Geophysical data fusion for characterizing landslide areas

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The French Research Projects

- **SIGMA & ECOUPREF: National Research Project on landslides**
- **Research laboratory & Private compagnies**
  - BRGM, LCPC, CETE Lyon
  - Univ. Caen, Polytechnique Grenoble, Ecole Centrale de Paris, LGIT, CEMAGREF
  - CPS, SAGE geotechnics
- **Different research axes:**
  1. Morpho-structure characterisation (geophysics, geomorphology)
  2. Monitoring technologies (piezometry, GPS, inclinometry, etc)
  3. Geomechanical & hydromechanical modelling

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Outline

An example of geophysical study in the ECOUPREF context

- Aim
  - Mass estimation from structural characterization
  - Information on mechanisms controlling the movements
- Field works (Example of the Super-Sauze landslide)
  - Seismic tomography : P-wave velocity distribution
  - SASW: S-wave velocity distribution
  - Electrical tomography : electrical resistivity distribution
- Methodology
  - Fusion of geophysical tomographies

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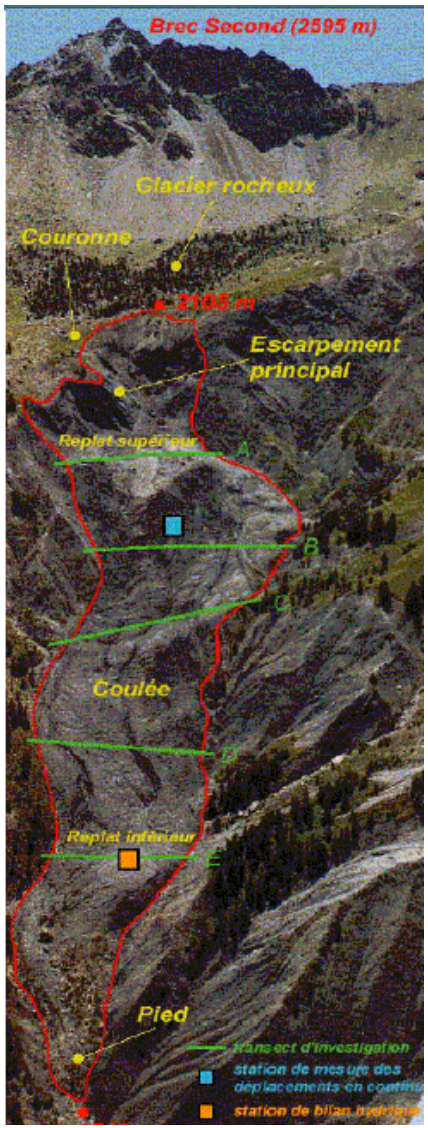
Case of the Super-Sauze earthflow

Context of French Alps

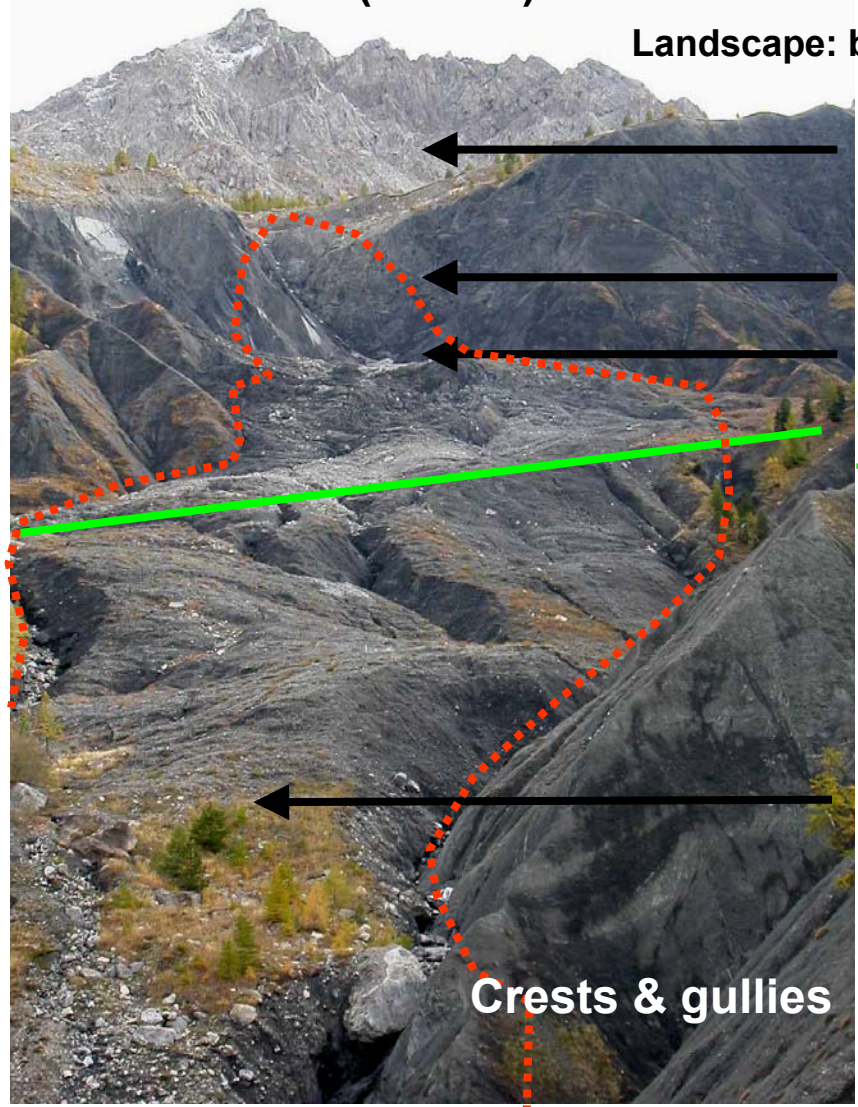
Localization: Barcelonette valley

Rocks: black marls

Landscape: bad lands



Brec Second (2595m)



Rocky glacier

Main scarp

Top zone

Geophysical transect

earthflow

Bottom zone

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Tomography: 2D data inversion

> Seismic (Grandjean and Sage, 2004)

- Forward problem: Eikonal equation solved with a FMM (Fast Marching Method)
- Numerical computation of traveltimes using Fresnel volumes
- Inversion: with a SIRT algorithm (Simultaneous Iterative Reconstruction Technique)

> Electrical (Loke, 1999)

- Forward problem : Poisson equation solver
- Numerical computation of potentials using a Finite Difference scheme
- Inversion: linearized with L^2 norm

> SASW (Grandjean and Bitri, 2005)

- Local dispersion diagrams computation
- Inversion: Surf96 (Hermann, 1994)
- 2D interpolation

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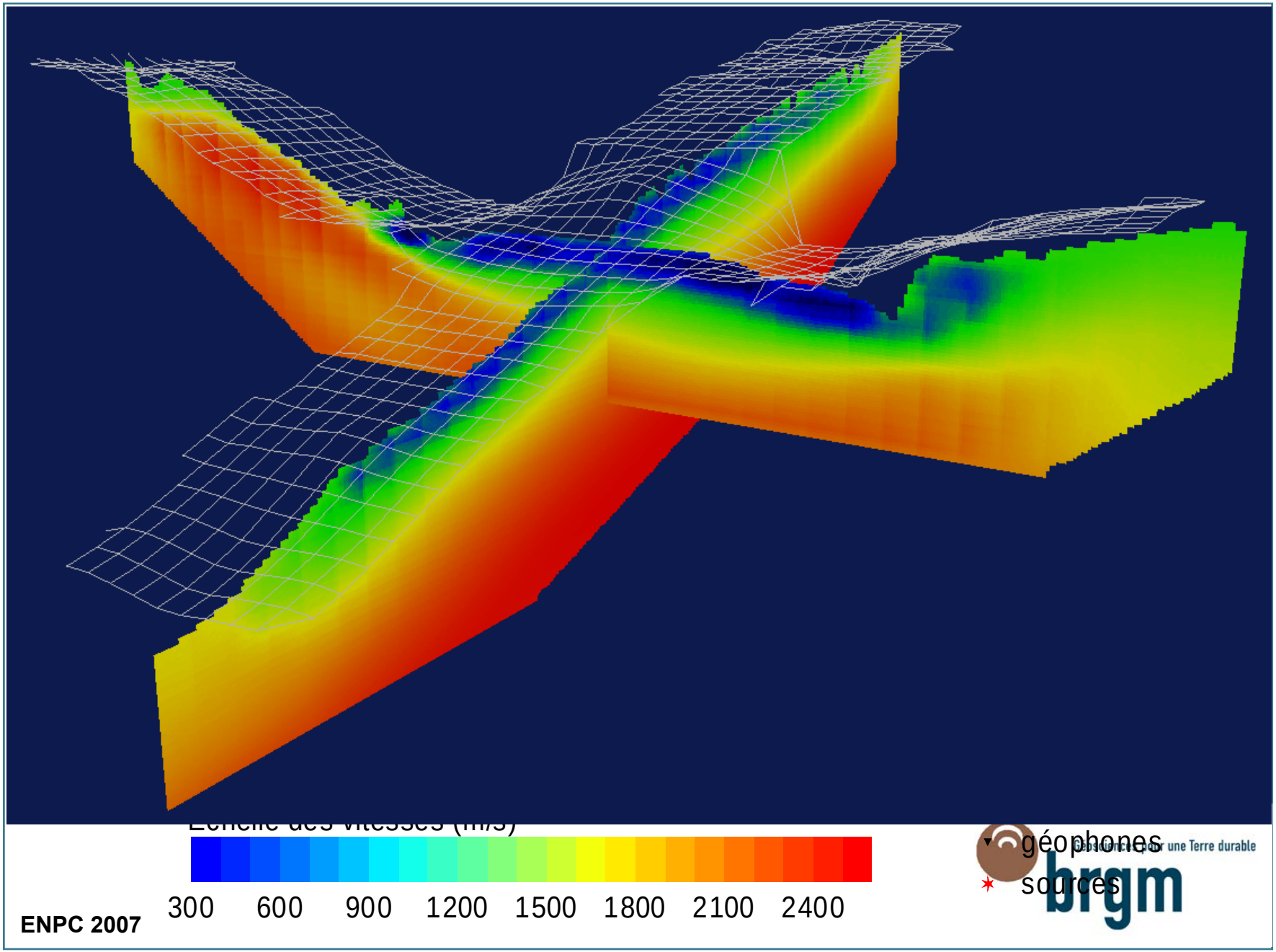
Echelle des vitesses (m/s)
300
600
900
1200
1500
1800
2100
2400
géophones
sources
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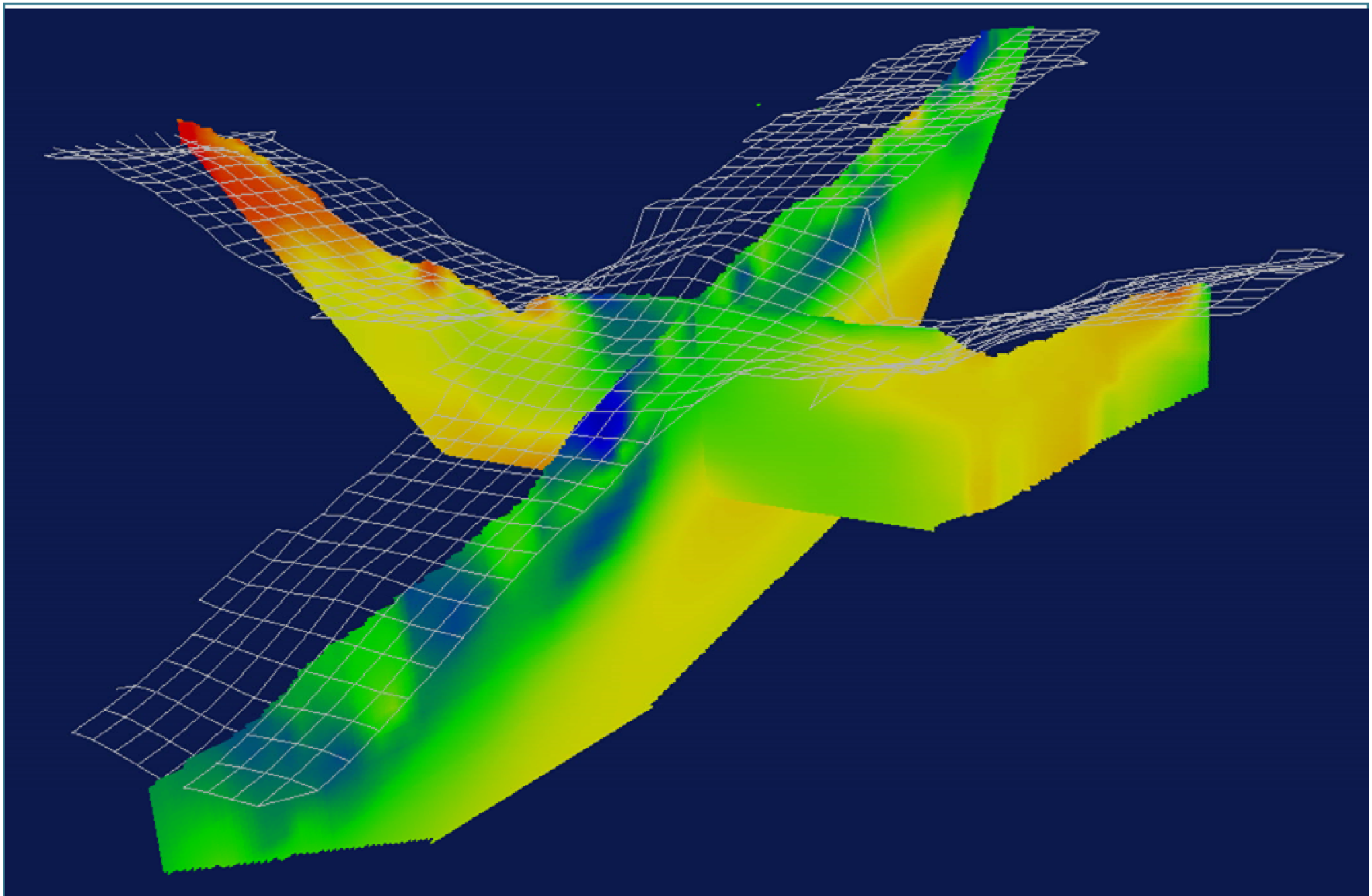

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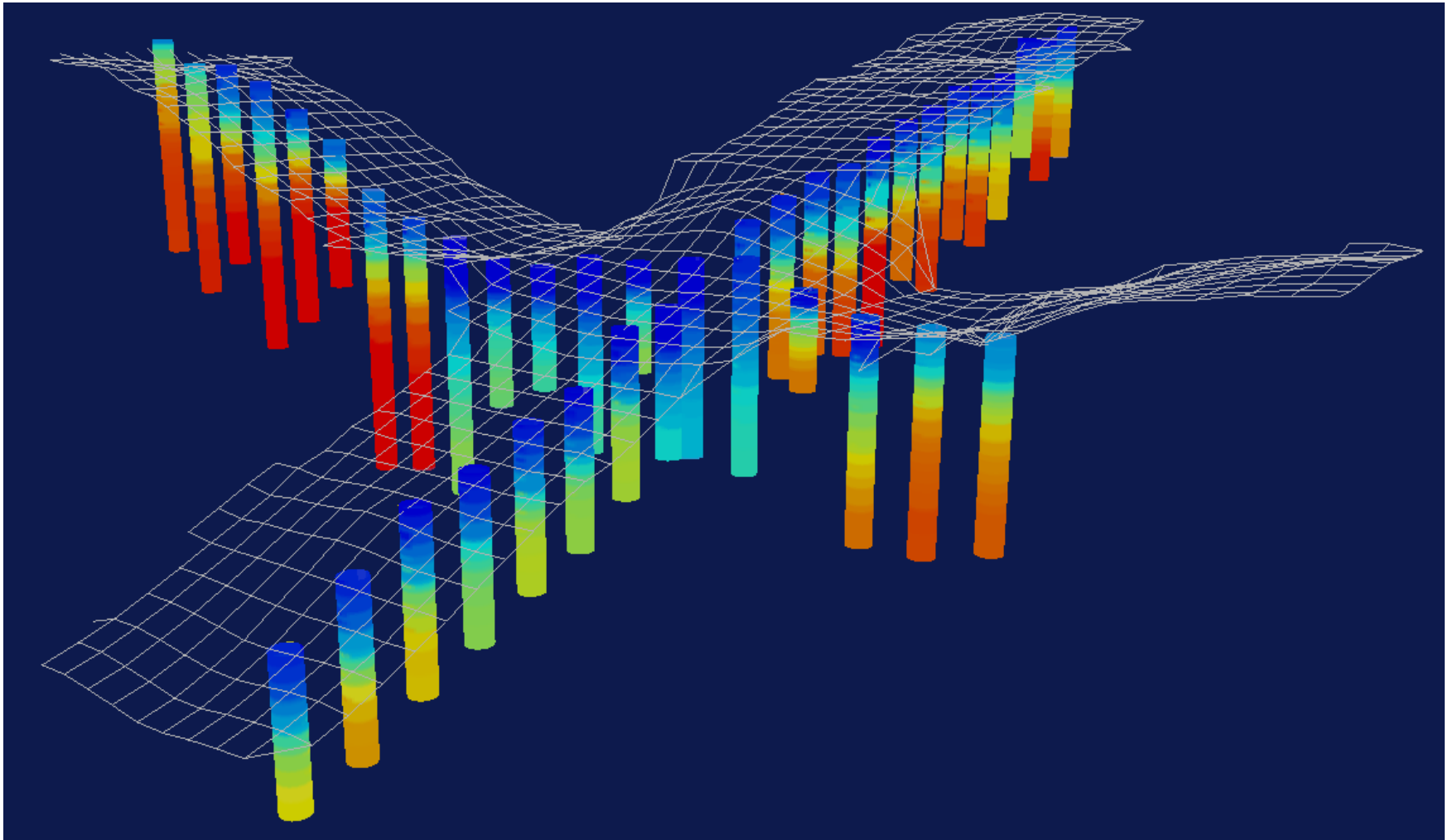
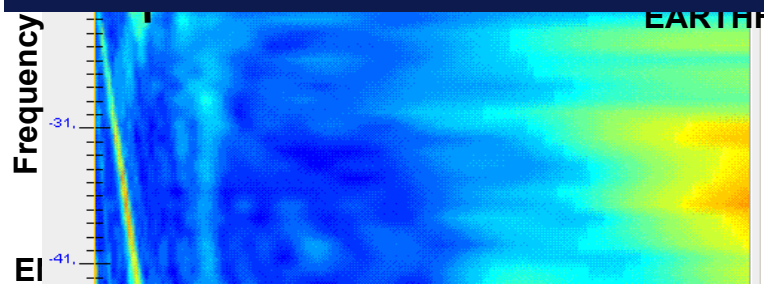
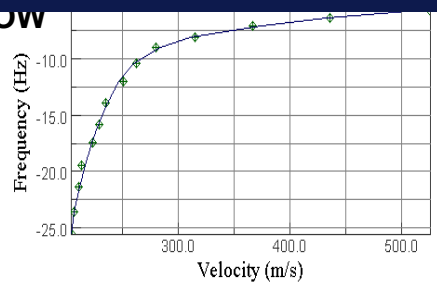
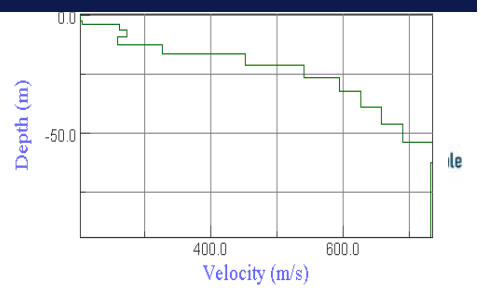



Frequency
-31.
-41.


Frequency (Hz)
-10.0
-15.0
-20.0
-25.0
300.0
400.0
500.0
Velocity (m/s)

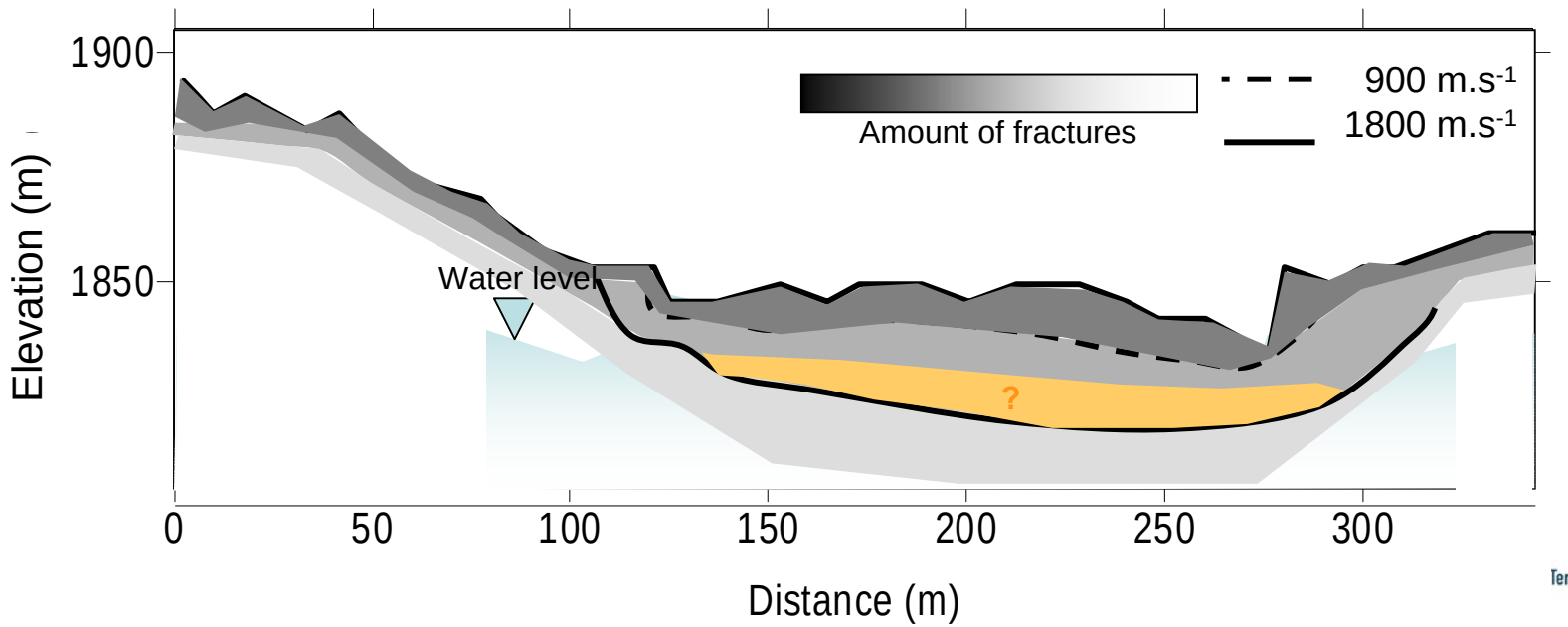

Depth (m)
-50.0
400.0
600.0
Velocity (m/s)

Qualitative interpretation

> Vp decreases if the fissure amount increases, fissure amount is maximum at the surface on the earthflow

➢ρ decrease if water saturation increase, water saturation is maximum on the earthflow, in the gullies

How to go through a more rigorous interpretation ?



Terre durable

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Error model: defining likelyhood functions, i.e., the places where inverted quantities are reliable on each tomogram

Acoustic Tomography

LVp: Iterative likelyhood function ponderated with Fresnel density distribution

$$L_{Vp} = \exp\left(\frac{-\sum_{N} \left(\frac{t^C - t^O}{\sigma} \right)^2}{2} \right) \Delta_{i,j}$$

Surface wave Inversion

LVs: taken as the diag of the resolution matrix

LVs = diag(R)

with

R = W-1 V (L2+s2 I)-1 L2 VT W

W is the weight matrix,

V and L are defined by the SVD of the inverse generalised G=U L VT

Resistivity Tomography

Lρ: computed from a Gaussian error model, knowing the standard deviation

$$L_\rho = \sigma\sqrt{2\pi\varphi} \text{ with } \varphi(\varepsilon) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(\frac{-\varepsilon^2}{2\sigma^2} \right)$$

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Fuzzy sets and possibility theory

Belonging function

The reference space : $S \subset R$

$\exists$ subset *X* of *S* :

$$\mu(x) = \begin{cases} 1 \text{ if } x \in X \\ 0 \text{ if } x \notin X \end{cases}$$

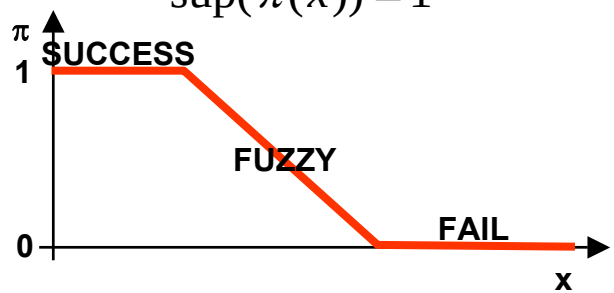
Possibility function

The reference space : $S \subset R$

$\exists$ x of *S* :

$$\pi : S \rightarrow [0,1]$$

$$\sup(\pi(x)) = 1$$



Fusion operators

The reference space : $S \subset R$

$\forall$ x $\in$ S, $\exists$ subset *X,Y* of *S* :

$$\mu(x) = \begin{cases} 1 \text{ if } x \in X \\ 0 \text{ if } x \notin X \end{cases} \quad \nu(x) = \begin{cases} 1 \text{ if } x \in Y \\ 0 \text{ if } x \notin Y \end{cases}$$

$$\forall x \in S, (\mu \cap \nu)(x) = \min[\mu(x), \nu(x)]$$

$$\forall x \in S, (\mu \cup \nu)(x) = \max[\mu(x), \nu(x)]$$

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Fusion operators

$$\pi(x) = \pi_1 \oplus \pi_2 = \frac{\pi_1(x) \wedge \pi_2(x)}{\sup(\pi_1(x) \wedge \pi_2(x))}$$

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Fusion of geophysical tomographies using fuzzy theory

> Defining 3 fuzzy functions

- hypothesis h1 defines the possibility p1 that the rock is fissured according the variations of the P-wave velocity.
- hypothesis h2 defines the possibility p2 that the rock is water saturated according the values of the resistivity.
- hypothesis h3 defines the possibility p3 that the rock is shear-bent according the values of the S-wave velocity.

> Fusion with likelyhood

> Defining 2 meta functions

$$\pi^*(x) = \pi(x) \vee (1 - L(x)) = \max(\pi(x), 1 - L(x))$$

- H1: defines the possibility for the earthflow material to be featured by a solid-body mechanical behaviour.

- H2: defines the possibility for the earthflow material to be featured by a plastic mechanical behaviour.

$$\Pi_1 = \pi_1^* \oplus \pi_2^* \oplus \pi_3^*$$

$$\Pi_2 = \overline{\pi_1^*} \oplus \pi_2^* \oplus \pi_3^*$$

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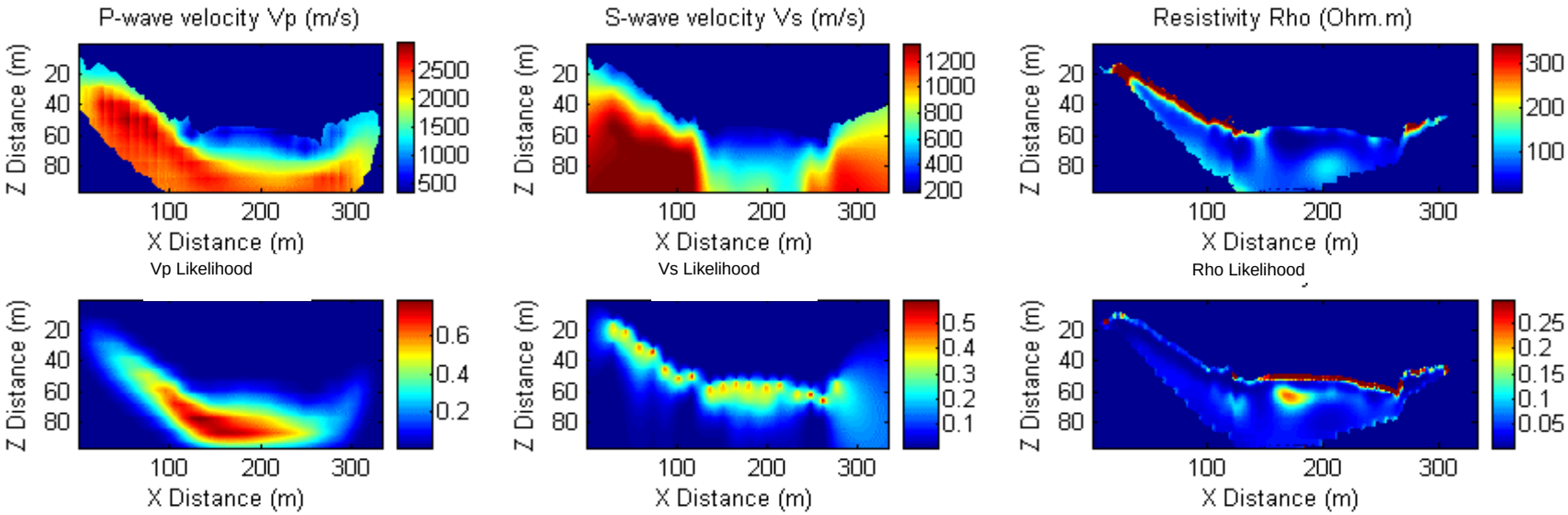
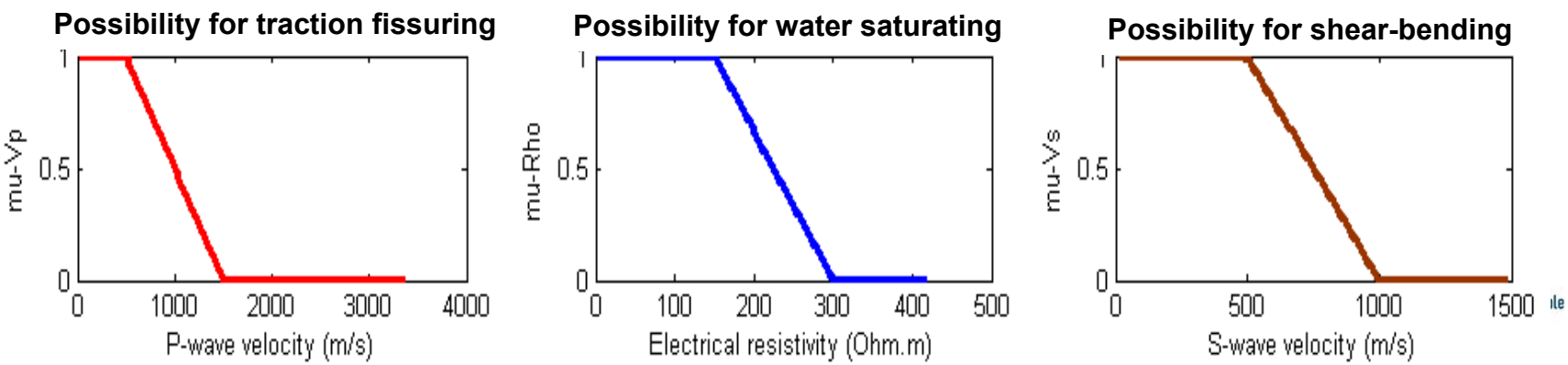
Application to Super-Sauze earthflow

Geophysical tomographies + likelyhood



Possibility fonctions



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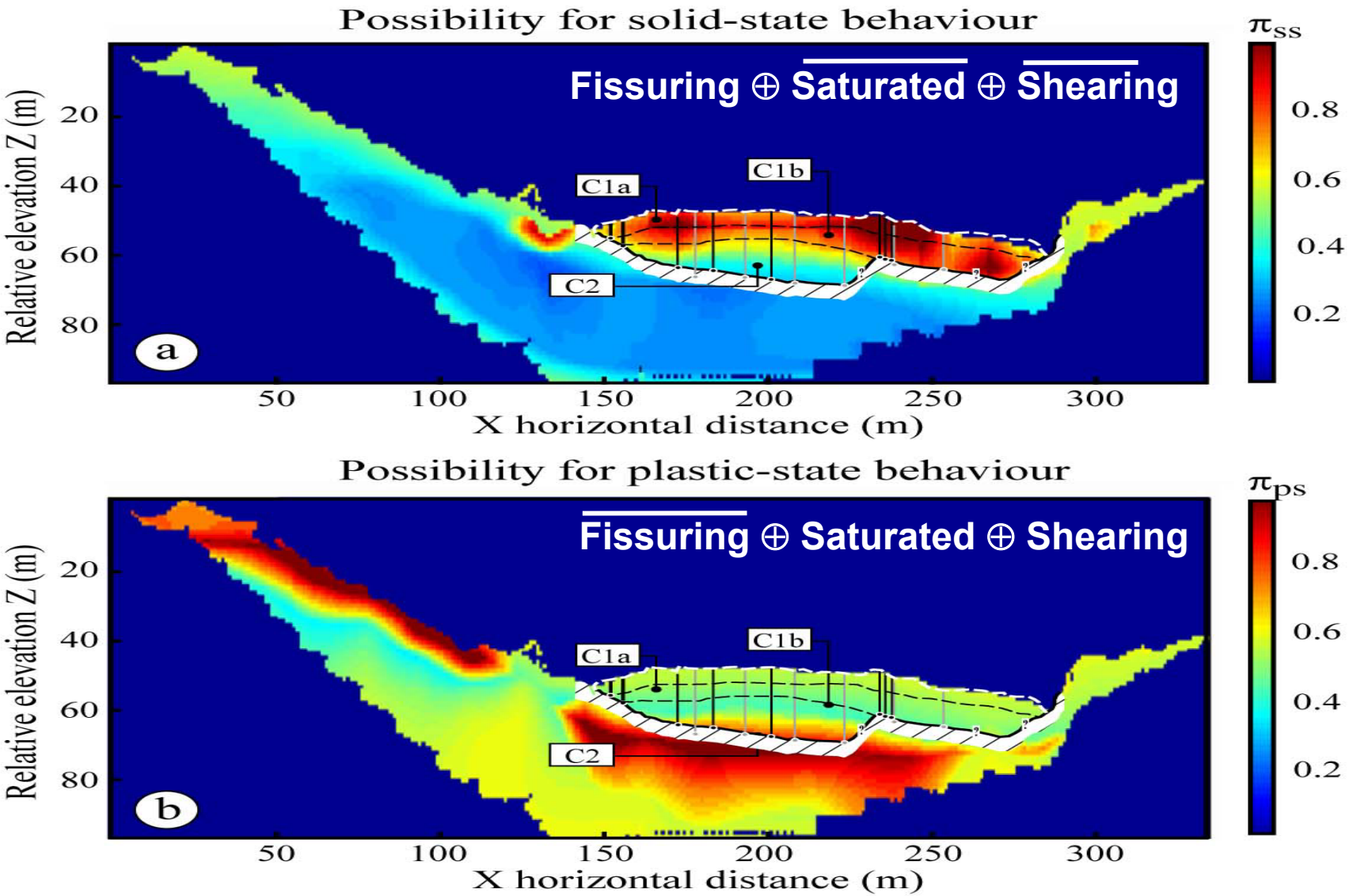
Geomechanical tomographies



Conclusion

- **Geophysical data fusion is a new tool for integrating geophysical tomograms into a unique document:**
  - Different hypotheses concerning mechanical behaviors can be easily tested (plastic, solid-body, etc);
  - Possibility function can be easily modified if additional information is *à posteriori* obtained;
  - This methodology can be easily adapted to other problematic such as fractured rocks;
- **The SIGMA project will aim to study other Alpine landslides**
  - Presently: Ballandaz (Savoie, France)

***Grandjean, G., Jean-Philippe Malet, Adnand Bitri and Ombeline Méric, 2007. Fusion de données géophysiques par logique floue pour imager le comportement géomécanique des glissements-coulées en roches argilo-marneuses, Bull. Soc. Géol. France*; v. 178; no. 2; p. 127-136**.