Lessons Learned from Monitoring and Studies of Recent Icelandic Eruptions: Precursors, Eruption Dynamics and Timescales

FUTUREVOLC

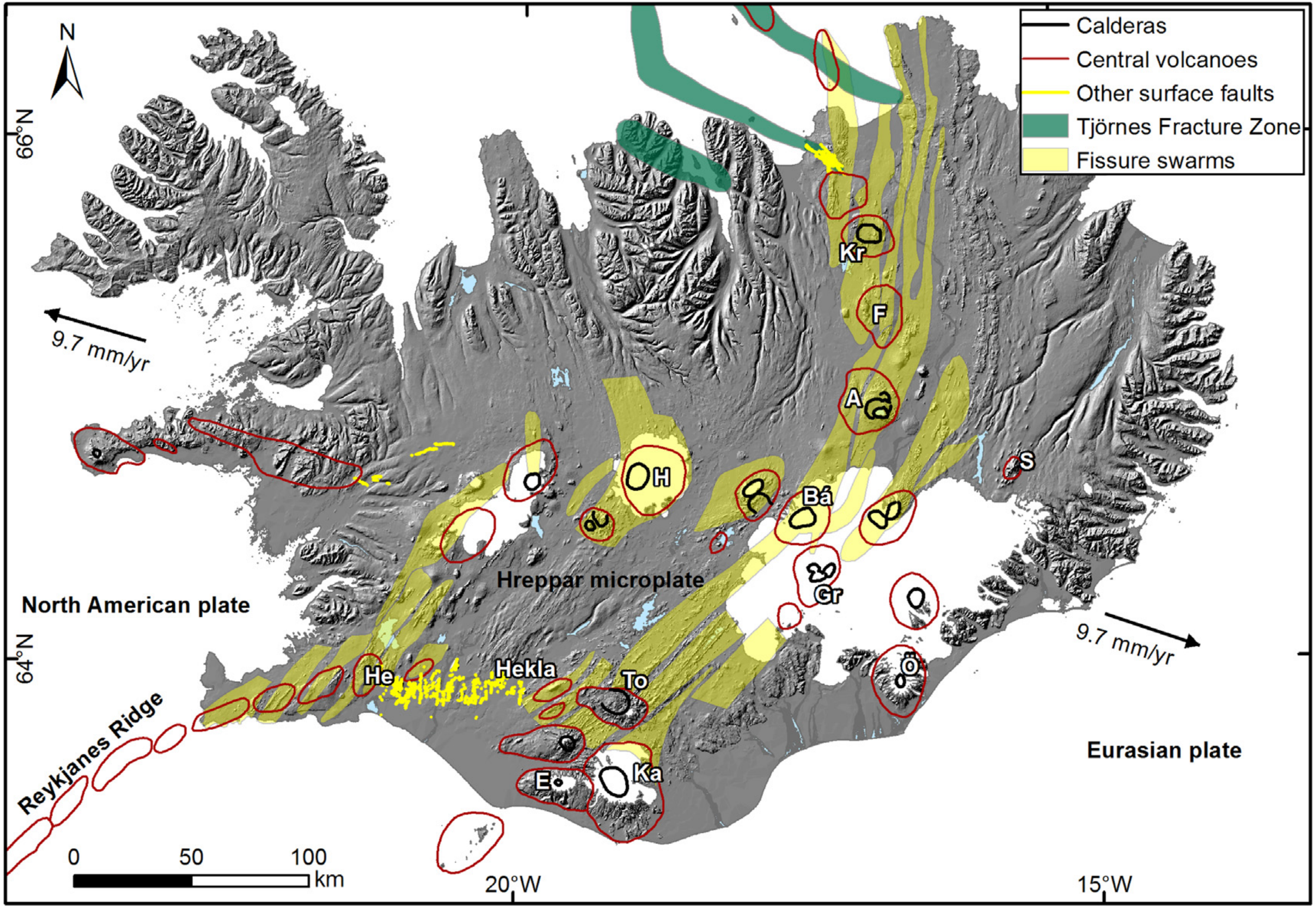
EUROVOLC

Holuhraun lava 2014-2015
Bárðarbunga volcanic system
Iceland

Freysteinn Sigmundsson[1], Magnús Tumi Guðmundsson[1], Kristín Vogfjörð[2], Benedikt G. Ófeigsson[2], Páll Einarsson[1], Michelle Parks[2], Sæmundur Ari Halldórsson[1], Kristín Jónsdóttir[2], Halldór Geirsson[1], Andy Hooper[3], Sigrún Hreinsdóttir[4]

(1) Nordvulk, Inst. of Earth Sciences, Univ. of Iceland
(2) Icelandic Meteorological Office, Iceland
(3) COMET, University of Leeds, UK
(4) GNS Science, New Zealand

Photo: Magnús T. Gudmundsson, University

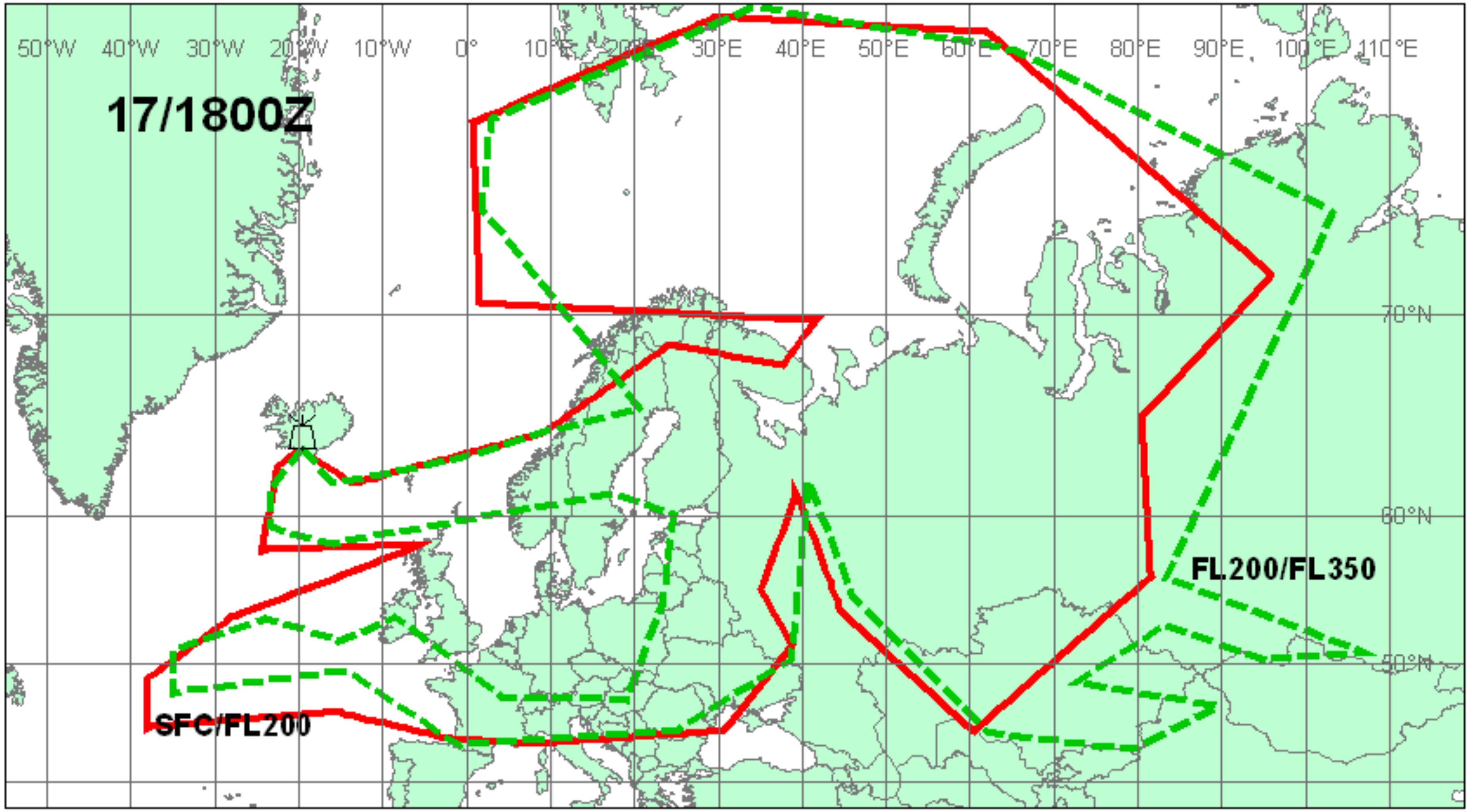


Iceland
Volcanic systems

Kr = Krafla,
F = Fremri Námar
A = Askja
S = Snæfell
Ö = Öræfajökull
Bá = Bárðarbunga
Gr = Grímsvötn
E = Eyjafjallajökull
Ka = Katla
He = Hengill
To = Torfajökull
H = Hofsjökull
Hekla

Sigmundsson et al. (2019), Geodynamics of Iceland and the signatures of plate spreading, J. Volcanol. Geotherm. Res.

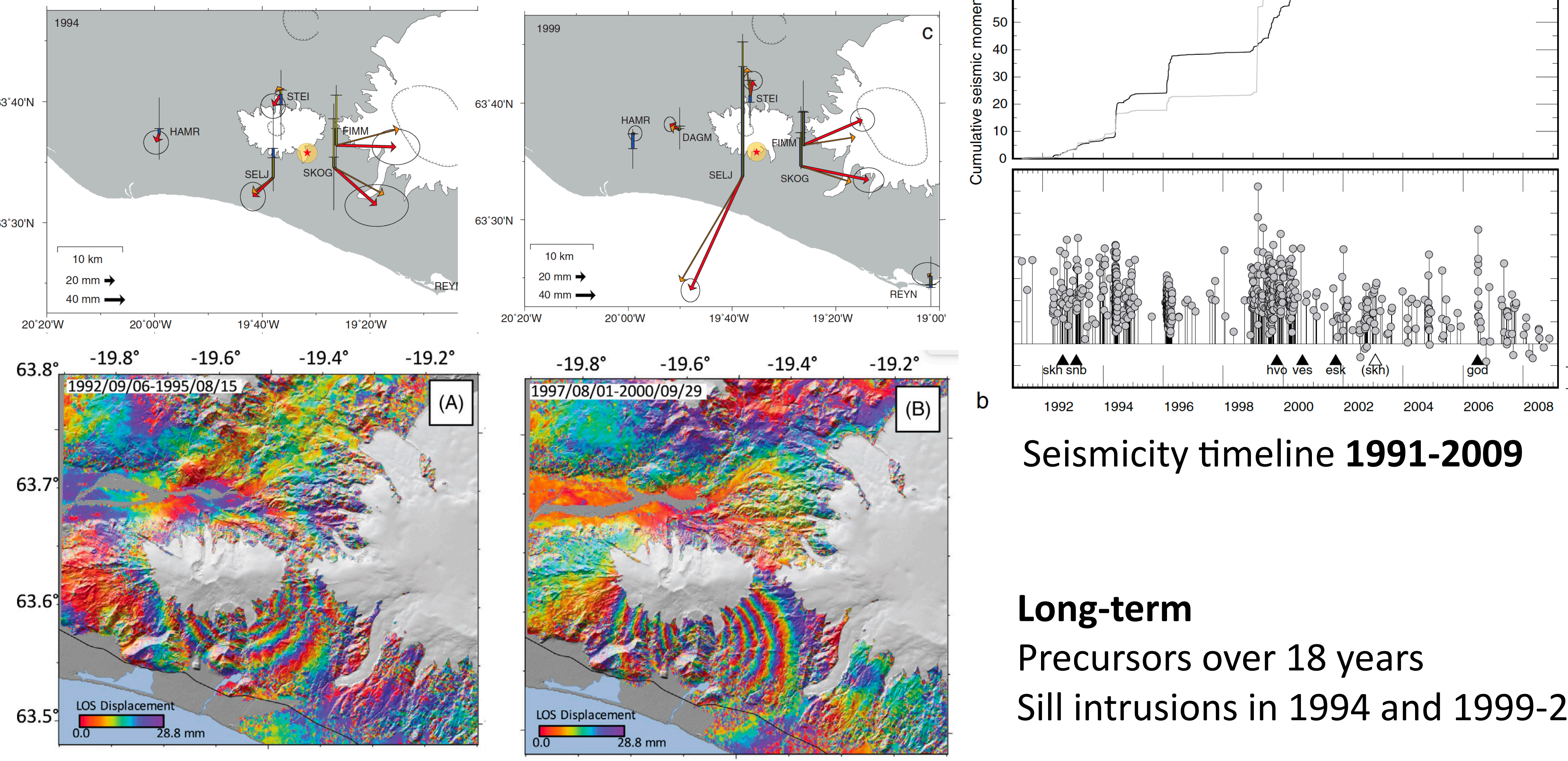

Reykjavík
Eyjafjallajökull
Summit eruption
2010
Airplane SAR



Advice of the Volcanic Ash Advisory Centre in London (London VAAC) formed the basis for closure of large part of European air space 15-21 April, leading to cancellation of over 100000 European flights

Eyjafjallajökull 2010 Summit eruption

1994   1999-2000



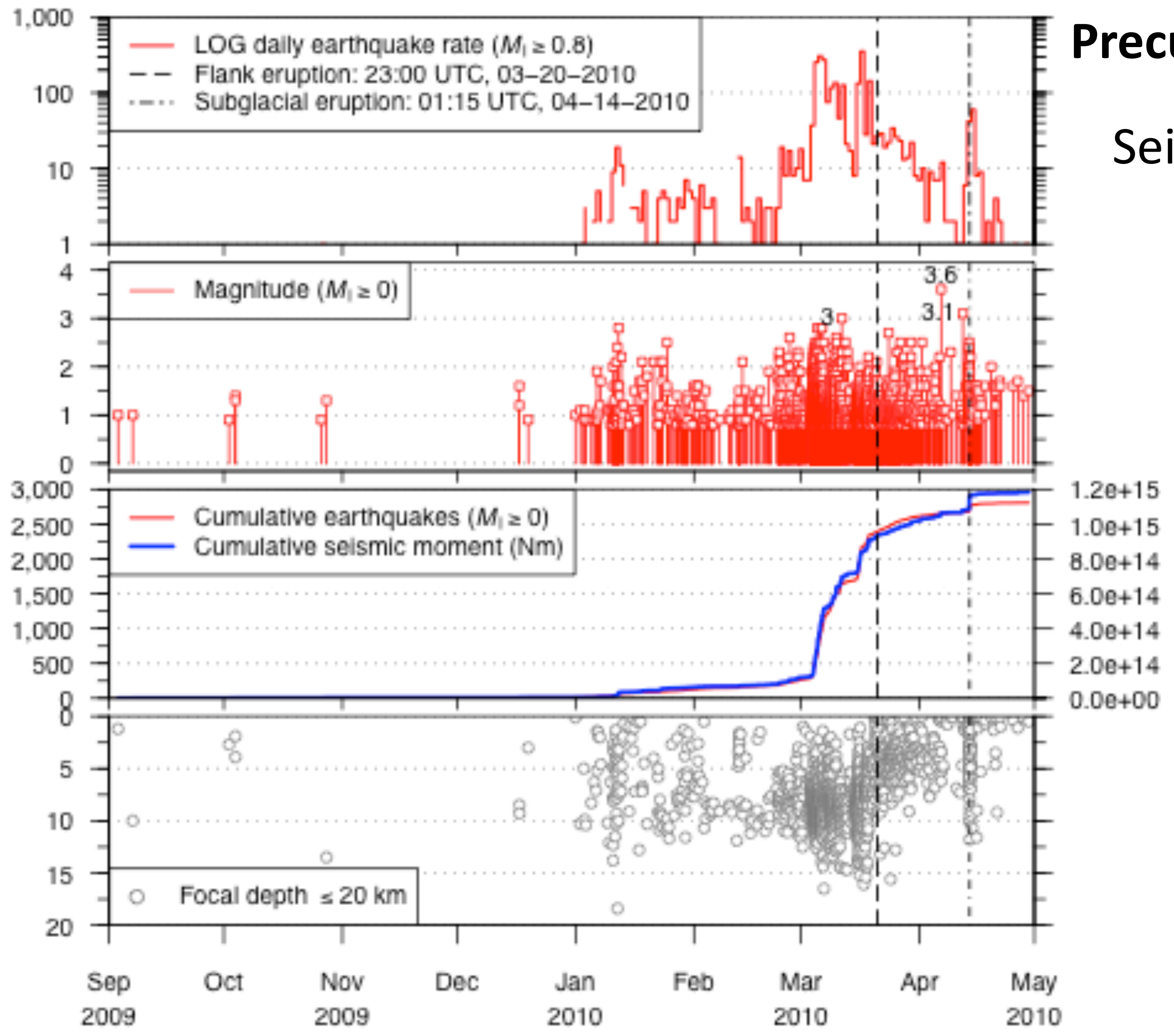
Seismicity timeline **1991-2009**

Long-term

Precursors over 18 years

Sill intrusions in 1994 and 1999-2000

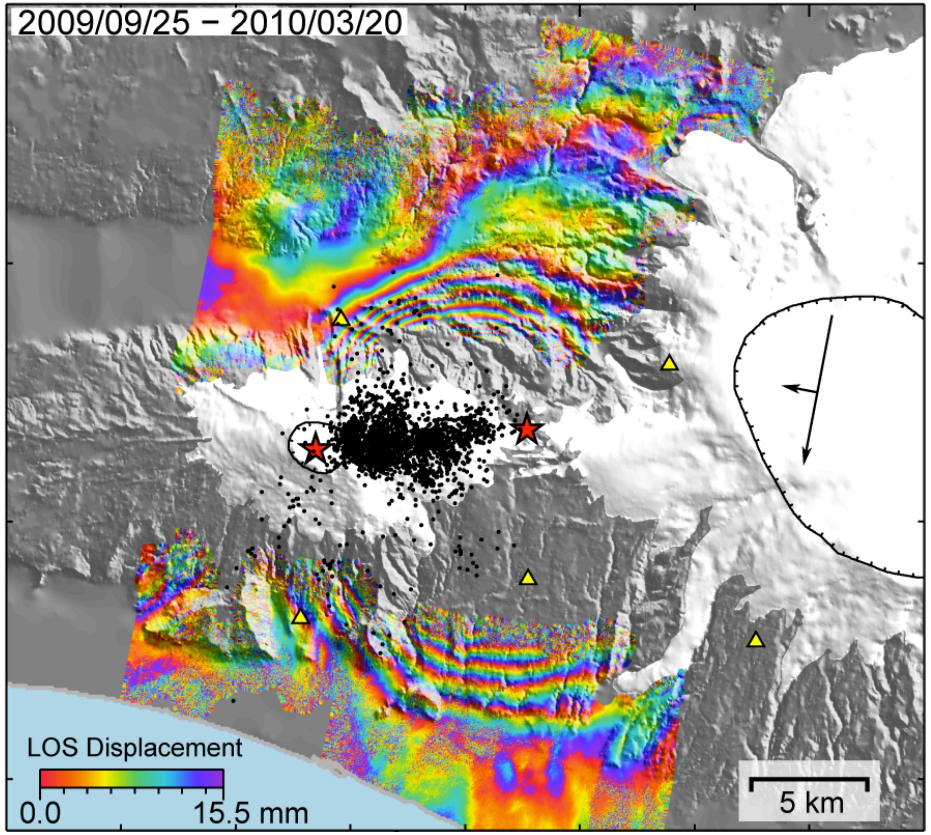
Hjaltadóttir et al., 2015; and Sigmundsson et al., 2018



Precursors over few months

Seismicity

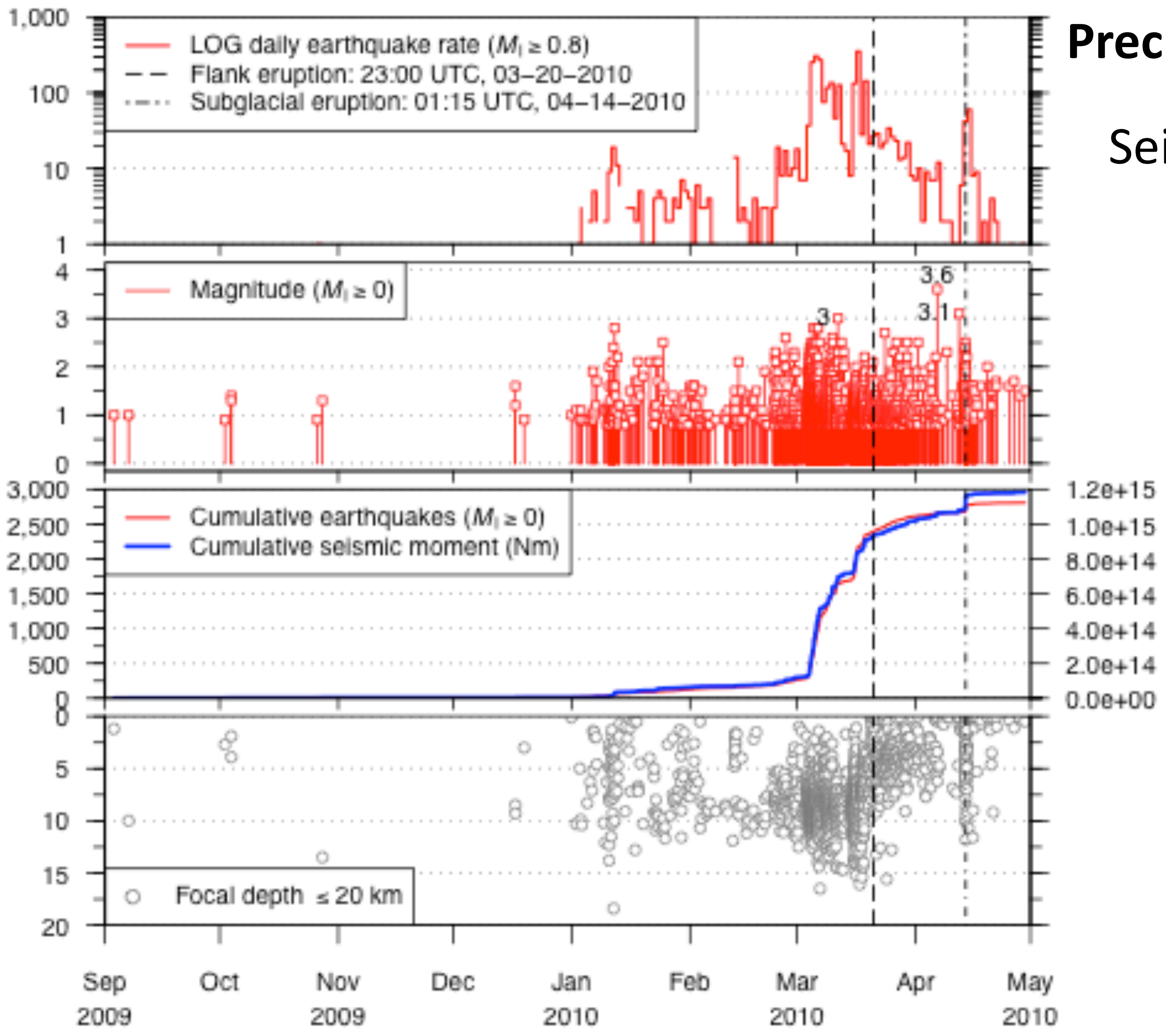
Deformation:
InSAR



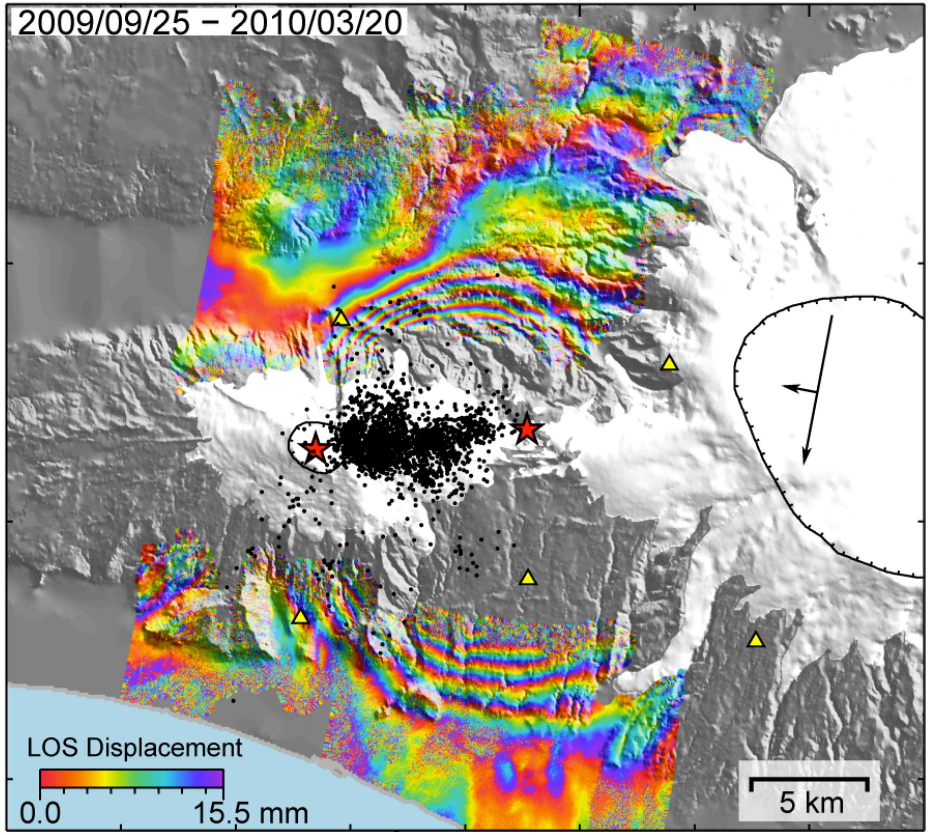
Sigmundsson et al. (Nature, 2010)
Intrusion triggering of the 2010 Eyjafjallajökull explosive eruption

Precursors over few months

Seismicity



Deformation:
InSAR



Sigmundsson et al. (Nature, 2010)
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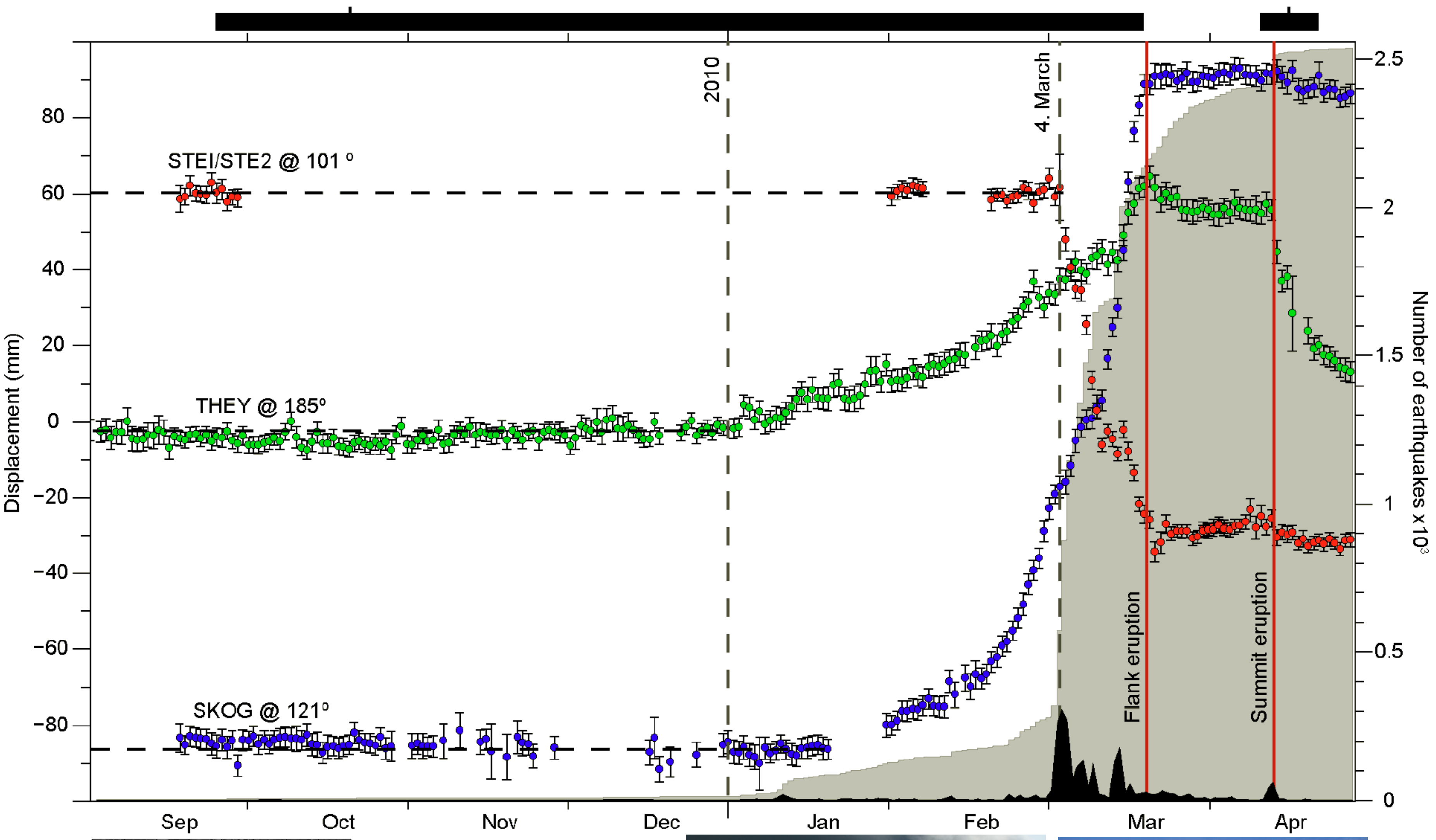
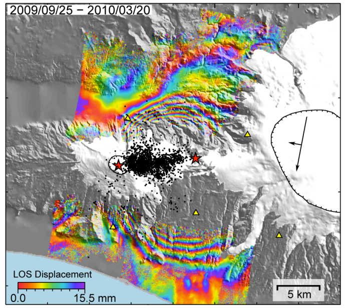




GPS-displacements
Seismicity

Sigmundsson et al., 2010

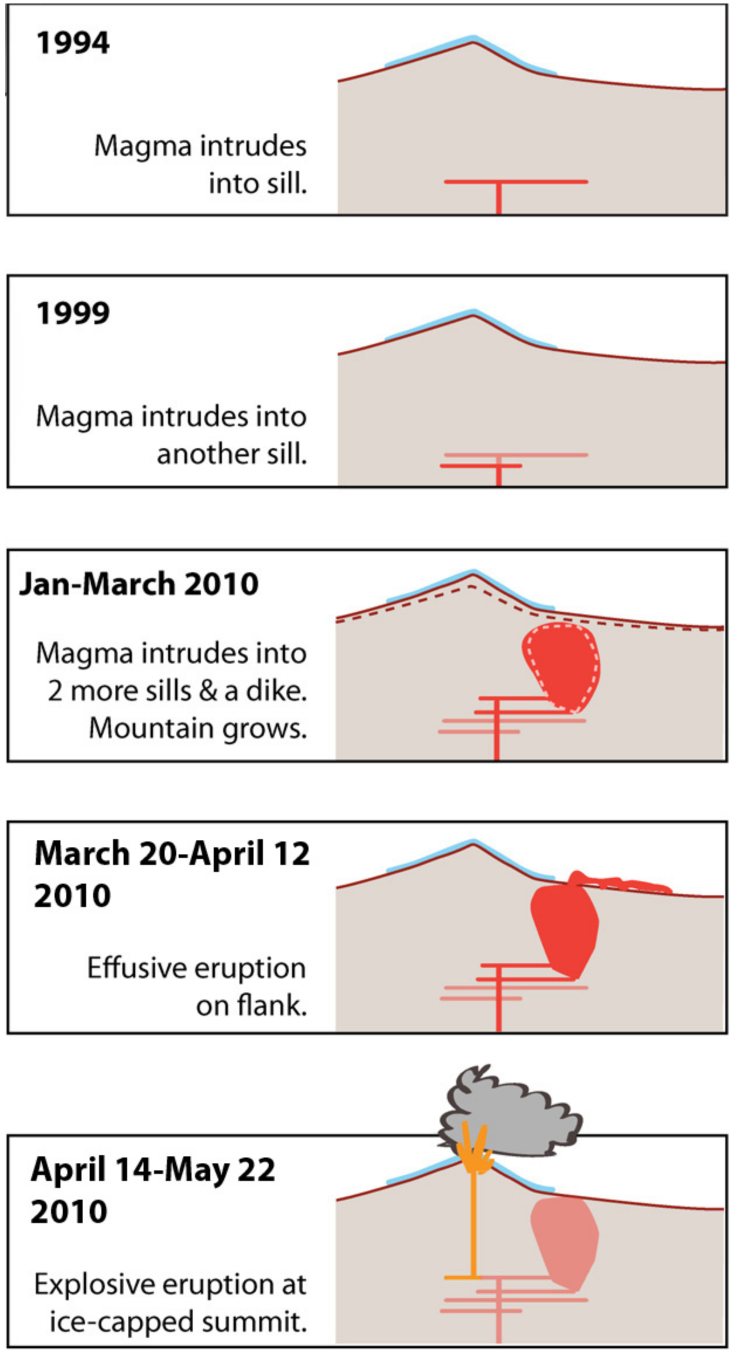
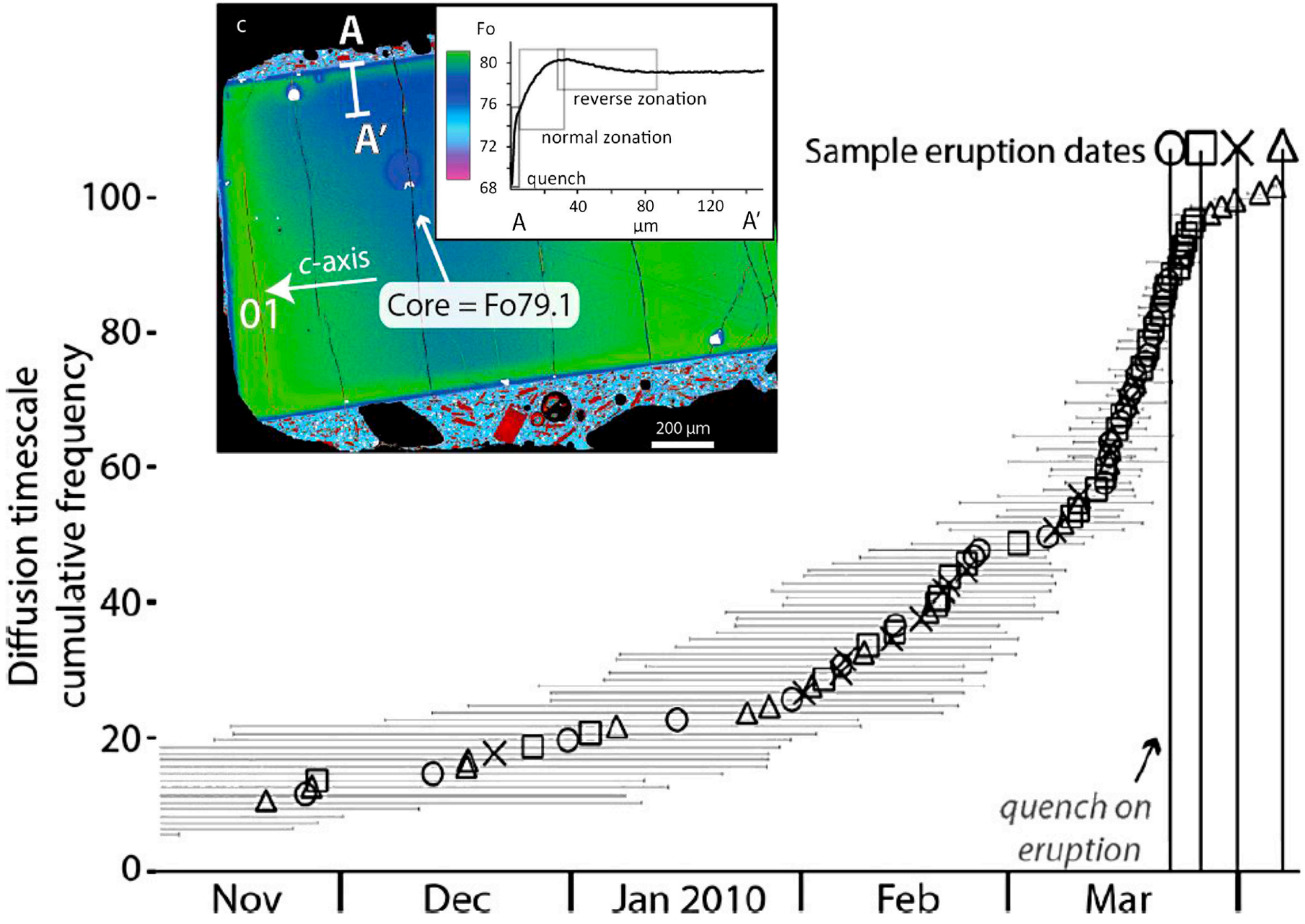


Figure: Zina Deretsky, NSF

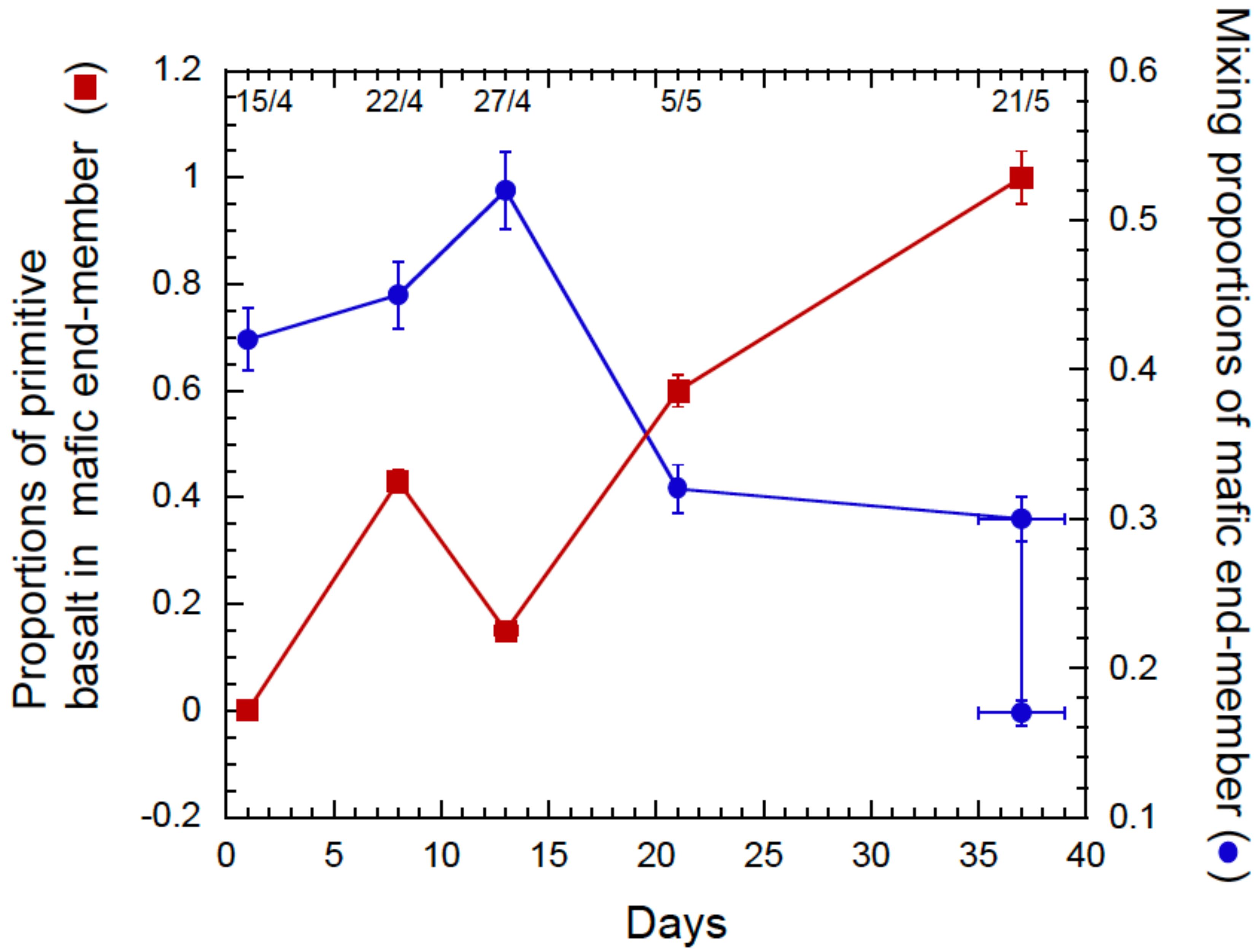
Olivine macrocrysts



Pankhurst, Morgan, Thordarson, Loughlin: **Magmatic crystal records in time, space, and process, causatively linked with volcanic unrest**, Earth Planet Sci. Lett., 2019

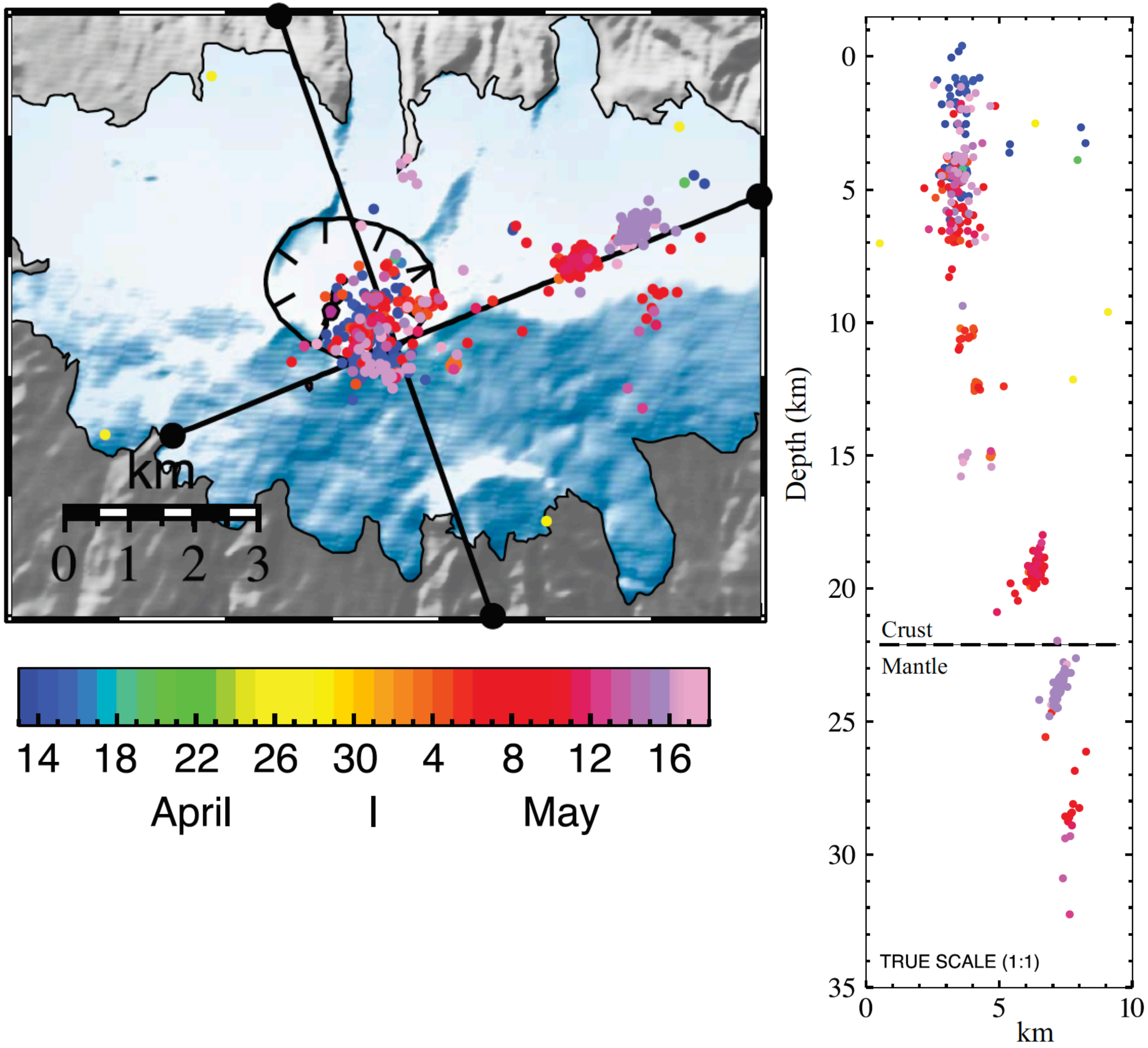
Diffusion timescales (n = 103) (cumulative frequency) retrieved from reverse zoned olivine in flank eruption products. A continuous array from several months before eruption is observed, which continues after the onset of eruption.

Crystal rain: Disequilibrium processes in sills form systematic population



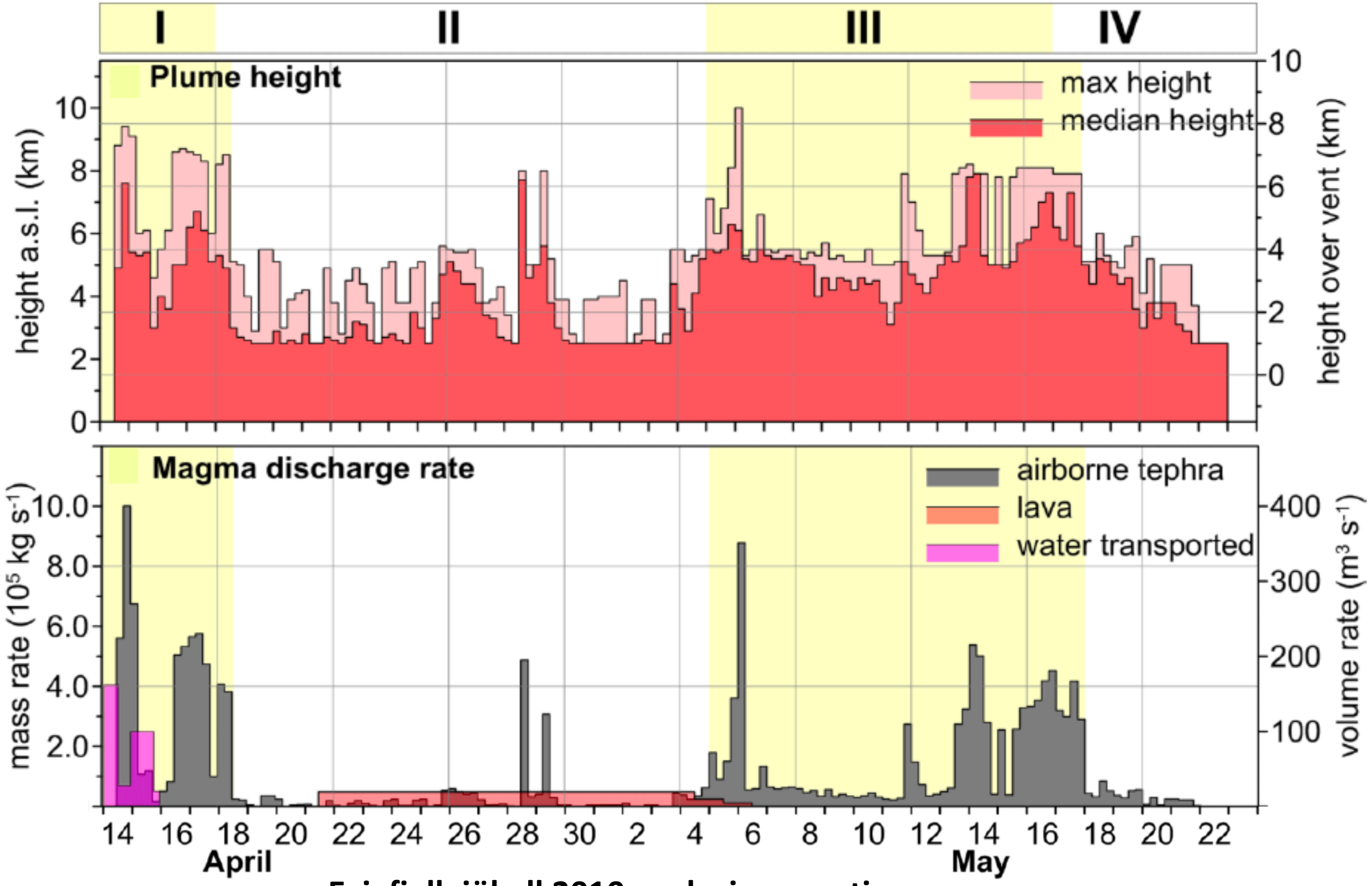
Olgeir Sigmarsson et al., **Remobilization of silicic intrusion by mafic magmas during the 2010 Eyjafjallajökull eruption**, Solid Earth, 2, 271–281, 2011

Mixing (and mingling) proportions, as a function of time, of primitive basalt in the mafic end-member on that of basalt melt in the benmoritic tephra of Eyjafjallajökull



Jon Tarasewicz et al.
(University of Cambridge)
Using microearthquakes to track repeated magma intrusions beneath the Eyjafjallajökull stratovolcano, Iceland
J. Geophys. Res.

Seismicity (color-coded by date) extends into the mantle, revealing an interconnected magmatic system.
Seismicity occurs in pulses



Eyjafjallajökull 2010 explosive eruption

Gudmundsson et al. (2010): Ash generation and distribution from the April-May 2010 eruption of Eyjafjallajökull, Iceland, Scientific Reports.

Grímsvötn 2011

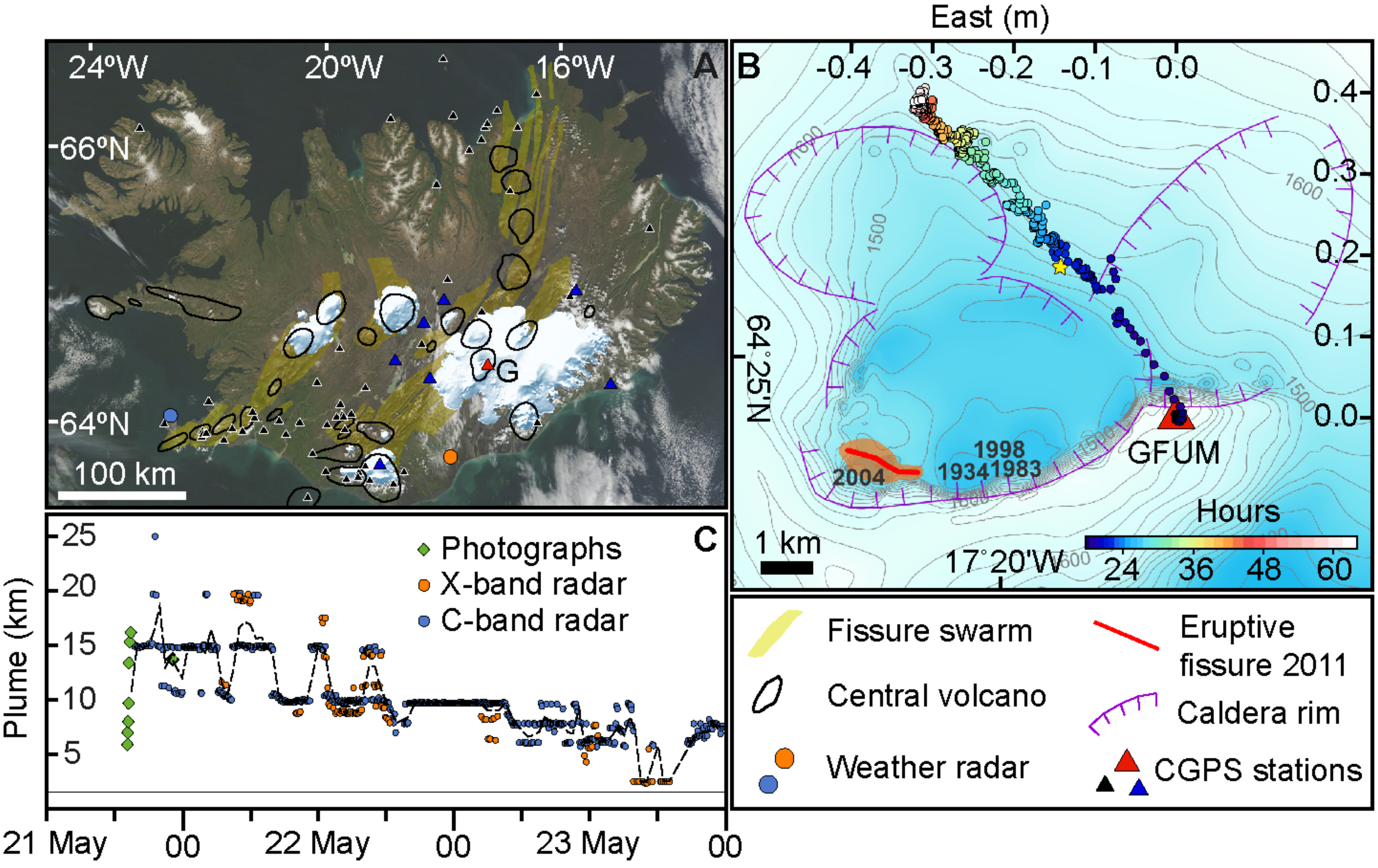
21-28 May (7 days)

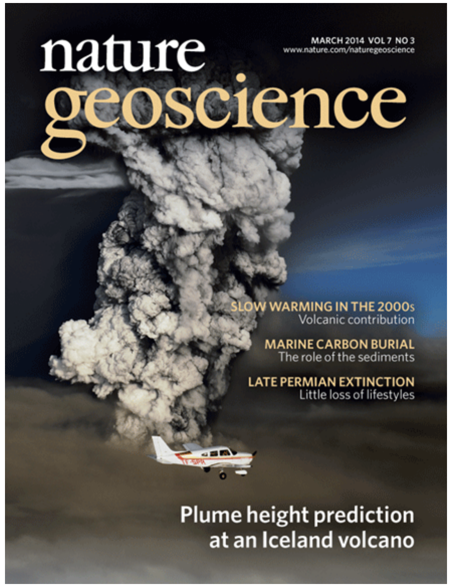
VEI 4

Phreatomagmatic
and magmatic.

DRE volume: ≈ 270±70 10^6 m^3

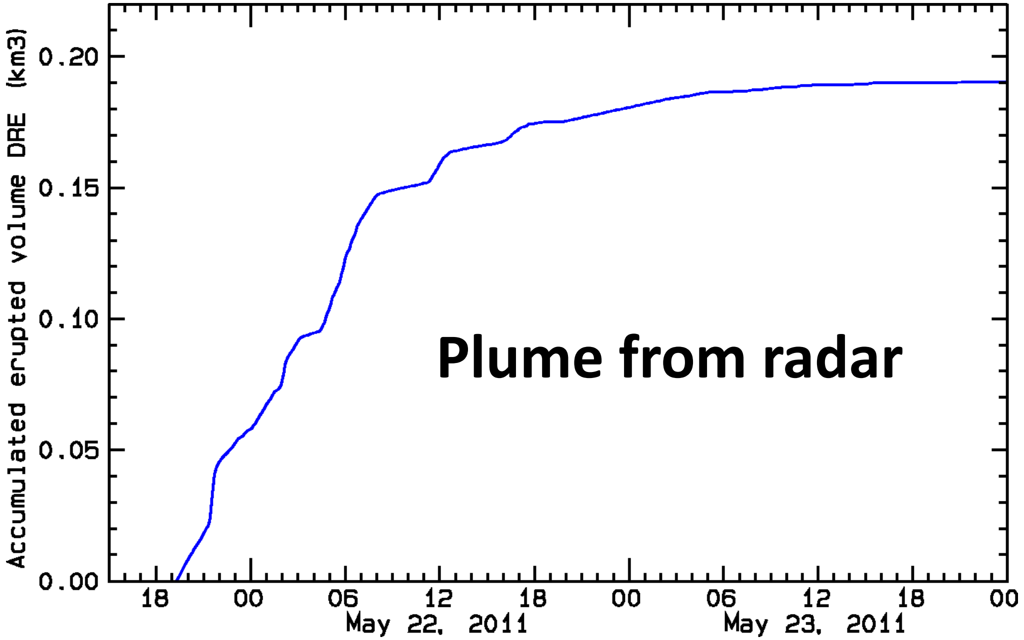
Basaltic





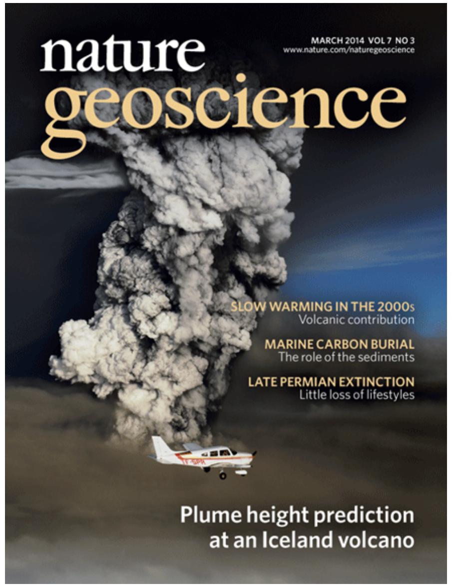
Co-eruptive deformation and plume height

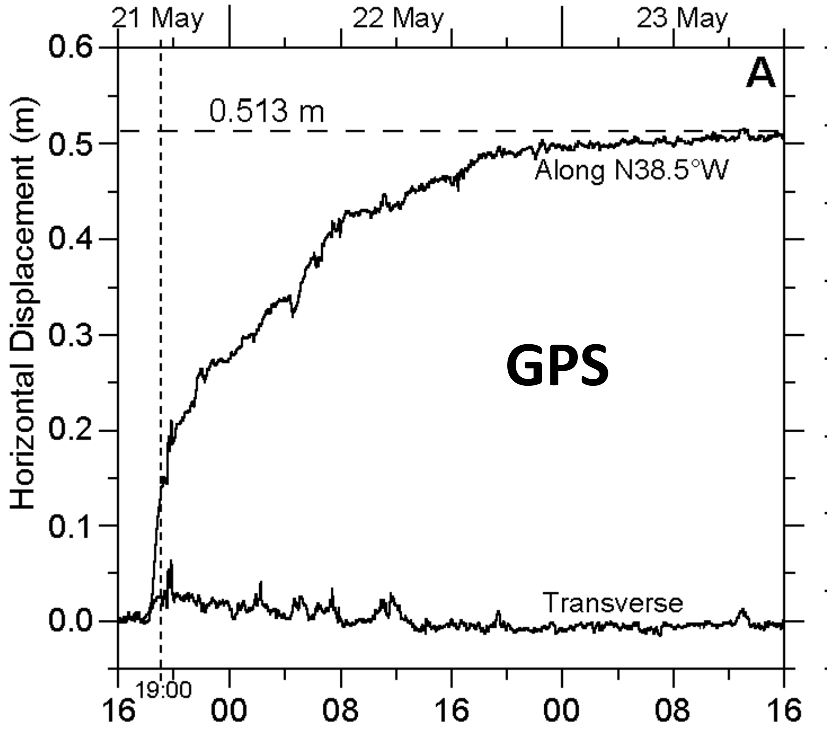
Hreinsdóttir, Sigmundsson et al., Nature Geoscience 2014

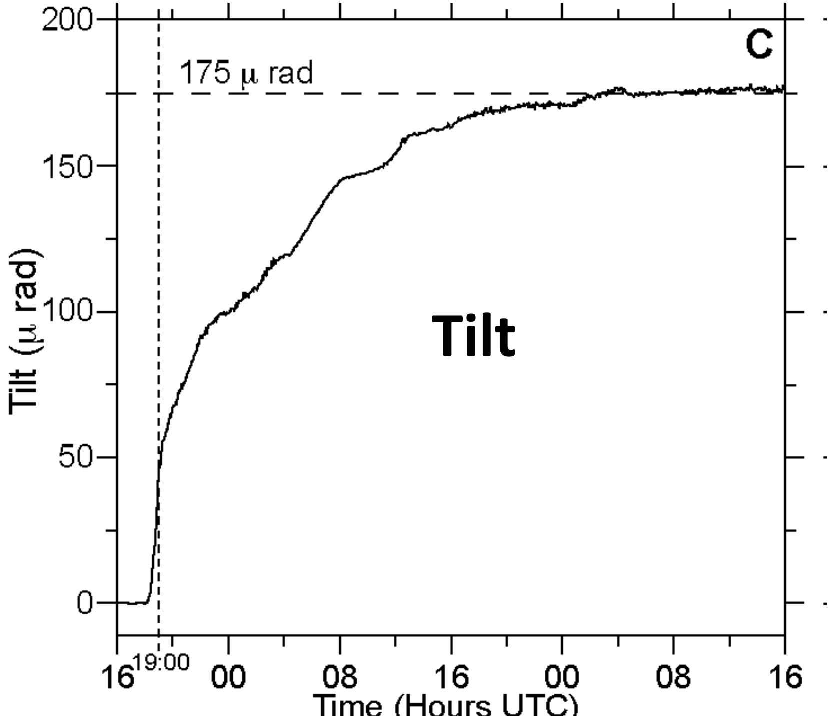


Magma flow rate
Use empirical relation between plume height, H, (km), and magma flow rate (Mastin et al., 2009)

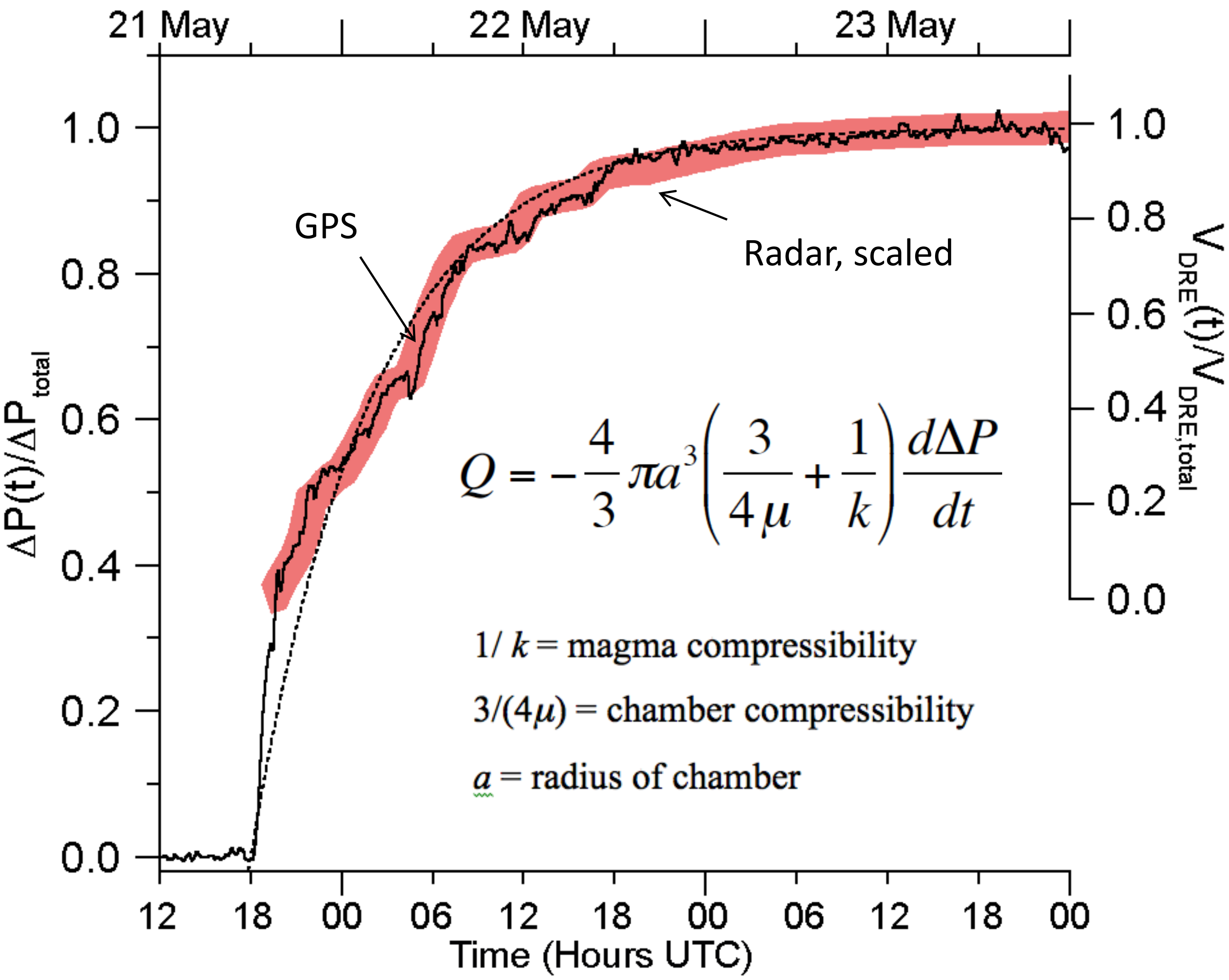
$$H = 2.0\dot{V}^{0.241}$$

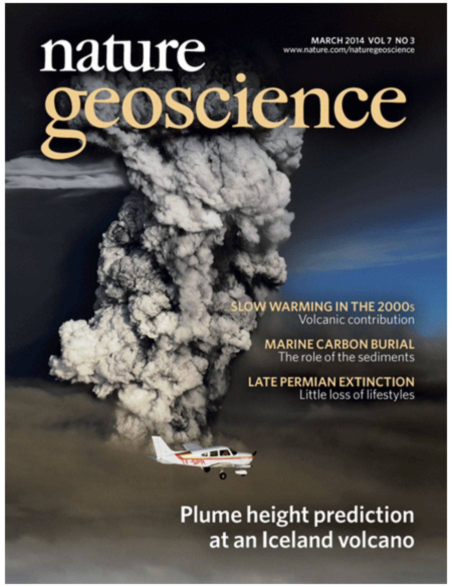




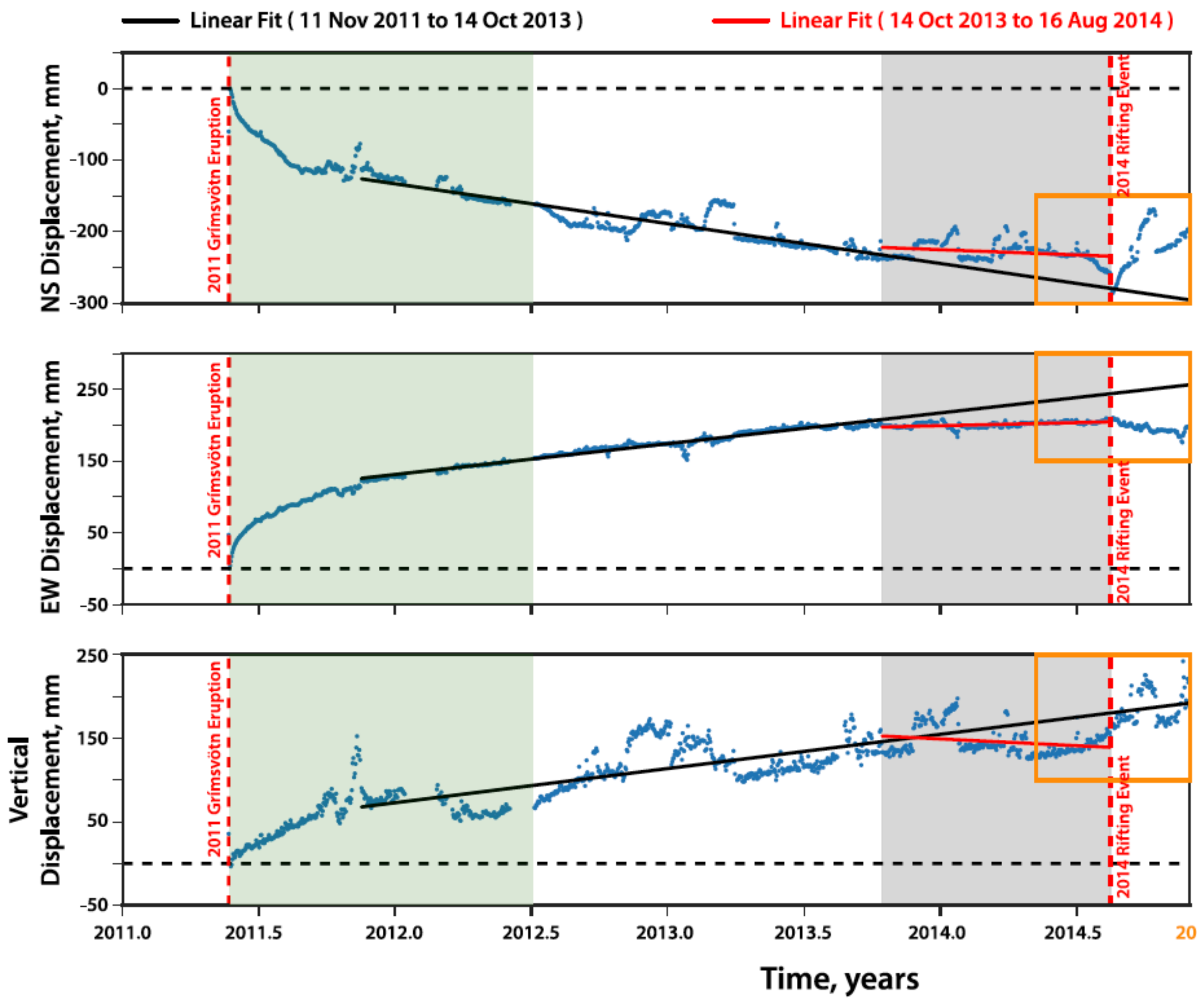


Exponentially declining pressure in a magma body drives magma flow, modulated by conduit processes



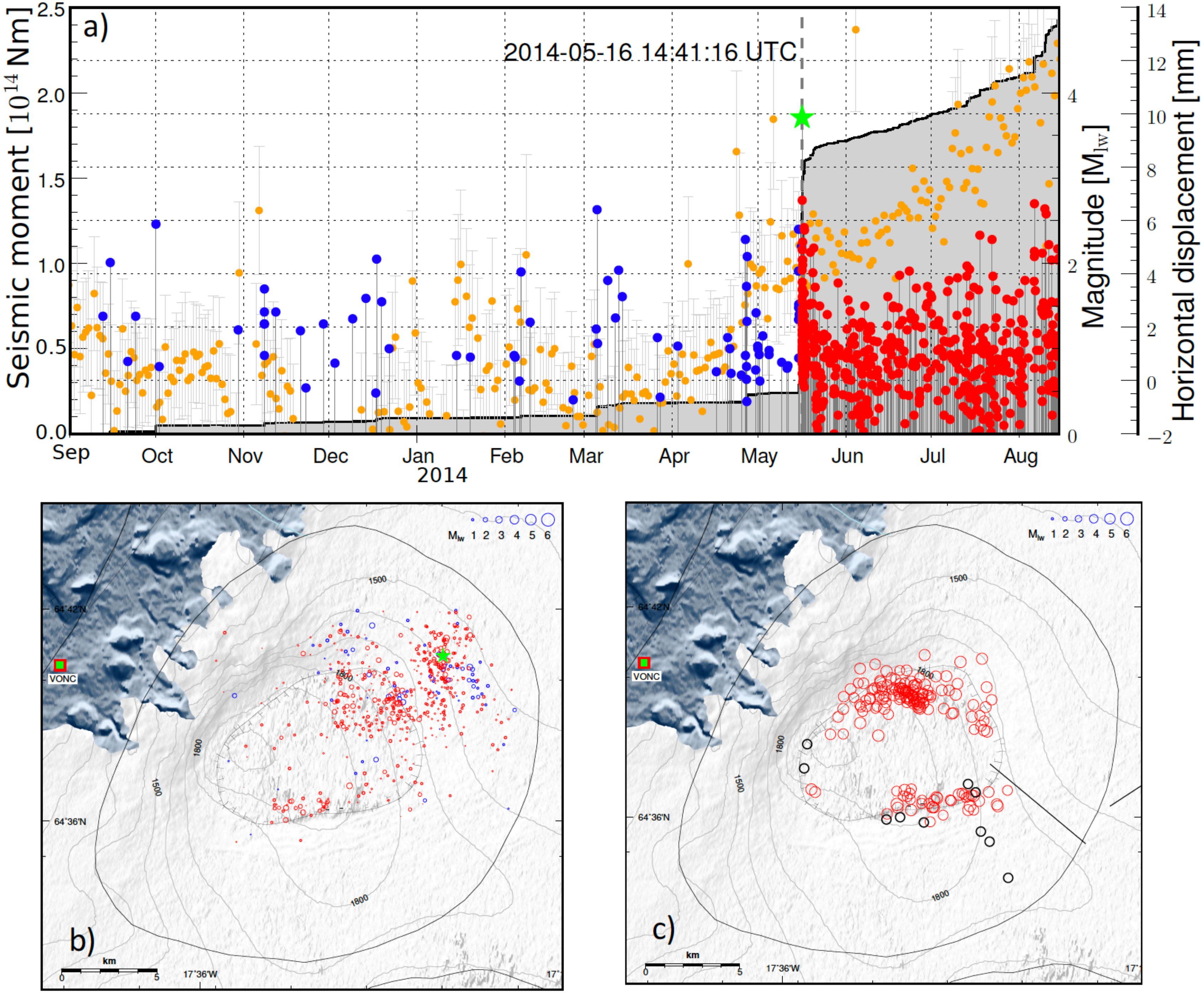


Hreinsdóttir, Sigmundsson et al., Nature Geoscience 2014



Grímsvötn
Long-term GPS time series reveals magma recharging

Bato, Pinel et al.,
Possible deep connection between volcanic systems evidenced by sequential assimilation of geodetic data
Scientific Reports, 2018



Bárðarbunga 2014-2015 Pre-eruptive seismicity and deformation

a, Earthquakes and cumulative seismic moment (shaded in grey; left axis). VONC GPS horizontal displacement in direction 283.5 (yellow dots), detrended

b, Location of the earthquakes shown in **a**, with earthquakes prior to the M3.7 event on 16 May 2014 in blue and red afterwards.

c, Location of M>4.6 earthquakes during the caldera collapse.

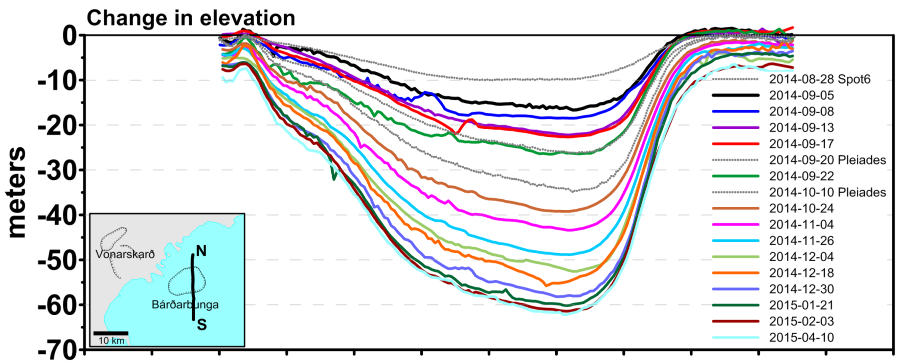
Straight lines: dike segments
Black open circles: ice cauldrons

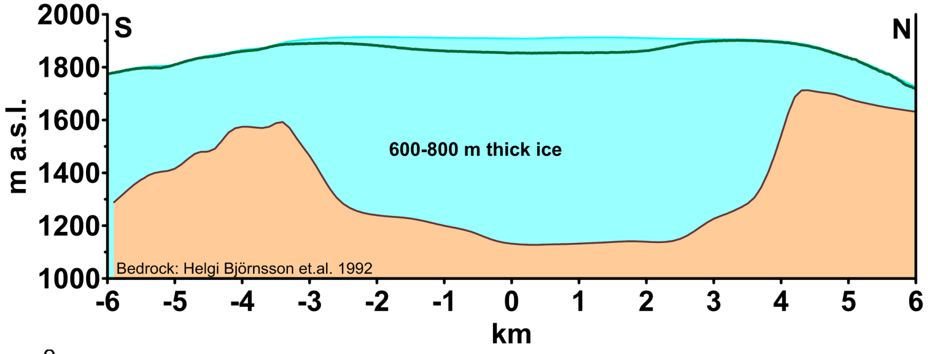
Bárðarbunga 2014-2015

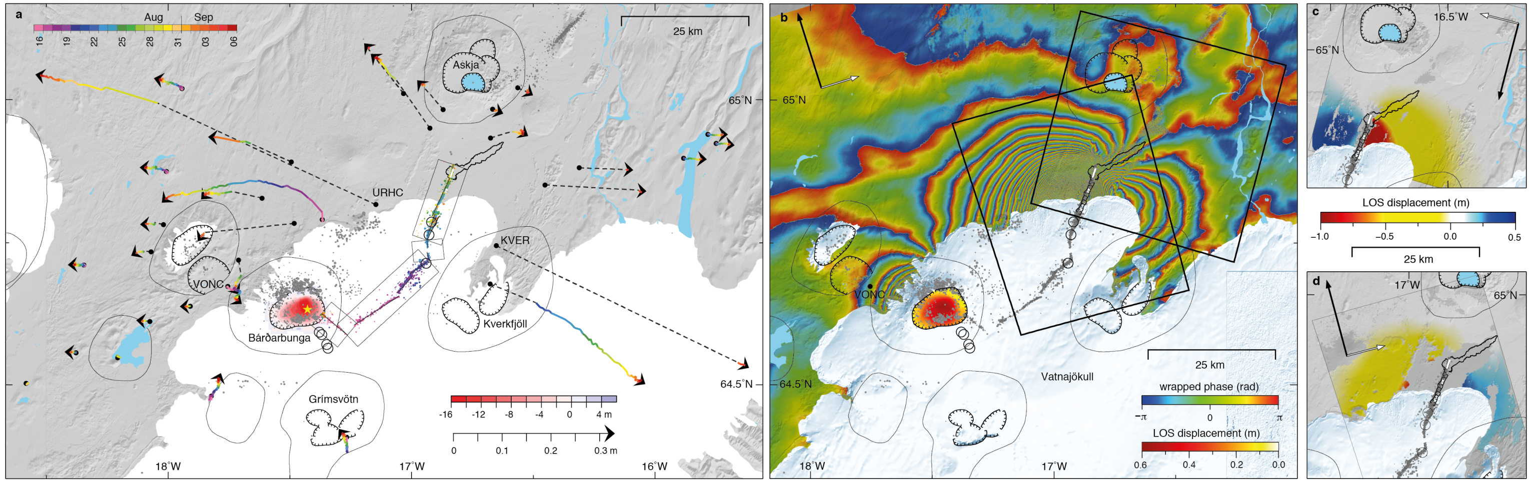
Online MOOC:

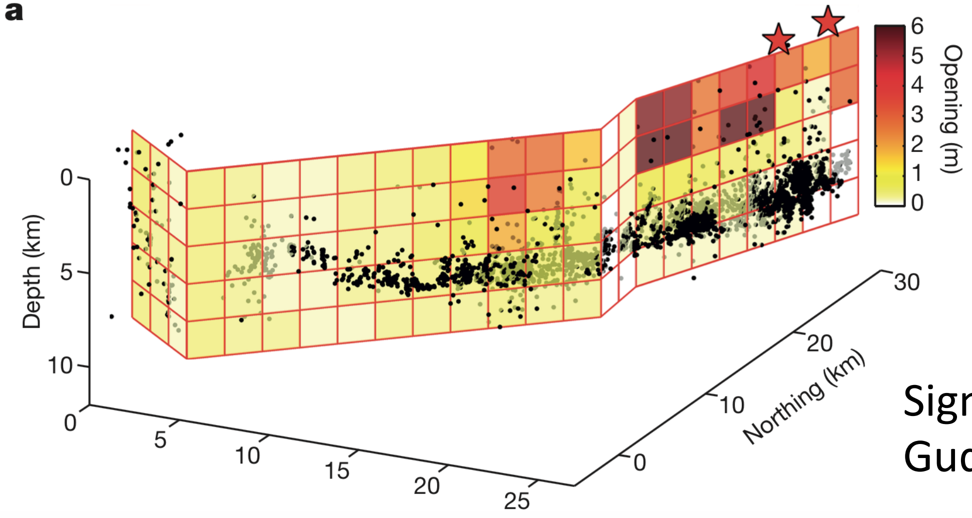
edX.org

search for: volcano









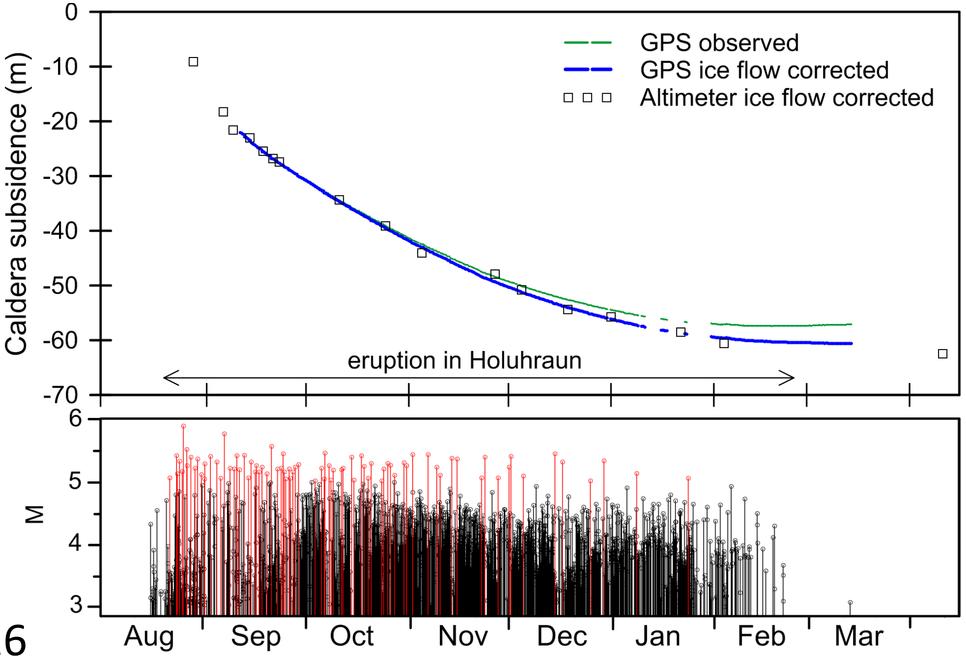
Lateral dike injection

Gradual caldera collapse

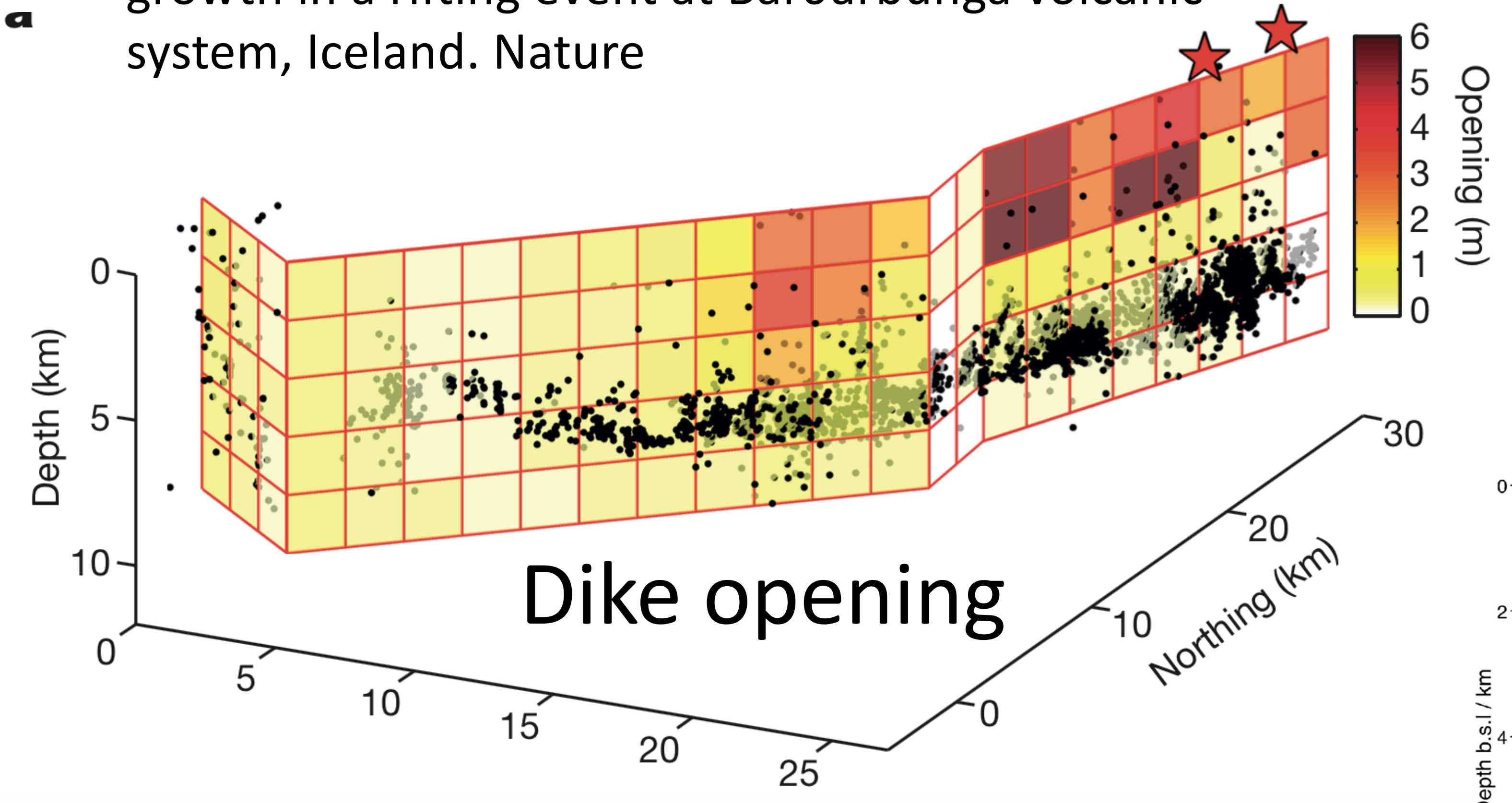
Major effusive eruption

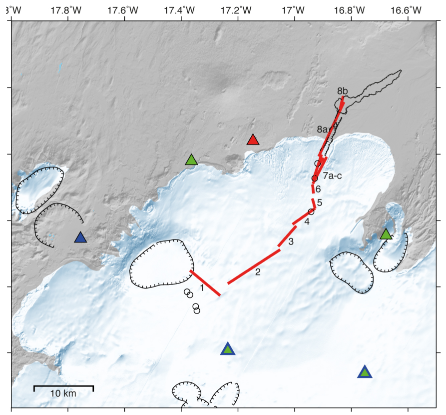
Sigmundsson et al., Nature 2015

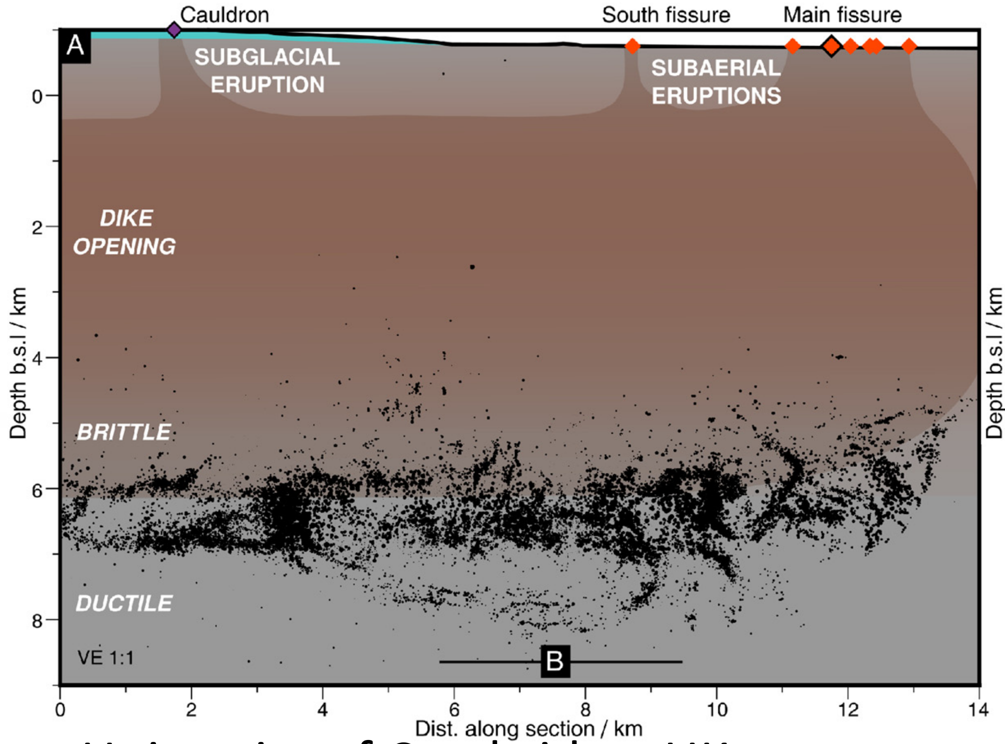
Gudmundsson et al., Science 2016



Sigmundsson et al. (2015) Segmented lateral dyke growth in a rifting event at Bárðarbunga volcanic system, Iceland. Nature







University of Cambridge, UK

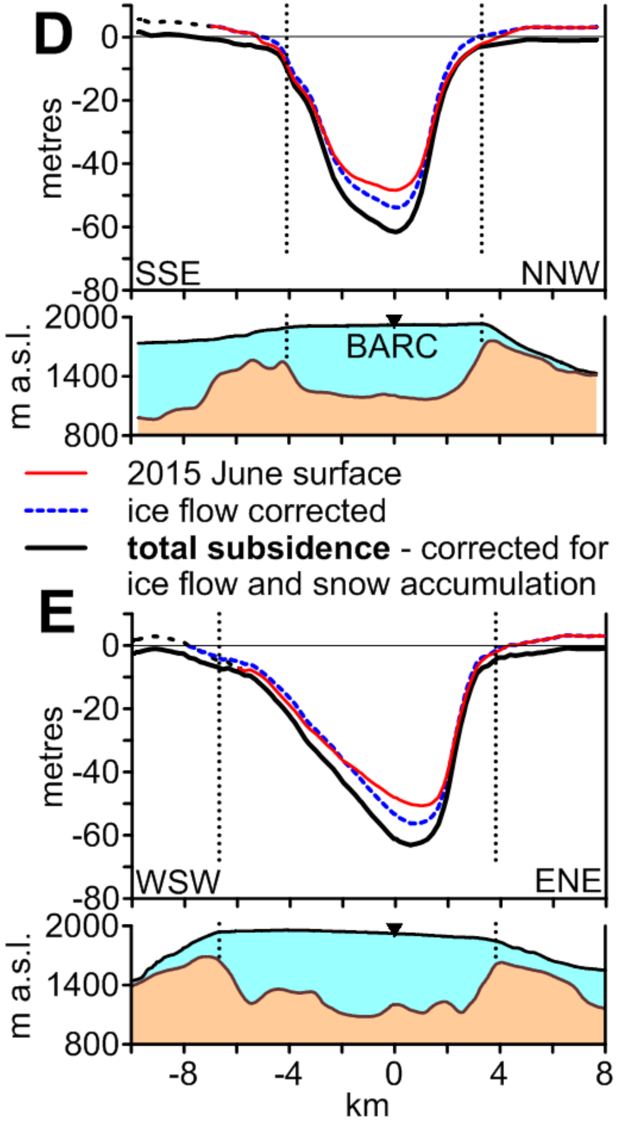
Woods et al., Earth Planet. Sci. Letters, 2019

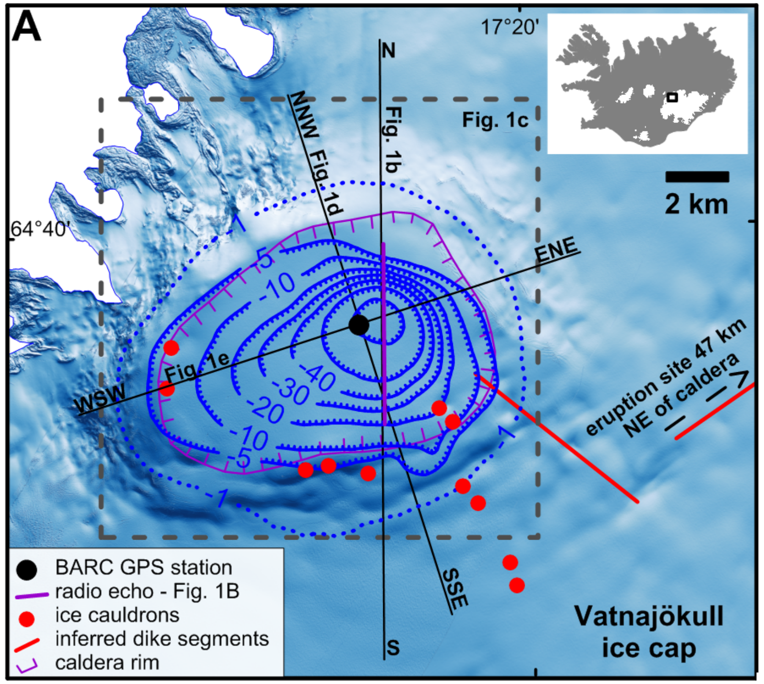
GPS and InSAR constrain a dike

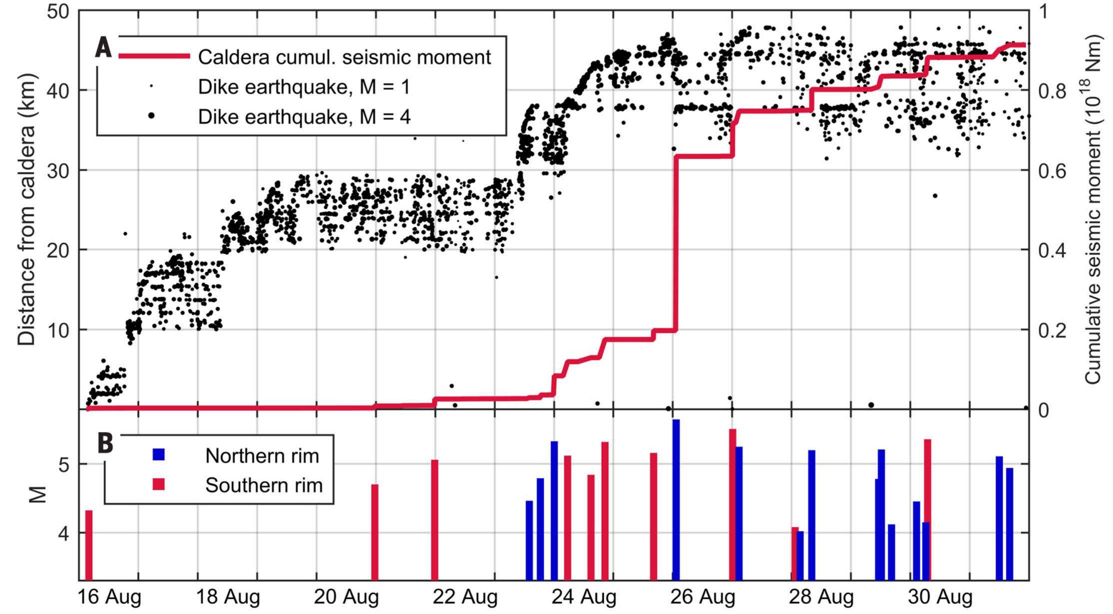
Inferred volume: ~ 0.5 km^3 Average flow rate: ~ 260 m^3/s

Modelling by Andy Hooper, University of Leeds

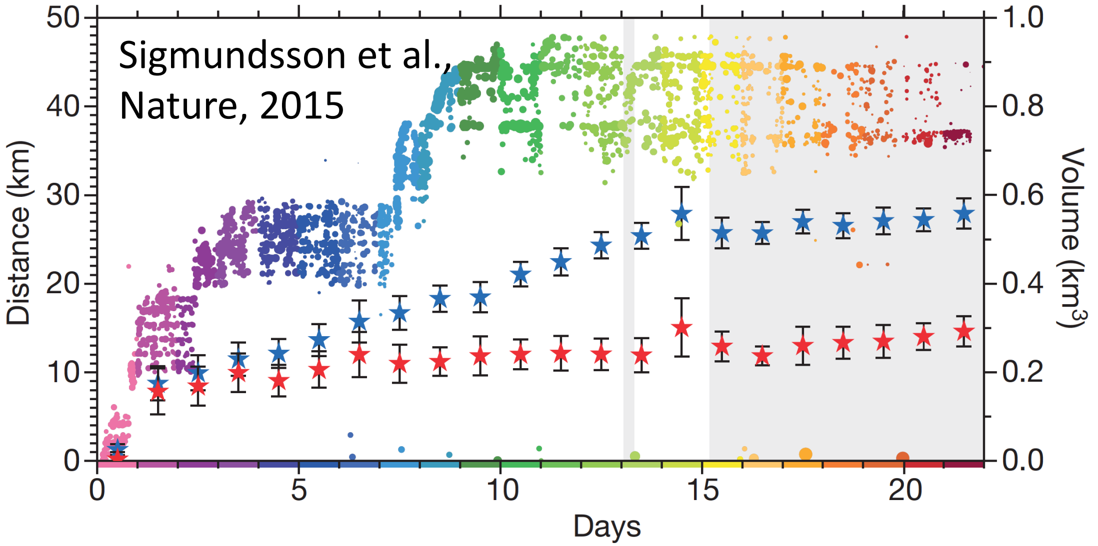
Gudmundsson et al. (Science, 2016) Gradual caldera collapse at Bárdarbunga volcano, Iceland, regulated by lateral magma outflow.

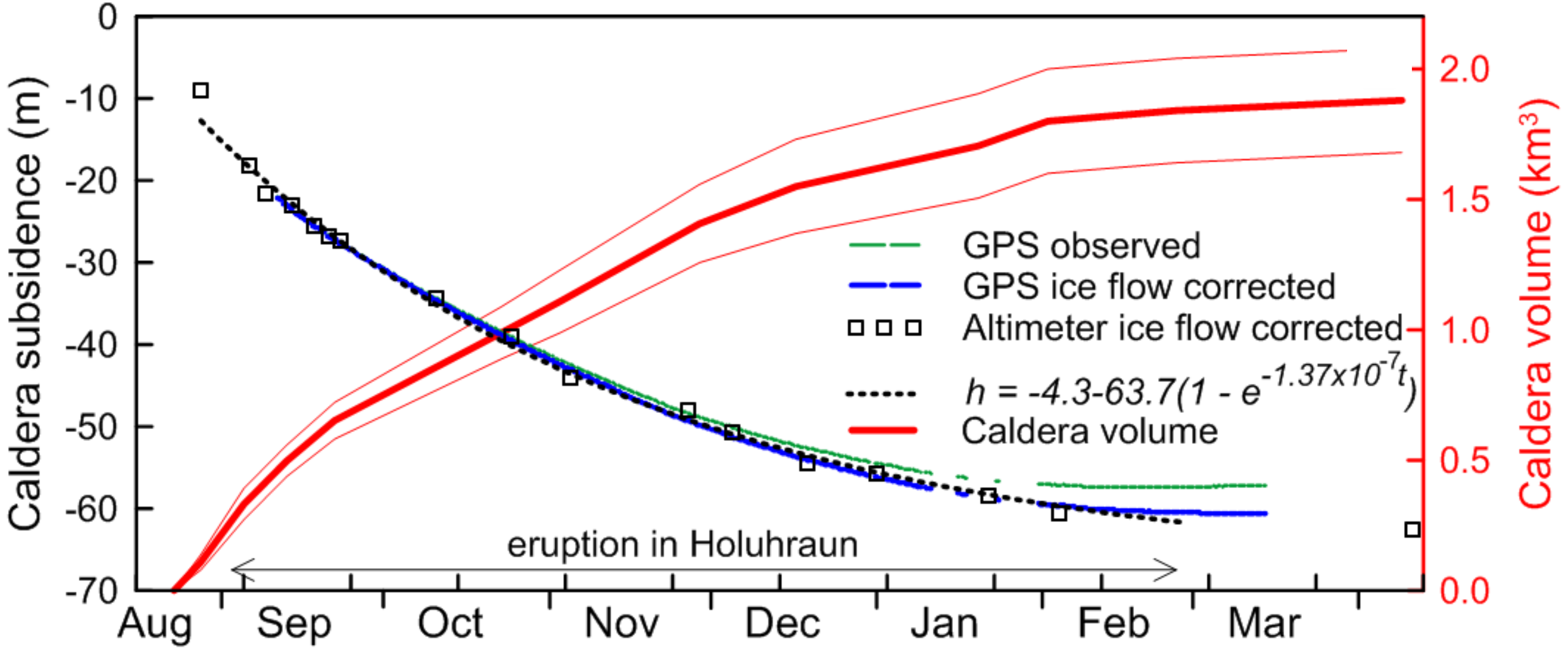




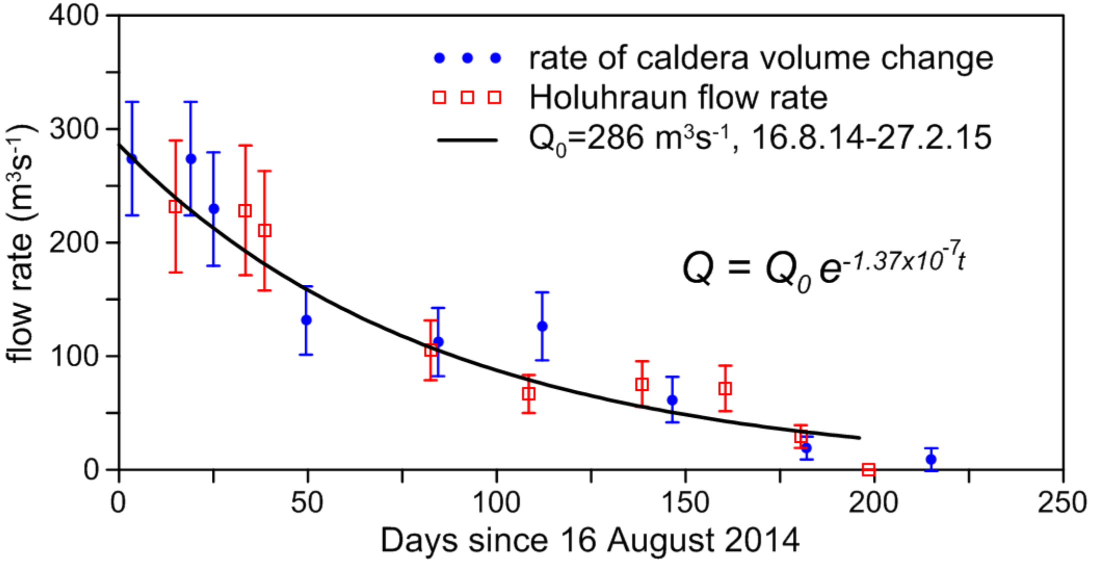


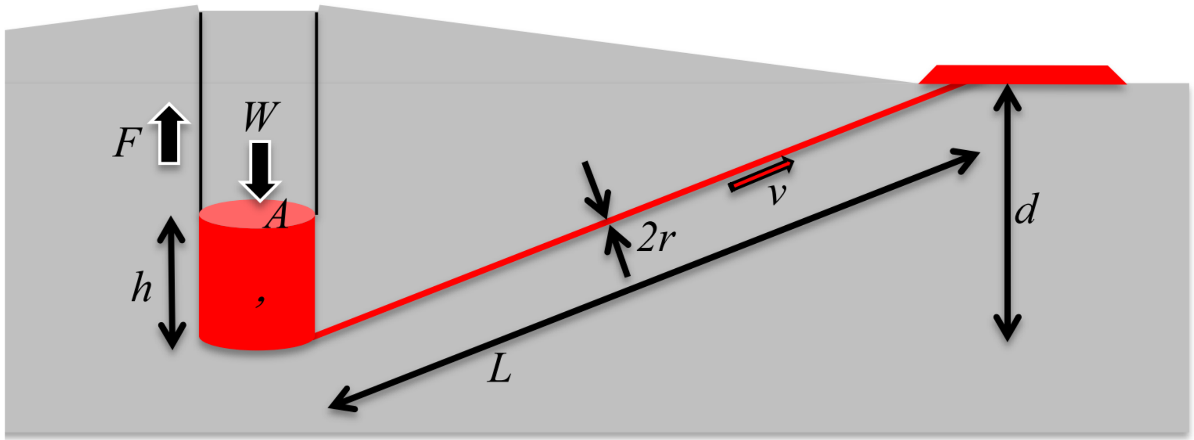
- 24 August (Day 8)
- Onset of frequent M>5 earthquakes
- 0.3 km^3 of magma had flowed into the dike when caldera fault failure occurred

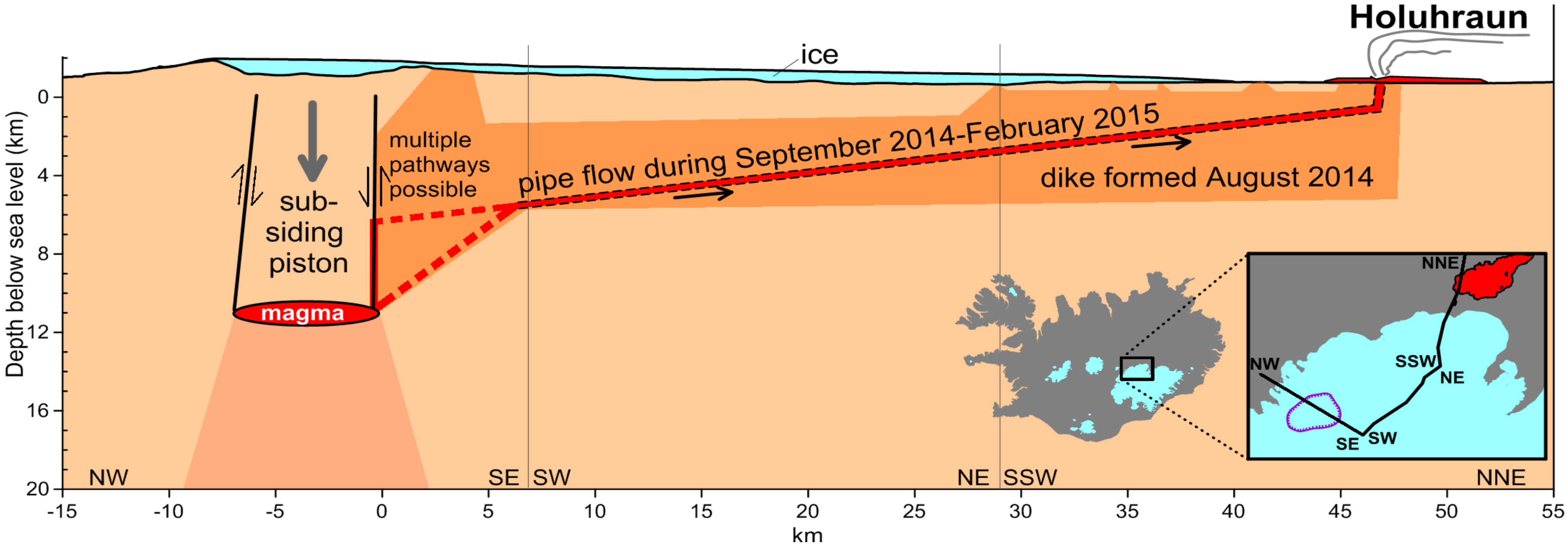


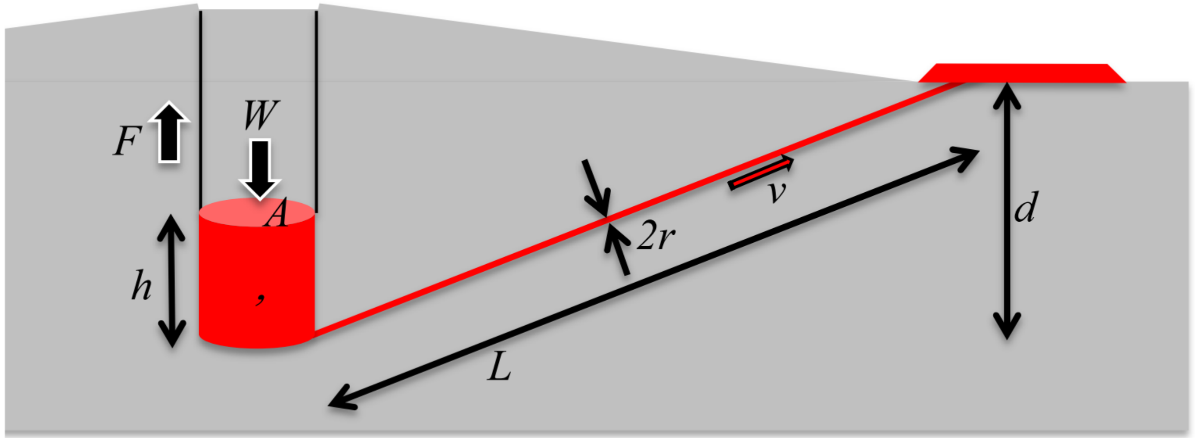


Gudmundsson et al. (2016)









$$\frac{d\Delta P}{dt} = -\frac{\pi\rho g r^4}{8A\eta L}\Delta P$$

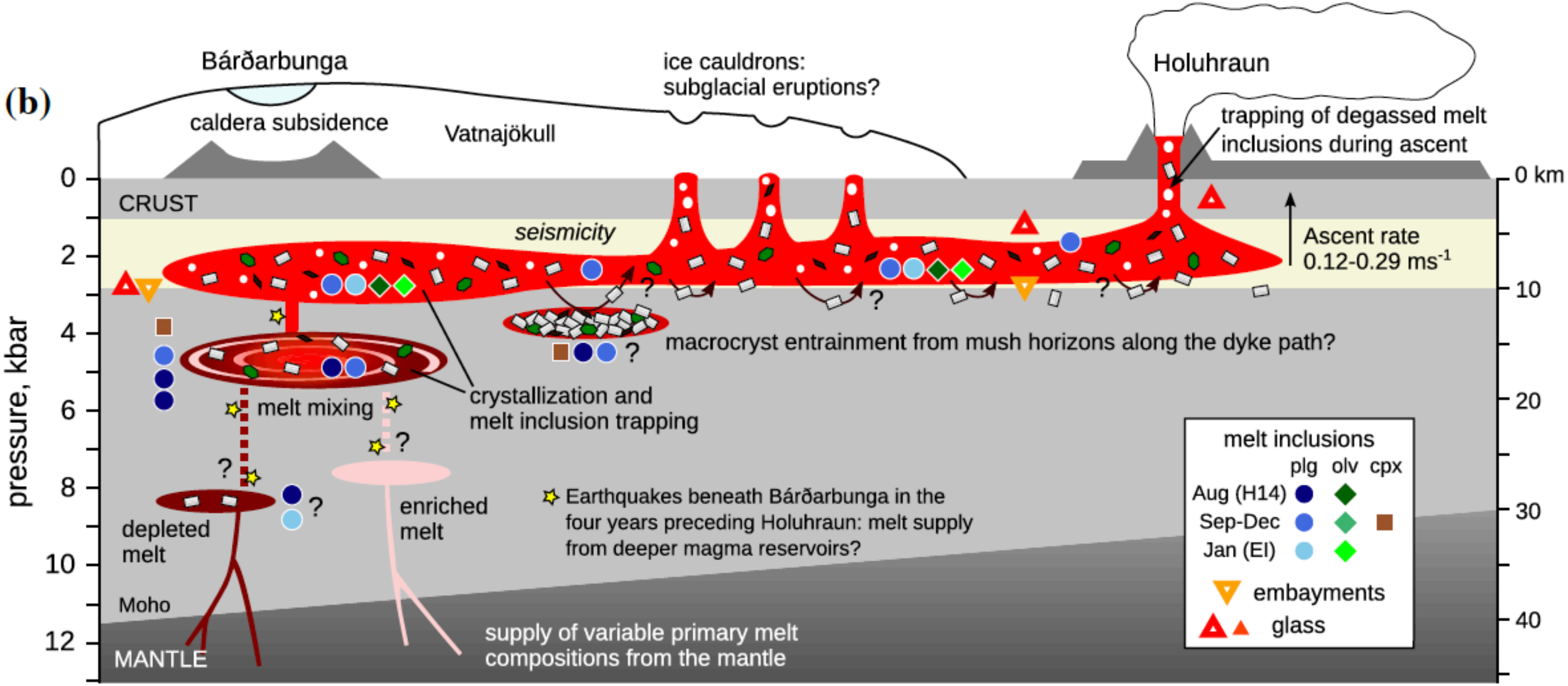
$$\Longrightarrow \Delta P = \Delta P_0 e^{-\frac{\pi\rho g r^4}{8A\eta L}t}$$

At onset of piston movement $\Delta P_0 = 1.7$ MPa

Guðmundsson et al., Science, 2016

Model: Andy Hooper

Schematic illustration showing how the Holuhraun magma may have been assembled and transported
M. Hartley et al. (2018): Melt inclusion constraints on petrogenesis of the 2014–2015 Holuhraun eruption, Iceland, *Contributions to Mineralogy and Petrology*



Crystals have been brought into the magma only shortly before or during the eruption.
Suggestion: important process for formation of sustained magma channels is the addition of mush crystals to a magmatic liquid as it leaves a magma body and rises towards the surface.

General failure criterion for a magma body

Sigmundsson et al., work in progress

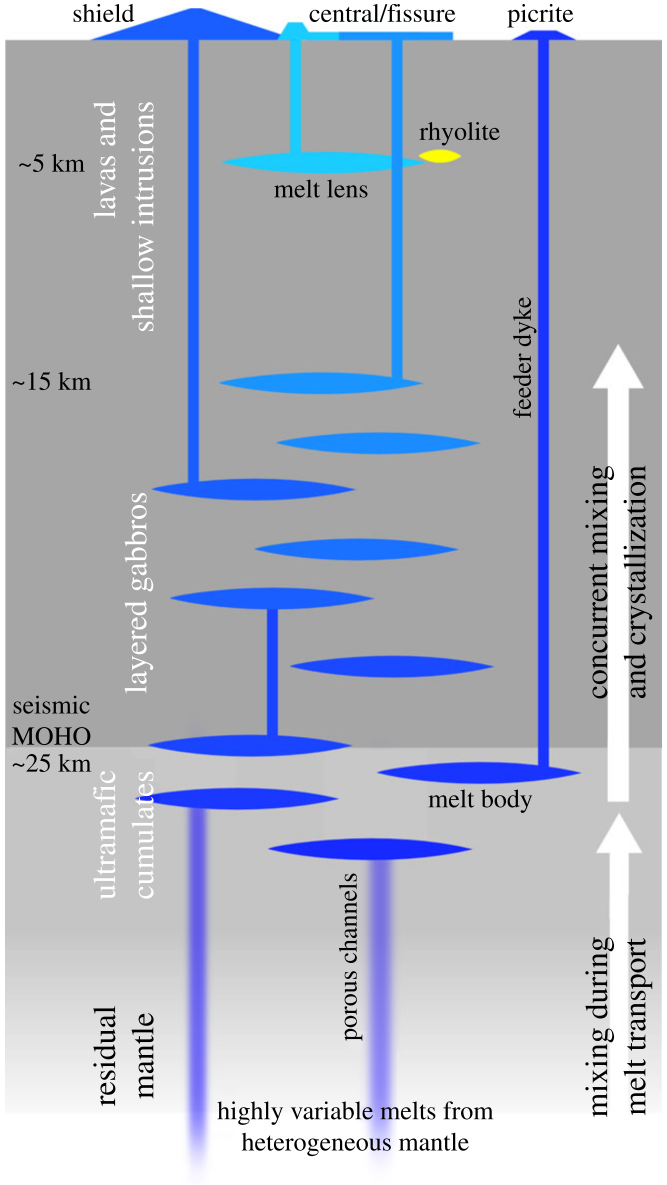
$$\Delta\rho g h + \Delta P_{magma\ body,flow} \geq \sigma_{failure} + \sigma_{external}$$

Buoyancy pressure

Pressure due to magma inflow or outflow

Failure limit

Deviatoric stress due to all external processes acting perpendicular to the plane of failure



Schematic image of a model of magma storage and transport under an Icelandic rift-zone volcanic system.
John Maclennan, 2019. Mafic tiers and transient mushes: evidence from Iceland. *Phil. Trans. R. Soc. A*

Conclusions – three Icelandic eruptions

- **Eyjafjallajökull 2010 summit eruption** (6 weeks): Episodic injection of basaltic magma into more evolved magma during Eyjafjallajökull 2010 explosive eruption, driving pulses in activity and irregular mass eruption rate over a six-week long eruption. Precursors: episodic sill intrusions (strongest)
- **Grímsvötn 2011** (7 days): Relaxation of overpressure in a shallow magma body built up by previous magma inflow; superimposed pulses in activity due to conduit processes. Precursors: long-term magma inflow (strong)
- **Bárðarbunga/Holuhraun 2014-2015** (6 months) Magma buoyancy in a deep magma body driving magma upward and into a lateral dyke, with associated development of underpressure under weak caldera faults, triggering caldera collapse. After onset of caldera collapse, piston-style subsidence driving flow out of magma body. Precursors: elevated seismicity, minor deformation (weak)