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Anomalous earthquakes associated with Nyiragongo Volcano

Ashley Shuler
Lamont Doherty Earth Observatory
New York
USA

Anomalous Earthquakes Associated with Nyiragongo Volcano

Ashley Shuler and Göran Ekström
Lamont-Doherty Earth Observatory

August 20, 2009

Photo from www.volcanodiscovery.com

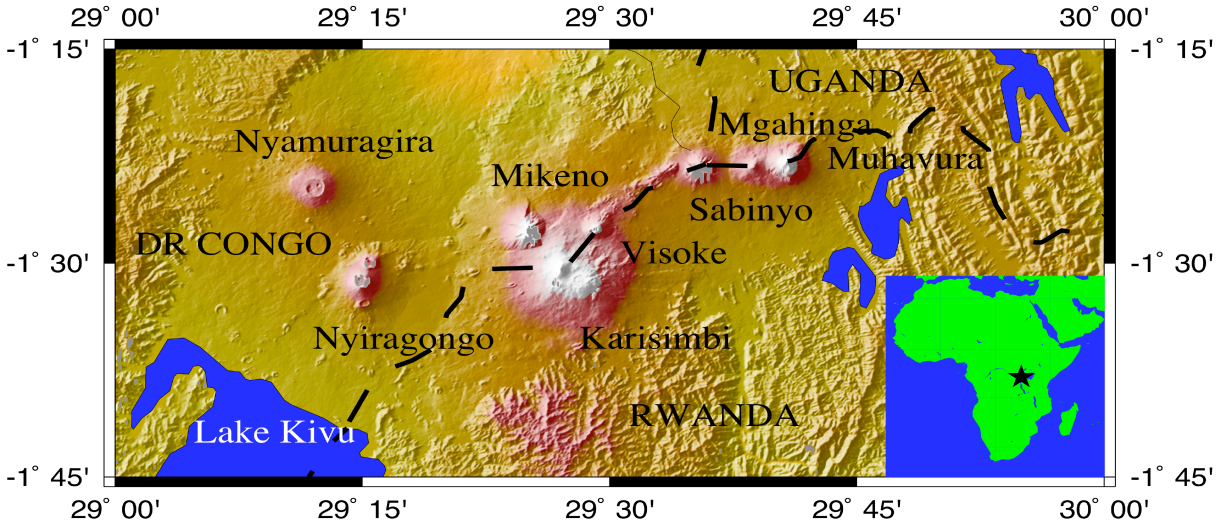
Talk Outline

- Background on Nyiragongo
- Detection of Unusual Earthquakes
- Event Description
- Source Modeling
- Physical Mechanism
- Future Work

Image from Smithsonian Institution

Introduction to Nyiragongo

- Stratovolcano located in the Virunga Volcanic Province in the Western Branch of the East African Rift
- Decade Volcano, known for its lava lake activity and 2 recent catastrophic eruptions (1977 and 2002).
- Site of a series of five newly detected earthquakes ($4.6 \leq M_w \leq 5.3$), occurring between 2002 and 2005.



Event	Date	M_w
1	1/21/2002	5.3
2	1/22/2002	5.3
3	1/22/2002	4.6
4	5/17/2003	4.6
5	4/15/2005	4.7

Shuler and Ekström (2009)

2002 Eruption of Nyiragongo

- 2002 fissure eruption was initiated by regional rifting event
- 1977 fractures reopened on the southern flank and ruptured the edifice of the volcano, releasing degassed magma from the lava lake and upper conduit, as well as additional gas-rich magma due to depressurization of the source region.
- Fractures propagated towards the city of Goma, 20 kilometers away.
- The eruption is estimated to have lasted 24 hours (Tedesco et al., 2007)

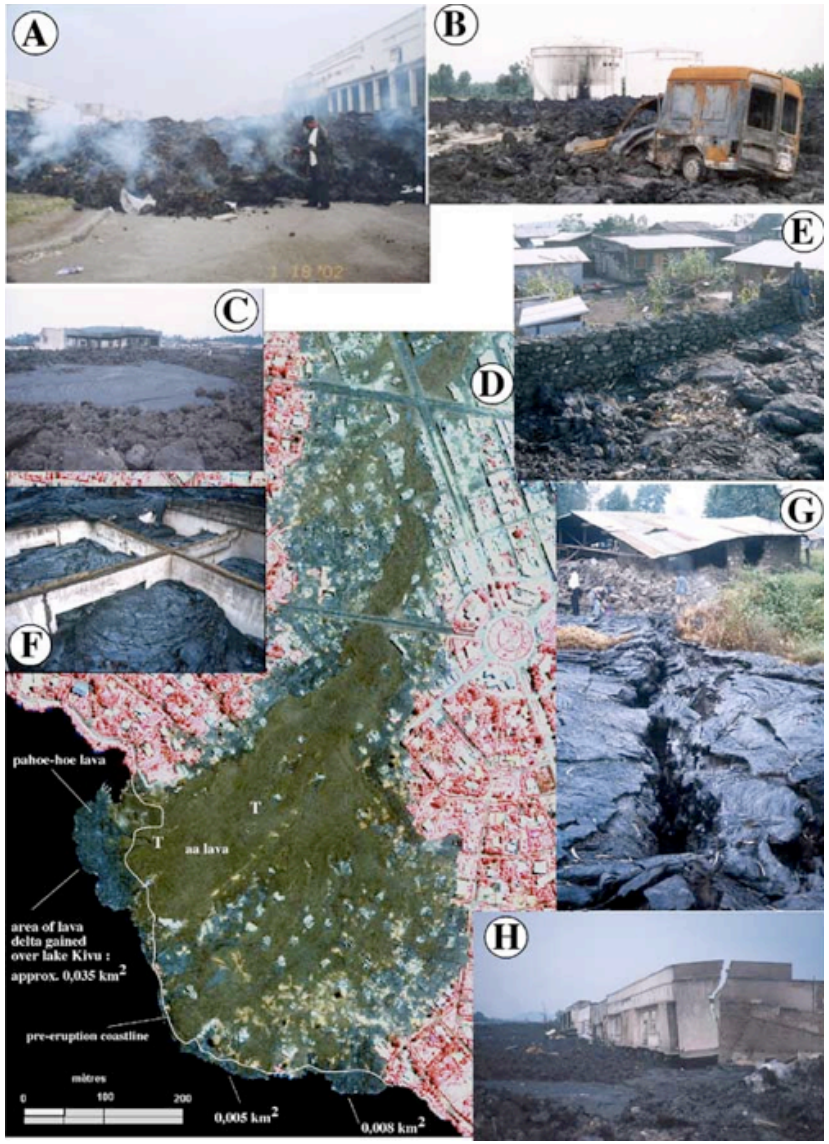
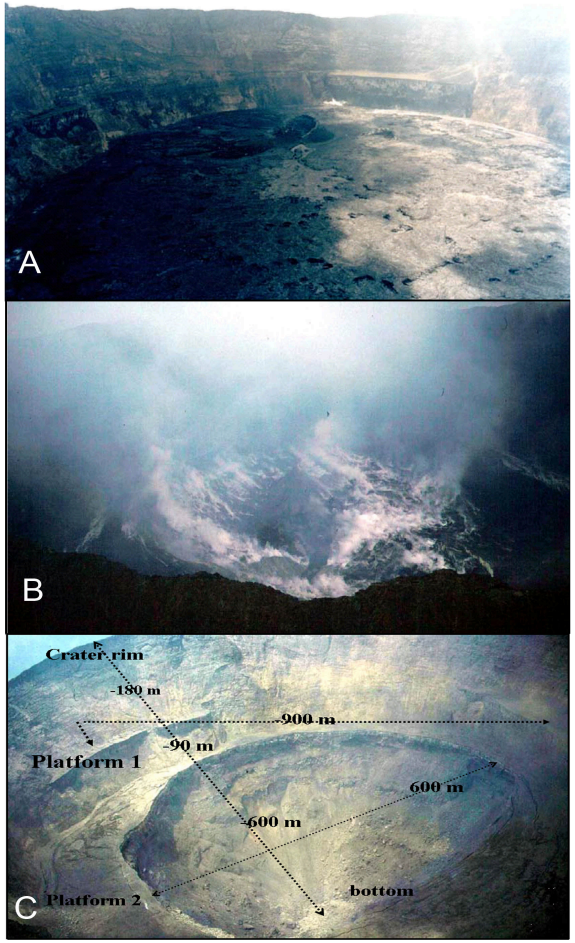


Image from Komorowski et al. (2002/2003)

Crater Collapse

Five days after the eruption, the summit crater abruptly collapsed, deepening by 620 meters.



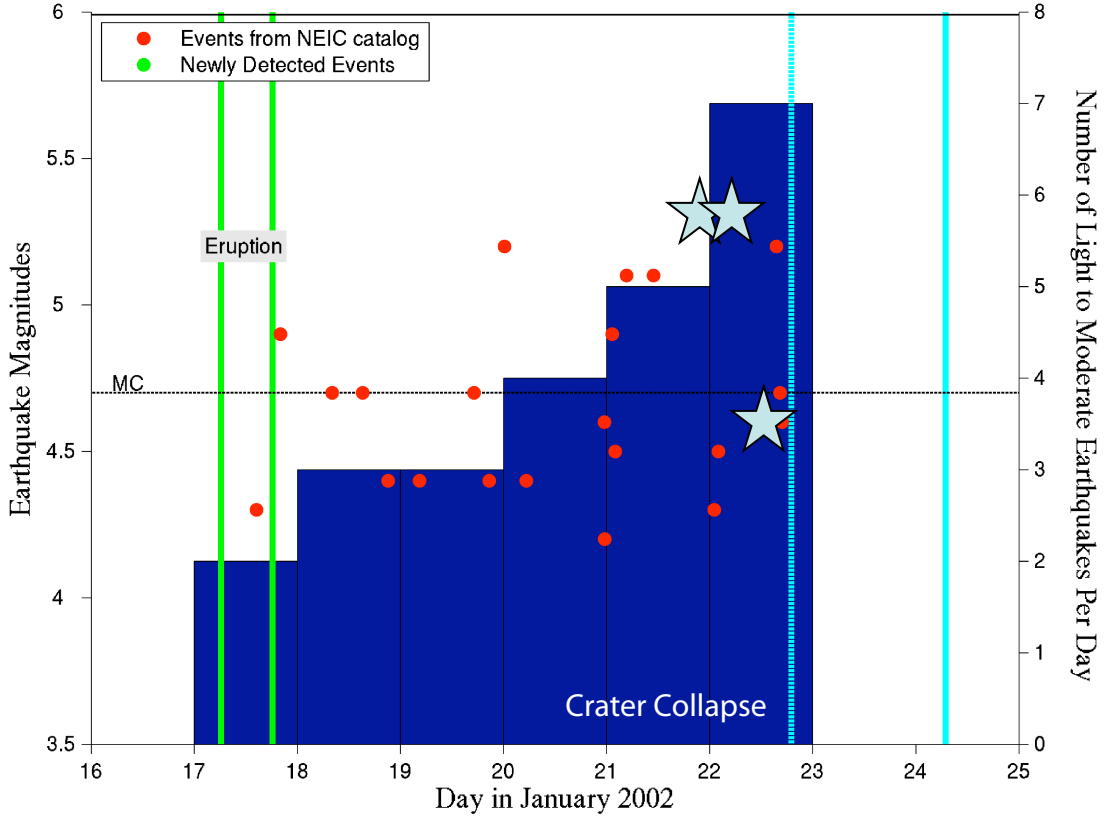
Crater in 1995

Crater on January 21 - 1 day before the crater collapse

After collapse

Image from Tedesco et al. (2007)

Post-Eruption Seismicity



Seismicity increased following the eruption, and all events M>4 occurred between the start of the eruption and the crater collapse. Includes 3 newly detected events.

Shuler and Ekström (2009)

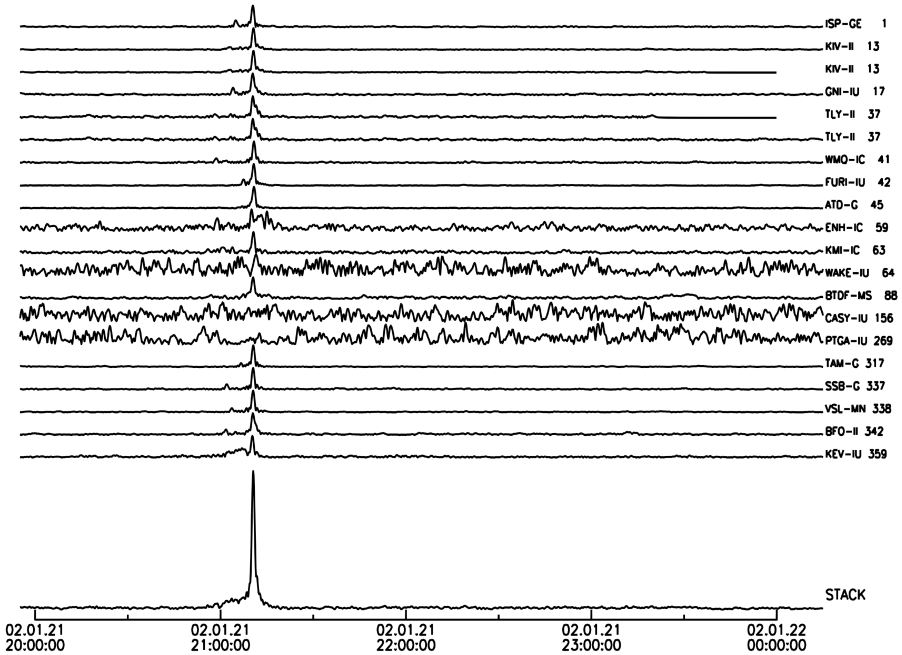
Post-Eruption Activity (2002-2005)

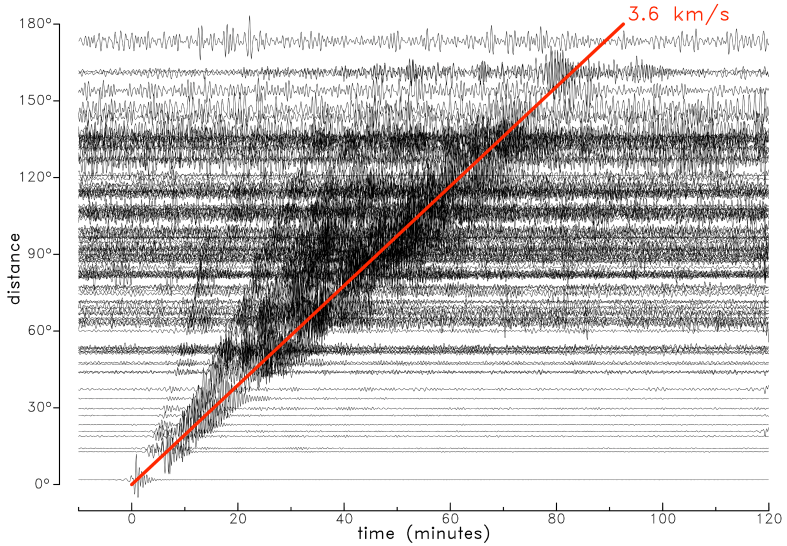
- Lava lake activity returned to the summit crater in the summer of 2002.
- Lava fountaining, long-period earthquakes and intense degassing of SO_2 accompanied the refilling of the lava lake
  --> 4th event
- Steady-state convection was reached over time. Lower gas emissions, and stablility of lava lake during ongoing refilling
  --> 5th event

Image from www.volcanodiscovery.com

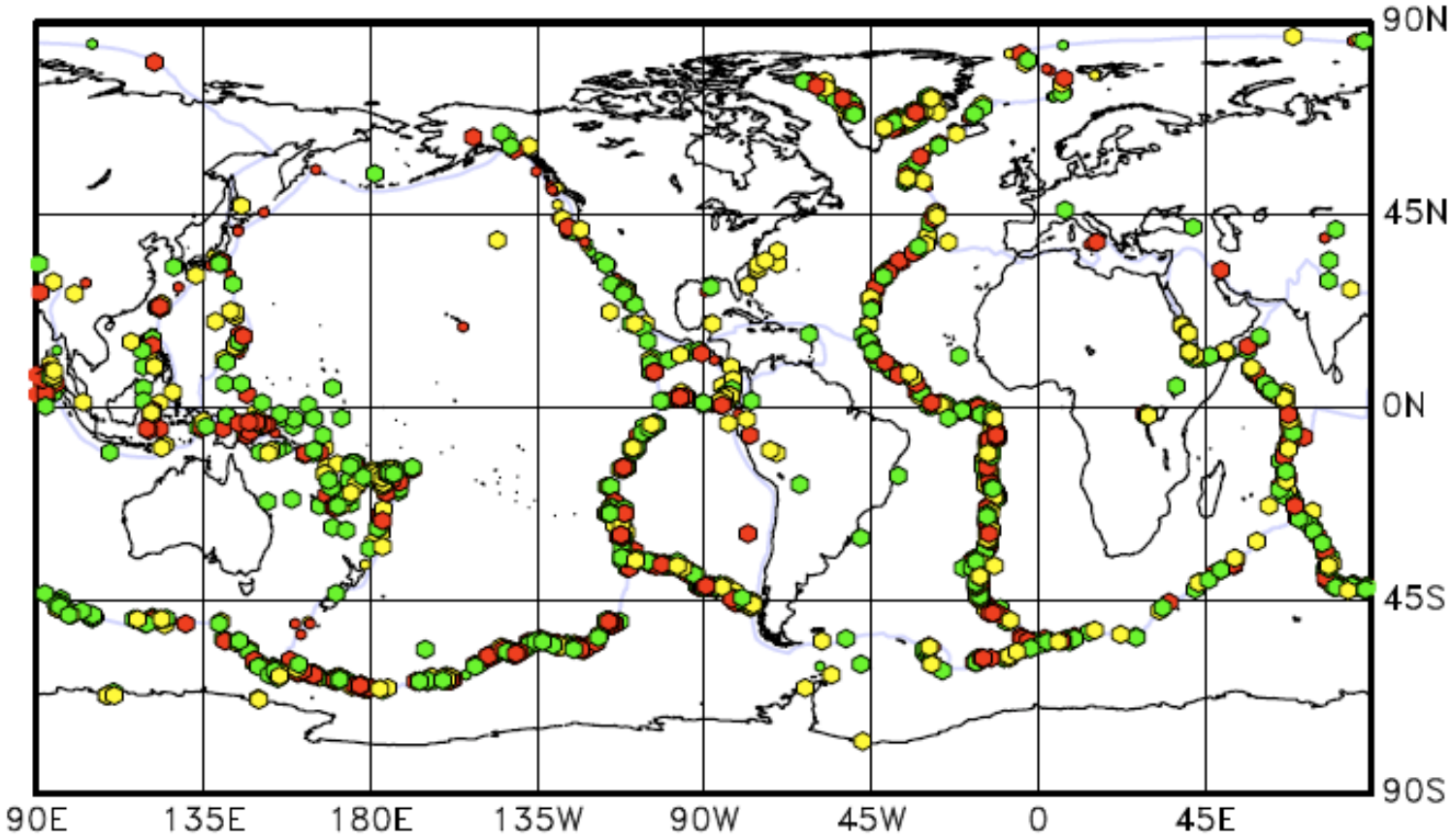
Surface Wave Event Detection

These 5 events were detected using the method of Ekström (2006), which uses locates events using long-period surface waves from the GSN.



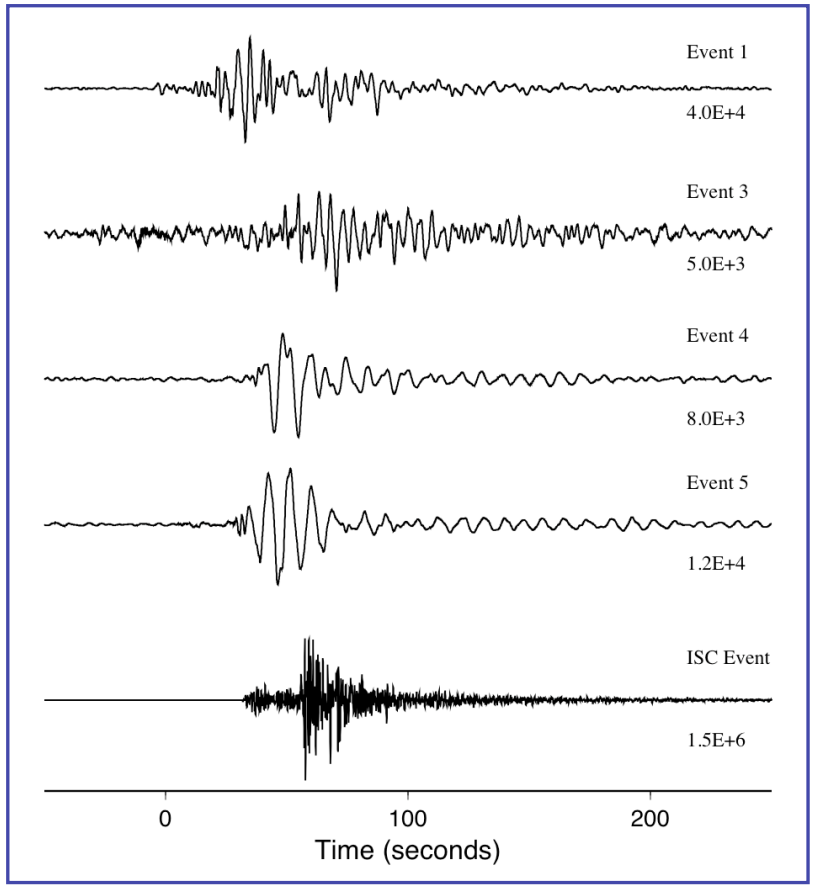


Shuler and Ekström (2009)



A catalog of newly detected events contains 1700 events from 1991-2006. These events could represent newly observed or unusual seismogenic processes.

Comparison to Tectonic Earthquakes



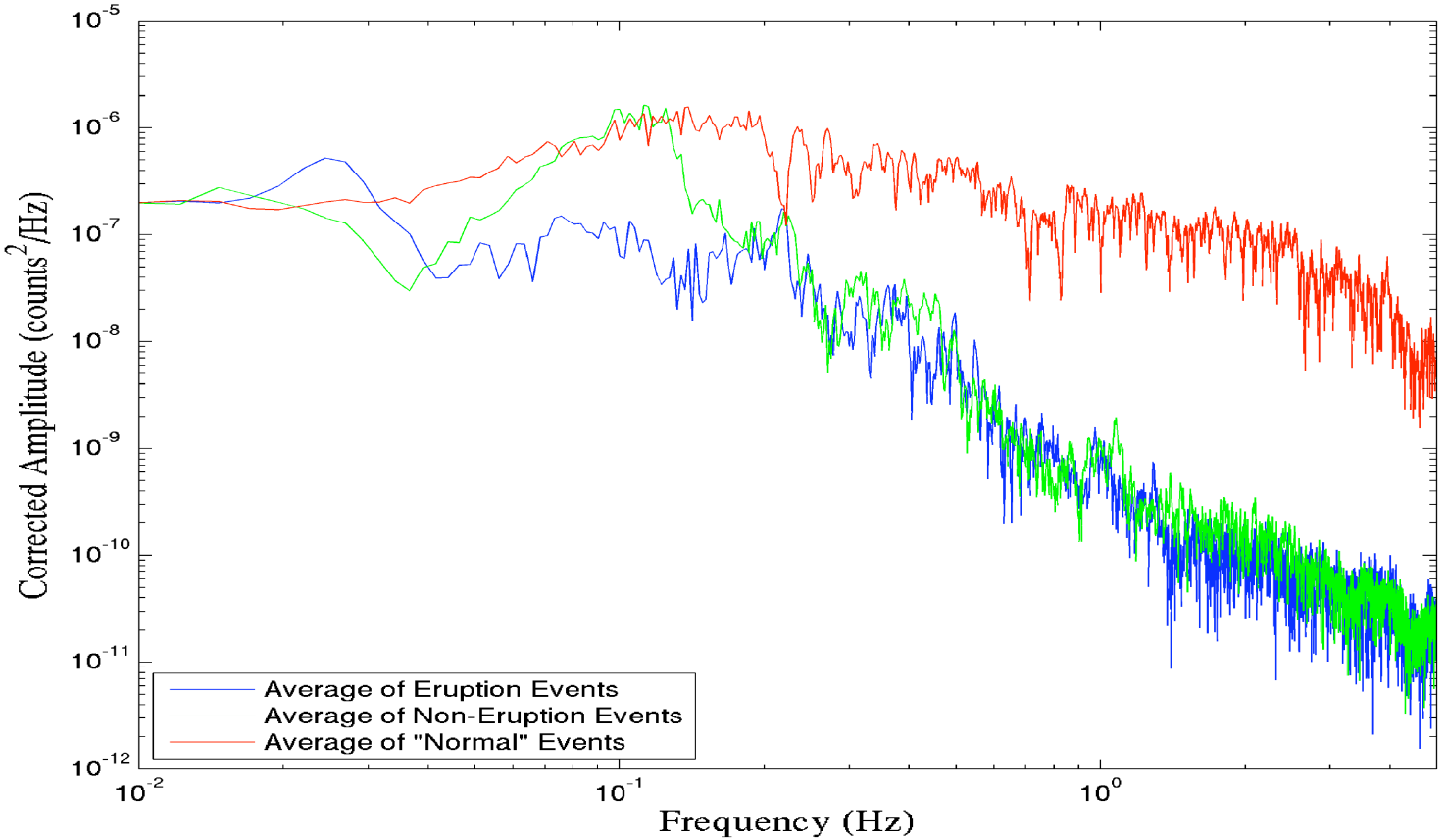
Events after 2002 Eruption

Non-Eruption Events

Tectonic Earthquake in ISC catalog

Newly detected events have little or no P-wave energy, and are mainly composed of low-frequency surface waves.

Shuler and Ekström (2009)

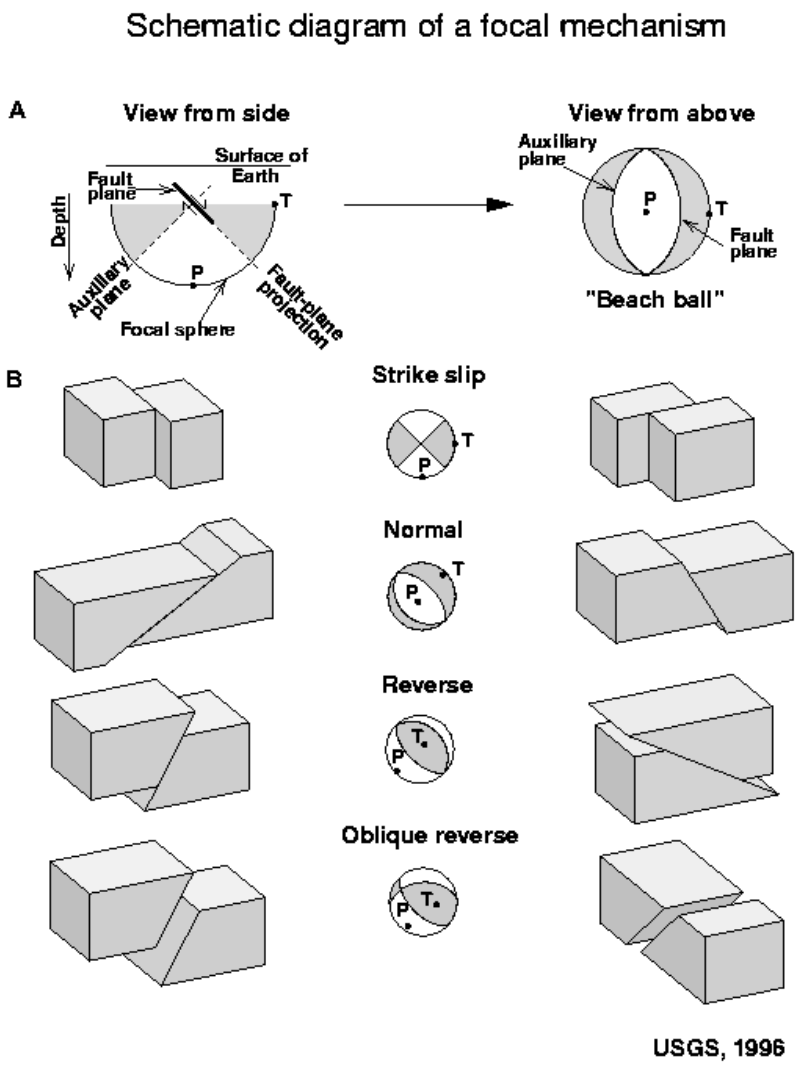


- Newly detected events are greatly depleted in high frequencies, and have a fundamentally different decay for high-frequencies.
- Their lower corner frequency implies that they have longer duration (slow events).
- Spectral differences correlate with eruptive activity

Shuler and Ekström (2009)

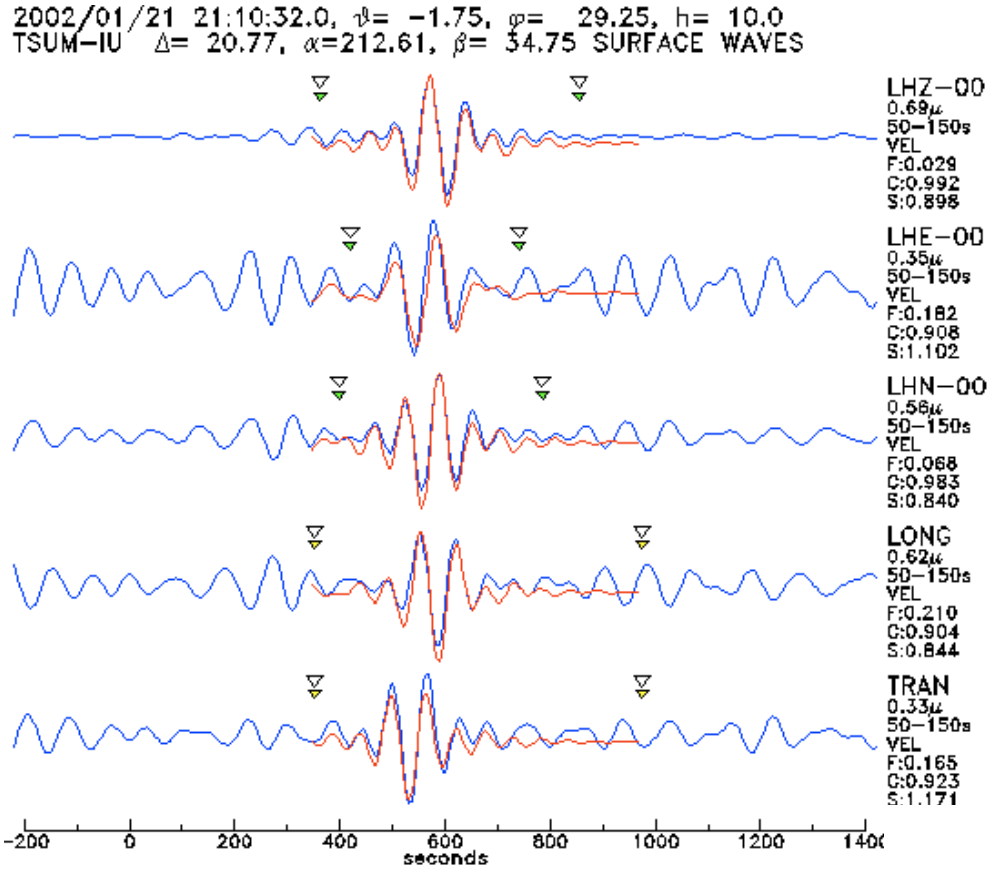
Centroid Moment Tensor Solutions

- We compared synthetic seismograms to a variety of source models to constrain the physical mechanism of the newly detected earthquakes.
- CMT solutions use the full waveform to constrain the radiation pattern of the earthquake.
- We solved for a deviatoric source (no volume change).

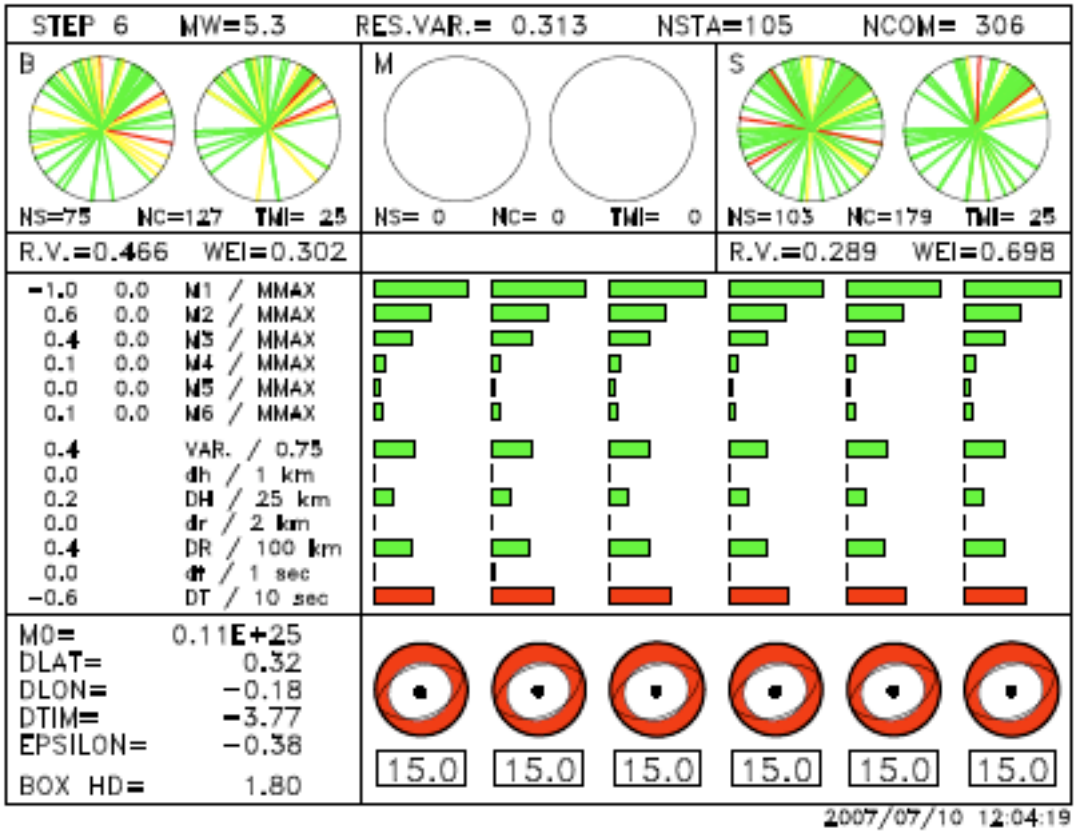


Centroid Moment Tensor Solutions

- 6 parameters of the moment tensor, as well as latitude, longitude, depth and time shift are altered to provide the best fit between observed and synthetic seismograms.



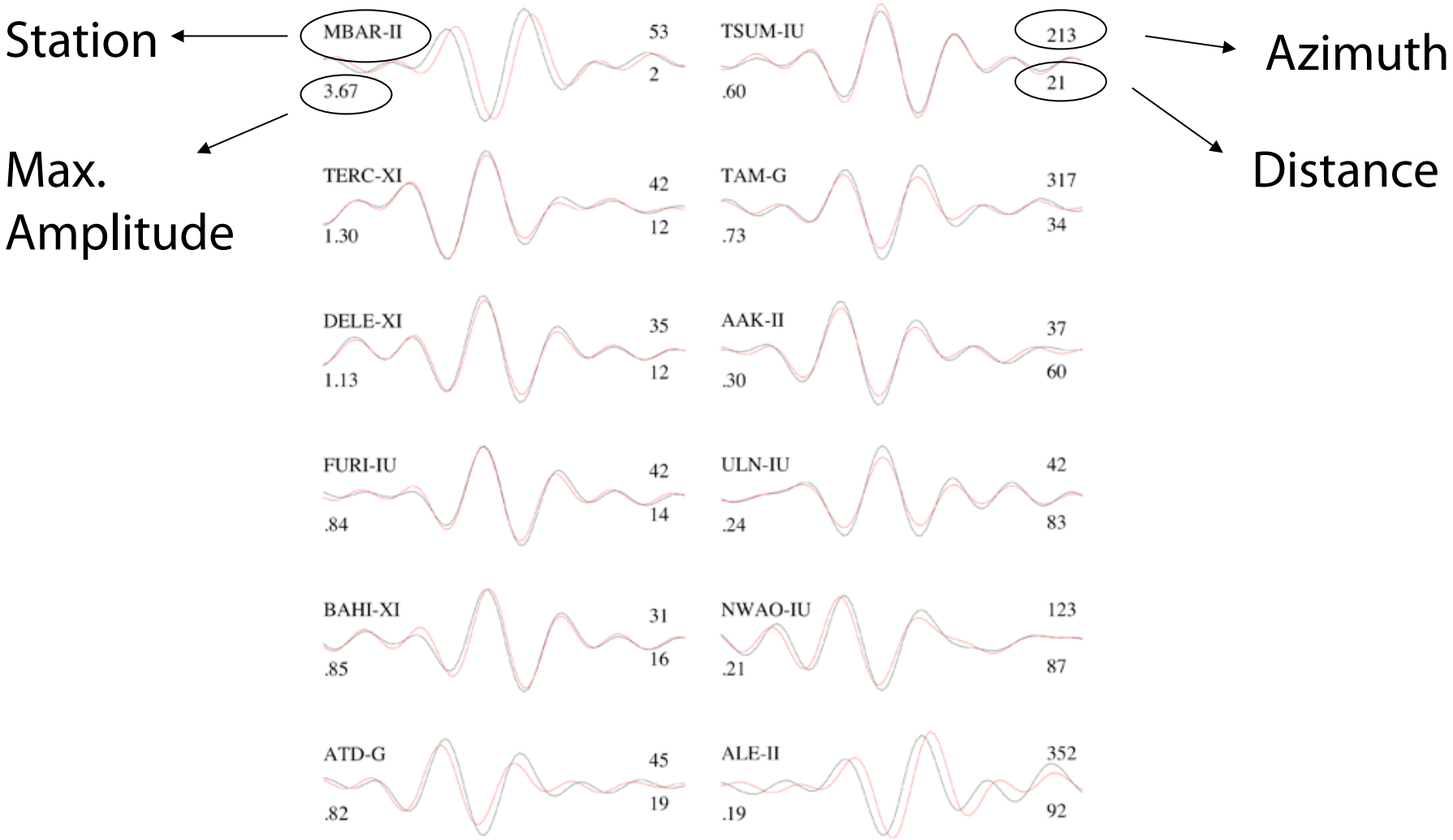
Centroid Moment Tensor Solutions



Excellent Azimuthal Coverage and Fit to Data

Stability of Moment Tensor Components

Centroid Moment Tensor Solutions



Shuler and Ekström (2009)

Centroid Moment Tensor Solutions

- Excellent fit to the data is achieved when the centroid location is constrained to be Nyiragongo.
- Highly non-double-couple focal mechanisms with a large CLVD component.

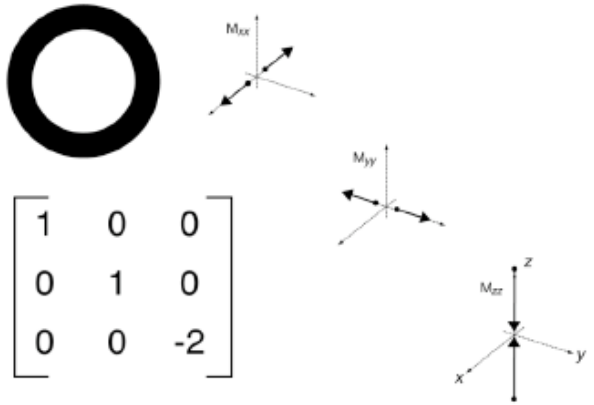
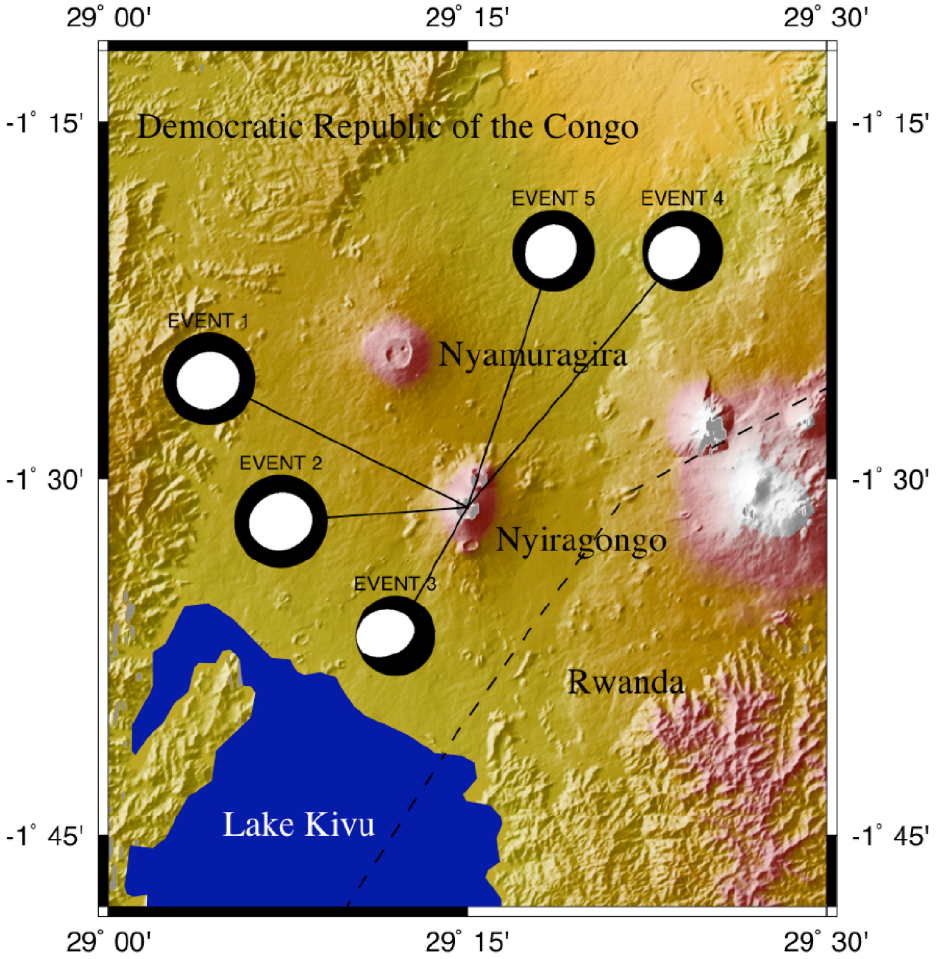
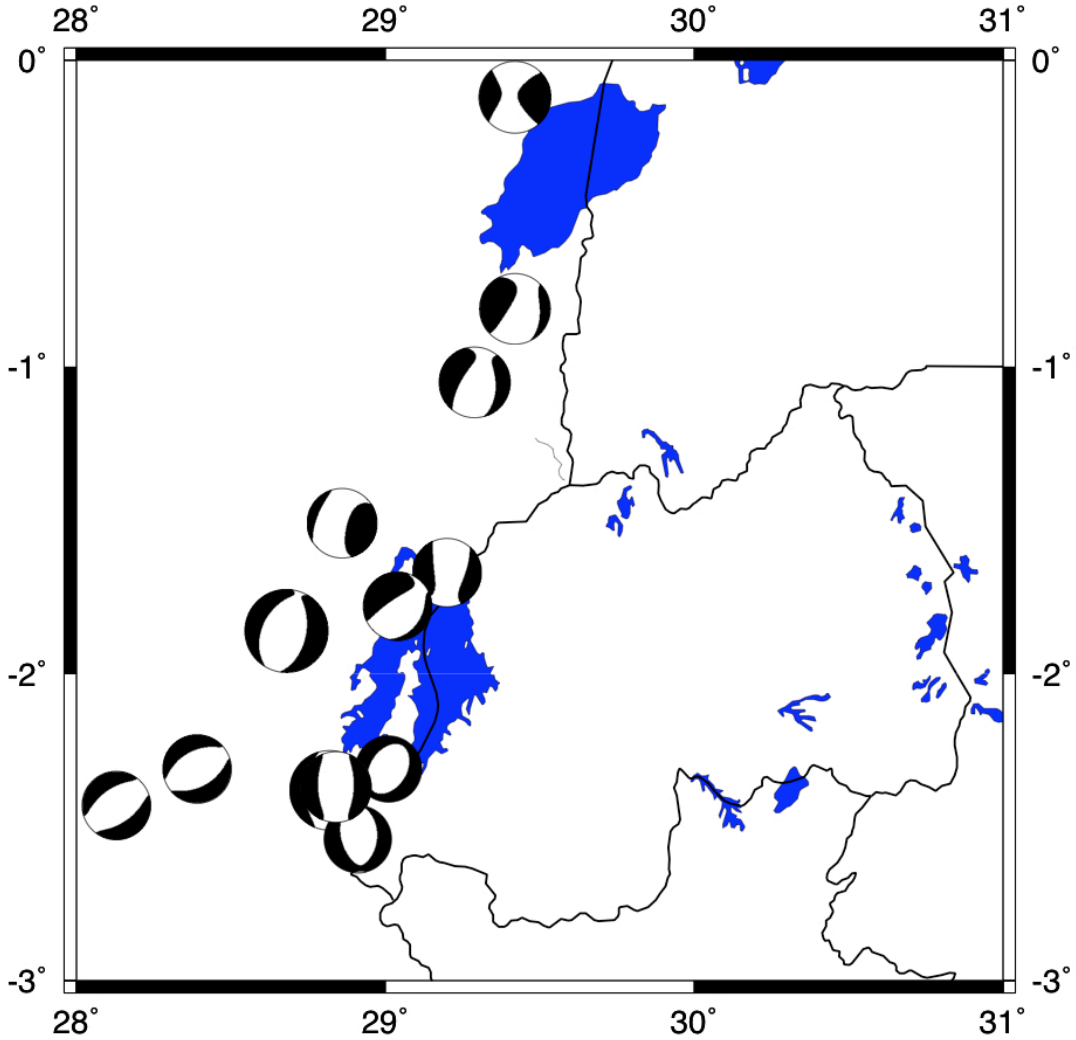


Image from MTU



Shuler and Ekström (2009)

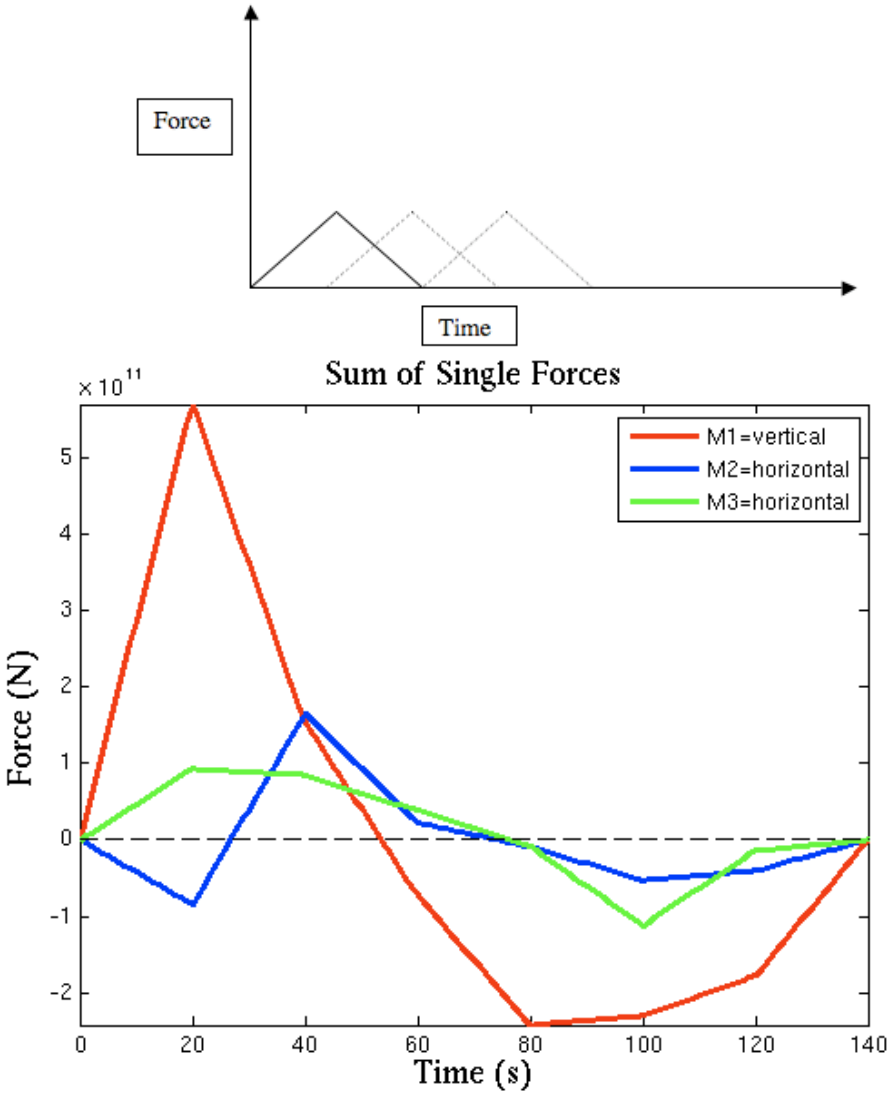
Regional Focal Mechanisms (1976-2009)



Solutions from Global CMT Catalog

Time-Varying Force Solutions

- Modeled by a source consisting of a series of forces (often used to model landslides and collapses).
- An iterative method solved for the amplitude and direction of the best-fitting forces.
- Each event was well fit by an upward force followed by a downward force (although a CMT solution provided a better fit to the data with fewer free parameters).



Two Potential Mechanisms

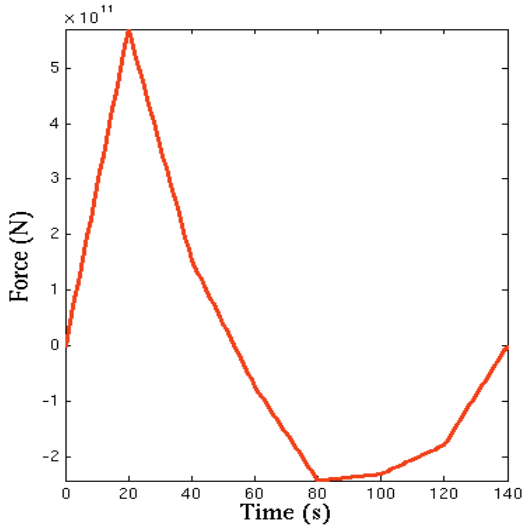
- Gravitational Collapse - Earthquakes are caused by either the incremental collapse of a portion of the solidified lava lake surface or the lid of a shallow magma chamber.
- Slip on a Non-Planar Fault - Earthquakes are caused by slip on a vertical or conical shaped ring fault either along the edge of the solidified lava lake surface or above a shallow magma chamber.

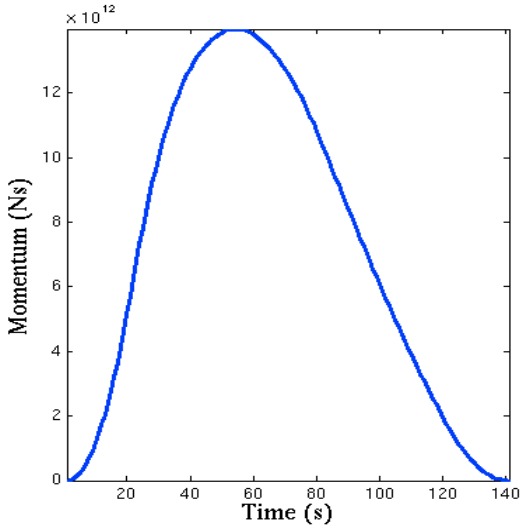
Evaluation of Gravitational Collapse Mechanism

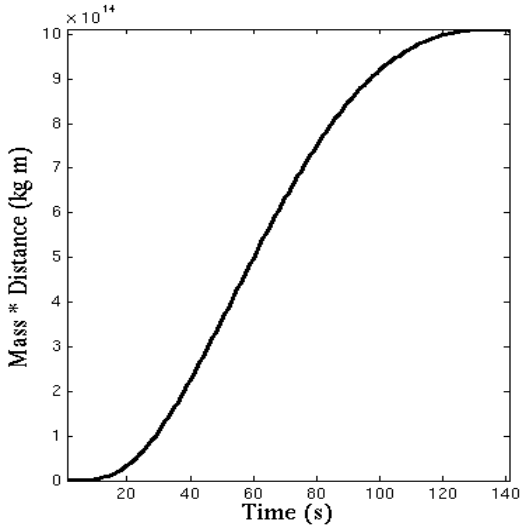
- The double integral of F(t) gives the product of the mass and displacement required in each event.

$$\mathbf{F}(t)_{\text{on Earth}} = -\frac{d(m\mathbf{v}(t))_{\text{collapse}}}{dt} = -\frac{d\mathbf{p}(t)}{dt}$$

$$\iint \mathbf{F}(t)dt = \int -\mathbf{p}(t)dt = -m\mathbf{D}(t) = -\rho V\mathbf{D}(t)$$







Evaluation of Gravitational Collapse Mechanism

- Magnitude of modeled forces is too high for either collapse scenario (part of solidified lava lake or roof of shallow magma chamber).
- CMT provides better fit with fewer free parameters.
- This mechanism alone cannot explain the occurrence of the newly detected events.

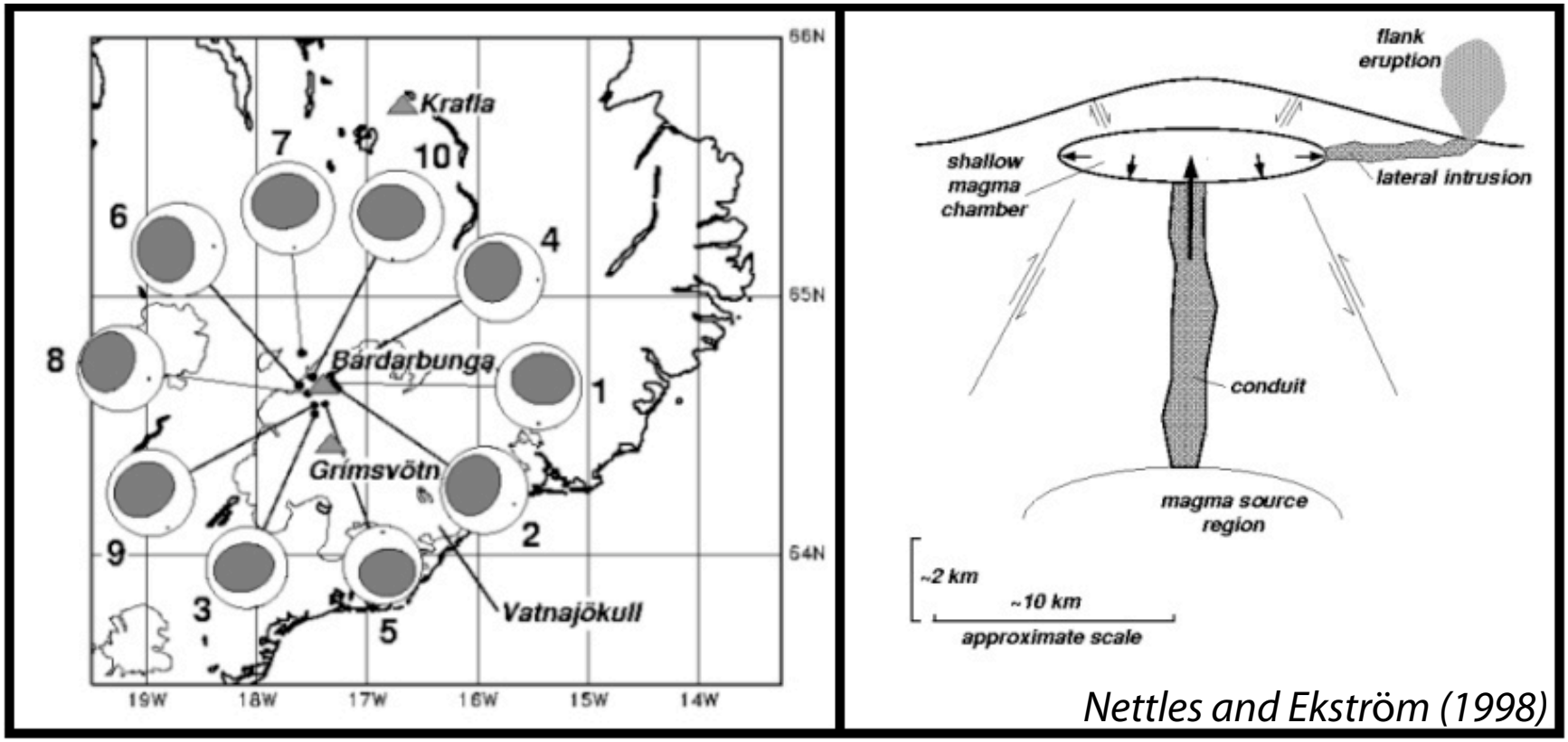
Evaluation of Ring Fault Mechanism

- Circular or elliptical faults are commonly observed at active and eroded volcanoes. These faults are associated with inflation and deflation of shallow magma chambers.
- Slip on pre-existing ring faults can be triggered by the evacuation of magma from these magma chambers.
- Realistic slip (cm to dm) on a ring fault above a shallow magma chamber could produce earthquakes of the observed magnitude.

$$M_0 = \mu A \bar{d}$$

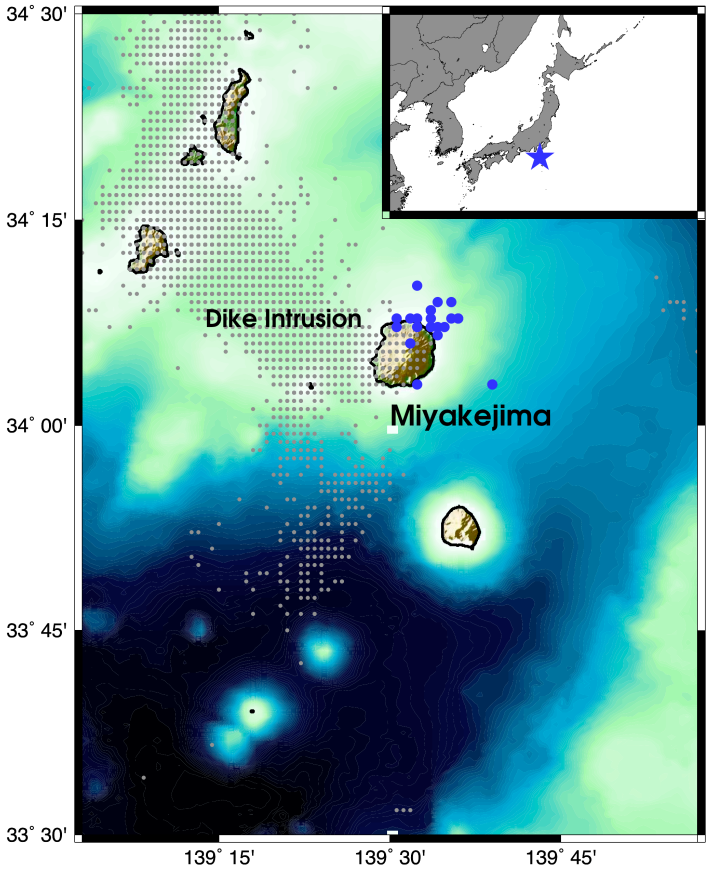
- Such a mechanism has been suggested to explain highly non-double-couple events at other active volcanoes (Bardarbunga, Miyakejima).

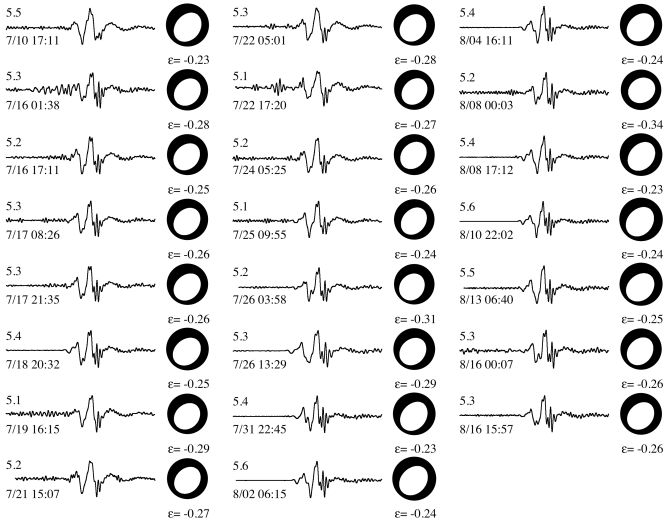
Similar Earthquakes at Bardarbunga



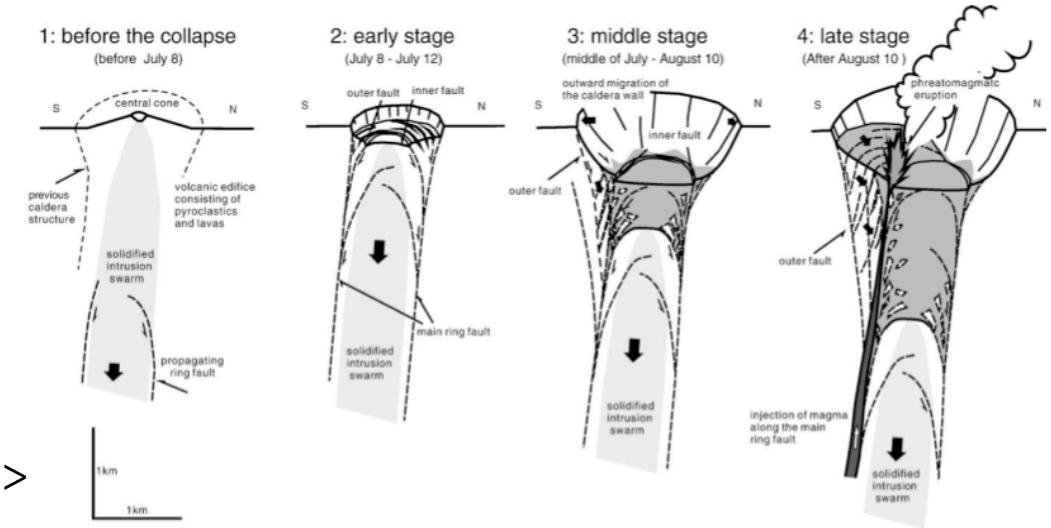
Ten earthquakes associated with inflation of shallow magma chamber prior to 1996 subglacial eruption

Similar Earthquakes at Miyakejima



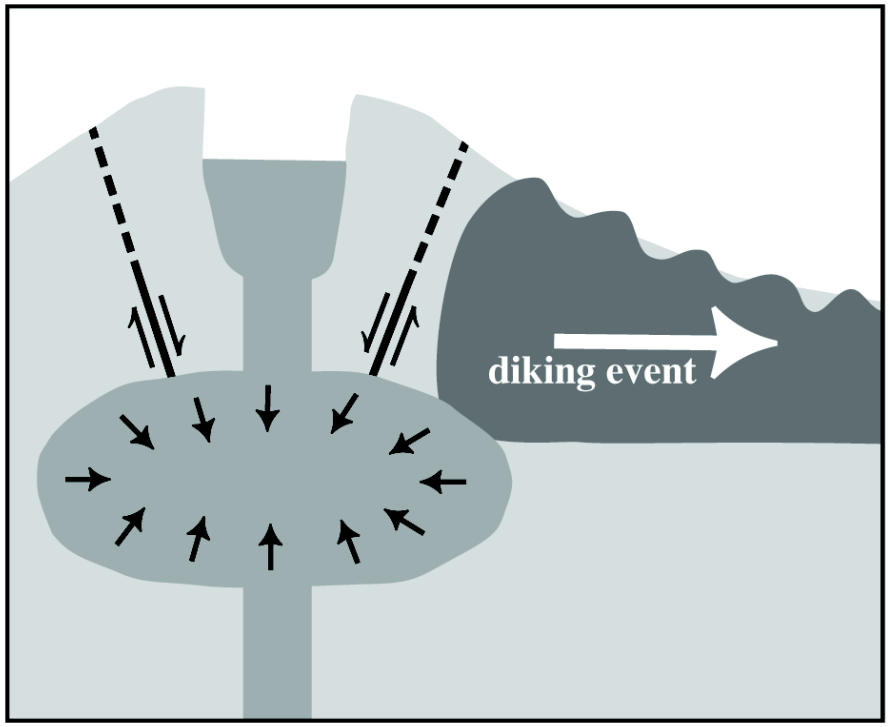


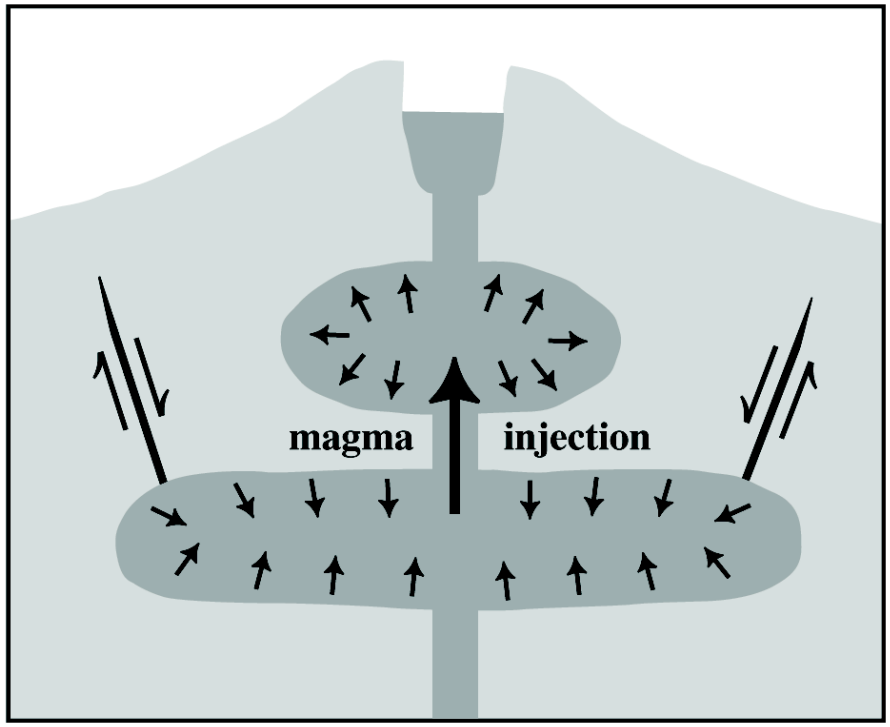
Shuler and Ekström (in prep.)



Geshi (2009) --->

Preferred Mechanism





Events 1-3

Events 4-5

Shuler and Ekström (2009)

Conclusions

- 5 anomalous earthquakes are attributed to slip on pre-existing ring faults located above evacuating shallow magma chambers under Nyiragongo volcano.
- The first three events were triggered by diking events associated with the local rifting event and 2002 eruption of Nyiragongo.
- The last two events were caused by the injection of magma from a deeper reservoir into a shallow reservoir.

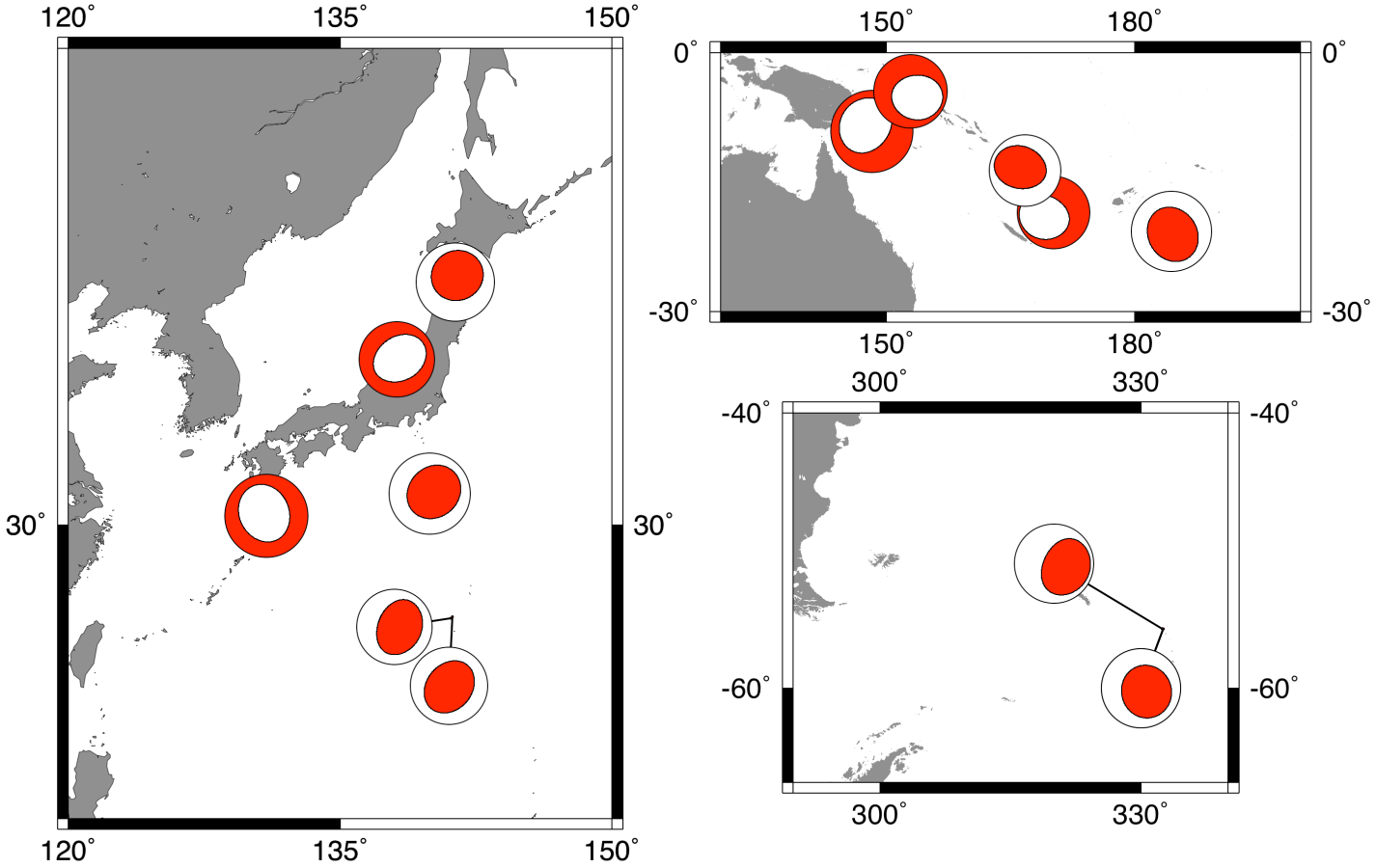
Future Work - Where Else Do We See Vertical CLVD Earthquakes Near Active Volcanoes?

2 Datasets to Search:

1. Global CMT catalog
2. Surface Wave catalog

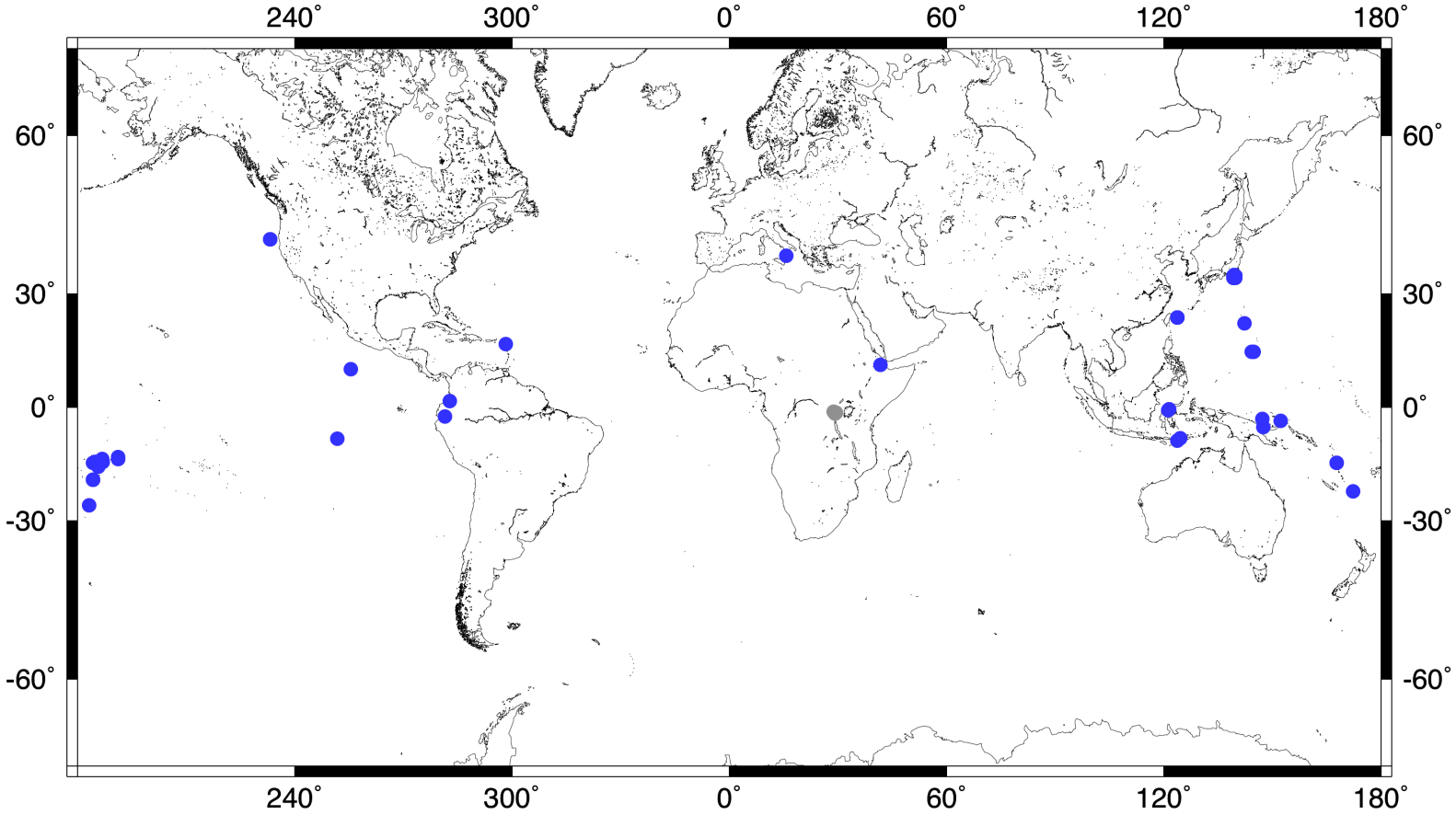
Do these events happen at a certain type of volcano? Are they associated with a particular type of volcanic activity?

Global CMT Catalog (1976-2009)



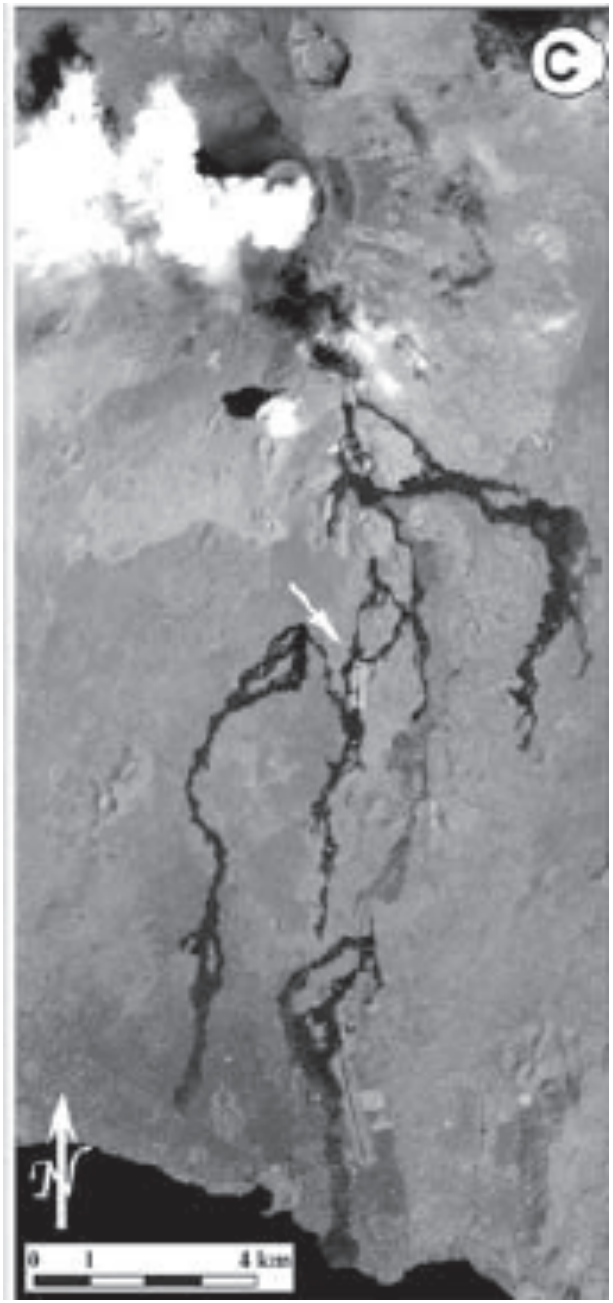
Shuler and Ekström (in prep.)

Surface Wave Catalog (1993-2003)



Newly detected earthquakes that are located within 100 km of a volcano that has erupted since 1900

Shuler and Ekström (in prep.)



Thanks for
your attention!

Questions?

Image from Komorowski et al. (2002/2003)