Taking advantage of the Galápagos archipelago as a high-visibility natural laboratory for volcanology

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Mechanical modeling of circumferential and radial dike intrusion on Galápagos volcanoes

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Abstract: Circumferential and radial dike intrusion on Galápagos volcanoes is a complex process that can be modeled using a combination of numerical and analytical methods. The models take into account the effects of magma chamber pressure, magma viscosity, and the mechanical properties of the host rock. The results show that the intrusions can propagate radially and circumferentially, leading to the formation of melt-porous zones and the development of dike swarms. The simulations are used to predict the distribution of magma and the resulting volcanic activity, providing insights into the dynamics of these volcanoes.

Introducetion

The Galápagos Islands are a well-studied volcanic province, with a history of extensive dike intrusion activity. The complex magma systems and the diverse eruptive styles make this region a prime example for studying the mechanics of dike intrusion. The models presented here aim to provide a better understanding of the processes involved in the formation of dike swarms and their influence on volcanic activity.

The models are based on the equilibrium between the mechanical forces acting on the dike and the stresses within the magma chamber. The results show that the dike intrusions can propagate both radially and circumferentially, leading to the formation of melt-porous zones. These zones are crucial for the propagation of the dike and the development of the dike swarms.

The mechanical properties of the host rock, such as its strength and elasticity, play a significant role in the propagation of the dike. The models indicate that the dike can propagate more easily in regions where the mechanical properties of the host rock are less favorable. This can lead to the formation of complex dike networks and the development of dike swarms.

The models also take into account the effects of magma chamber pressure and magma viscosity. The results show that these factors can significantly influence the propagation of the dike and the formation of the dike swarms. The models predict that at higher pressures and lower viscosities, the dike can propagate more easily and form larger swarms.

In conclusion, the models presented here provide a better understanding of the mechanics of dike intrusion on Galápagos volcanoes. The results can be used to predict the distribution of magma and the resulting volcanic activity, providing insights into the dynamics of these volcanoes.
A revolution…

Amelung et al., 2000
Inspiration!
Low-hanging fruit

I. Magma supply
   – Rate from hotspot
   – Partitioning between volcanoes

II. Magma storage and transport
   – Geometry of magma storage
   – Getting from the source to the surface

III. Structural evolution of basaltic shields
    – Interactions (volcano and tectonic)
    – Rift zones, calderas, flank instability

IV. Volcanic eruptions
    – Explosive basaltic volcanism
    – Eruption cycles (24 eruptions in last 50 years!)
I. MAGMA SUPPLY

• What is the rate of magma supply to the Galápagos volcanoes?
• How is magma supply partitioned between volcanoes?
• Is the rate of magma supply constant?
• How does magma supply relate to volcanic activity?
### Magma supply to Kīlauea, Hawai‘i

<table>
<thead>
<tr>
<th>Time period</th>
<th>Supply (km$^3$/yr)</th>
<th>Method</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1918–1979</td>
<td>0.08</td>
<td>Ratio between repose times and erupted volumes</td>
<td>Klein, 1982</td>
</tr>
<tr>
<td>1919–1990</td>
<td>0.09</td>
<td>Effusion rate of several sustained eruptions</td>
<td>Dvorak and Dzurisin, 1993</td>
</tr>
<tr>
<td>1952–1971</td>
<td>0.11</td>
<td>Effusion rate of three sustained eruptions</td>
<td>Swanson, 1972</td>
</tr>
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<td>1956–1983</td>
<td>0.09</td>
<td>Average summit and rift deformation and eruption volumes</td>
<td>Dzurisin et al., 1984</td>
</tr>
<tr>
<td>1959–1990</td>
<td>0.06</td>
<td>Average based on deformation and eruption volumes</td>
<td>Dvorak and Dzurisin, 1993</td>
</tr>
<tr>
<td>1960–1967</td>
<td>0.02–0.18</td>
<td>Deformation-inferred refilling of summit reservoir</td>
<td>Dvorak and Dzurisin, 1993</td>
</tr>
<tr>
<td>1966–1970</td>
<td>0.07</td>
<td>Deformation and eruption volumes</td>
<td>Dvorak et al., 1983</td>
</tr>
<tr>
<td>1967–1975</td>
<td>0.05–0.18</td>
<td>Deformation and eruption volumes</td>
<td>Wright and Klein, 2008</td>
</tr>
<tr>
<td>1971–1972</td>
<td>0.08</td>
<td>Deformation and erupted volumes</td>
<td>Duffield et al., 1982</td>
</tr>
<tr>
<td>1975–1977</td>
<td>0.07–0.16</td>
<td>Microgravity and deformation</td>
<td>Dzurisin et al., 1980</td>
</tr>
<tr>
<td>1983–1984</td>
<td>0.12</td>
<td>First 20 episodes of Pu‘u <code>O</code>o eruption</td>
<td>Wolfe et al., 1987</td>
</tr>
<tr>
<td>1983–2002</td>
<td>0.12</td>
<td>Pu‘u <code>O</code>o eruption volumes</td>
<td>Heliker et al., 2003</td>
</tr>
<tr>
<td>1983–2002</td>
<td>0.13</td>
<td>SO$_2$ emissions from ERZ</td>
<td>Sutton et al., 2003</td>
</tr>
<tr>
<td>1991</td>
<td>0.08</td>
<td>Deformation and effusion rates</td>
<td>Denlinger, 1997</td>
</tr>
</tbody>
</table>

**Average supply rate:** ~0.1 km$^3$/yr
A change in magma supply

- CO$_2$ emissions increased by 2.5x in 2003–2004
- SO$_2$ emissions indicated higher lava effusion rates
- Summit inflation
- Increased summit earthquake rates
- Introduction of primitive magma to Kīlauea
- SURGE IN SUPPLY FROM MANTLE IN 2003-2007

Poland et al., in review
Eruption data
• Deformation
• Seismicity
• Gas emissions

Figure courtesy of Cindy Ebinger
Figure courtesy of Marco Bagnardi and Scott Baker
II. MAGMA STORAGE AND TRANSPORT

• What is the geometry and depth of magma storage beneath Galapagos volcanoes?
• How is magma transported between storage reservoirs and the surface?
Deflation:  deflation, inflation, and displacement.

- Summit inflation near center of caldera
- Summit inflation in southeast caldera
- Summit inflation in south caldera
- Summit deflation, east rift zone dike emplacement

Poland et al., in review
Oct 2005 – Sep 2010 (average displacements)
Sill-like reservoir at 2 km depth beneath Sierra Negra.

Cannot distinguish between a sill and a diapir, however.
Fernandina —
2005 eruption

Circumferential eruptive fissure on southwest flank
Fernandina — 2005 eruption

Co-eruptive deformation indicates magma storage at ~1 and ~5 km depths.

Circumferential eruptive fissure propagated upward from shallow magma storage area.
Fernandina — 2009 eruption

range change

January 30 –
April 10 (8 AM), 2009

Figure courtesy of Marco Bagnardi
Fernandina — 2009 eruption

Same stacked reservoir geometry and sill-like initiation, but, like 1995, a shallow-dipping dike feeding the fissure.

Figure courtesy of Marco Bagnardi
III. EVOLUTION OF BASALTIC SHIELDS

• What causes the pattern of radial and circumferential eruptive fissures?
• Where are the rift zones?
• Is there any sign of flank instability?
• How do neighboring volcanoes interact?
• What are the causes and consequences of volcano-tectonic interactions?
• How do basaltic calderas develop?
A curious pattern
radial vs.
circumferential
eruptive fissures
Figure courtesy of Marco Bagnardi
Rift Zones

Where are they?

Chadwick and Howard, 1991
Flank instability

2006-2007
3 cm/yr

USGS
There is geologic evidence for flank instability, but nothing from deformation measurements (yet?). So how does flank instability develop at ocean island volcanoes?
Volcano-volcano interactions

- Eight active volcanoes within 130 x 130 km area
- Volcano growth is contemporaneous
- Do the volcanoes interact?

- Illegitimate (bastard) magmas

Geist et al., 1999
Sierra Negra subsidence brackets the 2008 eruption of Cerro Azul.
Sierra Negra Intracaldera “sinuous ridge”

Volcano-tectonic interactions

Photo by P. Ramon, 2005

Photo by U.S. Air Force, 1946
- Trapdoor faulting at Sierra Negra in 1998 and 2005
- Inflation promotes faulting
- Faulting encourages dike emplacement to the north
- Faulting allows for more inflation without eruption

Jónsson, 2009
Calderas

- Formation
- Morphology
IV. VOLCANIC ERUPTIONS

- What are the characteristics and causal mechanisms of explosive basaltic eruptions?

- What characterizes the stages of a basaltic volcano’s eruption cycle?
Explosive basaltic eruptions

- Basaltic volcanoes are effusive, right?
- Work at Kīlauea indicates otherwise and demonstrates the extreme hazard
- So where can one study explosive basaltic volcanoes?
Eight recently active volcanoes within a 130 km x 130 km area, all in different stages of the eruption cycle.
Galápagos volcanoes erupt more often than we might appreciate (24 times in past 50 years). A great place to observe basaltic eruptions!
Summary

• Natural laboratory
  I. Magma supply
  II. Magma storage and transport
  III. Evolution of basaltic shields
  IV. Volcanic eruptions

• But is it worth the effort?
<table>
<thead>
<tr>
<th><strong>Downers</strong></th>
<th><strong>Uppers</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>• Remoteness of location</td>
<td>• Exceptional volcanic activity</td>
</tr>
<tr>
<td>• Lack of infrastructure</td>
<td>• New technology and satellites</td>
</tr>
<tr>
<td>• Working in a National Park</td>
<td>• Public visibility and notoriety</td>
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