Deformation and Stress-Change Modeling of Sierra Negra Volcano, Galápagos, from Envisat InSAR and GPS Observations

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Radar data provided by ESA through Category-1 project #3493
Purpose

§ To explain the sequence of events leading to the Oct. 2005 eruption at Sierra Negra and the interplay between caldera inflation and faulting

Outline:

§ Background
§ Measurements of the inflation and modeling
§ Observations of the intra-caldera faulting
§ Stress change calculations
§ Conclusions
Galápagos Volcanoes

Basaltic shield volcanoes with large summit calderas, 1-2000 m in elevation,
Deformation map from InSAR 1992-1998 showing that all the volcanoes are actively deforming
Sierra Negra uplifted by over 2 m, and subsidence found on recent lava flows

Sierra Negra Caldera Uplift

GV04

Sinuous ridge

Elevated inner caldera floor

South moat
Ø Over 50 cm of uplift in one year
Ø Mogi or finite ellipsoid do not work
Ø Inflating sill at 2.2 km depth can explain the deformation
Ø Still differences, which may be due to 3-dimensionality of the source
• From GPS we know much deformation is due to uplift
• Assume uplift pattern is the same as in 2004, then scale and subtract it from the interferogram
• Only left with deformation due to the faulting
Trapdoor Faulting on 16 Apr 2005

§ Only InSAR recorded the trapdoor faulting in 1998 and then the interpretation was a south-dipping fault!!

§ Resolving this dip-inconsistency is important to understand the volcano dynamics

§ How well can we constrain the fault dip from the deformation data?
Estimating the Fault-Dip Uncertainty

§ We analyzed the structure and power of a few non-deforming areas north of the caldera.
§ Determined the average empirical covariance structure, which we used to form the data covariance matrix.
§ Created multiple synthetic data sets by adding several thousands different random realizations to the original data.
§ Estimated model parameters from each synthetic data set and inspect the distribution of parameters.
§ Approximate the marginal PDF with a Gaussian distribution.
§ Fault dip 67-74° to the north, at a 95% confidence level.
Sierra Negra Stress-Changes

Mean stress change: $\Delta \sigma_{kk} / 3$

Bar thickness reflects differential stress change: $| \Delta \sigma_1 - \Delta \sigma_3 | / 2$
Coulomb Failure Stress Change due to the Inflating Sill

\[ \Delta \text{CFS} = \Delta \tau_s + \mu_f \left( \Delta \sigma_n - \frac{B}{3} \Delta \sigma_{kk} \right) \]

- Pure dip-slip (north side up), and calculate \( \Delta \text{CFS} \) at 1.5 km depth
- Positive \( \Delta \text{CFS} = \) closer to failure

Assume the following:
- Coeff. friction: \( \mu_f = 0.75 \)
- Shear modulus: \( \mu = 10 \) GPa
- Poisson’s ratio: \( \nu = 0.25 \)
- Skempton’s coeff.: \( B = 0.5 \)
Ø Inflating sill promotes thrust faulting on north dipping faults
Ø Vertical or south-dipping normal faults unlikely
Ø The maximum Coulomb Failure Stress Change is found on a fault dipping 72 degrees to the north

Ø Cool!
Did the faulting reduce the magma pressure?
The trapdoor faulting causes more than 3 MPa mean stress change, relieving the magma pressure.

Negative mean stress change to the south, preventing sill growth to the south.
Conclusions

§ Inflating magma sill triggers repeating trapdoor faulting on Sierra Negra
§ Coulomb failure stress calculations confirm the steeply dipping thrust fault estimated from the geodetic data
§ The trapdoor faulting relieves the magma pressure, tends to thicken the sill, prevents southward magma propagation and somewhat postpones eruptions
§ More than 5 m of co-eruption subsidence occurred on Sierra Negra in October 2005 and after the eruption the caldera floor has already uplifted by 2-3 meters.

Photo by M. Hall, GVP
Now the $\Delta CFS$ is positive everywhere. Large $\Delta CFS$ occur near the peripheries of the sill. The maximum occurs in the south, exactly on the estimated fault plane.
Does a 70° dipping thrust fault make sense?
Fault model parameter marginal pdfs

- Length [km]
- Width [km]
- Depth [km]
- Dip
- Strike
- East [km]
- North [km]
- Strike-slip [m]
- Dip-slip [m]