Time-dependent modelling of the electric and magnetic fields caused by fluid flow in Vulcano, Italy

Emilie Walker & Paul Glover

Université Laval, Québec, Canada

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Introduction

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SP anomalies are observed within many volcanic and hydrothermal regions

SP variations are linked to changes in volcanic activity and hydrothermal fluid flow

Hence monitoring anomalies on active volcanoes may help forecast eruptions and understand interaction between magmatic and groundwater systems (Lewicki et al., 2003)

SP anomalies observed in volcanic systems have been primarily attributed to electrokinetic (EK) processes → Negative SP signals from pore fluid convection controlled by heat, gravity and fluid pressure

and/or

Rapid fluid disruption (RFD) - charge separation by rapid disruption or vaporization of liquid water by high heat and/or gas flow (Johnston et al. 2001) → Positive SP anomalies in thermal areas far above the groundwater table as charge is carried by water droplet and/or vapor flow

Theory 1

Electro-kinetic coupling can be described in matrix form

$$\begin{bmatrix} Q \\ J \end{bmatrix} = \begin{bmatrix} L_{11} & L_{12} \\ L_{21} & L_{22} \end{bmatrix} \begin{bmatrix} \nabla P \\ \nabla V \end{bmatrix}$$

or alternatively

$$Q = -\frac{k}{\eta}\nabla P - L_{12}\nabla V$$

$$J = -L_{21}\nabla P - \sigma_f \nabla V$$

where $L_{12} = L_{21} = -\dfrac{\varepsilon_r \varepsilon_o \zeta}{\eta}$

Hence the subsurface electrical current, the fluid flow, the subsurface electrical field, and the subsurface pore fluid pressure field are all interdependent

Since the fluid flow depends upon the density of the fluid, which depends upon temperature, the thermal state of the model is also important

Theory 2

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A full modelling needs to solve the coupled partial differential equations

A. Fluid flow → Darcy's law or Navier-Stokes equation
B. Electrical conduction → Ohm's law
C. Heat flow → Heat transfer equation

where heat affects both the fluid flow and the electrical solutions

and the fluid and electrical solutions are linked by the electro-kinetic mechanism

Additionally, ALL parameters may vary in space and time (4D)

This presentation reports only a start to this work

Vulcano 1

Vulcano is a small volcanic island in the Eolian archipelago (southern Italy).

The northmost of its two craters has been chosen for this project (the Fossa di Vulcano).

Vulcano is an active stratovolcano
Phreatic and phreato-magmatic eruptions
Producing pyroclastic dust, ashfall and rivers of viscous magma.

The Fossa was formed 24 000 to 13 000 years ago and has been active during the Holocene (10 000 years ago to the present).

The last major eruption was from 1888 to 1890.

Vulcano 2

The island is small – exhaustive geophysical measurements can be made easily and cheaply.

The population of the island are in constant danger from the volcano.

There have been other high quality recent studies of the volcano and its possible electro-kinetic phenomena [Revil et al., 2008; Aubert et al., 2008].

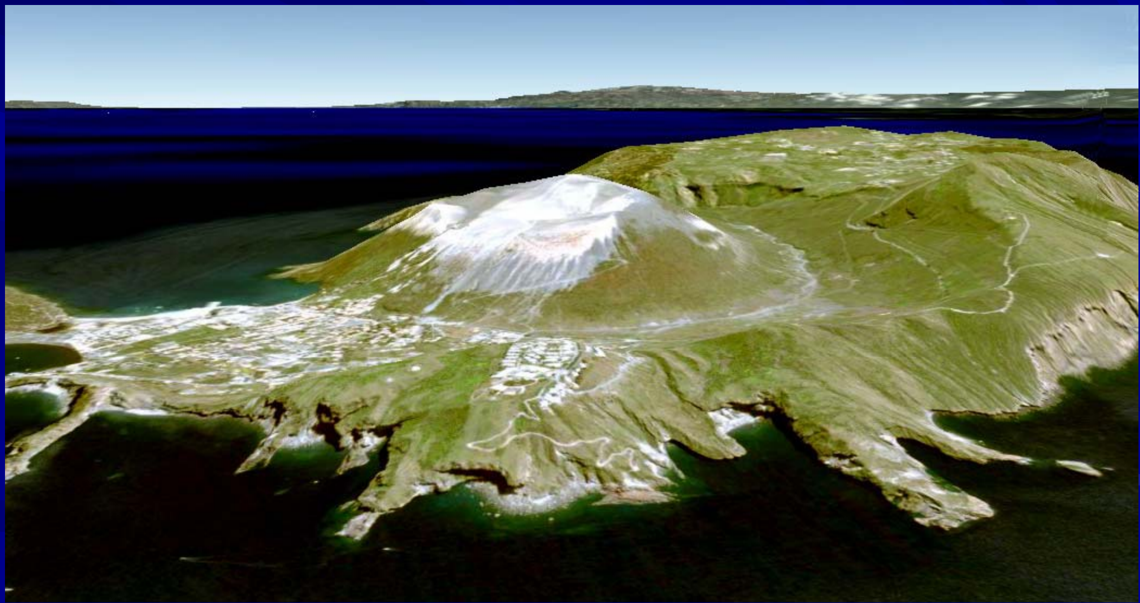

Figure 1. Vulcano (plan view and from the NW. The orange line shows the profile used

Vulcano 3

Electrical tomography indicates the possible presence of hydrothermal systems.

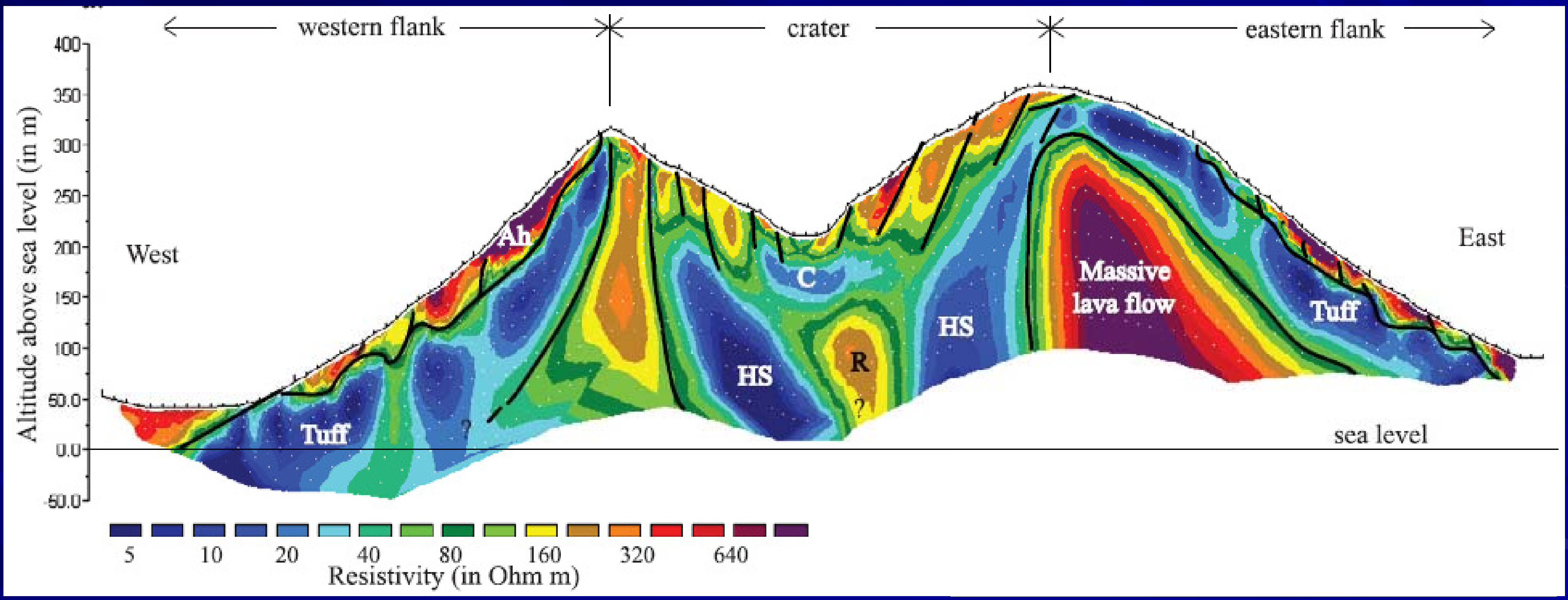

Figure 3. Electrical tomography of Vulcano on an E-W profile (Ah=ash, HS= hydrothermal system, C=conductive, R=resistive) [Revil et al., 2008].

Model 1

The DEM along the profile taken from satellite data every 29.53 m laterally

Internal plumbing informed by electrical tomography results [Revil et al., 2008]

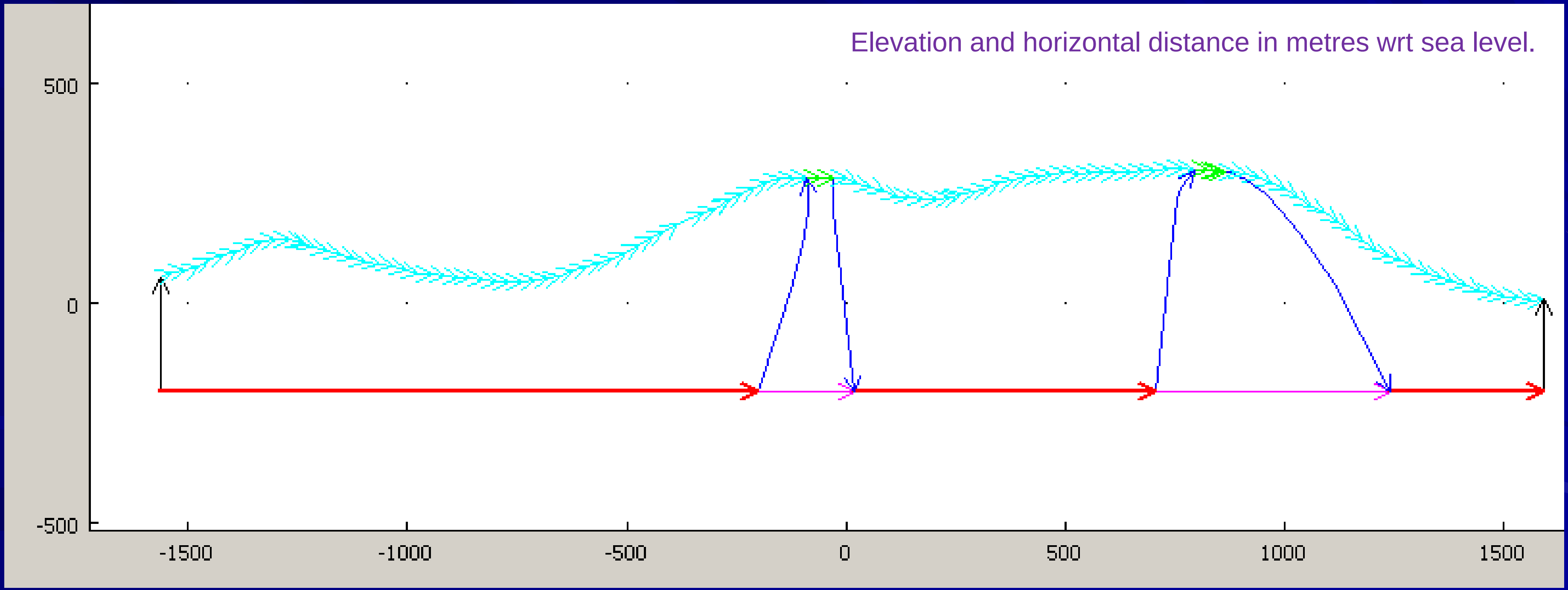

Figure 4. Topography of the model

Model 2

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Light blue	Homogeneous constant precipitation, no current loss, conductive heat loss
Light green	Homogeneous constant precipitation, no current loss, conductive heat loss
Dark blue:	Electrical and hydraulic continuity and convective flux
Red	Fluid flow, current flow and convective flux
Pink	Fluid flow, current flow and convective flux
Black:	Fluid flow, current flow and convective flux

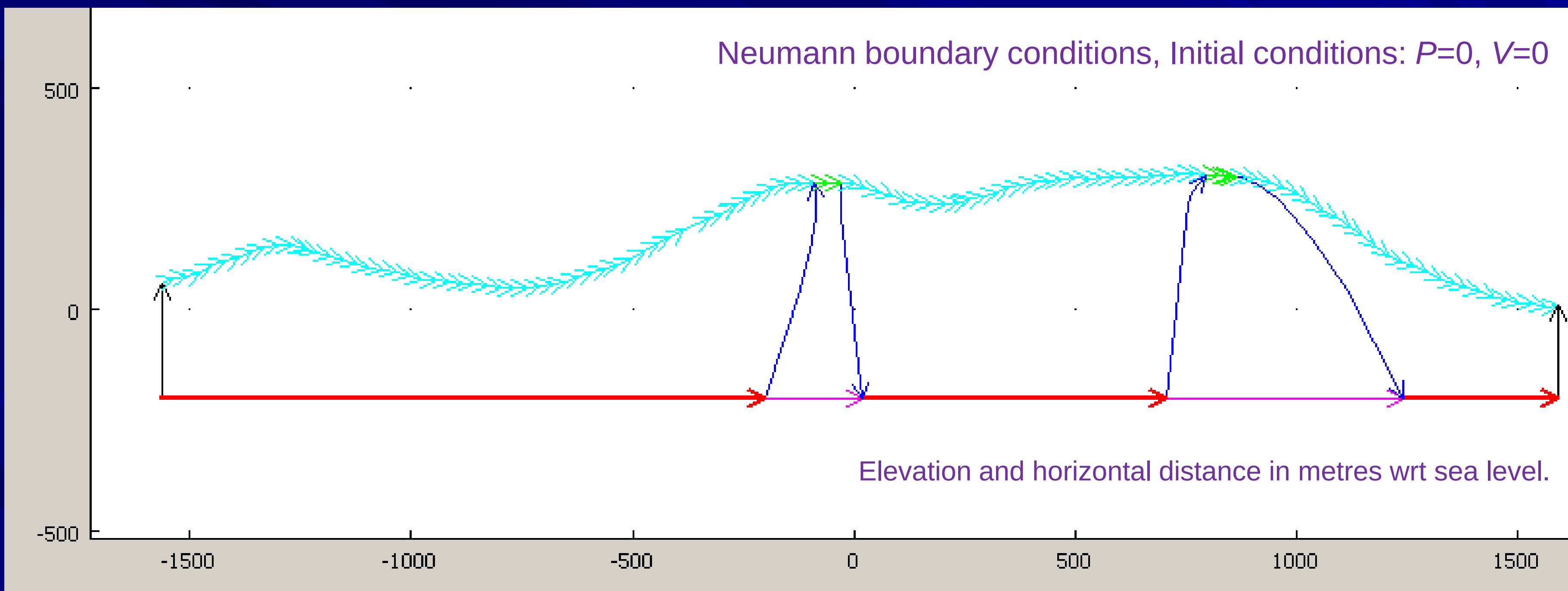

Figure 5. The boundary conditions of the model.

Model 3

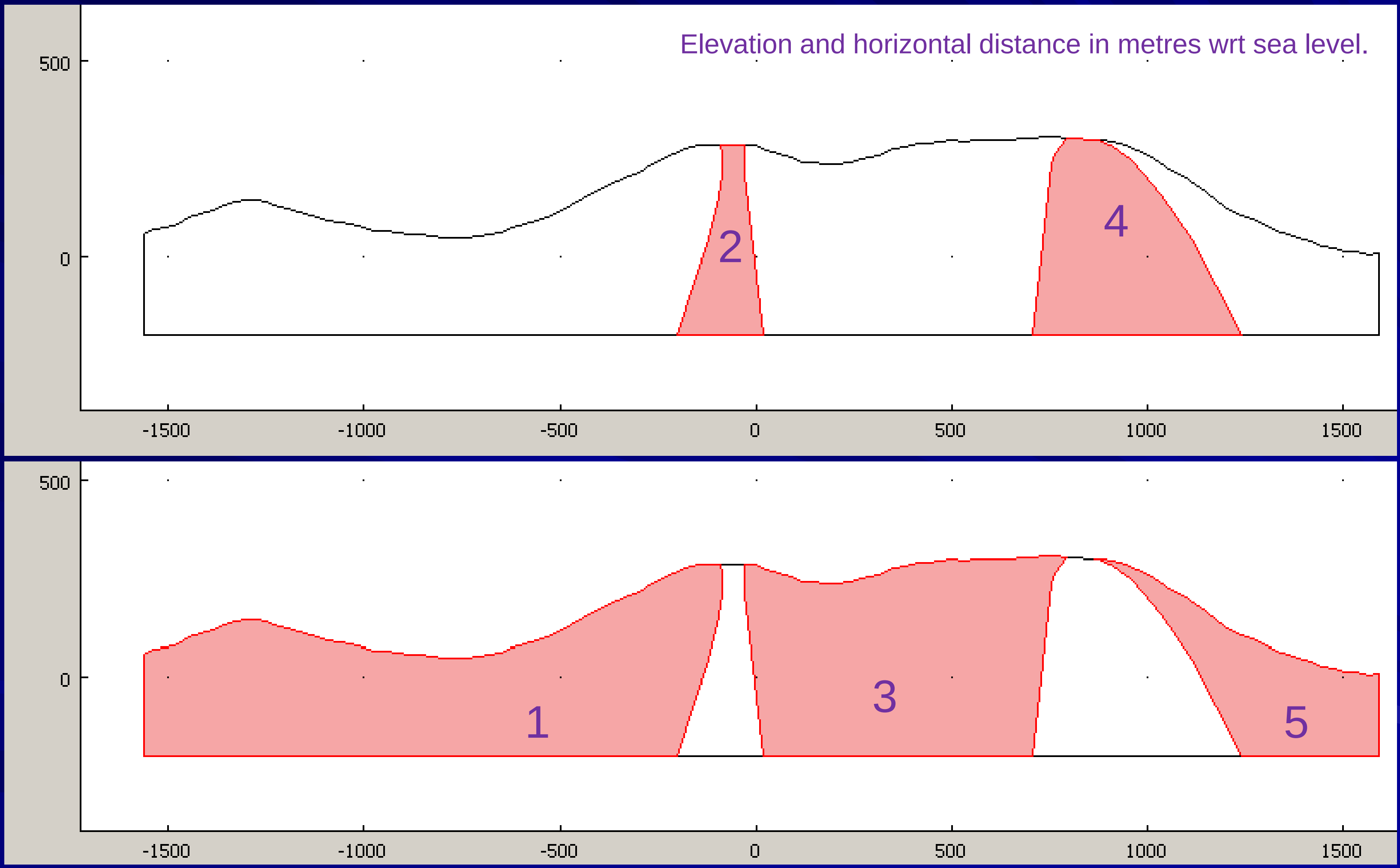

Figure 6. Position of the volcanic conduits in the modelled system.

Model 4

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Name of constant	Units	Description
Global variables		
eta	Pa s	Dynamic viscosity of the fluid
rho	kg/m^3	Density of the pore fluid
g	m/s^2	Acceleration due to gravity
Sub-domains 2 and 4 (volcanic conduits open at the surface)		
sigma1	S/m	Electrical conductivity of the rock
alpha1	$A\ s^2/kg$	Electrokinetic coupling coefficient
kappa1	m^2	Hydraulic permeability of the rock
u1=rho*g*kappa1/eta	A s/kg m	Percolation velocity of fluid at the surface
Sub-domains 1, 3 and 5 (body of the volcano)		
sigma2	S/m	Electrical conductivity of the rock
alpha2	$A\ s^2/kg$	Electrokinetic coupling coefficient
kappa2	m^2	Hydraulic permeability of the rock
u2=rho*g*kappa2/eta	A s/kg m	Percolation velocity of fluid at the surface

Table 1. The main modelling variables.

Both fluid density and viscosity were modelled as a function of temperature.

Temperature was allowed to increase only with depth.

It would be an improvement to the model to have a full 2D heat flow solution incorporated in the model.

Model 5

Element size was controlled at surfaces and interfaces

Tests have been carried out using different grids – there is no significant difference in the results whether the grid is 10 more dense or 10 times less dense.

All solutions were found in less than 2 minutes on a desktop PC.

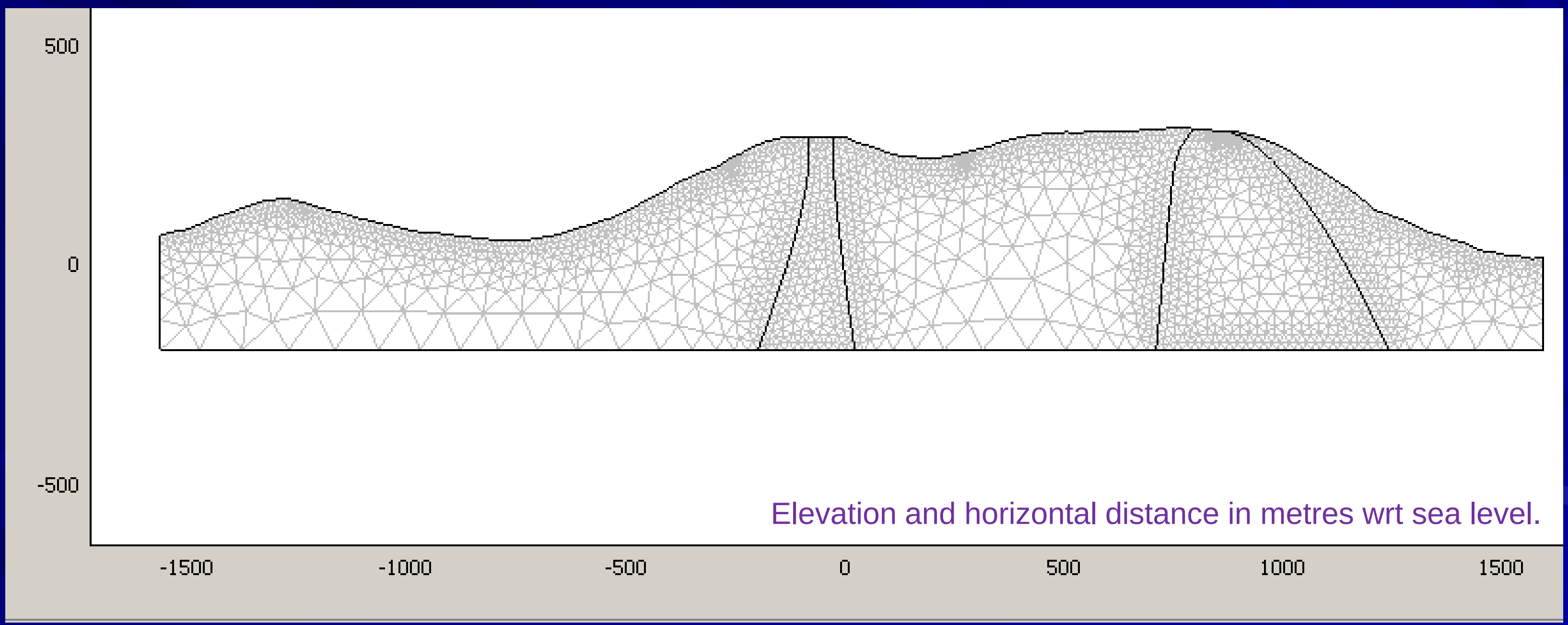

Figure 6. The finite element modelling grid used in the modelling.

Results 1

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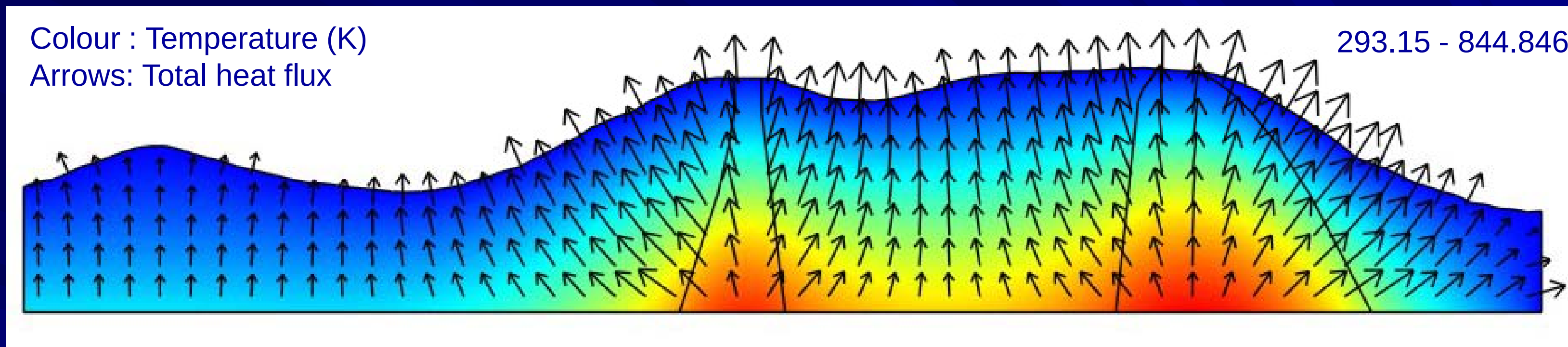
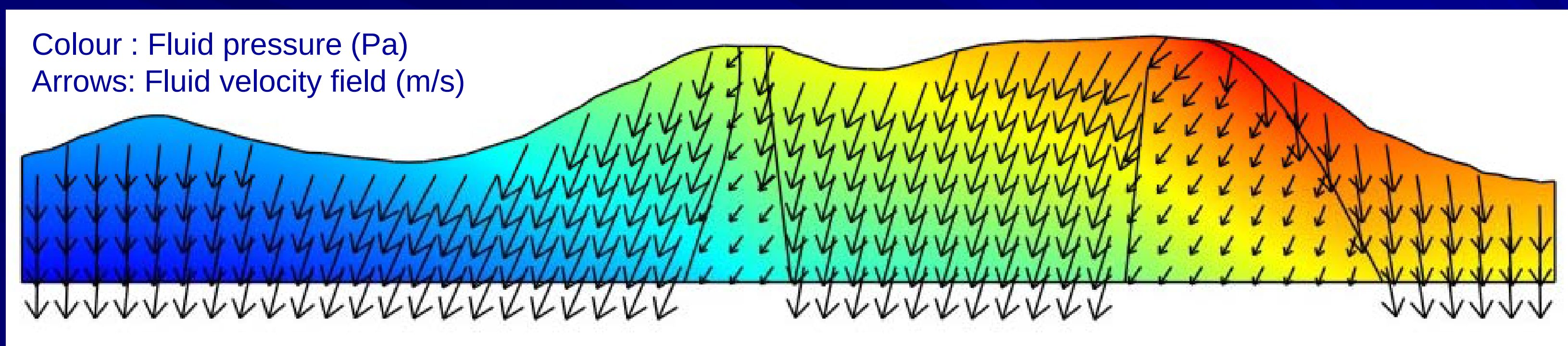
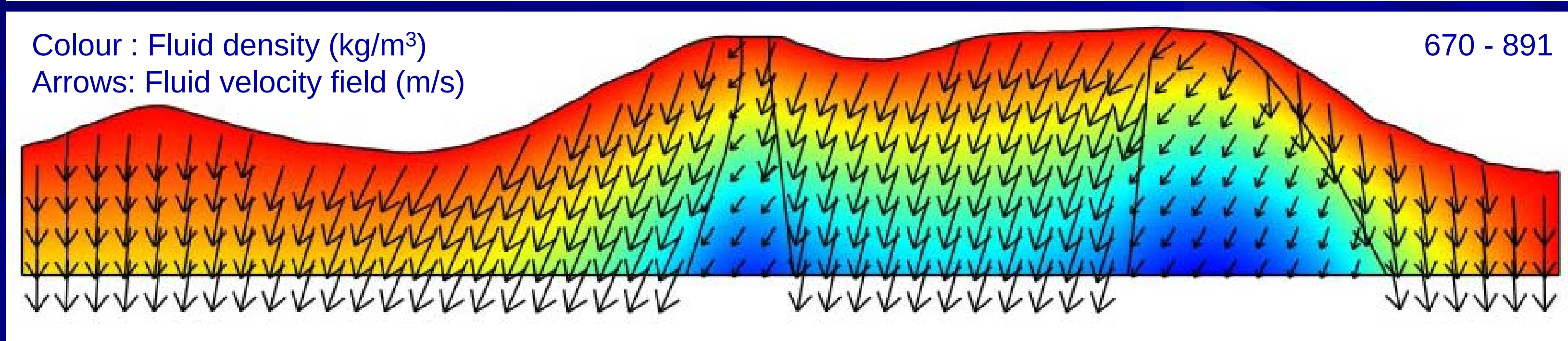
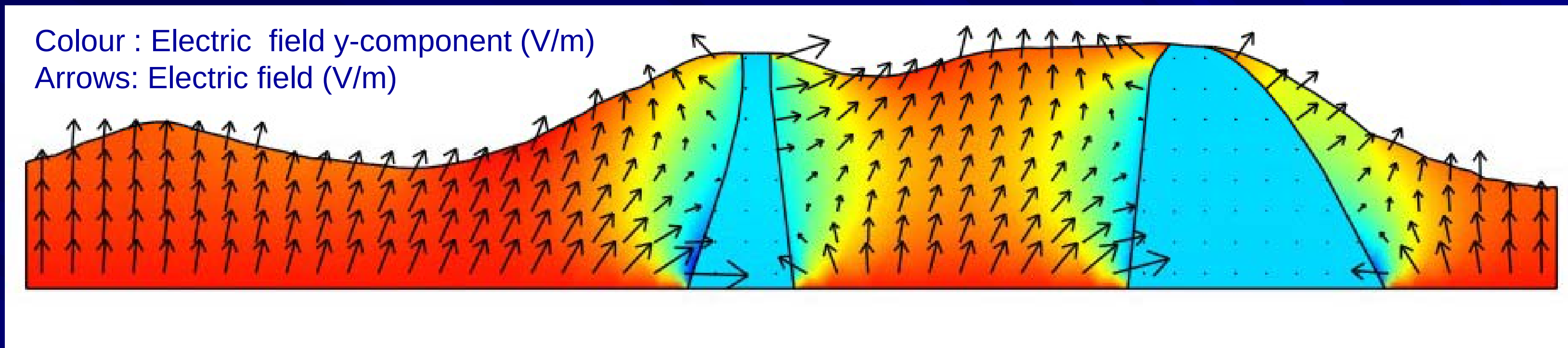
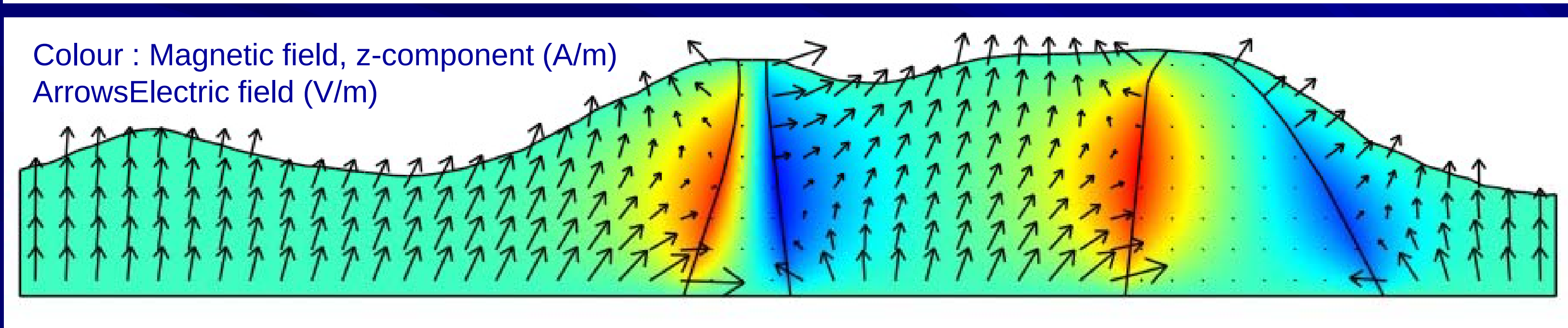






Results 2



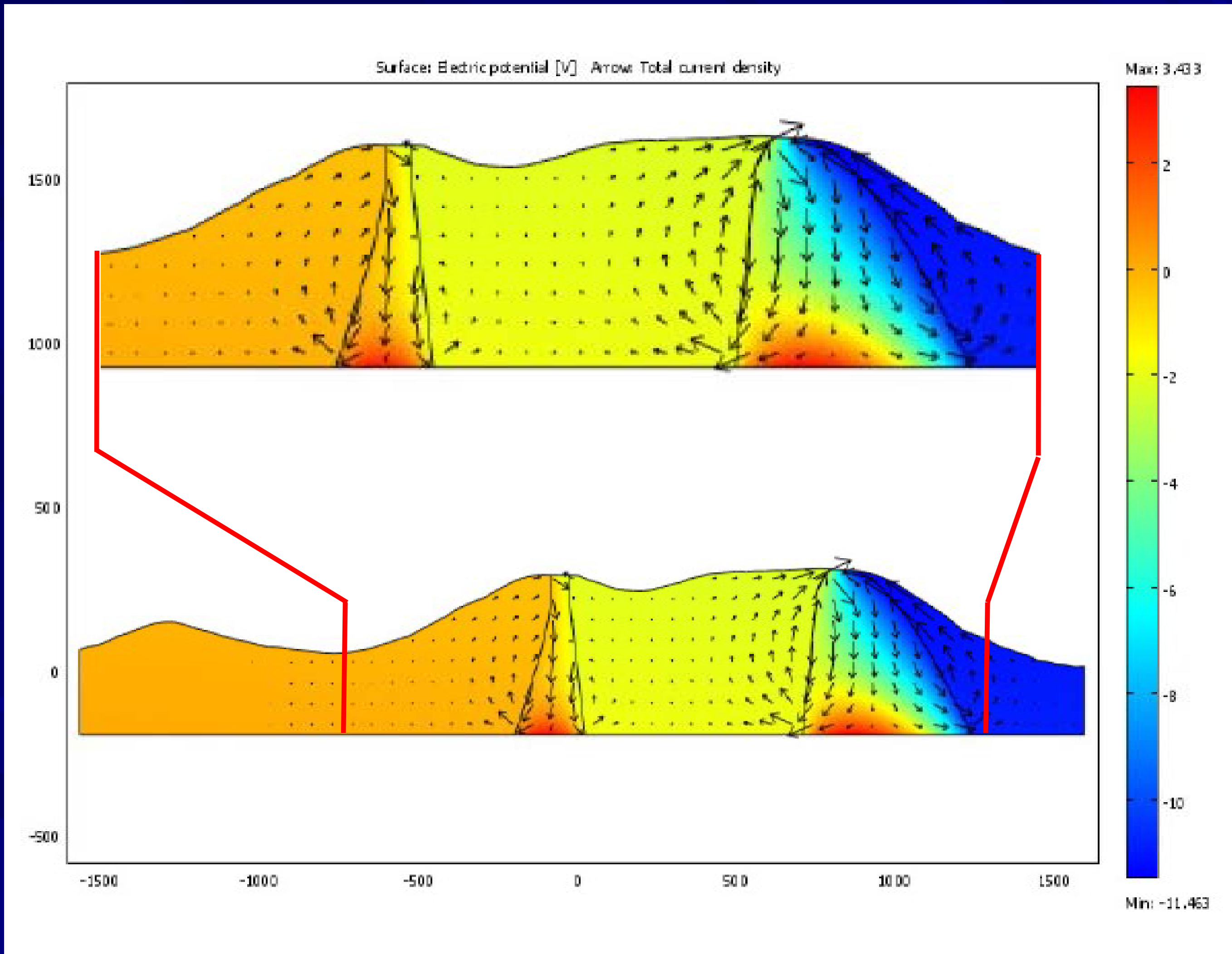


Modelling shows the electric and magnetic fields are significantly altered by the flow of fluid.

The results are not reliable since they do not take into consideration the possible convection of fluids in sub-domains 1, 3 and 5.

Results 3

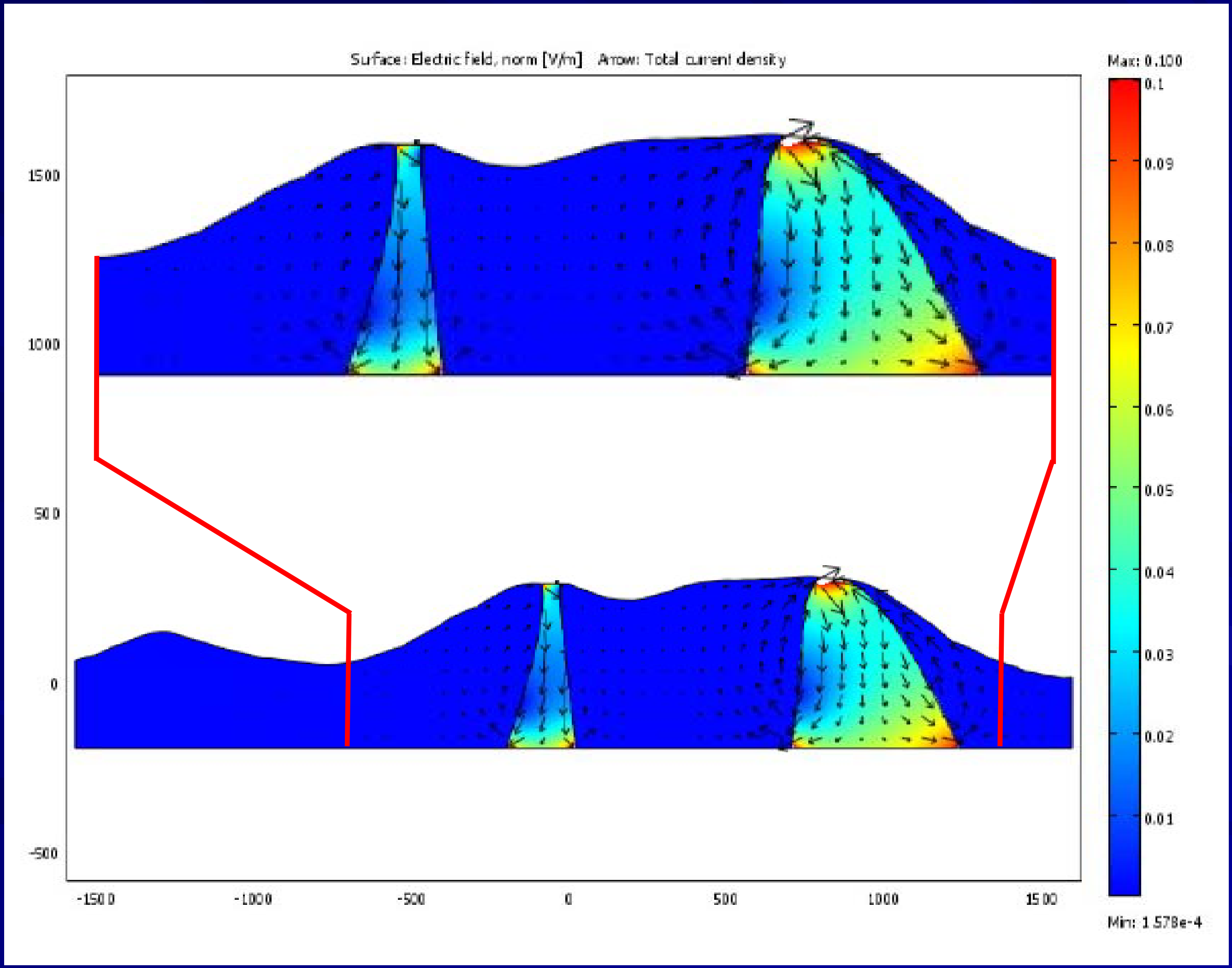
Magma body less permeable and less conductive than the surrounding rock



sigma1= 0.001 S/m
sigma2=0.1 S/m
kappa1=5x10^{-11} m^2
kappa2=10^{-10} m^2

Results 4

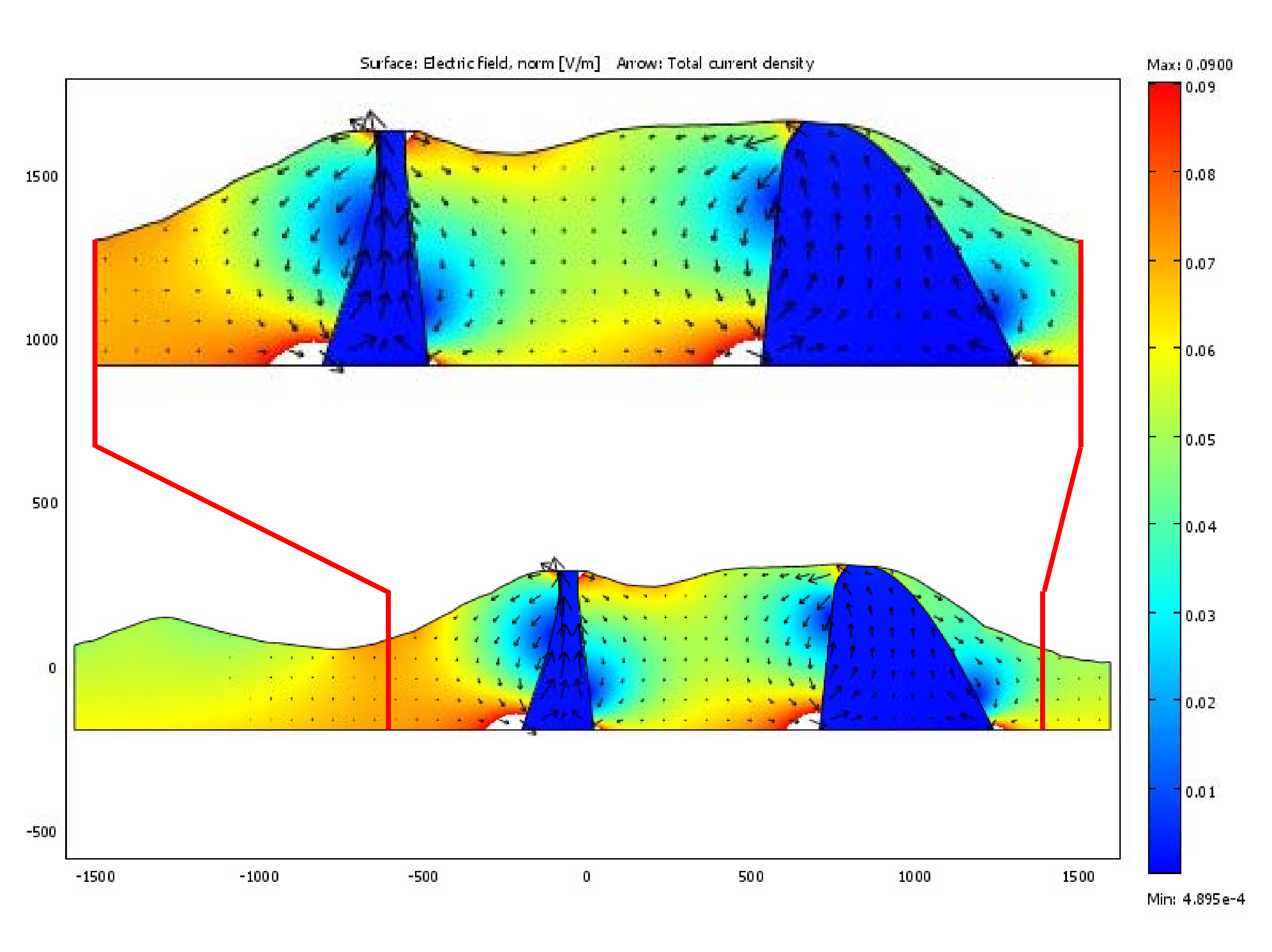
Magma body less permeable and less conductive than the surrounding rock



sigma1= 0.001 S/m
sigma2=0.1 S/m
kappa1=5x10^{-11} m^2
kappa2=10^{-10} m^2

Results 5

Magma body less permeable and more conductive than the surrounding rock



sigma1= 0.1 S/m
sigma2=0.001 S/m
kappa1=10^{-11} m^2
kappa2=10^{-10} m^2

Conclusions 1

1. Initial work.
2. Comsol multiphysics provides a simple and fast method for modelling the electro-kinetic mechanisms operating in volcanoes.
3. A normal PC is sufficient to model a linked physics problem in two dimensions.
4. The models are very sensitive to edge effects, which should be quantified before further modelling is carried out.
5. True time-dependent modelling has not yet been possible, the emplacement of magma has been simulated by comparing the results calculated from where the magma chamber contains magma of different conductivities.
6. These results show that the electric and magnetic fields are highly sensitive to changes in the properties of the magma body.

Conclusions 2

7. Further work will be carried out in 2009/2010 in order to provide a model that contemporaneously solves a 2D problem for hydraulic flow and the electrical and magnetic problems, together with the heat flow with a time-dependent pde solver.
8. Modifications to the codes are also being carried out in order to obtain the values of the various computed parameters on the surface of the volcano.
9. Then will it be possible to compare the results of the modelling with the measured surface SP values correctly.
10. Given the sensitivity of the model, a reliable set of rock physics data is needed for the forward modelling. This will provide a future challenge.
11. However, it also offers the hope that inverse modelling will be able to provide clearer indications of whether some significant internal changes to the volcano have taken place from the observed SP data.

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