UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES

JULY 8-18 JUILLET 2019 | MONTRÉAL, CANADA
27th IUGG General Assembly
27e Assemblée Générale de l'UGGI
International Union of Geodesy and Geophysics | Union Géodésique et Géophysique Internationale
IUGG Centennial | 1919-2019 | Centenaire de l'UGGI

ISTITUTO NAZIONALE DI GEOFISICA E VULCANOLOGIA

Hundred-Year Advances in Volcano Modelling

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Istituto Nazionale di Geofisica e Vulcanologia – Sez. Pisa, Italy

Session V01b - Celebrating 100 Year of Volcanic Activity: 1919-2019

Background photo courtesy of Amanda Clarke

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ISTITUTO NAZIONALE DI GEOFISICA E VULCANOLOGIA

Modelling Volcanic Processes

Why and when did we start modelling volcanic processes?

How is modelling of volcanic processes helping understand the volcanic system?

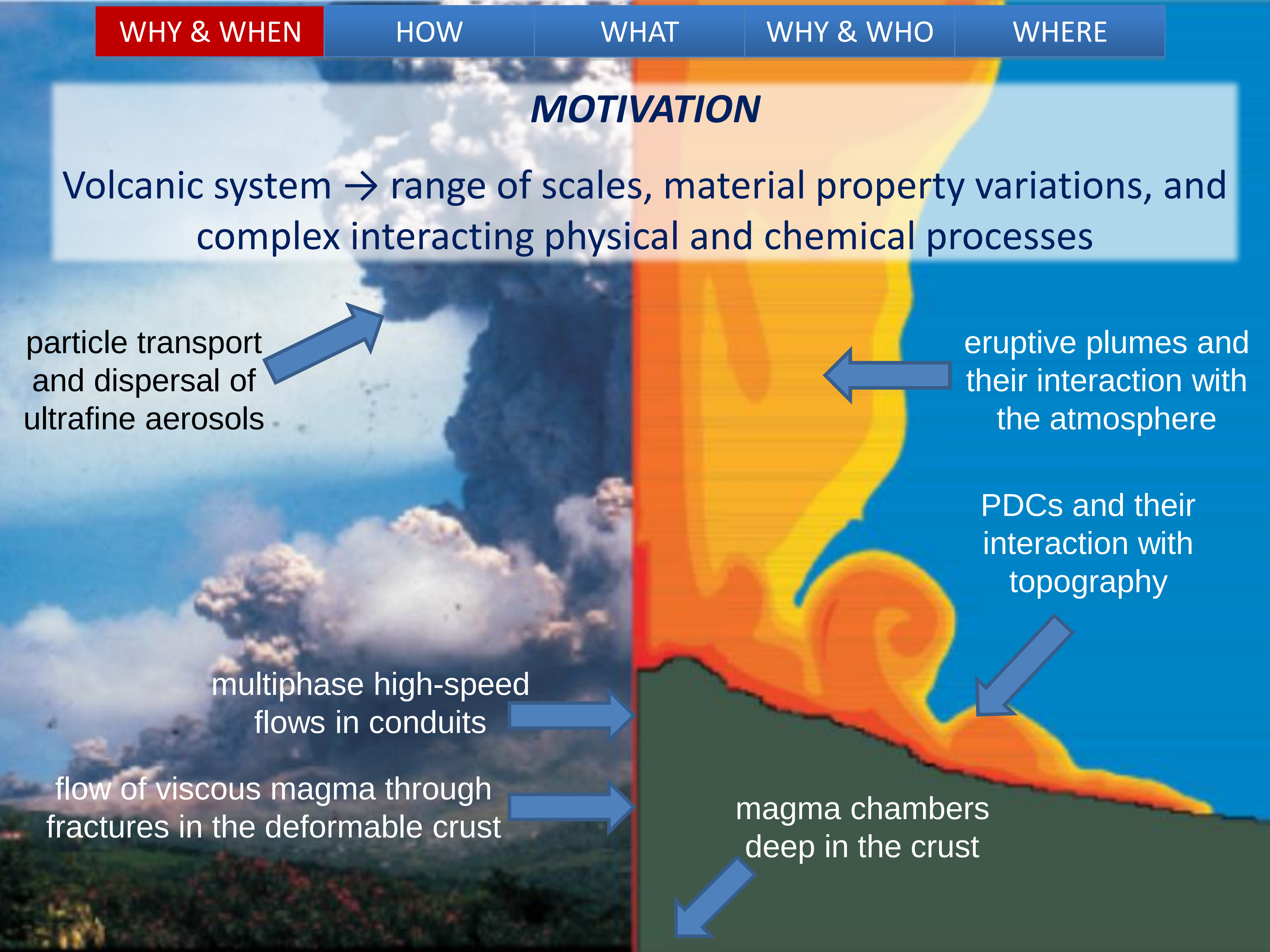
What is the relationship between volcano modelling and the natural system?

Why do we still need volcano modelling? Who needs it?

Where do we go from here?

MOTIVATION

Volcanic system → range of scales, material property variations, and complex interacting physical and chemical processes



MOTIVATION

Volcanologists have the drive and the responsibility to progress their science to improve **understanding** and **mitigation** of the effects of volcanic eruptions

Many key volcanic processes cannot be observed and analysed directly

Hazardous processes are required to be analytically and numerically described for both real-time forecasting and long-term risk reduction strategies

A variety of dedicated models of different complexity needed to be developed at multiple scales that could address different purposes

DEVELOPMENT OF VOLCANOLOGY SPURRED BY CRISES AND CATASTROPHES

"The world quickly learned that the impacts of large geophysical events are global, and that they demonstrate the inter-dependence of land, sea, and air" Simkin and Fiske 1984

Vesuvius

Tambora

Krakatau

Soufr. St Vincent

Santa Maria

Mt Pelée

79AD

1815

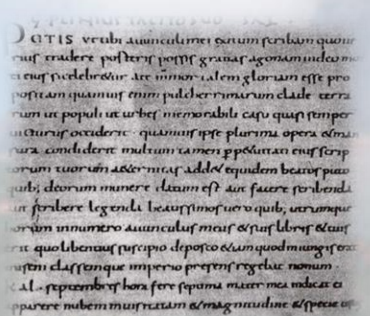
1883

1902

79AD

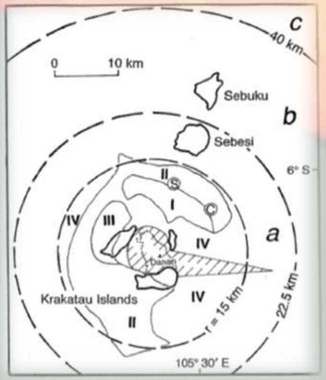
1855

1885



Letters of Pliny the Younger

Zollinger (1855)



Verbeek (1885)

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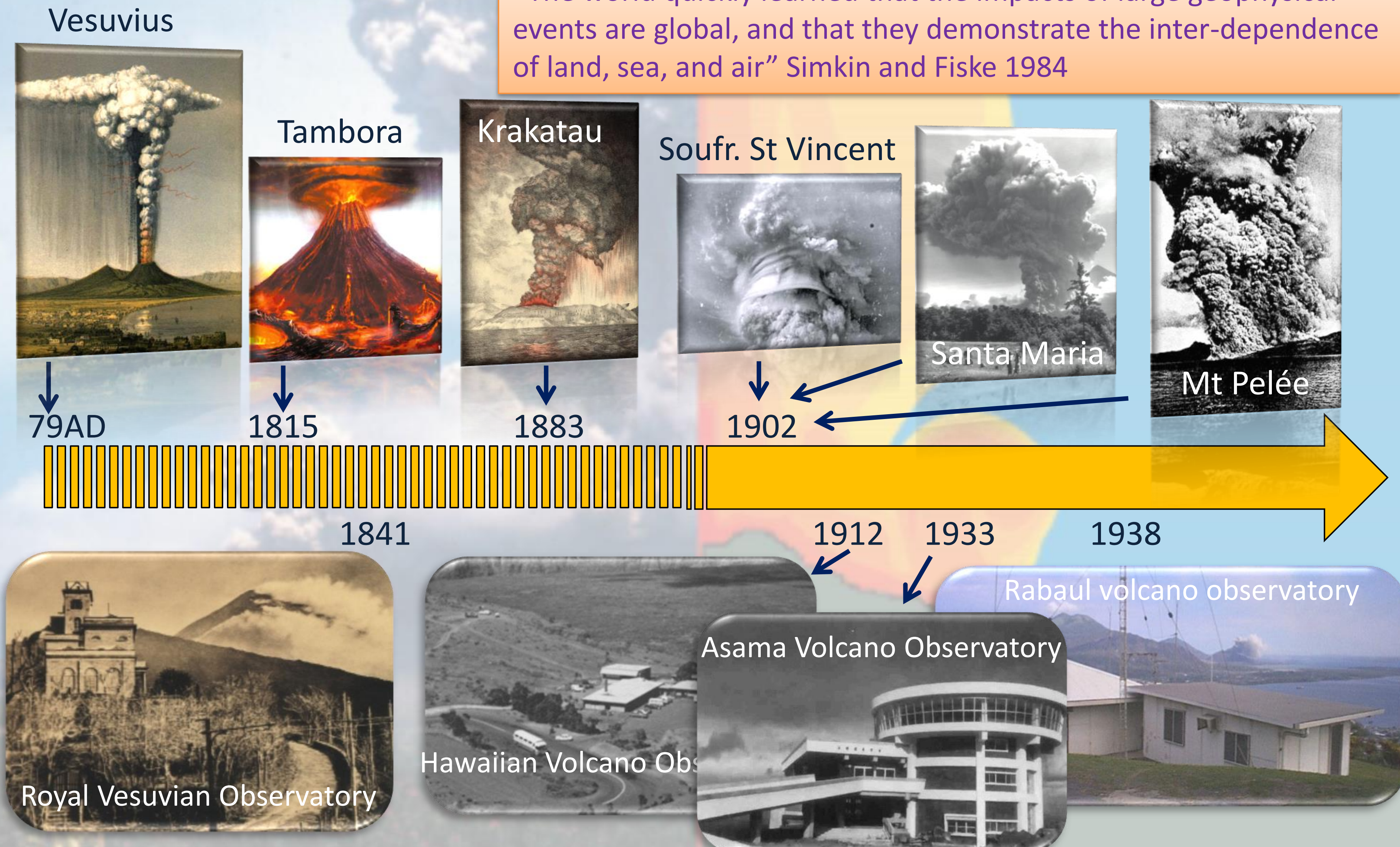

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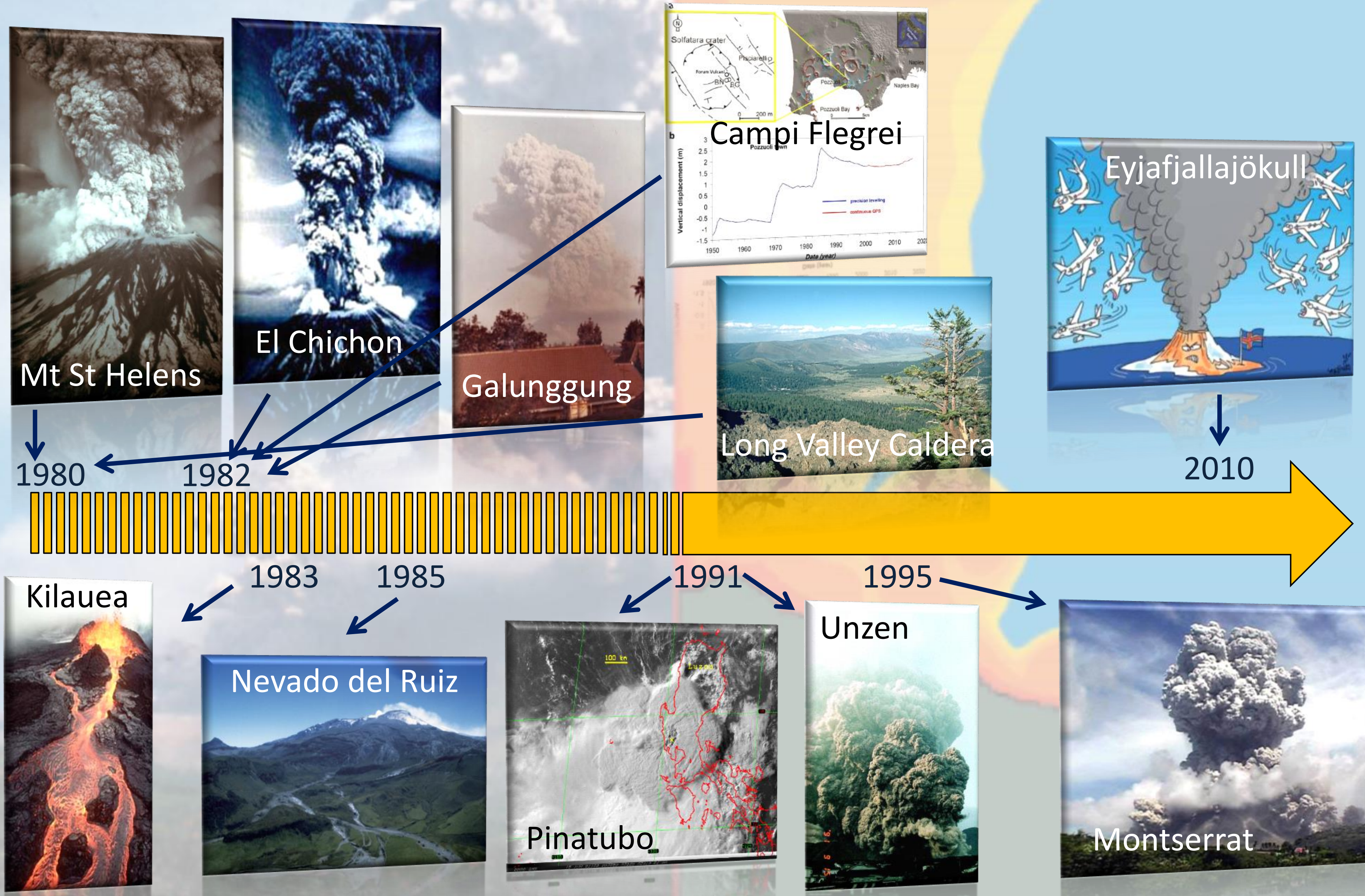


FIRST GENERATION OF VOLCANO MODELLING

1970-1990: analytical, 1-2D, homogeneous and steady models

→ to explain and understand fundamental volcanic processes (e.g. magma chambers, plumes, tephra fallout, column collapse, lava flows)

→ based on a combination of observations, experiments, theoretical models

SECOND GENERATION OF VOLCANO MODELLING (> 1990)

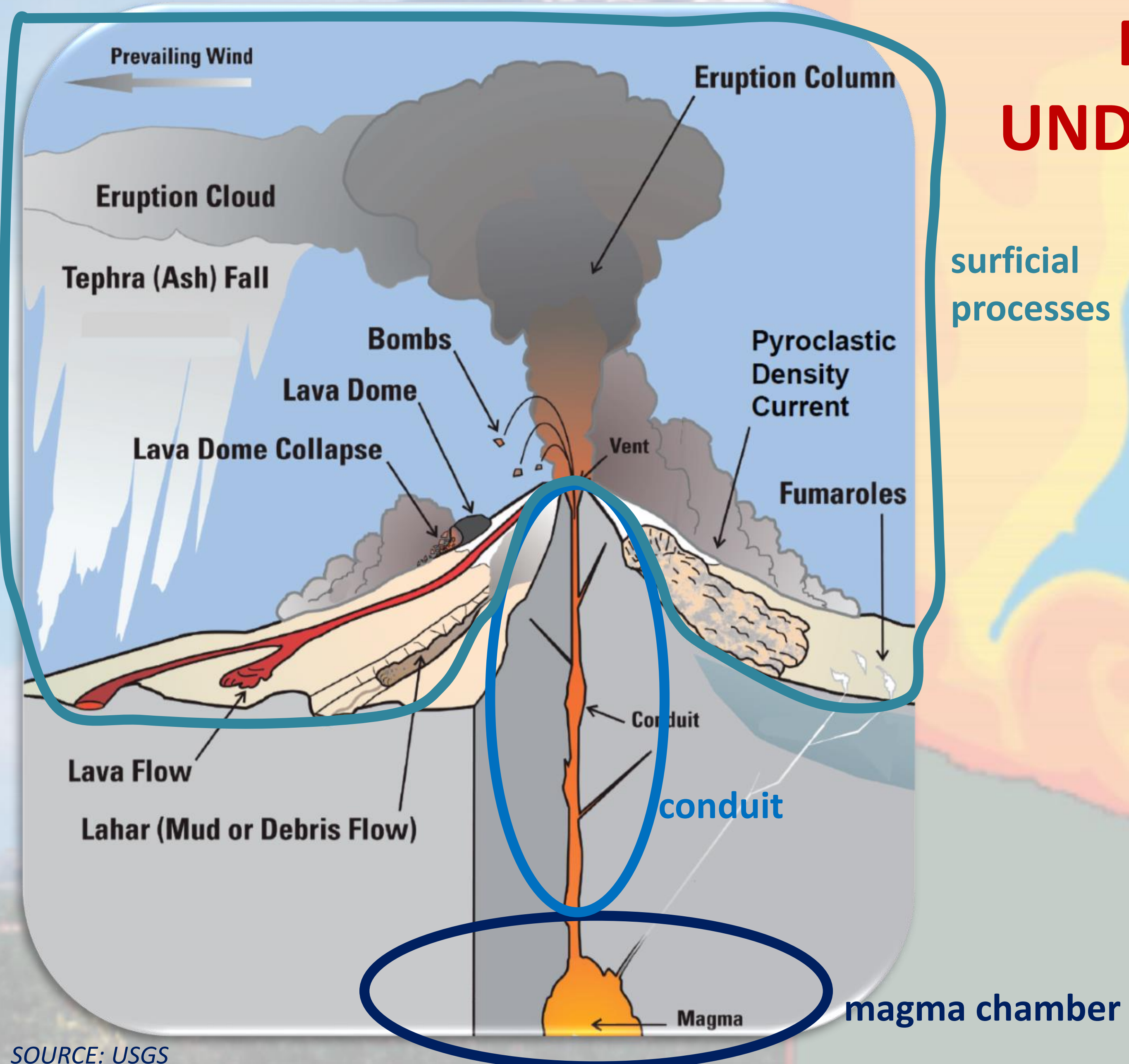
→ Further development of volcano models for a better understanding of volcanic processes

→ Further development of 1-2D models

→ Development of 3D models

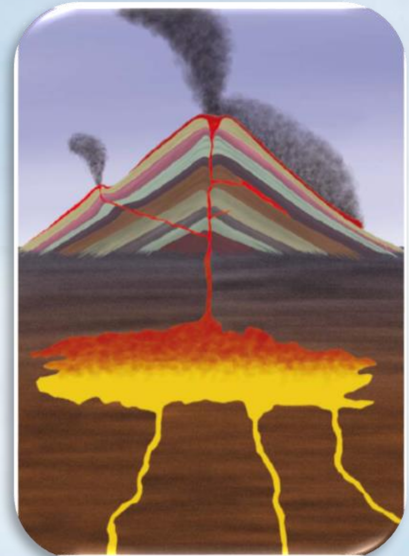
→ Development of hazard models for both long-term hazard assessment and real-time forecasting

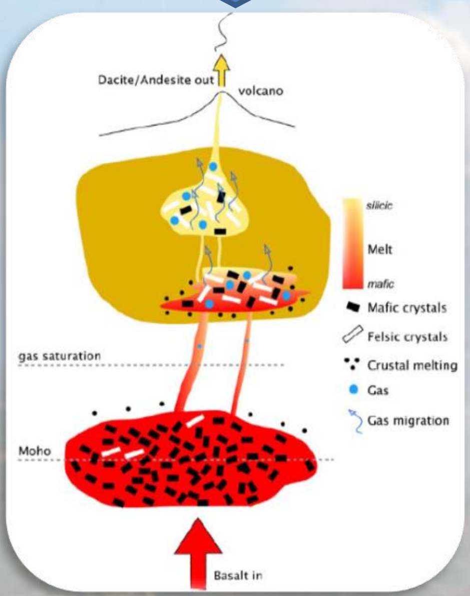
PHYSICAL UNDERSTANDING



SOURCE: USGS

Magma chamber





SOURCE: Caricchi and Blondy 2015

Dynamics of magma chambers

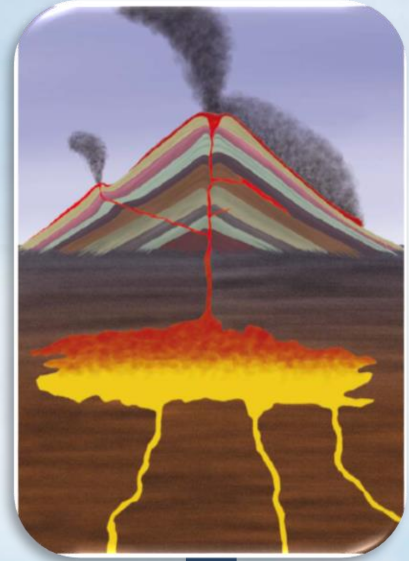
<1990 *→ crystal settling, intrusion of hot and dense magma, magma mixing, convection, large-scale cyclic layering*

>1990 *→ crystal-rich mushes, zoning in magma chambers, magma mixing and compositional heterogeneities*

Triggering mechanisms of volcanic eruptions

→ elastic model (magma input; volatile oversaturation), visco-elastic model (accumulation of overpressure; large-caldera forming eruptions), chaotic mixing (mixing to eruption time)

Magma chamber



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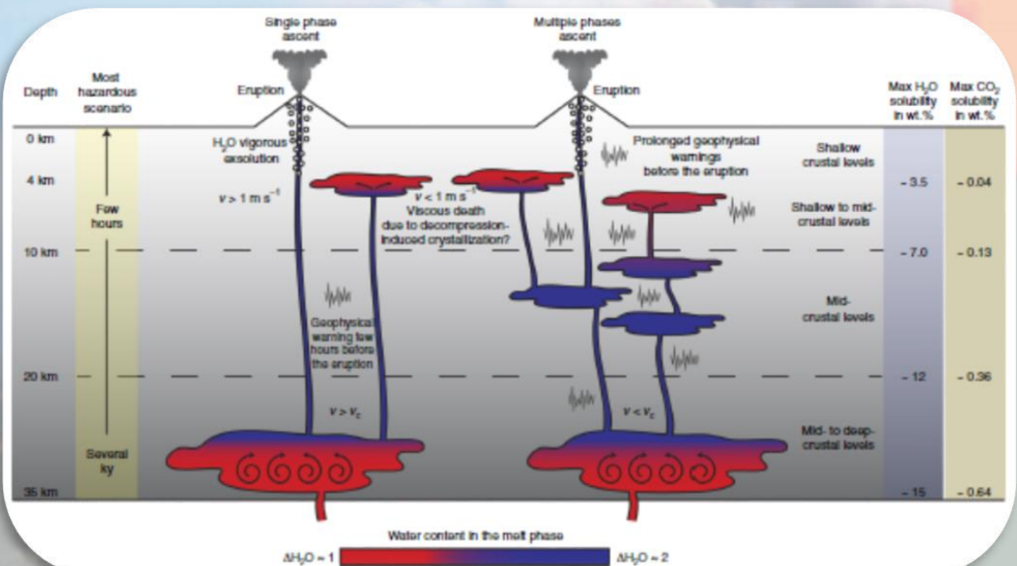
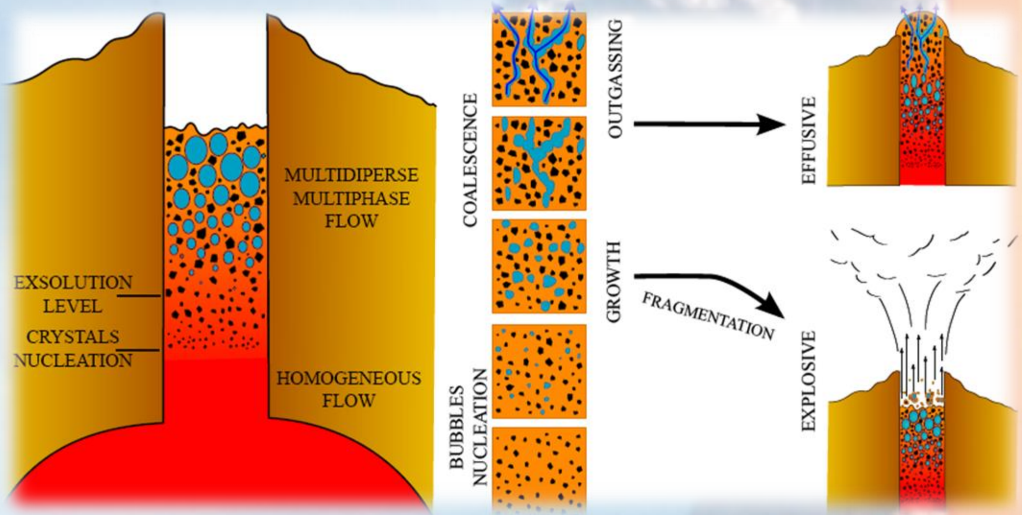


SOURCE: Petrelli et al. 2018

Numerical simulations and geophysical observations

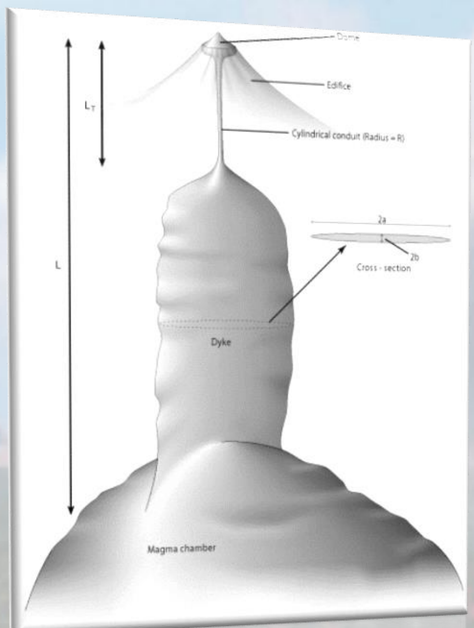
- ***Magmatic volatile phase*** *→ relationship between eruption potential and excess sulfur*
- ***Deformation*** *→ decrease of shallow system pressure associated with magma rise*
- ***Seismic signals*** *→ relationship with mingling, magma rise and water accumulation*

Volcanic conduit



Conduit models are particularly challenging due to:

- *transition to various phase regimes and lack of similarities with other fields*
- *coexistence of several interdependent, poorly-understood physical processes, which act at different temporal and spatial scales (e.g. crystallization occurs at a microscale, but affects the macroscale dynamics through viscosity)*



SOURCE: Costa et al. 2007

Dynamics of magma ascent

<1995

→ isothermal, 1D, steady, homogeneous models

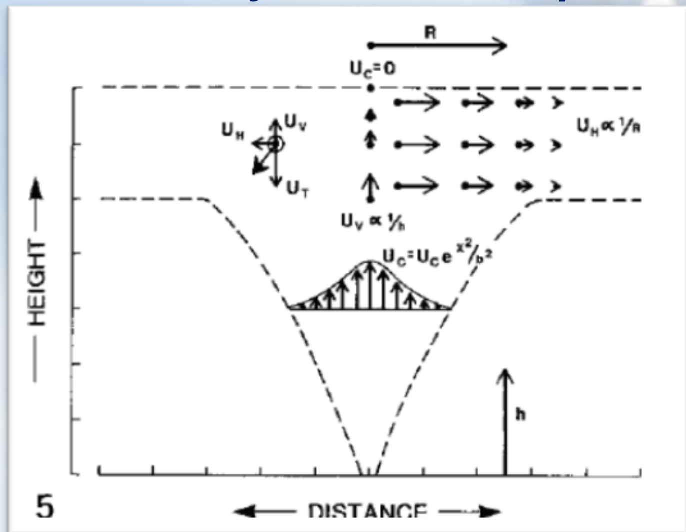
>1995

→ 1.5-2D multiphase/non-homogeneous transient models

→ effect of magma composition, temperature variation, complex geometry and wall-rock interaction on magma rise

→ coupling of different domains in 1D models

Plume dynamics and tephra fallout



SOURCE: Carey and Sparks 1986

<1990:

1-2D steady, homogeneous models

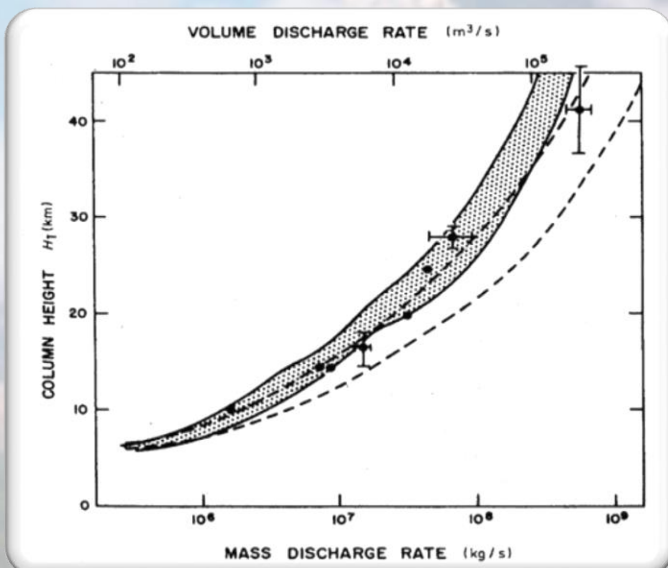
→ *Wind and radial entrainment*

→ *Sedimentation distance vs plume height*

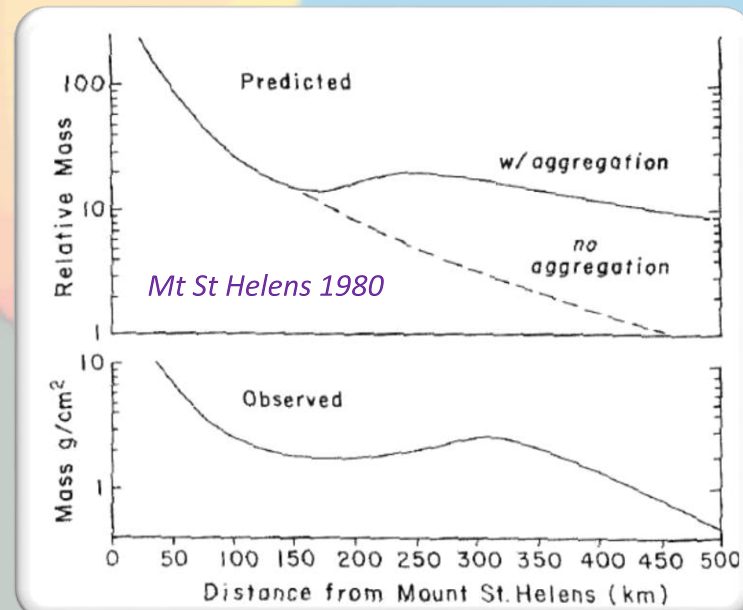
→ *Relationship height-MER*

→ *Effect of wind advection on particles dispersal*

→ *Particle aggregation*

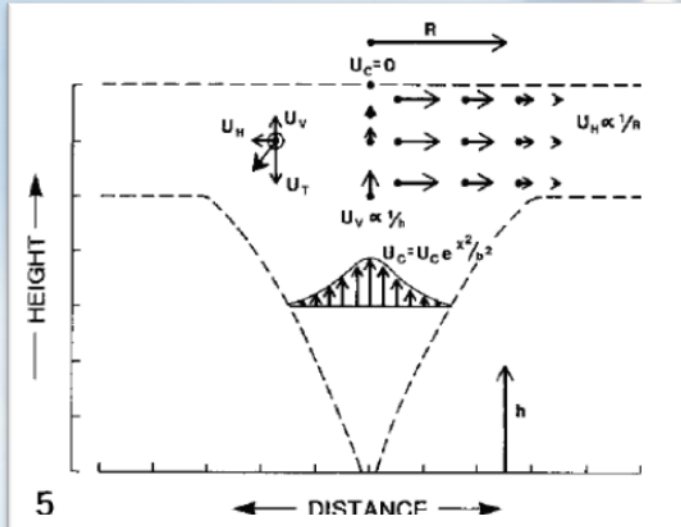


SOURCE: Sparks 1986

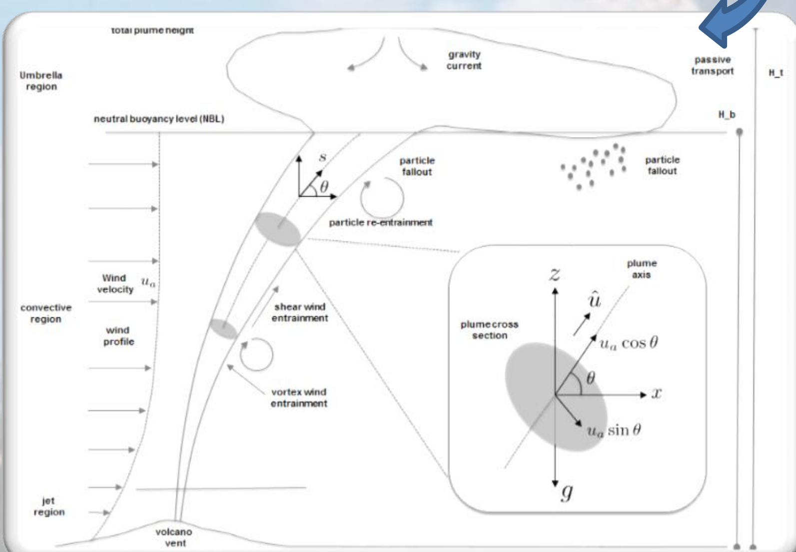


SOURCE: Carey and Sigurdsson 1982

Plume dynamics and tephra fallout



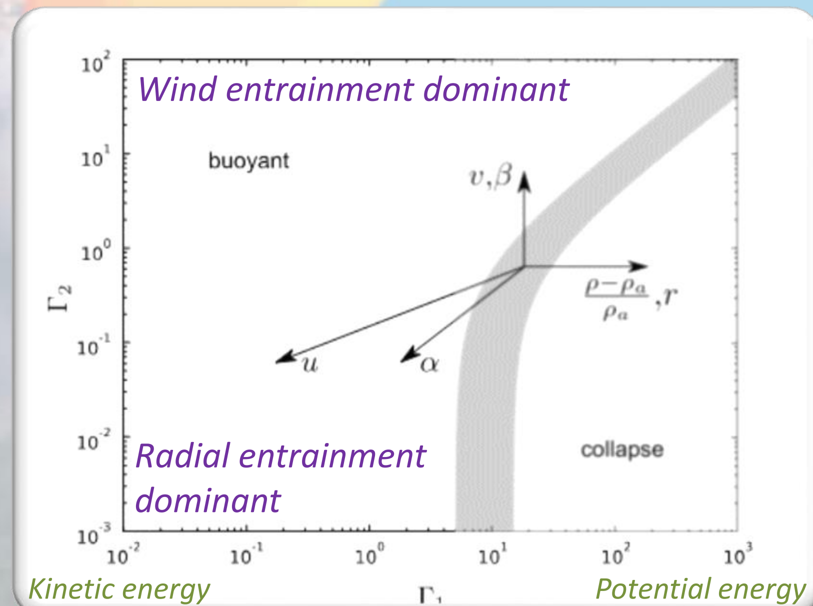
SOURCE: Carey and Sparks 1986



SOURCE: Folch et al. 2011

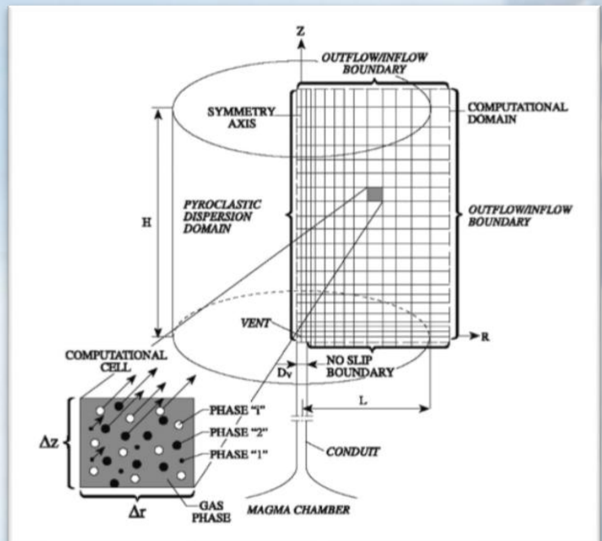
>1990:
1-2D steady, homogeneous models

- → *Superbuoyancy*
- → *Effect of Reynolds number on particle fallout*
- → *Gravity-current spreading*
- → *Effect of wind on plume rise*
- → *Column collapse steady state*
- → *Particle aggregation in plume models*
- → *Water phase transition*

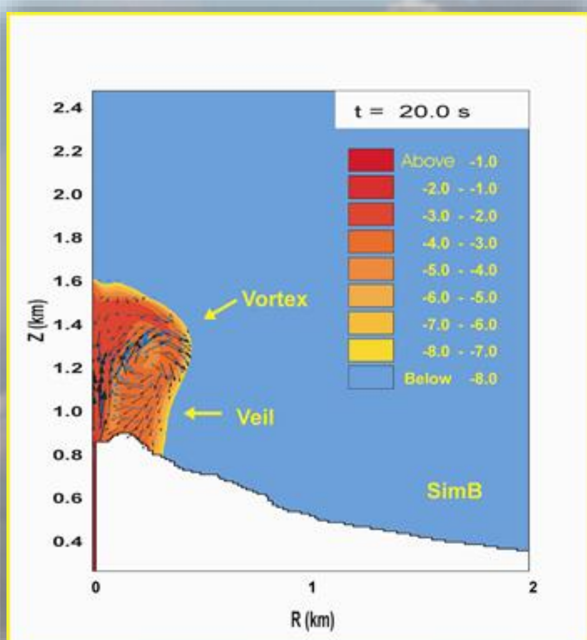


SOURCE: Degruyter and Bonadonna 2013

Plume dynamics and tephra fallout



SOURCE: Dobran at al. 1993



SOURCE: Clarke et al. 2002

>1990:

1-2D steady, homogeneous models

→ *Superbuoyancy*

→ *Effect of Reynolds number on particle fallout*

→ *Gravity-current spreading*

→ *Effect of wind on plume rise*

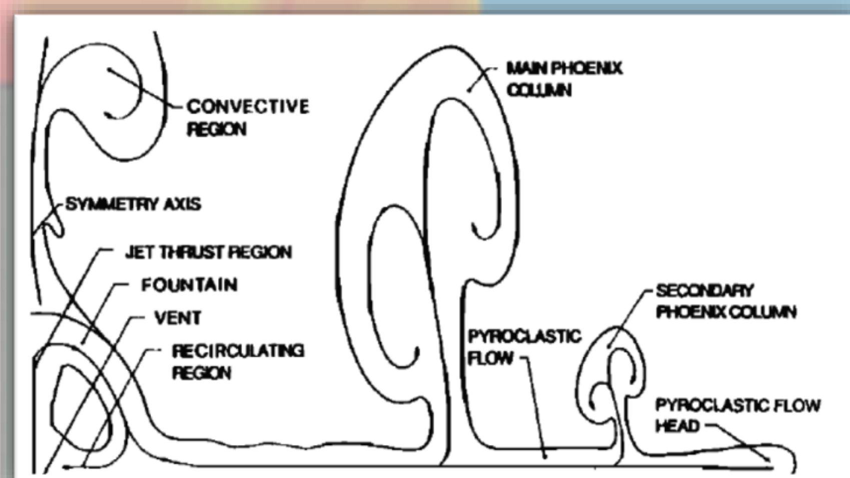
→ *Column collapse steady state*

→ *Particle aggregation in plume models*

→ *Water phase transition*

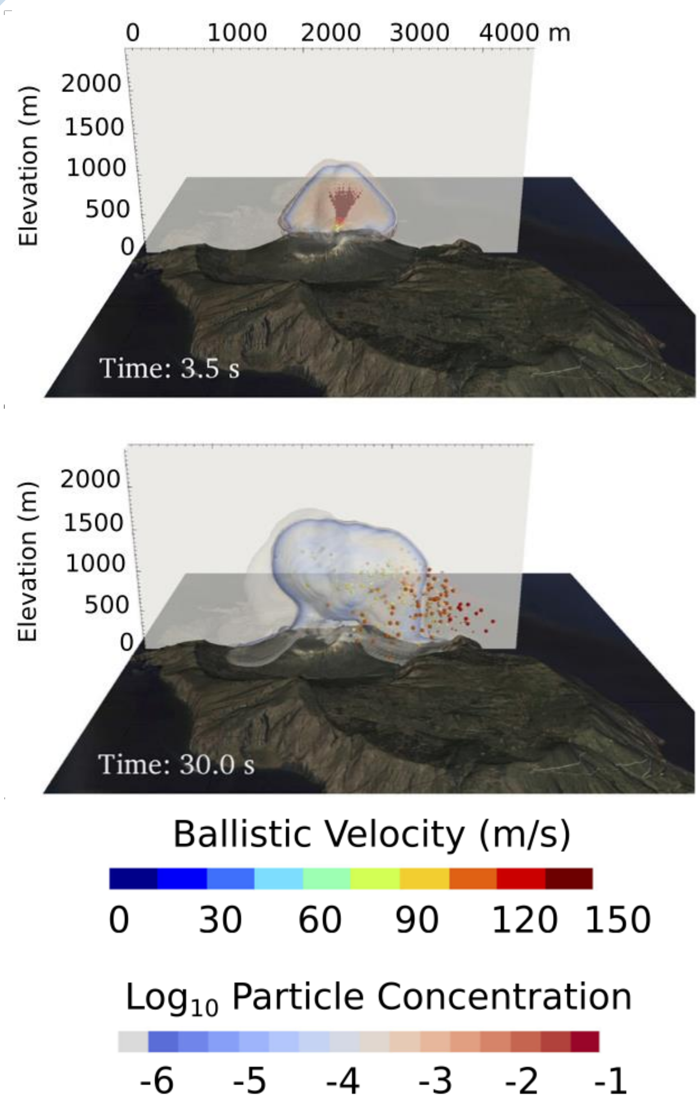
2D transient multiphase flow models

→ *Transition from mean values of properties along the plume axis to a horizontal spatial distribution*



SOURCE: Neri and Dobran 1994

Plume dynamics and tephra fallout



SOURCE: Rosi et al. 2018

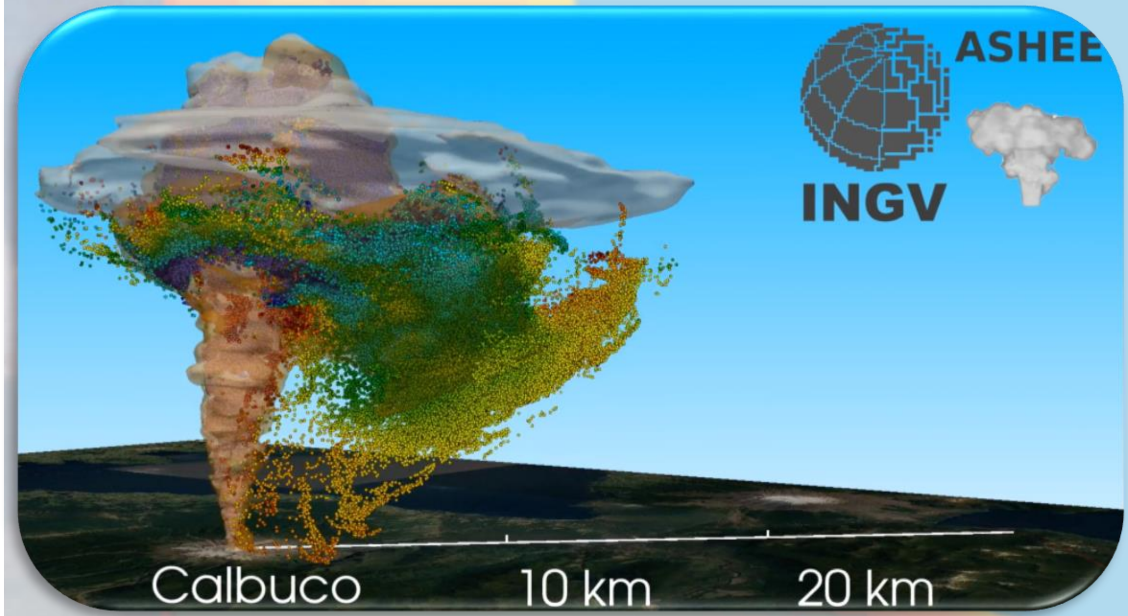
>1990:

3D transient multiphase flow models

→ *wind shear on plume dispersal*

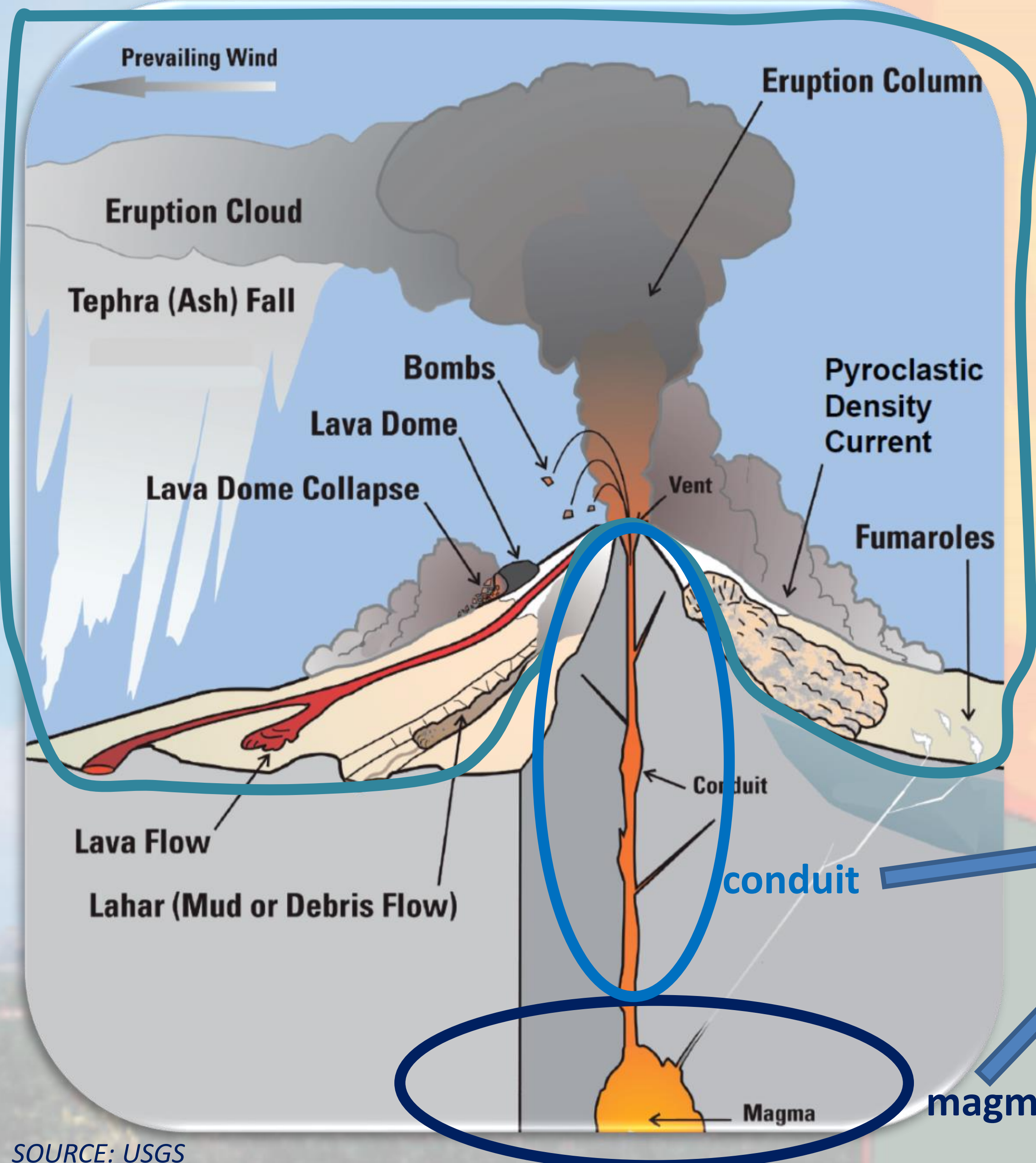
→ *effect of topography on flow inundation*

→ *more accurate description of the multiparticle nature of the pyroclastic mixture*



SOURCE: Cerminara et al. 2016

HAZARD ASSESSMENT



SOURCE: USGS

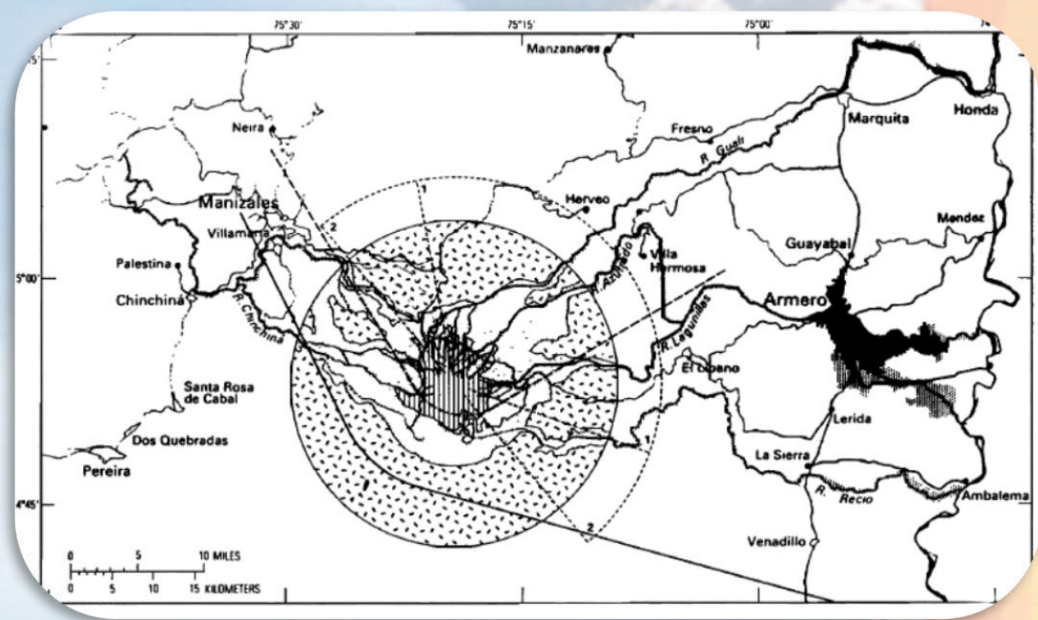
surficial processes

FORECASTING

PREDICTION

magma chamber

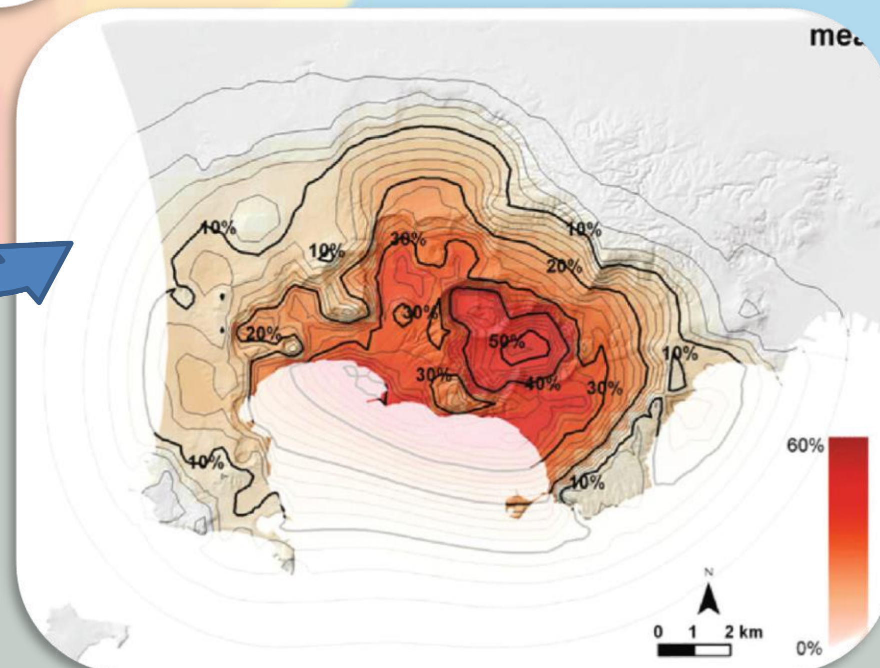
HAZARD ASSESSMENT



Hazard Zonation Map Nevado del Ruiz; Tilling 1989

<1990: ***hazard maps reflected areas that had been affected by past events***

Probability map of PDC inundation combined with probability of vent location opening at Campi Flegrei (weighted by expert elicitation); modified from Bevilacqua (2016) and Neri et al. (2015)

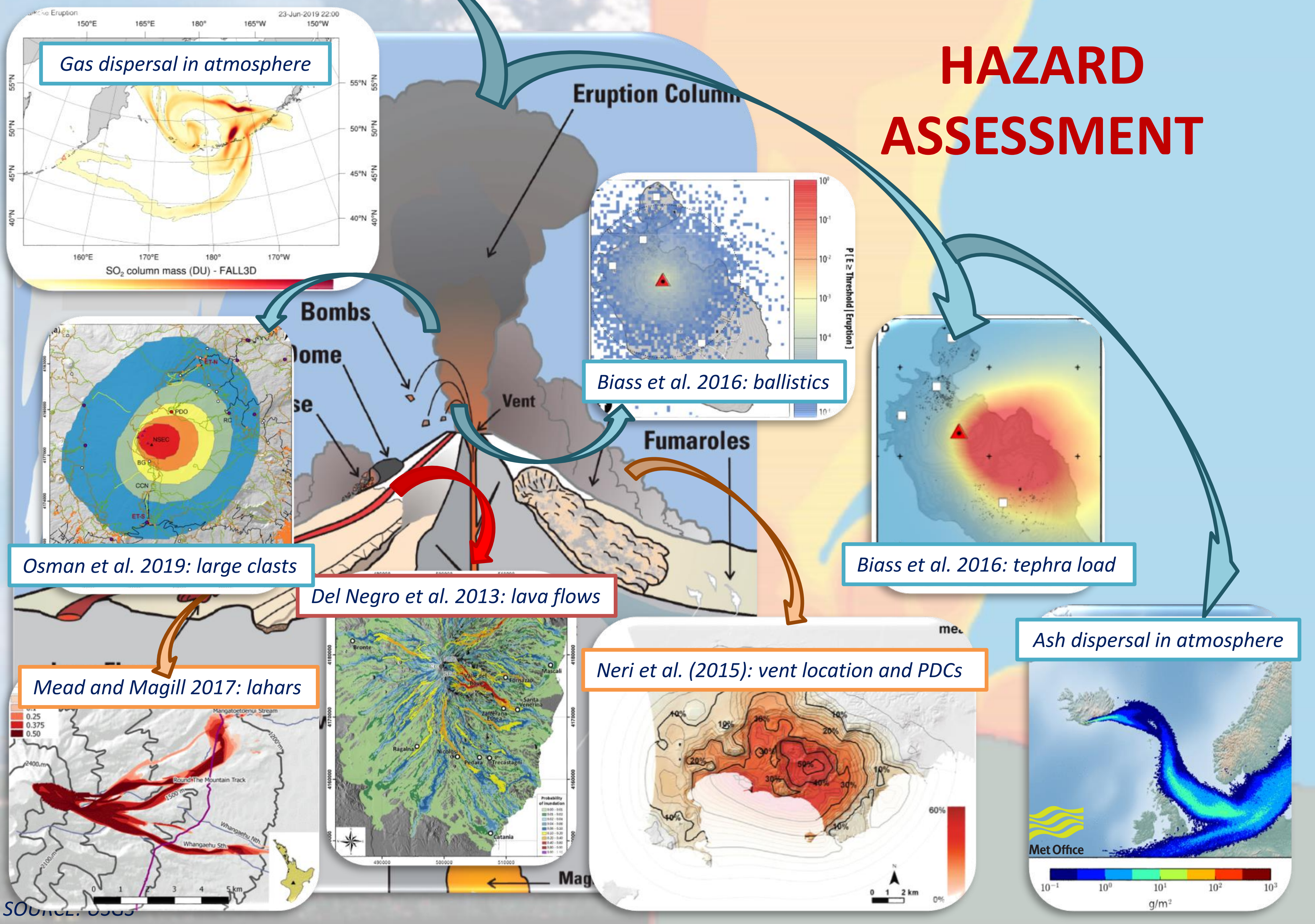


>1990: Analytical and numerical description of…

Gas dispersion
Ballistics
Lava flows
PDCs and lahars
Tephra fallout and dispersal
Ash resuspension

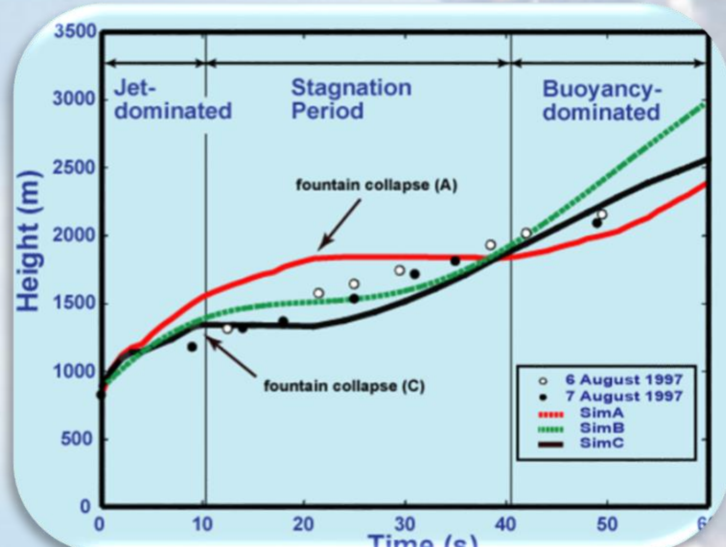
>2000:
Probabilistic hazard assessment
Real-time forecasting

HAZARD ASSESSMENT

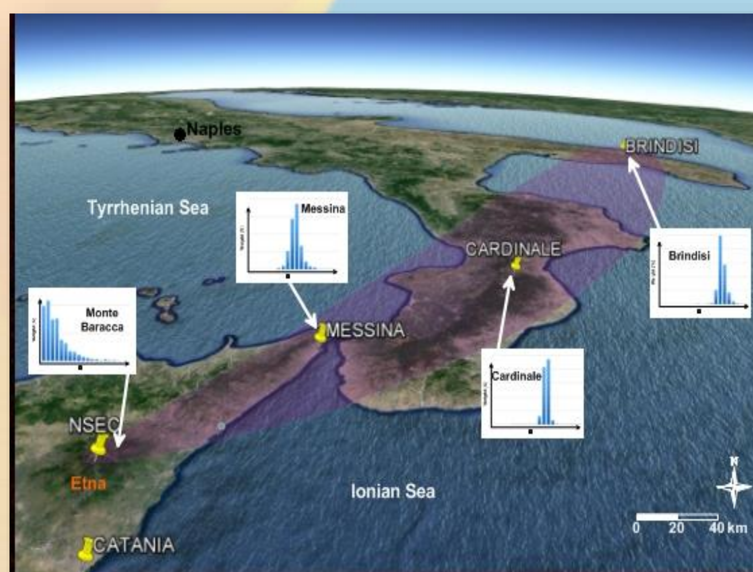


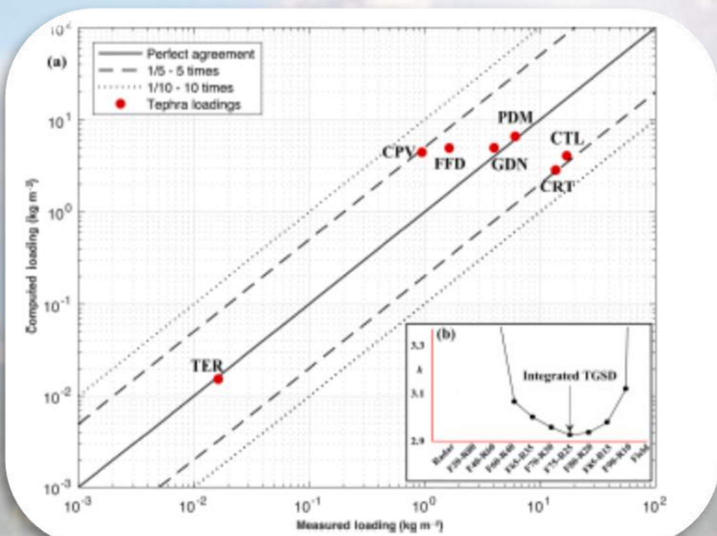
RELATIONSHIP BETWEEN NATURAL SYSTEM AND VOLCANO MODELLING

Model "validation" (=testing), calibration and integration

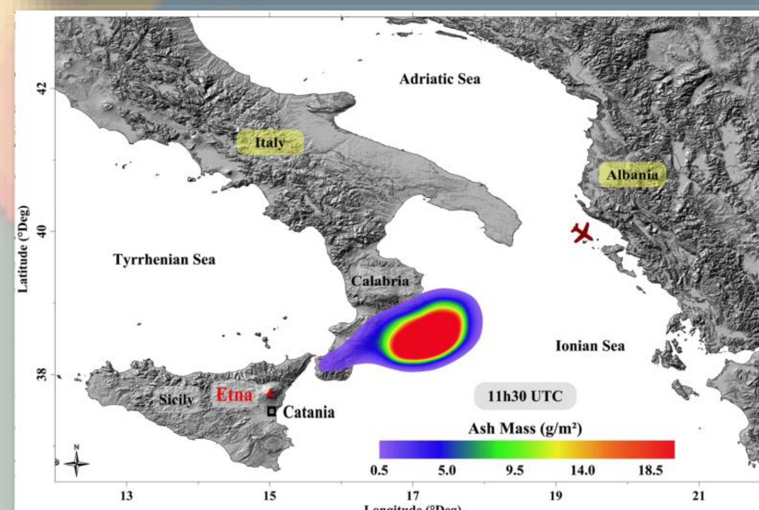


SOURCE: Clarke et al. 2002





SOURCE: Poret et al. 2017

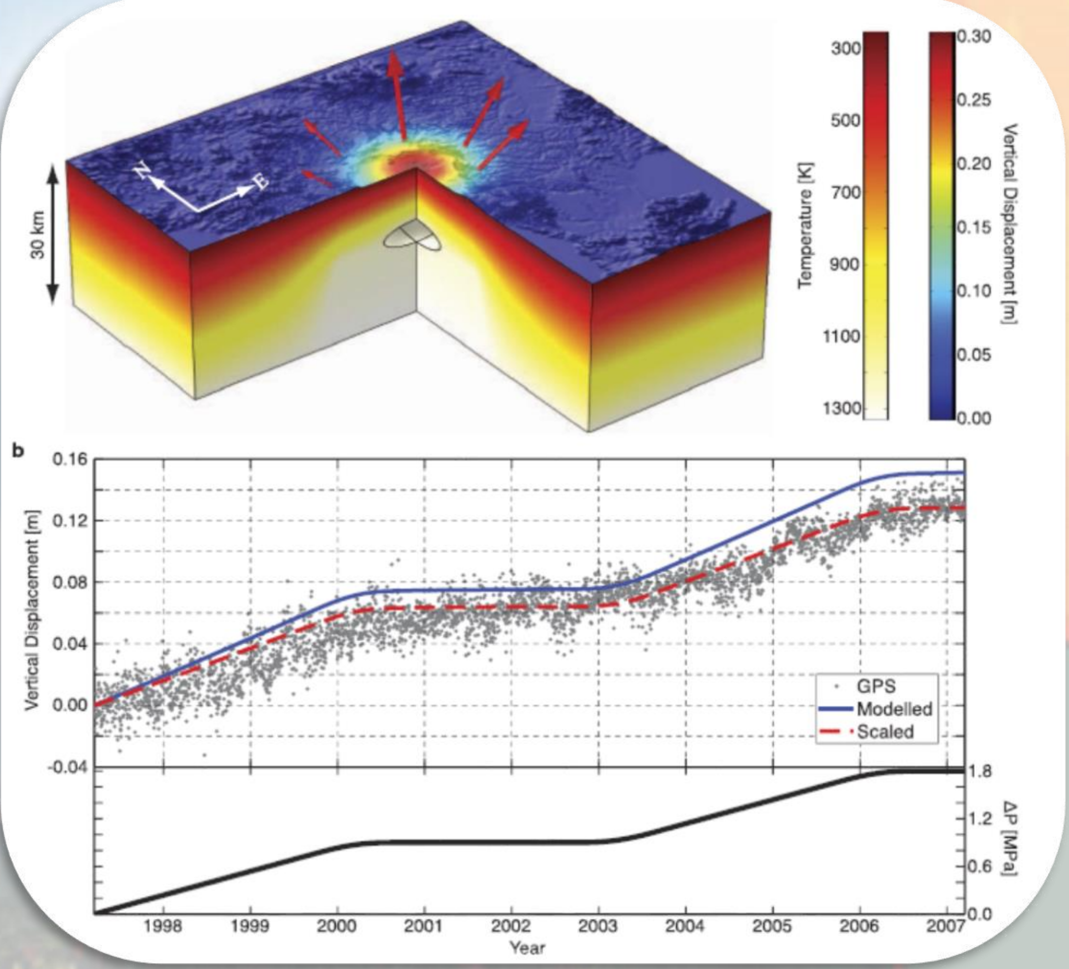


SOURCE: Poret et al. 2017

RELATIONSHIP BETWEEN NATURAL SYSTEM AND VOLCANO MODELLING

Inversion of observation data

→ *inverting deformation data to characterize magma supply rate (Aira caldera, Japan)*

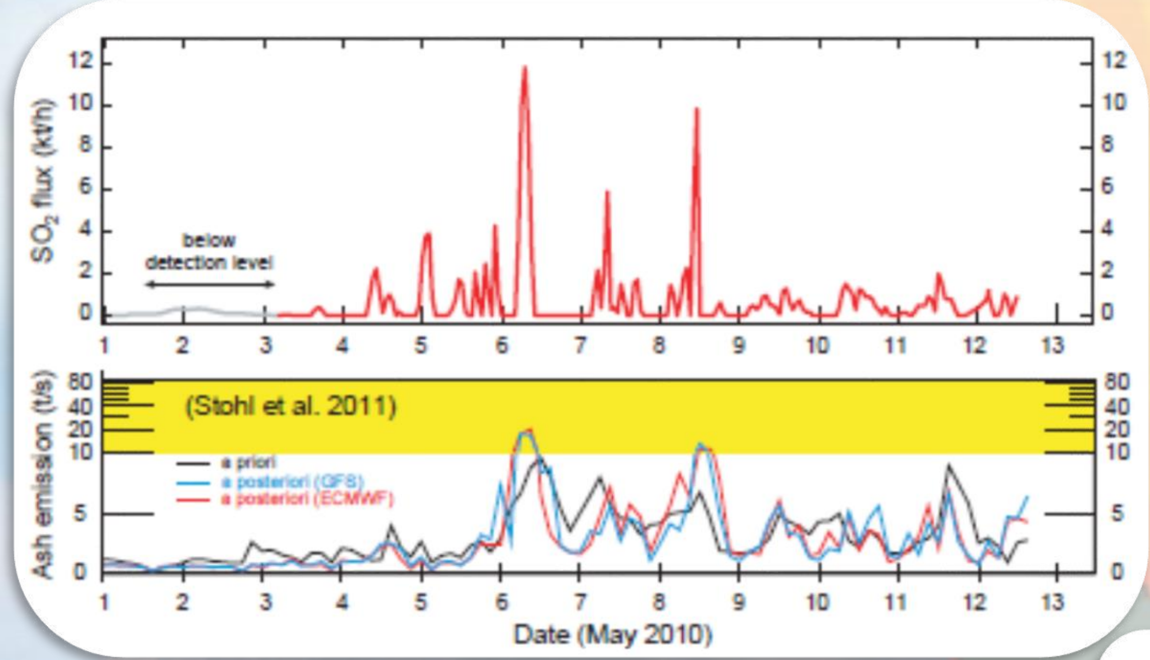


SOURCE: Hickey et al. 2016

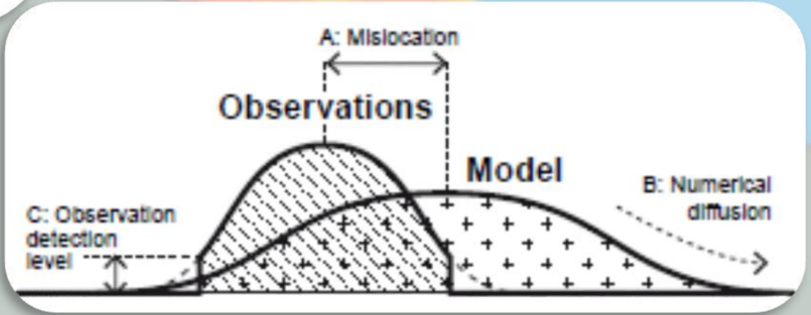
RELATIONSHIP BETWEEN NATURAL SYSTEM AND VOLCANO MODELLING

Inversion of observation data

→ inverting for volcanic SO_2 flux based on satellite imagery and chemistry-transport model (CHIMERE) (Eyjafjallajokull 2010)



SOURCE: Boichu et al. 2013



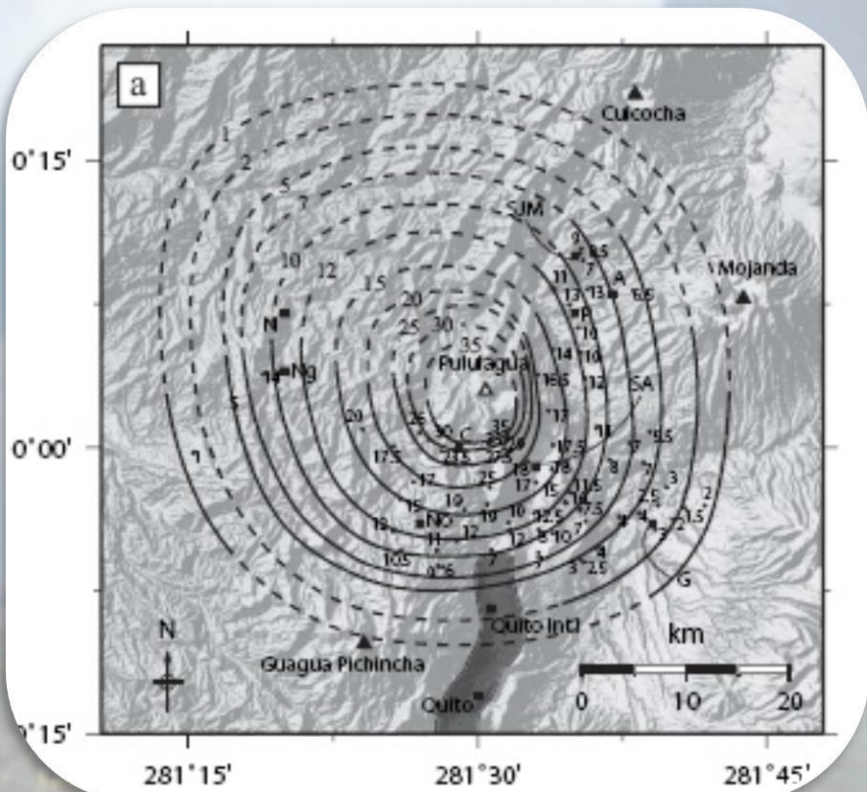
RELATIONSHIP BETWEEN NATURAL SYSTEM AND VOLCANO MODELLING

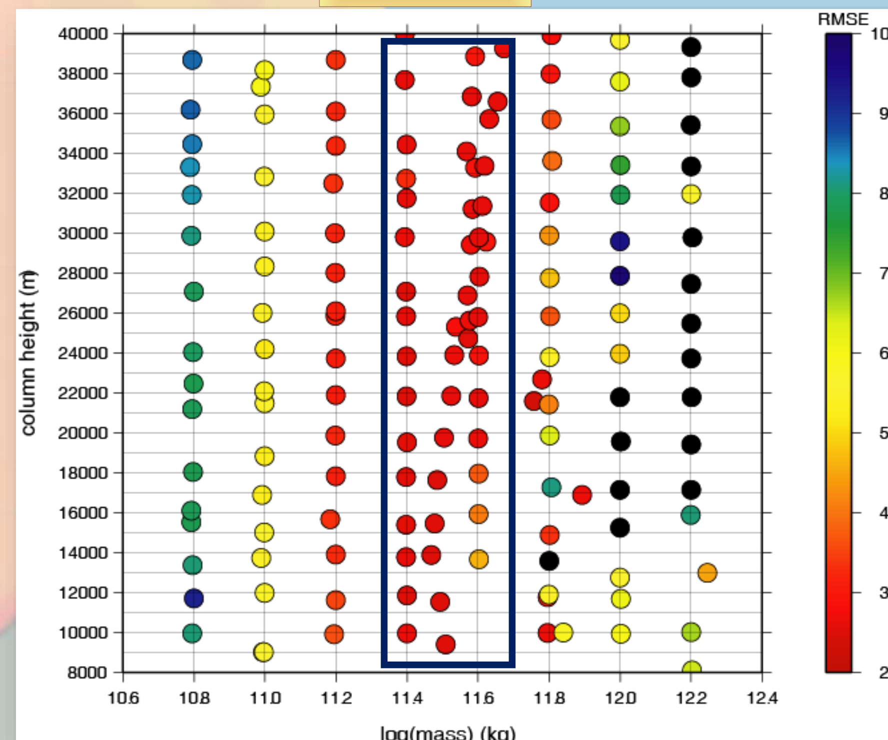
Inversion of observation data

→ inverting for erupted mass and plume height based on deposit observations and advection-diffusion model (TEPHRA2) (Pululagua 2450BP, Ecuador)

Mass/Area (at each outcrop) → TEPHRA2 → Eruption parameters (mainly erupted mass)

OPTIMIZE





Mass = 3±1x10^{11} kg (mass/area)

SOURCE: Volentik et al. 2010

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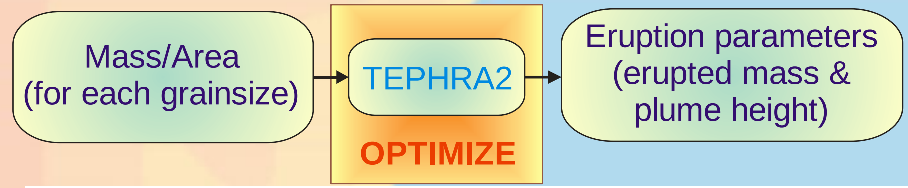
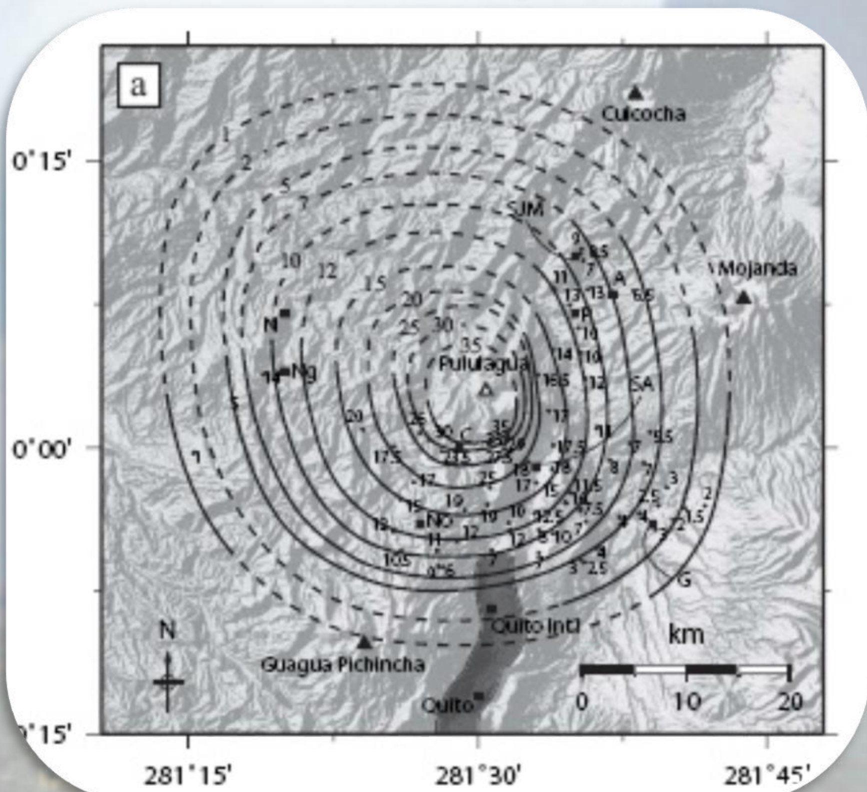
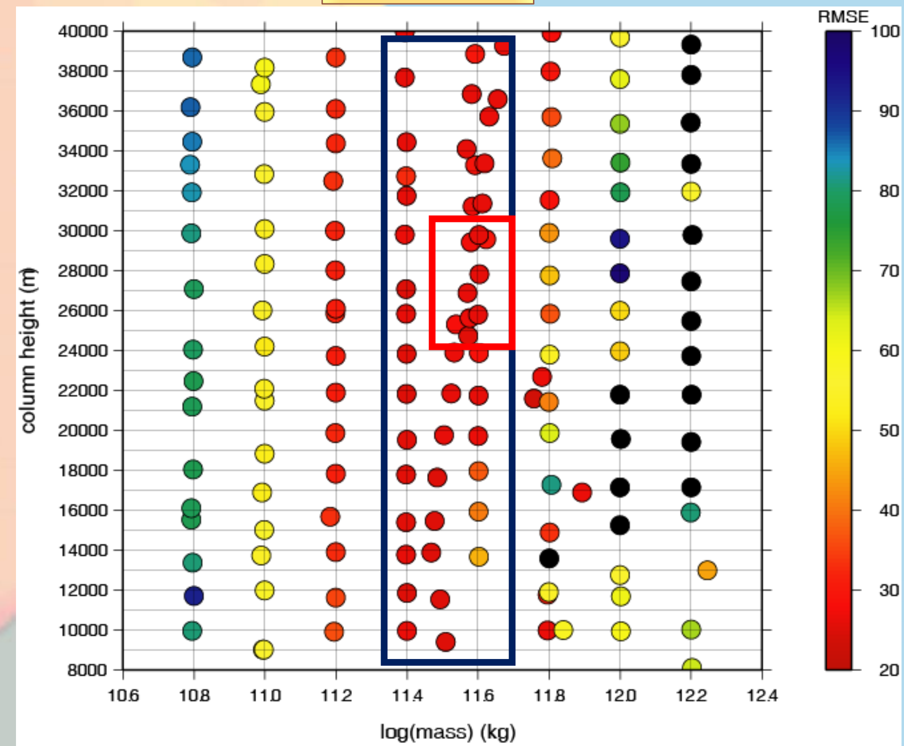






Mass = 3±1x10^{11} kg (mass/area)

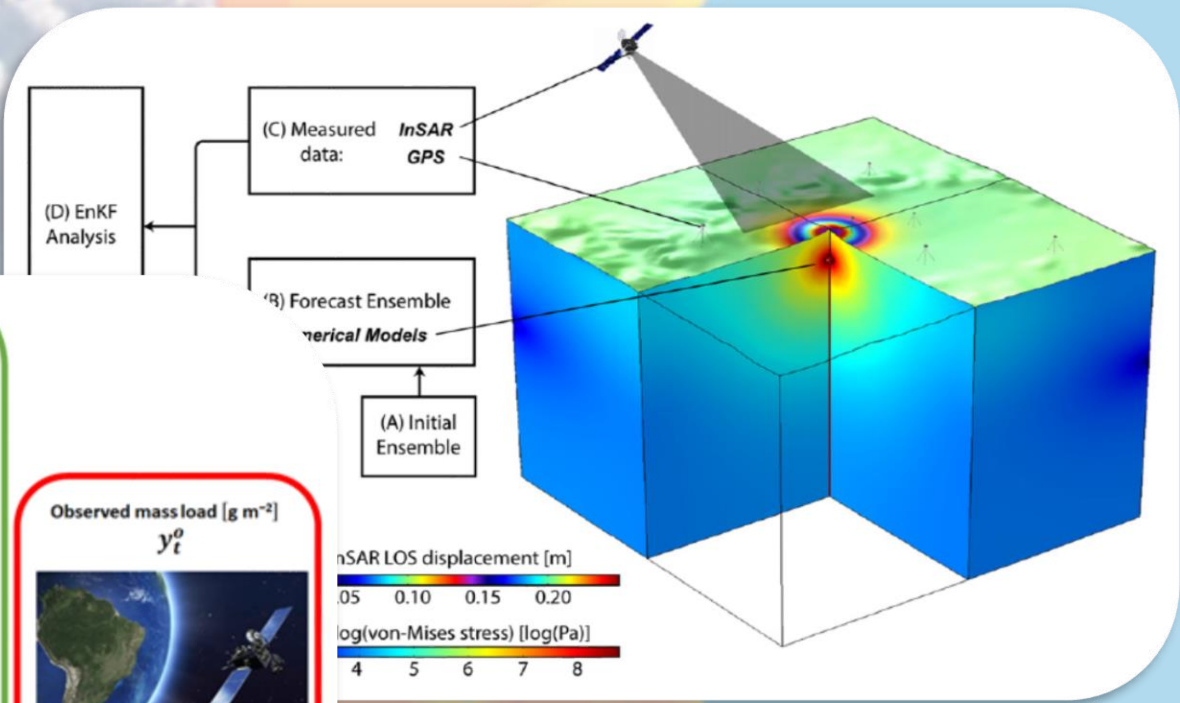
Mass = 4x10^{11} kg (grainsize)

Ht = 27±3 km (grainsize)

SOURCE: Volentik et al. 2010

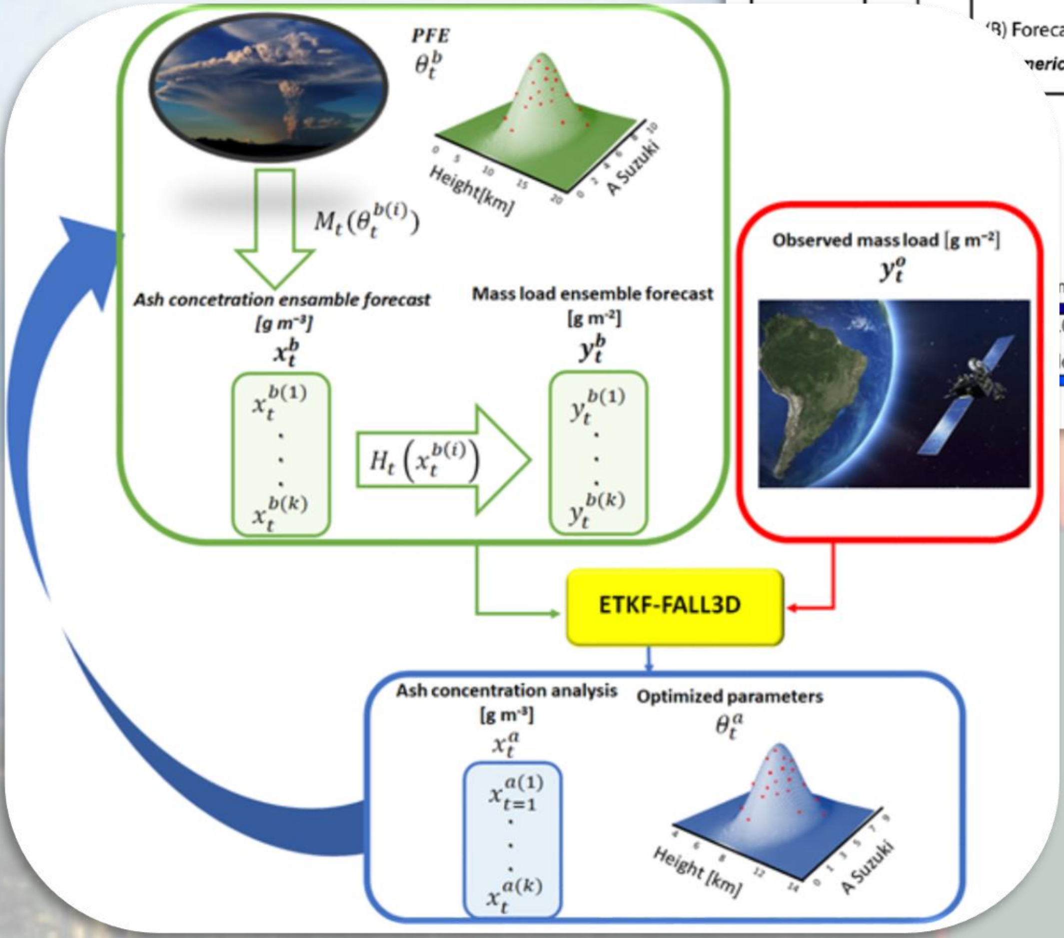
RELATIONSHIP BETWEEN NATURAL SYSTEM AND VOLCANO MODELLING

Data assimilation



SOURCE: Zhan and Gregg and 2017

SOURCE: Osores et al. 2019

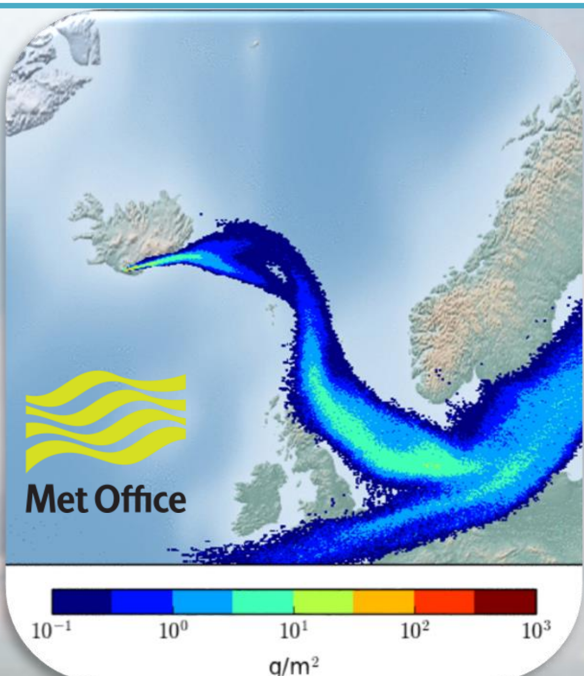


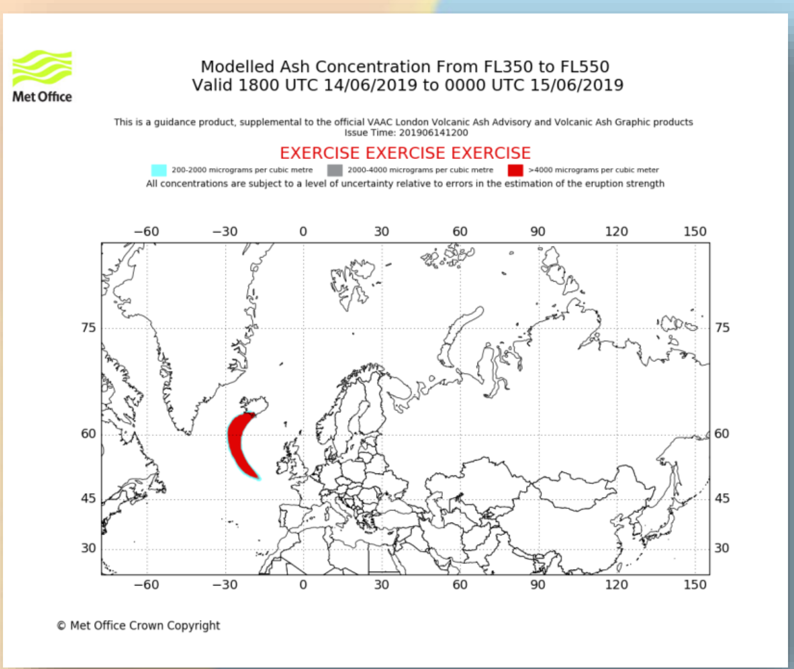
CURRENT NEEDS IN VOLCANO MODELLING

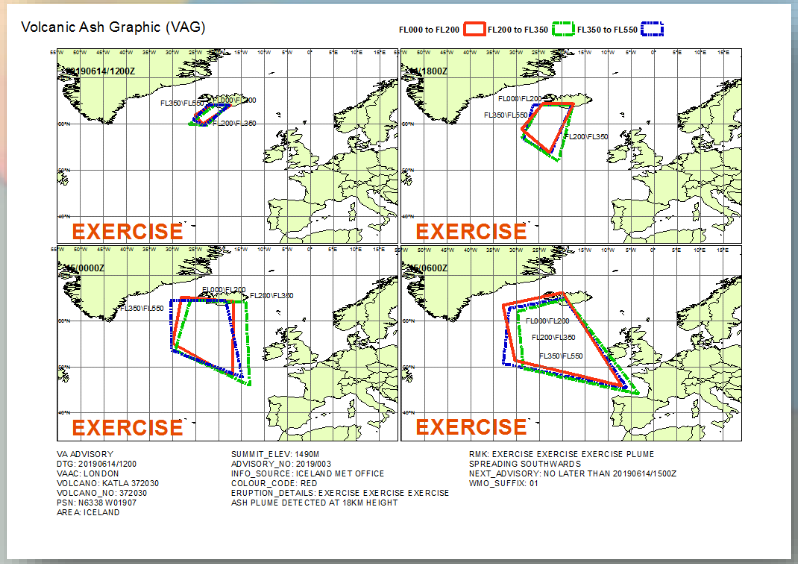
Risk reduction

→ real-time forecasting

No Fly Zone > 4mg/m^3
Time-Limited Zone 2-4 mg/m^3
Enhanced Procedures 0.2-2 mg/m^3







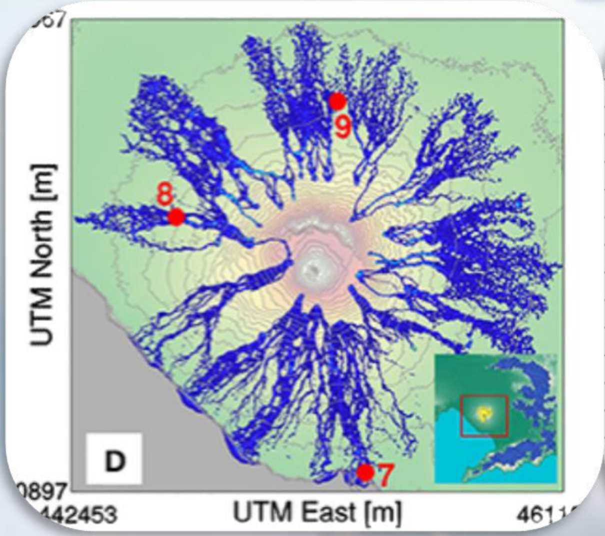
Treatment of uncertainties: ESPs, modelling, hazardous concentrations

CURRENT NEEDS IN VOLCANO MODELLING

Risk reduction

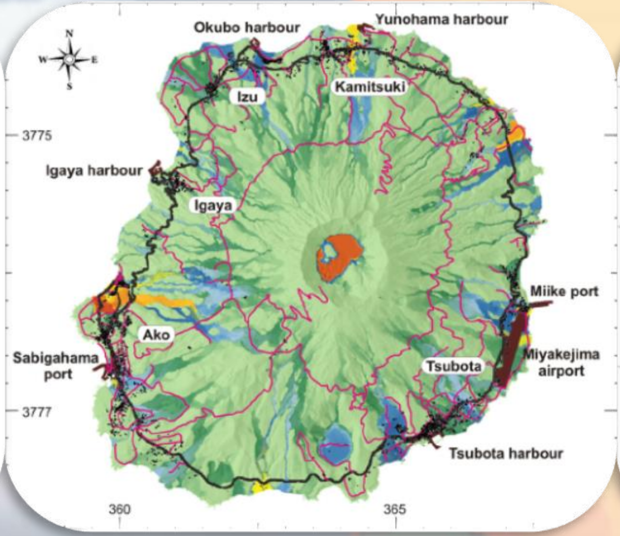
→ *long-term hazard/risk assessment: probability maps of…*

Lahars



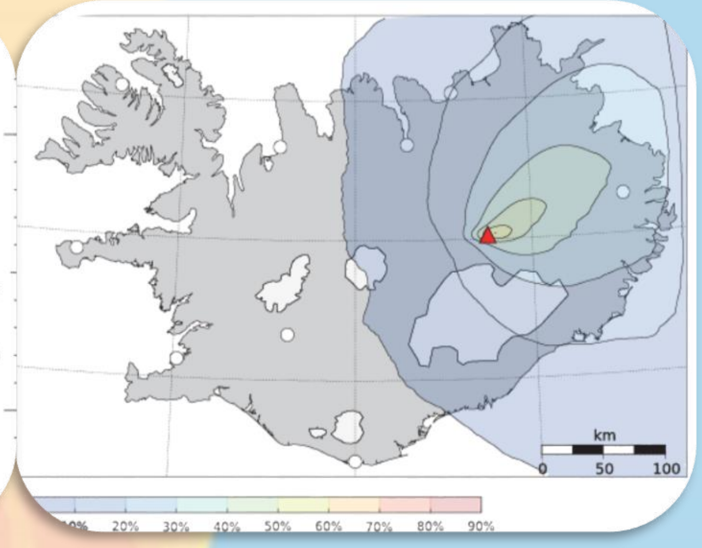
SOURCE: Tierz et al. 2017

Lava flows



SOURCE: Cappello et al. 2015

Tephra load (1 kg/m²)

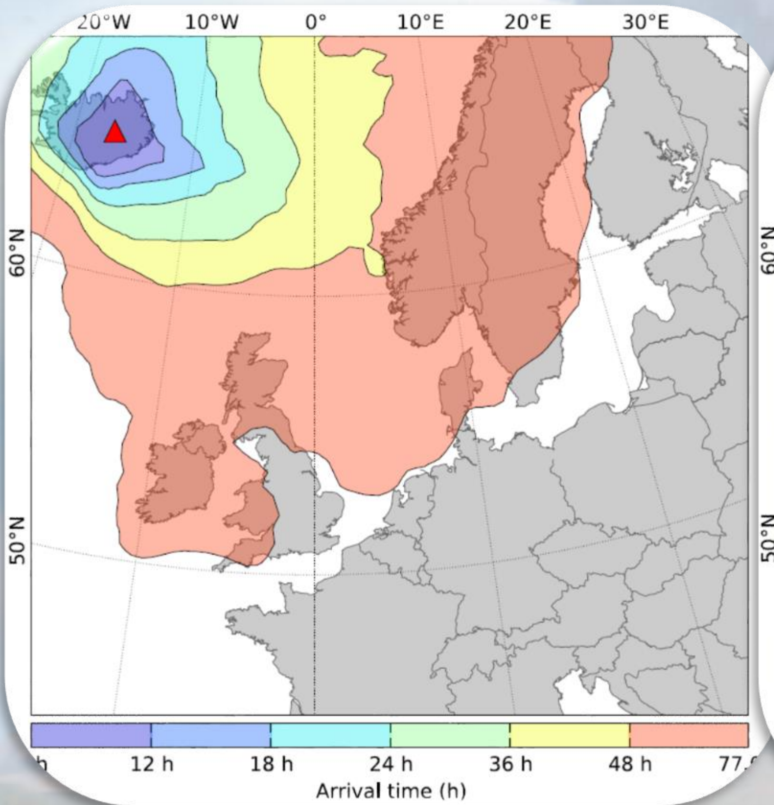


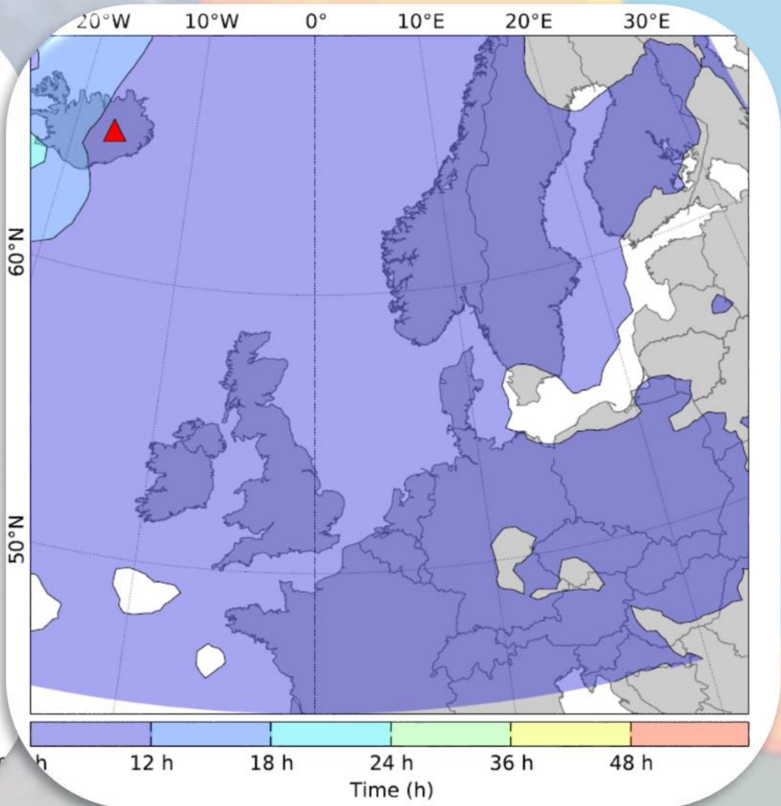
SOURCE: Biass et al. 2014

CURRENT NEEDS IN VOLCANO MODELLING

Risk reduction

→ long-term hazard/risk assessment: probability maps of…





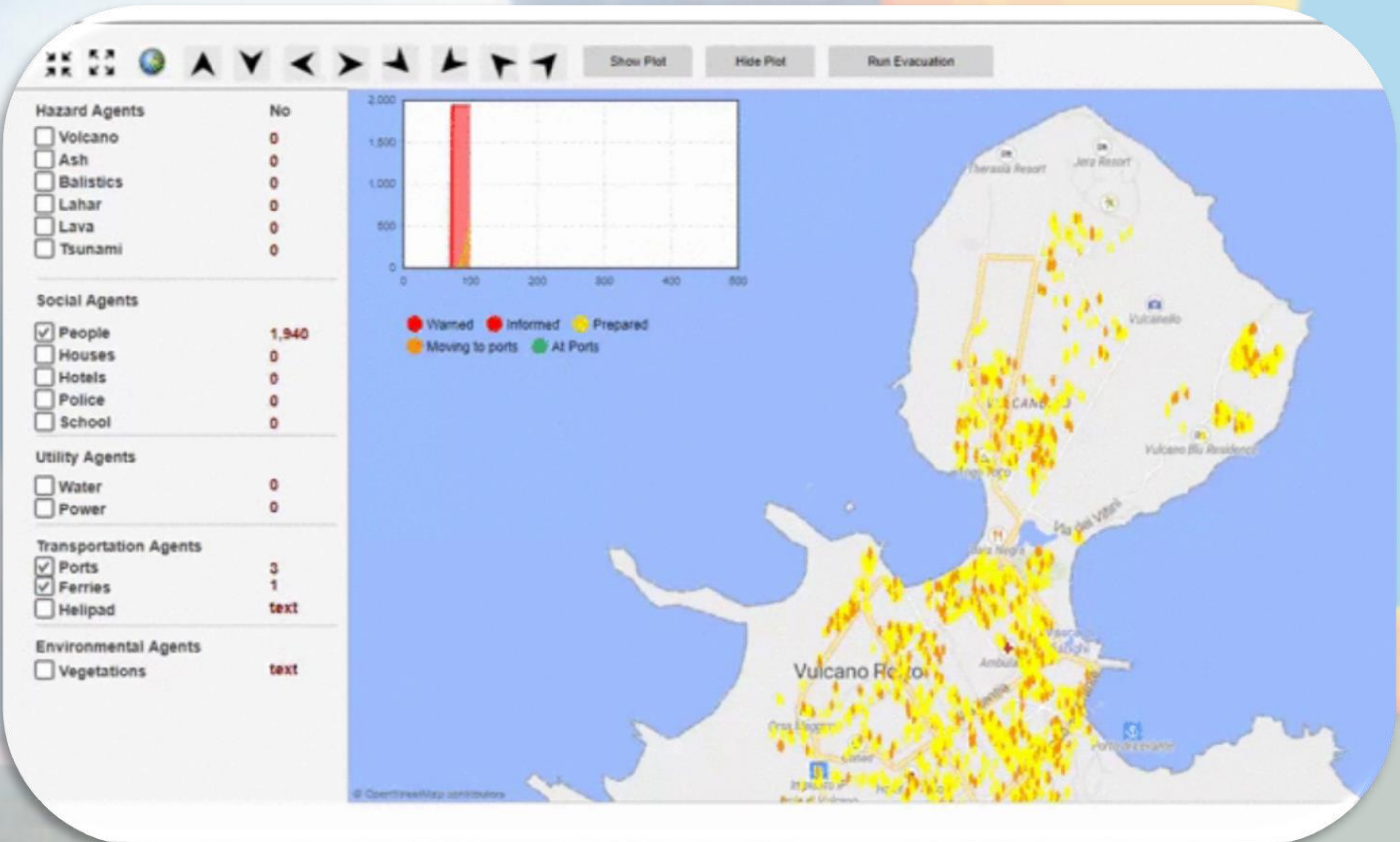
SOURCE: Biass et al. 2014

Mean arrival and residence time (2 mg/m^3)

CURRENT NEEDS IN VOLCANO MODELLING

Emergency preparedness

→ *evacuation analysis*



Agent-based modelling to analyze evacuation operations: duration, routes, scenarios (e.g. partial vs total evacuation)

CURRENT NEEDS IN VOLCANO MODELLING

Advance our understanding of the volcanic system

When will a volcano erupt?

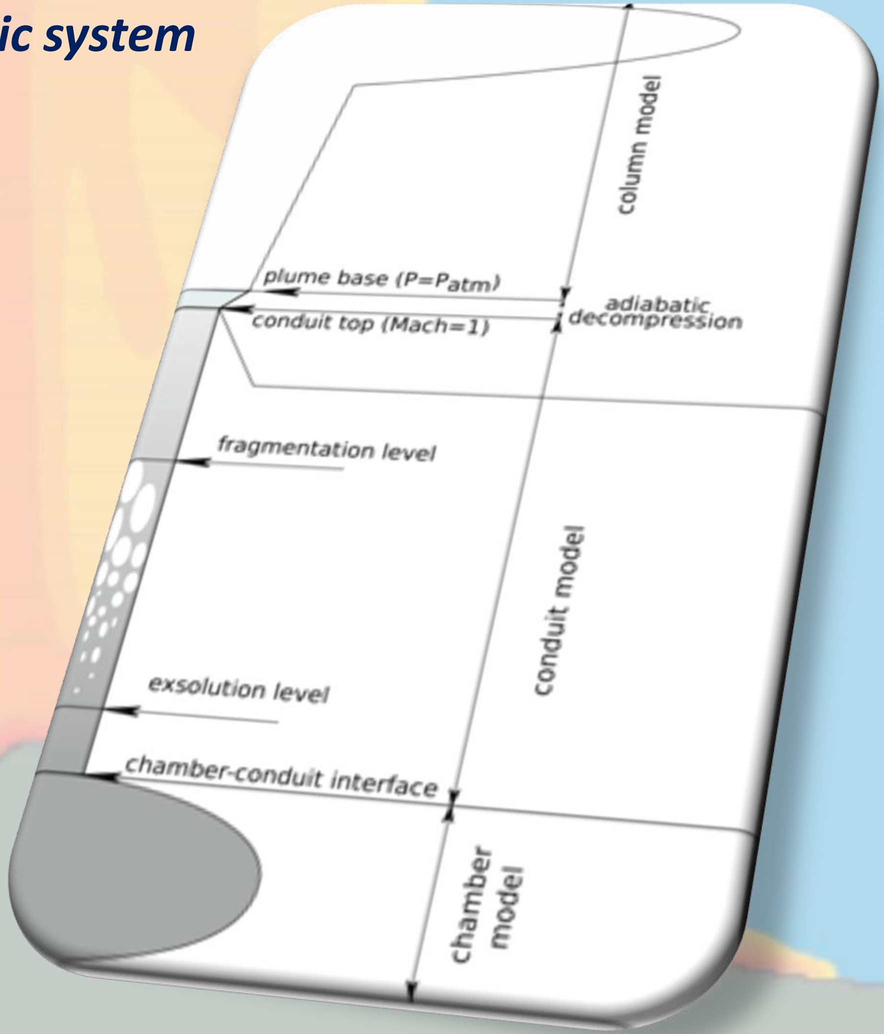
How much magma will be erupted?

…with which style and consequences?

How long will the eruption last?

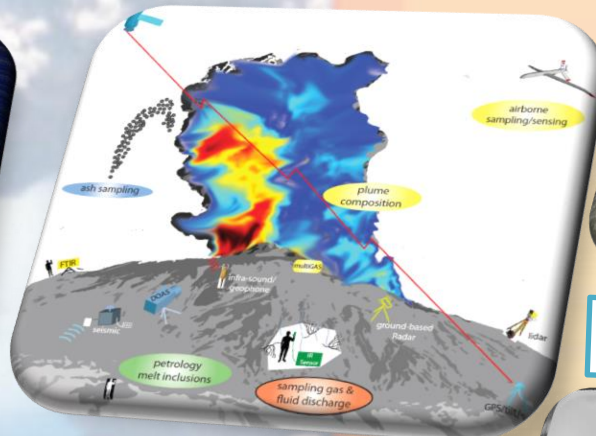
Which geophysical and geochemical precursors do we need to focus on to predict time and duration of an eruption?

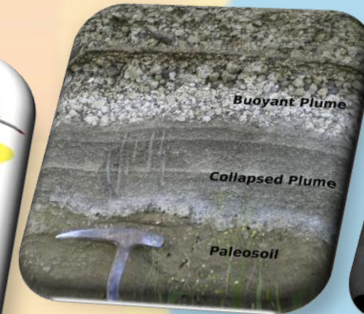
→ coupling the modelling of subsurface and subaerial processes for short term predictions and assessment of eruption evolution

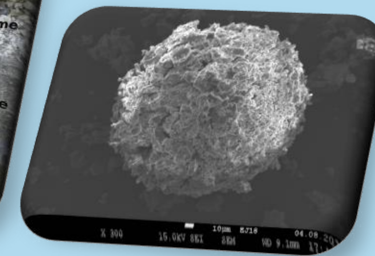


e.g. Colucci et al. 2014, Koyaguchi and Suzuki 2018

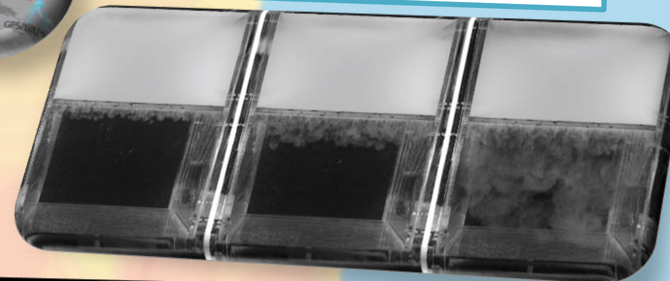
COMPONENTS REQUIRED TO ADVANCE IN OUR UNDERSTANDING OF THE VOLCANIC SYSTEM AND IN THE MITIGATION OF THE ASSOCIATED EFFECTS

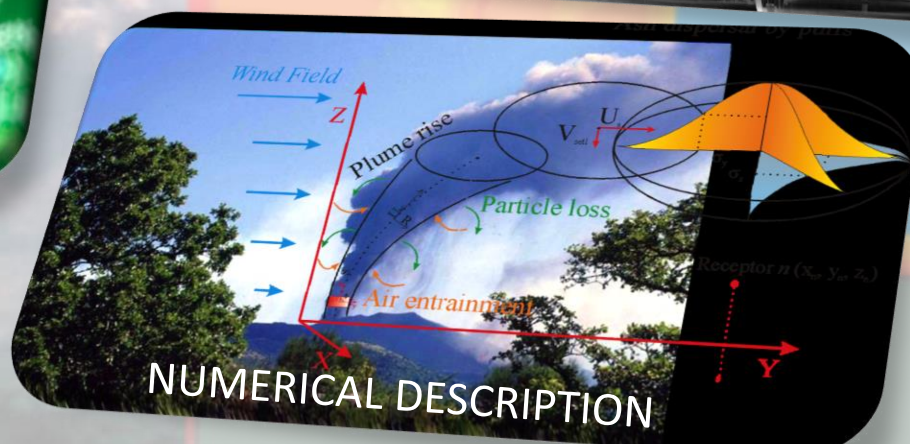


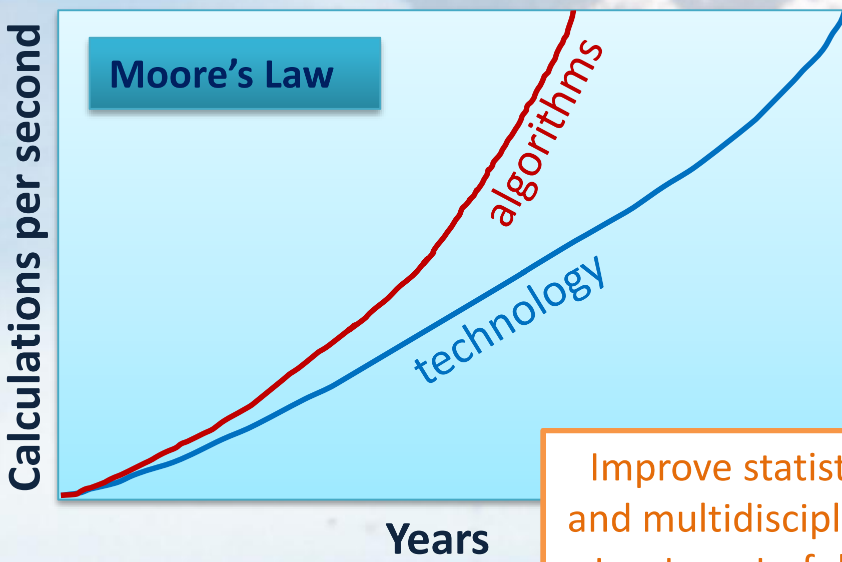




PHYSICAL DESCRIPTION







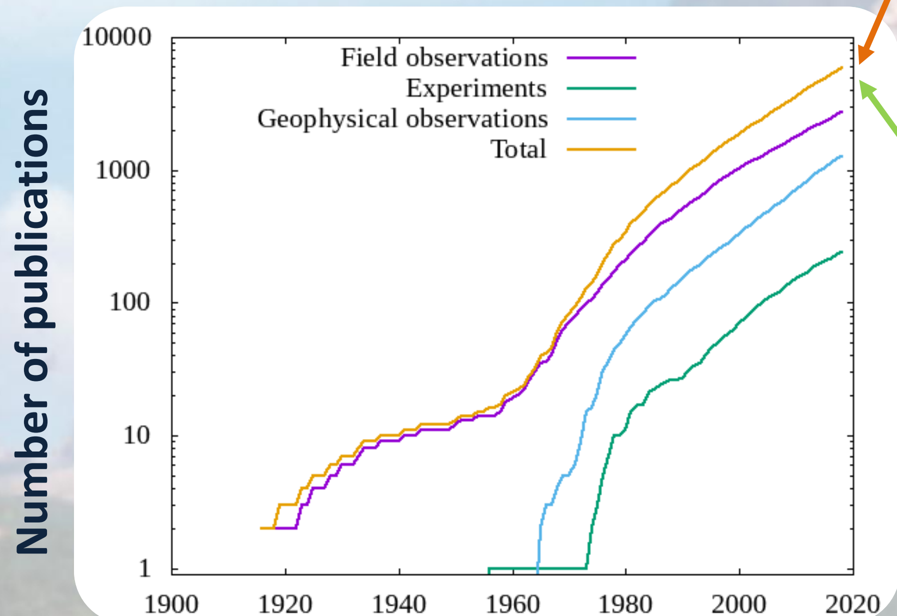
Processing power for computers doubles every two years

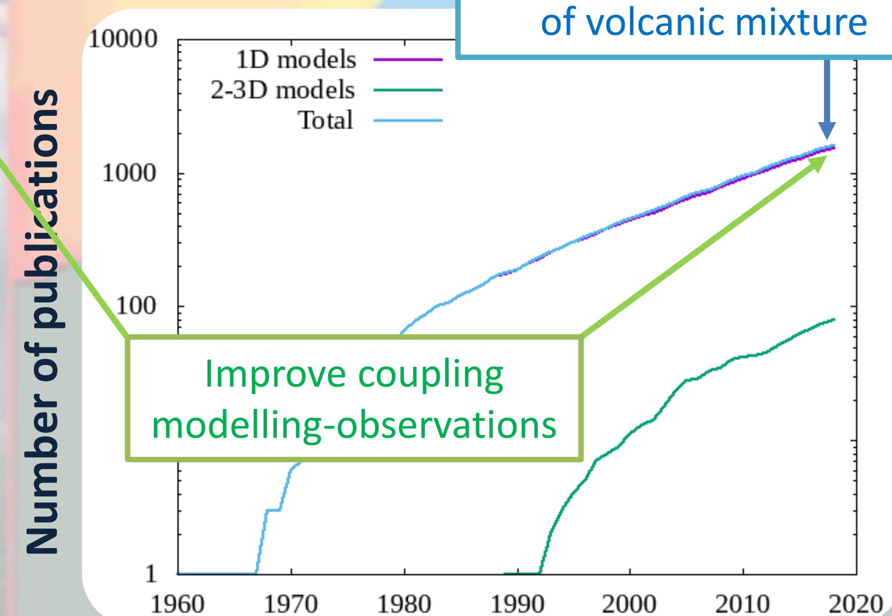
Numerical model resolution does not increase linearly with computer power

Improve resolution and scale of the physical process (→integrating small-scale processes into large-scale dynamics)

Improve statistical and multidisciplinary treatment of data

Development of more accurate constitutive eq. of volcanic mixture





Improve coupling modelling-observations

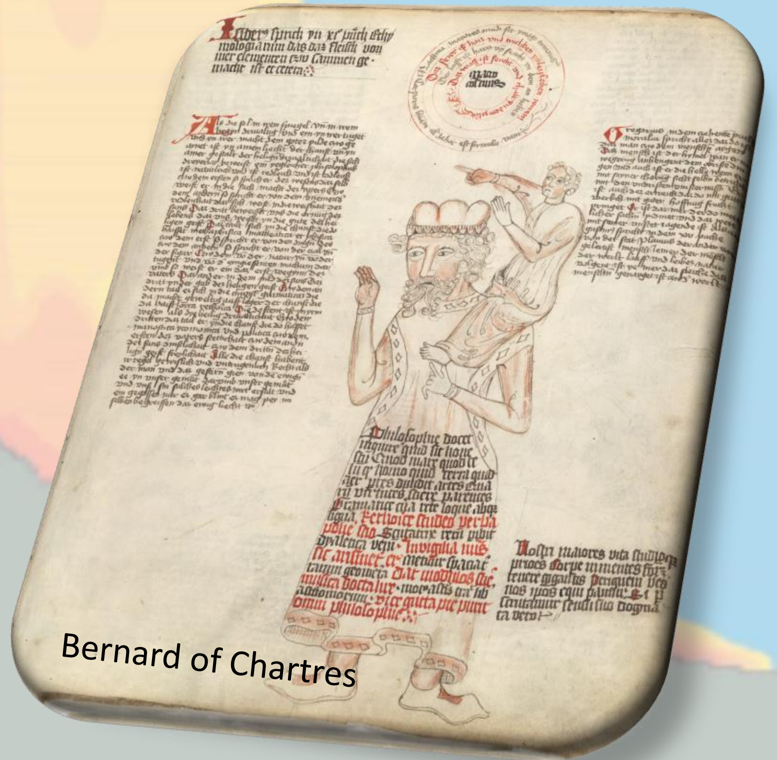
FUTURE PERSPECTIVES: CHALLENGES AND OPPORTUNITIES

Rapid evolution of technology and computational fluid dynamics

→ use of 3D models and AI also in hazard-assessment applications

*→ need of collaboration on existing models in order to advance our understanding as a community (=“**discovering truth by building on previous discoveries”**)*

→ use of open source to promote exchange, optimize advancement and replicate results



FUTURE PERSPECTIVES: CHALLENGES AND OPPORTUNITIES

Rapid evolution of technology and computational fluid dynamics

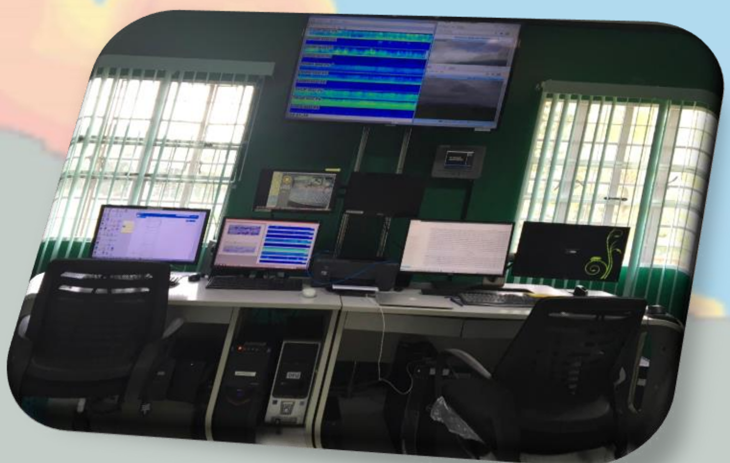
Application of improved technology

→ maintain a strong relationship with the natural system to formulate the right questions

→ need for systematic benchmarking and model intercomparison (Sahagian 2005; Bonadonna et al. 2011; Cordonnier et al. 2016; Costa et al. 2016; Suzuki et al. 2016; Dietterich et al. 2017)

→ implementation of scientific innovation into operations

→ application of innovation: capacity vs resources (models may not need to be complex to capture the most important processes, although calibration and testing is required)

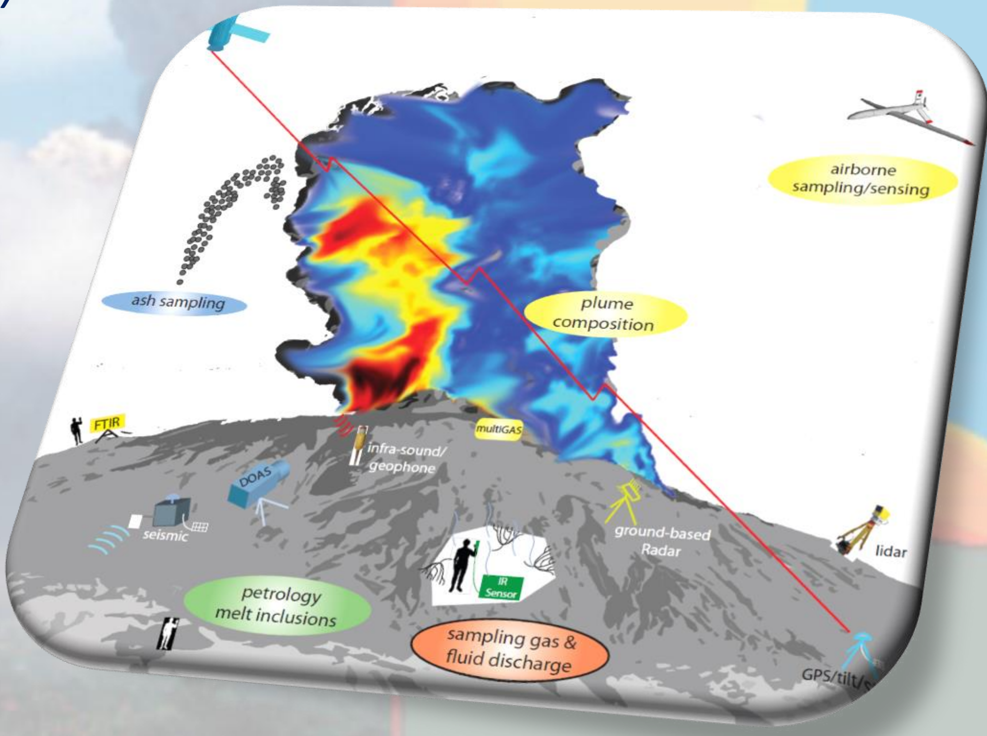


FUTURE PERSPECTIVES: CHALLENGES AND OPPORTUNITIES

Rapid evolution of technology and computational fluid dynamics

Application of improved technology

Need of implementation of systematic ground and space-borne monitoring for active volcanoes with different characteristics (both for scientific and risk-reduction perspectives)



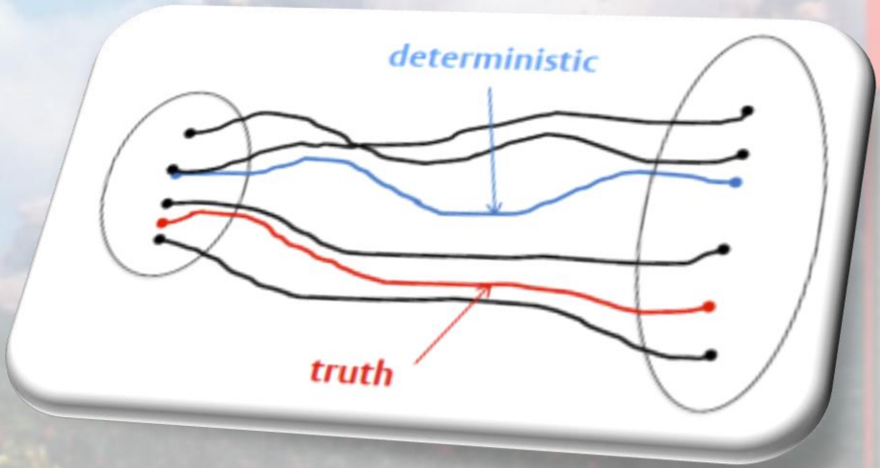
FUTURE PERSPECTIVES: CHALLENGES AND OPPORTUNITIES

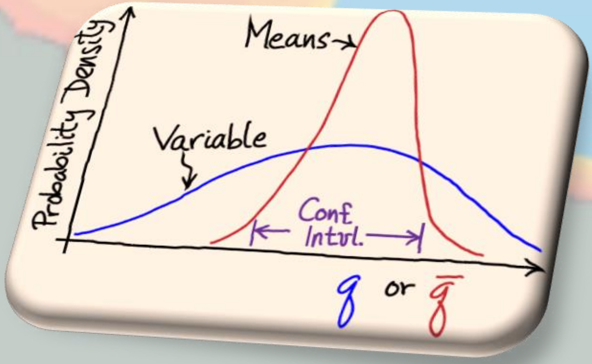
Rapid evolution of technology and computational fluid dynamics

Application of improved technology

Need of implementation of systematic ground and space-borne monitoring for active volcanoes with different characteristics

Epistemic and aleatoric uncertainties in the physical and numerical description of the natural system
→ need to better characterize (ensemble; PDFs) and communicate uncertainties





FUTURE PERSPECTIVES: CHALLENGES AND OPPORTUNITIES

Rapid evolution of technology and computational fluid dynamics

Application of improved technology

Need of implementation of systematic ground and space-borne monitoring for active volcanoes with different characteristics

Epistemic and aleatoric uncertainties in the physical and numerical description of the natural system

Opportunity and need of multidisciplinary studies (from subsurface to space) for a better understanding of the volcanic system (unrest and eruption onset, size, style and duration)
→ take advantage of advancements in geophysical observations and technology for a stronger coupling modelling-observations (e.g. data assimilation and inversion)

IAVCEI COMMISSIONS → PROMOTE MULTIDISCIPLINARY COLLABORATIONS AND ADVANCE AS A COMMUNITY

THANK YOU !!!