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le 9 mars 2006
Strasbourg

Electrical imaging techniques for hydrological and risk assessment studies

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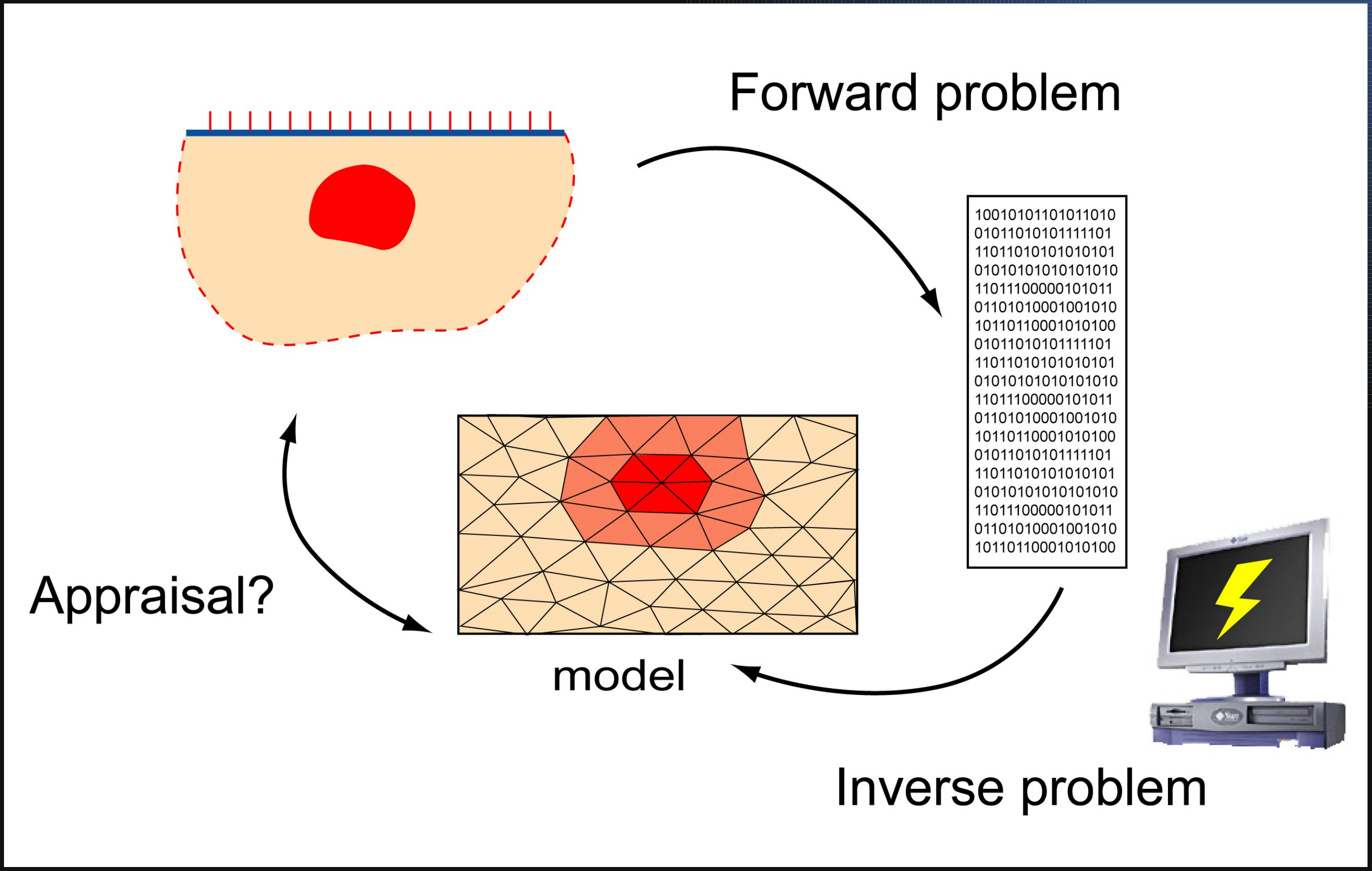
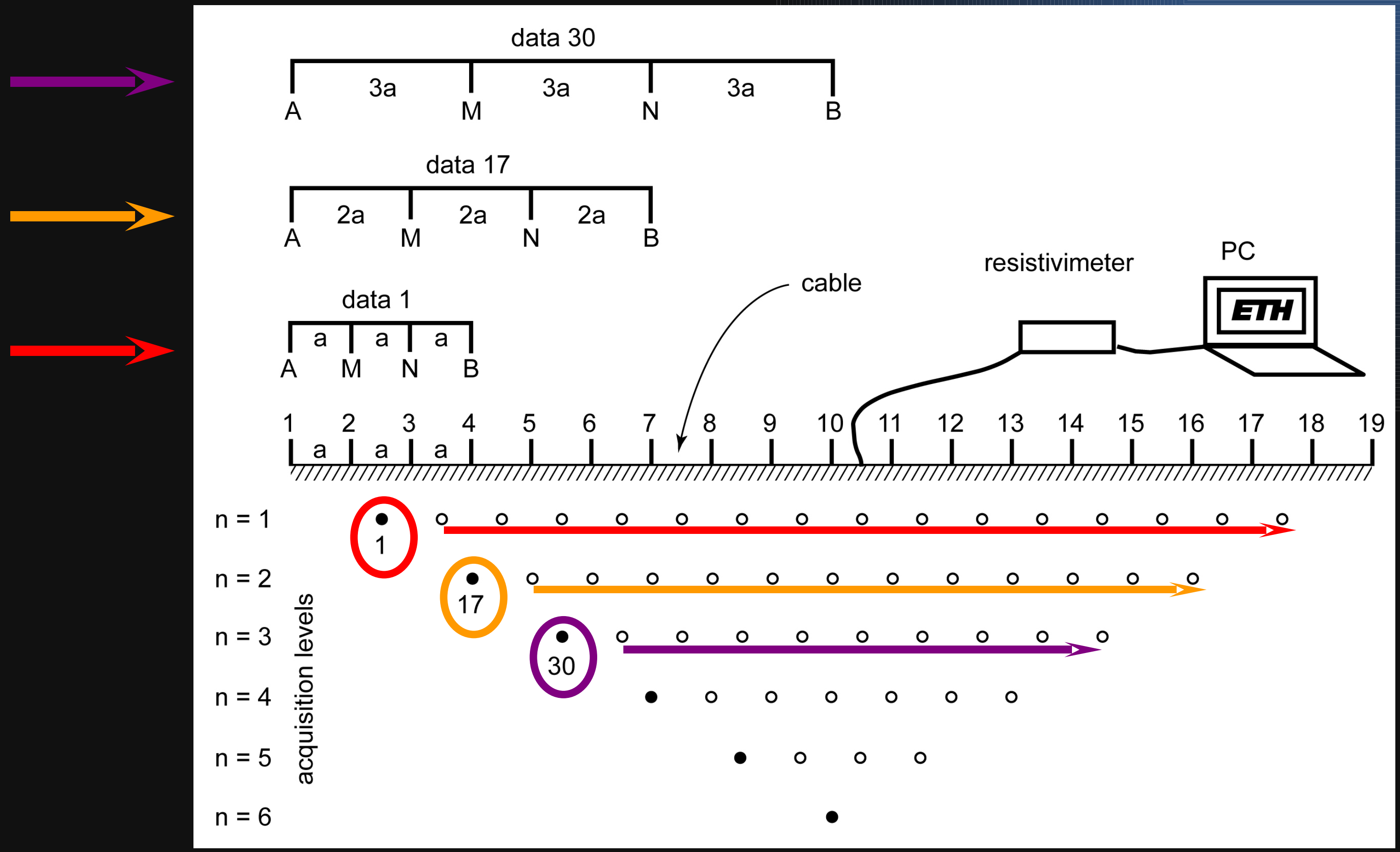
Electrical Resistivity Imaging



Forward Problem



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Source: P. Martínez Pagán, Universidad Politécnica de Cartagena

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The Inversion: Traditional way…

Gauss-Newton smoothness constrained least squares equation (L_2 norm) with the Marquardt-Levenberg modification

$$\left(\mathbf{J}_\mathbf{k}^\mathbf{T}\,\mathbf{R}_\mathbf{d}\,\mathbf{J}_\mathbf{k} + \lambda_k\,\mathbf{F}_\mathbf{R}\right)\;\Delta\mathbf{q}_\mathbf{k} = \mathbf{J}_\mathbf{k}^\mathbf{T}\,\mathbf{R}_\mathbf{d}\;\;\mathbf{g}_\mathbf{k} - \;\lambda_k\,\mathbf{F}_\mathbf{R}\;\left(\mathbf{q}_{\mathbf{k-1}} - \mathbf{q}_\mathbf{0}\right)$$

$$\mathbf{F}_\mathbf{R} = \alpha_s\,\mathbf{R}_\mathbf{s} + \alpha_x\,\mathbf{C}_\mathbf{x}^\mathbf{T}\,\mathbf{R}_\mathbf{x}\,\mathbf{C}_\mathbf{x} + \alpha_z\,\mathbf{C}_\mathbf{z}^\mathbf{T}\,\mathbf{R}_\mathbf{z}\,\mathbf{C}_\mathbf{z}$$

$\mathbf{q}_0$ is a homogeneous reference model

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Appraisal: The Depth Of Investigation (DOI)

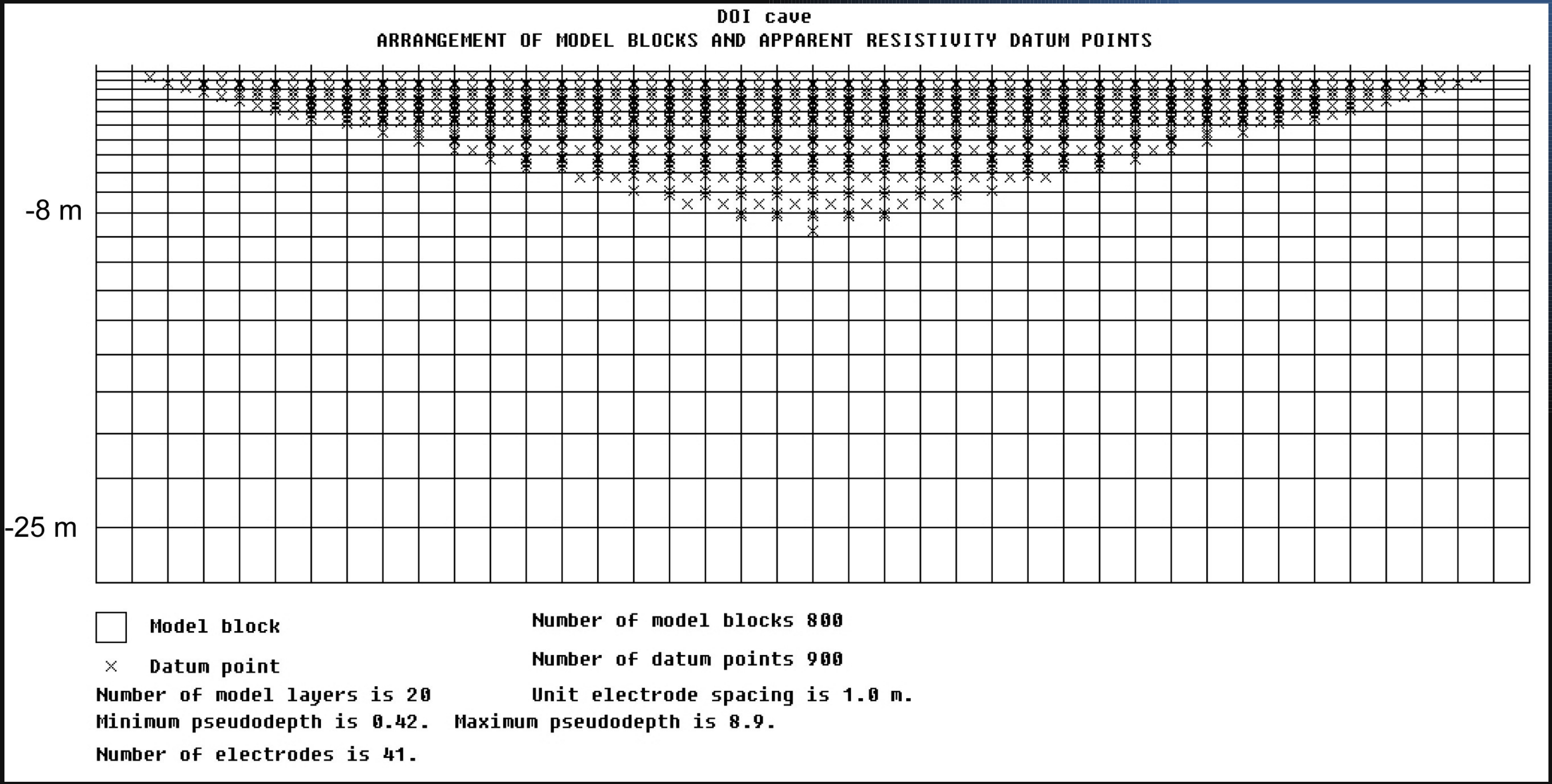
The method carries out 2 inversions of the same data set using different values of the reference resistivity $\mathbf{q_0}$:

the two inversions reproduce the same resistivity values in areas where the data contain information about the resistivity of the subsurface

whereas …

the final result depends on the reference resistivity in areas where the data do not constrain the model

Model Cells for Surface Surveys



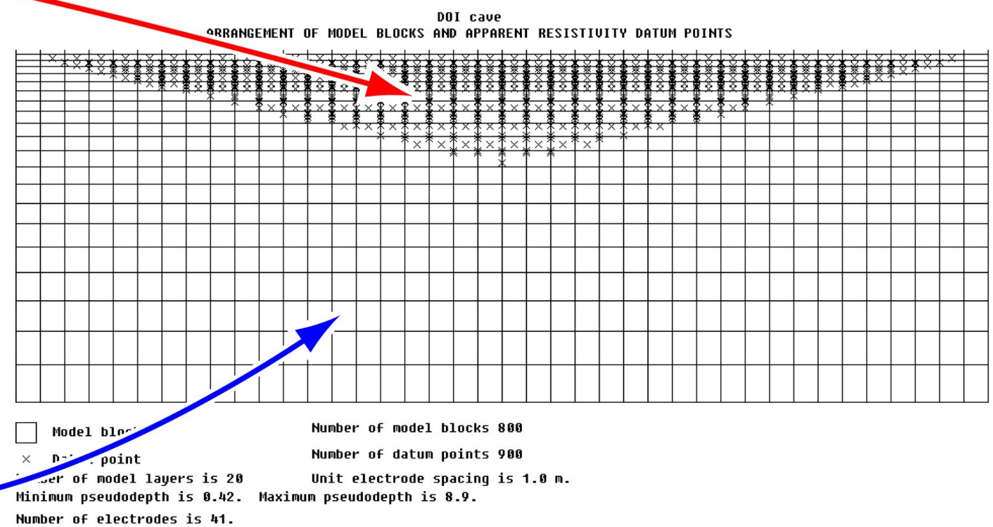
The Depth Of Investigation (DOI) index

$$R_{AB}(x,z) = \frac{q_A(x,z) - q_B(x,z)}{q_A - q_B}$$

$$R(x,z) = \frac{q_A(x,z) - q_B(x,z)}{R_M(q_A - q_B)}$$

Cells well constrained by data $R \cong 0$

Cells poorly constrained by data $R \rightarrow 1$



Parameters used for the Inversion

$$\left(\mathbf{J}_{\mathbf{k}}^{\mathbf{T}}\,\mathbf{R}_{\mathbf{d}}\,\mathbf{J}_{\mathbf{k}}+\lambda_k\,\mathbf{F}_{\mathbf{R}}\right)\;\Delta\mathbf{q}_{\mathbf{k}}=\mathbf{J}_{\mathbf{k}}^{\mathbf{T}}\,\mathbf{R}_{\mathbf{d}}\;\;\mathbf{g}_{\mathbf{k}}-\;\lambda_k\,\mathbf{F}_{\mathbf{R}}\;\left(\mathbf{q}_{\mathbf{k-1}}-\mathbf{q}_{\mathbf{0}}\right)$$

$$\mathbf{F}_{\mathbf{R}}=\alpha_s\,\mathbf{R}_{\mathbf{s}}+\alpha_x\,\mathbf{C}_{\mathbf{x}}^{\mathbf{T}}\,\mathbf{R}_{\mathbf{x}}\,\mathbf{C}_{\mathbf{x}}+\alpha_z\,\mathbf{C}_{\mathbf{z}}^{\mathbf{T}}\,\mathbf{R}_{\mathbf{z}}\,\mathbf{C}_{\mathbf{z}}$$

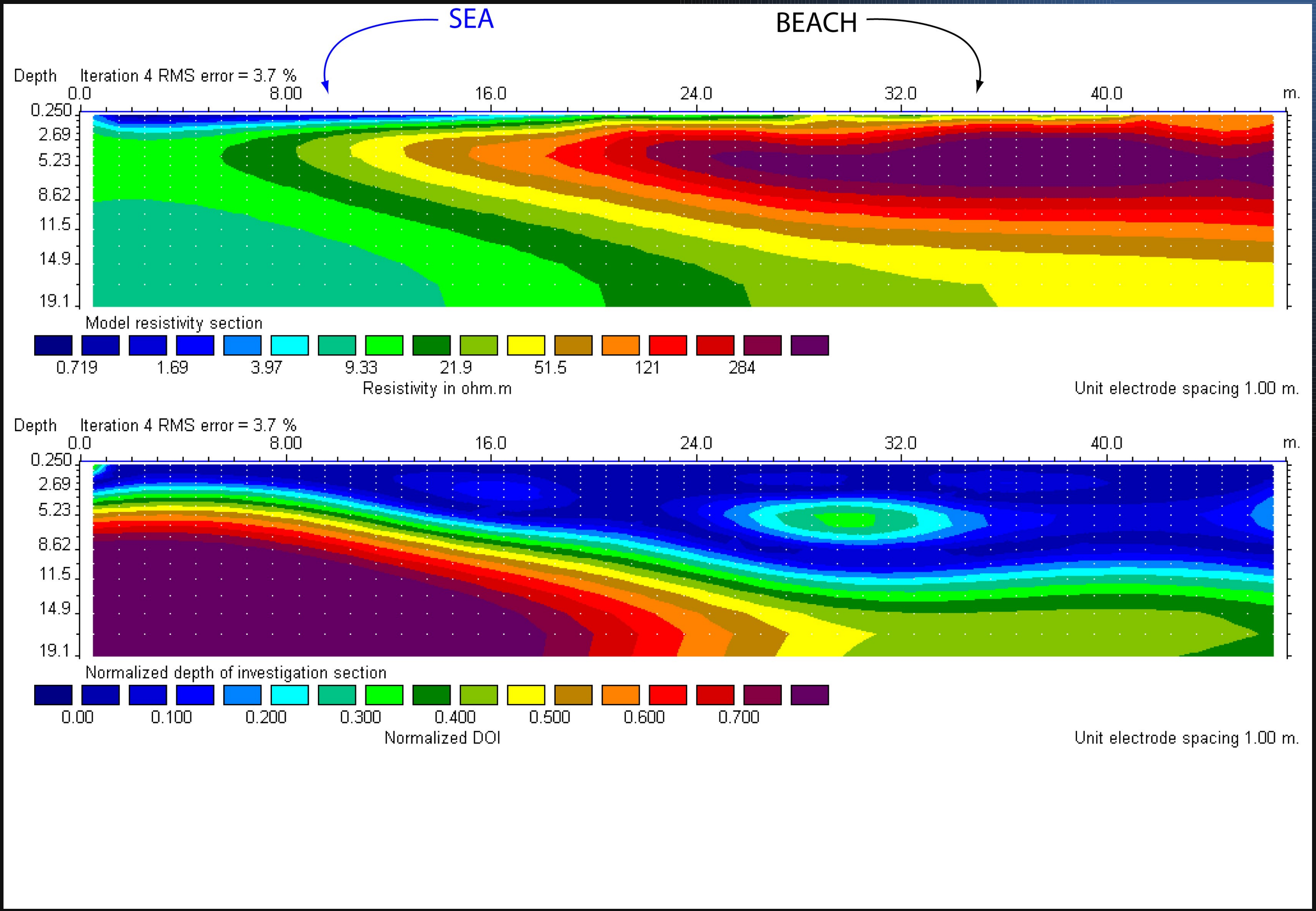
Inversion 1 $\mathbf{q}_a = 0.1 \times \mathbf{q}_0$

Inversion 2 $\mathbf{q}_b = 10 \times \mathbf{q}_0$

DOI: Field Example

Electrical imaging in marine environment, Denmark

DOI: Field Example



Source: Marescot and Loke, SAGEEP 2004

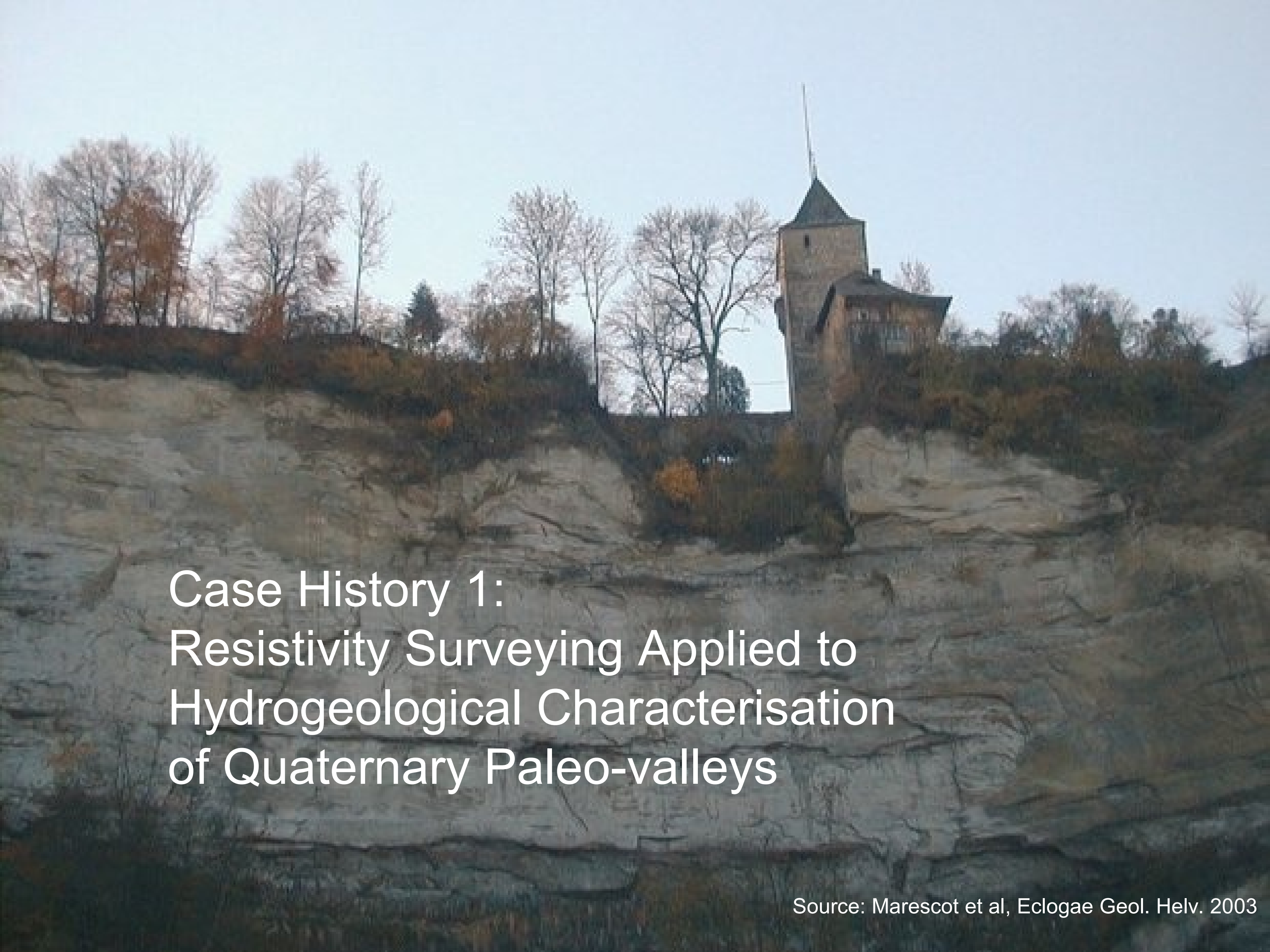
Three Examples:

Case 1: Resistivity Surveying Applied to Hydrogeological Characterisation of Quaternary Paleo-valleys

Case 2: 2D Electrical Resistivity Imaging in Mountain Permafrost Studies

Case 3: Permanent 3D Rainfall Infiltration Monitoring in Soils

Case History 1:
Resistivity Surveying Applied to Hydrogeological Characterisation of Quaternary Paleo-valleys



Source: Marescot et al, Eclogae Geol. Helv. 2003

Aim of the Study…

To image a complex Quaternary paleo-valleys framework near the city of Fribourg (Switzerland) using geoelectrical methods

These data are useful for:

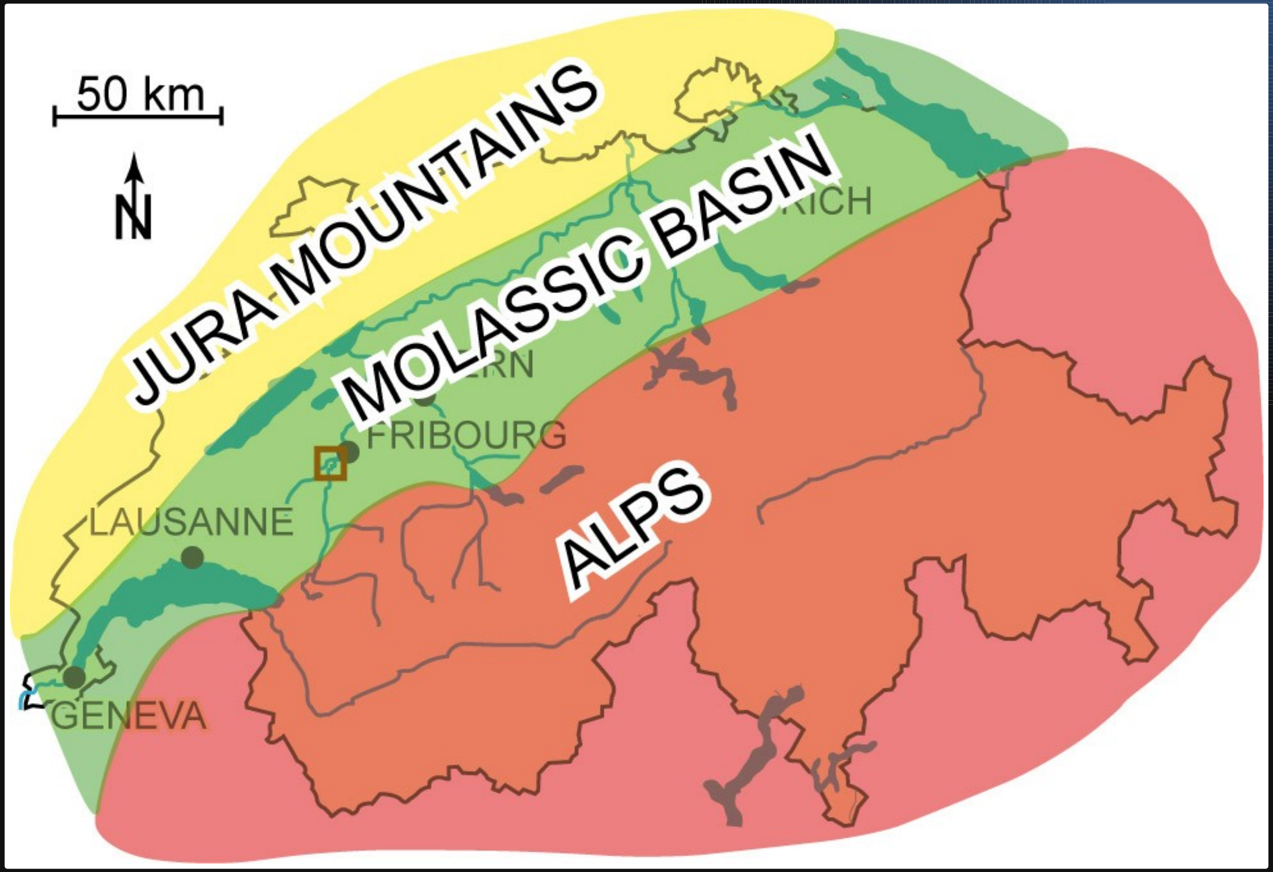
… understanding the groundwater circulations and the risk of pollutant migrations for future geotechnical and hydrogeological modelling

… planning the creation of protected areas

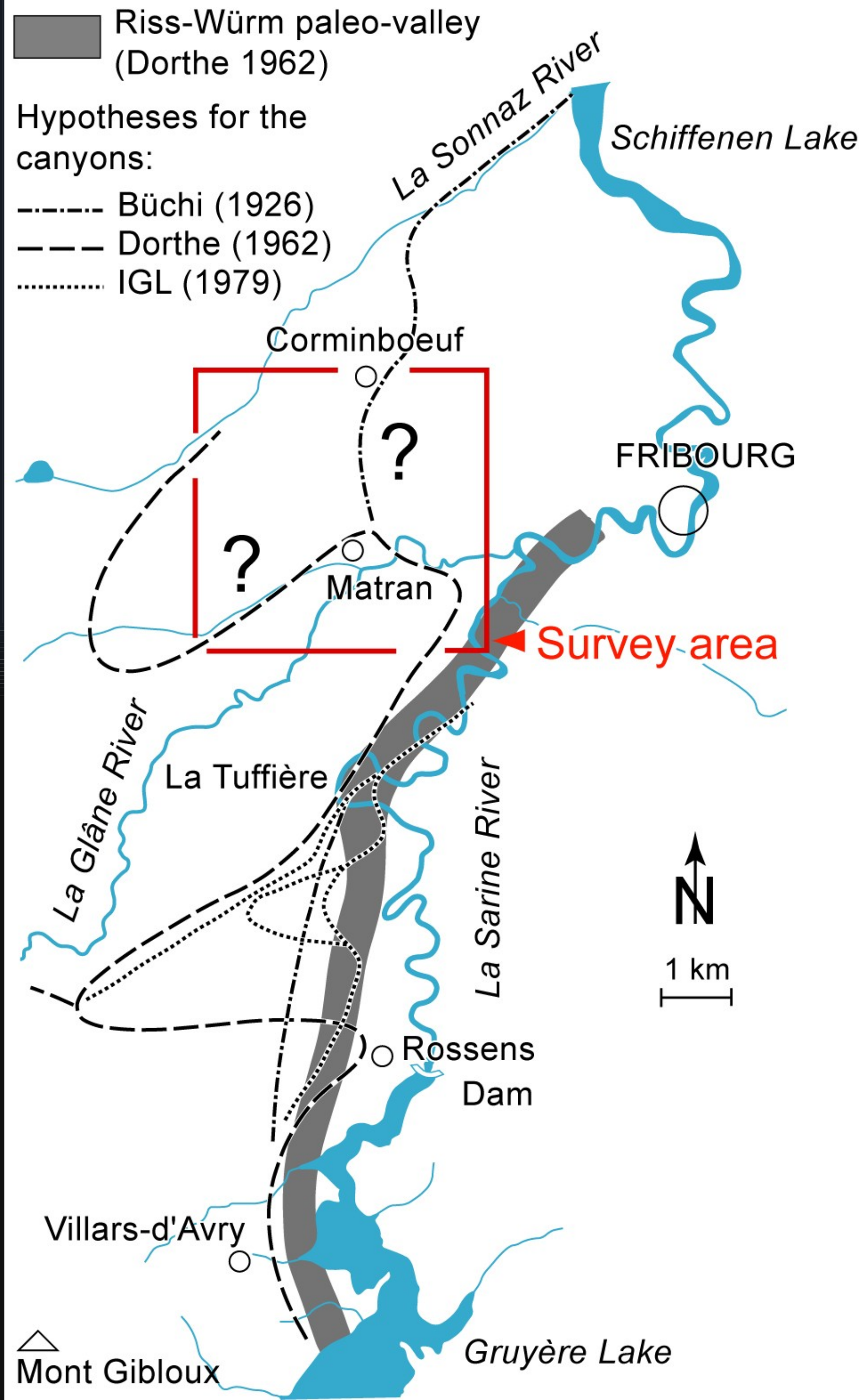
… planning further geophysical and geotechnical surveys

Geographical Location

Brief Geological Outline



Paleo-valleys



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Canyons

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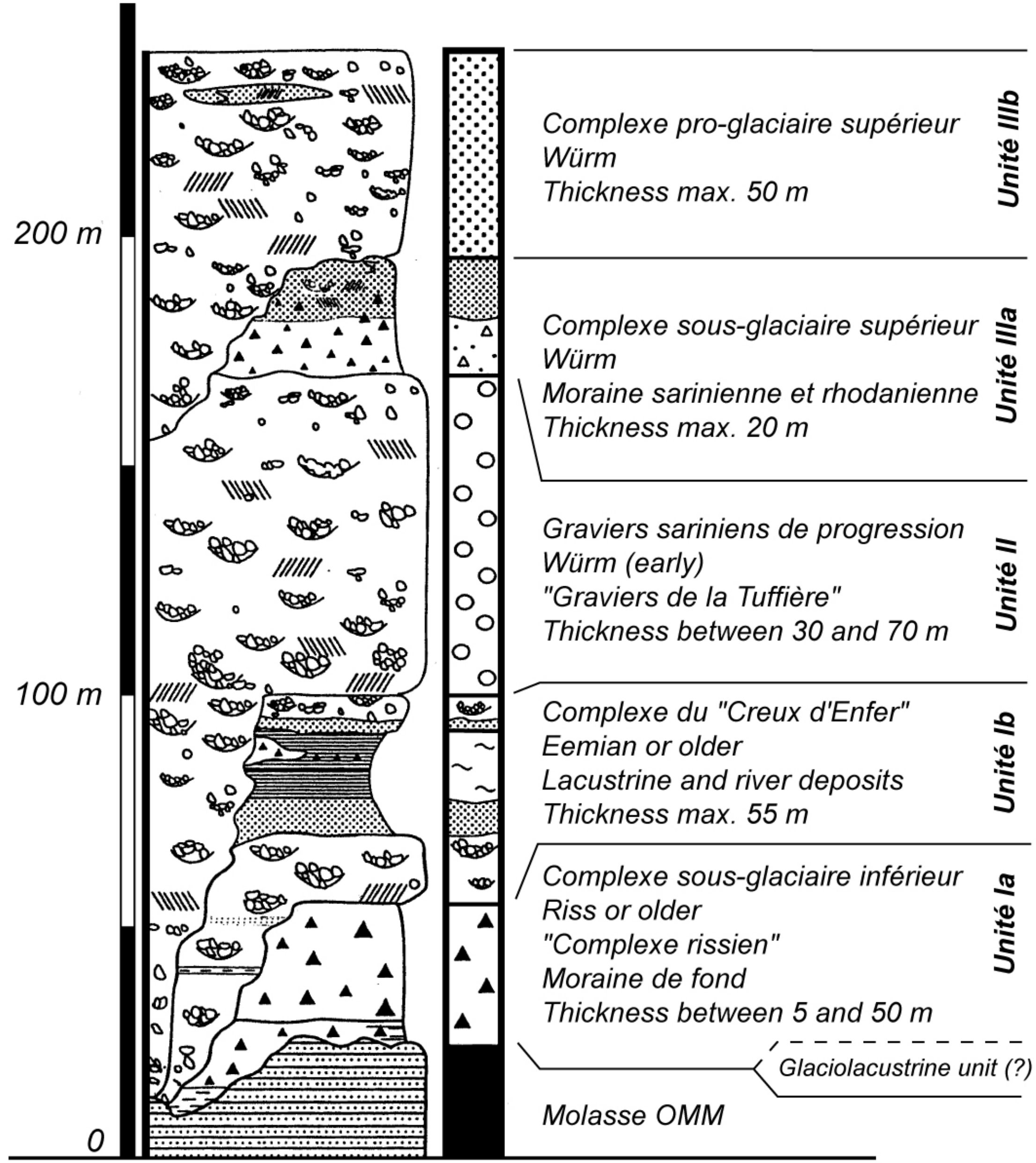
Stratigraphy



General Methodology

Collecting geological, hydrogeological and geotechnical information

Parametrical study

Resistivity mapping (Schlumberger configuration, array length 200m): 680 data points

35 vertical electrical soundings

20 profiles of 2D resistivity imaging

Bedrock topography modelling

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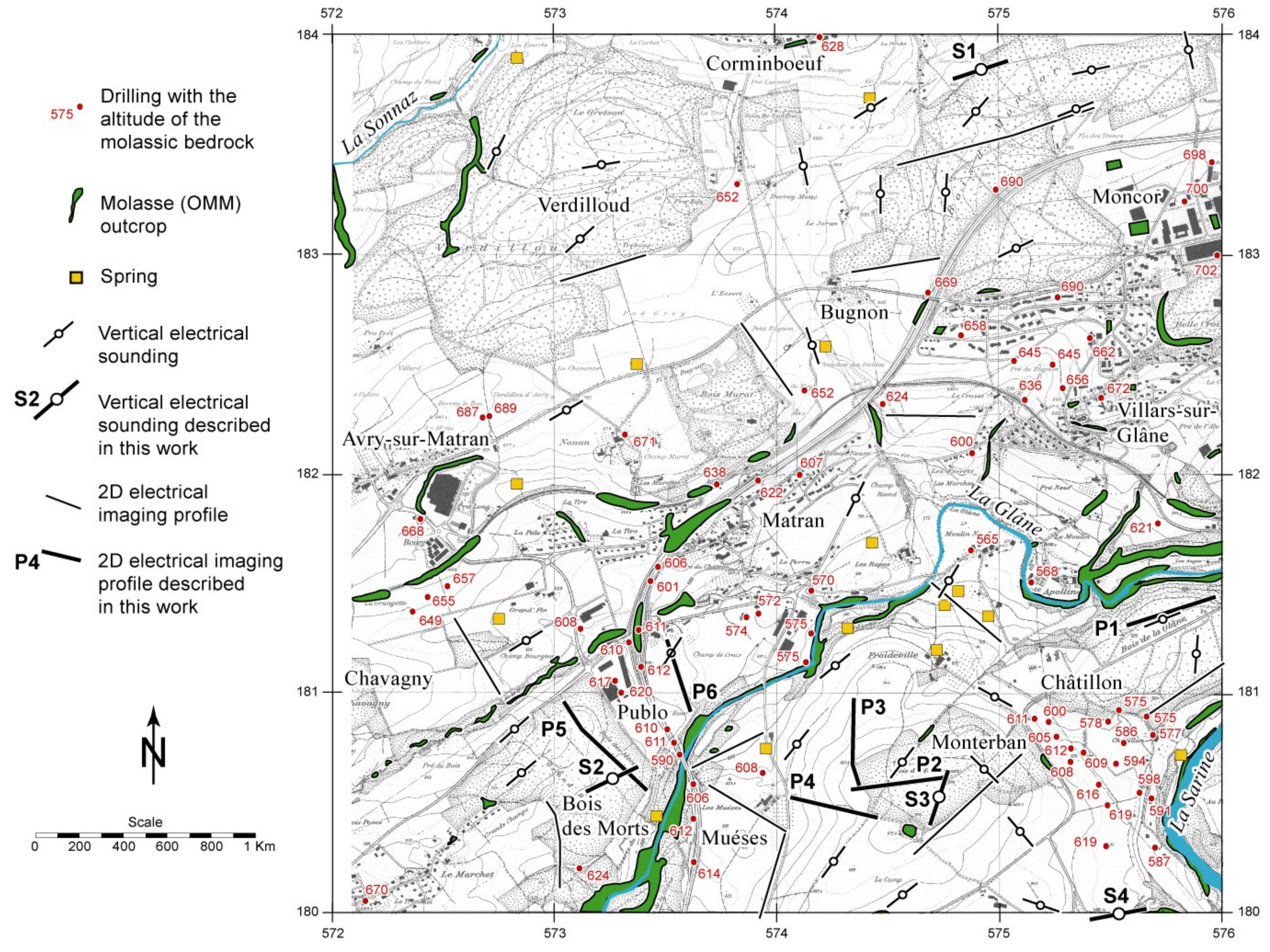
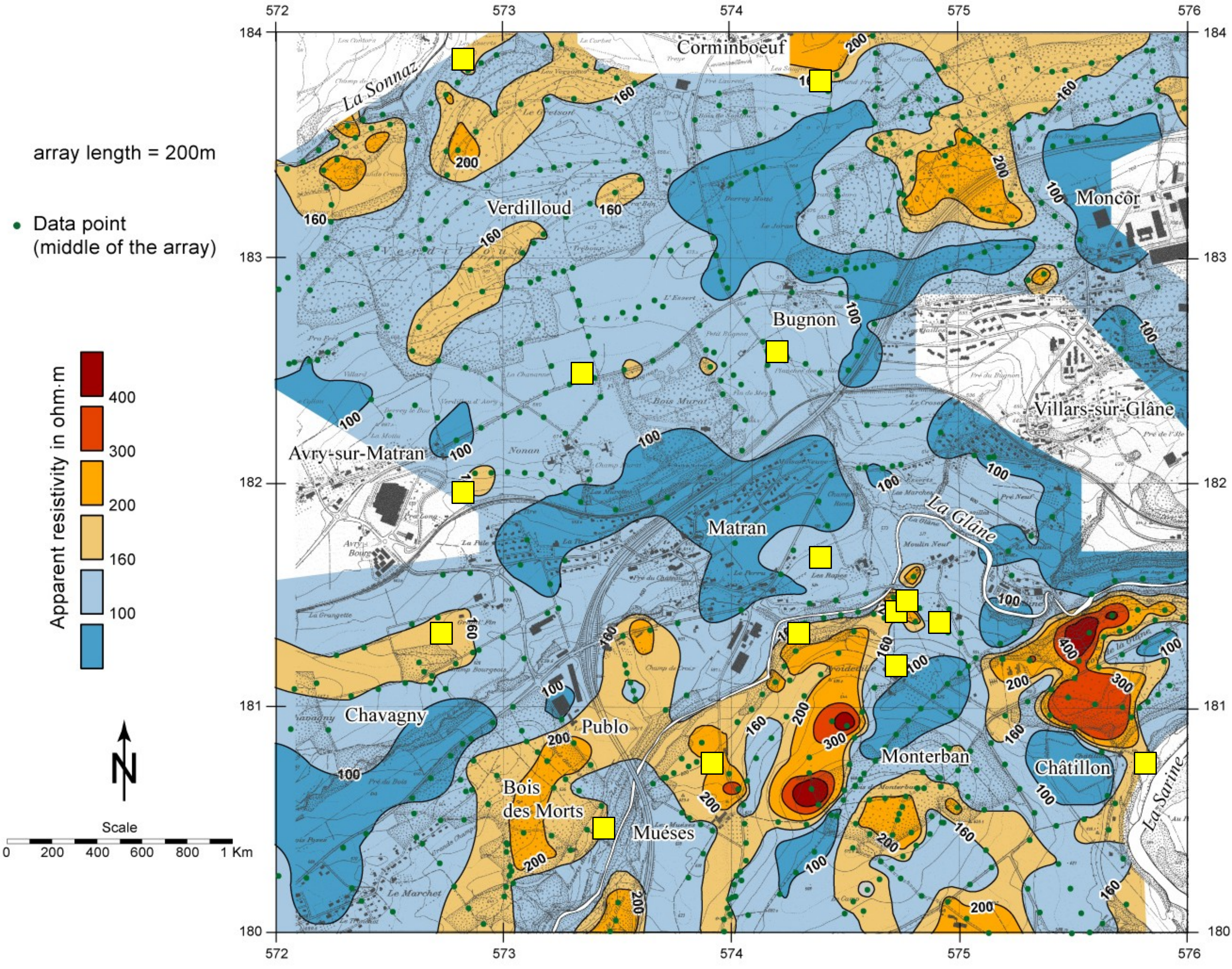
The Lithology Resistivity

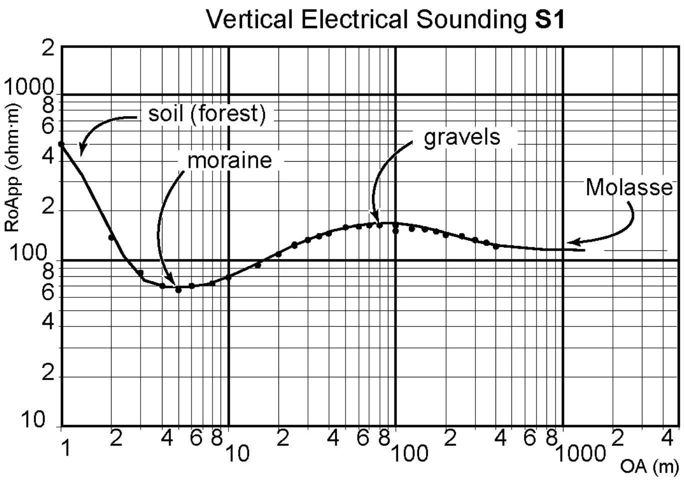
Quaternary		
Post glacial sediments	:	200 - 300 ohm.m
Moraine (with clay)	:	60 – 150 ohm.m
Gravel (with water)	:	160 – 250 ohm.m
Gravel (dry)	:	500 – 1000 ohm.m
Sand	:	60 – 100 ohm.m
« Complexe rissien »	:	30 – 60 ohm.m

Tertiary		
Molasse (bedrock)	:	110 – 170 ohm.m

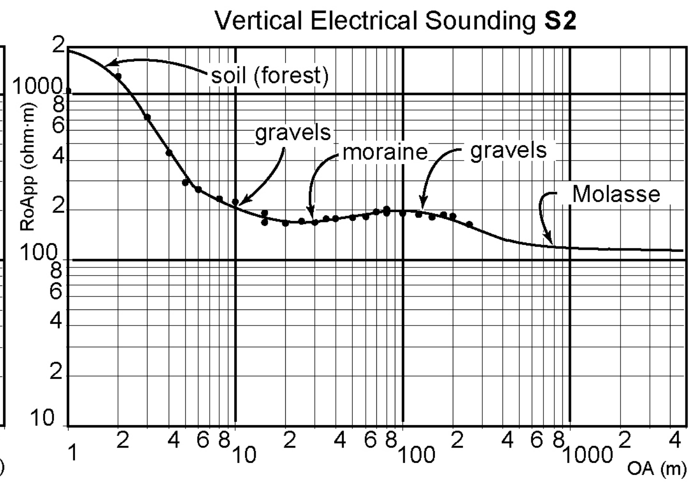


575 Drilling with the altitude of the molassic bedrock
Molasse (OMM) outcrop
Spring
Vertical electrical sounding
S2 Vertical electrical sounding described in this work
2D electrical imaging profile
P4 2D electrical imaging profile described in this work
N
Scale
0 200 400 600 800 1 Km
572
573
574
575
576
184
183
182
181
180
La Sonnaz
Corminboeuf
Verdilloud
Moncor
Bugnon
Avry-sur-Matran
Villars-sur-Glâne
Matran
La Glâne
Chavagny
Châtillon
Publo
Monterban
Bois des Morts
Muéses
La Sarine
S1
S2
S3
S4
P1
P2
P3
P4
P5
P6

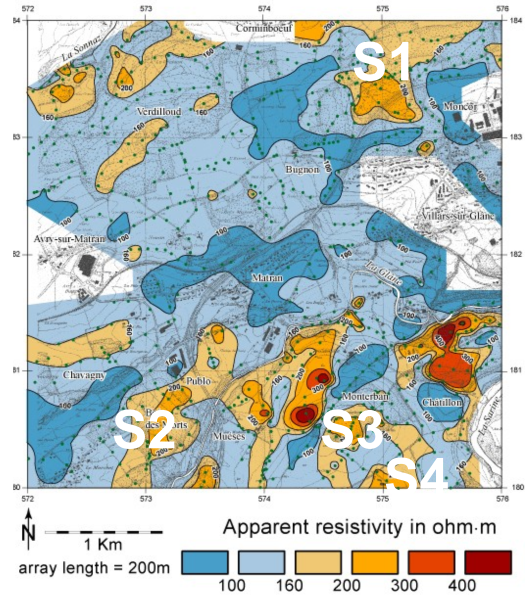

array length = 200m
Data point
(middle of the array)
Apparent resistivity in ohm·m
400
300
200
160
100
Scale
0
200
400
600
800
1 Km
572
573
574
575
576
184
183
182
181
180
Corminboeuf
La Sonnaz
Verdilloud
Moncor
Bugnon
Villars-sur-Glâne
Avry-sur-Matran
Matran
La Glâne
Chavagny
Publo
Monterban
Châtillon
Bois
des Morts
Muéses
La Sarine

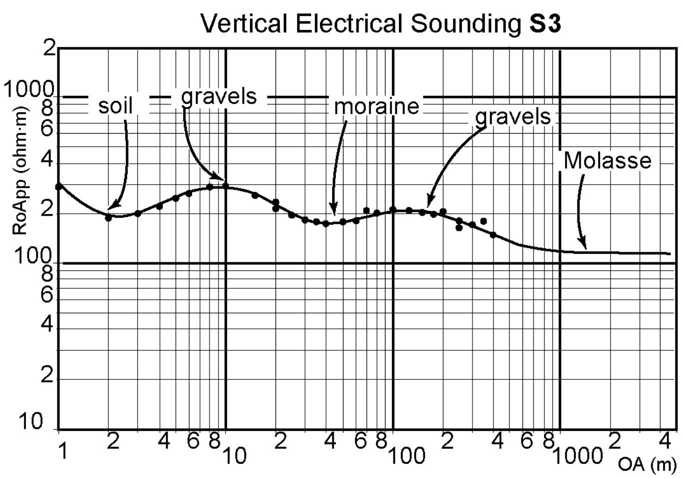


Layer N°	Resistivity (ohm·m)	Thickness (m)	Depth (m)	Altitude
1	900	0.6		670
2	63	6.8	0.6	669.5
3	300	2	7.4	662.7
4	200	58	9.4	660.7
5	115		67.3	602.7

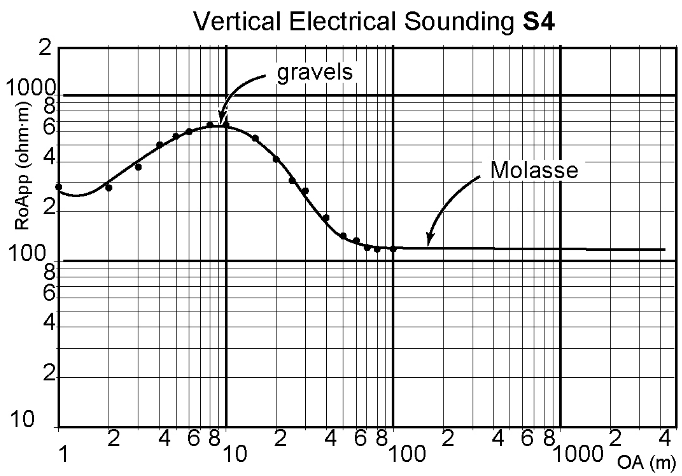


Layer N°	Resistivity (ohm·m)	Thickness (m)	Depth (m)	Altitude
1	2000	1.2		635
2	215	7.5	1.2	633.8
3	101	9.2	8.7	626.3
4	281	47.5	17.9	617.1
5	117		65.4	569.6



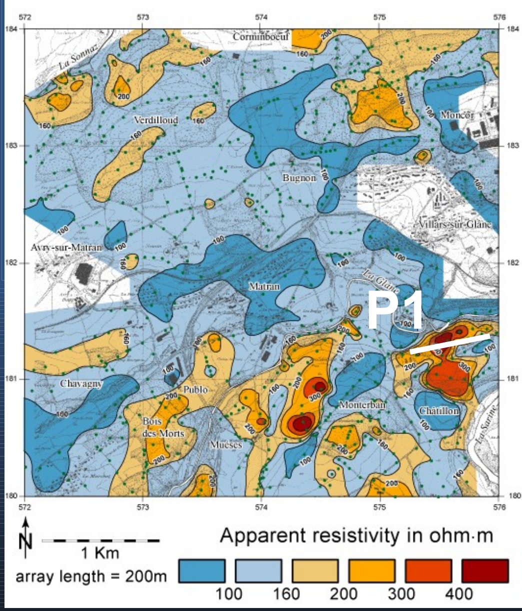


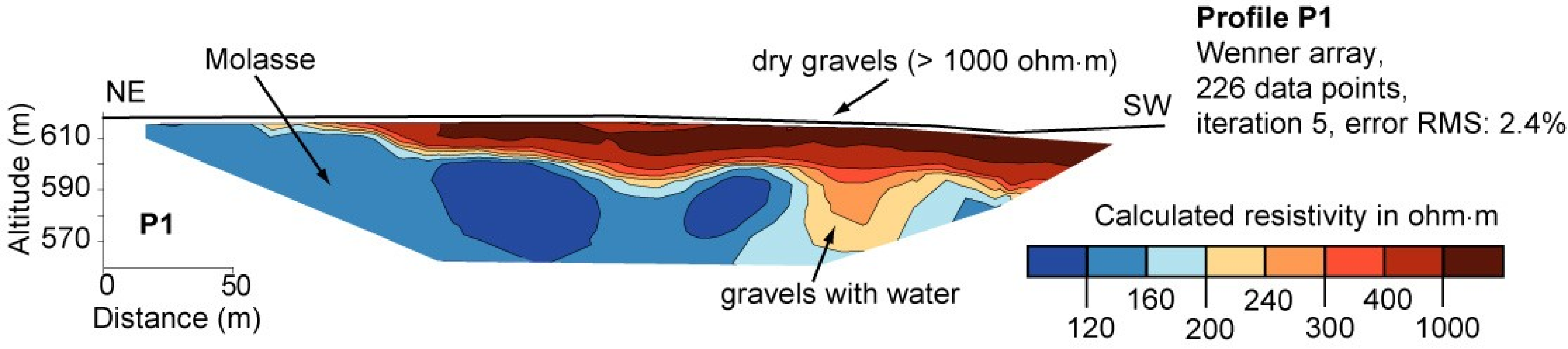
Layer N°	Resistivity (ohm·m)	Thickness (m)	Depth (m)	Altitude
1	460	0.5		677
2	92.5	0.9	0.5	676.5
3	475	4.8	1.4	675.6
4	102	15	6.2	670.8
5	303	53.5	21.2	655.8
6	123		74.7	602.3



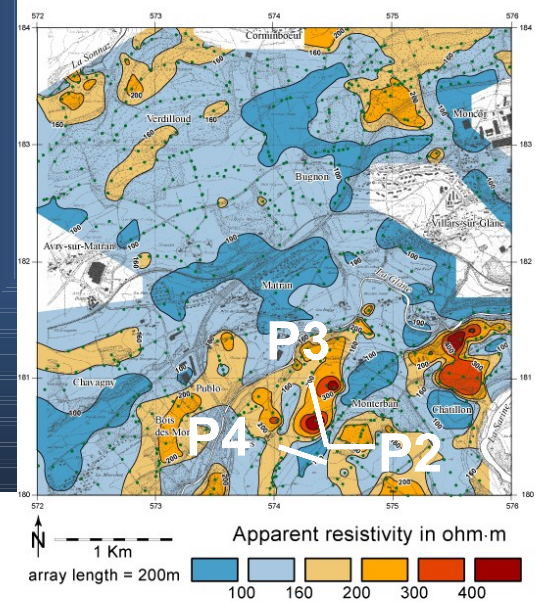
Layer N°	Resistivity (ohm·m)	Thickness (m)	Depth (m)	Altitude
1	266	0.7		621
2	119	0.3	0.7	620.3
3	1175	5.5	1.0	620
4	84	14	6.5	614.5
5	124		20.5	600.5

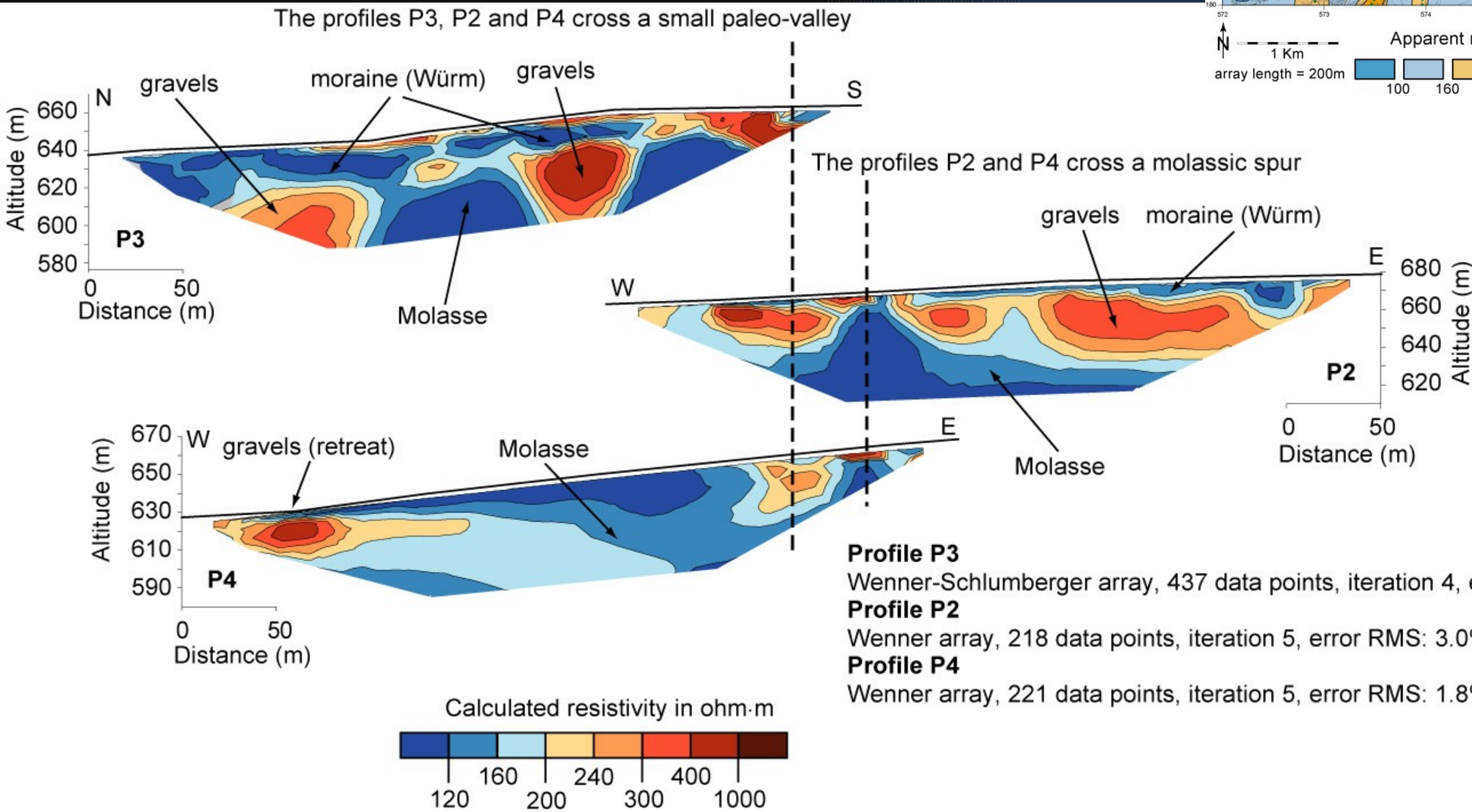
2D Resistivity Imaging





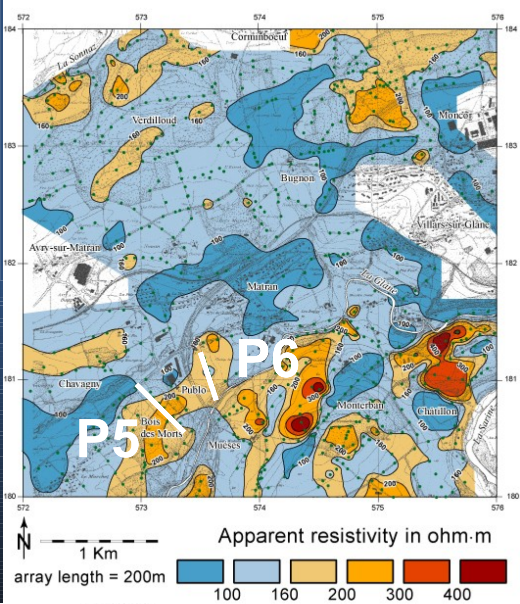
2D Resistivity Imaging

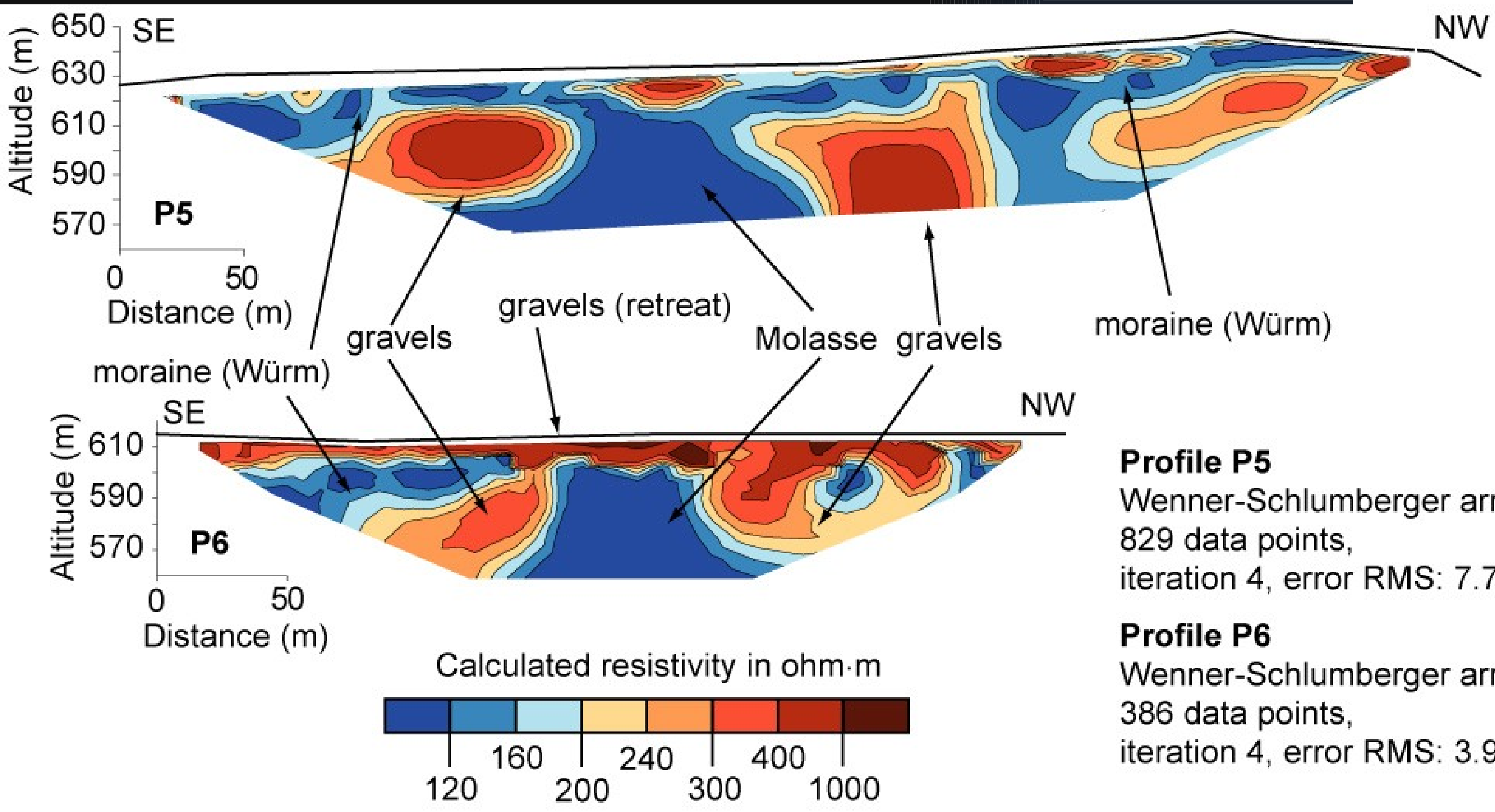




Profile P3
Wenner-Schlumberger array, 437 data points, iteration 4, error RMS: 3.9%
Profile P2
Wenner array, 218 data points, iteration 5, error RMS: 3.0%
Profile P4
Wenner array, 221 data points, iteration 5, error RMS: 1.8%

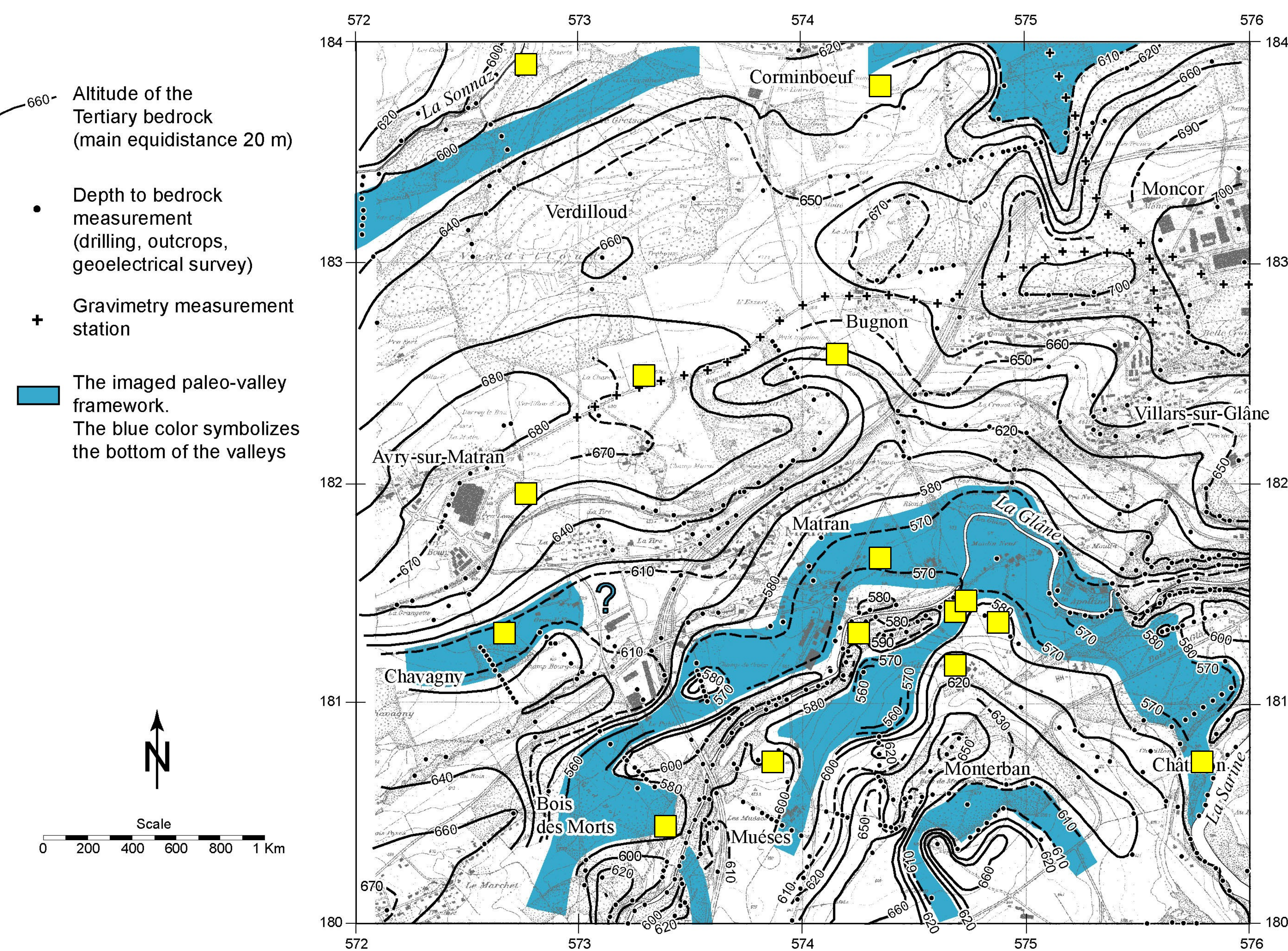
2D Resistivity Imaging





Profile P5
Wenner-Schlumberger array,
829 data points,
iteration 4, error RMS: 7.7%

Profile P6
Wenner-Schlumberger array,
386 data points,
iteration 4, error RMS: 3.9%


Altitude of the Tertiary bedrock (main equidistance 20 m)
Depth to bedrock measurement (drilling, outcrops, geoelectrical survey)
Gravimetry measurement station
The imaged paleo-valley framework.
The blue color symbolizes the bottom of the valleys
N
Scale
0 200 400 600 800 1 Km
572
573
574
575
576
184
183
182
181
180
La Sonnaz
Corminboeuf
Verdilloud
Moncor
Bugnon
Villars-sur-Glâne
Avry-sur-Matran
Matran
La Glâne
Chavagny
Monterban
Bois des Morts
Muéses
La Sarine
?

Hydrogeological Implications

The paleo-valley framework is located in urban and industrial areas

Clear connexions between the main paleo-valleys and the springs

Clear connexions between the main paleo-valleys and the actual rivers

The paleo-valley infilling can be connected with the surface or protected by the moraine

The resistivity of the gravel infilling ranges from 200 to 500 ohm.m

Pollutant migration risk from the surface to the rivers is plausible

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Conclusions

Resistivity methods give a general overview on the paleo-valley framework

Limitations of the method: lateral effects, loss of resolution at depth, resistivity contrast

Good correlation between the geoelectrical information and the borehole data for the bedrock altitude

Further investigations (e.g. high resolution seismics) can be conducted following the resistivity survey results

The paleo-valleys do not continue to the North

Case History 2:

2D Electrical Resistivity Imaging in Mountain Permafrost Studies

Source: Marescot et al., Near Surface Geophysics 2003

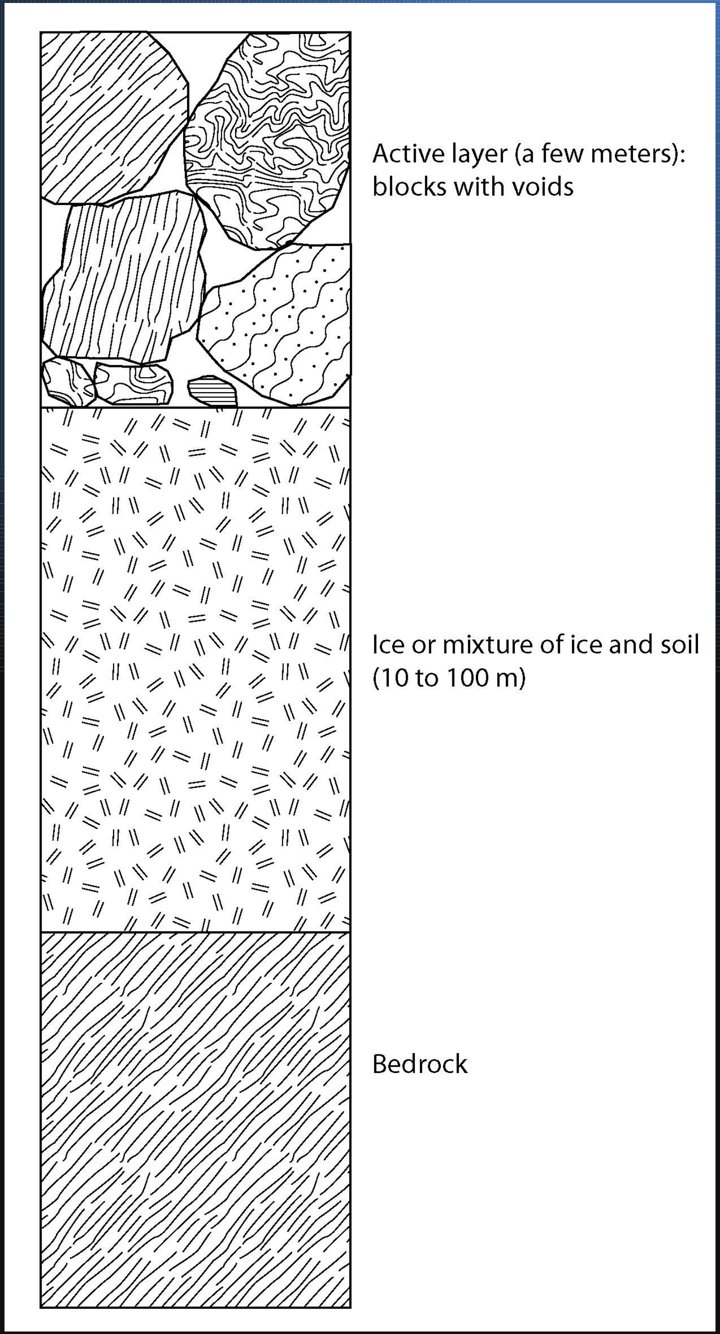
What is permafrost?

Lithological material with a temperature below 0°C during at least one whole year.

What is a rock glacier?

A mass of blocks cemented with ice. The velocity of an active rock glacier can reach a few centimetres per year.

A schematic lithology of a rock glacier:



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A global warming process could partially thaw permafrost.

Potentiality and magnitude of slope instabilities are increased (landslides, mud flows)

Constructions are endangered (ski resort buildings, cable cars poles, roads…)

Ways to study permafrost

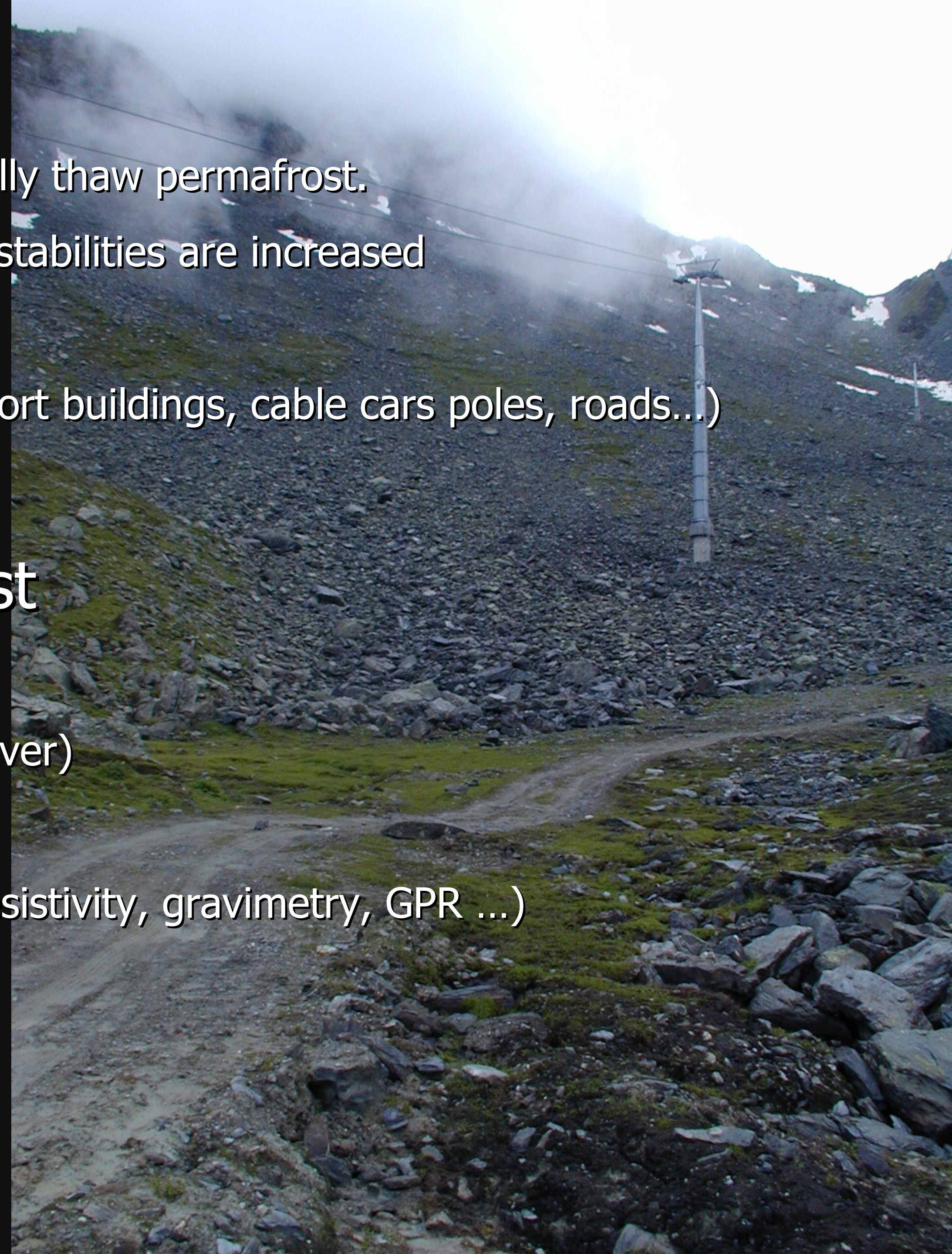
Geomorphology

BTS (Bottom Temperature of Snow cover)

Radiometry

Geophysics (refraction seismics, DC resistivity, gravimetry, GPR …)

Drilling



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Objectives of resistivity surveys

Distribution of permafrost (mapping, thickness).

Characterization of ice content in permafrost.

Monitoring.

Difficulties

Significant topographic variations.

The surface layer consists of large blocks with air voids.

Methodology

Long (> 1 m) steal stakes

Sponges with salt water

Acquisition characteristics

Contact resistance: about 80’000 Ohm

Injected current: about 2 to 5 mA

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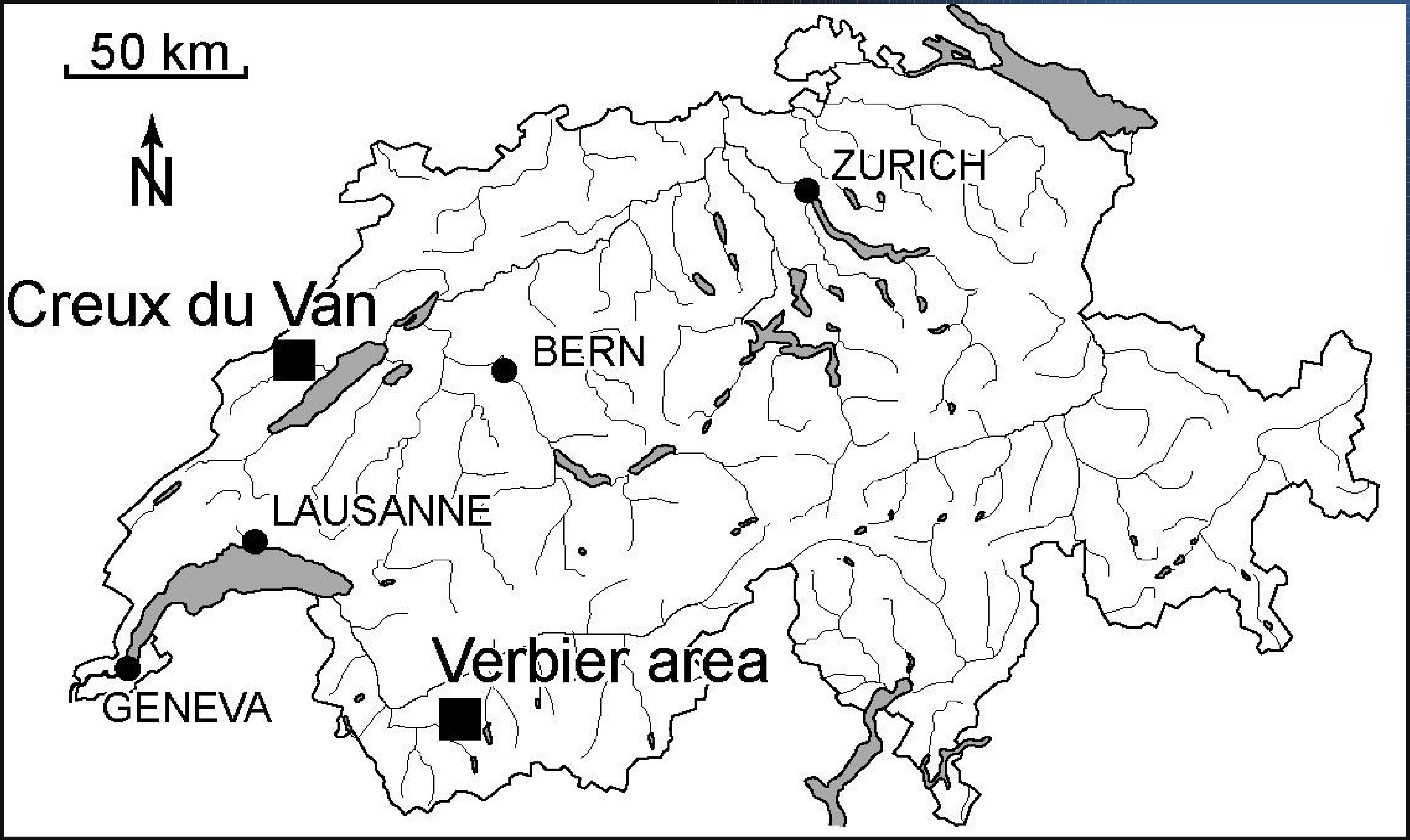
The research sites location



A dangerous job …

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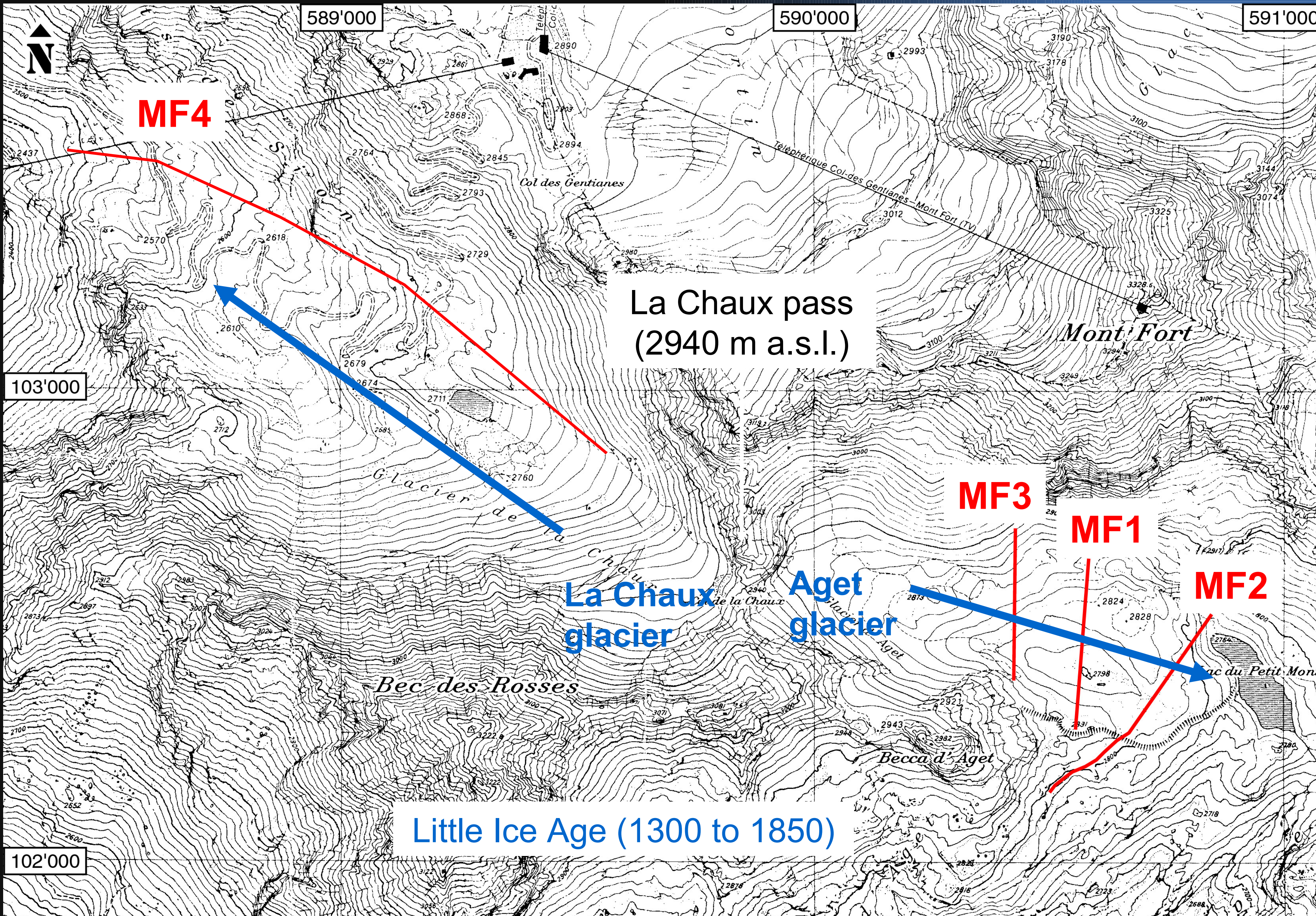
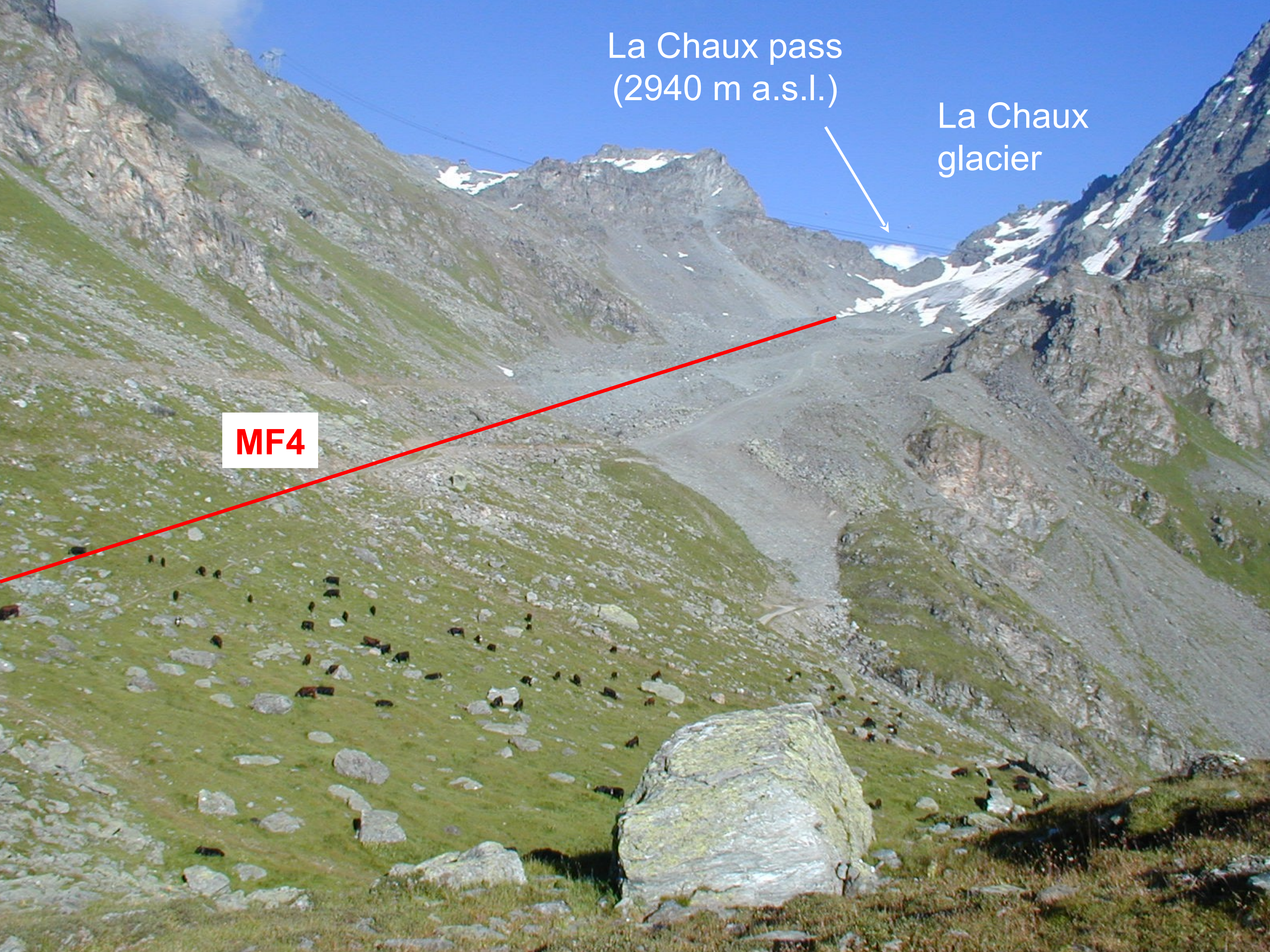
The Mont Fort survey




La Chaux pass
(2940 m a.s.l.)
La Chaux
glacier
MF4

La Chaux
pass
(2940 m a.s.l.)

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Mont Fort (3329 m a.s.l.)

La Chaux
pass
(2940 m a.s.l.)

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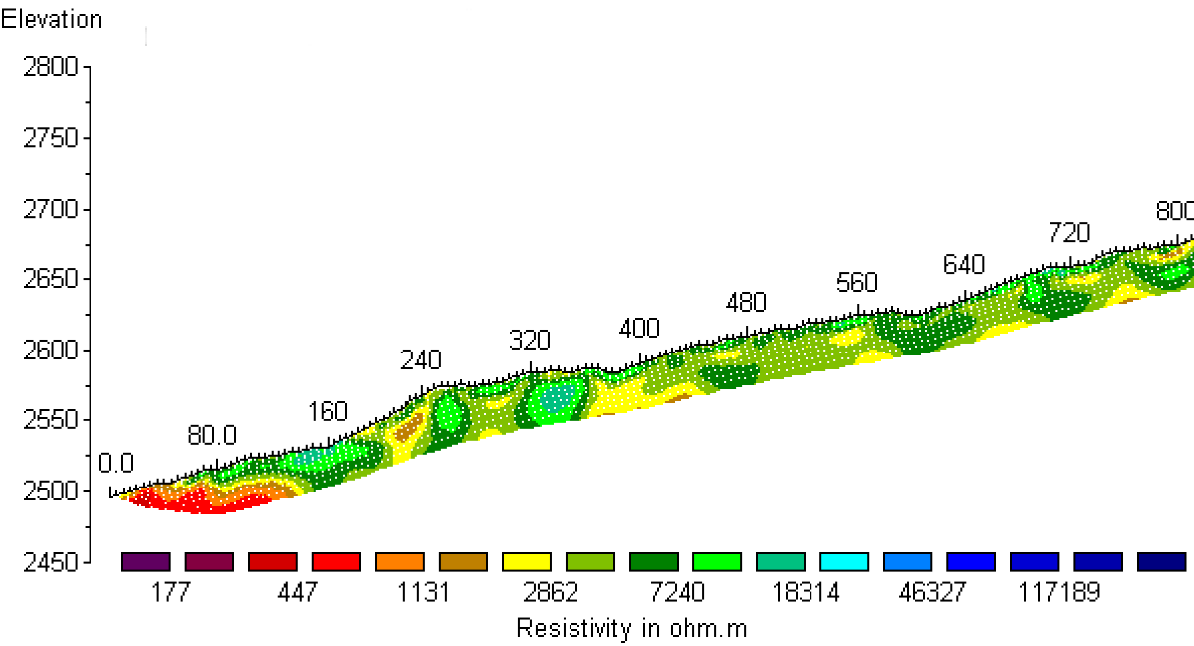
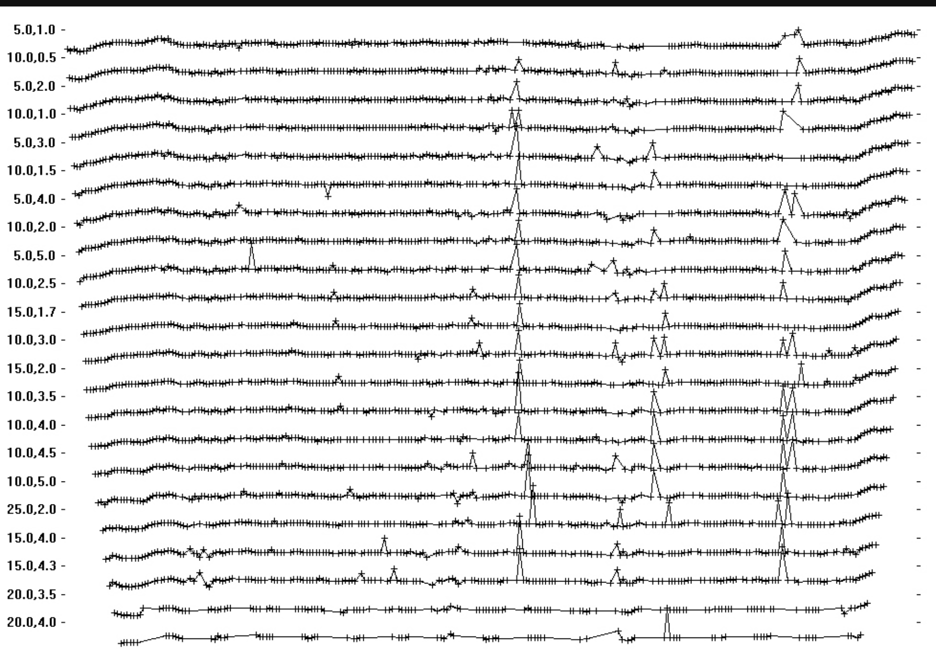
Aget glacier proglacial margin


MF2

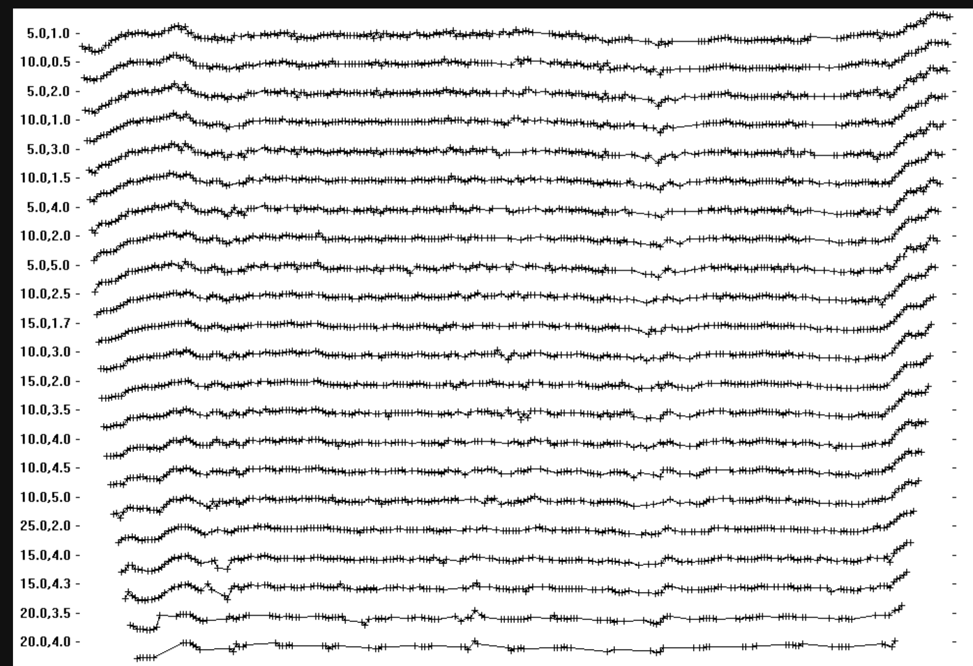


MF4
Wenner-Schlumberger array,
unit electrode spacing 5 m,
4472 data points,
iteration 3,
RMS error 8.9%

Raw data set

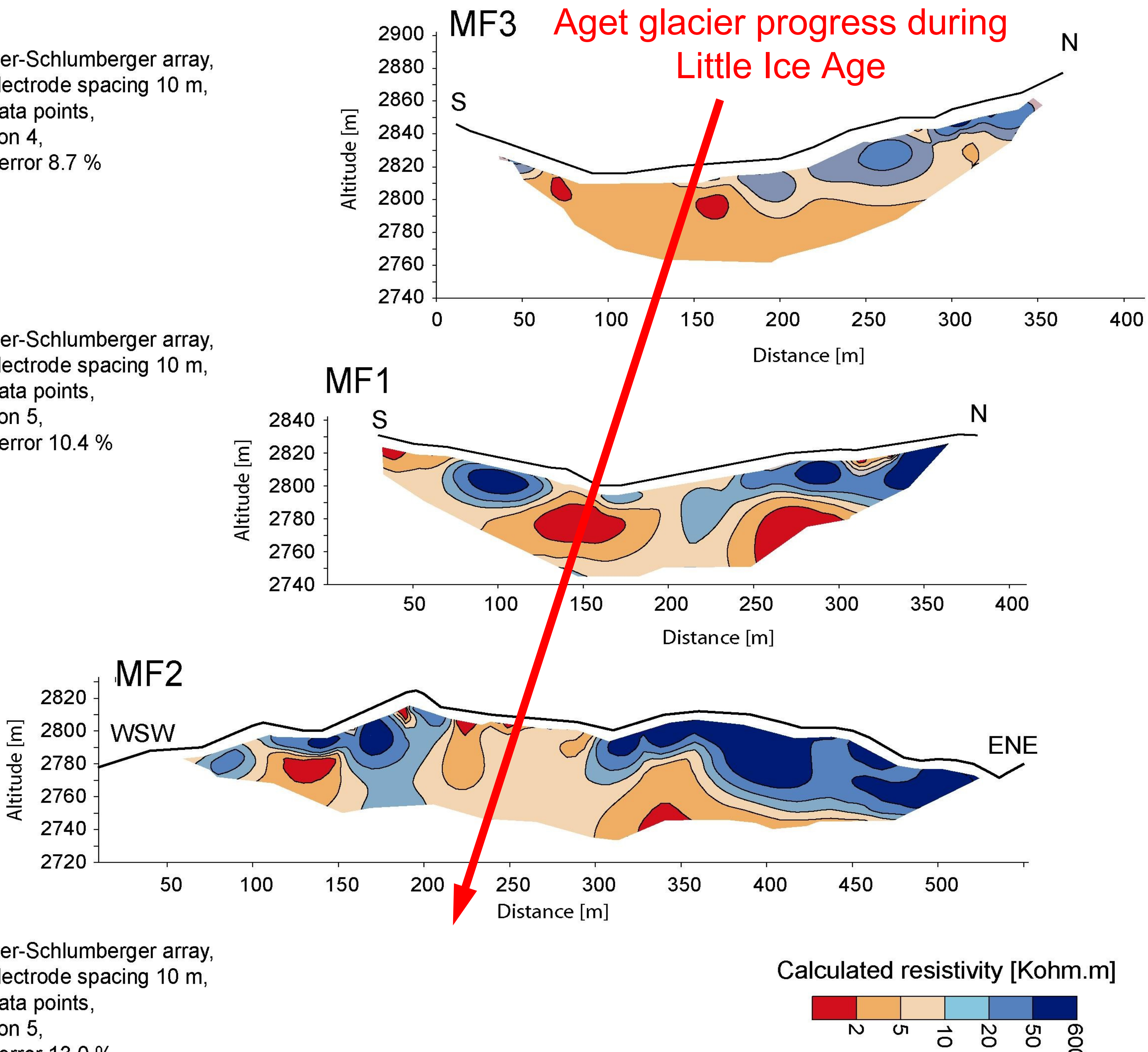


The same set without the bad data



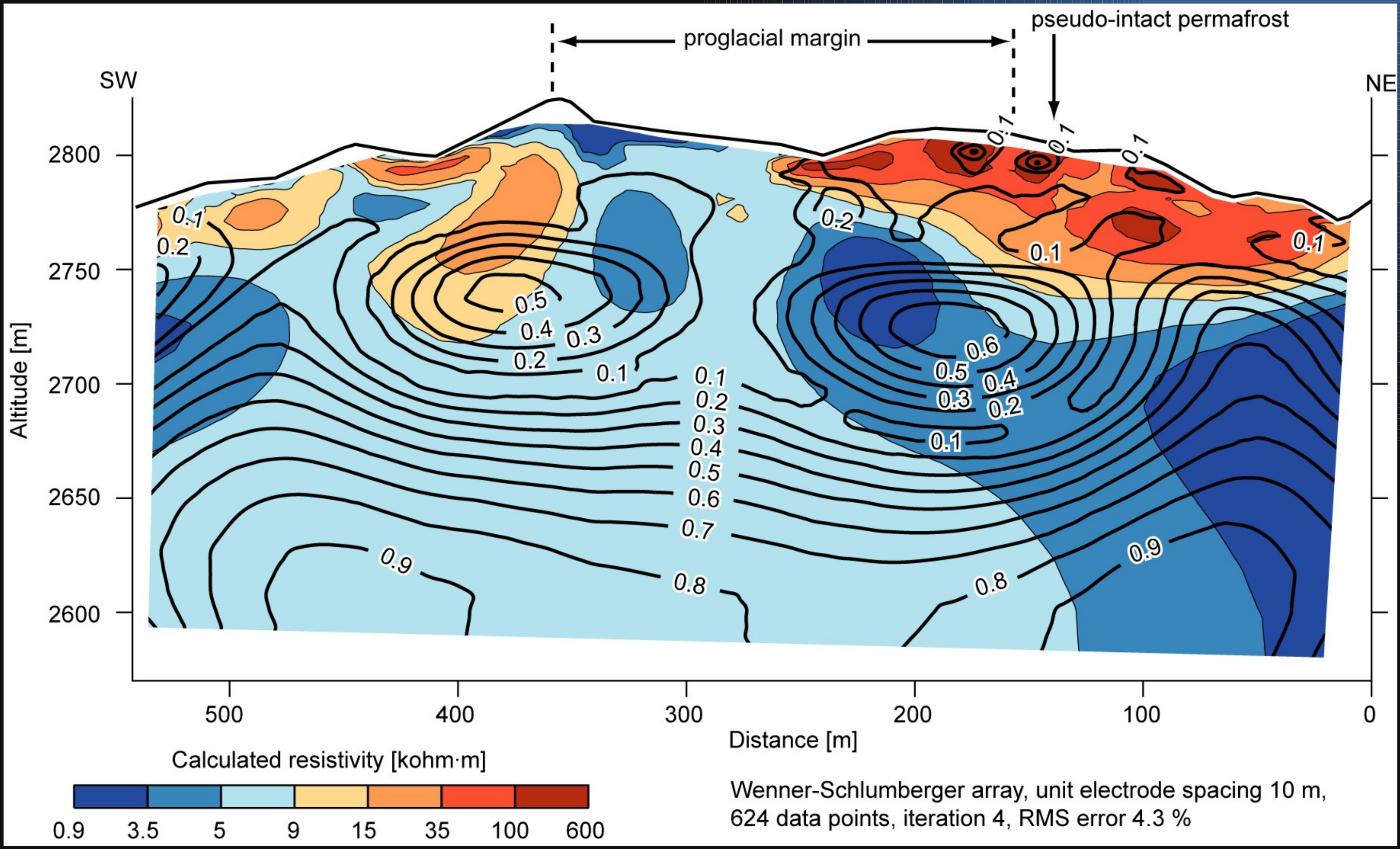
MF3
Wenner-Schlumberger array,
unit electrode spacing 10 m,
510 data points,
iteration 4,
RMS error 8.7 %

MF1
Wenner-Schlumberger array,
unit electrode spacing 10 m,
510 data points,
iteration 5,
RMS error 10.4 %



MF2
Wenner-Schlumberger array,
unit electrode spacing 10 m,
765 data points,
iteration 5,
RMS error 13.0 %

Field Example 1: Resistive Structures



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Source: Marescot et al, 2003

Conclusion

Effectiveness of 2D resistivity imaging is proven despite unfavourable contact resistance due to the presence of large surface blocks with voids.

Penetration depth is low under the frozen material!

This method provides information on:

The distribution (extent, +/-thickness) of ice in the rock glacier.

The ice content in soil:

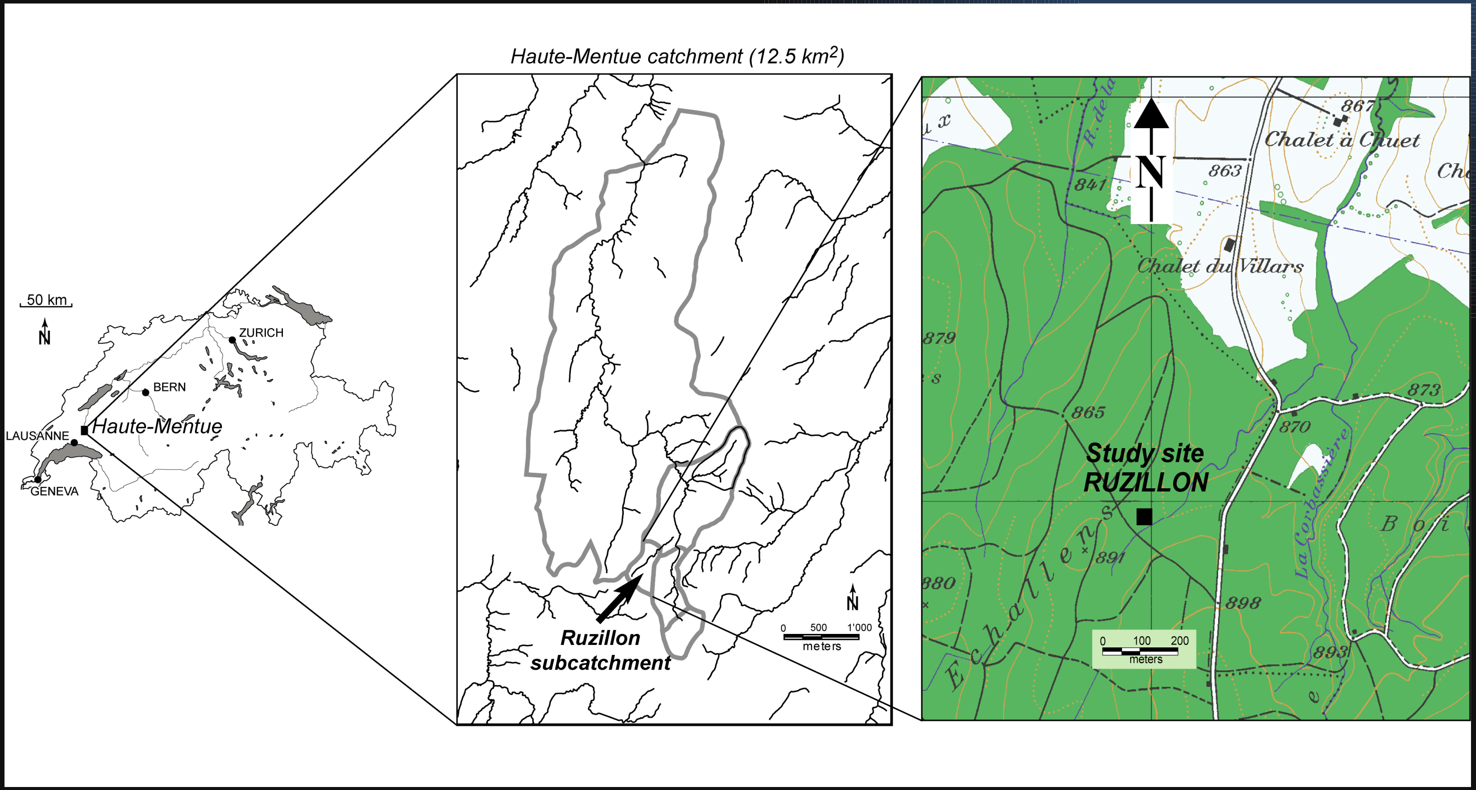
unfrozen scree with voids: 30 to 200 Kohm.m

frozen-water in interstices: 10 to 500 Kohm.m

buried dead glacier ice: 100 to 2000 Kohm.m

The evolution of ice in the future (monitoring).

Case History 3:
Permanent 3D Rainfall Infiltration Monitoring in Soils



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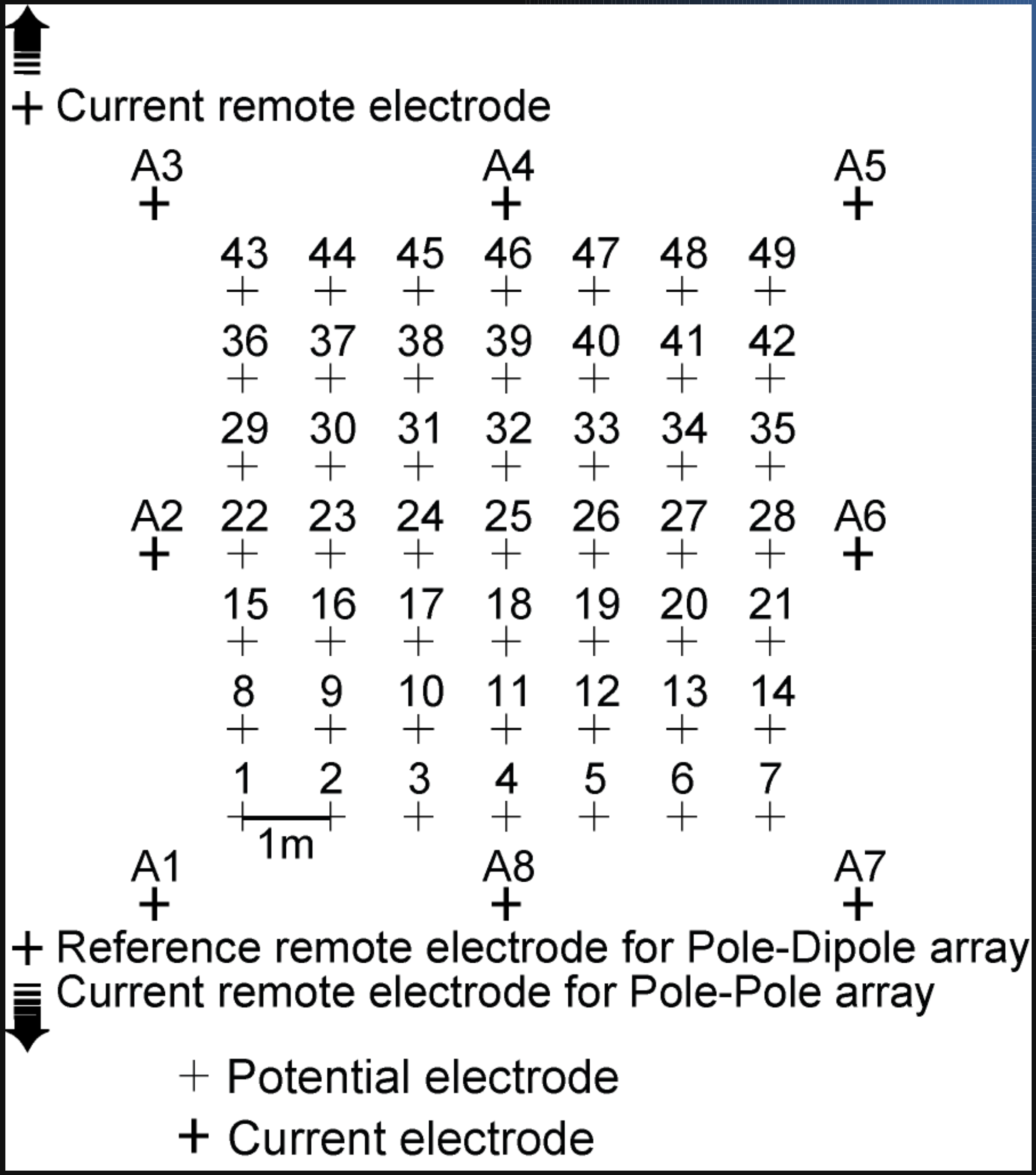
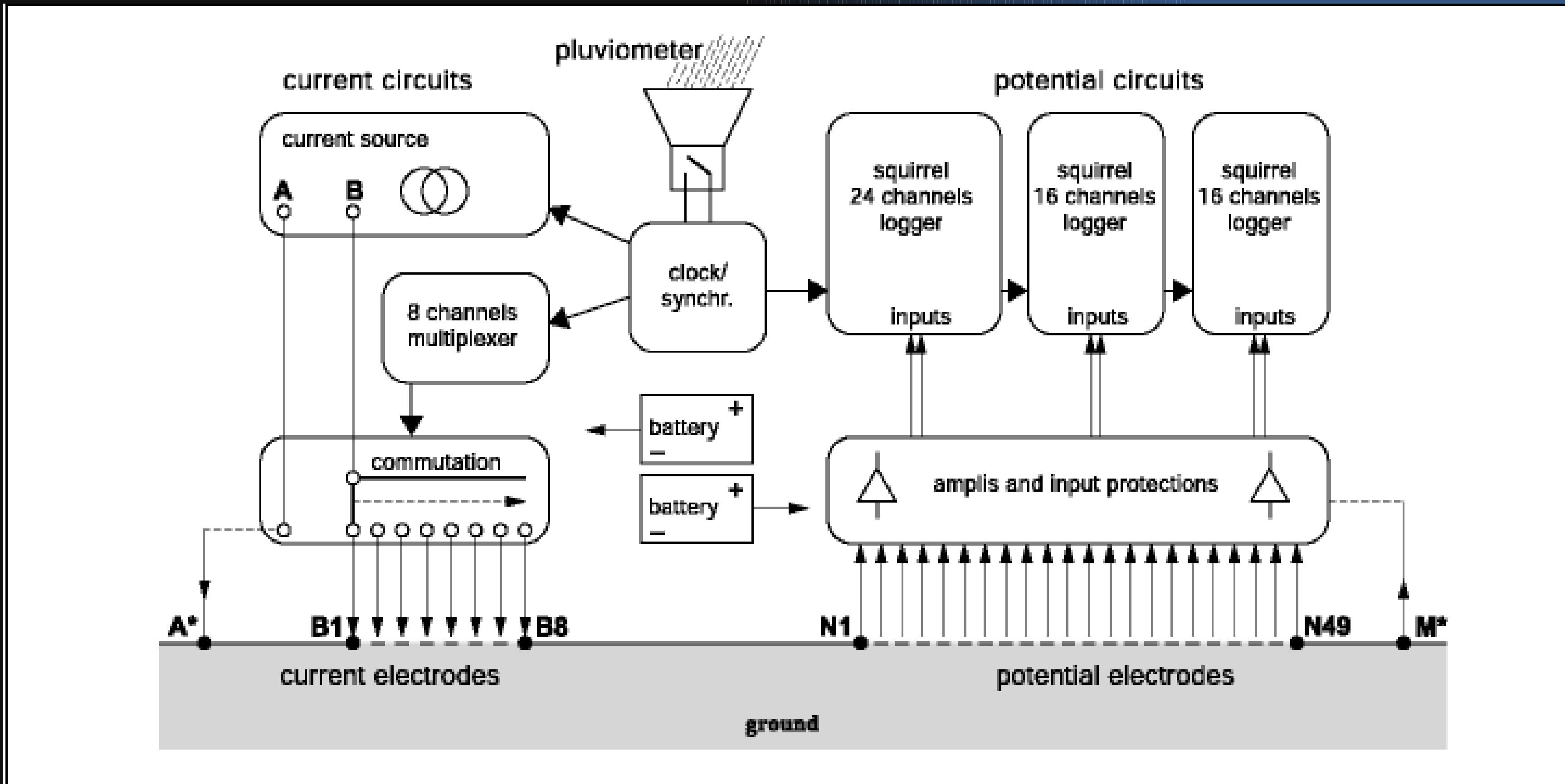
Source: N. Denchik, University of Lausanne


Current remote electrode
A3
A4
A5
43 44 45 46 47 48 49
36 37 38 39 40 41 42
29 30 31 32 33 34 35
A2 22 23 24 25 26 27 28 A6
15 16 17 18 19 20 21
8 9 10 11 12 13 14
1 2 3 4 5 6 7
1m
A1
A8
A7
Reference remote electrode for Pole-Dipole array
Current remote electrode for Pole-Pole array
Potential electrode
Current electrode


pluviometer
current circuits
potential circuits
current source
A
B
clock/
synchr.
8 channels
multiplexer
squirrel
24 channels
logger
inputs
squirrel
16 channels
logger
inputs
squirrel
16 channels
logger
inputs
battery
+
–
battery
+
–
commutation
amplis and input protections
A*
B1
B8
N1
N49
M*
current electrodes
potential electrodes
ground

Loggers:

Squirrel 1000 (64’000 slots)

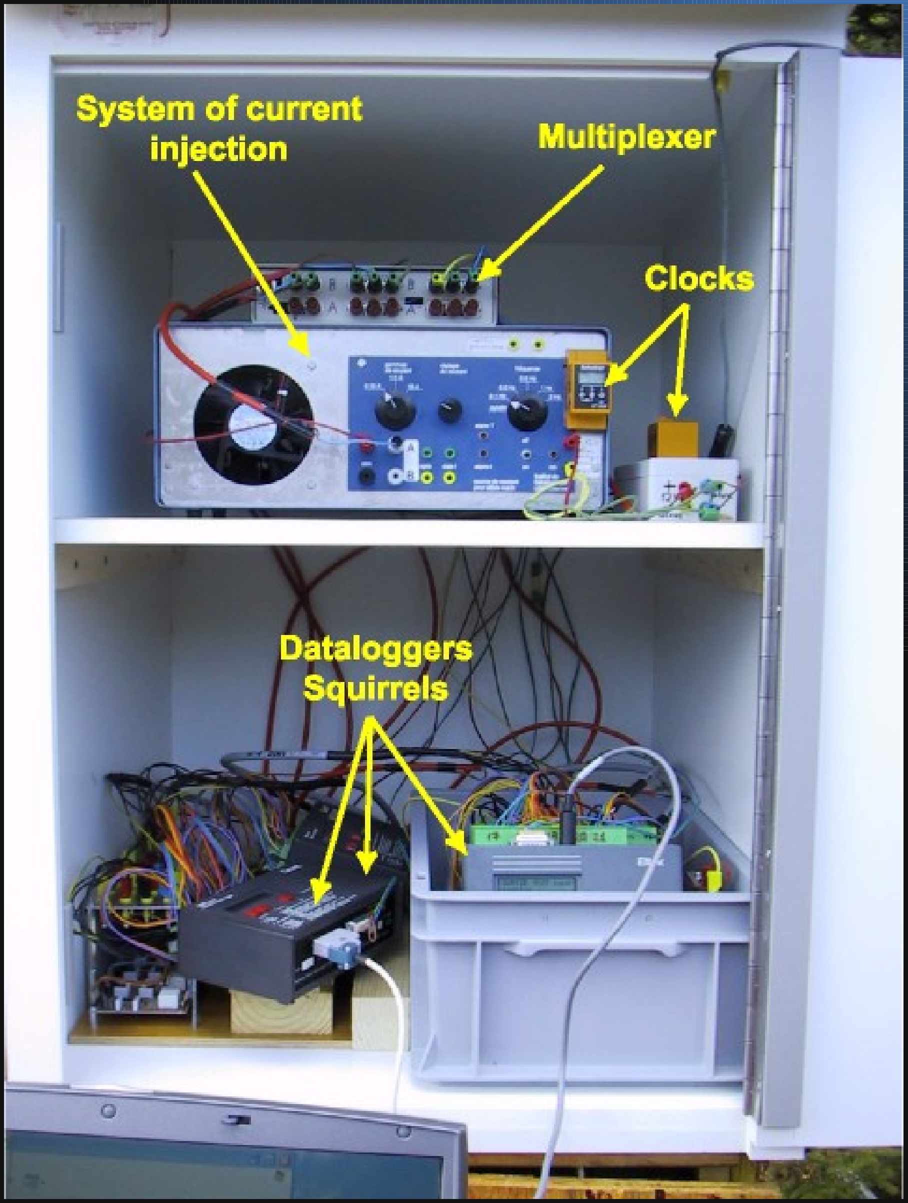
Squirrel 1200 (41’000 slots)

1 slot = 12 bits

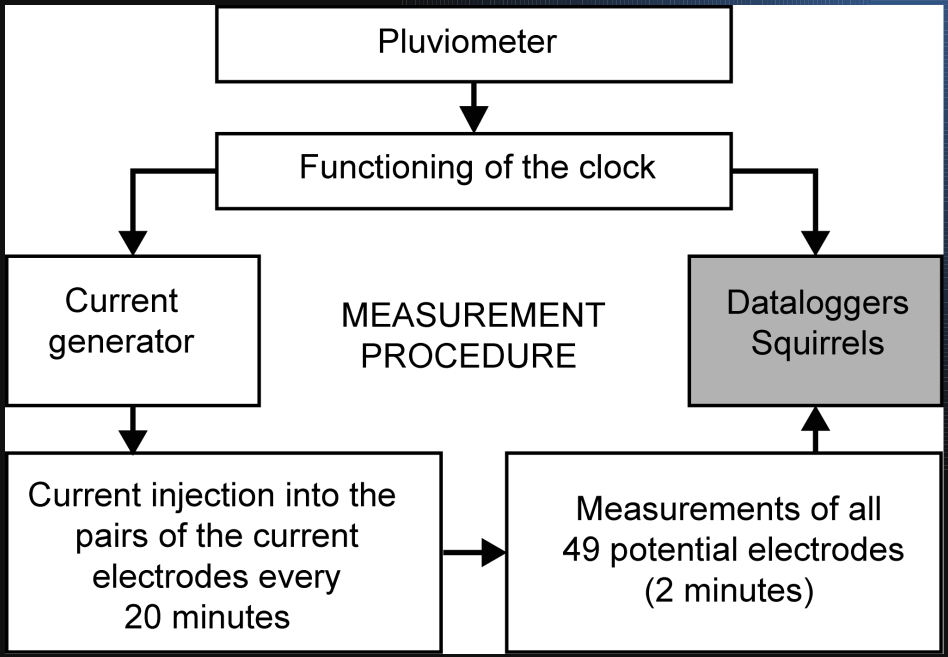
Current:

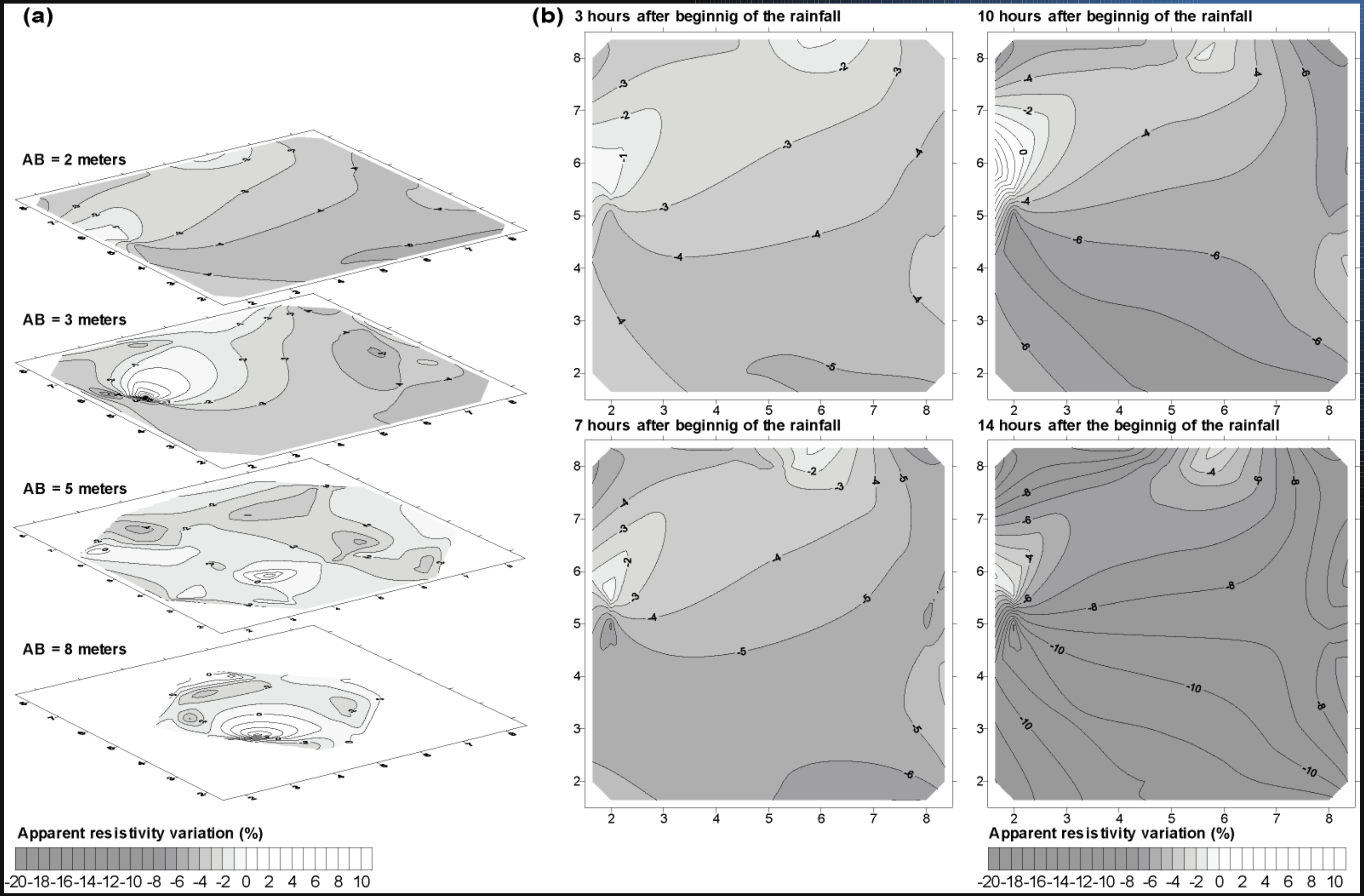
20 mA

Positive/negative cycles 5 s



Measurement procedure





Joint inversion…

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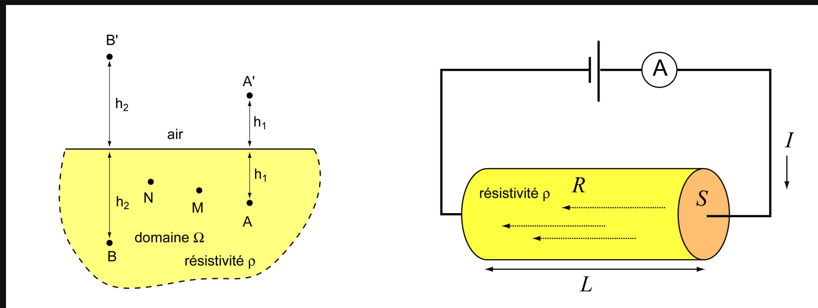
Analytic



$$\rho_{app} = G\,R$$

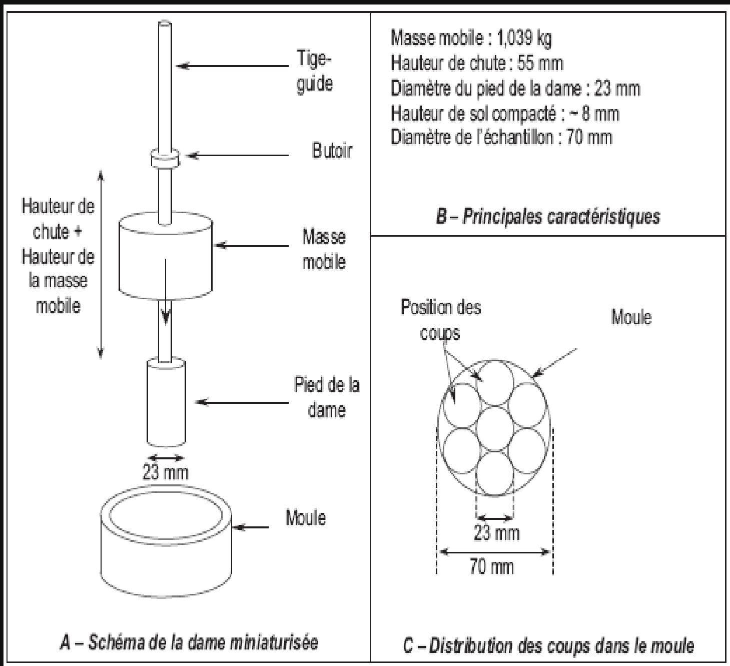
$$G = \frac{4\pi}{\frac{1}{AM} - \frac{1}{AN} - \frac{1}{BM} + \frac{1}{BN} + \frac{1}{A'M} - \frac{1}{A'N} - \frac{1}{B'M} + \frac{1}{B'N}}$$

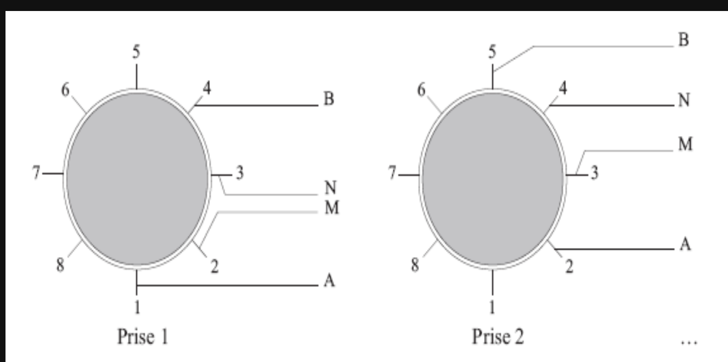
General Geometrical Factor

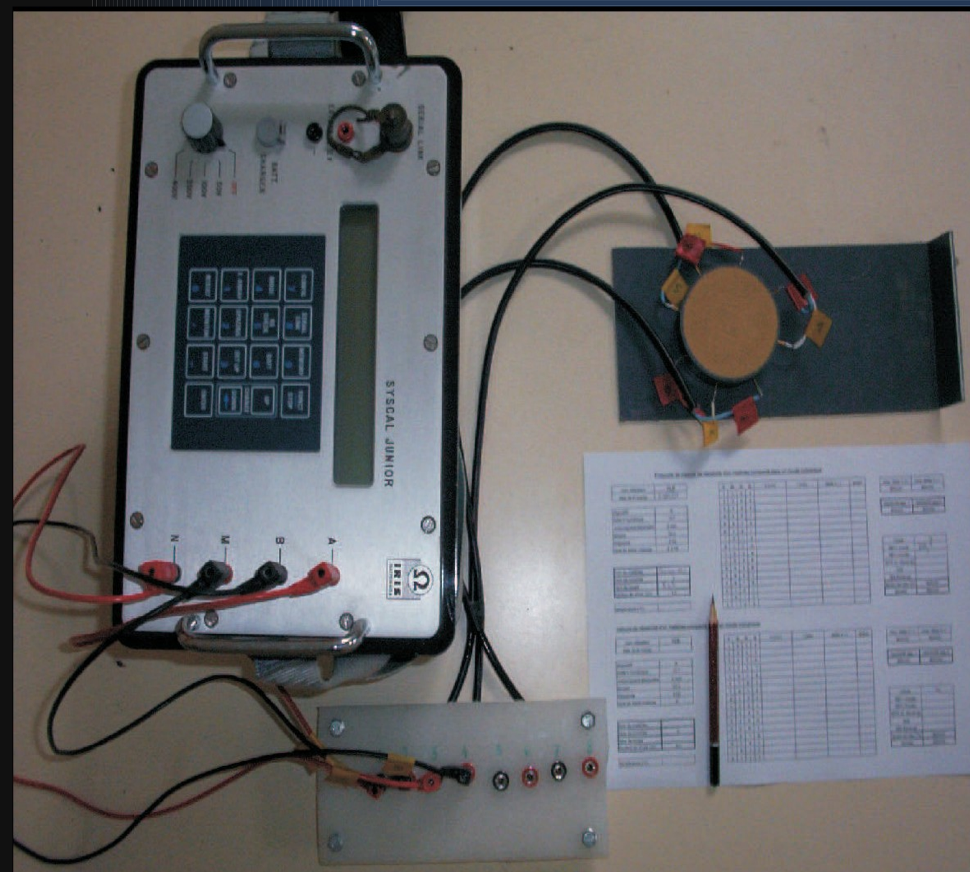
$$\rho_{app} = \frac{R}{R_0}\,\rho_0$$

$$G = \frac{\rho_0}{R_0}$$

Source: Marescot et al., Journal of Applied Geophysics 2006







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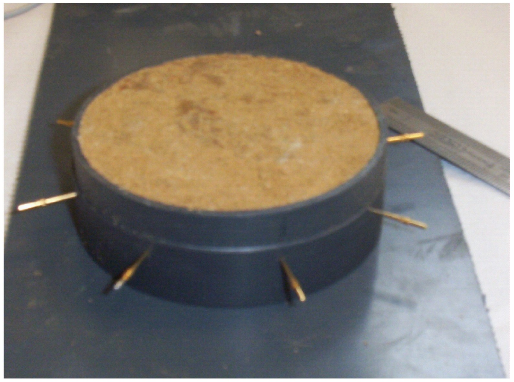
Source: S. Palma Lopes, LCPC

Water Content Calibration

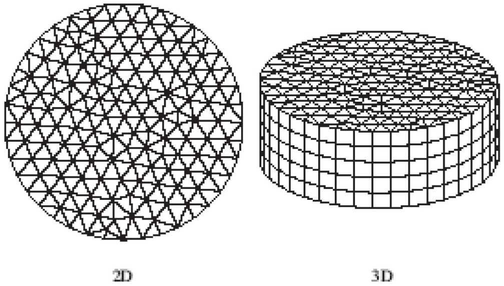
CLAY MEASUREMENTS

cell (ΔV measurements)



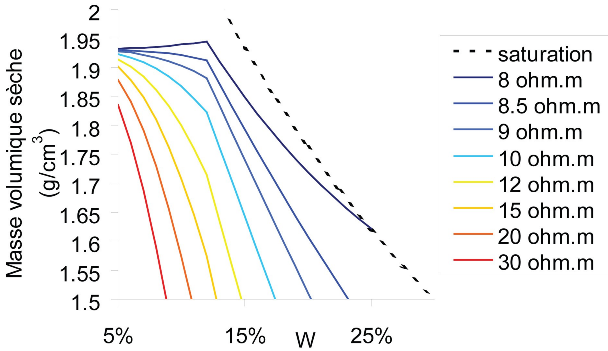
1

FE mesh used for Δv_0 calculation



2

example of calculation (water content)



3

$$\rho_{app} = \frac{R}{R_0}\,\rho_0$$

Conclusions

The resistivity method is a effective technique for water infiltration monitoring

Permanent instrumentation can be easily installed in the field

Need for effective 3D joint inversion technique

Calibration of water content possible using the General Geometrical Factor approach

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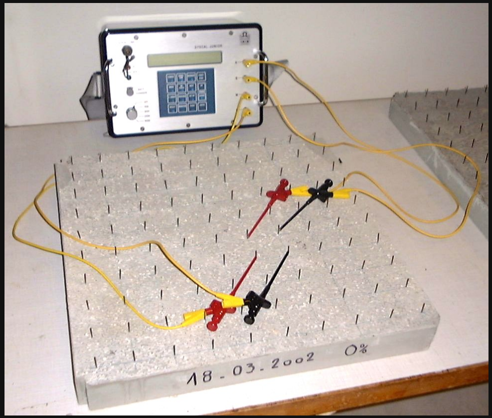
Final Comments

Resistivity imaging is:

Cost-effective technique: permanent electrodes in the field

Adapted to monitor spatial and temporal water variations

Multi scale technique: large scale geophysics to NDT



Possible developments:

Intensive research in 3D inversion for large models

Appraisal part of the problem

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