# Volcano-tectonic interactions


John Stix

McGill University


*Pan-American Studies Institute*

*Magma-Tectonic Interactions in the Americas*

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# Hekla volcano, Iceland, 1900 hours, 29 March 1947

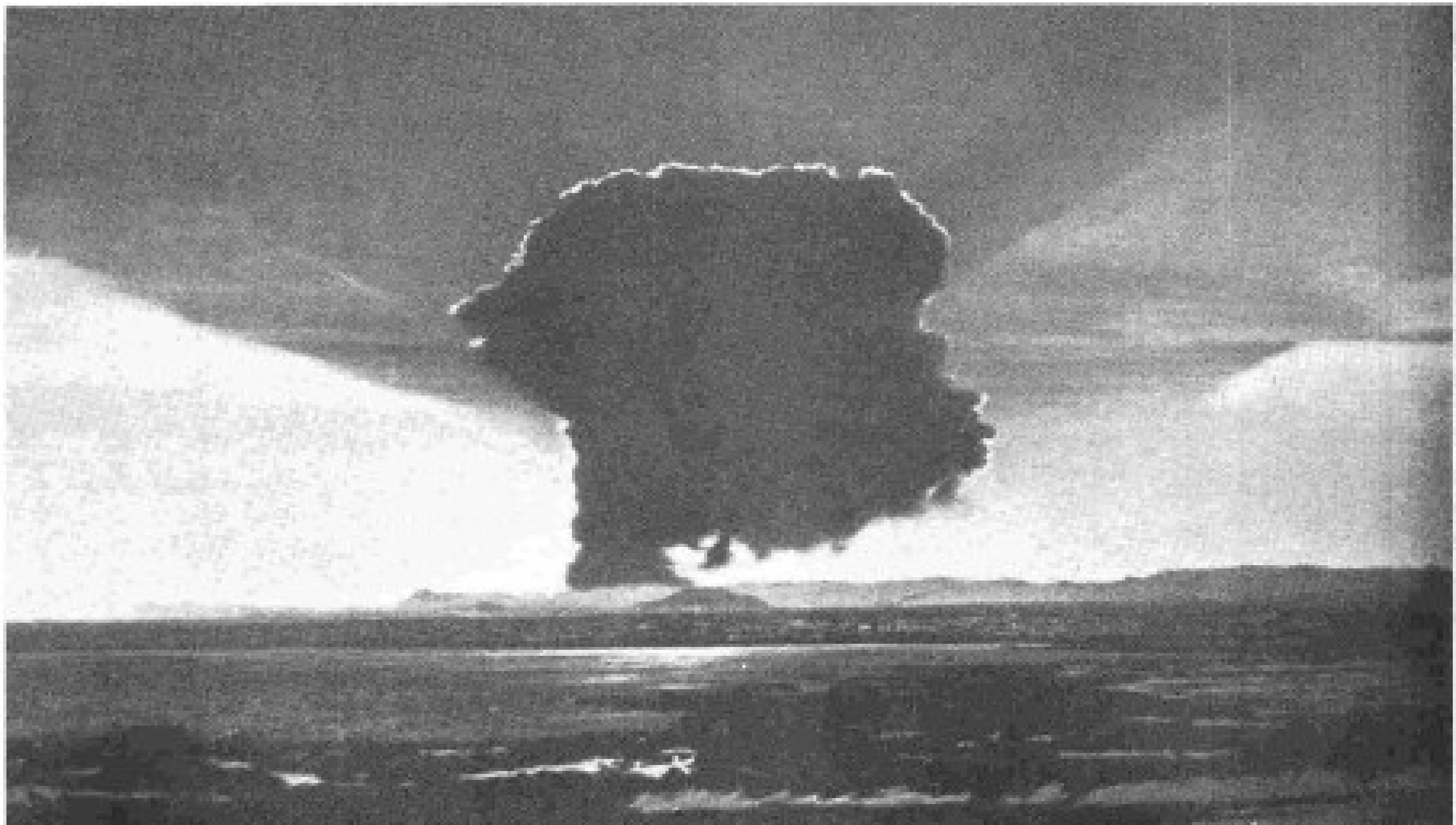


Fig. 2 - The Hekla eruption seen from Vatnsleysuströnd on Reykjanes, 120 km west of the volcano on March 29th 1947 at 7th o'clock. Height of column 27000 m.

Photo: S. THÓRARINSSON.

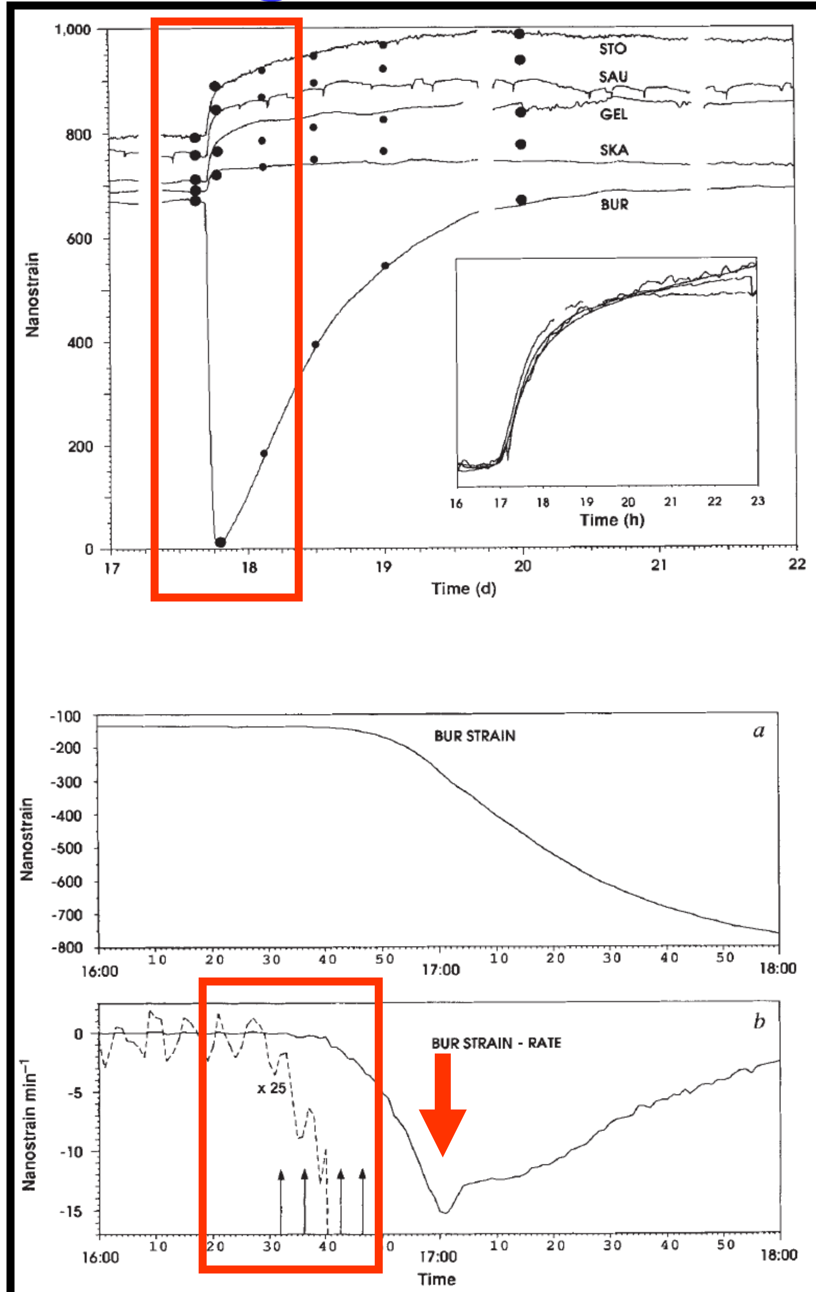
Thorarinsson S, 1950. Bull Volcanol 10: 157-168

# Explosive eruptions at Cerro Negro and Hekla

- **Very unpredictable** – few if any precursors

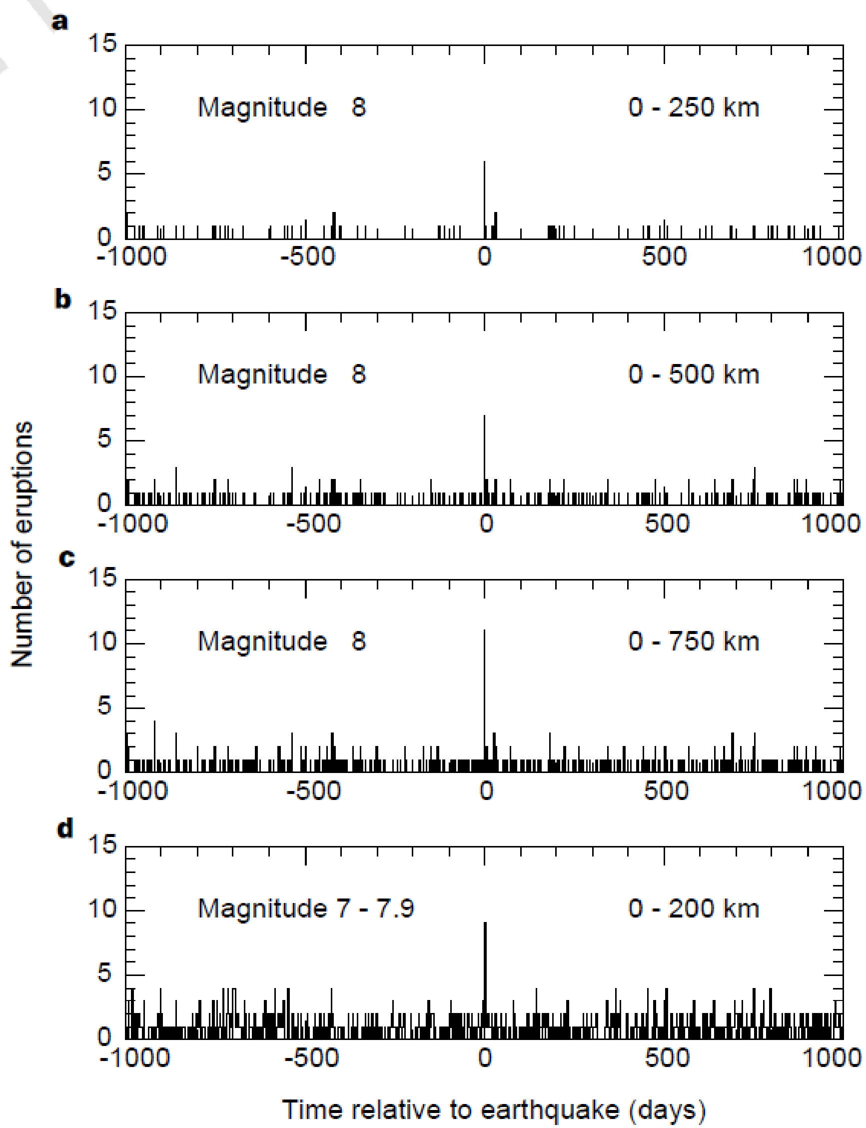
- Very sudden eruption onsets
- Initial eruptive phases highly explosive
- An initial massive release of gas
- Very frequent eruptions, every 10-20 yrs
- Both volcanoes are probably "primed"
- How can we better forecast their activity?

**<u>We should be planning for these eruptions</u>**

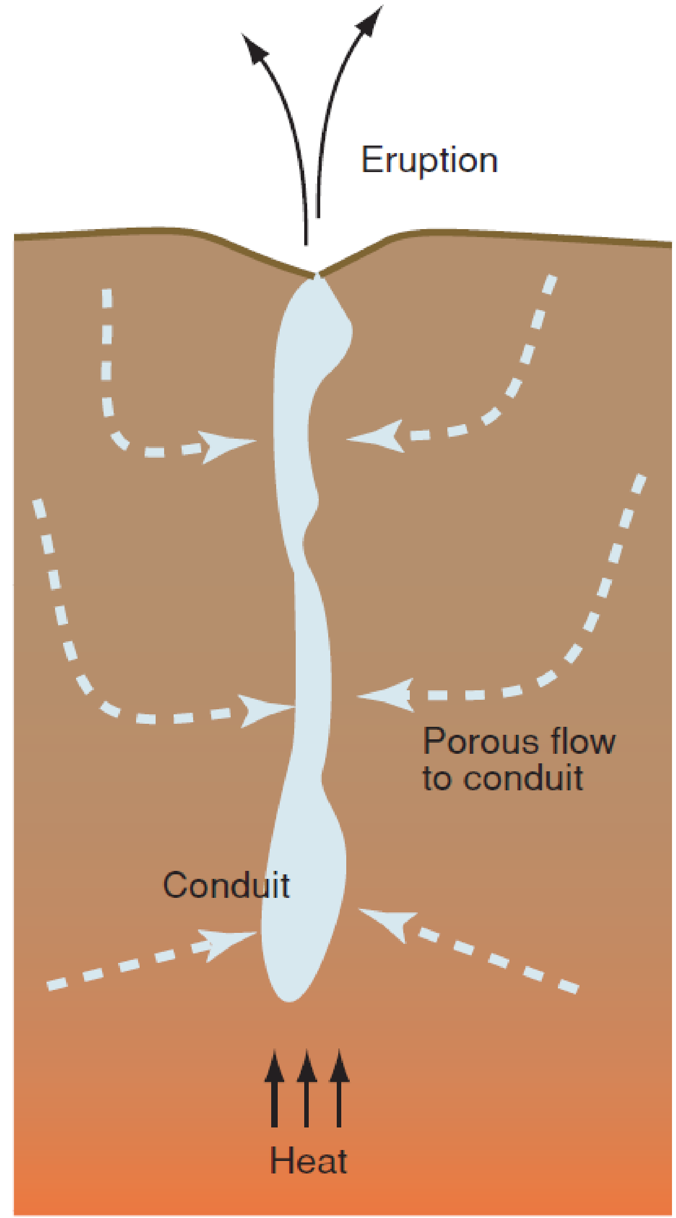



Linde AT, Agustsson K, Sacks IS, Stefansson R, 1993. Nature 365: 737-740

# Magma-tectonic interactions




Linde AT, Sacks IS, 1998. Nature 395: 888-890




Manga M, Brodsky E, 2006. Ann Rev Earth Planet Sci 34: 263-291

# My themes

1. “Critical” and “near-critical” systems
2. Static and dynamic triggering of magmatic systems
3. Permeability – its spatial and temporal character
4. Stacked and connected crustal magma reservoirs
5. The importance of magma recharge

# Earthquake triggering

Stresses produced by both static and dynamic triggering tend to be small (usually a few MPa or less) compared to lithostatic stresses, magma pressures and overpressures (usually $10^1$-$10^2$ MPa)

# Static and dynamic stresses

**Static stresses** tend to be quite low (<0.1 MPa) at distances of tens of km or more from the source

For **dynamic triggering**, we need to better address the following issues:

- intensity and duration of ground movement
- the relative roles of P, S, Rayleigh, and Love waves
- the role of the waves' frequencies…are low-frequency waves more capable of triggering events, as suggested by Brodsky and others?
- what are the roles played by (a) distance from the source and (b) directionality of the propagated waves?

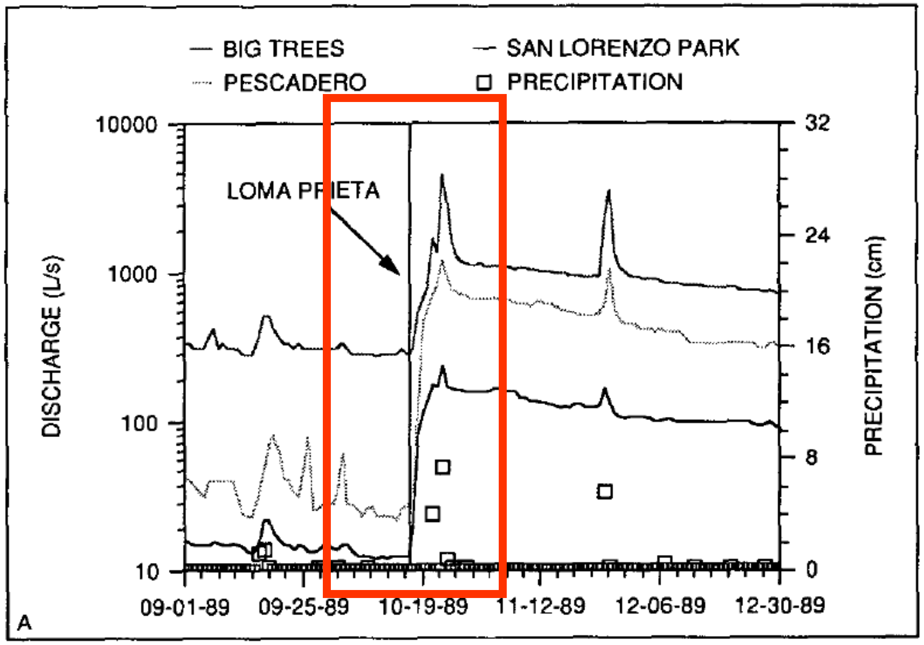
# “Critical” systems

- Hydrologic / hydrothermal systems
- Basaltic vs. andesitic vs. rhyolitic magma systems
- Shallow vs. deep magma reservoirs
- Open-vent vs. closed-vent volcanoes

**Systems which are in a state of incipient failure…”weak” systems which may be fractured, have high pore pressures, etc.**

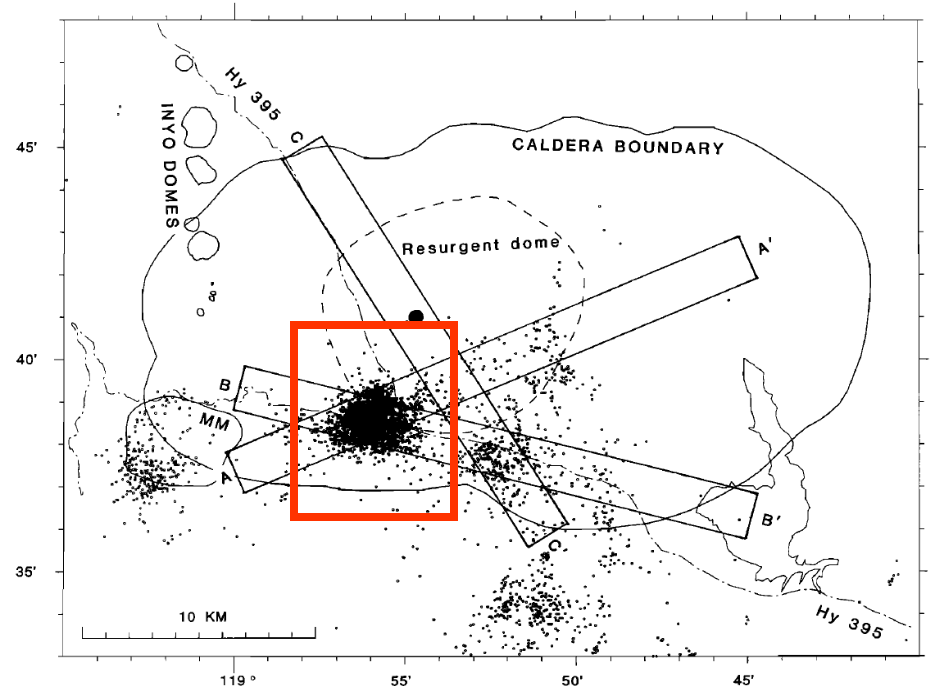
# Two examples of potentially critical systems

**Loma Prieta, California**




Rojstaczer S, Wolf S, 1992. Geology 20: 211-214

**Long Valley caldera, California**




Langbein J, Hill DP, Parker TN, Wilkinson SK, 1993.
J Geophys Res 98: 15851-15870

# “Critical magma”

**What constitutes so-called “critical magma”, i.e., magma that is sensitive to far-field static and/or dynamic stresses and is thus disturbed able to erupt as a result?**

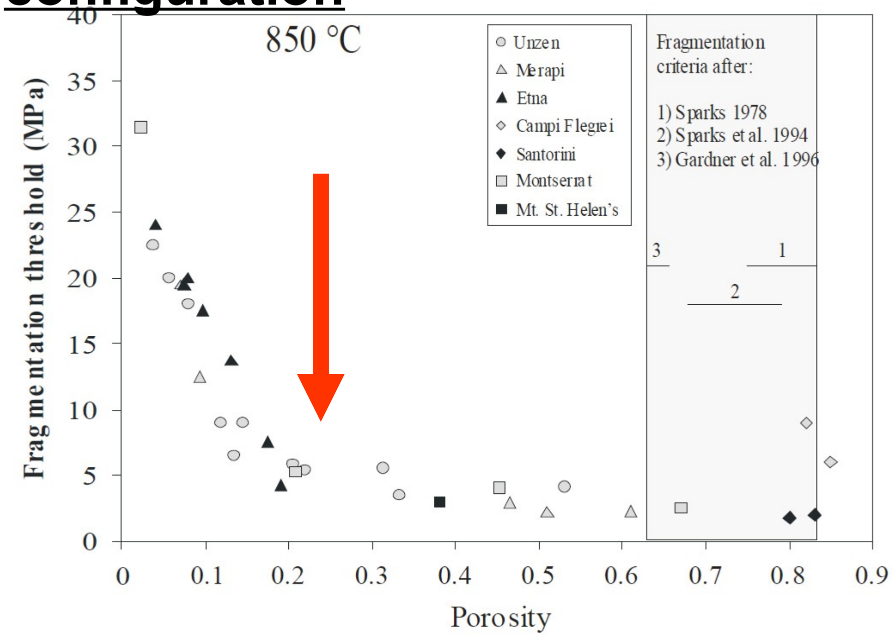
Some possibilities:

- Low-viscosity magma
- Gas-rich magma
- Gas-saturated magma (free bubbles)
- Compressible magma

Two illustrations follow

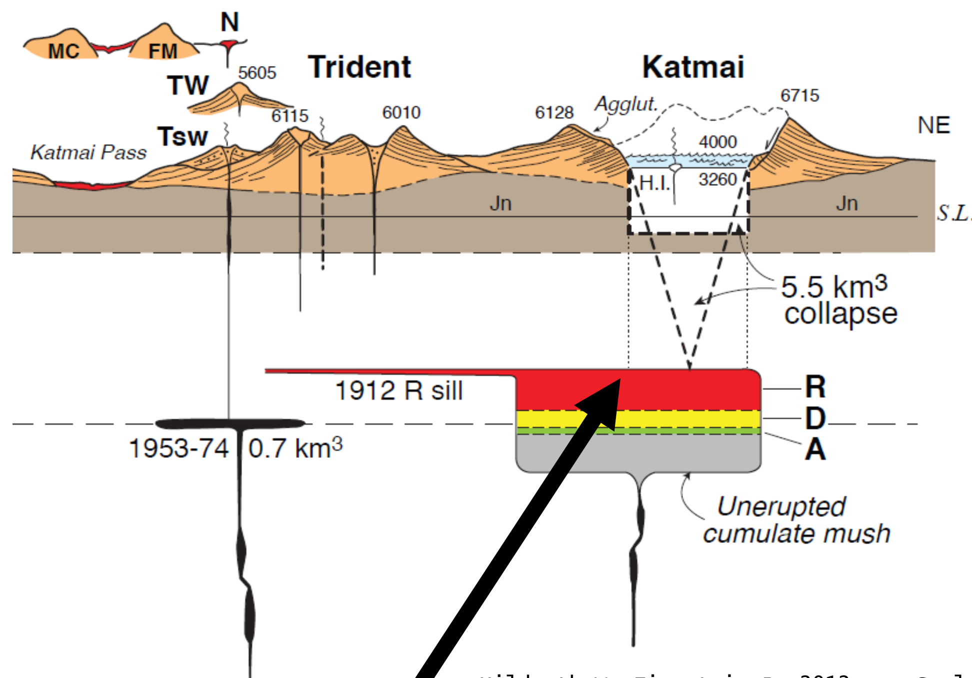
# Weak rocks, runny magma

## Spieler's fragmentation threshold configuration




Spieler O, Kennedy B, Kueppers U, Dingwell DB, Scheu B, 2000. Earth Planet Sci Lett 226:139-148

## Pre-1912 Katmai magma

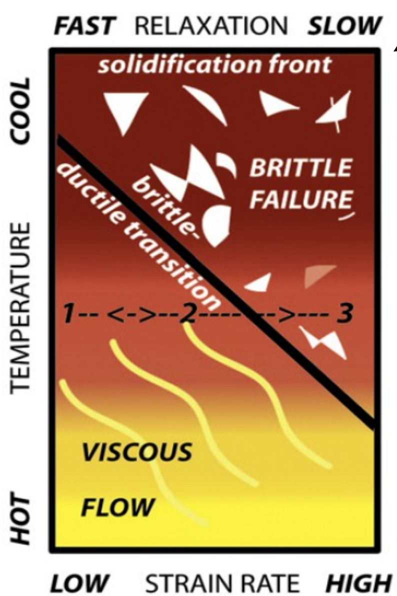



Hildreth W, Fierstein J, 2012. us Geol Surv Prof Pap 1791: 1-259

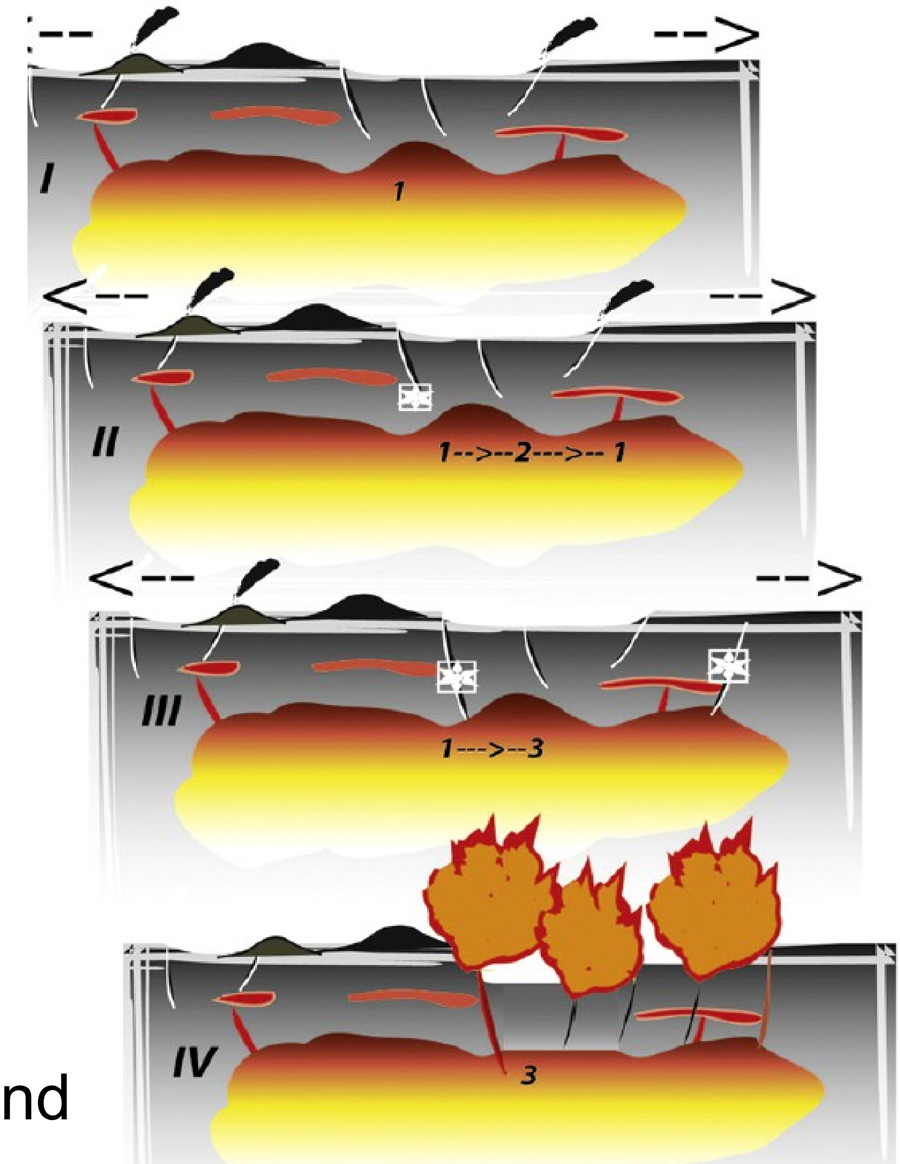
**hot, aphyric, volatile-rich rhyolite (possible bubbly)**

# "Critical magma" - continued

Or maybe such magma is actually quite different in nature, one that is **crystal-rich and volatile-poor** …a magma mush or crystallized carapace…one that is **stiff and brittle**…




…with **rapid decompression** and **high strain rates**




Gottsman J, Lavallée Y, Martí J, Aguirre-Díaz, 2009. Earth Planet Sci Lett 284: 426-434

# Permeability changes

**How is permeability affected by far-field stresses?**

It is likely that permeability is **highly variable** in both a spatial sense and a temporal sense

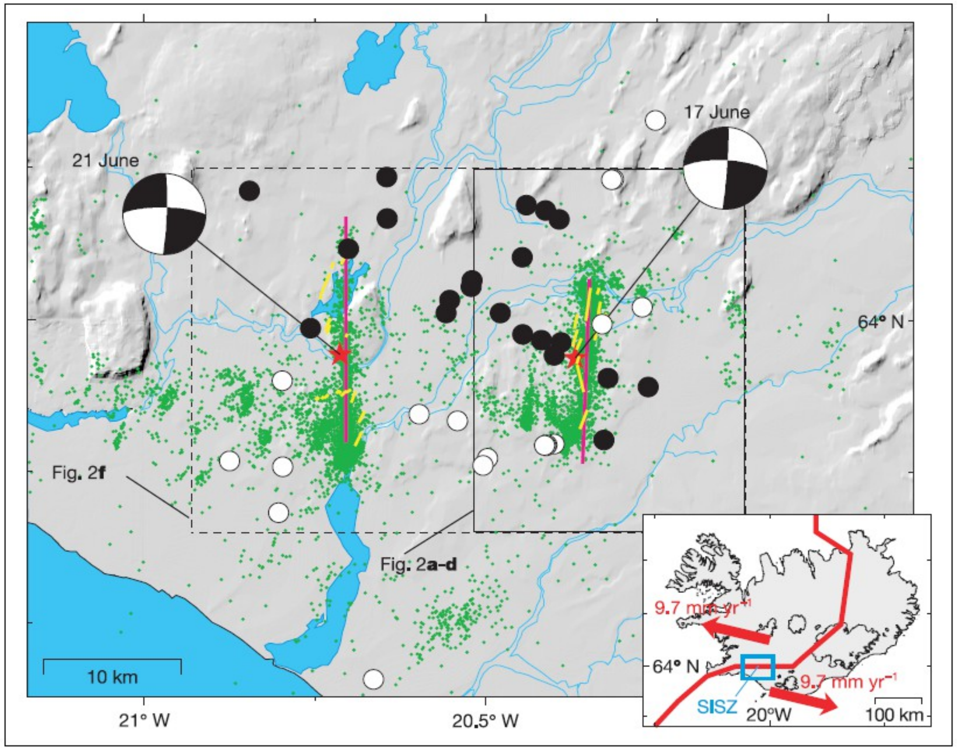
Permeability may be **time-dependent**….far-field stresses may generate fractures and microfractures which can subsequently seal up through mineral precipitation, etc.

Magmas have their own permeability relationships which control degassing

Rise of magma can also alter permeability relationships in the magma and surrounding country rocks

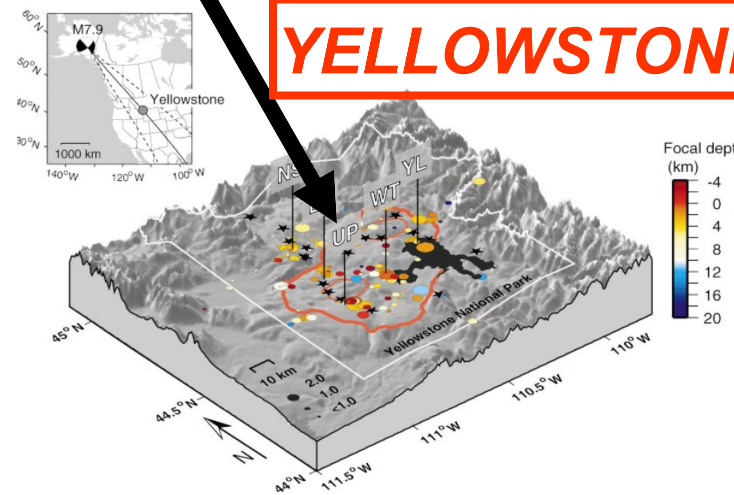
Jónsson S, Segall P, Pedersen R, Björnsson G, 2003. Nature 424: 179-183

Husen S, Taylor R, Smith RB, Healser H, 2004. Geology 32: 537-540




**Remotely triggered earthquakes within 6 h of M7.9 2002 Denali earthquake**

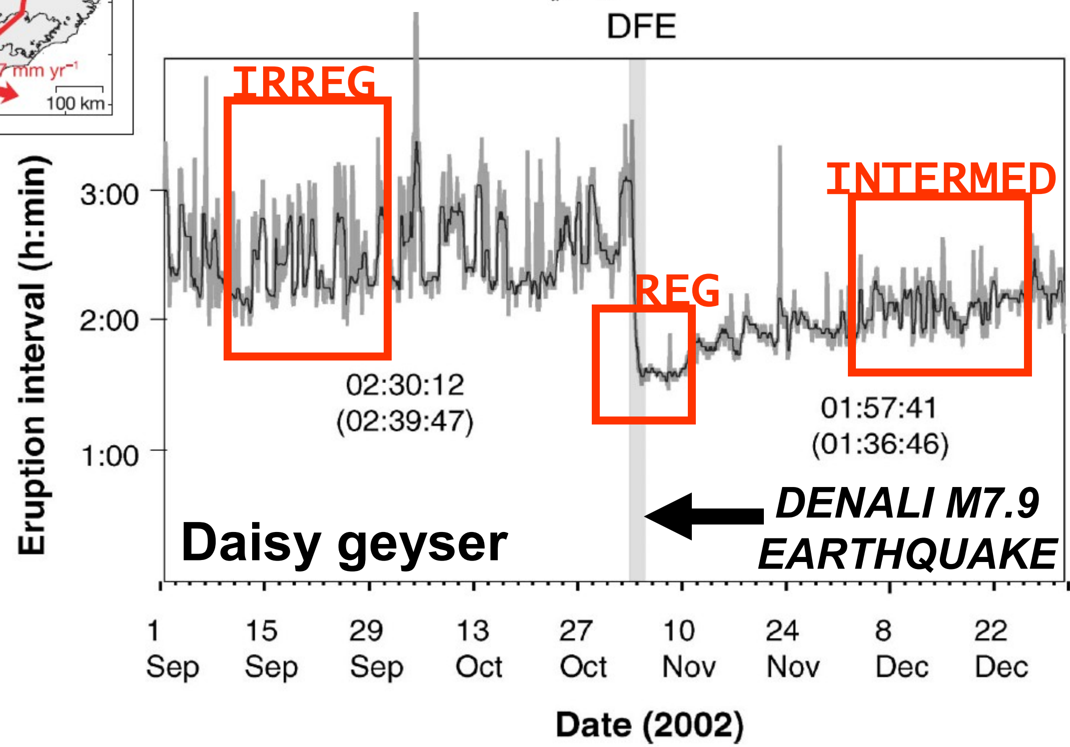
***YELLOWSTONE***




## Geothermal well response after quakes:

- ● water level increase
- ○ water level decrease

***SOUTH ICELAND SEISMIC ZONE***



# Stacked and connected crustal magma reservoirs

- There is good evidence that crustal magmatic systems are **stacked vertically**, from near-surface environments to near-mantle depths

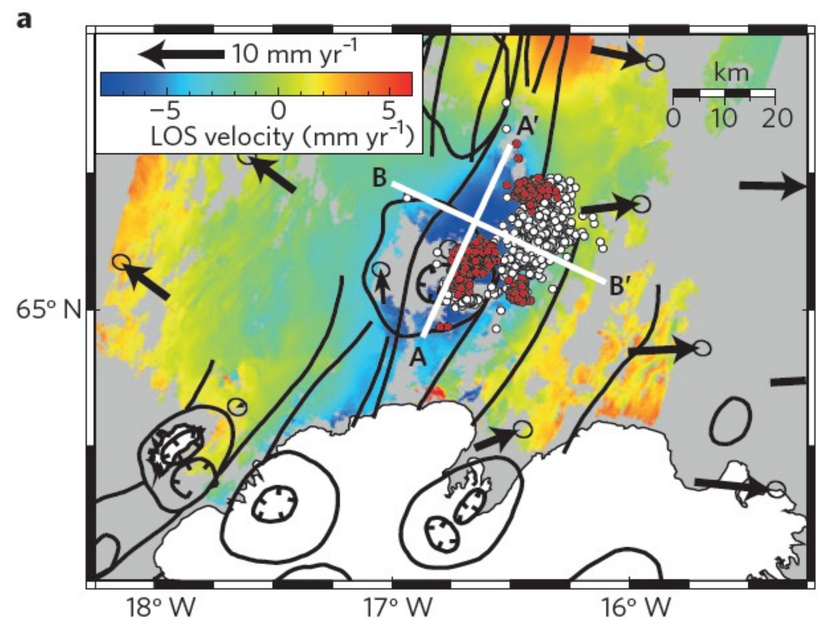
- Some reservoirs probably extend into the mantle itself

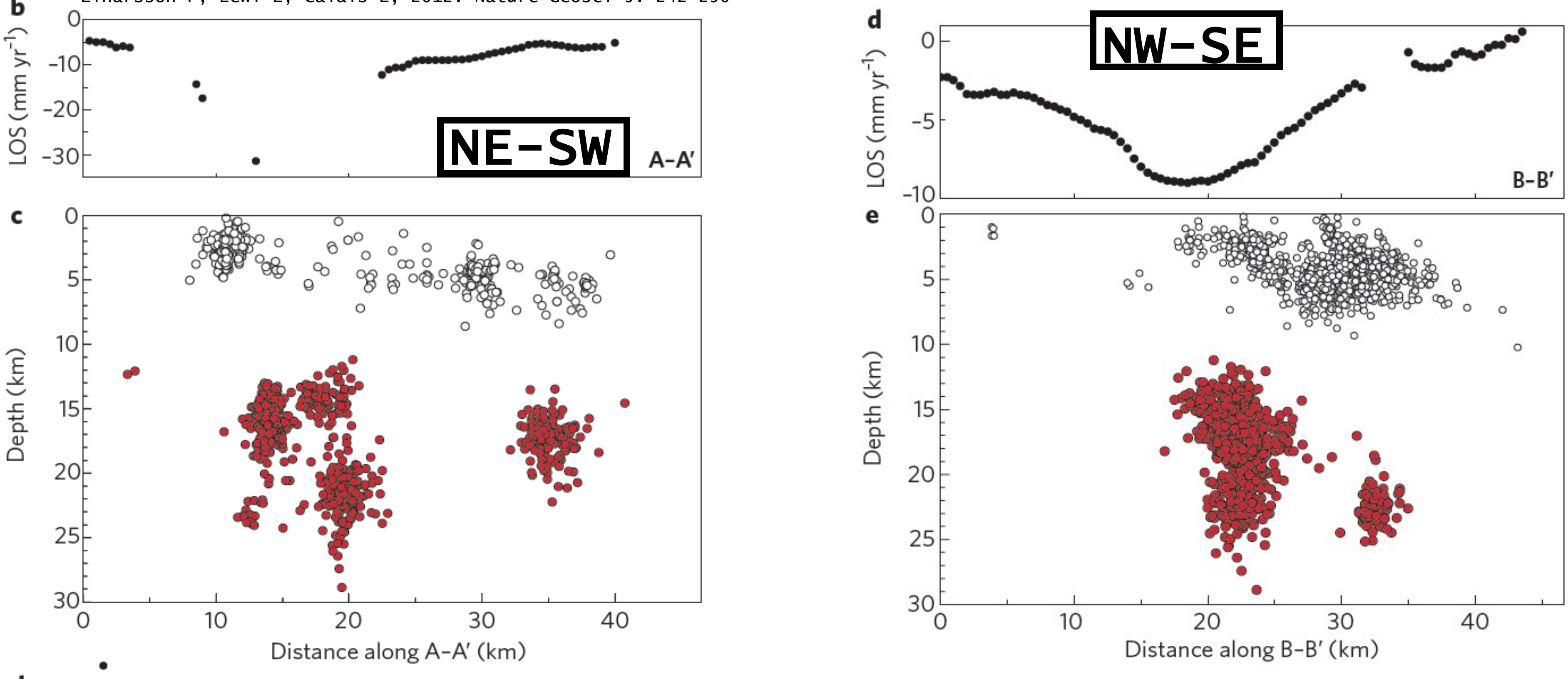
- Deeper (and larger?) mid-crustal magma reservoirs feed shallow reservoirs

- In extensional environments (e.g., Taupo, New Zealand), space is provided for large poolings of magma at shallow levels (~5 km)

# Askja (Iceland) subsidence and seismicity, 1993-2004

Wright TJ, Sigmundsson F, Pagli C, Belachew M, Hamling IJ, Brandsdóttir B, Keir D, Pedersen R, Ayele A, Ebinger C, Einarsson P, Lewi E, Calais E, 2012. Nature Geosci 5: 242-250



# Shallow – deep connections

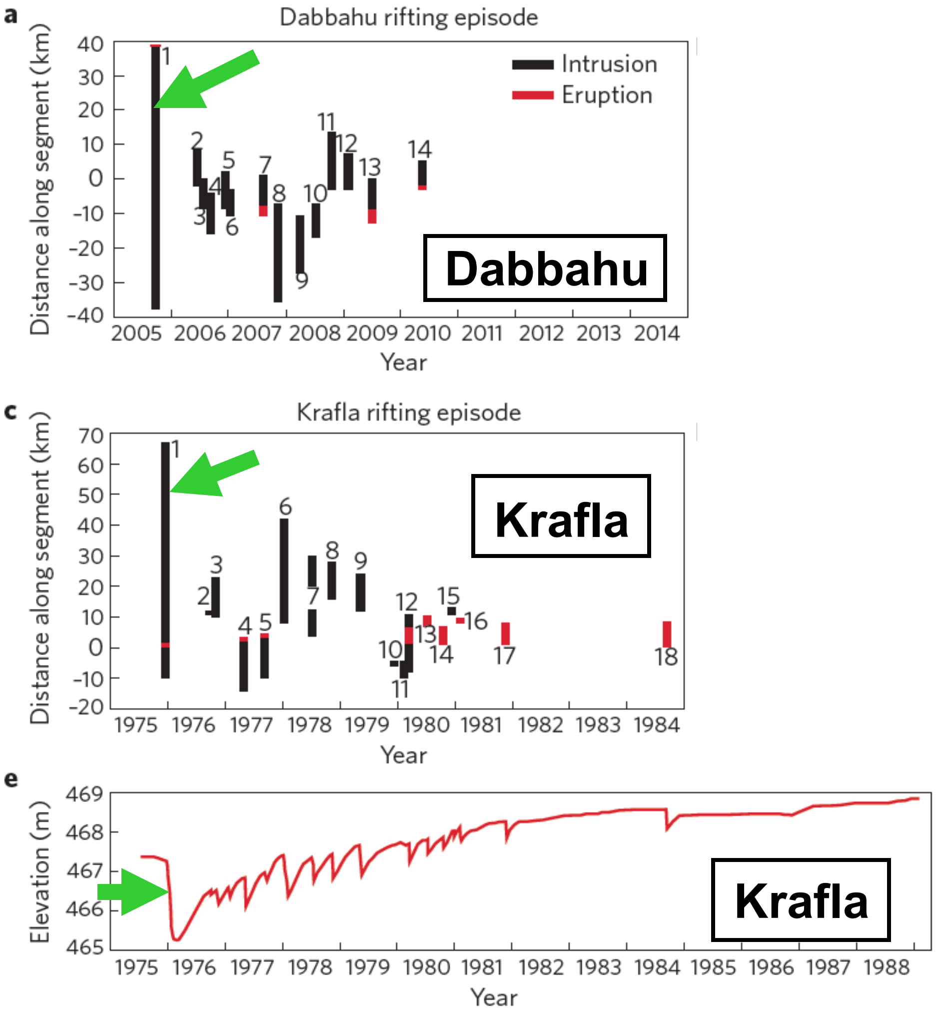
After an eruption, there is good evidence for:

(a) **Magma replenishment** from deep to shallow levels

(b) **“Seismic deepening”** – a response of the deep system to shallow / surface events

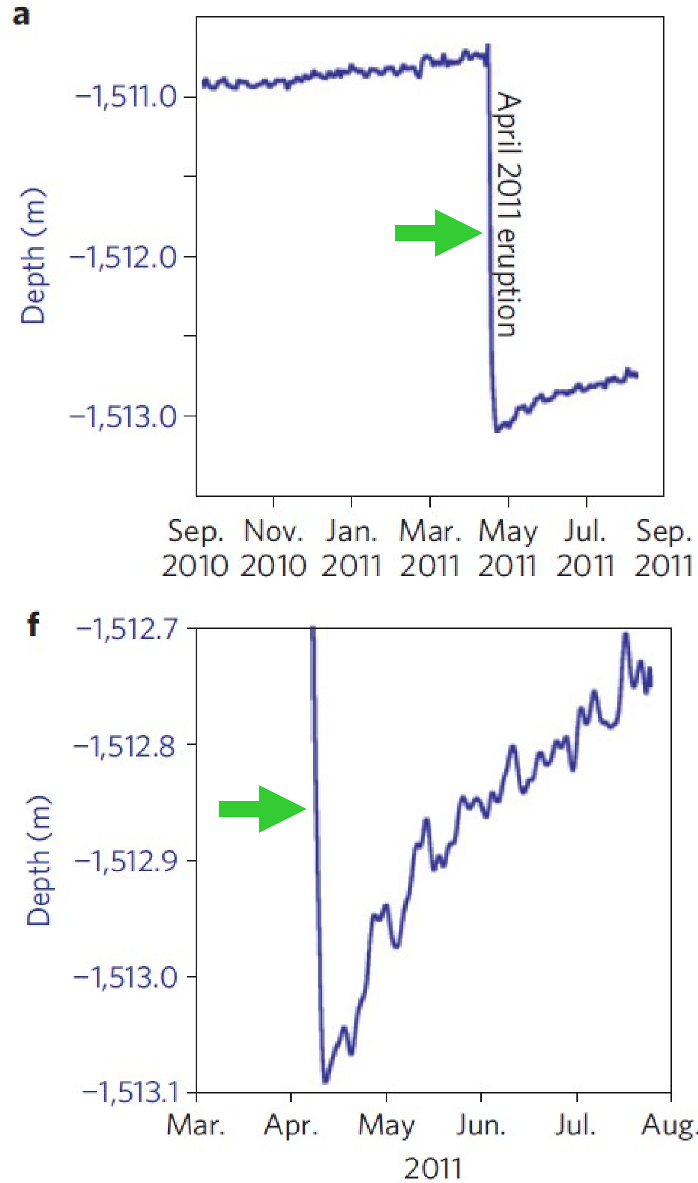
# (a) Post-eruptive magma replenishment

## Dabbahu (Afar) and Krafla (Iceland) intrusions / eruptions



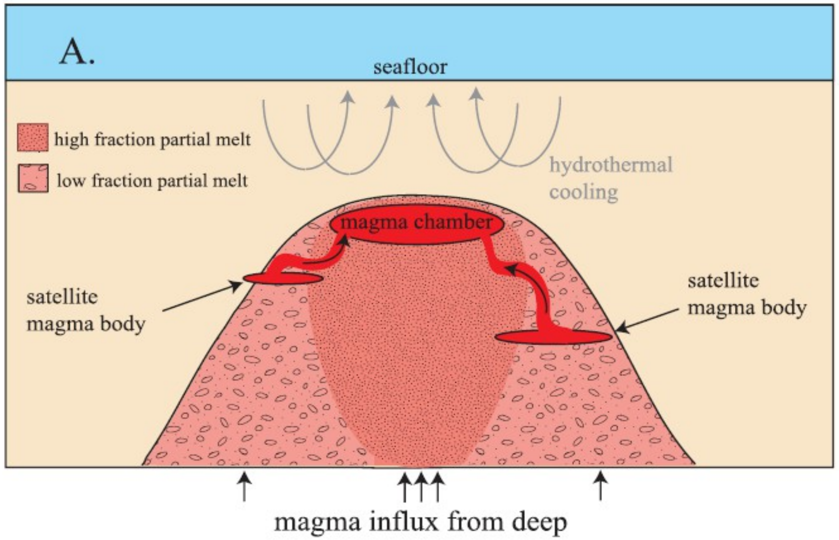

Wright TJ, Sigmundsson F, Pagli C, Belachew M, Hamling IJ, Brandsdóttir B, Keir D, Pedersen R, Ayele A, Ebinger C, Einarsson P, Lewi E, Calais E, 2012. Nature Geosci 5: 242-250

## Axial volcano, Juan de Fuca ridge, NE Pacific Ocean

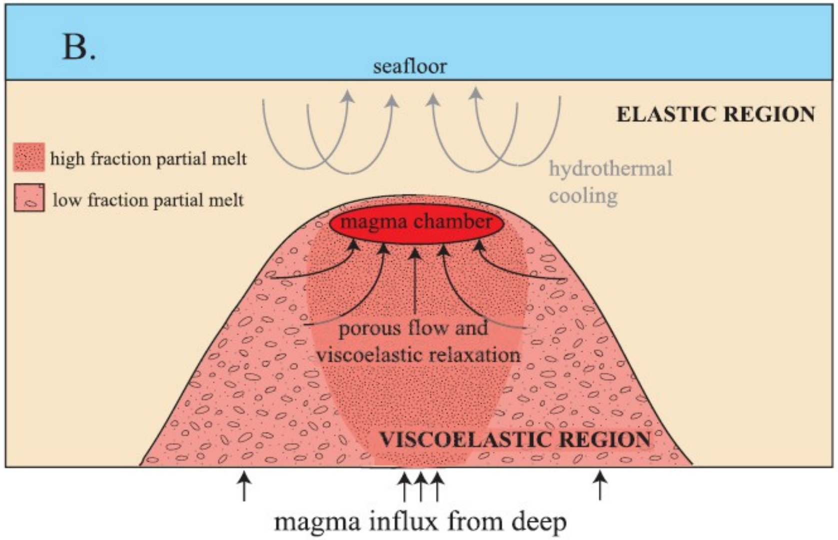



Chadwick WW, Nooner SL, Butterfield DA, Lilley MD, 2012. Nature Geosci 5: 474-477

# Magma replenishment or visco-elastic response of the crust?




***MAGMA REPLENISHMENT FROM SATELLITE BODIES***



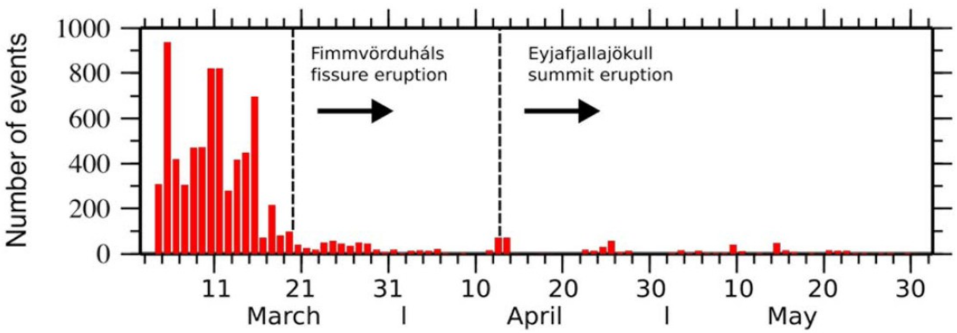

***POROUS FLOW, VISCOELASTIC RELAXATION***

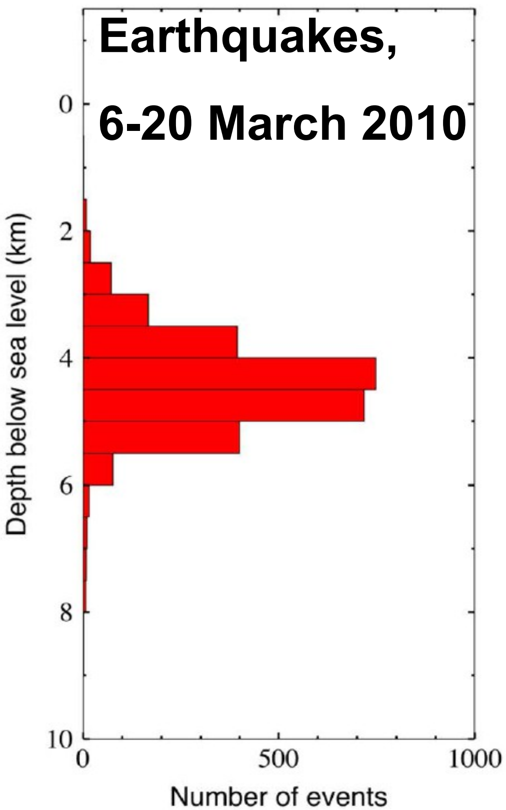
Nooner SL, Chadwick WW, 2009. Geochem Geophys Geosys 10: 1-14

# Magma replenishment

- There is good evidence that replenishment occurs **<u>after</u>** eruptions
- But the evidence is less clear – sometimes – if replenishment occurs **<u>before</u>** eruptions, i.e., acting as a trigger
- Might flow of deep magma into the shallow system occur as a result of "unclamping" due to far-field stresses ?
- Recharge provides **<u>volume</u>**, **<u>heat</u>**, **<u>volatiles</u>**, and **<u>low-viscosity magma</u>**

# (b) Seismic deepening



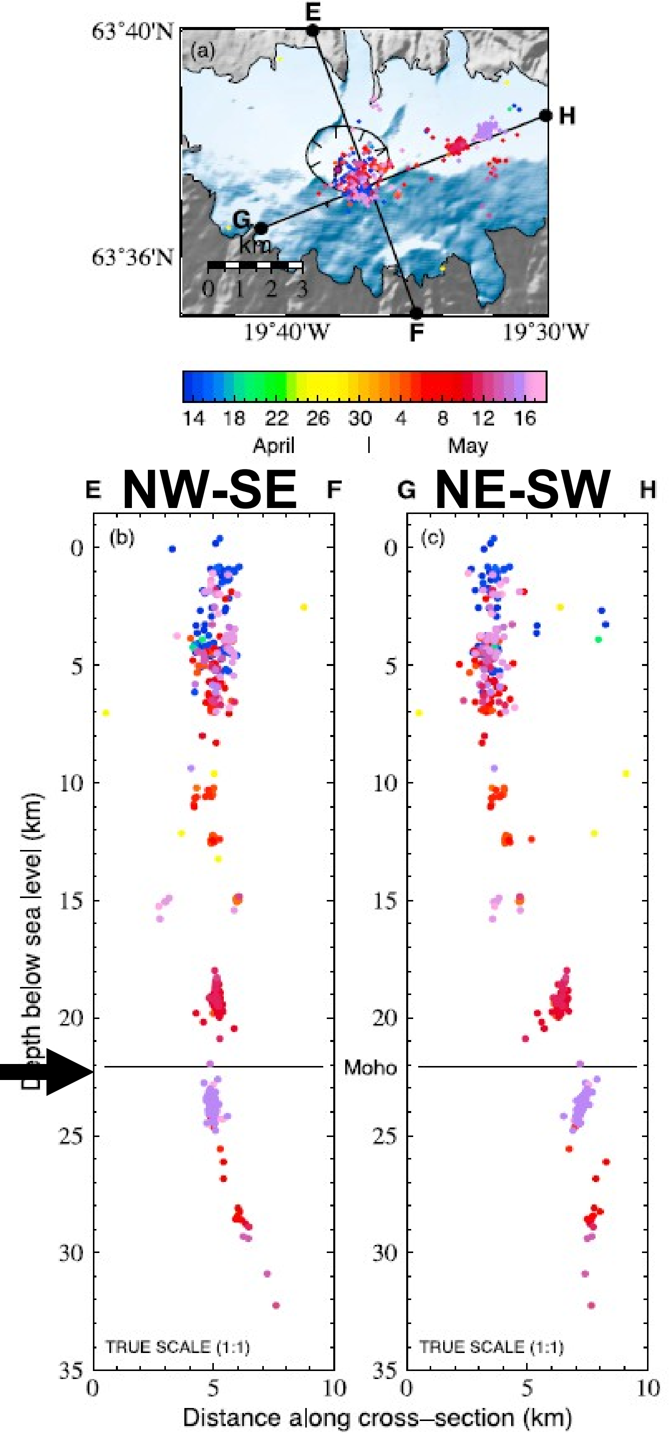



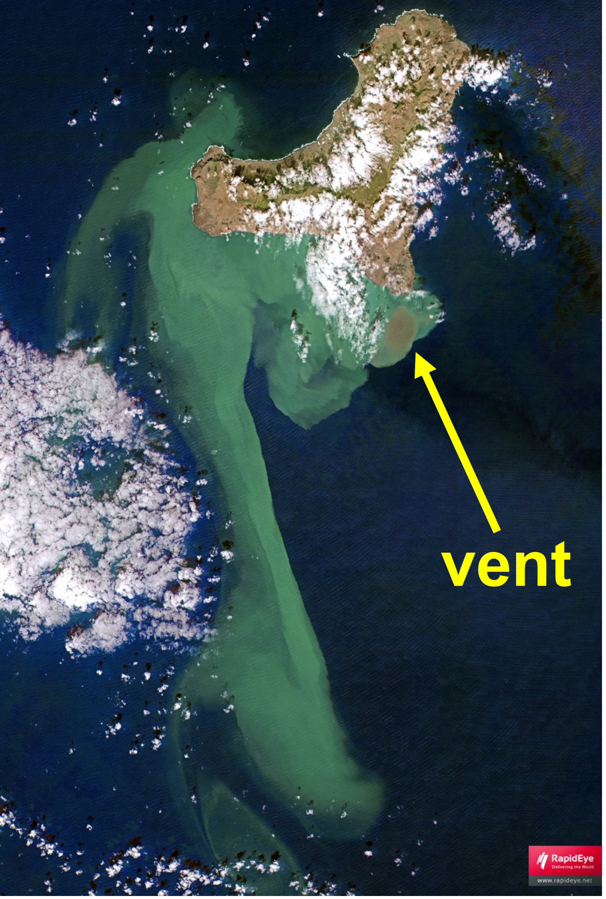

**Eyjafjallajökull**

**March-May 2010**

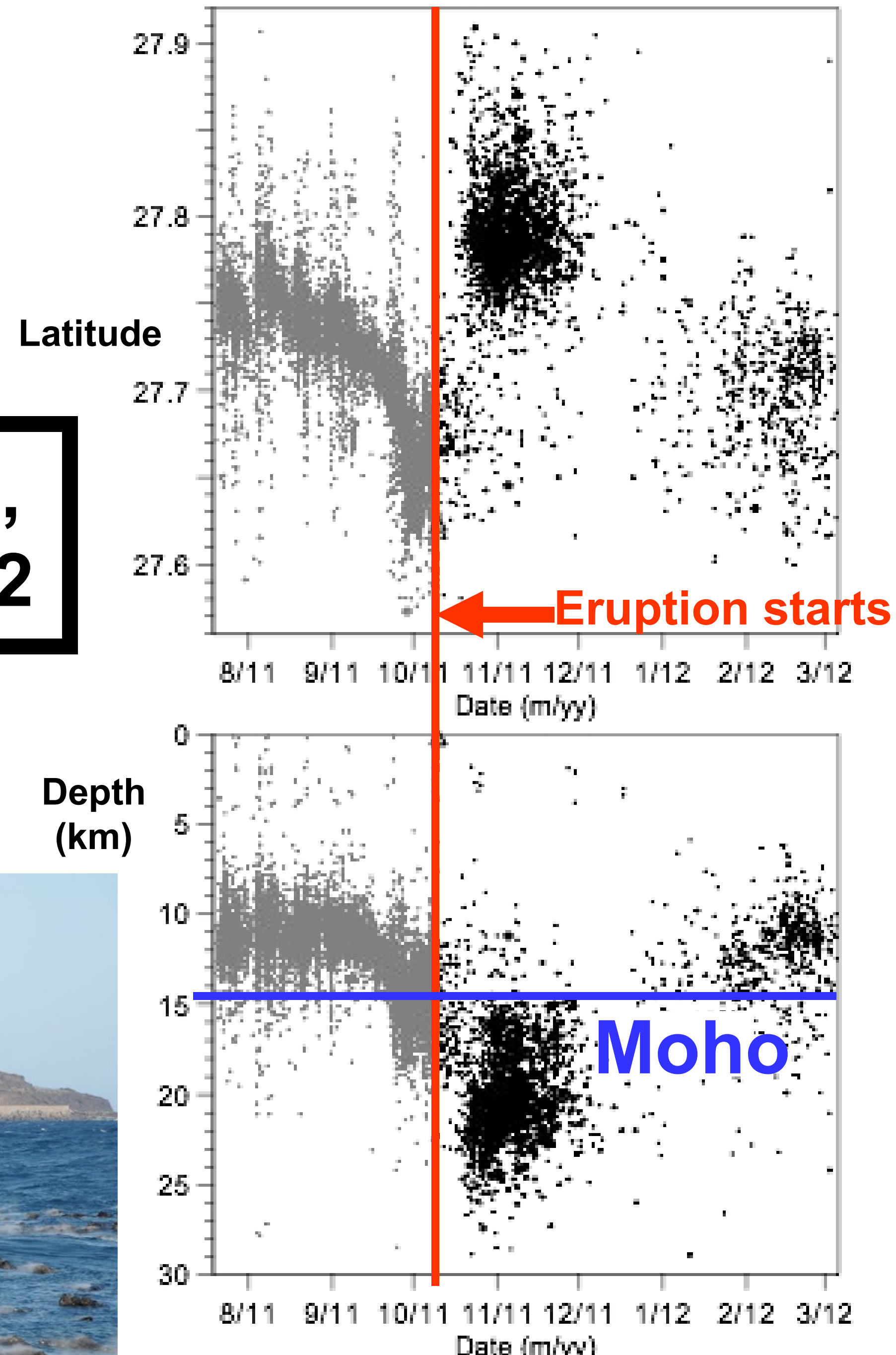
**Moho**

Tarasewicz J, Brandsdóttir B, White RS, Hensch M, Thorbjarnardóttir B, 2012. J Geophys Res 117:1-13






# El Hierro, 2011-2012




courtesy Instituto Geográfico Nacional

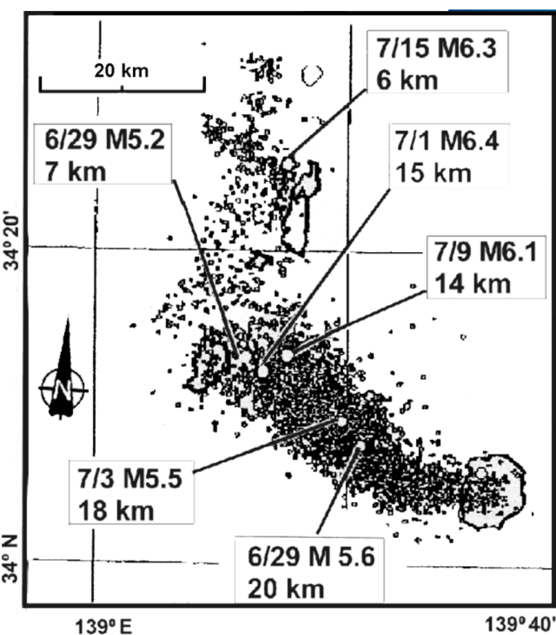
# Seismic deepening

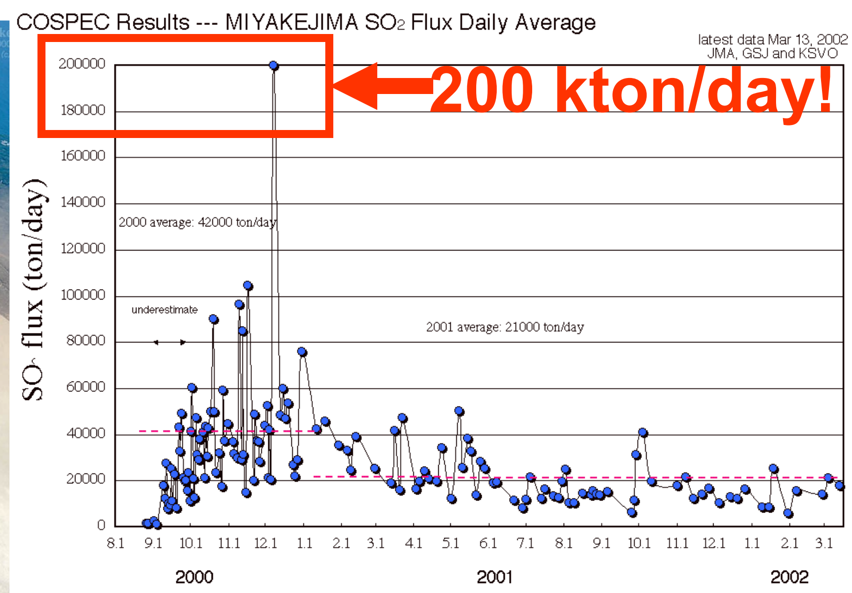
The Eyjafjallajökull and El Hierro examples suggest that magma flow occurs at deep levels as a result of magma movement at shallow levels

This deep flow can occur at mantle depths, indicating <u>**efficient magmatic connections**</u> between the surface and the upper mantle

# Miyakejima 2000 (Japan): a volcano that did it all

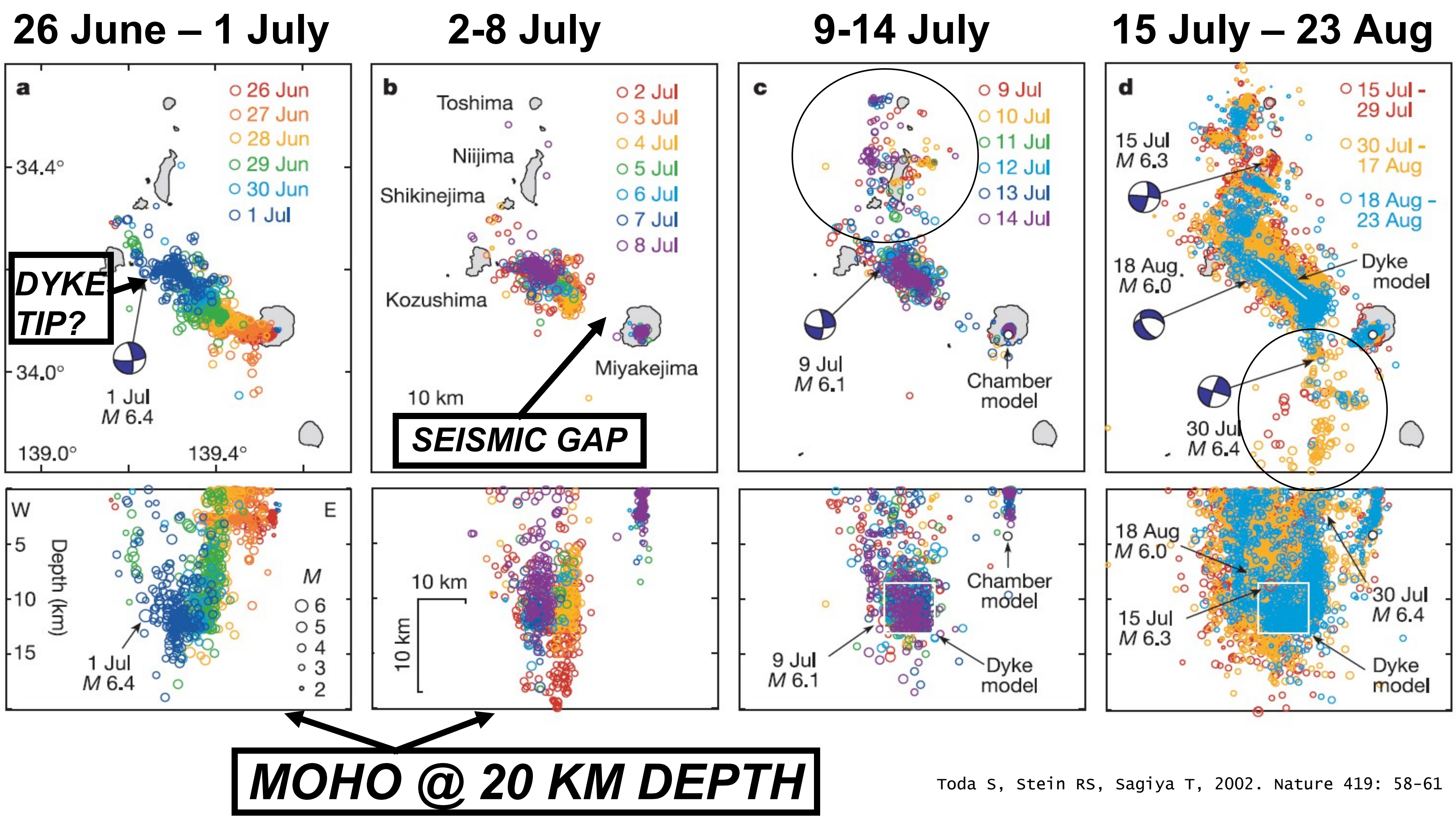
1. dike injection extending 50 km to NW →
2. magma drainage →
3. caldera formation starts 8 July to late Aug →
4. magma replenishment →
5. strongest quiescent $SO_2$ degassing ever measured



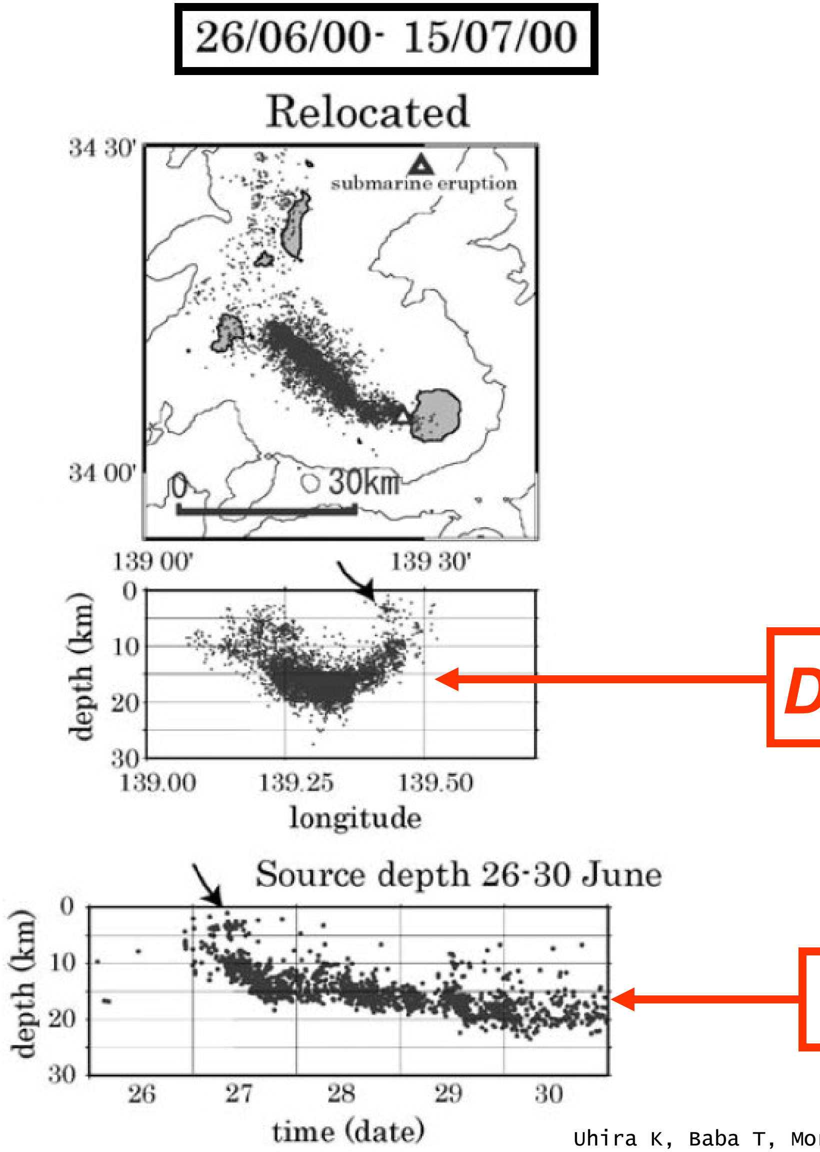

Images courtesy GVN, Japan Air Surveys, K Kazahaya

# Earthquake migration northwest of Miyakejima




Toda S, Stein RS, Sagiya T, 2002. Nature 419: 58-61

# Earthquake deepening

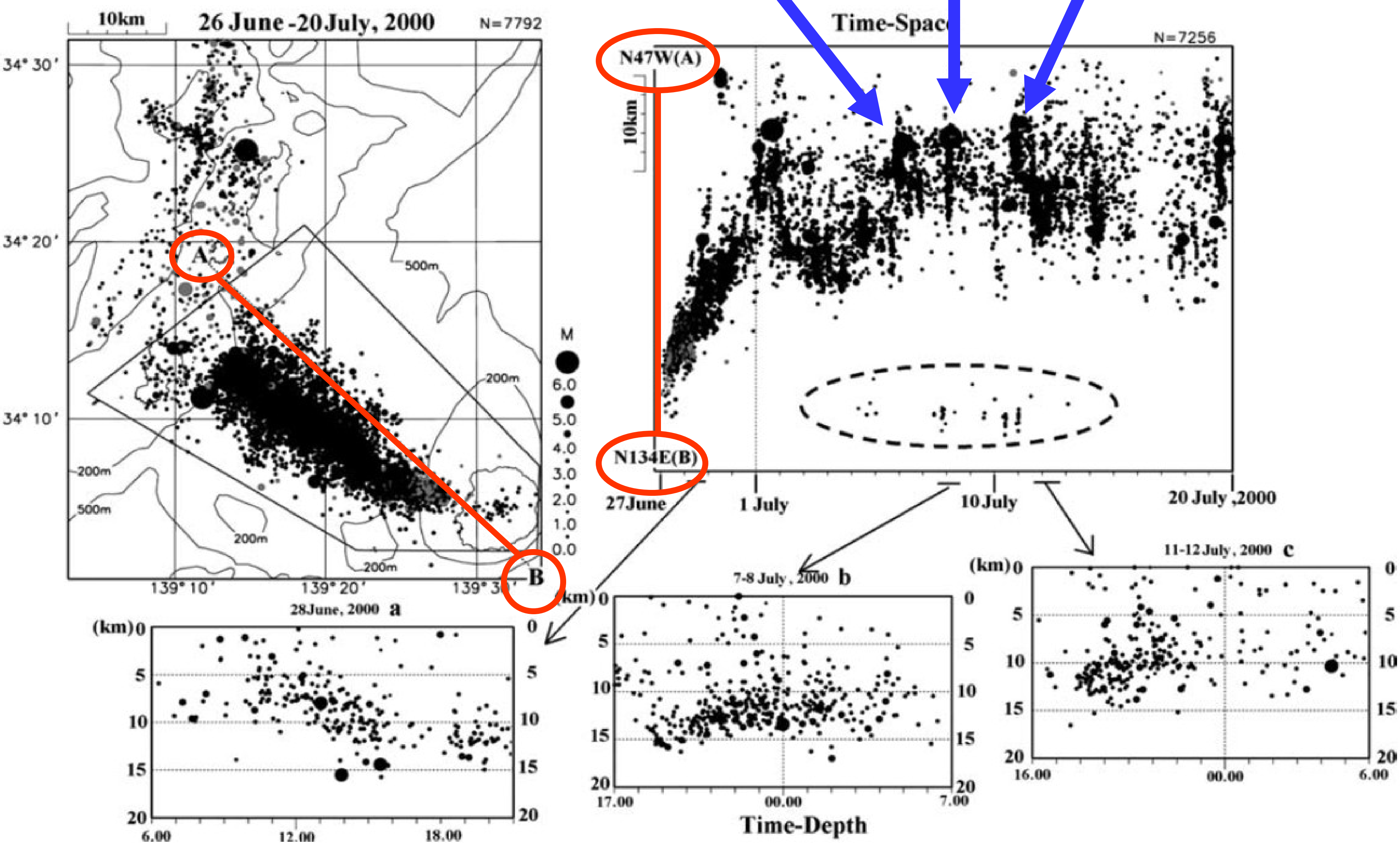



DEEPENING TO THE NW

DEEPENING WITH TIME

Uhira K, Baba T, Mori H, Katayama H, Hamada N, 2005. Bull Volcanol 67: 219-230

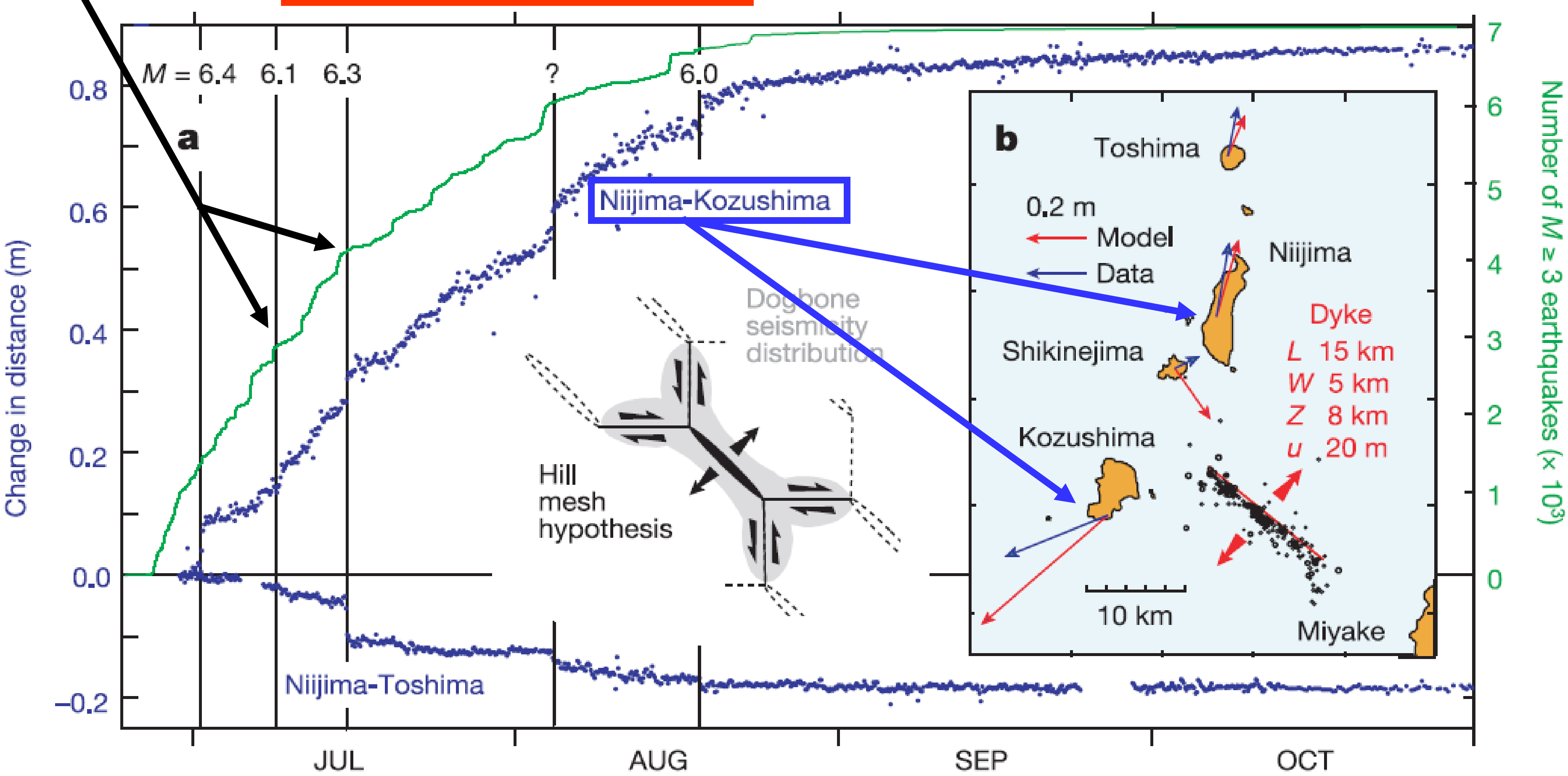
# Spatial earthquake swarms




Uhira K, Baba T, Mori H, Katayama H, Hamada N, 2005. Bull Volcanol 67: 219-230

NOTE ***INCREASING*** *SEISMICITY BEFORE M6 EVENTS AND* ***DECREASING*** *SEISMICITY AFTERWARD*

*CALDERA FORMATION*




Toda S, Stein RS, Sagiya T, 2002. Nature 419: 58-61

# Some concluding thoughts

- What constitutes a "critical" system, and how can we identify one ?

- What are the origin and nature of spatial and temporal permeability changes due to far-field stresses ?

- How can we better characterize magma connections and flow through the crust ?

***GRACIAS!   THANKS!***