Planning for natural hazards, lessons from Reykjanes and Krafla

Conference on Megaprojects and Risk

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Natural hazard

Phenomena, events, or processes in nature that are likely to cause damage or danger to humans, infrastructures, or natural systems ...

Examples: Earthquakes, landslides, volcanic eruptions, floods, hurricanes, tornadoes, blizzards, tsunamis, cyclones, wildfires, pandemics .....

Classes of natural hazards:

Volcanic	tefra, lava, fracturing, gas, lava domes
Earthquakes	collapsing houses, casualties, damag infrastructure
Mass wasting	landslides, snow avalanches, buildings, lost lives
Ocean flooding	houses collapsing, infrastructure, property loss
Floods, jökulhlaup	infrastructure, property loss
Foul weather	wind- and water damage, casualties
Climate change	foul weather, vegetation fires, sea level rise, refugee environmental damage, destruction of habitats ...

Hazard chains:

Earthquake → Fire → Tsunami

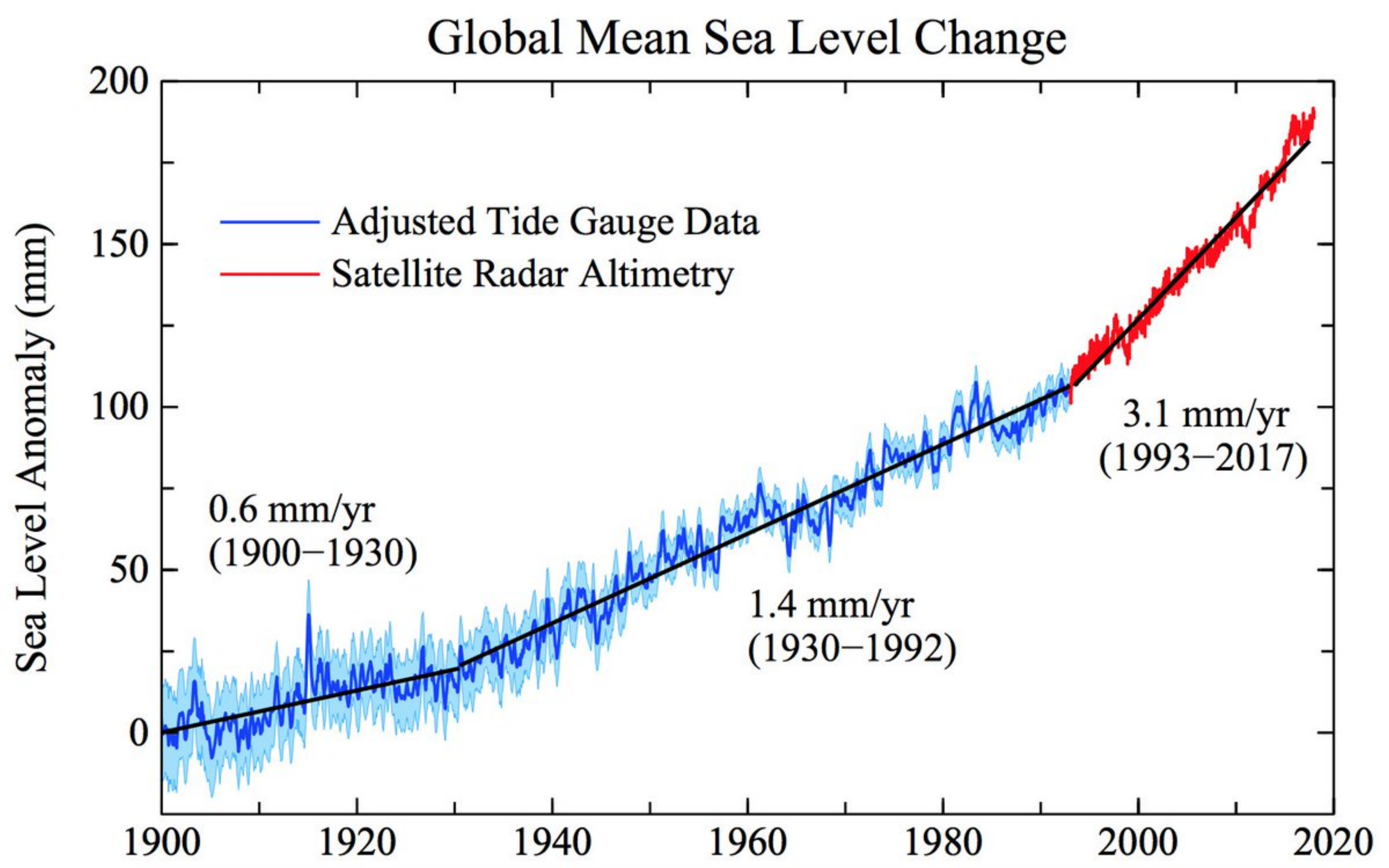
Earthquake → Slope failure → Eruption

Eruption → Slope failure → Tsunami

Climate change → Sea level rise → Storm surge

Climate change → Storms → Landslides

Climate change → Glacier change → Landslides → Volcani
activity

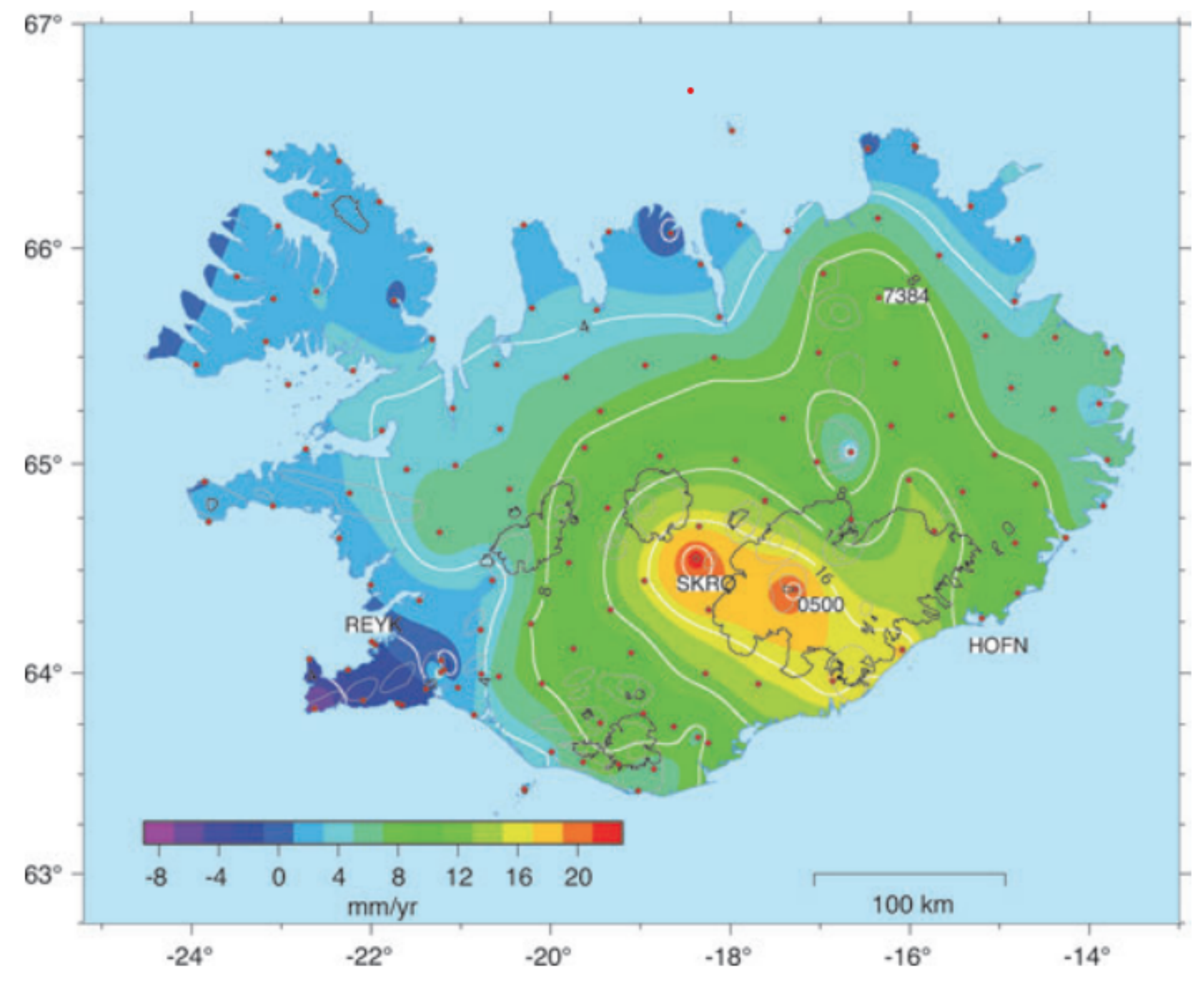


J.A. Church and N.J. White "Sea-level rise from the late 19th to the early 21st Century" Surveys in Geophysics (2011)

Vertical crustal movements in Iceland 1993-2004, GPS-measurements

Most of Iceland rises due to decreasing load of shrinking glaciers more than 30 mm/year in Central Iceland.

Reykjanes Peninsula subsides due to plate divergence and lack of magmatic feeding at the plate boundary.

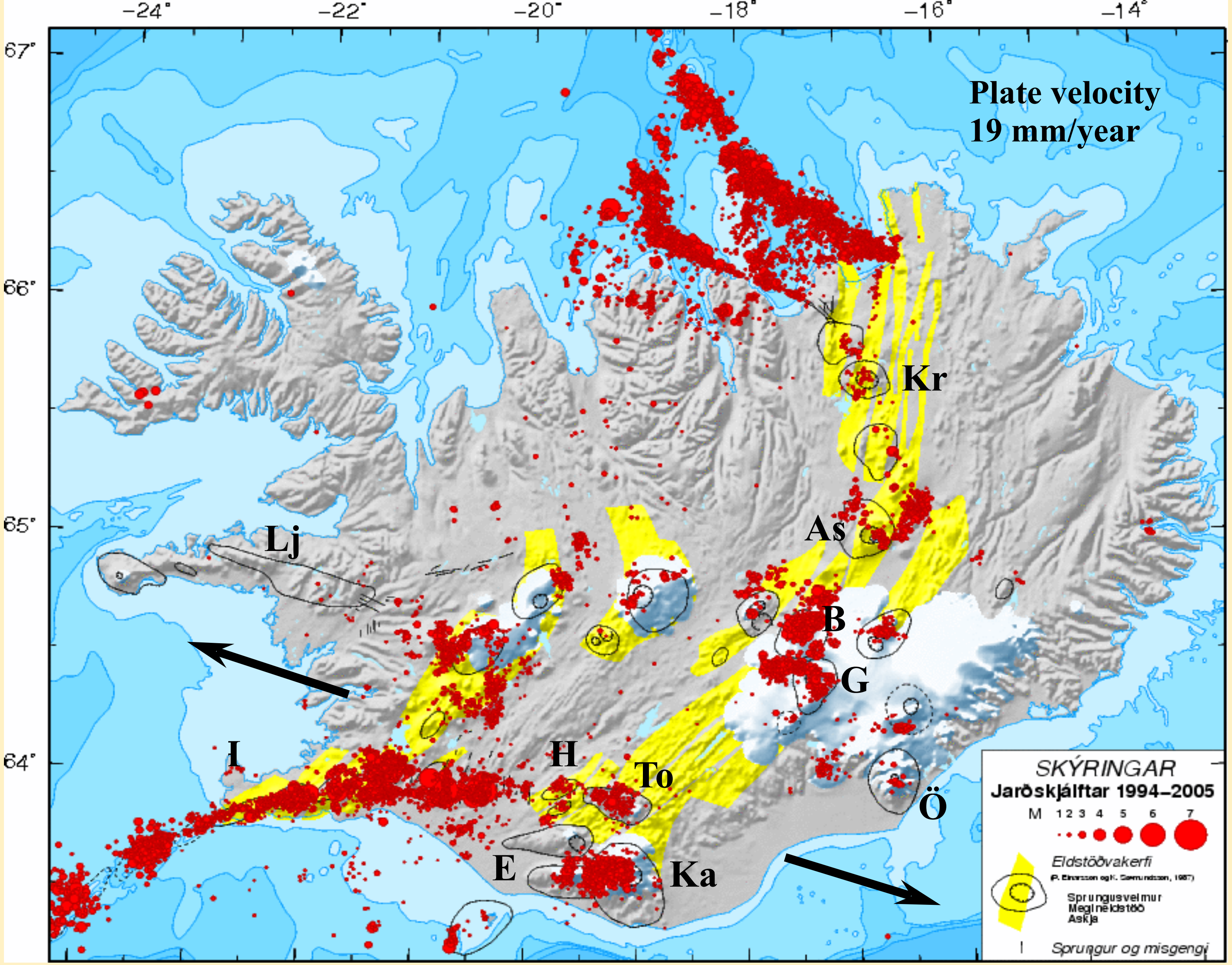


Þóra Árnadóttir et al. 2009

Spring tide in Reykjavík in September 2020

Sea level rises and the SW-corner of Iceland subsides

Keflavík harbor at spring tide in Octóber 2021. Kjartan Már Kjartansson



Krafla

Askja
Ljósufjöll

Bárðarbunga
Grímsvötn
Hekla
Torfajökull
Reykjanes
Öræfajökull
Eyjafjallajökull
Katla

Iceland: Volcanic systems and earthquake epicenters 1994-2005

Earthquake data from Icelandic Meteorological Office

Hazards related to the position of Iceland on a plate boundary and as a hotspot:

1. Volcanic hazards: ~ 30 active volcanic systems. Tefra fall, ash plumes, disruption of air traffic, glacier floods, lava flows, gas pollution. Eruptions every 2-3 years, of very variable intensity. Only two towns have the possibility of eruption occurring within the town. Several towns can be affected by lava flows, floods, ash, or gas from more distant sources.

2. Seismic hazards: Earthquakes of magnitude > 6 in two areas, transform zones of South Iceland and off the north coast. Building codes have proven to be effective to prevent major damage.

3. Surface fracturing: An additional type of hazard has been demonstrated during two episodes of rifting and magmatism at the plate boundary: Krafla 1974-1989 and Reykjanes Peninsula 2019 - ?

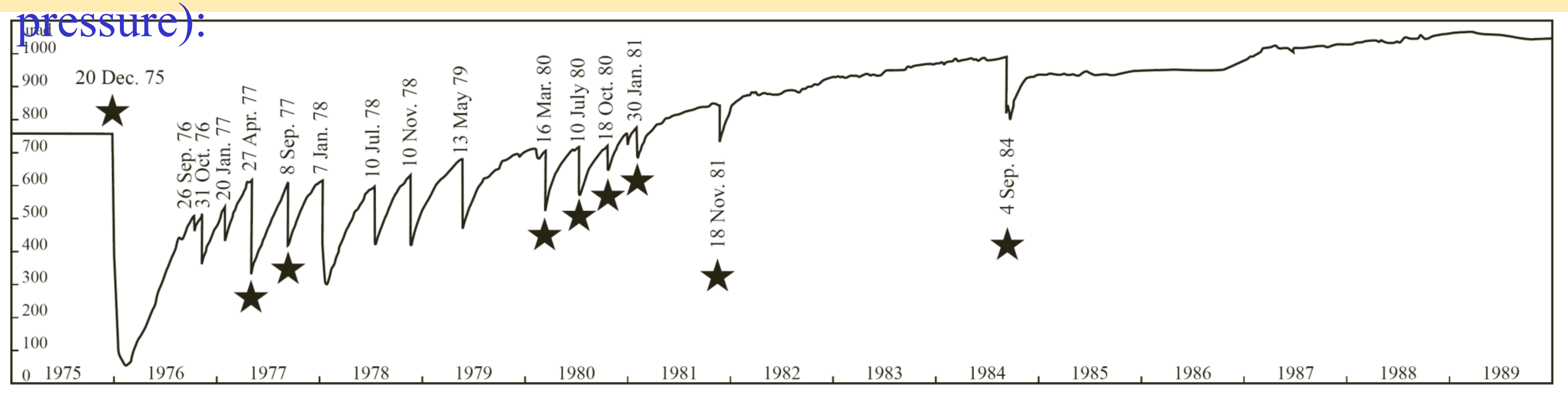
The Krafla Rifting Episode of 1974-1989: Overview

Krafla tectonic and magmatic episode 1974-1989

Accompanied by one of the largest earthquakes swarms on the MAR plate boundary recorded so far.

Many processes: Deflation, inflation, rifting, diking, transform faulting

Tilt as a function of time (proxy for magma chamber pressure):

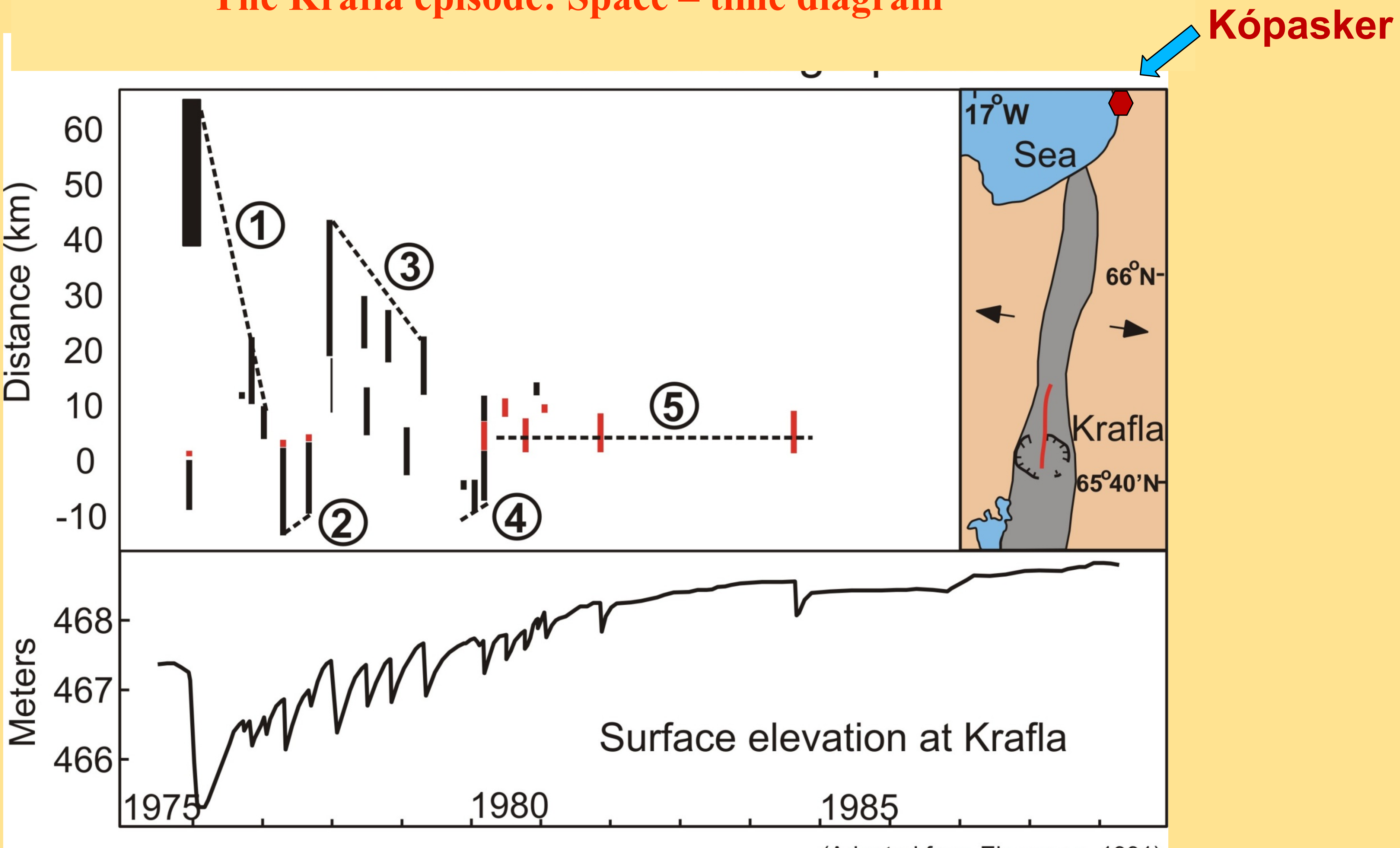


(from Sturkell et al., JVGR, 2006 – modified from Eysteinn Tryggvason)

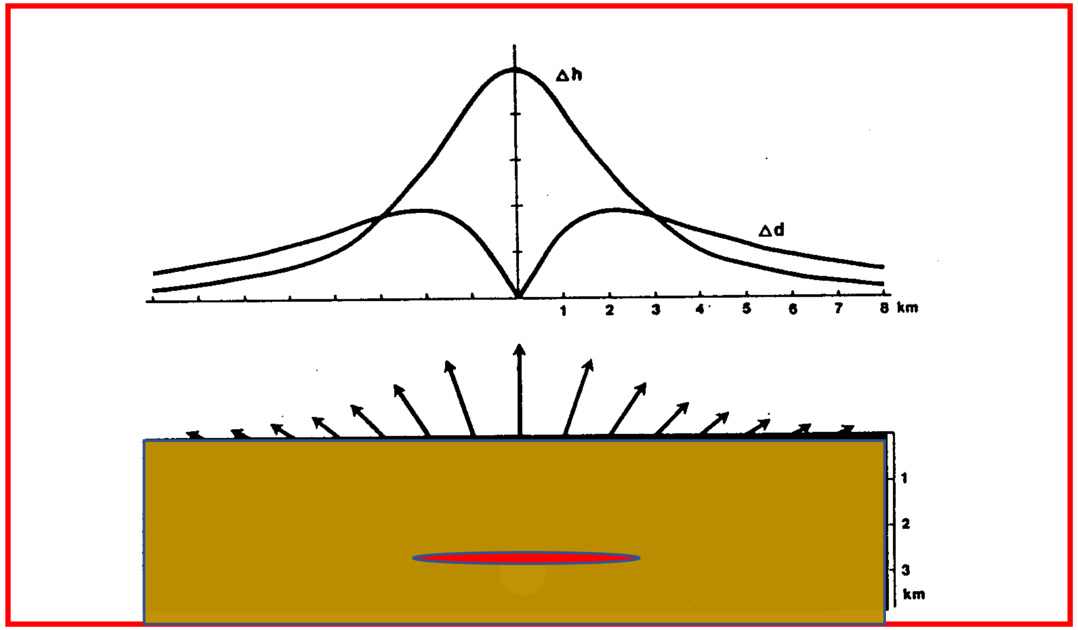
- long periods of inflation, magma accumulated at shallow depth within the Krafla caldera (activity limited to caldera, inflation and earthquakes)

- short deflation periods, magma intruded into the fissure swarm or erupted. (deflation in caldera, then followed by earthquakes and rifting in fissure swarm)

The Krafla episode: Space – time diagram



(Adapted from Einarsson, 1991)



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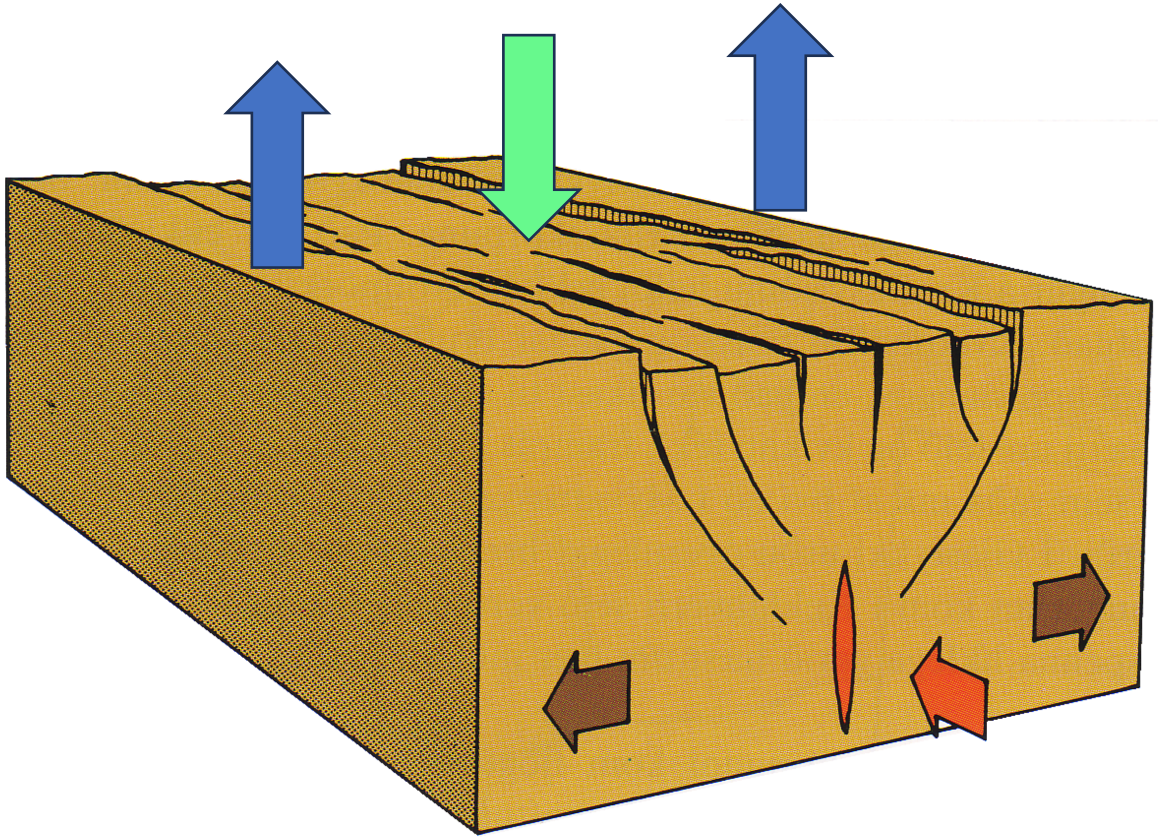

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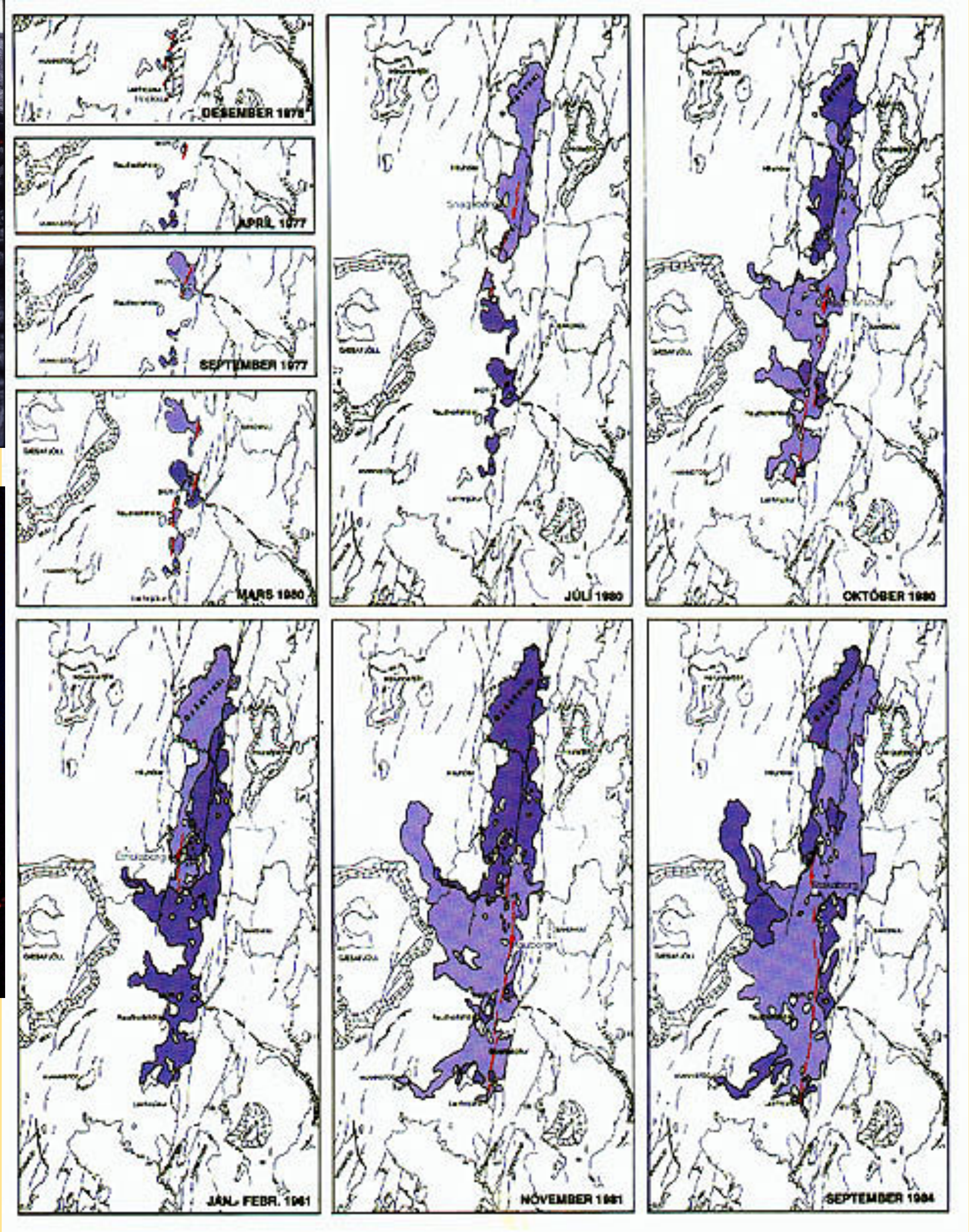

Maps from Sæmundsson, 1991

Damage in the Krafla episode:

1. Diatomite factory at Mývatn Lake suffered considerable damage due to surface fracturing. Storage ponds for raw material had to be rebuilt, and the main office building was seriously damaged. Infrastructure was damaged, roads and pipelines crossing fissures.

2. The triggered Kópasker earthquake caused damage in Kópasker town, mostly houses that stood on fractures that were activated by the shaking.

3. The Krafla geothermal system was affected by the magmatic injections in the caldera.

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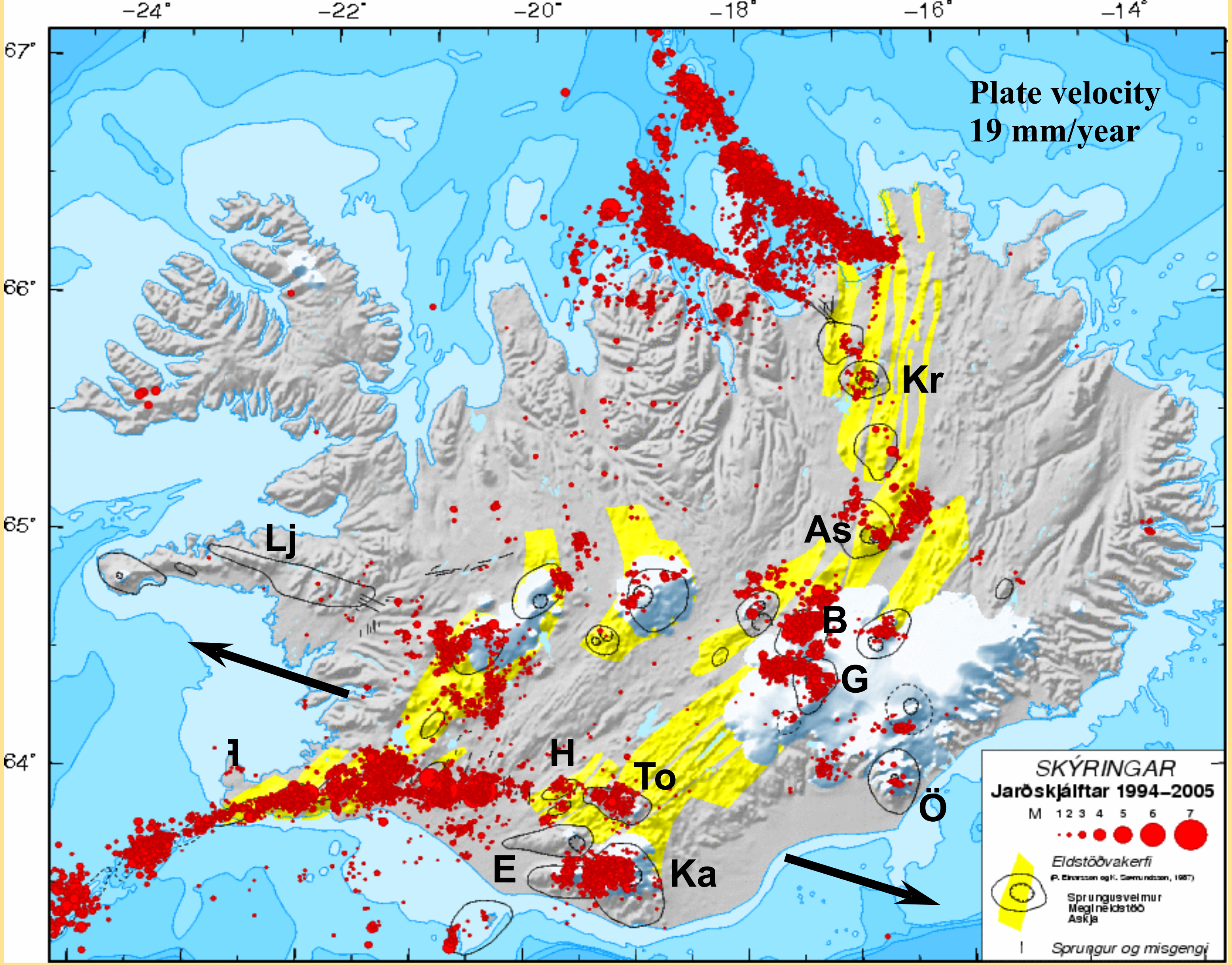
Lesson from Krafla: Don´t build across fractures!

This was added into building regulations



Krafla

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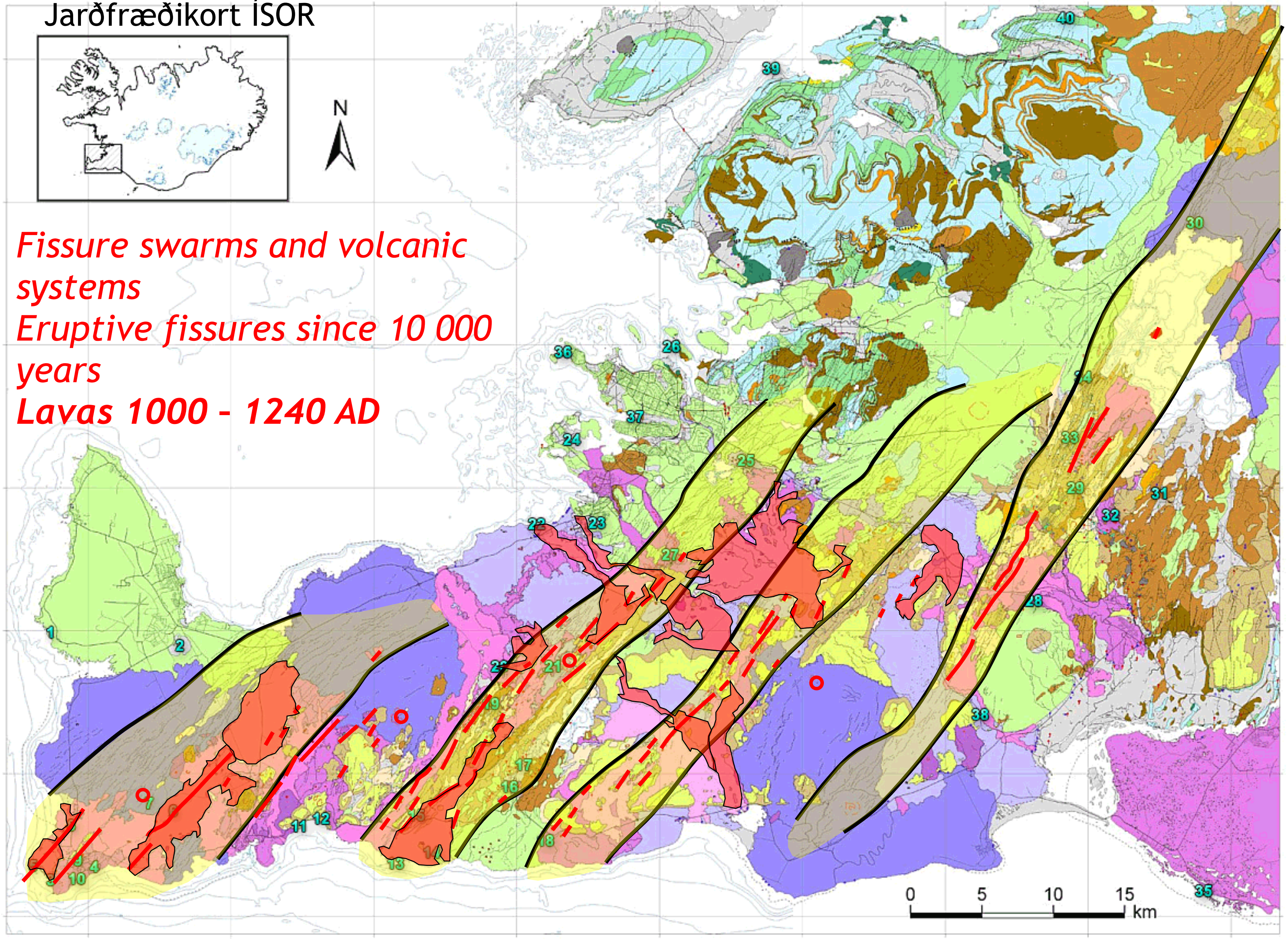
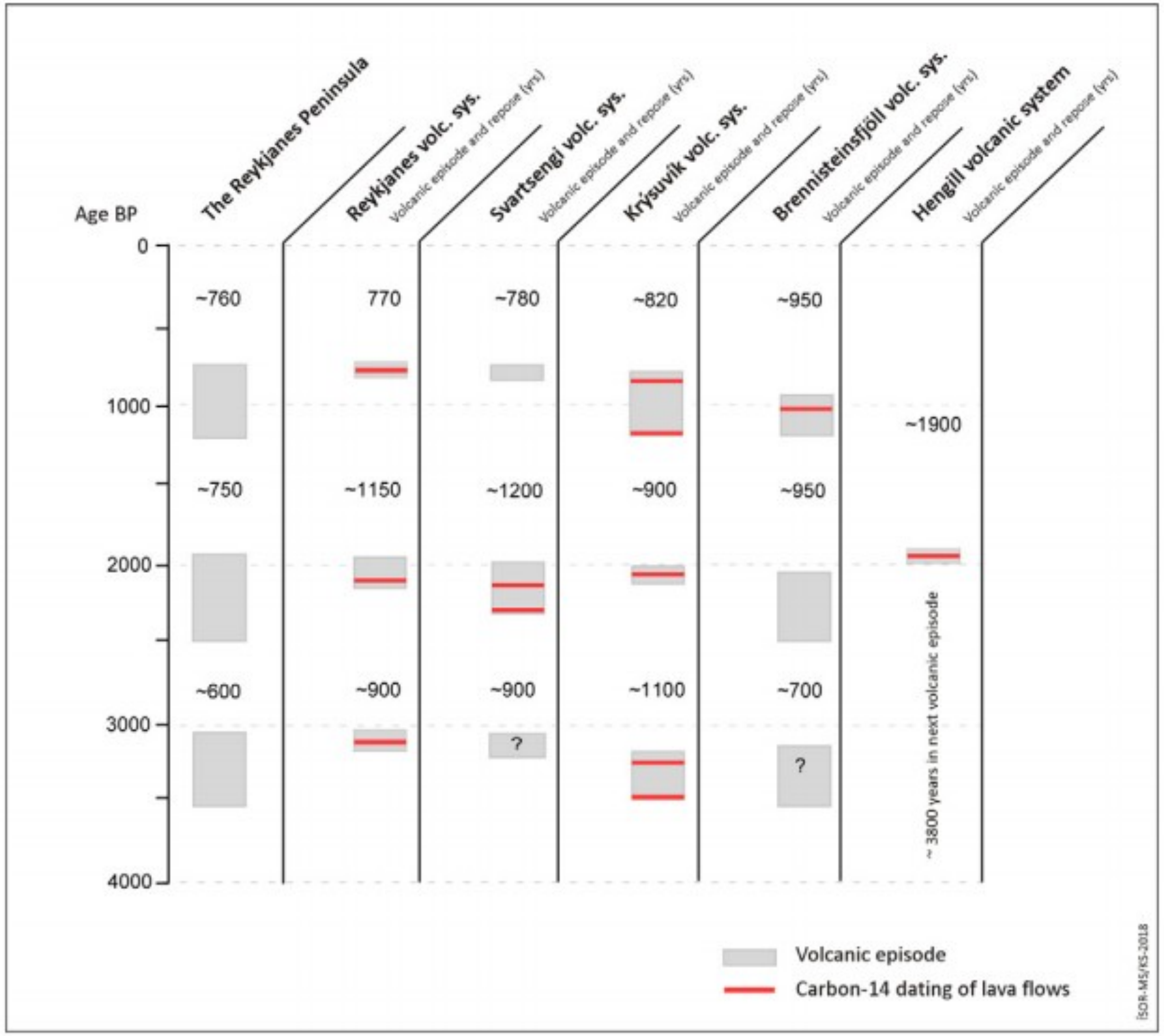


Fissure swarms and volcanic systems

Eruptive fissures since 10 000 years

Lavas 1000 - 1240 AD

History of volcanism on the Reykjanes Peninsula



Latest eruption prior to the present episode, 1240 AD

Magmatism is episodic.

Each episode lasts a few centuries. Cycle ~ 1000 years

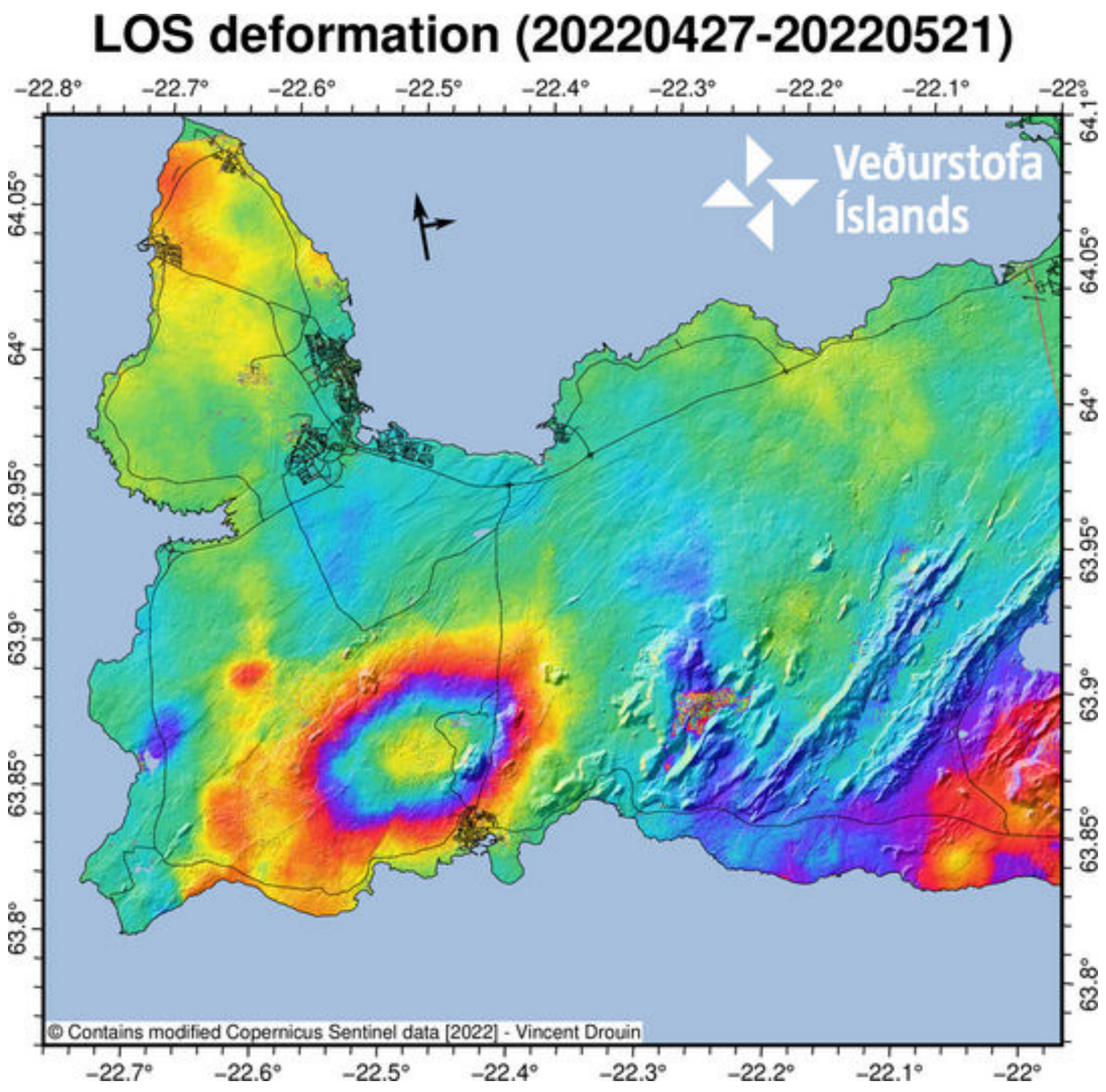
(From Sæmundsson et al. 2020)

Reykjanes Peninsula. Beginning of the story

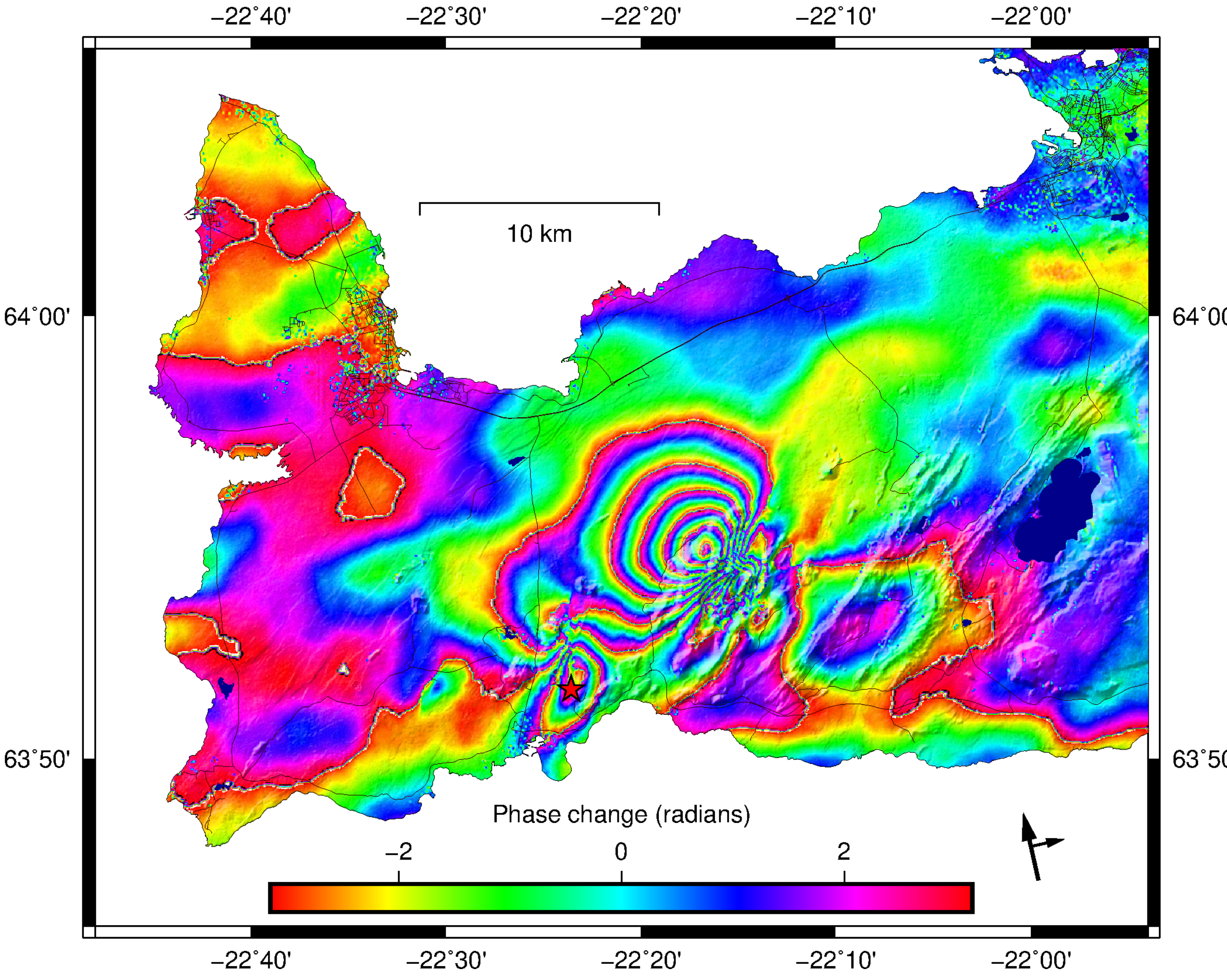
December 2019	Earthquake swarm at Fagradalsfjall
January 2020	Inflation west of Thorbjörn. Three episodes in next months. Earthquake swarms and possible inflation at Reykjanes.
August-Oct. 2020	Inflation at Krísuvík. Earthquakes include one of M 5,7
24. February 2021	Earthquake M 5,65 at Litli-Hrútur, dike intrusion begins, triggering earthquakes
19. March 2021	Small eruption begins at Geldingadalir. Earthquakes stop.

Etc. Etc.

Radar interferometry from satellite

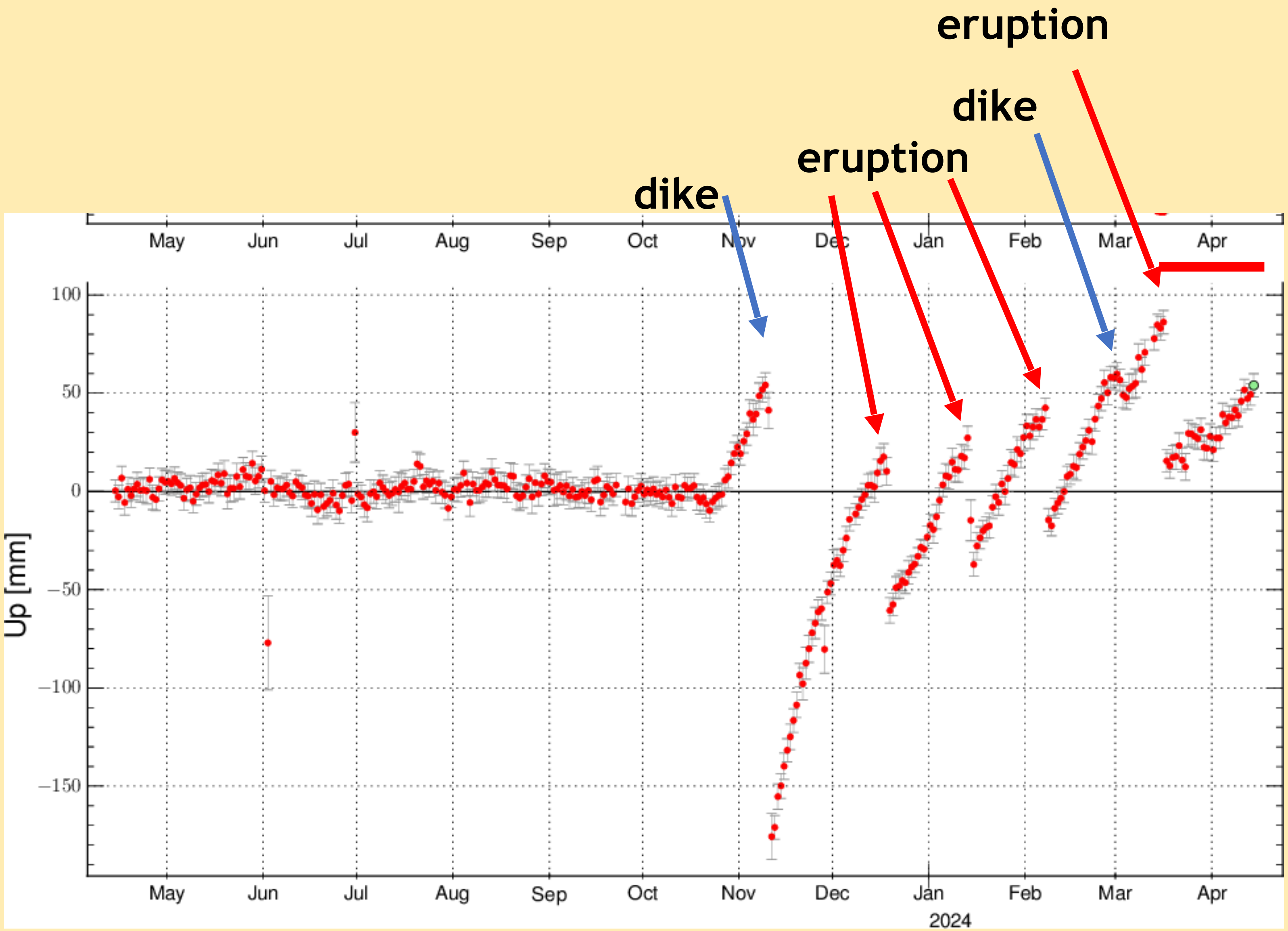


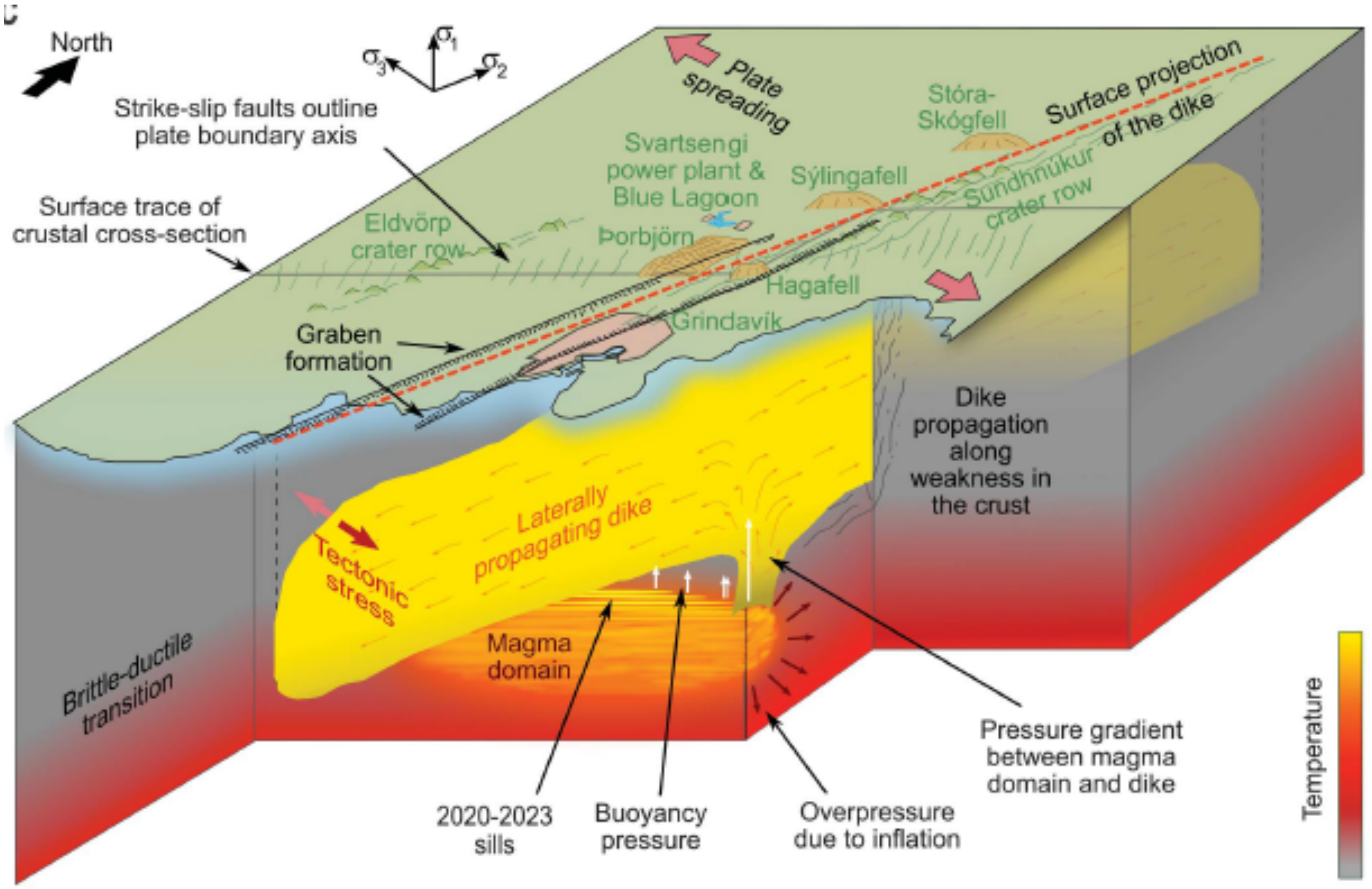
Inflation and uplift at Svartsengi in May 2022



Dike propagating in July 2022

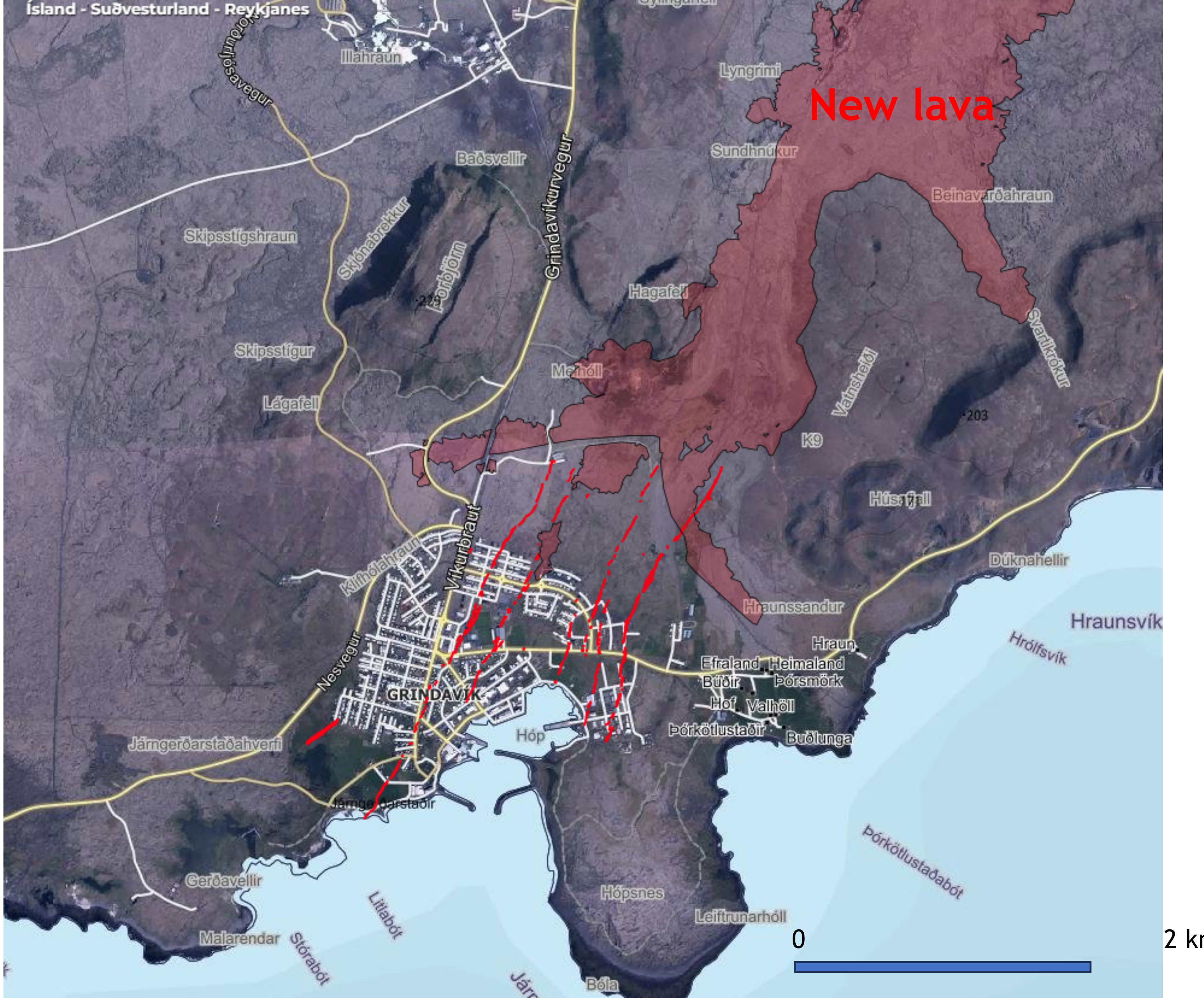
Vertical displacement at Eldvörp





From: Sigmundsson et al. 2024

Fractures in Grindavík



From map.is

In spite of seven eruptions and numerous earthquakes of $M > 5$ the single most damaging event of the ongoing series is the dike intruded beneath Grindavík in November 2023.

Extensive surface faulting during that event caused damage to numerous houses in Grindavík, as well as infrastructure such as pipelines, power lines, streets and roads. The town was evacuated during the intrusion and still is uninhabitable.

Three houses were destroyed by lava in the December eruption, but most other houses destroyed beyond repair were located across fissures that moved during the November intrusion.

The main lesson of the Krafla episode appears to have been forgotten.

Future prospects: Many different scenarios possible

Magma stops flowing towards the surface. Activity stops. Peace for a while.

Magma continues flowing towards the same centers. Repeated eruptions in the same systems.

Magma begins flowing to new centers. Dike injections along other fissure swa
Krísuvík-Heiðmörk-Rauðavatn. Brennisteinsfjöll-Bláfjöll-Sandskeið.
Reykjanes.

Dikes lead to eruptions in new areas. Eruptions on land mostly lava, explosive
off shore or in geothermal areas.

Earthquakes as large as M 6 - 6,5 possible in the eastern part of the peninsula

Hazards mitigated by sensible planning, include:

- 1. Sea-level rise
- 2. Lava flows
- 3. Fracture movements, by both magma intrusion and earthquake faulting