two factors. *First*, many volcanic eruptions are preceded by pronounced ground deformation in response to increasing pressure from magma chambers, or to the upward intrusion of magma [1]. In general, it is expected that a volcano is subject to inflation prior to an eruption, in which case magma migrates from depth, causing localized inflation. Subsequent eruption causes deflation as some or all of this magma is erupted to the surface. Analysis of surface deformation associated with eruptions or intrusions, along with seismicity and other information, provide significant inputs for studying magma dynamics. *Second*, the Alaska-Aleutian arc contains more than 6% of the world's active volcanoes. During the past decade, there has been an average of about 3-4 explosive eruptions per year. Although the rate of eruptive activities in the arc is very high, these volcanoes remain relatively poorly studied due to the remote locations, difficult logistics, high cost of field measurement, and persistent cloud cover. Therefore InSAR can significantly improve our understanding of activity at these volcanoes.

We study magma body systems by mapping the surface deformation and modeling the observed deformation. The deformation is measured using the InSAR technique [2,3] with images collected by ERS-1/ERS-2 satellites. InSAR measures the corresponding phase difference resulting from the difference in the round trip path length to the same ground point between two SAR images. The phase difference is due mainly to five effects: (1) differences in the satellite orbits in the two passes, (2) topography, (3) ground deformation, (4) atmospheric propagation delays, (5) systematic and environmental noise. Knowledge of the position and attitude of satellites is required to remove the effect caused by the differences in the satellite orbits of the two passes. The topographic effects in the interferogram can be removed by producing a synthetic interferogram based on an accurate digital elevation model (DEM) and subtracting it from the interferogram to be studied [2,3]. This results in a deformation interferogram. The component of ground deformation along the satellite's look direction can potentially be measured with a precision of from sub-centimeters to centimeters using C-band ERS-1/ERS-2 SARs. Because of problematic atmospheric propagation delays, repeat observations are important to confidently interpret small geophysical signals related to volcanic activities [4]. To understand the magma processes, we use numerical models to invert the physical parameters based on the observed deformation [5,6]. These models provide insightful evidence of magma processes.

In this paper, we summarize our recent InSAR studies at six Alaska volcanoes, including Okmok, Akutan, Kiska, Augustine, Westdahl, and Peulik volcanoes (Fig. 1a).

II. INSAR STUDY OF ALASKA VOLCANOES

A. Okmok volcano

Okmok volcano, a broad shield topped with a 10-km-wide caldera, is located in the central Aleutian arc (Fig. 1a). Catastrophic pyroclastic caldera-forming eruptions occurred ~8000 and 2400 years ago [7]. Eruptions in this century happened in 1931, 1936, 1938, 1943, 1945, 1958, 1960, 1981, 1983, 1986, 1988, and 1997 [7]. Intensive InSAR studies were made of the latest eruption of Okmok volcano (February-April 1997) [8,9]. Interferograms constructed from ERS-1/ERS-2 SAR images indicated surface inflation of more than 18 cm (between 1992 and 1995) prior to eruption in February-April 1997, more than 140 cm of surface deflation associated with the eruption (Fig. 1b), and 5-10 cm/year inflation after the eruption. Numerical modeling suggested the magma reservoir responsible for the eruption resided at about 2~3 km depth beneath the center of the caldera, which was about 5 km from the eruptive vent. This study demonstrated that InSAR is capable of measuring pre-eruptive, co-eruptive, and post-eruptive deformation in the sub-arctic environment [8,9].

B. Akutan volcano

Akutan is the second most active volcano in Alaska, and sits in the central Aleutian volcanic arc (Fig. 1a). In March 1996, an intense swarm of volcano-tectonic earthquakes (~3000 felt by local residents, maximum magnitude 5.1) beneath Akutan Island, produced extensive ground cracks but no eruption of Akutan volcano. InSAR images spanning the time of the swarm revealed complex island-wide deformation: the western part of the island including Akutan volcano moved upward while the eastern part moved downward [10] (Fig. 1c). The axis of the deformation approximately aligns with new ground cracks on the western part of the island and with Holocene normal faults that were reactivated during the swarm on the eastern part of the island. The axis is also roughly parallel to the direction of greatest compressional stress in the region. No ground movements greater than 2.83 cm were observed outside the volcano's summit caldera for periods of 4 years before the swarm [10]. With the observed deformation, seismicity, and ground cracks as input, we modeled the deformation primarily as the emplacement of a shallow, east-west-trending, north-dipping dike plus inflation of a deep Mogi-type magma body beneath the volcano. The pattern of subsidence on the eastern part of the island is poorly constrained. It might have been produced by extensional tectonic strain that both reactivated preexisting faults on the eastern part of the island and facilitated magma movement beneath the western part. Alternatively, magma intrusion beneath the volcano may have been the cause of extension and subsidence in the eastern part of the island. This study demonstrated that InSAR can not only provide a basis for interpreting and modeling movement of shallow magma bodies that feed eruptions, but also for detecting intrusive activities that do not result in an eruption [10].

C. Kiska volcano

Kiska volcano is the westernmost historically active volcano in the Aleutian arc, Alaska (Fig. 1a). Sequential InSAR images of Kiska show that a circular area about 3 km in diameter centered near the summit subsided by as much as 7 cm from 1995 to 2001, mostly from 1998 to 2000 [11] (Fig. 1d). An elastic Mogi-type [5] deformation model suggests that the source is within 1 km of the surface. Based on the shallow source depth and recent reports of vigorous steaming in the summit area, we attribute the subsidence to decreased pore-fluid pressure within a shallow hydrothermal system beneath the summit [11].

D. Augustine volcano

Augustine volcano, an 8 by 11 km island, is located in lower Cook Inlet, Alaska (Fig. 1a). The volcano consists of a central dome and lava flow complex, surrounded by pyroclastic debris [7]. Augustine volcano has had six significant eruptions in last two centuries: 1812, 1883, 1935, 1963-64, 1976, and 1986. Eruptions typically consist of multiple phases spanning several months; explosive ash eruptions are often accompanied by mud-flows and pyroclastic flows [7]. ERS-1/ERS-2 interferograms showed that the pyroclastic flows from the 1986 eruption have been experiencing subsidence/compaction at a rate of about 3 cm per year (Fig. 1e). The observed deformation will be used to study the characteristics of the pyroclastic flows. No sign of significant volcano-wide deformation has been observed since 1992.

E. Westdahl volcano

Westdahl is a young glacier-clad shield volcano located on the central Aleutian arc (Fig. 1a). The edifice is composed of a thick sequence of pre-glacial basalt lava flows. The volcano was frequently active during the latter half of the 20th century, with documented eruptions in 1964, 1978-79, and 1991-92 [7]. The background level of seismic activity since the last eruption in 1991-92 has been low (about five $M < 3$ earthquakes per year) and no unusual activity has been detected. Using ERS-1/ERS-2 interferograms, we mapped the progressive inflation of Westdahl volcano, Alaska, during a six-year period of quiescence following its most recent eruption in 1991-92 [12]. About 17 cm of volcano-wide inflation from September 1993 to October 1998 was observed (Fig. 1f). Multiple independent interferograms reveal that inflation rate decreases with time during 1992 and 2000. This example demonstrates that InSAR seems to be the best tool available for detecting deep, aseismic magma accumulation by measuring broad, subtle deformation of the ground surface, to identify restless volcanoes long before they become active, and before seismic and other precursors emerge [12].

F. Peulik volcano

Peulik, a stratovolcano, is located on the Alaska Peninsula about 550 km southwest of Anchorage, Alaska (Fig. 1a). The volcano has been active only twice during historical time, in 1814 and 1852, and was otherwise quiescent during the 1990s [7]. A series of ERS interferograms that collectively span the time interval from July 1992 to August 2000 reveal that a presumed magma body located 6.6 ± 0.5 km beneath the Peulik volcano inflated 0.051 ± 0.005 km^3 between October 1996 and September 1998 [13]. The average inflation rate of the magma body was about 0.003 km^3/month from October 1996 to September 1997 (Fig. 1g), peaked at 0.005 km^3/month during June 26-October 9, 1997, and dropped to 0.001 km^3/month from October 1997 to September 1998. Deformation before October 1996 or after September 1998 is not significant [13]. An intense earthquake swarm, occurred about 30 km northwest of Peulik from May to October, 1998, around the end of the inflation period. The 1996-98 inflation episode at Peulik confirms that InSAR can be used to detect magma accumulation beneath dormant volcanoes at least several months before other signs of unrest are apparent. This application represents a first step toward understanding the eruption cycle at Peulik and other stratovolcanoes with characteristically long repose periods [13].

III. SUGGESTIONS AND CONCLUSIONS

The evolving satellite radar imagery combined with InSAR techniques has proven a powerful space geodetic tool to study volcanic eruptions, detect aseismic deformation at quiescent volcanoes preceding seismic swarms, enhance our understanding of volcanic plumbing systems, and guide scientists to better focus their monitoring efforts. However, the range change caused by the atmospheric delays is significant for interferograms over the Aleutian volcanoes. For example, range change up to 6 cm was detected over a distance of 8 km over Okmok volcano [9]. Therefore, multiple observations from independent interferograms for similar time intervals should be used to verify any apparent deformation [4,9]. Also, reduction of radar coherence is the major obstacle to applying InSAR on Aleutian volcanoes. At Alaska volcanoes, processes that reduce interferometric coherence include snow/ice melting and accumulation, freezing/thawing of surface material, erosion/deposition of volcanic ash, and dense vegetation. Therefore, the best chance of producing coherent interferograms is to use images acquired during summer or early fall, separated in time by one to a few years [14]. Nevertheless, good coherence at C-band can be maintained for at least three to five years on some volcanic surfaces. To obtain the most usable results for reliably near-real time monitoring of restless volcanoes in sub-arctic environment, future C-band satellite passes must be made at least every month from July through September, every week during the late spring/early summer or late fall, and every 2-3 days during the winter [14]. The spatial baseline length should be as small as possible to reduce the decorrelation effects.

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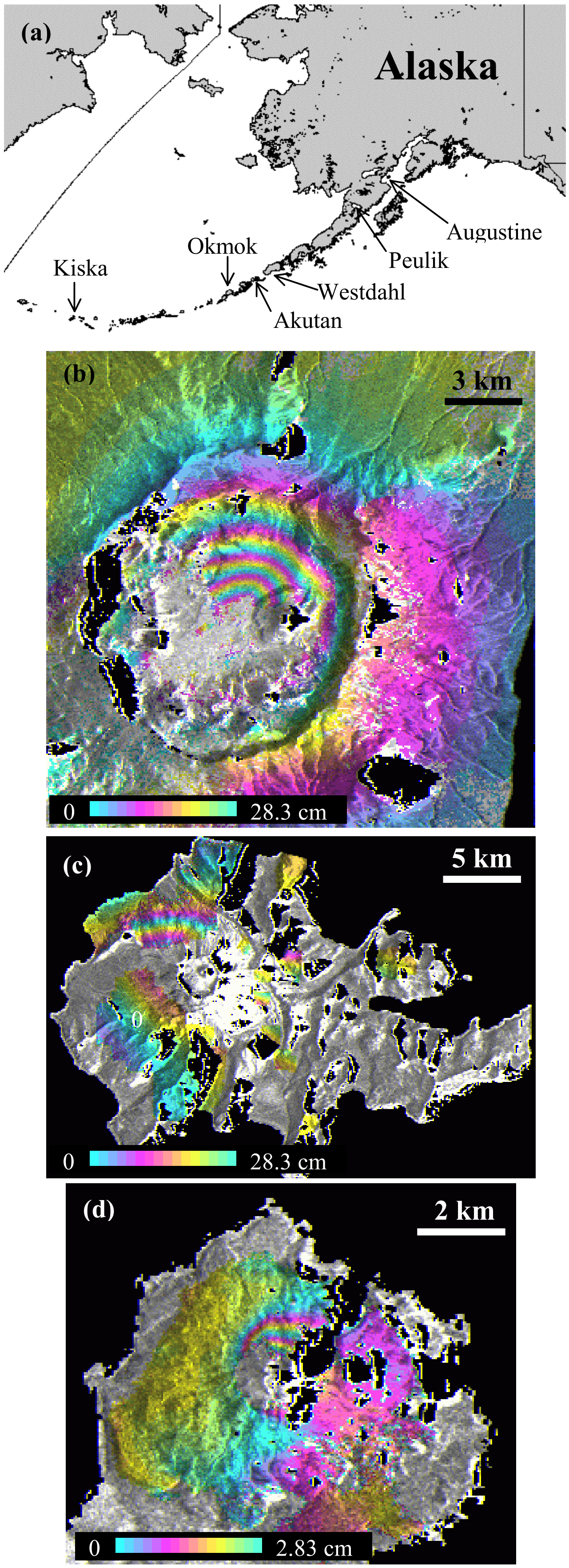

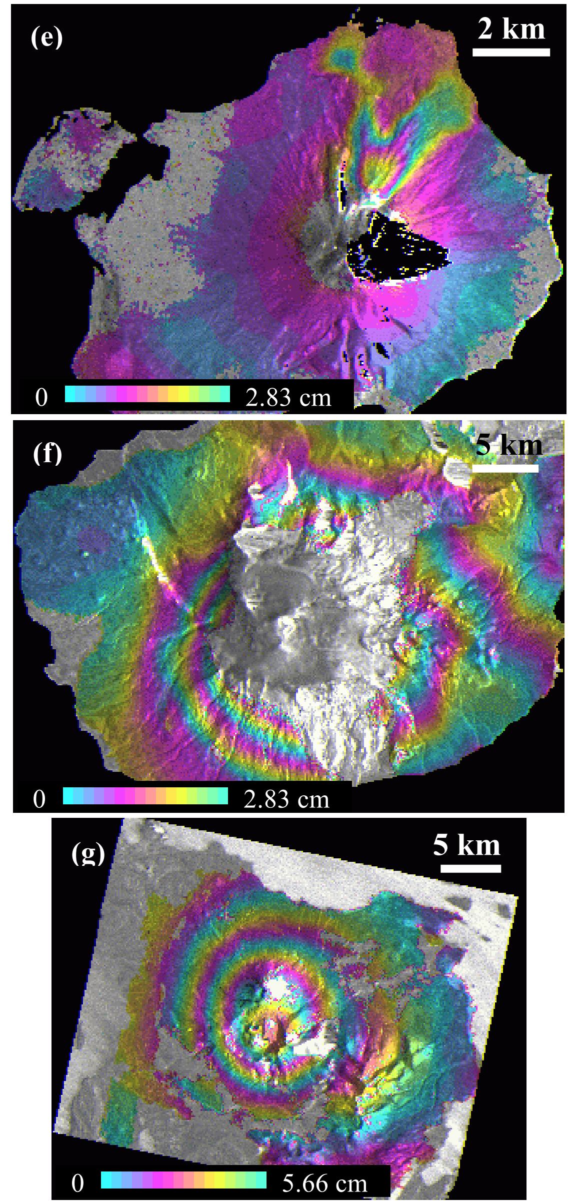

Fig. 1. (a) Location map showing the Alaska volcanoes reported in this paper. (b) Deformation interferogram (Oct. 1995 – Sep. 1997), bracketing the Feb. – Apr. 1997 eruption of Okmok volcano. (c) Deformation interferogram of Akutan volcano, spanning the March 1996 seismic swarm. (d) Deformation interferogram for Kiska volcano during Aug. 1999 and Aug. 2000. (e) Interferogram of Augustine volcano (1992-1993), depicting the deformation associated with the compaction of the 1986 pyroclastic flow deposits. (f) Aseismic inflation of Westdahl volcano, observed from a 1993-1998 InSAR image. (g) Interferogram (Oct. 1996 – Oct. 1997), representing ~17 cm of uplift centered on the southwest flank of Peulik volcano. Dark regions indicate areas with severe geometric distortion in the SAR images due to the side-looking nature of the radar sensor. Areas without interferometric coherence are uncolored.