Time series of volcanic deformation in the Galapagos: A perspective from InSAR, GPS, and seismic data

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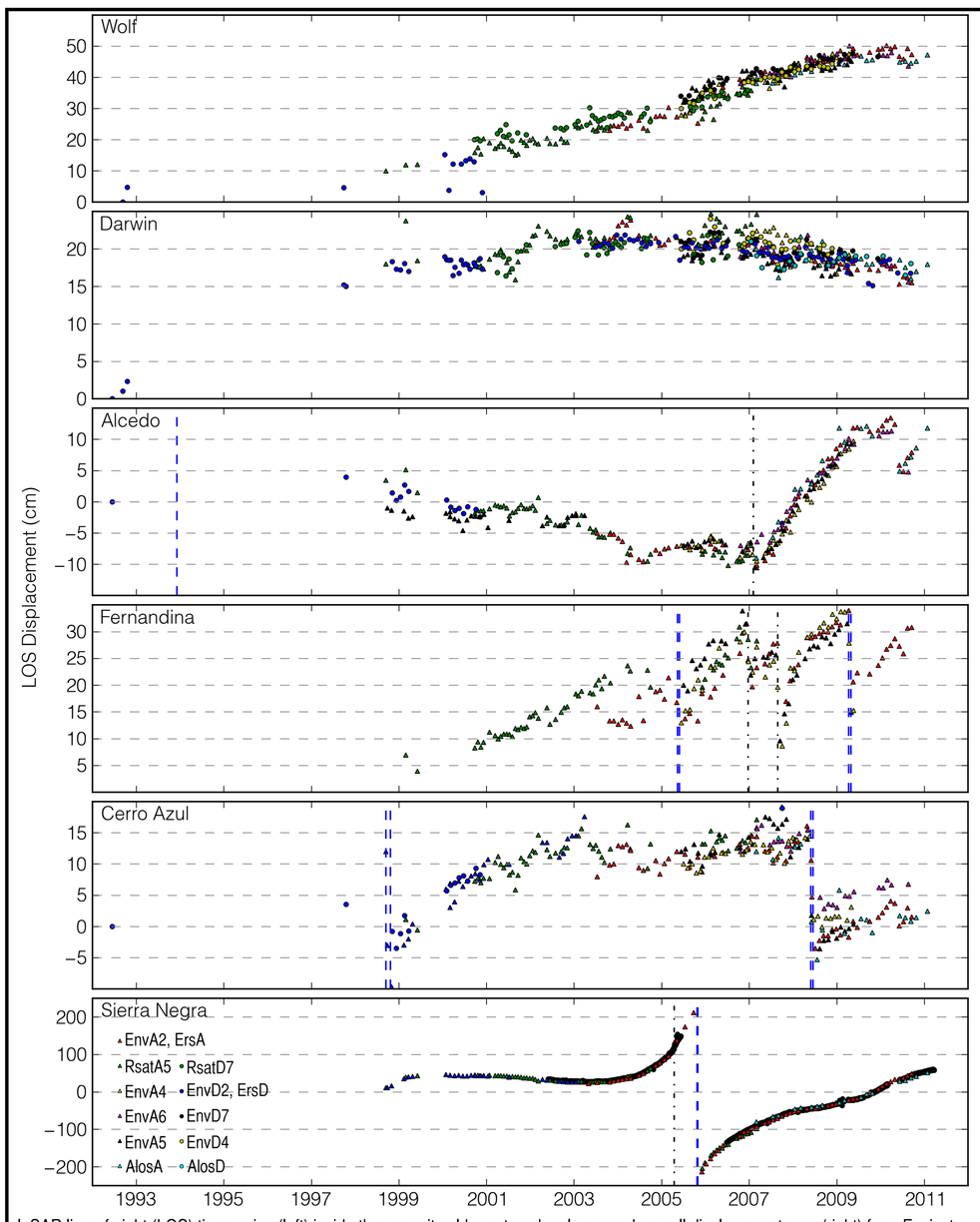
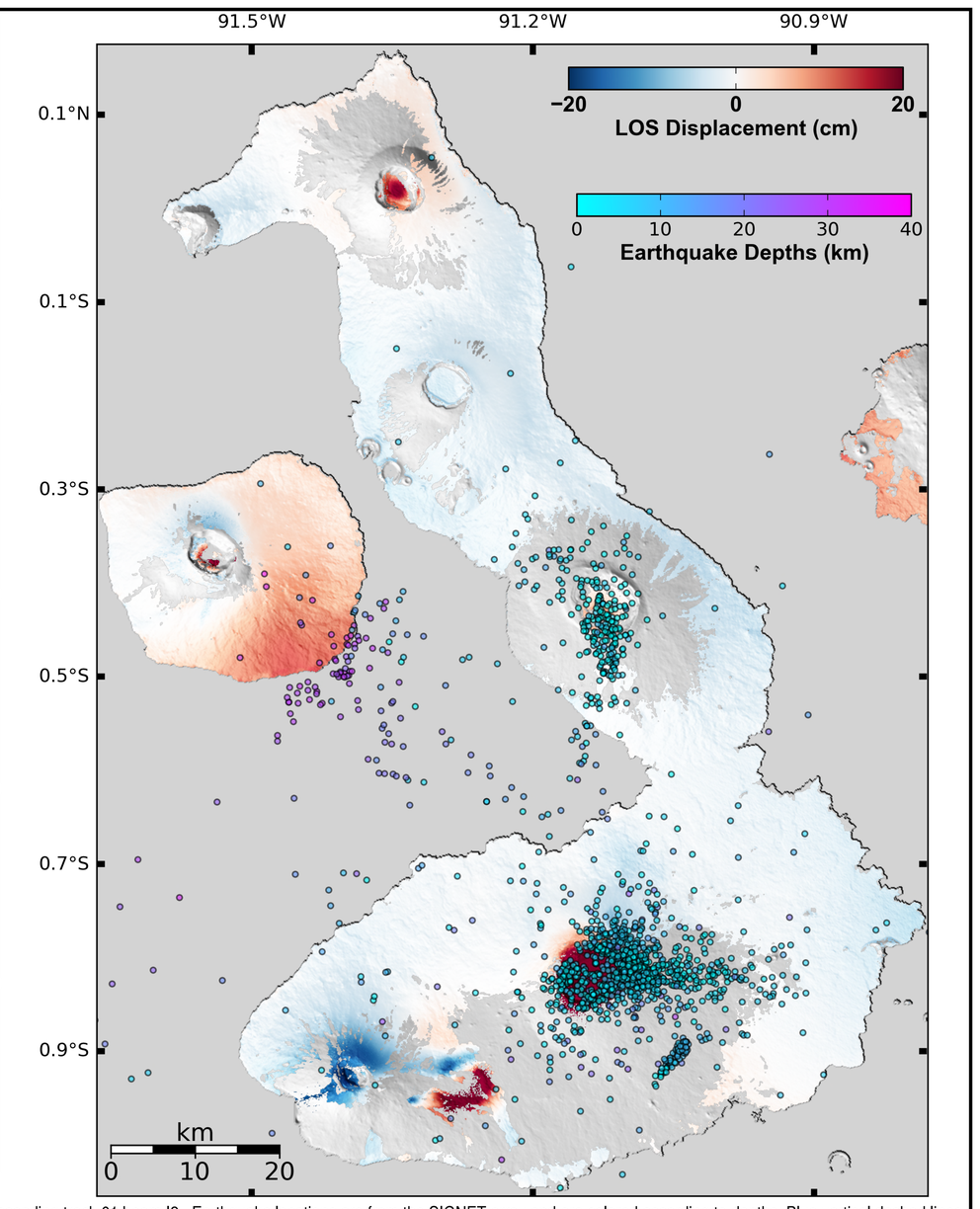
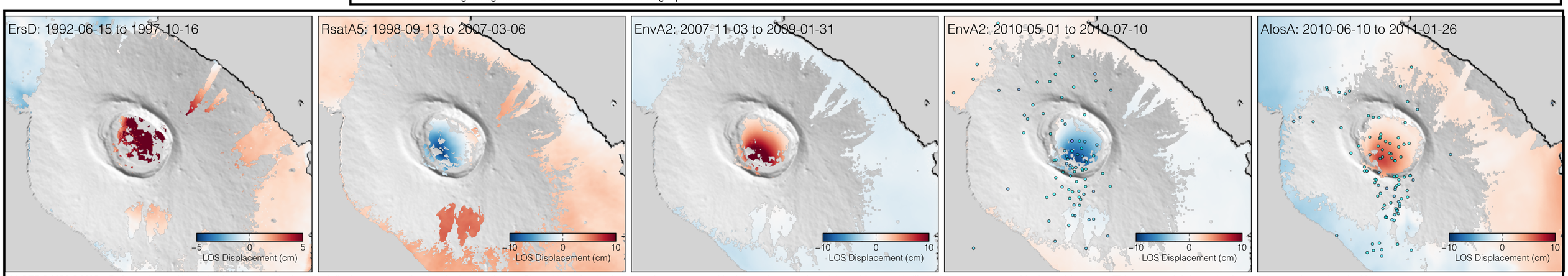
ABSTRACT: The Galapagos Islands are home to some of the most active volcanoes in the world, but given their geographic location and difficult working conditions, the volcanoes have gone largely unmonitored until the last 19 years. Interferometric synthetic aperture radar (InSAR) provided surface displacement measurements across the island chain since 1992 and measurements covering six eruptions at three different volcanoes. A continuous GPS network established at Sierra Negra in 2003 provided daily three component surface displacements measurements at the volcano allowing precise measurements during the 2005 eruption and provided a comparison for the InSAR measurements. The temporary broadband seismic network established in 2009 around Sierra Negra and Cerro Azul provided unprecedented measurements of the seismicity at the volcanoes. Using InSAR from ERS-1, ERS-2, Radarsat-1, Envisat, and ALOS satellites from 1992 to 2011, we measured surface displacements at the active volcanoes in the Galapagos Islands and generated time series using the small baseline subset (SBAS) method. A time history of surface displacements was measured at Wolf, Darwin, Alcedo, Sierra Negra, Cerro Azul, and Fernandina volcanoes. Combined with the GPS and seismic data, the InSAR time series allowed us to correlate surface and subsurface activity at individual volcanoes. In addition to activity at individual volcanoes, interactions between neighboring volcanoes were also evident. A brief period of subsidence at Sierra Negra occurred during the 2008 eruption of Cerro Azul seen in both the InSAR and GPS time series. An interaction between Fernandina and Alcedo is also present in the InSAR time series, and the location of seismicity between the two volcanoes provides evidence for a subsurface linkage between them. These interactions are clearly evident in both the geodetic and seismic data, but the recorded seismicity also suggests links between Sierra Negra, Alcedo, and Fernandina further supporting an interconnected magmatic system throughout the island chain. By combining the InSAR, GPS, and seismic datasets, we obtain more details about the time-dependent relationship between what is being measured and the controlling processes beneath.

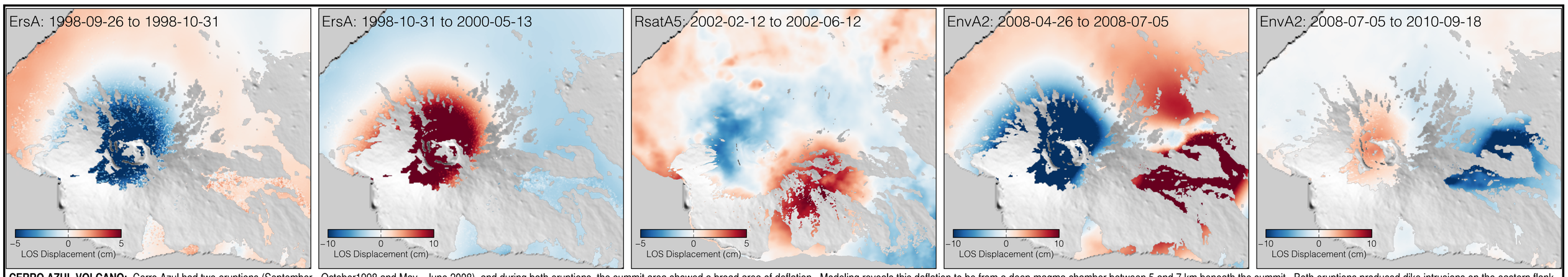




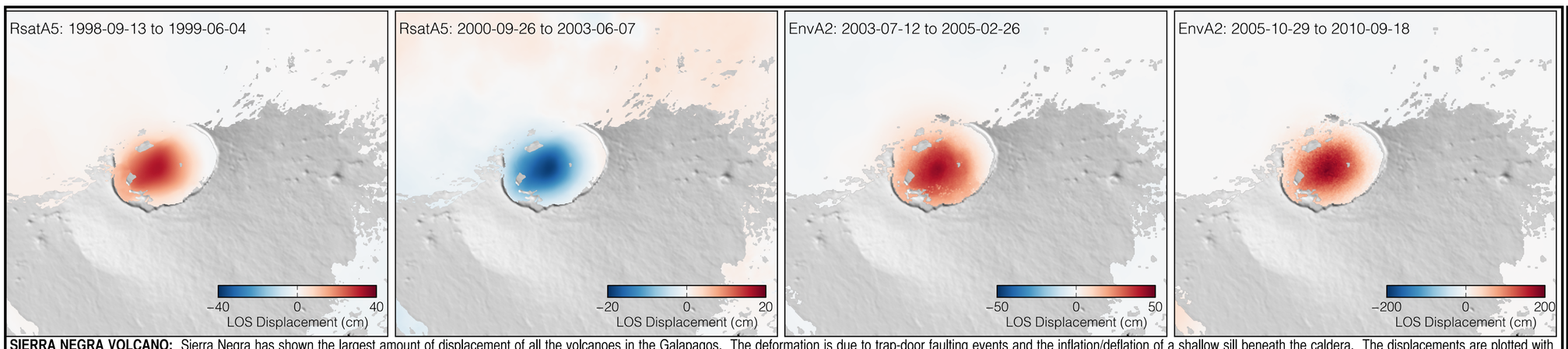
InSAR line-of-sight (LOS) time series (left) inside the summit caldera at each volcano and overall displacement map (right) from Envisat ascending track 61 beam I2. Earthquake locations are from the SIGNET array and are colored according to depths. Blue vertical dashed lines on time series mark periods of eruptive activity at the individual volcanoes and black vertical lines mark significant earthquakes (> 4.0 magnitude) in the vicinity of each volcano or trap-door faulting events. LOS time series from multiple satellites and tracks are plotted together for each volcano and show good agreement. Black dots on the Sierra Negra plot are for continuous GPS station GV02 located in the center of the caldera.



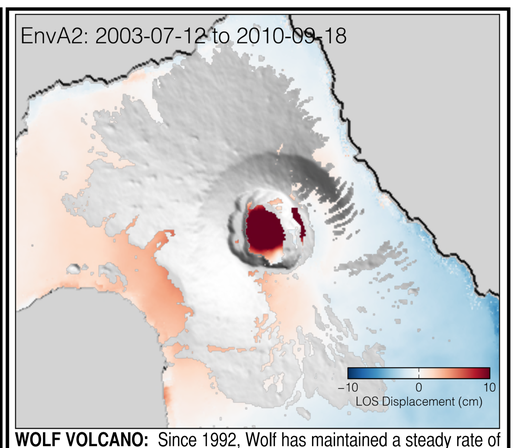
ALCEDO VOLCANO: Deformation at Alcedo is characterized by localized displacement confined to the inner caldera. Since 1998, the displacement is concentrated in the southern portion of the caldera and is likely the consequence of faults and fractures. This pattern of deformation is reminiscent of trap door faulting.



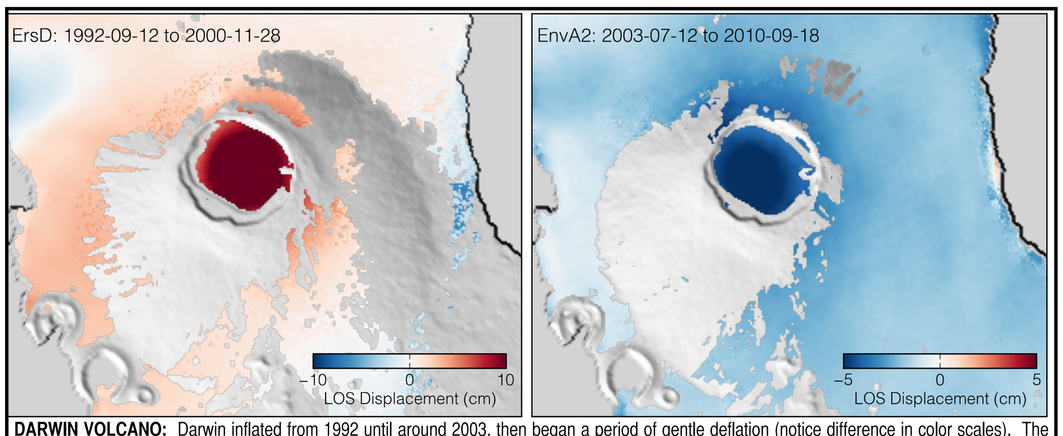
CERRO AZUL VOLCANO: Cerro Azul had two eruptions (September - October1998 and May - June 2008), and during both eruptions, the summit area showed a broad area of deflation. Modeling reveals this deflation to be from a deep magma chamber between 5 and 7 km beneath the summit. Both eruptions produced dike intrusions on the eastern flank, with the 2008 dike being more complex and propagating further down the flank. Post-intrusion inflation is evident in 1998, but is absent following the 2008 eruption. Evidence for multiple magma bodies at Cerro Azul is also revealed by inflation on the eastern flank for a very brief period in 2002 (approximately 2 months). This area is situated directly beneath the eruptive vent from 1998, and preliminary models suggest a shallow sill-like source 2-4 km beneath the surface. Following the 2008 eruption, the area directly above the dike showed rapid subsidence, which is most likely related to cooling and contraction of the intruded magma..



SIERRA NEGRA VOLCANO: Sierra Negra has shown the largest amount of displacement of all the volcanoes in the Galapagos. The deformation is due to trap-door faulting events and the inflation/deflation of a shallow sill beneath the caldera. The displacements are plotted with different color scales, representing the various amounts of displacement taking place within the caldera. Since the 2005 eruption, the inner caldera has re-inflated nearly 3 m! The GPS station (GV02) was not operating immediately following the eruption, but good InSAR coverage shows a rapid inflation until 2007, and continued inflation through 2011 along with the GPS.



WOLF VOLCANO: Since 1992, Wolf has maintained a steady rate of inflation of approximately 3 cm/yr inside the caldera for a total of 50 cm over the 19-year period.



DARWIN VOLCANO: Darwin inflated from 1992 until around 2003, then began a period of gentle deflation (notice difference in color scales). The displacement is evenly distributed within the caldera and does not appear to be caused by trap-door faulting like at Alcedo and Sierra Negra.

DISCUSSION: Following the 1998 eruption at Cerro Azul, there was a rapid recharge of the deep magma chamber over the next year, but following the 2008 eruption there was no evidence for rapid recharge. One explanation for this could be the nature of the eruptions. The 2008 eruption had a much larger dike intrusion on the east flank, which possibly resulted in a depleted supply of magma available for rapid post-eruption inflation. The lack of 2008 recharge may also be the result of rapid inflation occurring at Sierra Negra. There is evidence from the time series that inflation at Sierra Negra wanes during the 2008 eruption and continues shortly after, and the deeper supply of magma for these two volcanoes could be going to Sierra Negra. This provides evidence for an interconnected magmatic system between these two volcanoes.

Fernandina and Alcedo also show evidence of inter-volcano interactions. In 2007, earthquakes located between the two coincide with changes and/or increases in the deformation at each volcano. The nature of the earthquakes in this area is still unclear, but these events were large enough to be recorded by the GNS global seismic network and several more events are listed in the catalog. Furthermore, the 2009 eruption at Fernandina brings an abrupt end to the rapid inflation that was occurring at Alcedo since 2007, suggesting a link in the magma supply between the two.

The earthquakes from August 2009 to January 2011 are concentrated at the summits of Alcedo and Sierra Negra. The earthquakes at Alcedo are located in the southern part of the summit area close to the area that is deforming, providing further insight into the processes beneath the summit. Sierra Negra has the highest amount of earthquakes, and this is not out of the ordinary given the large amount of surface displacement observed in the InSAR and GPS data. Although Cerro Azul shows a small of amount of inflation, there is virtually no seismic activity beneath the summit. It is unclear what the historical seismicity at Cerro Azul is like given the inadequate coverage of seismic stations in the past.