Monitoring the activity state of volcanoes

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Introduction

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Active volcanoes pose a significant risk on the world's population

Almost 14% of the world's 2015 population (1 billion) lived within 100 km of an historically active volcano

Monitoring systems and forecasting are fundamental tools to assess risk around volcanoes and prevent catastrophes

Volcano monitoring through relative-to-eruption-onset time

- **Pre-eruptive monitoring**
- Syn-eruptive monitoring
- Post-eruptive monitoring

Napoli and Vesuvio volcano (Italy)

Pre-eruptive monitoring

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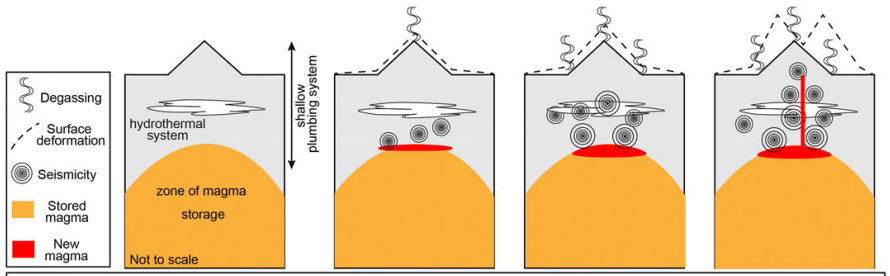
Restless phases (signs of potential activity) last from days to centuries

Eruption precursors

- vary in frequency and intensity
- differ from volcano to volcano
- monitored through several techniques
- must not be considered separately

Ability to forecast hazardous eruptions is still limited



STATE	a) Quiescence	b) Minor unrest	c) Major unrest	d) Impending eruption
PROCESS	No shallow magma emplacement	Shallow magma or fluid accumulation		Shallow magma or fluid transfer
DURATION	Years to thousands of years	Months to years		Days
DEFORMATION	None, or subsidence	Radial symmetry		Non-radial symmetry
		uplift cm/yr	uplift dm/yr to m/yr	uplift m/yr to dam/yr
SEISMICITY	None	Above intrusion, stationary		Above intrusion, migrating
		10^1 events/month	10^2 - 10^3 events/month	
		LP	LP - VLP/ULP/tremor?	LP/VLP/ULP/tremor
DEGASSING AND THERMAL ENERGY	H_2O, CO_2	H_2O, CO_2 (magmatic component)	H_2O, CO_2, SO_2? (magmatic component)	H_2O, CO_2, SO_2 (magmatic component)
RATE OF MONITORING INDICATOR	declining/ decelerating	steadily increasing	slowly accelerating	rapidly acccelerating

Main states of a volcano prior to eruption (Rosi et al., 2022)

La Fossa crater rim (Vulcano island, Italy)

Techniques and instruments

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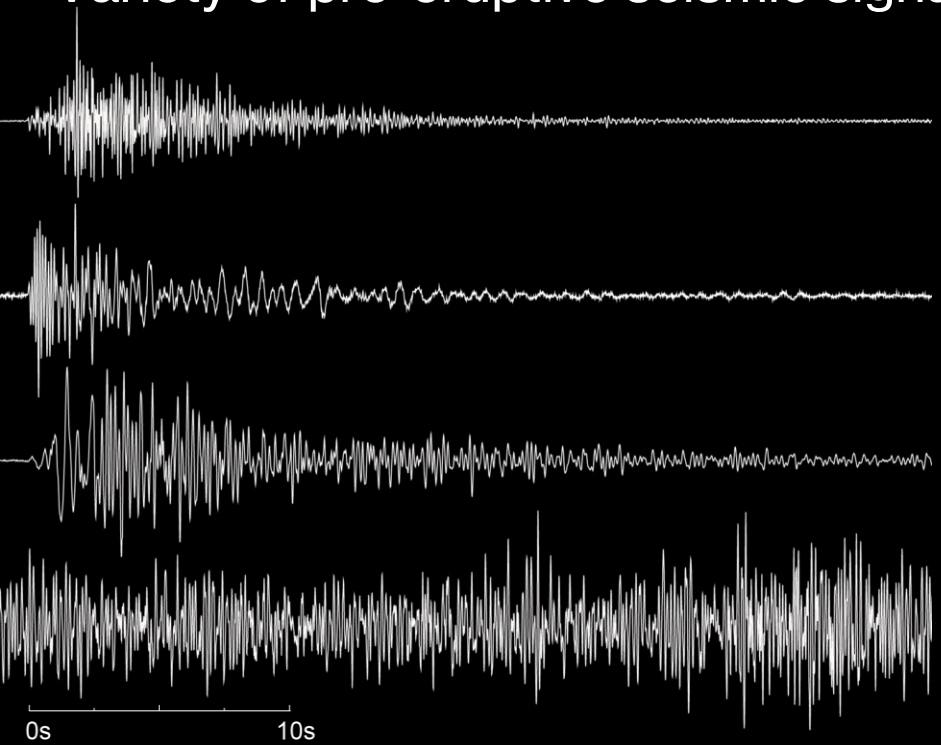
Seismic monitoring

Seismic unrest almost always precedes volcanic activity → Network of seismometers sending real-time signals to volcano observatory

Digital broadband seismometer

Variety of pre-eruptive seismic signals:



- Volcano-tectonic event (high-frequency)
- Hybrid event (mixed-frequency)
- Long-period event (low-frequency)
- Volcanic tremor (series of low-frequency event)

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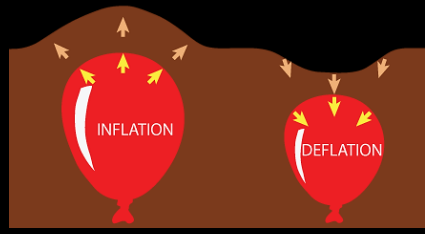
Ground deformation monitoring

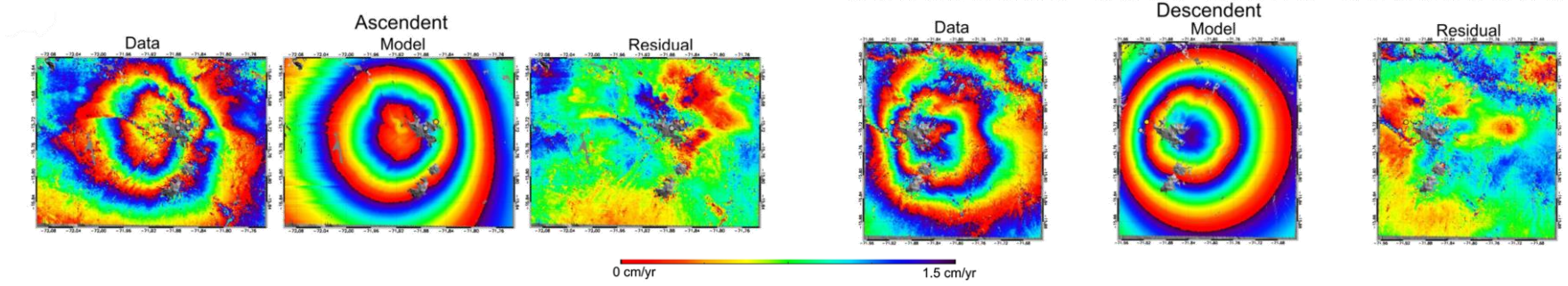
Magmatic pressure increases cause the ground surface to move upward and away from the pressure source



Measuring ground deformation:

- Ground-based
  - Leveling and distance measurements
  - **Tiltmeters** and strainmeters
  - **GPS** (Global Positioning System)
- Satellite remote sensing
  - **InSAR** (Interferometric Synthetic Aperture Radar)

Permanent GPS station



Differential InSAR (DInSAR) 2014-2016 ascending and descending time series and interpretation at Sabancaya volcano (Peru)

Techniques and instruments

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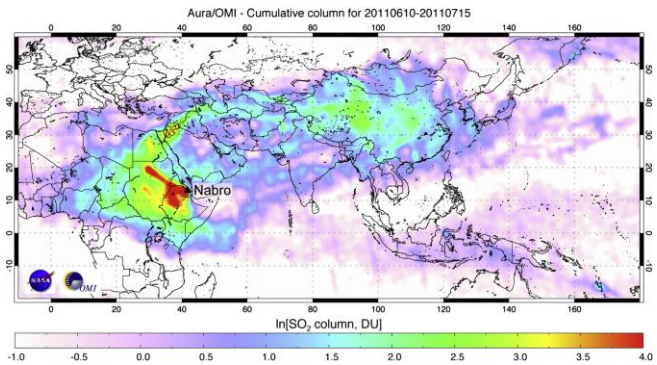
Gas monitoring

Most volcanic subaerial activity consists of gases emissions (gas plumes, fumaroles and soil emissions)

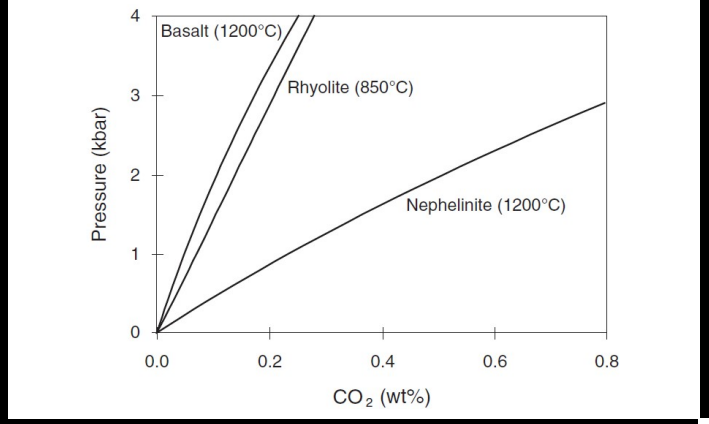
- In-situ measurements
- Remote sensing
- Satellite remote sensing

} various instruments depending on the target



Dissolved gases change their relative concentration during magma ascent, depending on their solubilities:

- Increase in CO_2 (first to exsolve) usually precedes eruptions
- Gases such as Cl and S exsolve at shallower depths (shallow magma)



Techniques and instruments

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Thermal monitoring

Fumarolic and ground temperature usually increases prior to eruptions

Thermal surveillance from the ground, air, or space using the shortwave IR (SWIR), mid-IR, and TIR wavelengths

La Fossa crater rim (Vulcano island, Italy)

Other types of monitoring

- **Infrasonic**
- **Gravity**
- Magnetic
- Water-level
- Observations
- Sampling

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Ground deformation and monitoring

1. Calculate a model for surface deformation at a volcano in terms of vertical and horizontal displacement components of the ground as a function of the distance away from the center of deformation.
   Plot the displacement data vs the radial distance and comment the two curves.

Surface deformation can be expressed by a spherical pressure source buried in an elastic medium. Therefore, a change in pressure (or in volume) at the source level causes a displacement at the surface:

Vertical displacement: $$U_z = \frac{3a^3\,\Delta P\,d}{4G\sqrt{(d^2+r^2)^3}}$$

Horizontal displacement: $$U_r = \frac{3a^3\,\Delta P\,r}{4G\sqrt{(d^2+r^2)^3}}$$

- a: radius of the source sphere
- d: depth to the center of the sphere
- G: shear modulus
- ΔP: change in pressure in the sphere
- r: radial distance on the surface

Considering that $\Delta V = \frac{\pi a^3 \Delta P}{G}$, these equations can be rewritten as functions of volume

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Ground deformation and monitoring

2. Estimate the magma chamber depth using the available GPS data and the just calculated model. To find the best fit between the displacements obtained with the model and the GPS data, use a Pearson's χ^2 test:

$$\chi^2 = \sum_{i=1}^{n} \frac{(Observed_i - Calculated_i)^2}{Calculated_i}$$

What is your best estimate for the magma chamber depth? What factors, simplified or not considered at all by the model, can play a role and cause mismatch between observed and modelled data?

3. On the same day, the volcano observatory sends you also the seismic data. Do you think the depth you obtained with the model is supported by the seismic data? What do you think is happening in the volcanic system? How do you think the situation could evolve and in what timescales?

Exercise

Ground deformation and monitoring