MAHIDOL UNIVERSITY
Wisdom of the Land

[SCPY384]

Geophysical Prospecting

Class 1: 21 JAN 2019

Content: Introduction to class, Electrical resistivity, Direct-current resistivity survey

Instructor: Puwis Amatyakul

JAN

21 2019

“Back to School”

Today's Goals

Part I: Get to know each other
Part II: Introduction to the class (SCPY384)
Part III: Introduction to geophysics (prospecting)
Part IV: Electrical resistivity of rocks
Part V: Direct-current (DC) resistivity survey (1)

Class Instructors

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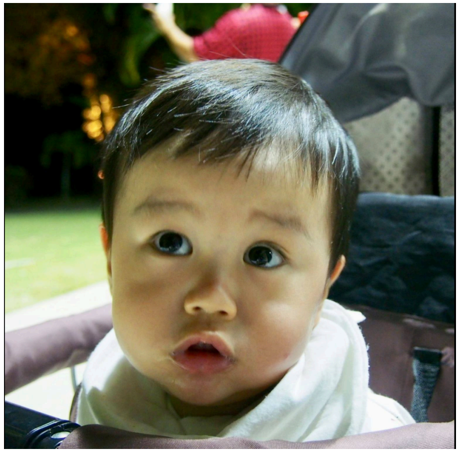

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Today's Goals

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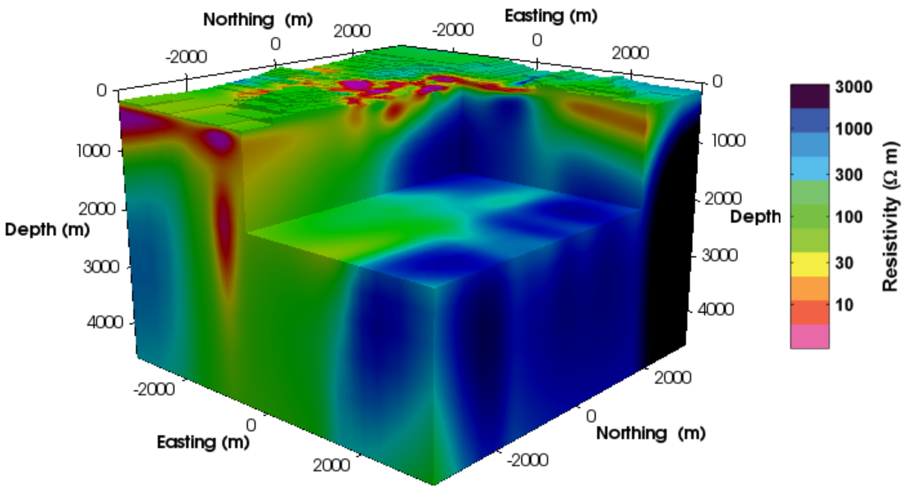
Why do we need to study this class?



Fang's resistivity structure from magnetelluric survey
(Amatyakul et al., 2016, Geothermics)

Subsurface
(Physical properties)

↑

Physics measurement
(mostly at Earth' surface)

Why do we need to study this class?

Geophysics → **Prosepecting**

"Imaging subsurface"

Unexploded Ordnance

Mapping

Oil and gas

Mining

Environment

Forensics

Archeology

Geohazard

Crustal studies

Engineerinåg

Groundwater

Natural hazard studies Earthquake Volcano Landslide Resource explorations Oil and gas exploration Mineral prospecting Geothermal exploration Groundwater exploration Engineering Underground utility locating Concrete inspection Rebar locating Pavement evaluation Underground void locating Ground strength testing (Shear modulus estimation of soil sand rocks) Environmental applications Underground storage tank locating Contamination delineation Landfill delineation Bedrock depth mapping Archaeological applications Forensic investigations

Why do we need to study this class?

Government

DEPARTMENT OF MINERAL RESOURCES

กฟผ

การไฟฟ้าฝ่ายผลิตแห่งประเทศไทย

กรมชลประทาน

DEPARTMENT OF GROUNDWATER RESOURCES

DEPARTMENT OF MINERAL FUELS

Industry

PTTEP

Chevron

Schlumberger

CGGVERITAS

HALLIBURTON

Class Organization

PART I

สัปดาห์ที่	หัวข้อ/รายละเอียด	จำนวนชั่วโมง	ผู้สอน
๑	บทนำเกี่ยวกับการสำรวจทางธรณีฟิสิกส์ วิธีสำรวจแบบใช้ความต้านทานไฟฟ้า (Electrical Resistivity Methods)	๓	อ.ดร.ภูวิศ อมาตยกุล
๒	วิธีสำรวจแบบใช้ความต้านทานไฟฟ้า (Electrical Resistivity Methods) (ต่อ)	๓	
๓	วิธีสำรวจแบบใช้ความต้านทานไฟฟ้า (Electrical Resistivity Methods) (ต่อ)	๓	
๔	วิธีสำรวจแบบใช้สนามแม่เหล็ก (Magnetic Methods)	๓	
๕	วิธีสำรวจแบบใช้สนามแม่เหล็ก (Magnetic Methods) (ต่อ)	๓	
๖	วิธีสำรวจแบบใช้คลื่นแม่เหล็กไฟฟ้า (Electromagnetic Methods)	๓	
๗	วิธีสำรวจแบบใช้คลื่นแม่เหล็กไฟฟ้า (Electromagnetic Methods) (ต่อ)	๓	
๘	นำเสนอเอกสารวิจัยและอภิปราย (Research paper and discussion)	๓	
๙	สอบกลางภาค		

Class Organization

PART II 

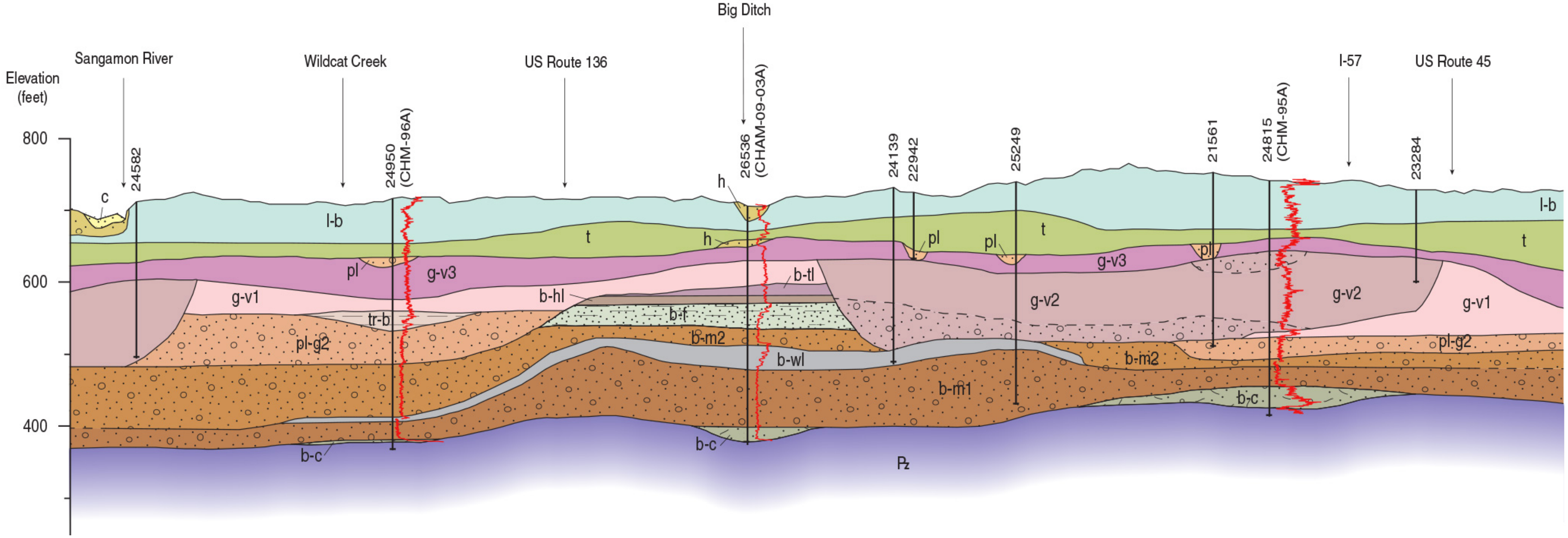
สัปดาห์ที่	หัวข้อ/รายละเอียด	จำนวนชั่วโมง	ผู้สอน
๑๐	เรียนรู้ภาคปฏิบัติ โดยการออกภาคสนามเพื่อเก็บข้อมูลจริง	๓	อ.ดร.สุทธิพงษ์ น้อยสกุล
๑๑	วิธีสำรวจแบบใช้แรงโน้มถ่วง (Gravity Methods)	๓	
๑๒	วิธีสำรวจแบบใช้แรงโน้มถ่วง (Gravity Methods) (ต่อ)	๓	
๑๓	วิธีสำรวจแบบใช้แรงโน้มถ่วง (Gravity Methods) (ต่อ)	๓	
๑๔	วิธีการหักเหของคลื่นไหวสะเทือน (Seismic Refraction Methods)	๓	
๑๕	วิธีการหักเหของคลื่นไหวสะเทือน (Seismic Refraction Methods) (ต่อ)	๓	
๑๖	วิธีการหักเหของคลื่นไหวสะเทือน (Seismic Refraction Methods) (ต่อ)	๓	
๑๗	**สอบปลายภาค**		

Class Organization

กิจกรรม	สัปดาห์ที่ประเมิน	สัดส่วนของการประเมินผล
การเข้าชั้นเรียน การบ้าน	ตลอดภาคการศึกษา	๔๐ %
การสอบข้อเขียน	สัปดาห์ที่ ๙ (กลางภาค) ๓๐% สัปดาห์ที่ ๑๗ (ปลายภาค) ๓๐%	๖๐ %

SCPY384 vs Geosciences & Env.



Source: http://www.isgs.illinois.edu/achievements/september/map-geologic-cross-sections-across-mahomet-bedrock-valley-now-available

SCPY384 vs Geosciences & Env.

Magnetotelluric data

$$\nabla \times \mathbf{H} = \sigma \mathbf{E}$$
$$\nabla \times \mathbf{E} = i\omega\mu \mathbf{H}$$

$\sigma = \sigma(x, y, z)$ is conductivity (inverse of resistivity ρ) distribution of the Earth.

Maxwell's equation

$$\nabla \times \mathrm{E} = -\frac{(\partial B)}{(\partial t)} \quad \text{Faraday's law}$$

$$\nabla \times \mathrm{H} = \mathrm{J} + \frac{(\partial D)}{(\partial t)} \quad \text{Ampere's law}$$

$$\nabla \cdot \mathrm{D} = \rho_{\mathrm{v}} \quad \text{Gauss's law}$$

$$\nabla \cdot \mathrm{B} = 0 \quad \text{Gauss's lawfor magnetism}$$

Constitutional relation

$$\mathrm{J} = \sigma \mathrm{E},$$

$$\mathrm{D} = \varepsilon \mathrm{E},$$

$$\mathrm{B} = \mu \mathrm{H},$$

Intrinsic properties of the materials through which the electromagnetic fields propagate

MT assumption
Plane wave / quasi-stationary approx.

$$\mathrm{E} = \mathrm{E}_0 \cdot e^{i(wt+kr)}$$

$$\mathrm{B} = \mathrm{B}_0 \cdot e^{i(wt+kr)}$$

$$\frac{\partial D}{\partial t} = 0$$

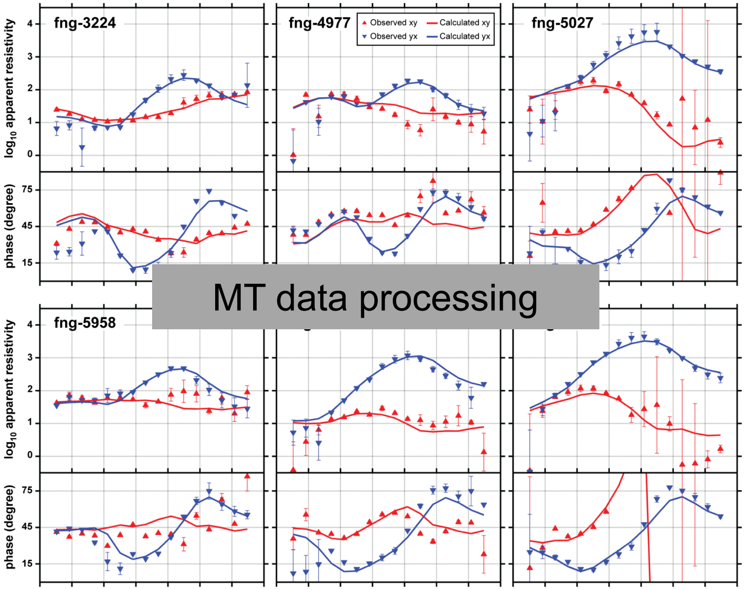
$$\nabla \times \mathrm{E} = -i\omega \mathrm{B} \qquad \nabla \cdot \mathrm{E} = \frac{(\rho\varepsilon)}{\epsilon}$$

$$\nabla \times \mathrm{H} = \mu_0 \sigma \mathrm{E} \qquad \nabla \cdot \mathrm{B} = 0$$

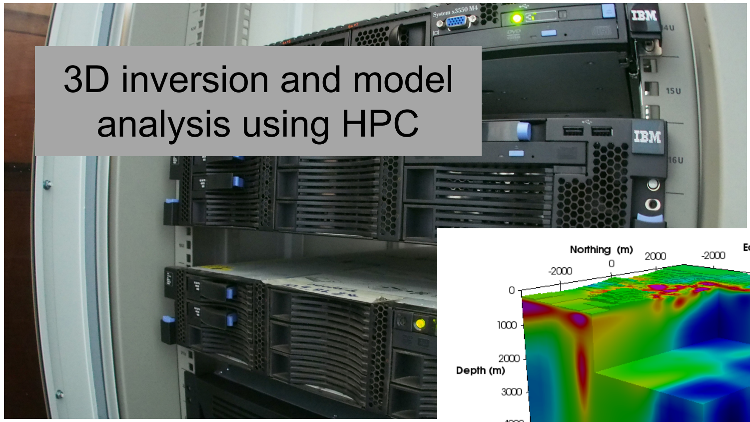
SCPY384 vs Geosciences & Env.

Magnetotelluric survey

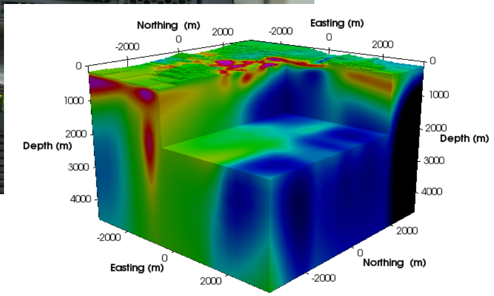
Field survey & data acquisition



MT data processing



3D inversion and model analysis using HPC



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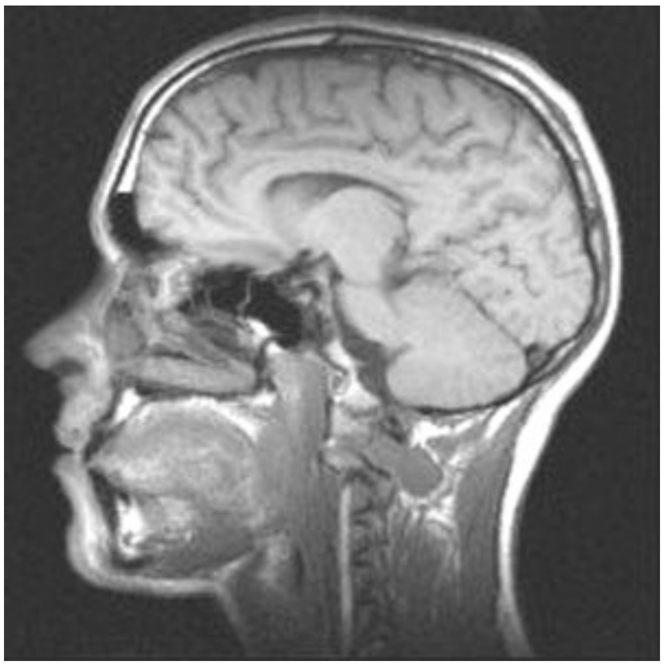
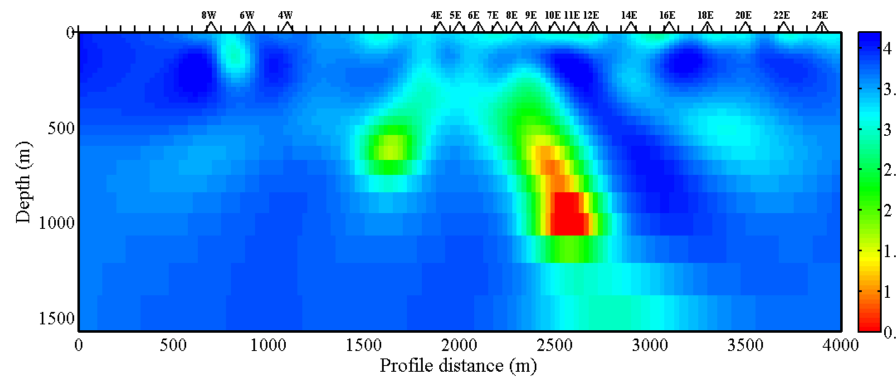
Medical VS Geophysical

Similarities and Differences?





Basic Principles

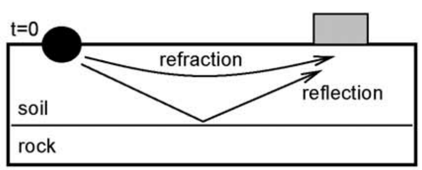
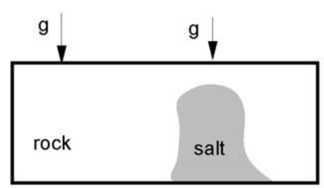
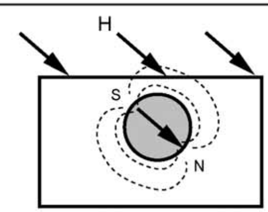
- ✓ All geophysical methods remotely sense a material property of the Earth (e.g. seismic velocity, rock density, electrical resistivity, magnetization etc)
- ✓ Knowledge of these material properties must then be interpreted to determine what rock type is present. Well log information is very important in this task.
- ✓ Geophysical methods can be divided into active and passive techniques.
  - ✓ In an **active technique**, it is necessary to generate a signal (e.g. in seismic reflection surveying, sound waves are generated with an explosion).
  - ✓ In a **passive technique** a naturally occurring signal is detected (e.g. the pull of gravity of a buried object)
- ✓ Geophysical and geological studies complement one another. **Geologists** are more effective with a basic knowledge of what geophysics can and cannot resolve. (Similarly, many **geophysicists would benefit from a basic knowledge of geology**).

Source: https://sites.ualberta.ca/~unsworth

Basic Principles

- ✓ **Geophysical imaging does not always give a unique answer!** Additional information is often needed to discriminate between possible solutions (e.g. other geophysical surveys, knowledge of local geology, well log information in the study area).
- ✓ In geophysical prospecting, physics needed which equally with mathematics and computer sciences.

SUMMARY OF GEOPHYSICAL EXPLORATION TECHNIQUES

	Seismic exploration	**Gravity exploration**	**Magnetic exploration**
Quantity measured in field survey	Travel times (t) and amplitude of seismic waves	Gravitational force on known mass (g)	Magnetic field (H)
Property calculated in data analysis	Seismic velocity (v)	Density (ρ)	Magnetic susceptibility (k) Remnant magnetization (M)
Survey layout			
Common applications	Depth to bedrock, geotechnical studies Oil and gas exploration Tectonic studies	Depth to bedrock Mapping salt domes Locating caves Mapping landfill geometry Tectonic studies	Locating metal drums and pipes Mineral exploration Depth to igneous basement Archaeology Tectonic studies

Source: https://sites.ualberta.ca/~unsworth

Medical VS Geophysical

Geophysics → **Methods / Techniques**

Spatial distribution

Subsurface Model
(Physical properties)

- Wave velocity
- Electrical resistivity
- Magnetic susceptibility
- Dielectric constant
- Density
- Heat conductivity
- …

Exploration Techniques

- Seismic
- Electrical
- Electromagnetics
- Gravity
- Magnetism
- Heat flow
- …

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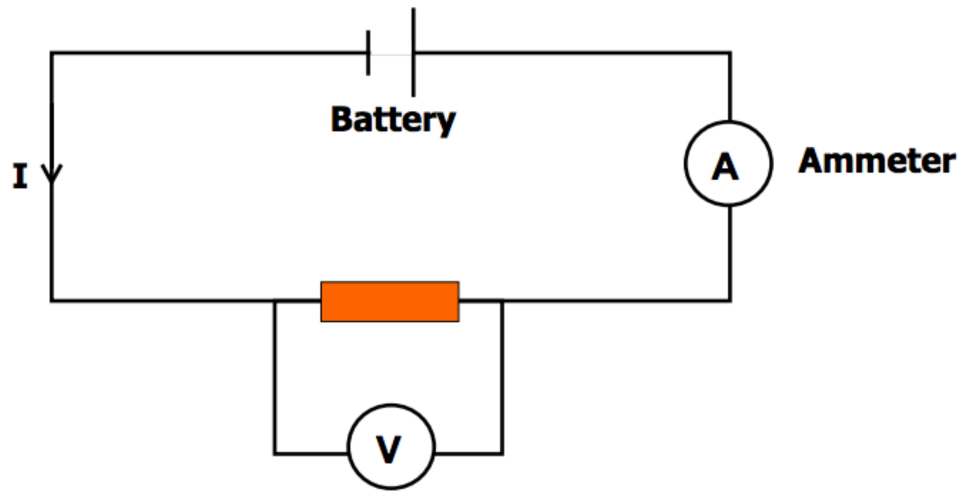
Basic Electrical Properties of Rocks

Electrical Current Flow

(a) Simple resistor in circuit

Ohm's Law states that for a resistor, the resistance (in ohms), R is defined as $R = \frac{V}{I}$

V = voltage (volts); I = current flow (amps)



Ohm's Law – V = I R

Basic Electrical Properties of Rocks

Electrical Current Flow

(b) Electric current flow in a finite volume

Ohm's Law as written above describes a resistor, which has no dimensions. In considering the flow of electric current in the Earth, we must consider the flow of electric current in a finite volume. Consider a cylinder of length L and cross section A that carries a current I

$$J = \text{current density} = \frac{I}{A}$$

$$R = \text{resistance of cylinder} \propto \frac{L}{A} = \frac{\rho L}{A}$$

where ρ is the **electrical resistivity** of the material (ohm-m). This is the resistance per unit volume and is an inherent property of the material.

$$\rho = \frac{RA}{L}$$

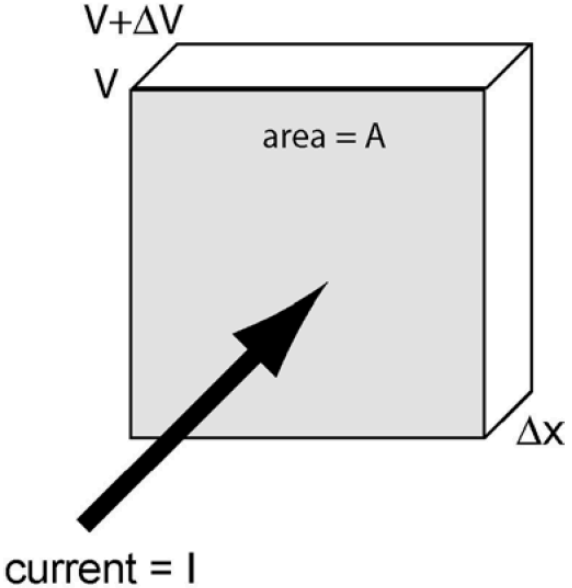
If we were to examine two cylinders made of the same material, but with different dimensions, they would have the **same** electrical resistivity, but **different** electrical resistances.

Basic Electrical Properties of Rocks

Electrical Current Flow

(c) Electric current flow across a slab of material

Consider an electric current (I) flowing through a slab of material with resistivity, ρ and cross-sectional area, A



Applying Ohms Law

$$R = \frac{V}{I}$$

$$\frac{\rho \Delta x}{A} = \frac{\Delta V}{I}$$

Rearranging gives $$\frac{\Delta V}{\Delta x} = \frac{I\rho}{A}$$

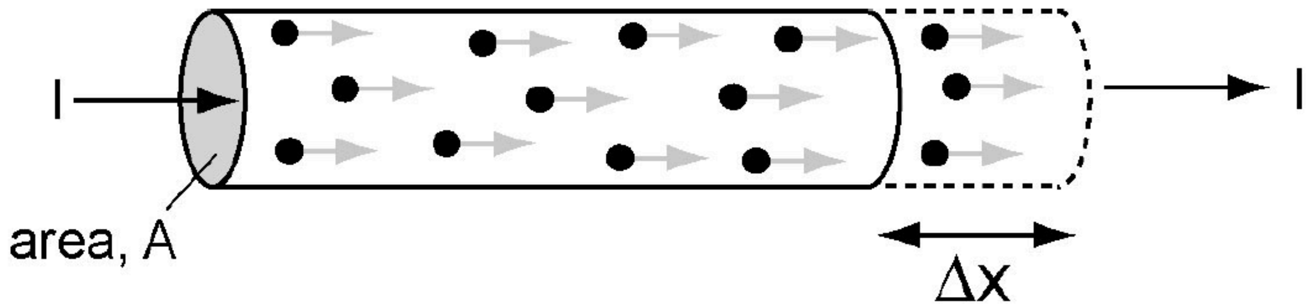
Taking limits $$\frac{dV}{dx} = E = \frac{I\rho}{A} = J\rho$$

Thus Ohms Law for a continuous medium can be written as $J = \sigma E$ where E is the electric field strength (Volts per m)

Electrical Current Flow

(d) Charge carriers

Electric current will flow through a medium as charge carriers move under an applied electric field (E). How is the resistivity (ρ) related to the number and type of charge carrier? Consider current flow through a cylinder of length *L* and area *A*.

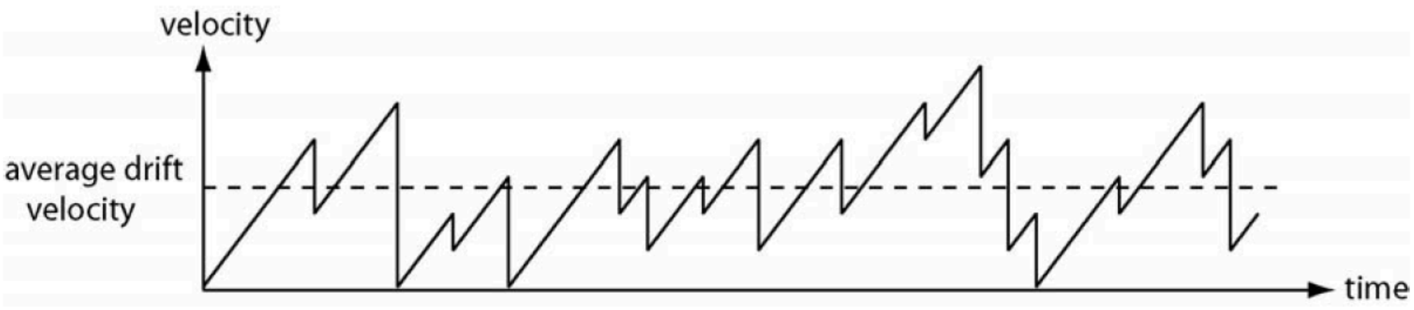


n = number of charge carriers per unit volume
q = the charge on each carrier

Basic Electrical Properties of Rocks

Electrical Current Flow

(d) Charge carriers



The ease with which the charge carrier can move is described by the mobility, μ, which is defined as the drift velocity per unit electric field = v/E

In a time Δt, the electric charges will move a distance $\Delta x = v\Delta t$.

This corresponds to a volume of charge carriers $= Av\Delta t$

The total charge leaving the cylinder is thus $\Delta q = nqAv\Delta t$

By definition, the current, I $= \dfrac{\Delta q}{\Delta t} = \dfrac{nqAv\Delta t}{\Delta t} = nqAv$

Basic Electrical Properties of Rocks

Electrical Current Flow

(d) Charge carriers

Thus current density, J $= \dfrac{I}{A} = nqv = nq\mu E$

By comparison with Ohms Law, we see that $\rho = \dfrac{1}{nq\mu}$

Thus a material will have a low electrical resistivity if it has many, highly mobile, charge carriers.

If several types of charge carriers are present, then the contribution from each type must be summed.

Basic Electrical Properties of Rocks

Electrical resistivity of pure elements and compounds

Several conduction mechanisms are possible in typical Earth materials. A list of some minerals is given on Telford, page 285.

- electronic conduction occurs in pure metals. Here the charge carriers are electrons and their high mobility gives a very low resistivity ($<10^{-8}$ ohm-m)

- semi conduction occurs in minerals such as sulphides. Here the charge carriers are electrons, ions or holes. Compared to metals, the mobility and number of charge carriers are lower, and thus the resistivity is higher (typically 10^{-3} to 10^{-5} ohm-m).

  This type of conduction occurs in igneous rocks and usually shows a temperature dependence of the form (thermally activated)

$$\rho \propto e^{\frac{E}{kT}}$$

  where T is the temperature in K, E is an activation energy and k is the Boltzmann constant.

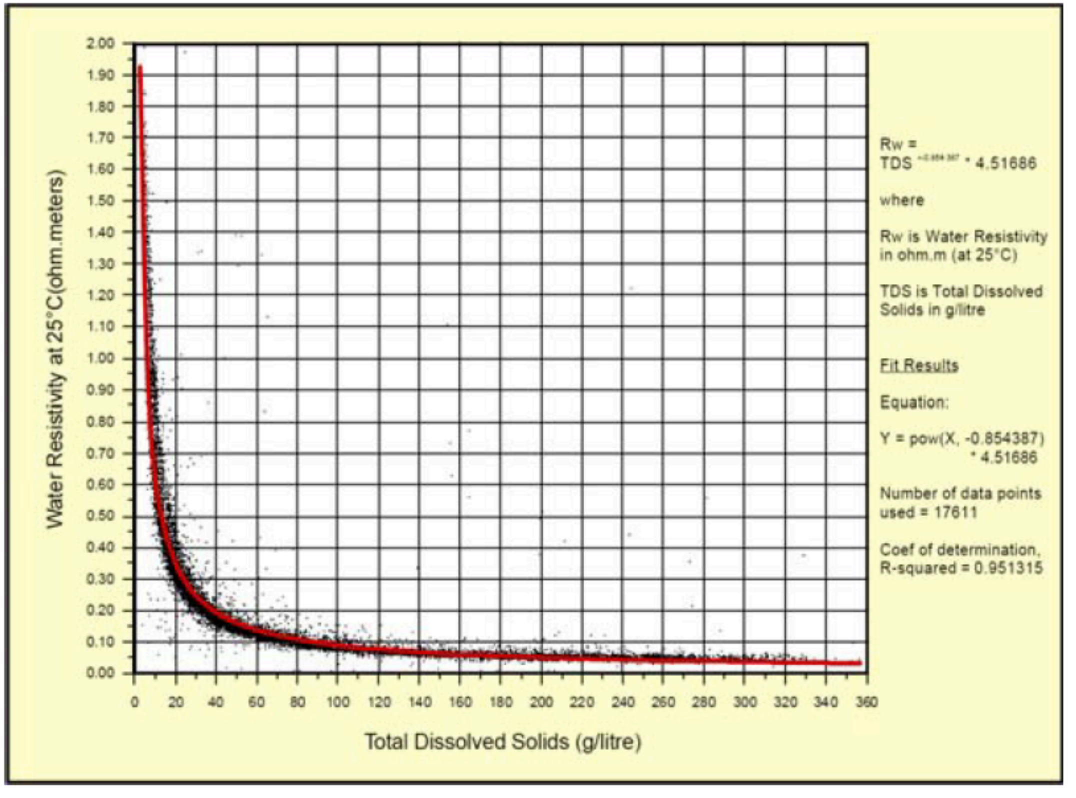
Basic Electrical Properties of Rocks

Electrical resistivity of pure elements and compounds

- Ionic conduction occurs in aqueous fluids or molten rocks. In this case the charge carriers are ions that can move through the fluid. The figure below shows that resistivity in brines decreases as the total dissolved solids (TDS) increases.

$\rho = 4.5\ \mathrm{TDS}^{-0.85}$ (ohm-m)

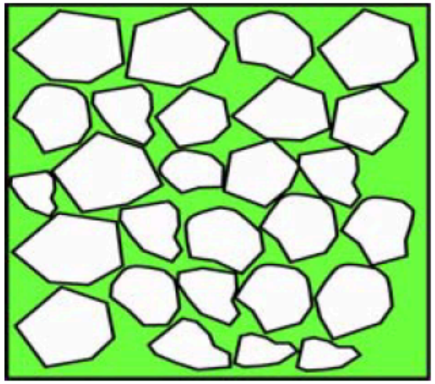
Can you explain the shape of the curve?



Basic Electrical Properties of Rocks

Electrical resistivity of multiphase materials

Pure materials are rarely found in the Earth and most rocks are a mixture of two or more phases (solid, liquid or gas). Thus to calculate the overall electrical resistivity of a rock, we must consider the individual resistivities and then compute the overall electrical resistivity. Consider a sandstone saturated with salt water. The grains are quartzite and have a high resistivity (> 1000 ohm-m).
In contrast, the pore fluid is conductive (~1 ohm-m).



To compute the overall electrical resistivity, we must consider current flow through each phase. However, given the much higher resistivity of the grains, most current will flow through the water, with ions as the charge carriers.

Basic Electrical Properties of Rocks

Electrical resistivity of multiphase materials

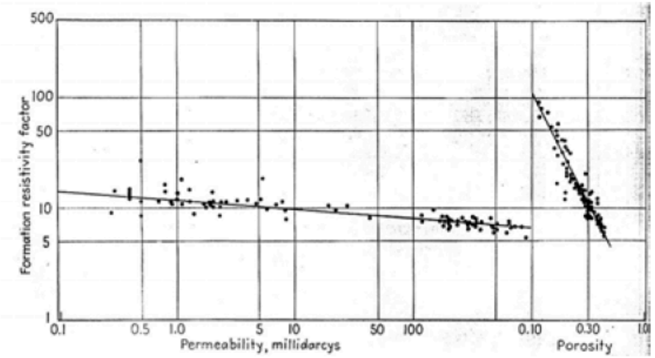
An empirical formula was developed for this scenario by Gus Archie in 1942. Archie's Law states that the resistivity of a completely saturated whole rock (ρ_o) is given by

$$\frac{\rho_o}{\rho_w} = F = \phi^{-m}$$

where F is called the **formation factor**, ρ_W is the resistivity of the pore fluid (water) and Φ is the porosity. On a log-log plot of ρ_o as a function of Φ, a straight line should result with slope $-m$. This exponent m termed the **cementation factor**. Typical values include:

1.8-2.0 for consolidated sandstones to 1.3 for unconsolidated sands. The graph on the right is taken from Archie (1942) from Nacatoch sand from Lousiana. What is the value of m for this set of samples?

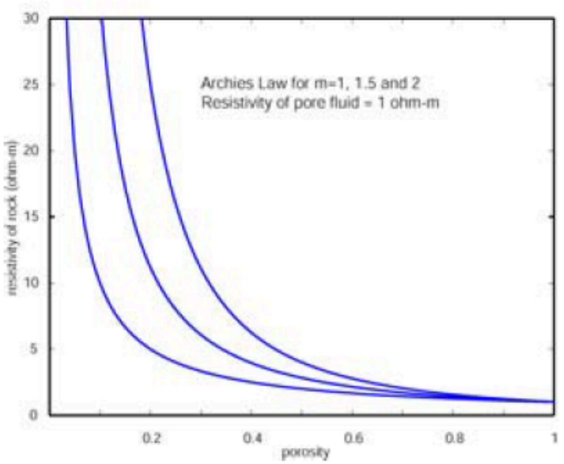
What is the difference between permeability and porosity? Are they correlated?

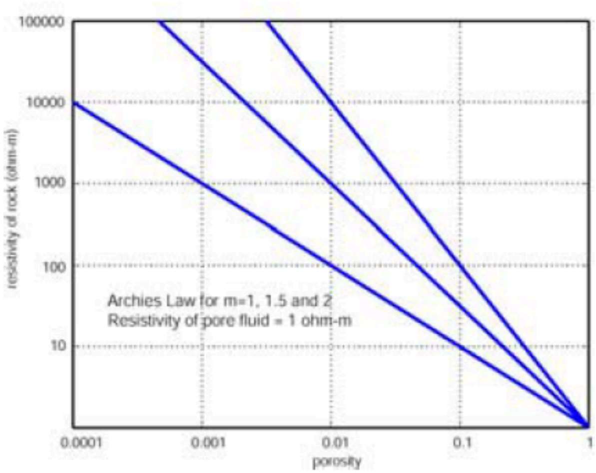


Basic Electrical Properties of Rocks

Electrical resistivity of multiphase materials

The exponent *m* is a constant termed the **cementation factor**. Typical values include: 1.8-2.0 for consolidated sandstones to 1.3 for unconsolidated sands. The following plots show **theoretical** results when $\rho_w = 1$ ohm-m.

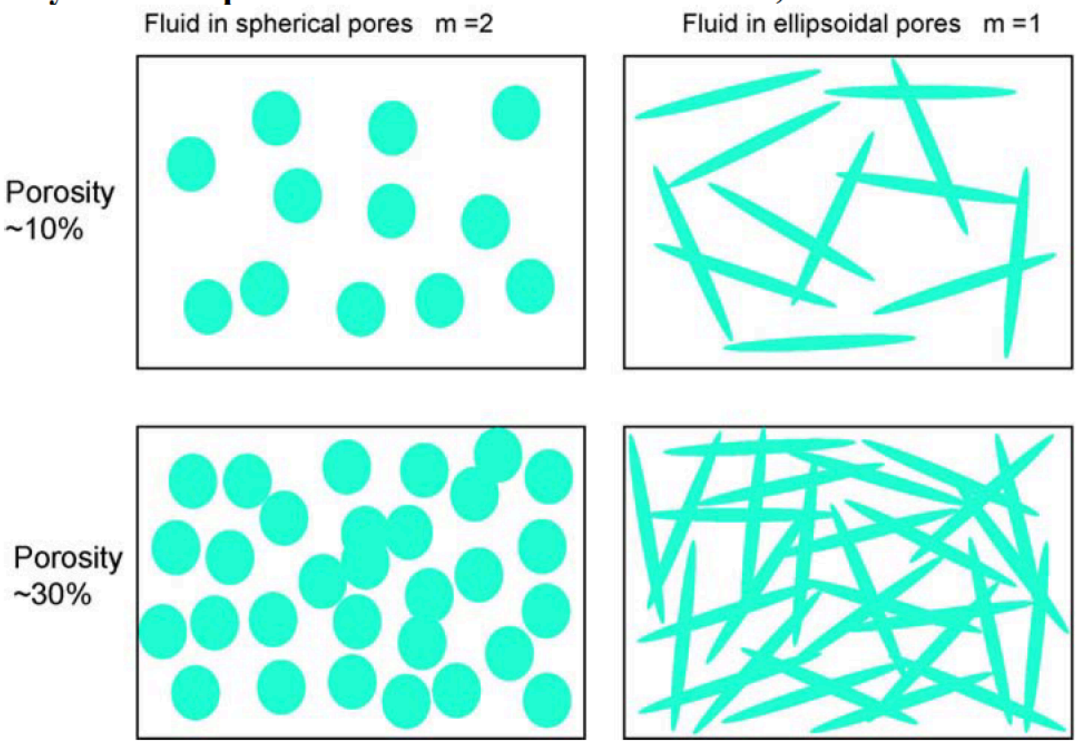




Basic Electrical Properties of Rocks

Electrical resistivity of multiphase materials

Physical interpretation of the cementation factor, m



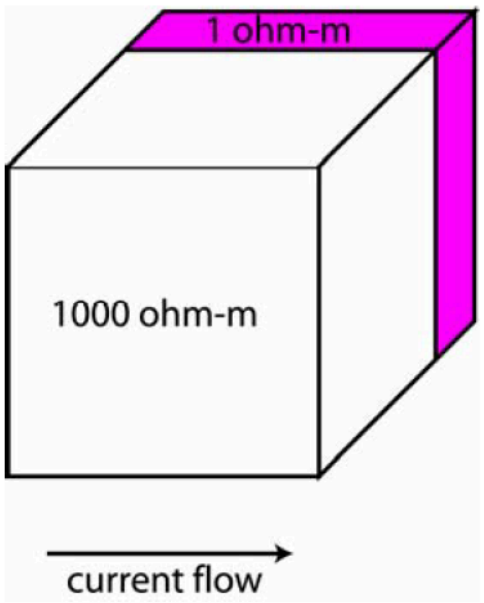
Note that the elongated pores will connect to form an interconnected electrical network at a lower porosity than the spherical pores. Is the permeability of the two cases different?

The above discussion shows that the resistivity of a fluid saturated rock depends on the **amount of fluid** and it's **distribution** (degree of interconnection).

Basic Electrical Properties of Rocks

Homework 1

A – Fluid in cracks parallel to electric current flow



The sample has 10% porosity. This fluid geometry represents a **parallel circuit**, and electric current can effectively bypass the resistive rock grains and travel through the sample entirely in the conductive liquid.

What is the overall resistivity of the cube?

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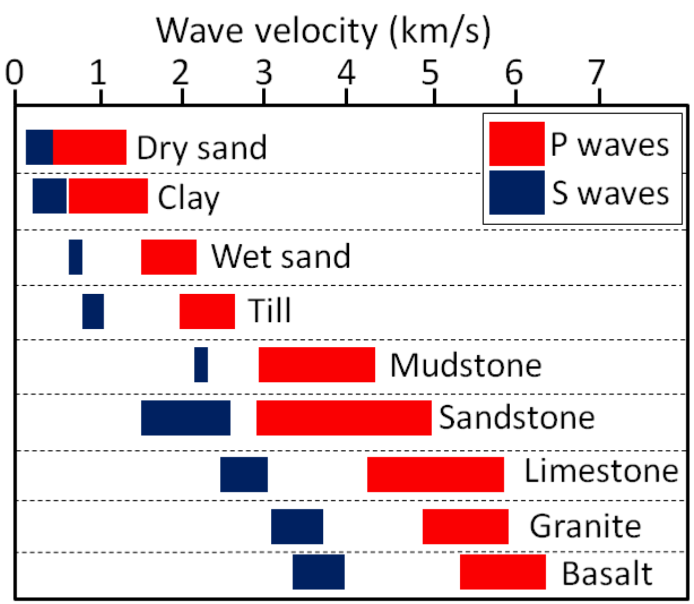
Geophysics ➜ Methods / Techniques

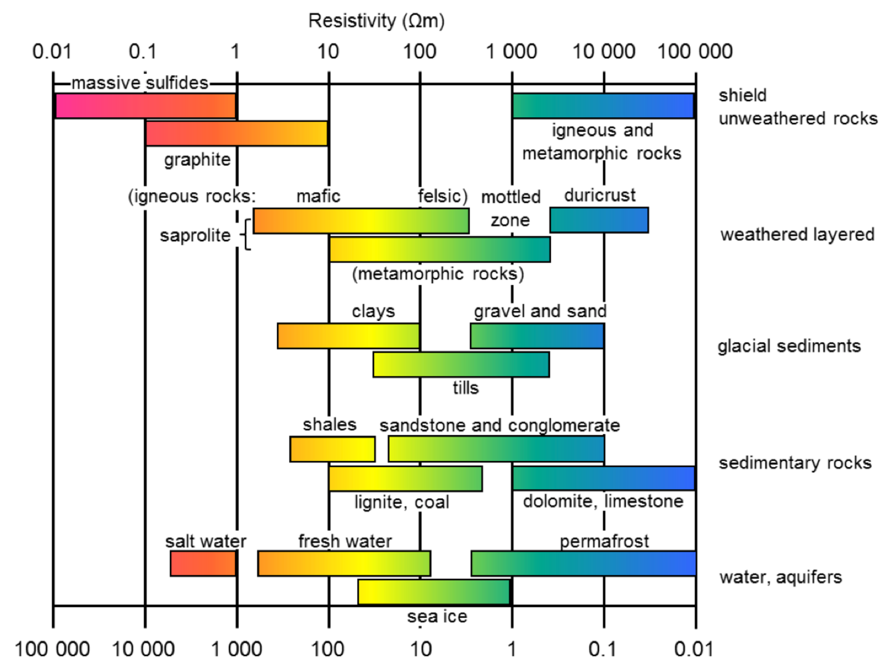
Subsurface Model → **Rocks / Geological Target**

Wave velocity



Source: https://opentextbc.ca/geology/chapter/9-1-understanding-earth-through-seismology/

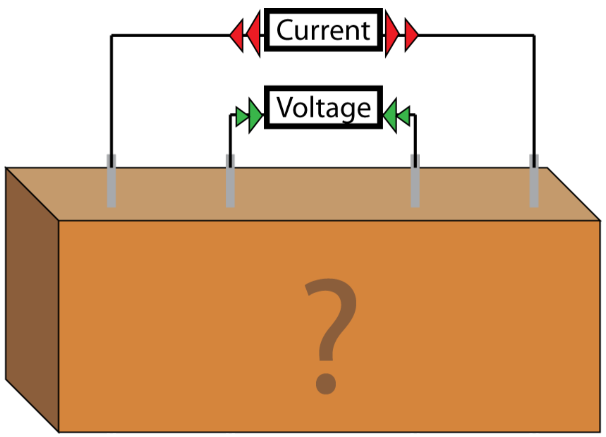
Electrical resistivity



Source: http://gpg.geosci.xyz/_images/resistivity_table1.png

DC Resistivity

Direct-current resistivity (DCR) method is a controlled-source electric geophysical method of imaging the earth's subsurface. DCR is generally used for a **shallow** application (< 1 km).



Ohm's law:

$$V = IR$$

Electrical resistivity:

$$R = K\rho$$

K = measurement factor

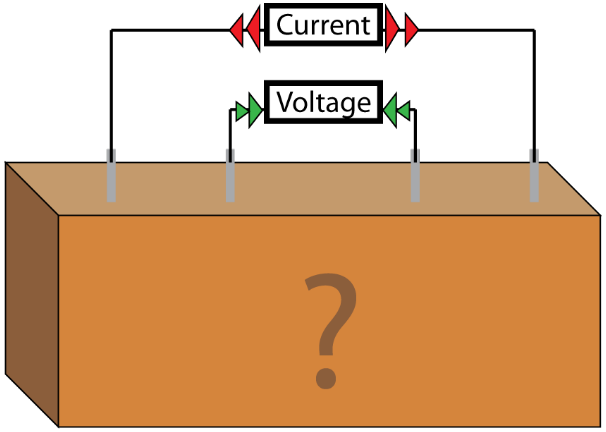
Injecting **I**
Measuring **V**

processin g →

Apparent resistivity (ρ_a)

Resistivity model

DC Resistivity



Injecting I
Measuring V

processing → **Apparent resistivity** (ρ_a)

DC Resistivity

Apparent resistivity (ρ_a)

Resistivity model

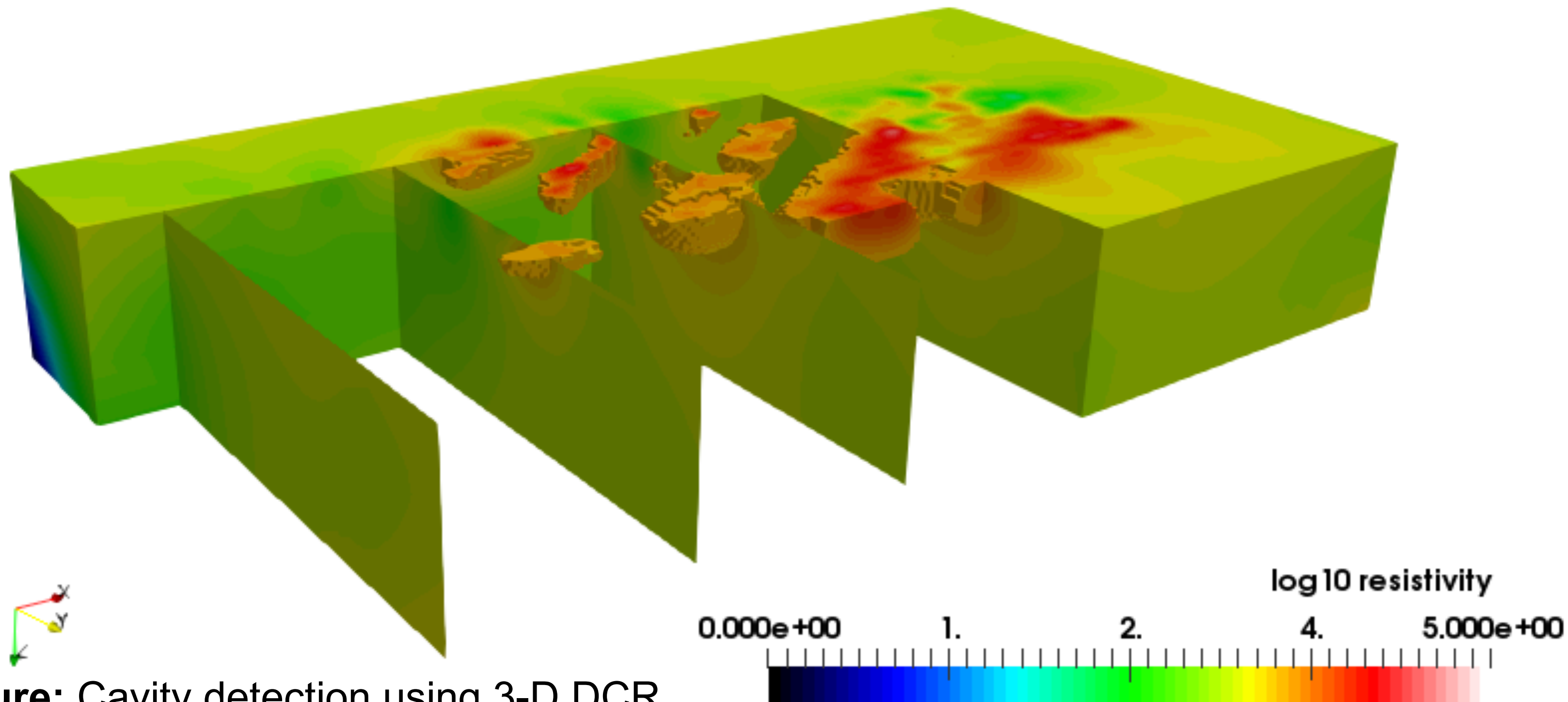


Figure: Cavity detection using 3-D DCR

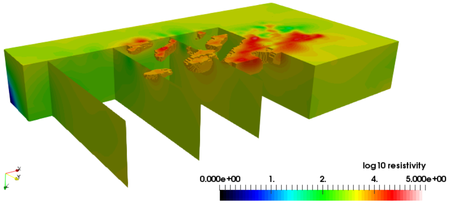
DC Resistivity

Data

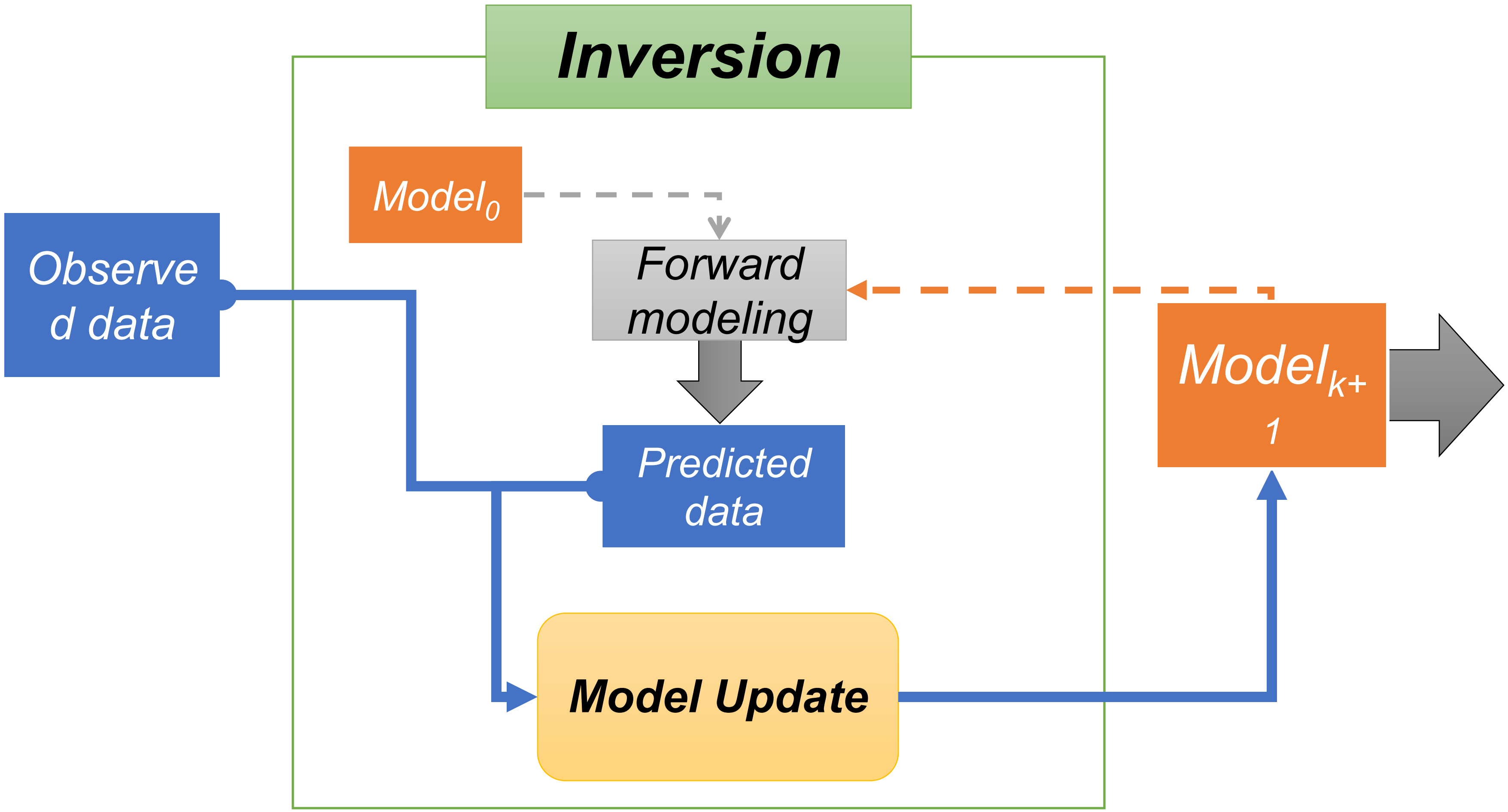
Inversion

Mathematical **optimization**

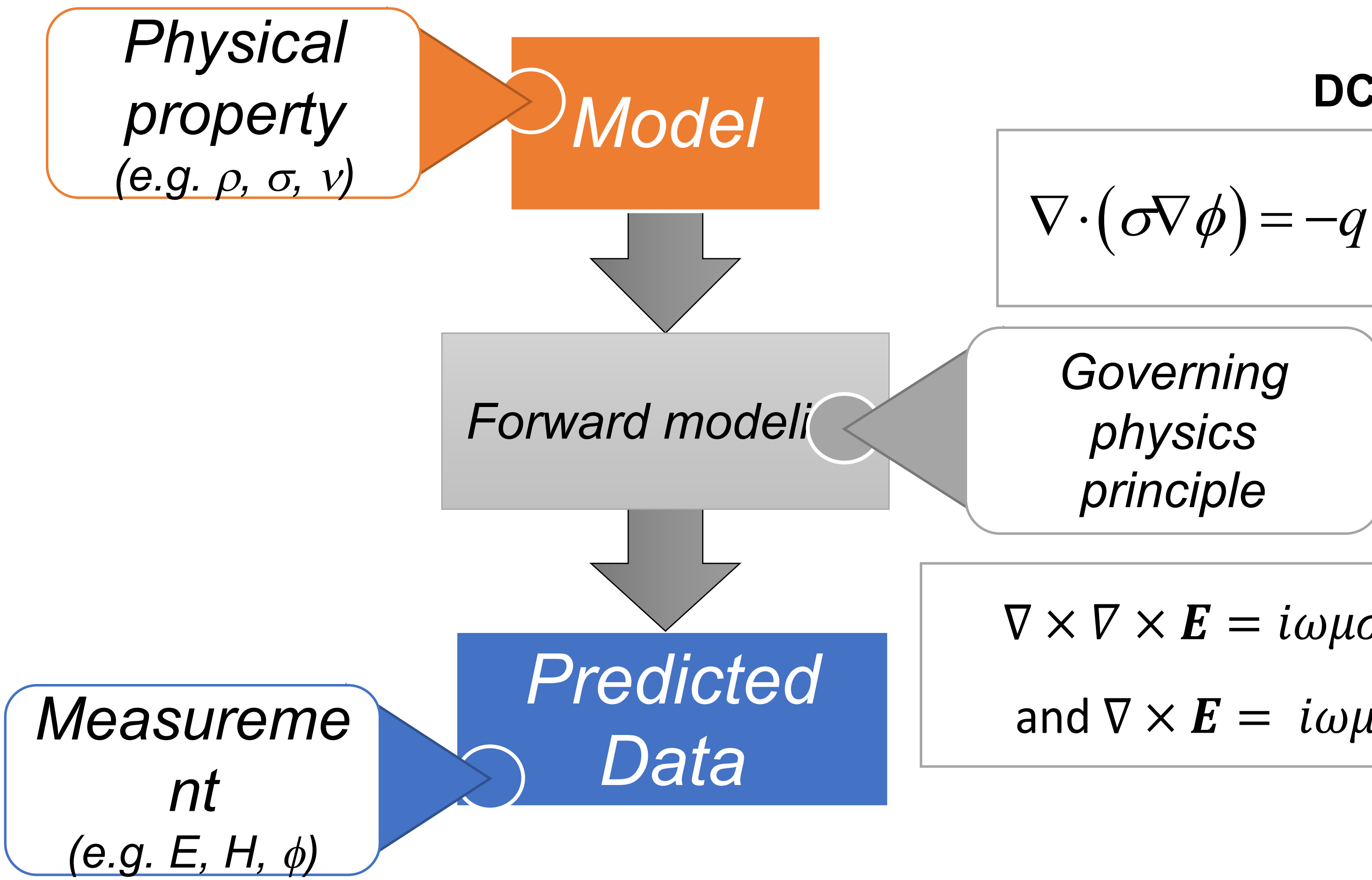
Mode
l



DC Resistivity



DC Resistivity



DCR

$$\nabla \cdot (\sigma \nabla \phi) = -q$$

MT

$$\nabla \times \nabla \times \boldsymbol{E} = i\omega\mu\sigma\boldsymbol{E}$$

and $\nabla \times \boldsymbol{E} = i\omega\mu\boldsymbol{H}$

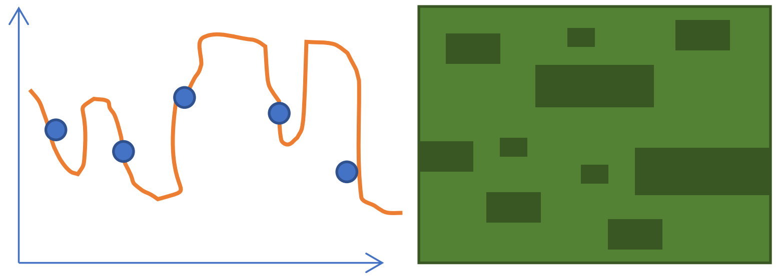
DC Resistivity

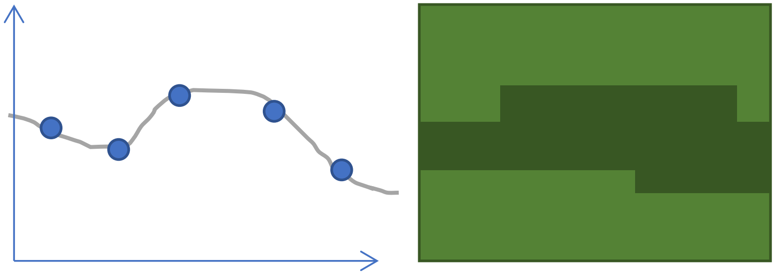
Inversion *Model*

Fit And ***Constrained***

Least-square

Smoothness constraint





DC Resistivity

Physics of the Earth and Planetary Interiors 215 (2013) 1–11

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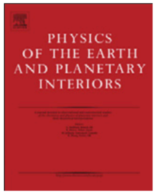

An efficient inversion for two-dimensional direct current resistivity surveys based on the hybrid finite difference–finite element method

Chatchai Vachiratienchai, Weerachai Siripunvaraporn *

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ThEP Center, Commision on Higher Education, 328 Si Ayutthaya Road, Bangkok 10400, Thailand

OUR SOFTWARE

Computers & Geosciences 102 (2017) 100–108

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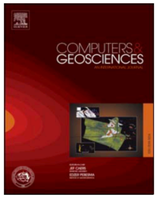


Case study

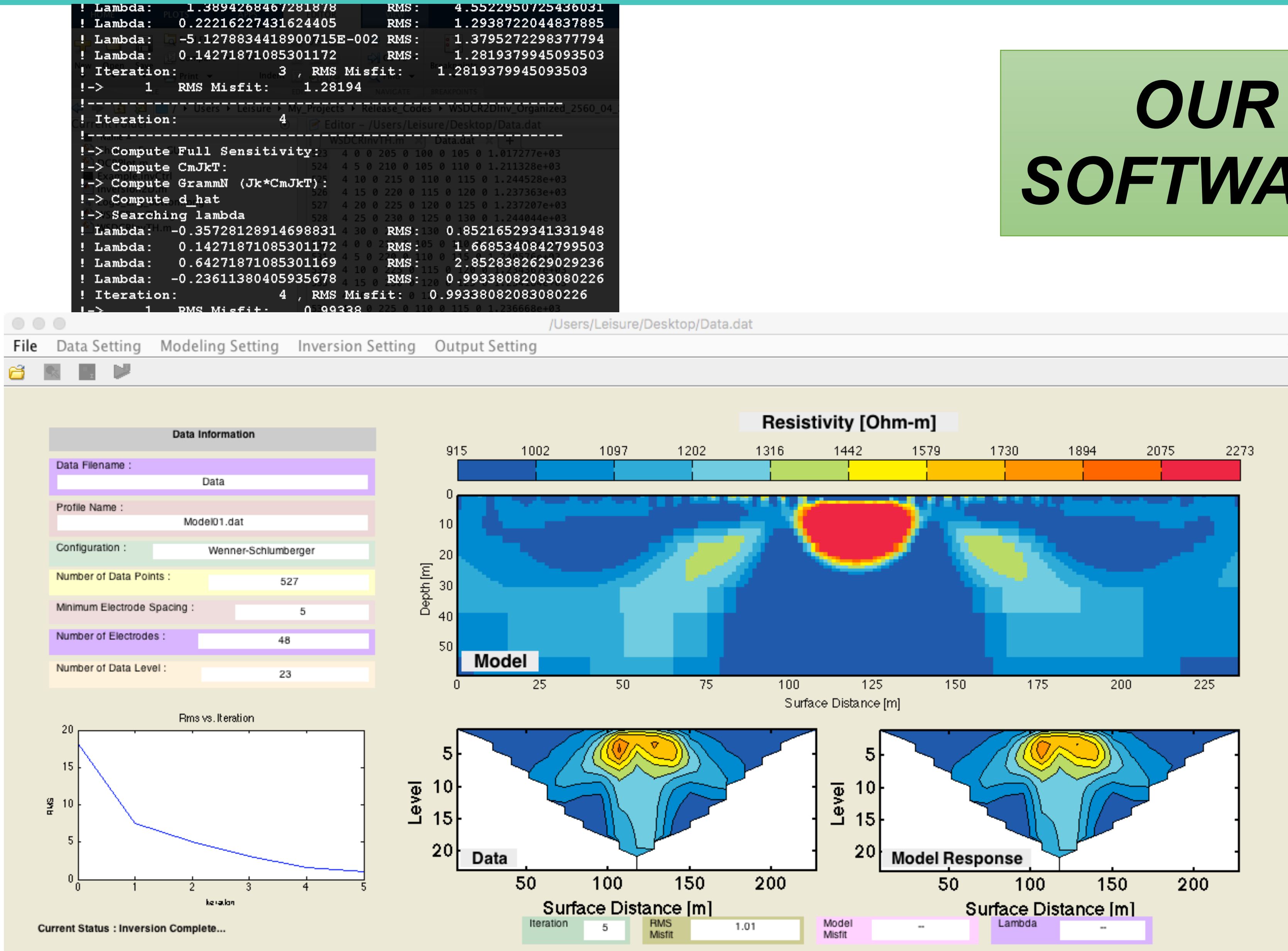
WSJointInv2D-MT-DCR: An efficient joint two-dimensional magnetotelluric and direct current resistivity inversion

CrossMark

Puwis Amatyakul[a], Chatchai Vachiratienchai[b], Weerachai Siripunvaraporn[a,*]

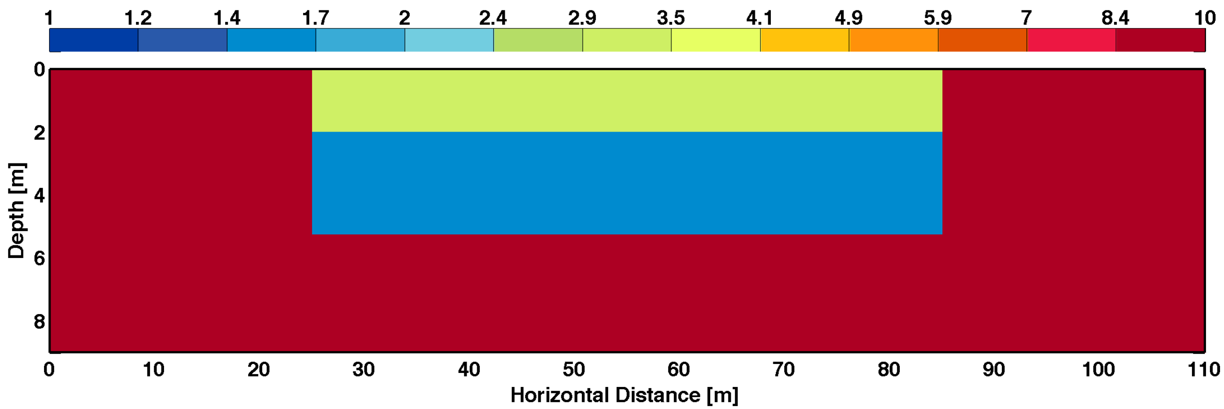
[a] *Department of Physics, Faculty of Science, Mahidol University, 272 Rama 6 Rd., Rachatawee, Bangkok 10400, Thailand*
[b] *Curl-E Geophysics Co. Ltd., 85/87 M. Nantawan Utthayan-Aksa Rd., Salaya, Phutthamonthon, Nakornpathom 73170, Thailand*

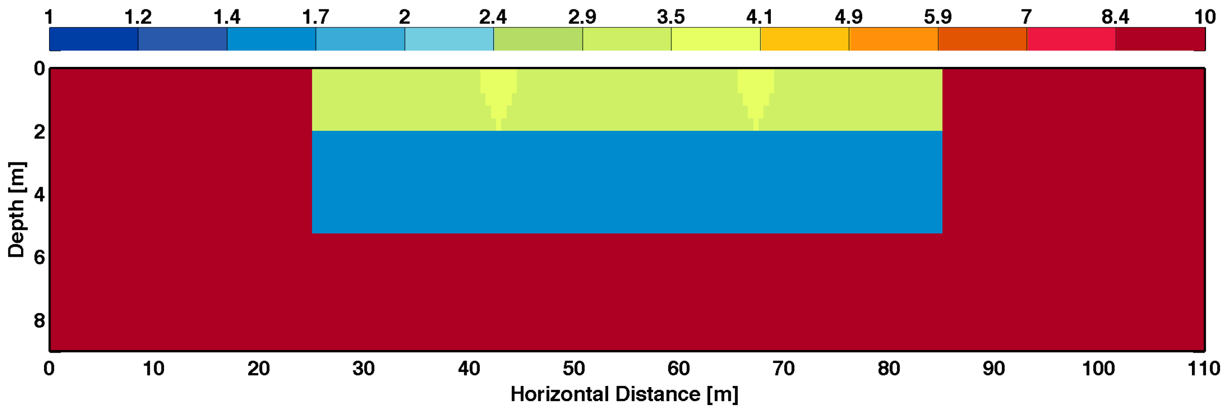
DC Resistivity

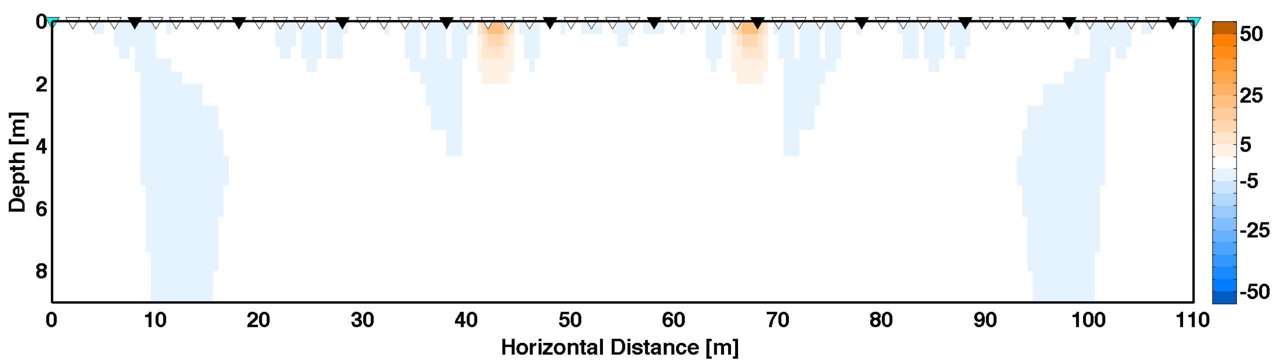


OUR SOFTWARE

DC Resistivity







OUR SOFTWARE

Time-lapse Inversion

DC Resistivity

Data **_Inversion_** *Model*

1D, 2D and 3D tomography

Time-lapse

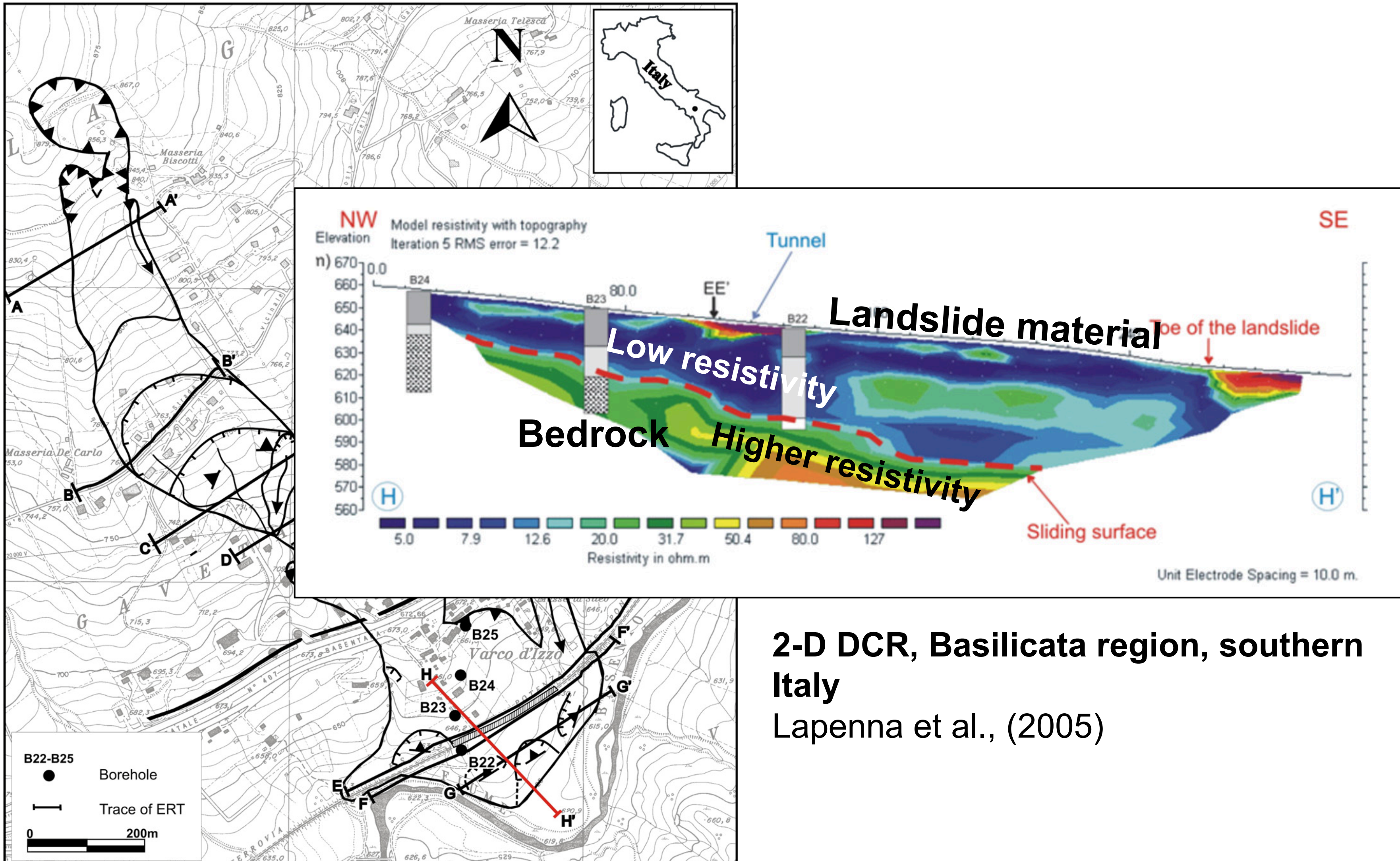
Ore deposit / groundwater

Monitoring

Incorporate with petrophysical property

$$\sigma_t = \sigma_w \phi^m S_w^n = \sigma_w F$$

Application: 2D DCR



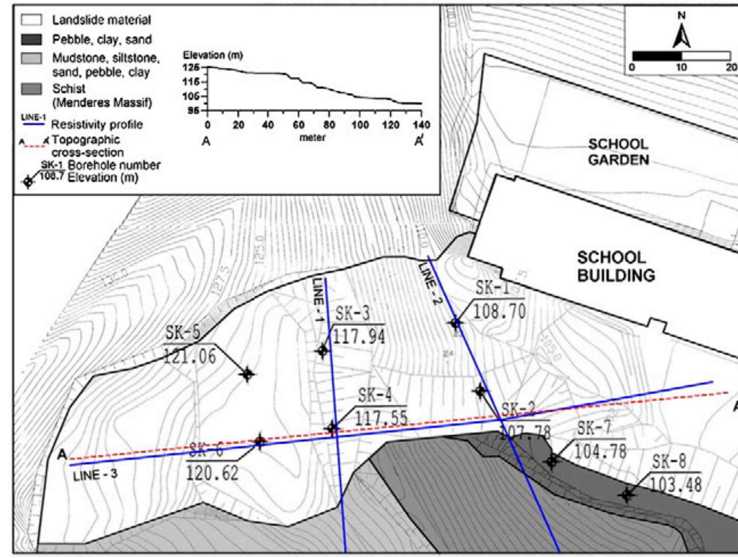
2-D DCR, Basilicata region, southern Italy

Lapenna et al., (2005)

Fig. 2. Varco d'Izzo landslide (Basilicata region, southern Italy): identification of the sliding surface and definition of landslide shape by the comparison between the HH' 2D ERT and the stratigraphic data inferred from boreholes B22, B23 and B24 (redrawn from Lapenna et al., (2005)).

Application: 3-D DCR

3-D DCR, Aydin (Turkey)
Source: Drahor et al., (2006)



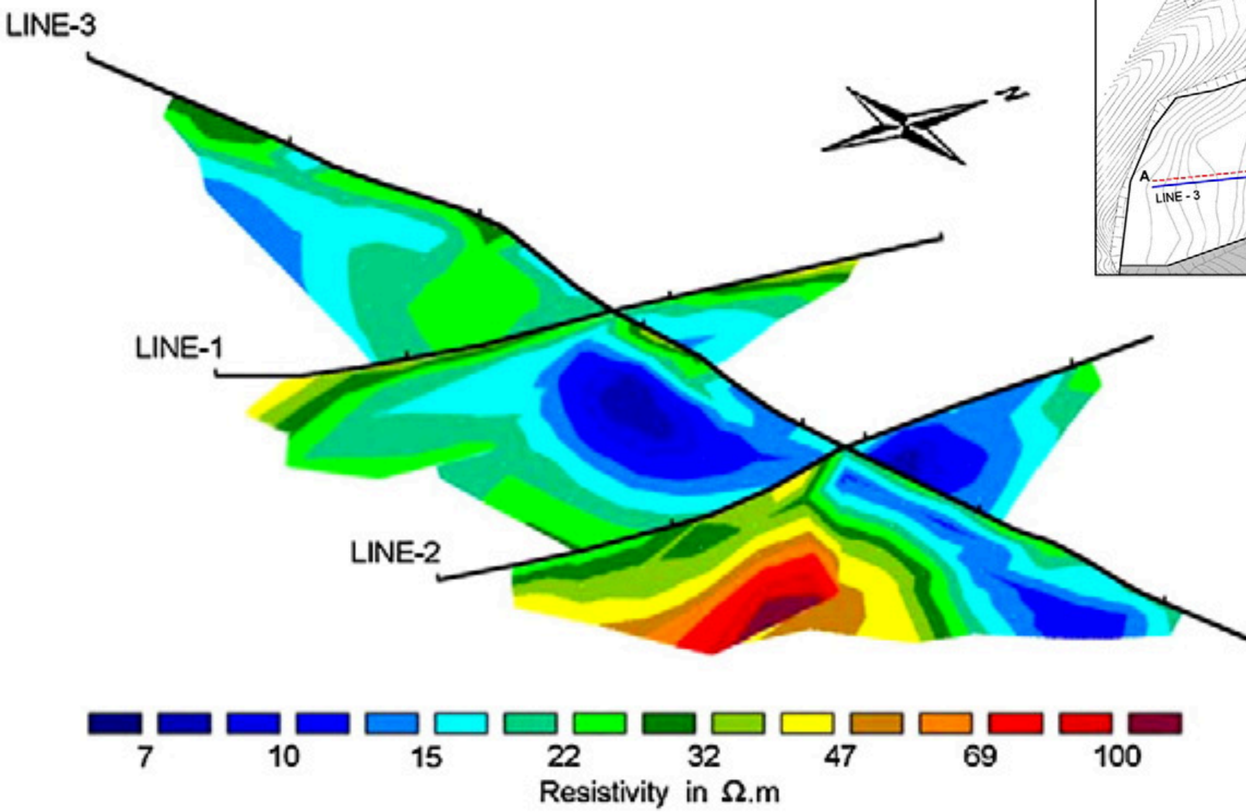
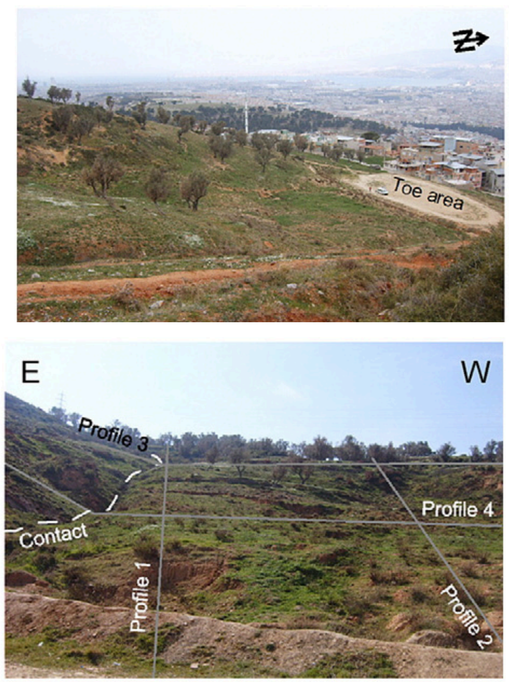
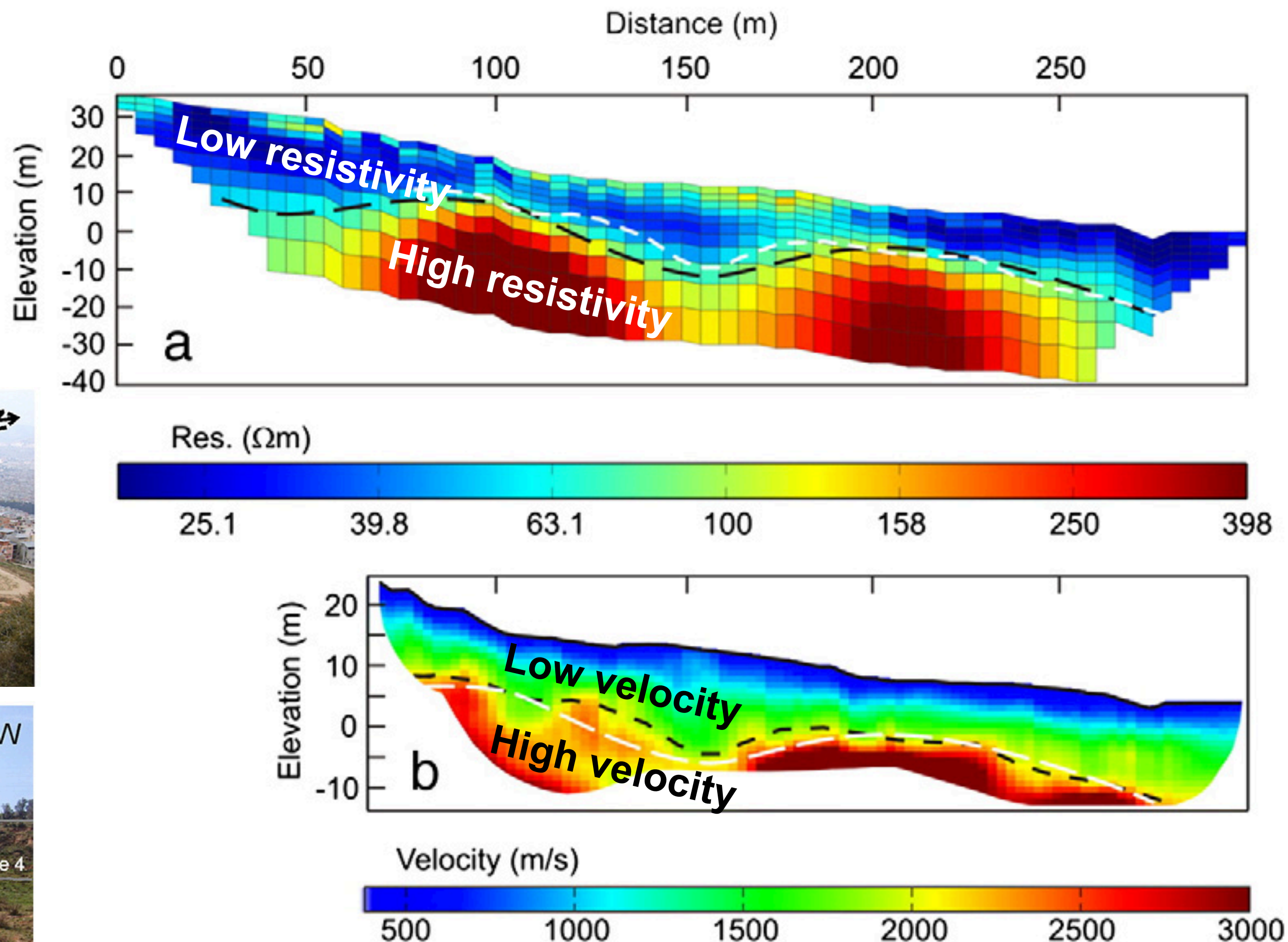


Fig. 5. Geological map of the Soke landslide area in the district of Aydin (Turkey) with location of measurement profiles. 3D fence diagram of the resistivity sections carried out on the landslide (redrawn from Drahor et al., (2006)).

Application: Joint DCR + Seismic

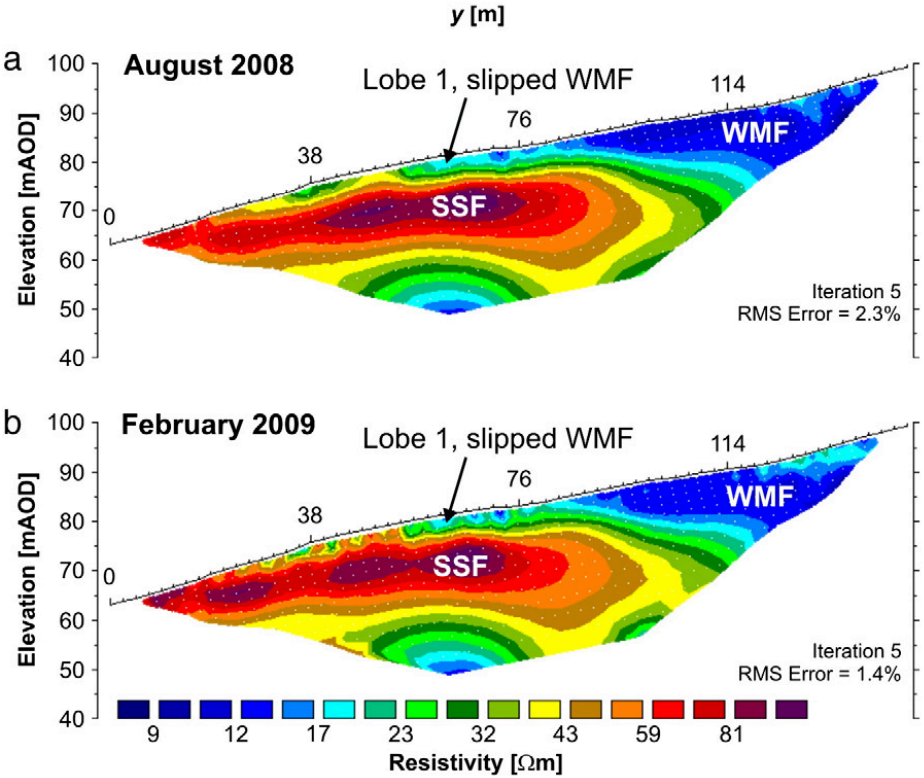


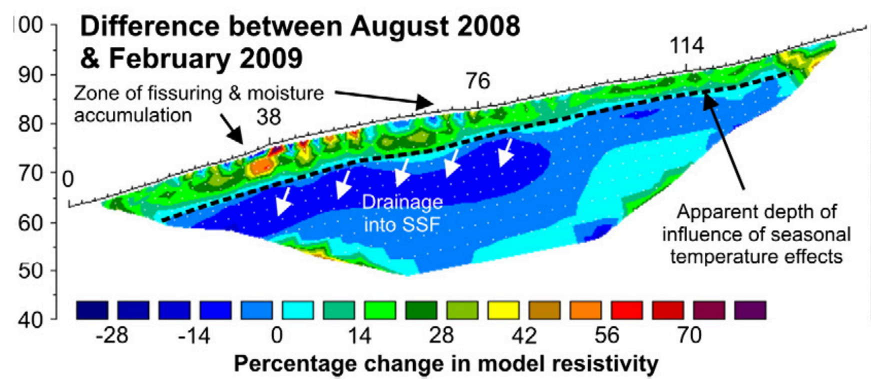


2-D DCR + Seismic, western Turkey
Goktukler et al., (2008)

Fig. 3. (Top) A general view of the Altındağ landslide site, İzmir (western Turkey) with location of measurement profiles; (bottom) identification of the sliding surface by the comparison between 2D ERT and the seismic refraction tomography carried out along the profile 1 (redrawn from Göktürkler et al., (2008)).

Application: Time-lapse Inversion

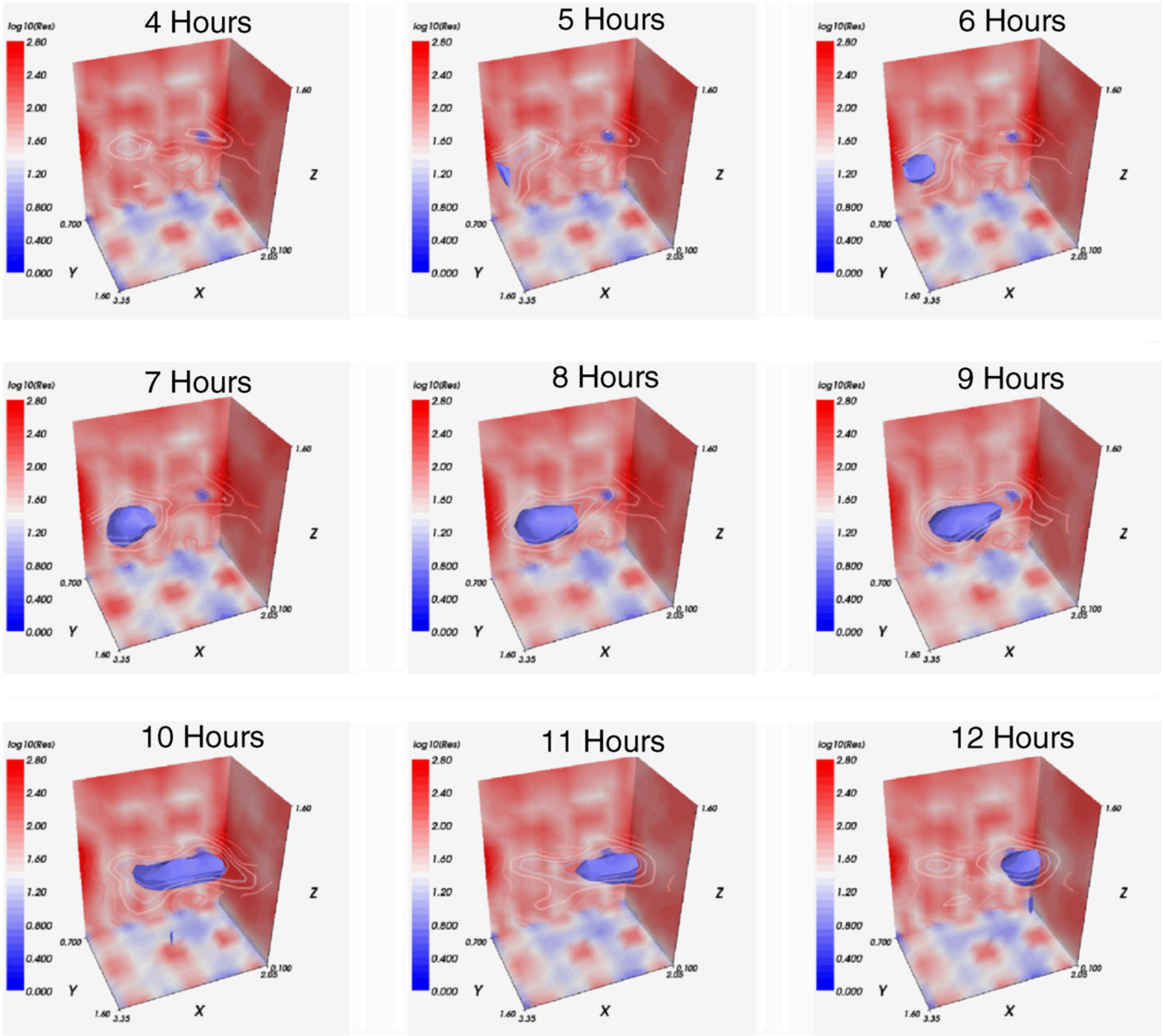




2-D DCR time-lapse, North Yorkshire, UK
Chambers et al., (2009)

Fig. 6. Landslide in Malton site (North Yorkshire, UK): Tl-ERT obtained by the ALERT (Kuras et al., 2009) data. (a) 2D ERT carried out on August 2008; (b) 2D ERT carried out on February 2009; (c) resulting differential resistivity image (after Chambers et al., (2009)).

Application: Time-lapse Inversion



Synthetic fluid tracking by using 3-D resistivity time-lapse inversion
Kuras et al., (2009)

Conclusion

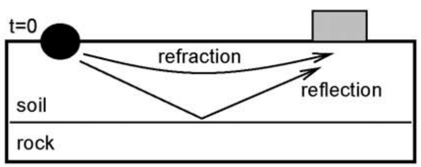
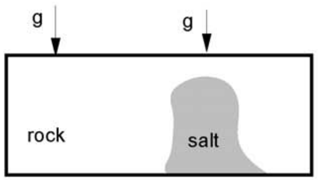
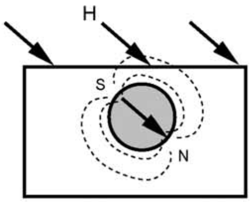
Geophysics ➜ **Prospecting**

- ✓ Geophysical exploration **reveals subsurface image**.
- ✓ **Electrical resistivity and seismic velocity** directly links to ore deposition / ground water /etc.
- ✓ Geophysical model can be **related with petrophysical** properties.
- ✓ **Integrated geophysical explorations** is required to reduce interpretation ambiguity.
- ✓ Explorations can be designed according to the purpose of the studies (**structural delineation and monitoring**)

DC Resistivity

Homework 2 Fill the table below for DC resistivity exploration

SUMMARY OF GEOPHYSICAL EXPLORATION TECHNIQUES

	Seismic exploration	**Gravity exploration**	**Magnetic exploration**	**DC resistivity exploration**
Quantity measured in field survey	Travel times (t) and amplitude of seismic waves	Gravitational force on known mass (g)	Magnetic field (H)	
Property calculated in data analysis	Seismic velocity (v)	Density (ρ)	Magnetic susceptibility (k) Remnant magnetization (M)	
Survey layout				
Common applications	Depth to bedrock, geotechnical studies Oil and gas exploration Tectonic studies	Depth to bedrock Mapping salt domes Locating caves Mapping landfill geometry Tectonic studies	Locating metal drums and pipes Mineral exploration Depth to igneous basement Archaeology Tectonic studies	

Next Class

Geophysical Workflow

Method / Fundamental (governing physics)			
Instrument	**Data Processing**	**Modeling/inversion**	**Interpretation**
✓ Sensor ✓ Raw data	✓ Signal processing ✓ Noise ✓ Processed data	✓ Math. optimization ✓ Physical model 1D/2D and 3D	✓ Geological model

End of L01

Fig. Magnetotelluric survey, somewhere in Thailand.