TEMPORAL DENSITOMETRY TOMOGRAPHY MEASUREMENT BY MUONS

-T2DM2-

(Funded by Physique &Univers IN2P3/INSU)

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COLABORATION
CEA/IRFU, Université de Sheffield, Géosciences Montpellier, Géophysique spatiale et planétaire (IPGP), Université d'Avignon et des Pays de Vaucluse (EMMAH), Université de la Méditerranée (CPPM), CFN Lisbonne, CERN

INTERDISCIPLINARITY
Astroparticules
Seismic Imagery
Gravimetric
Hydro geology
Rock Mechanics
EM imagery

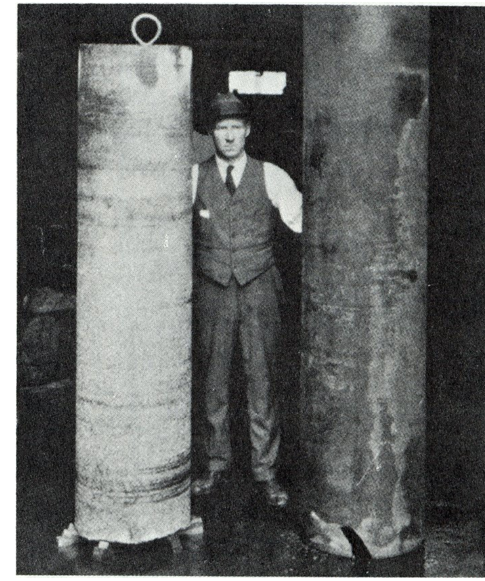
*On behalf of the T2DM2 collaboration

FUNDAMENTAL QUESTION:
What are the mechanical parameters of rock across a cluster?

- **Measurements on samples of small scales or large sizes**

The mechanical parameters are unknown to a mass scale:

Effective stress?
Friction effective?
Damage?



- **Empirical methods**

Measure: Mechanical parameters in small scale → Qualitative description of the rock mass (scale fracturing, alteration, hydraulic ...) → Estimation: Mechanical parameters at large scale

Bieniawski (1976), Hoek & Brown (1980)

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DETERMINE ρ, open a new measure field at natural scale

Description of the rock in the elastic approximation :

- Lamé parameters and density : λ, μ, ρ
- Wave velocity in soil : $\alpha = ((\lambda+2\mu) / \rho)^{1/2}$, $\beta = (\mu / \rho)^{1/2}$
- Young's modulus and Poisson's ratio : **E**, ν
- Uniaxial stress **($\sigma = E\,\varepsilon$), E = ($3\lambda+2\mu$) μ / ($\lambda+\mu$), ν = ($2-(\alpha/\beta)^2$) / ($2-2\,(\alpha/\beta)^2$)**
- Compressibility coefficient and shear modulus: **K, G**
- Modules and elastic coefficients are related: **1/E = 1/9K + 1/3G**

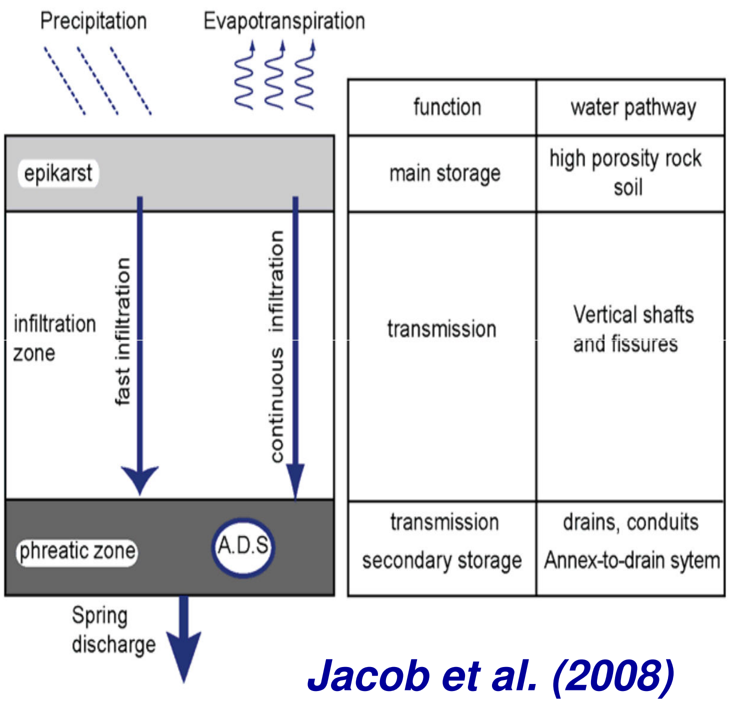
Problems of real massive

- **A building complex**

Damage (evolution of the fracture, internal erosion, ...)
Traffic fluid (chemical alteration, variation of porosity...)

- **A temporal evolution**

Ante/post-eruptive volcanoes phases
Managing resources and reserves (environment, hydrology karst)
Midfielder cashing storage (CO_2, chemical waste, nuclear, ...)
Underground Engineering (structures, mining)



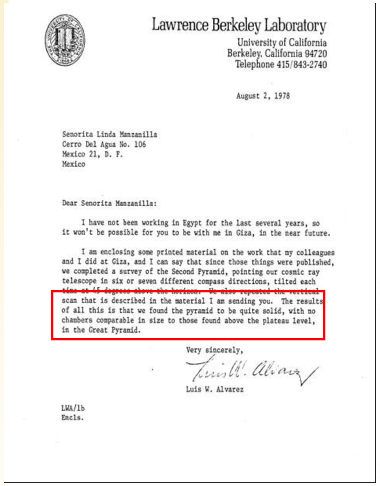
Jacob et al. (2008)

THE HISTORICAL AND RECENT EXPERIMENTS

Muons flux measure

- **Pyramid**
  Using cosmic rays in order to detect the presence of a secret chamber in the Pyramid of Chephren, experiment was install in the Belzoni chamber. Muons through a cavity lose less energy by interaction compared to crossing the limestone composing the pyramid.
  Luis Alvarez et al. (1970)

"the results of all this is that we found the pyramid to be quite solid, with no chambers comparable in size to those found above the plateau level, in the Great Pyramid."



Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720
Telephone 415/843-2740

August 2, 1978

Senorita Linda Manzanilla
Cerro Del Agua No. 106
Mexico 21, D. F.
Mexico

Dear Senorita Manzanilla:

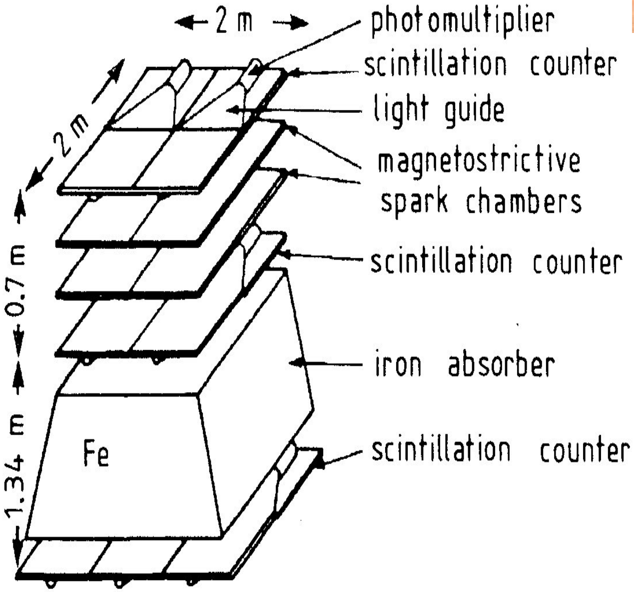
I have not been working in Egypt for the last several years, so it won't be possible for you to be with me in Giza, in the near future.

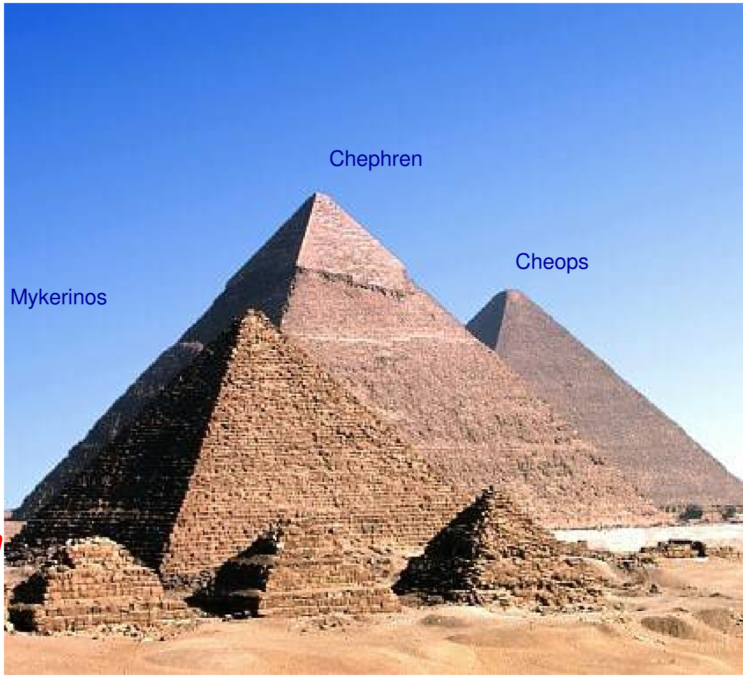
I am enclosing some printed material on the work that my colleagues and I did at Giza, and I can say that since those things were published, we completed a survey of the Second Pyramid, pointing our cosmic ray telescope in six or seven different compass directions, tilted each time at 45 degrees above the horizon. We also repeated the vertical scan that is described in the material I am sending you. The results of all this is that we found the pyramid to be quite solid, with no chambers comparable in size to those found above the plateau level, in the Great Pyramid.

Very sincerely,

Luis W. Alvarez

LWA/lb
Encls.





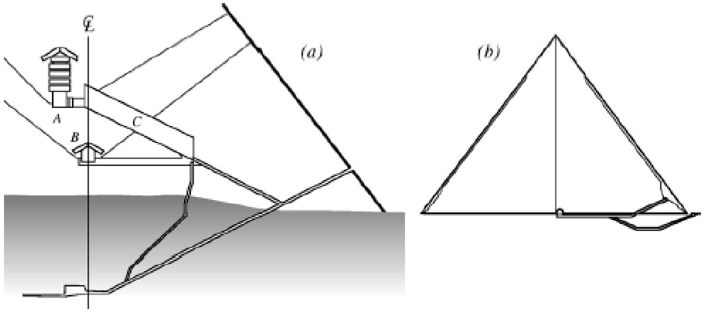
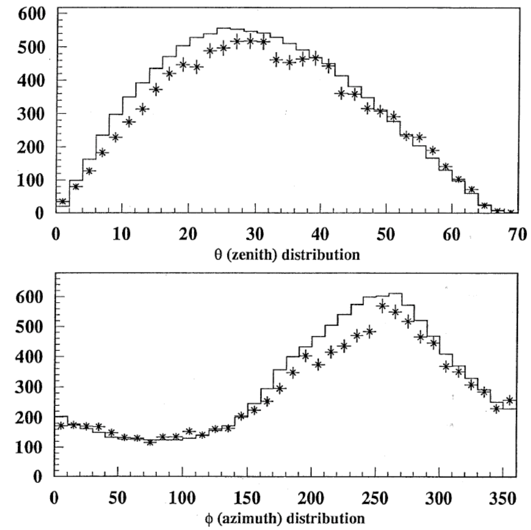


Fig. 2. (a) The known chambers in Cheops' pyramid. In the body are A, the King's Chamber; B, the Queen's Chamber; and C, the Grand Gallery. The centerline of the pyramid is indicated. (b) Are there undiscovered chambers in Chephren's pyramid?

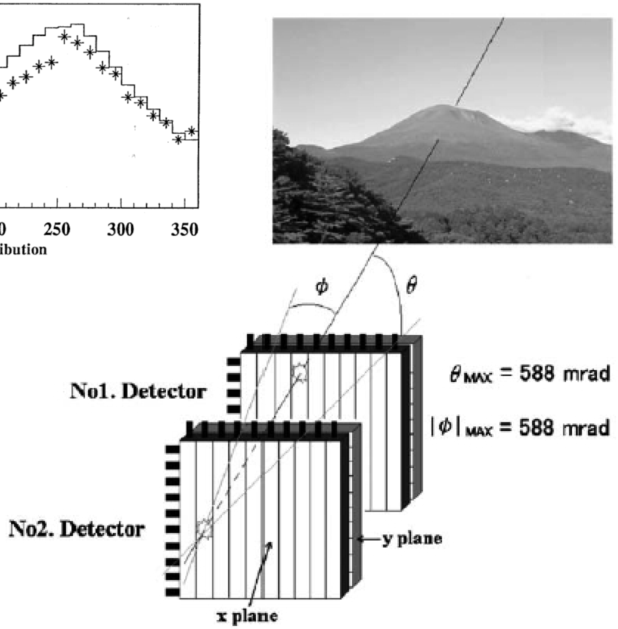
RECENT EXPERIMENTS



- **Neutrino CHOOZ experiment**

Highlighting some of azimuth differences between the flux of muons expected and actual flows measured at the detector at the site of the Chooz experiment. ***Baldini et al. (1995)***

This difference is attributed to crossing a geological level higher density for these specific azimuth and zenith.



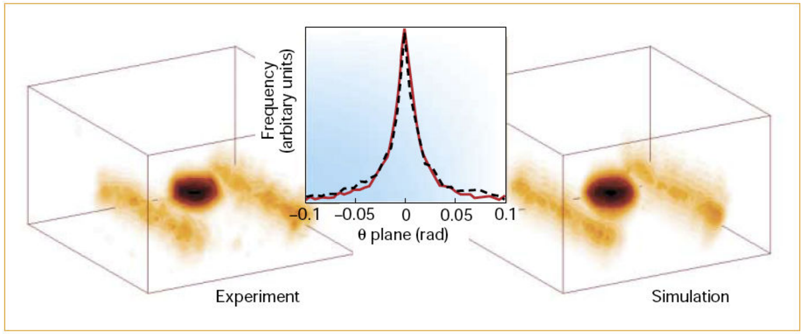
- **Other experiments**

In the case of Asama volcano ***Tanaka et al. (2005),*** shows that it is possible to distinguish the density contrasts of the order of 1 to 3%.

- **Control for cross-border transport of nuclear materials.**

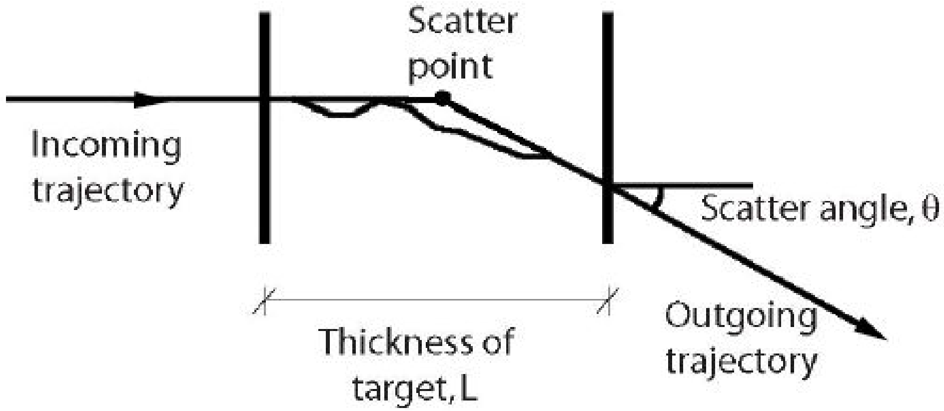
Radiographic imaging with cosmic-ray muons. ***NATURE-Vol422- (20 march 2003)***

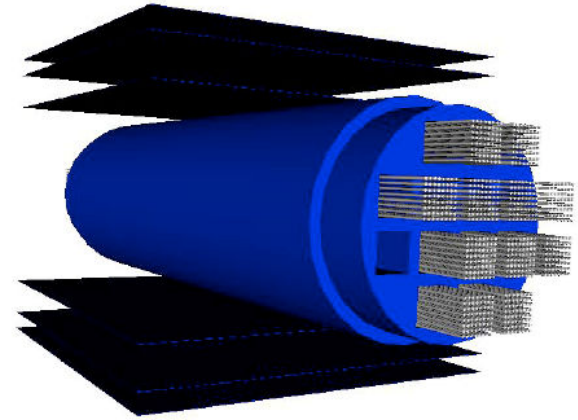
Natural background particles could be exploited to detect concealed nuclear materials.



TOMOGRAPHY BY MUONS SCATTERING

- Tomography of canisters for spent nuclear fuel





Joel Gustafsson (thesis)

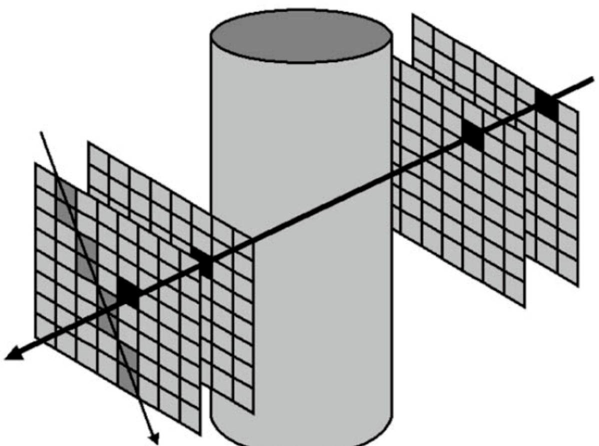


Fig. 6. A muon attenuation CT system.

A 525 (2004) 346–351

A prototype of the canister for spent nuclear fuel

OBJECTIVES OF THE PROJECT T2DM2

- **Accessing a new measure for characterizing geosciences mechanics of subsurface materials**
- **Develop a versatile and flexible instrument for the geosciences community**

- **Methodology for "muoscopy"**

Constraints: Size, solid geometry, time-scale processes, ...

Numerical simulation (Music, Kudryavtsev et al., 2008) prior to calibration:

- Duration of exposure vis-à-vis the time scale on the processes observed
- Cover and geometric topology of the network of telescopes and precision field of views and the surface of each detector,
- Number of detectors
- Spatial resolution possible based on solid geometry / network

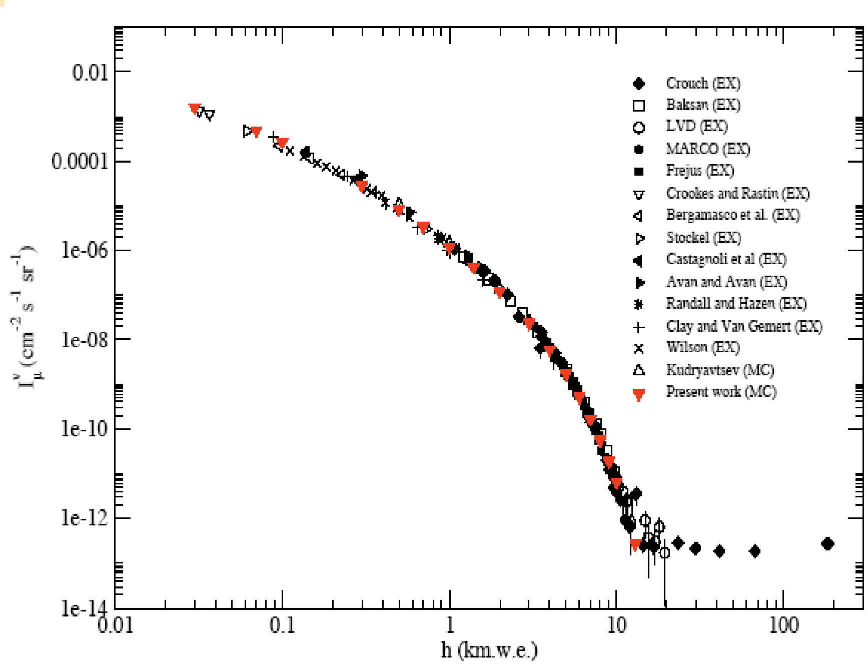
Muoscopy - Densitometry

- Construction of 4 prototypes and measures
- Establishment of codes of tomography inversion / simulation (Geant, Music…) & coupling between densitometry imaging and seismic imaging (Young's modulus)
- Coupling measures spatial-temporal density and field variations gravity (location, water flow dynamics in the ZNS)

DESIGN OF TELESCOPES NETWORK TO BASED ON THE SIMULATION

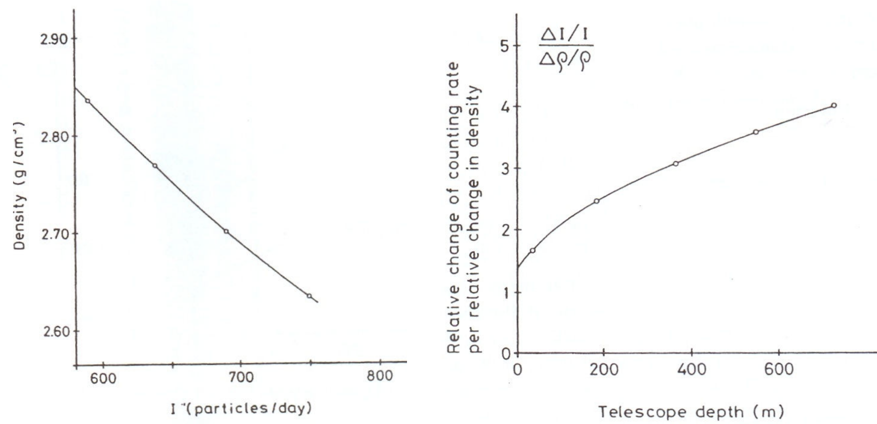
Count rate:

Number of muons (m^{-2} $day^{-1}sr^{-1}$): depending on the thickness, density & atomic compound of materials encountered

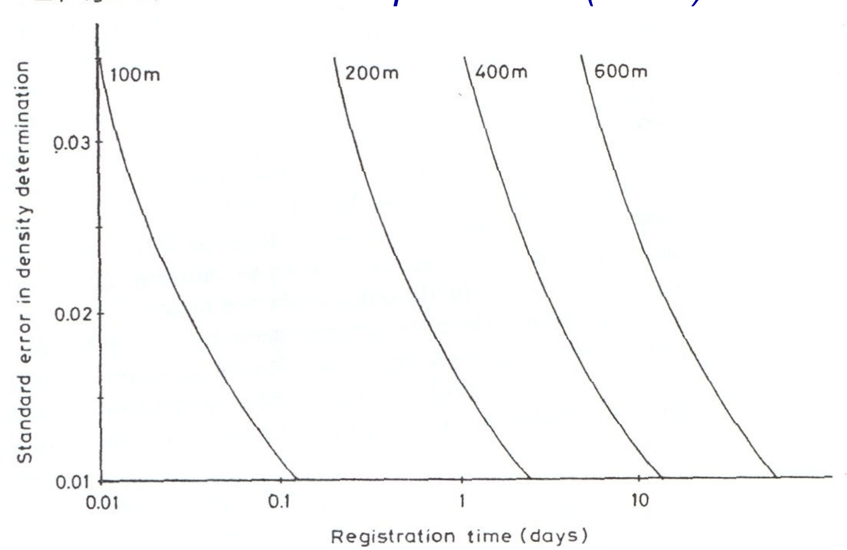


Average vertical muons intensity Iv μ(h) versus vertical depth h beneath a flat surface in standard rock.

arXiv:hep-ph/0604078 v2 25 Aug 2006



Malmqvist et al. (1979)



DESIGN OF TELESCOPES TO NETWORK BASED ON THE SIMULATION

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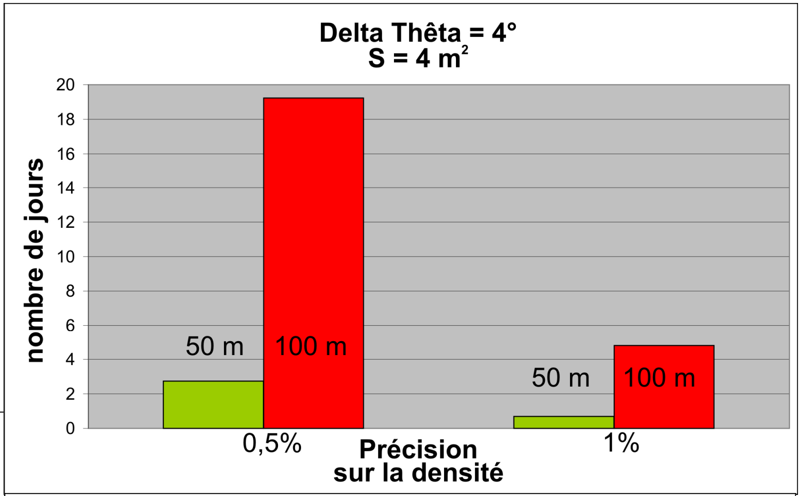
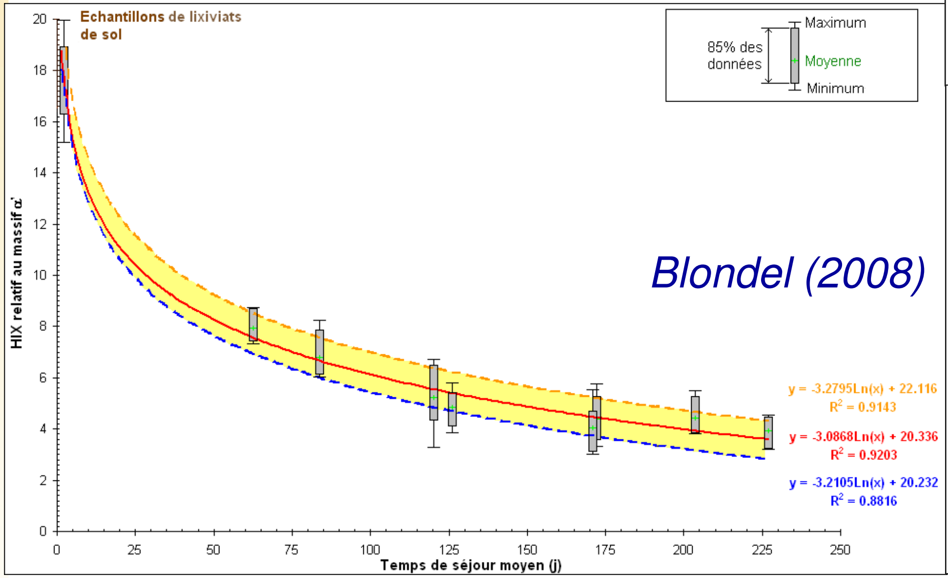
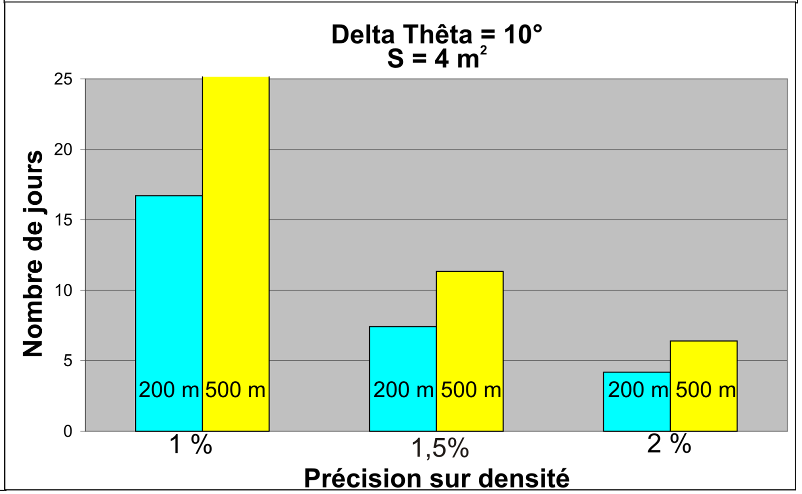
For each telescope:

•Exposure versus surface of the telescope
The temporal resolution depends on the speed physical processes observed, which are varying density, and duration of resilience of the environment. The required area depends on the time scale processes and counting rate.







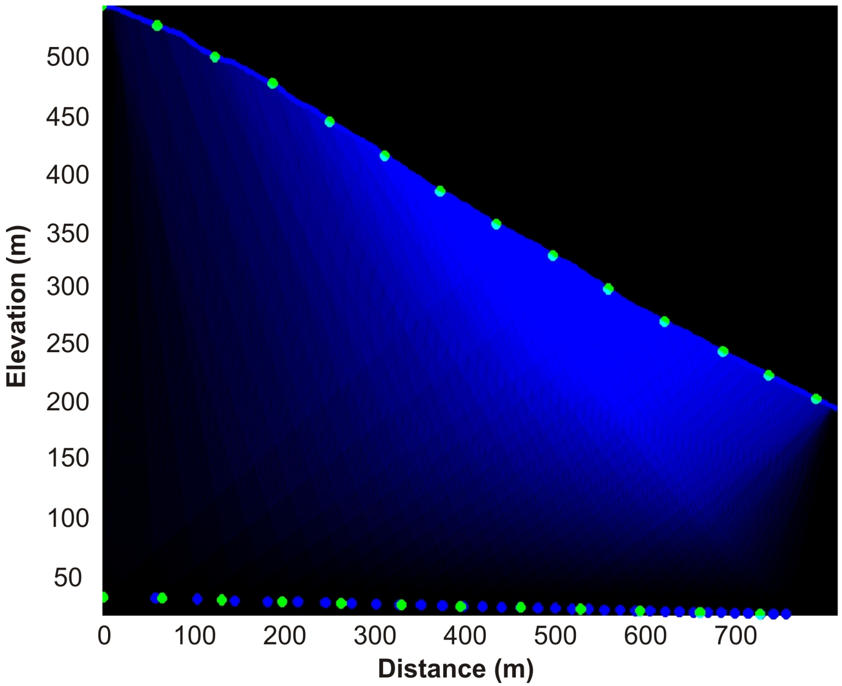
Residence time and exposure times depending on the depth and accuracy of measurement desired

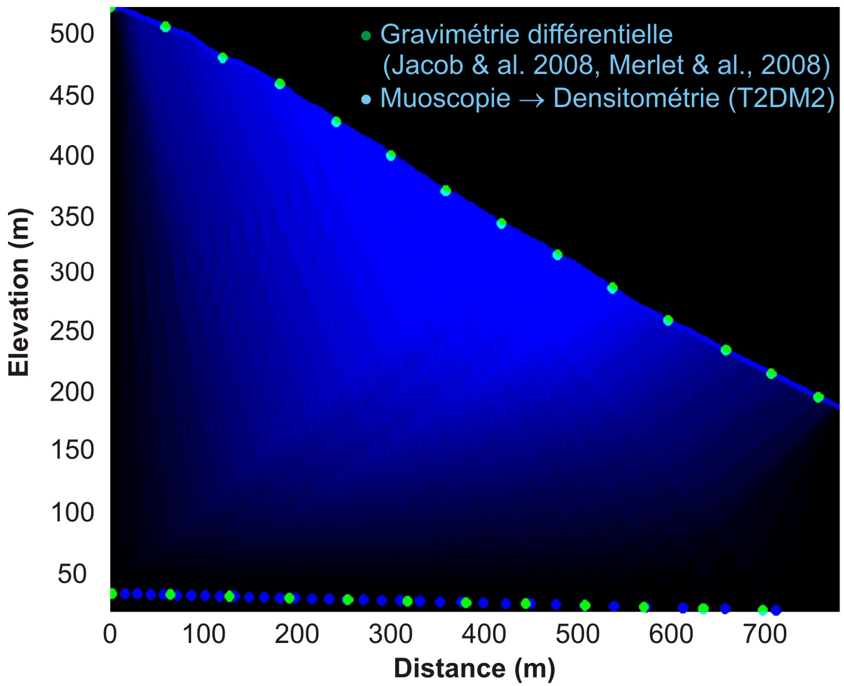
DESIGN OF TELESCOPES TO NETWORK BASED ON THE SIMULATION

Network design:

• Spatial resolution and number of detectors

Tomography requires redundancy absorption measurements under different zeniths and / or azimuths to get a good lighting environment. Binding global opening and the angular resolution of each telescope, the network topology to deploy and the number of telescopes.





Simulation:

• Optimizing coverage

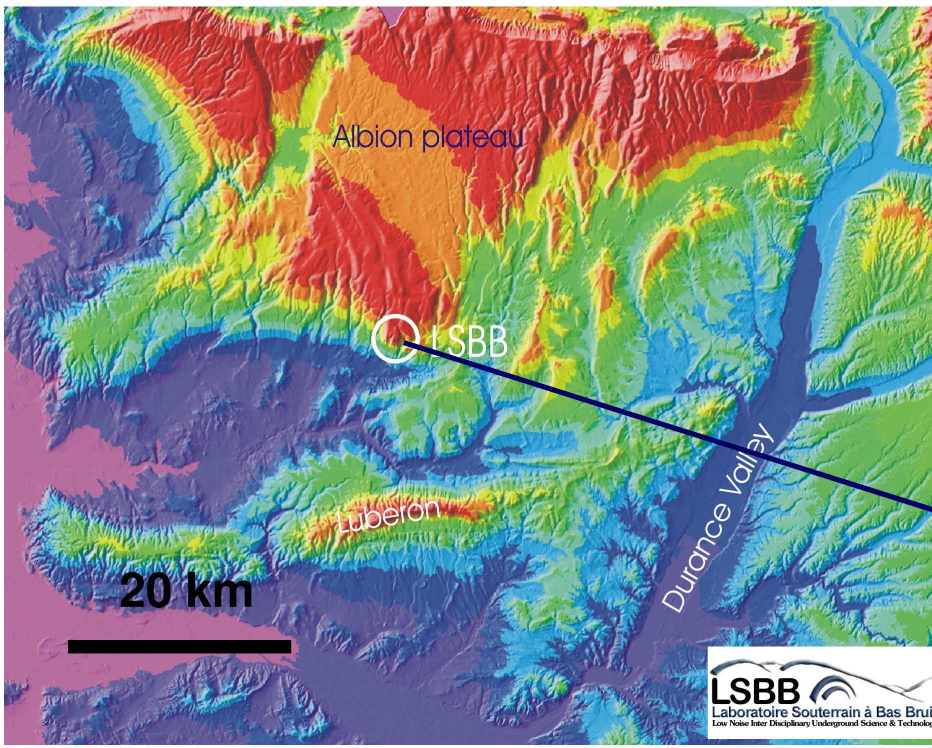
Surface, aperture and resolution

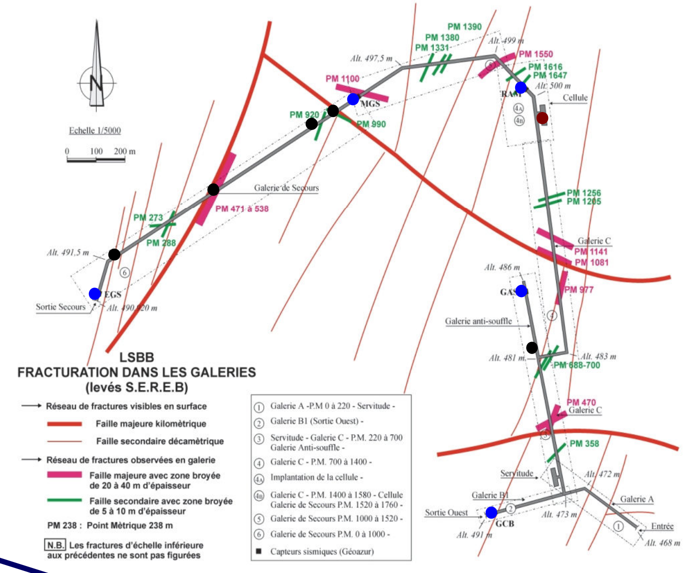
Inversion:

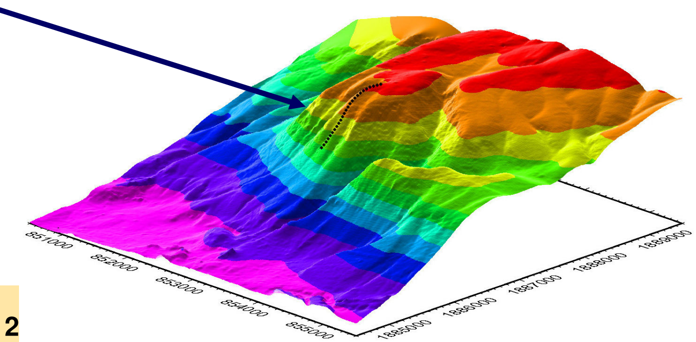
Iterative process involving modeling muons flux expected from the topology *(MUSIC, Kudryavtsev et al. 2008)*

PROTOTYPE DEVELOPPEMENT AND TUNING

Experimental development at LSBB (karst) to benefit from the combination of multi-parametric measurements from different scientific projects conducted in the laboratory





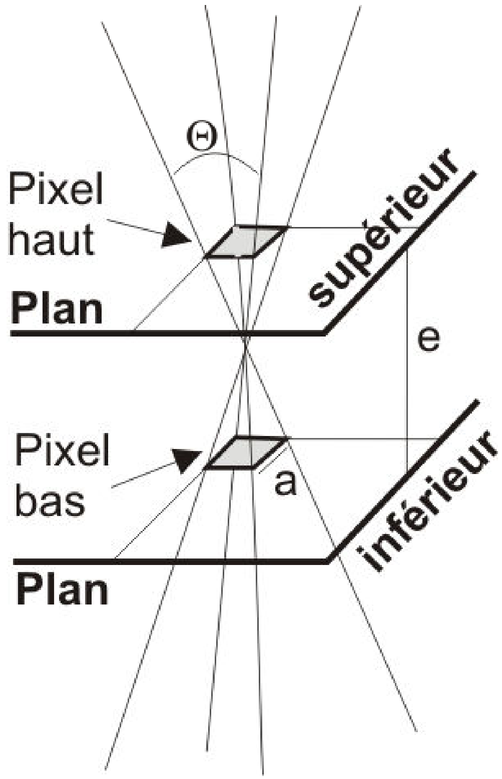


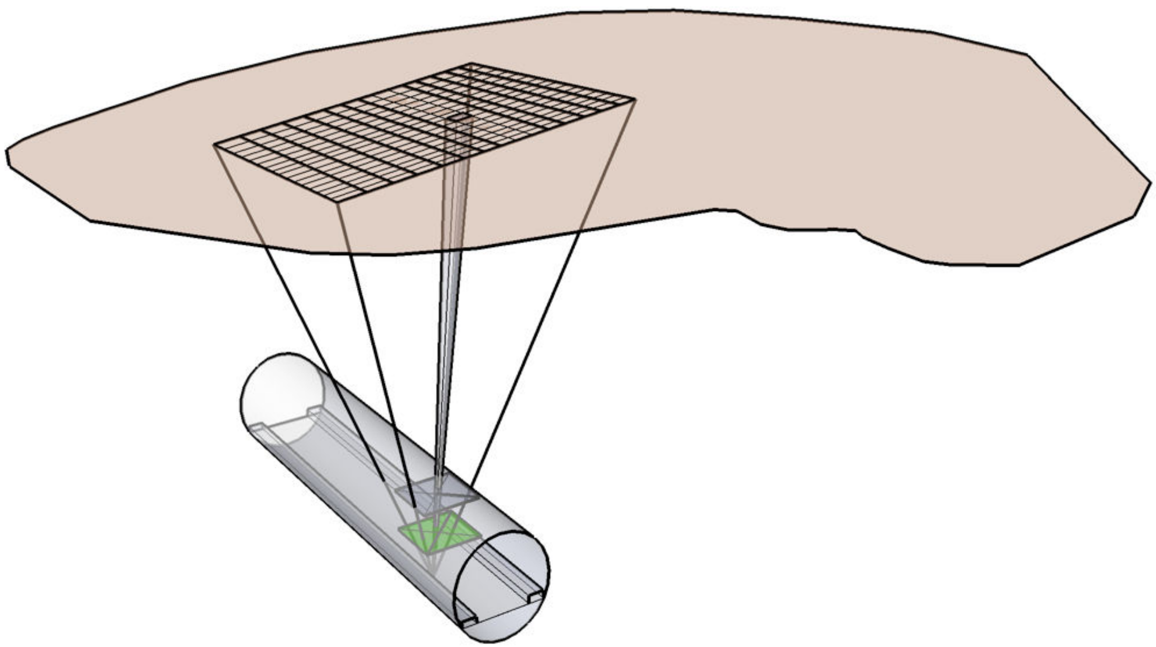
DESIGN OF TELESCOPES TO NETWORK BASED ON THE SIMULATION

Build the network:

• Pixelization (strips X & Y)

The angular resolution and the distance between planes require the pixel size.
The number of pixels and the electronics require (real time processing, discrimination and signal acquisition) forcing the cost.
The time measurement requires the surface of the telescope.
The angular resolution, the aperture, the exposed surface can vary for each, we must design a versatile and flexible telescope



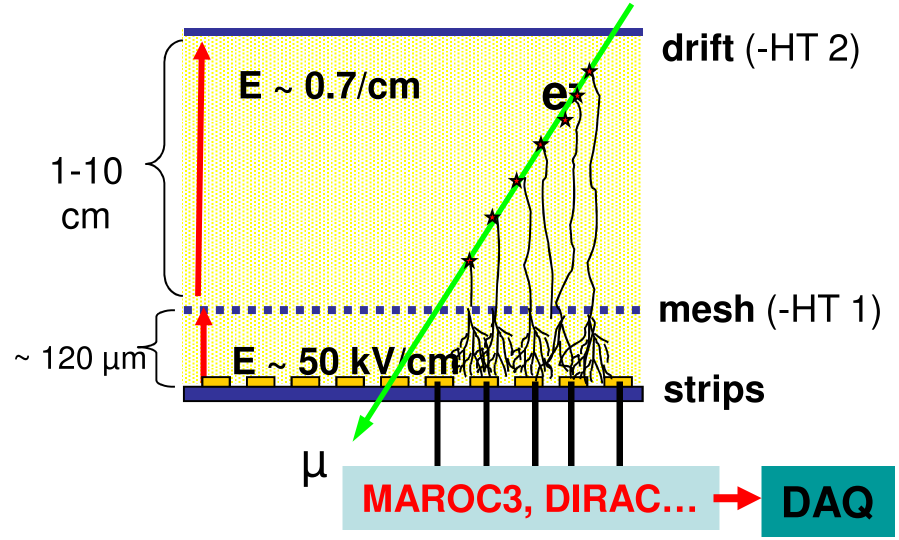


DESIGN OF TELESCOPE AND TECHNOLOGY CHOICES

Micromegas-Bulk in TPC mode

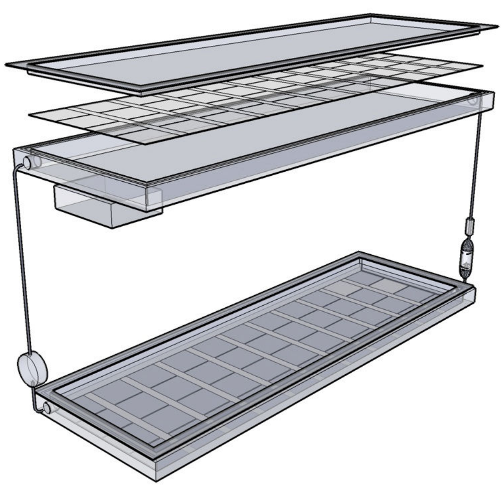
- Combine triggering and tracking functions
- Spatial resolution ~ 100 µm (Θ_{track}< 45°)
- Good double track resolution
- Time resolution ~ 5 ns
- Efficiency > 98%
- Rate capability > 5 kHz/cm^2
- Potential for going to large areas (1 x 2 m^2 with industrial processes)
- Cost effective

Thank to P. Lengo (CERN)



Four T2K prototypes will be used

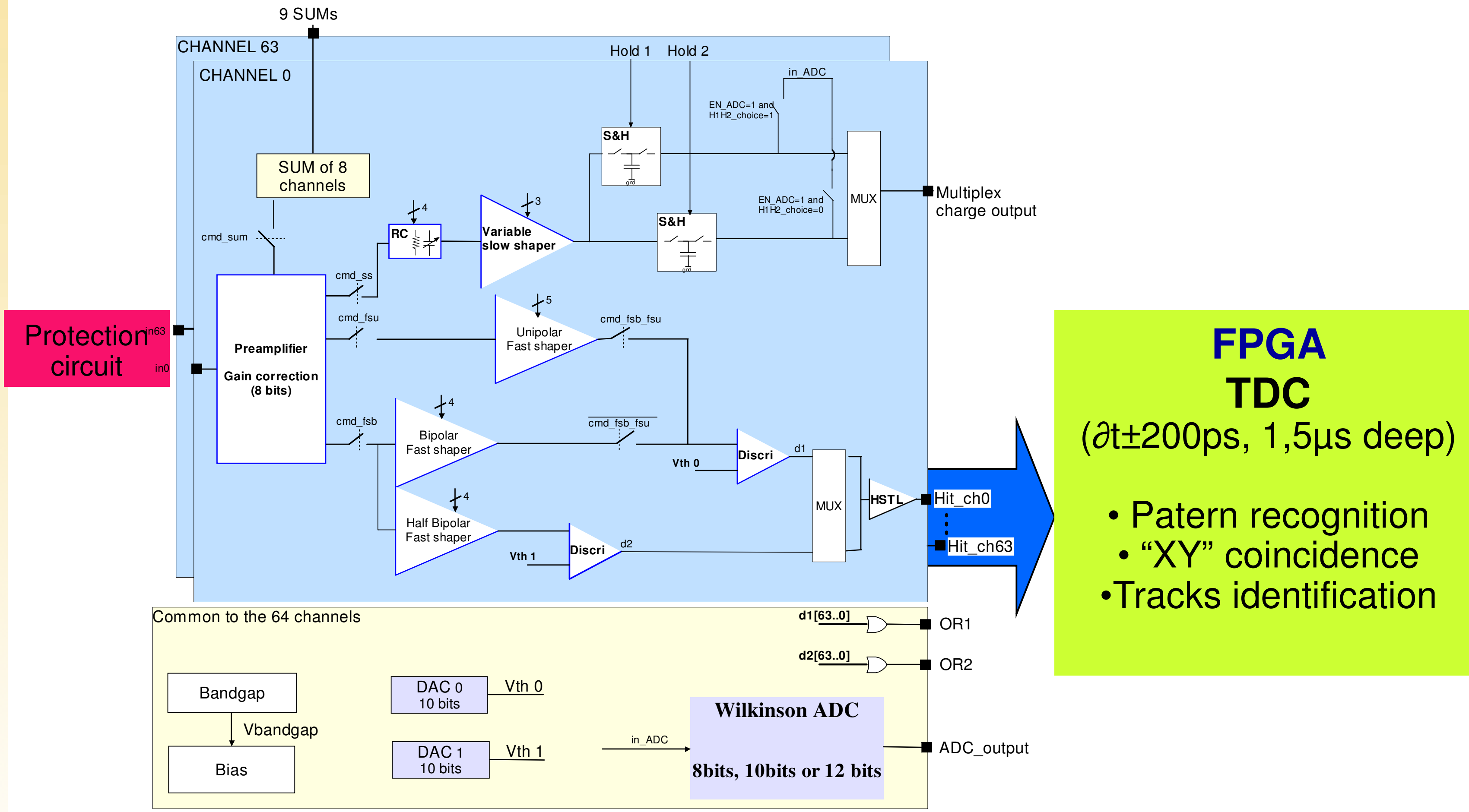
- For gas studies
- Electronic final choice
- FPGA configuration



« Micromegas in a bulk » NIM A 560 (2006) 405–408

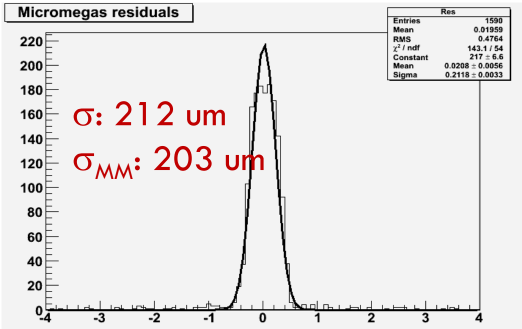
DESIGN OF TELESCOPE AND TECHNOLOGY CHOICES

MAROC3 ASIC



TECHNOLOGY & DIMENTIONAL CHOICES

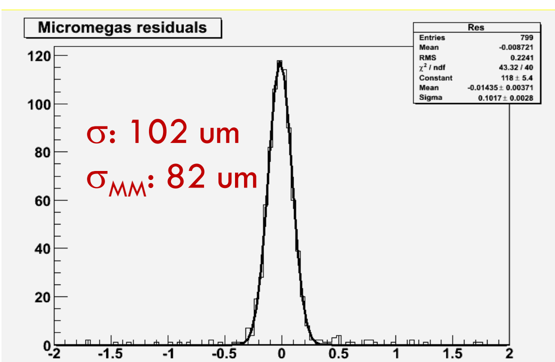
Track inclination: 40°
$Ar:CF_4:iC_4H_{10}$ (95:3:2)
Drift field: 360 V/cm

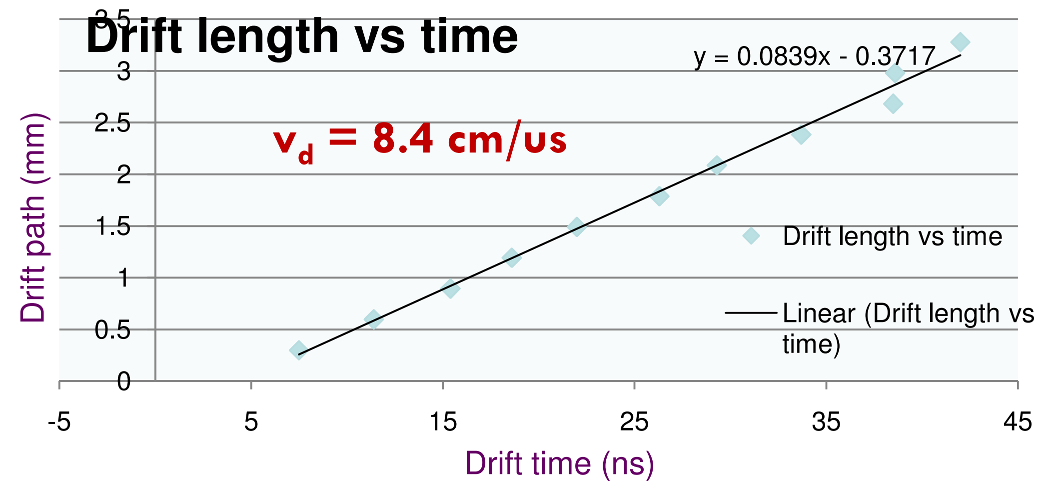


Strip pitch: 1000 µm
Strip width: 900 µm

If more money or increasing drift length!

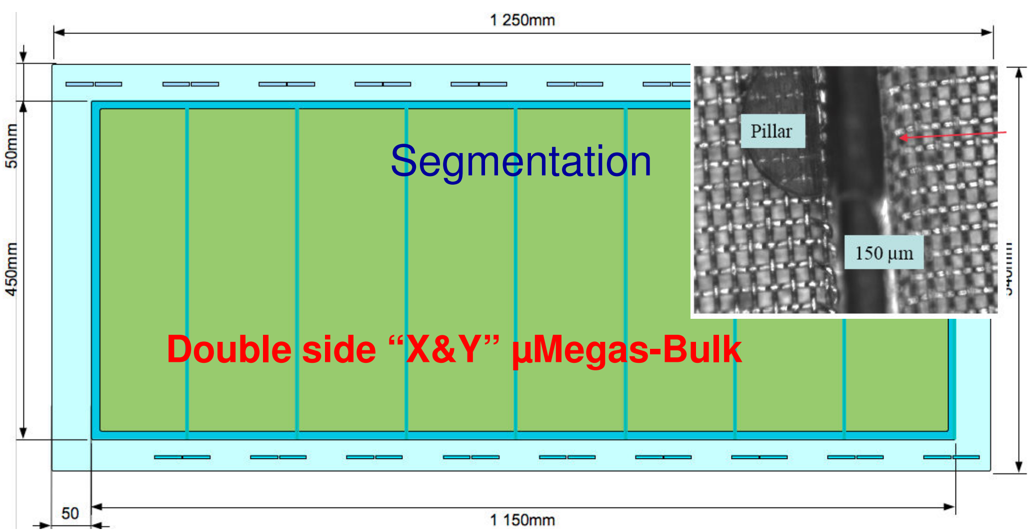
Strip pitch: 500 µm
Strip width: 400 µm





P. Lengo – IEEE-NSS 21 October 2008, Dresden

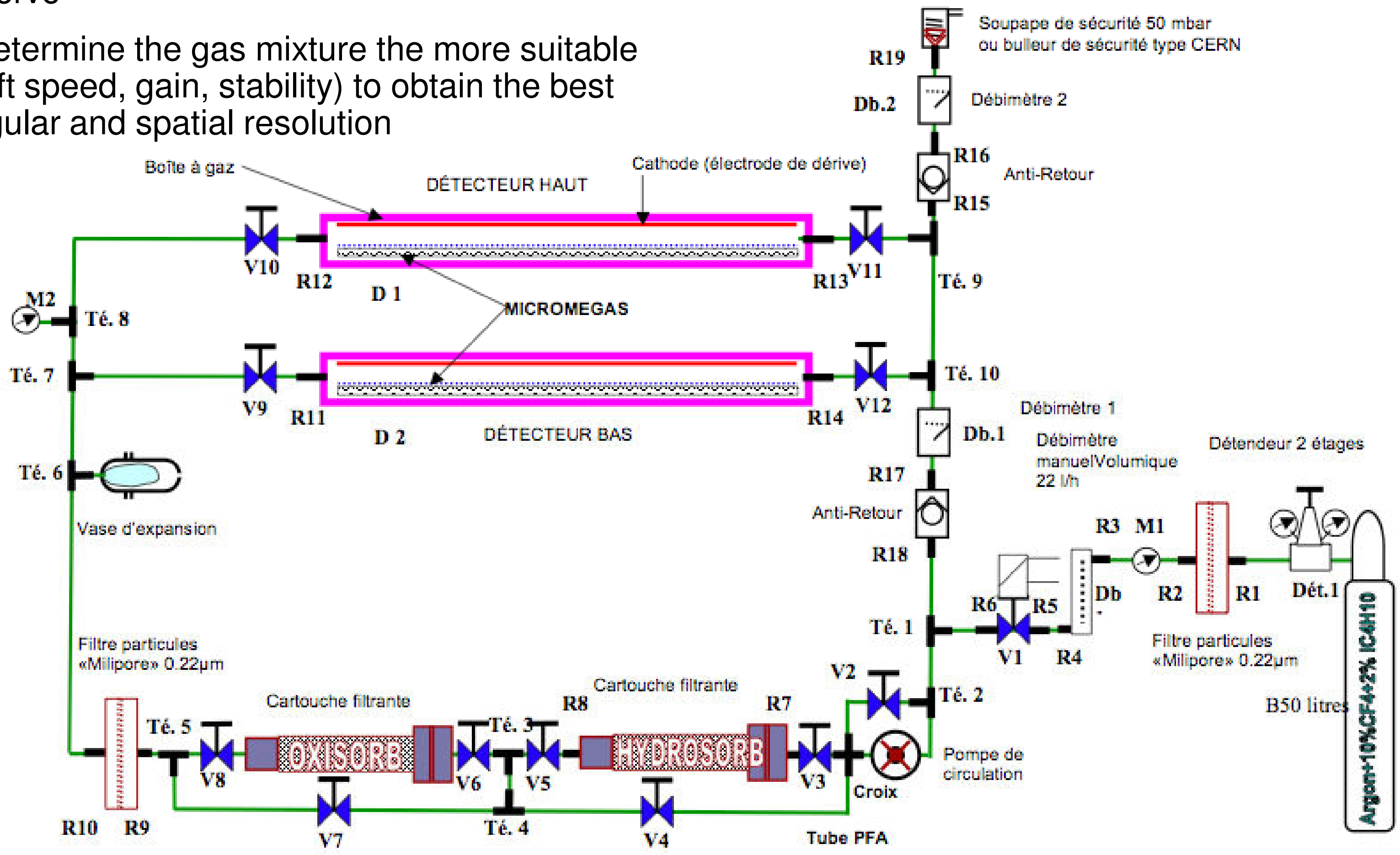
Prototype detector



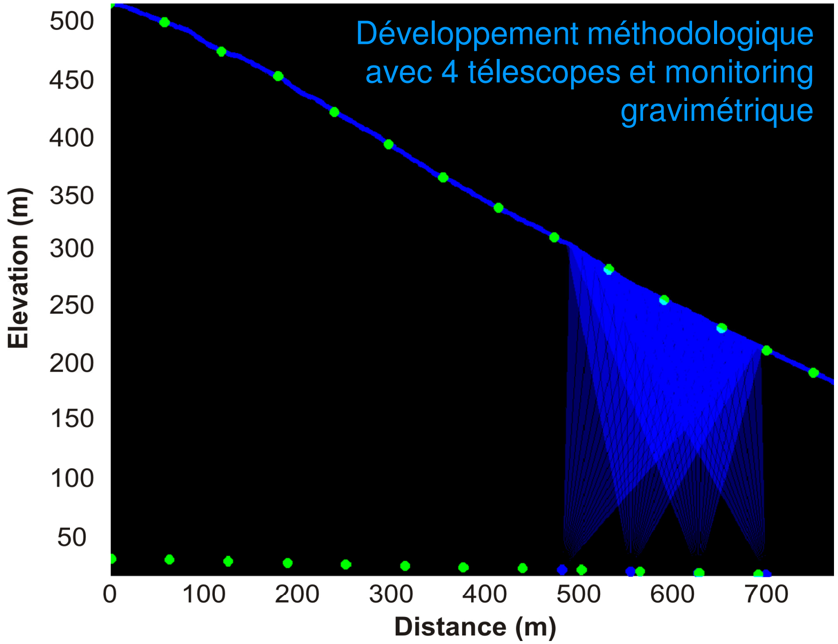
PROTOTYPE GAS-SETUP

GOALS:

- Demonstrate experimentally that it is possible to maintain the functional quality of gas for several months up to a year with a few liters reserve
- Determine the gas mixture the more suitable (drift speed, gain, stability) to obtain the best angular and spatial resolution



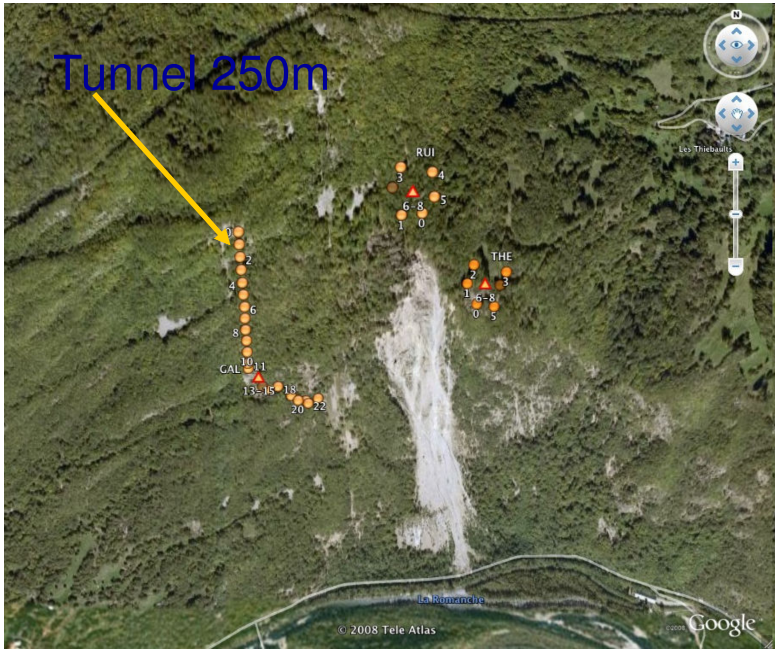
PROSPECTIVE MEDIUM AND LONG TERMS



Through the project T2DM2:

•Provide tools for digital modeling of device acquisition and reversal

• Develop a website to disseminate knowledge of this measure Federate a community of interest and define the outline fundamental questions that can be studied with the muoscopy



Beyond Project T2DM2:

Exploration of different problems: corruption within the gravitational movements (eg tunnel Séchillienne, gneiss), environmental monitoring in underground storage (Bures, clays) or even oil exploration. Create a national network of portable telescopes (number 50 to 100 telescopes?)

Generation Project, ANR, Region, Europe

CONCLUSION

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Technological choices:

- To have smaller pixels: monitoring and survey of civil engineering structures, wells (gas, oil, water, storage, ...)
- To have an overall height reduced through a measuring time on pixels (Equipment Gallery)

Applications:

- Involvement hydrogeology : hydraulic flow
- Involvement CO^2 stockage : macroscopic properties of the rock

Calendar:

- Methodology and test LSBB 2009-2010 ==> new funding for extension up to 80 telescopes
- Deployment then mine (water monitoring) and landslides (monitoring of damage)

Our needs :

- Embed a group for modeling aspects
- Generate an RDA project to develop a network of observation from 40 to 80 telescopes

We research collaborations and related applications into existing programs

ANY HELP WILL BE WELCOME!!

Some bibliographic references

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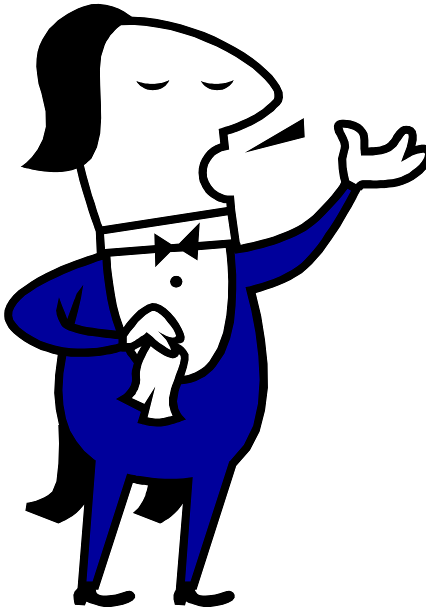
Thanks for your attention!



Questions and Answers

INTERIMAGES PROJECT (2006): SEISMIC IMAGING OF PROPERTIES
Coll. Geosciences Azur, MIGP, Univ Paris-Sud, Univ J. Fourier, UNAM

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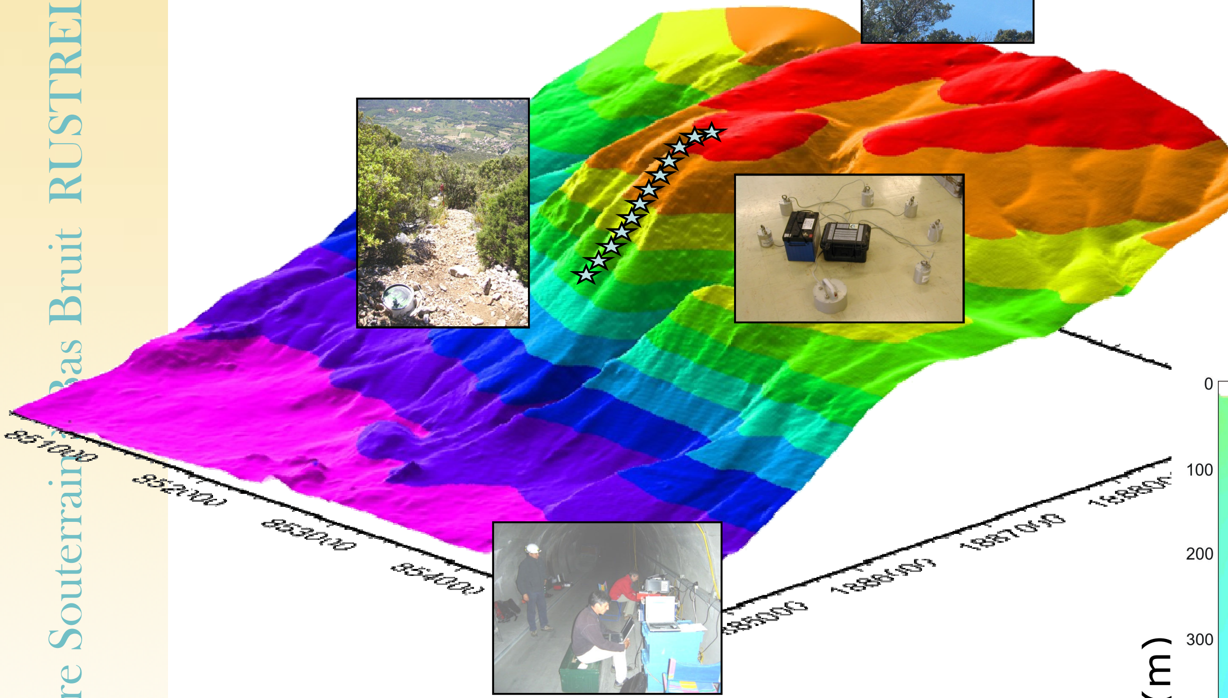
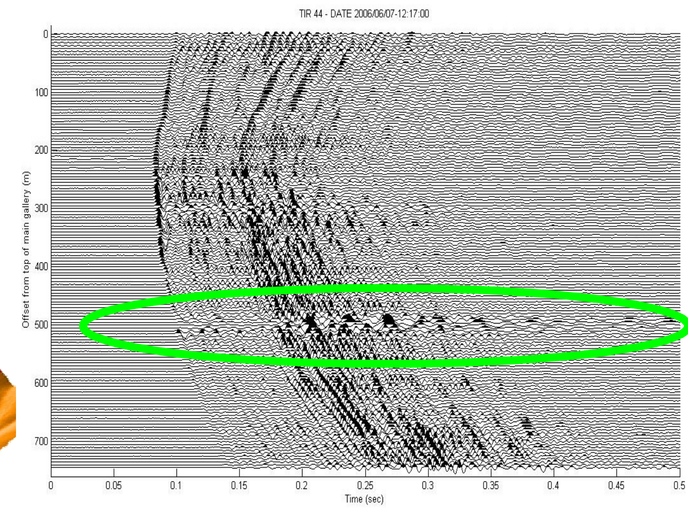
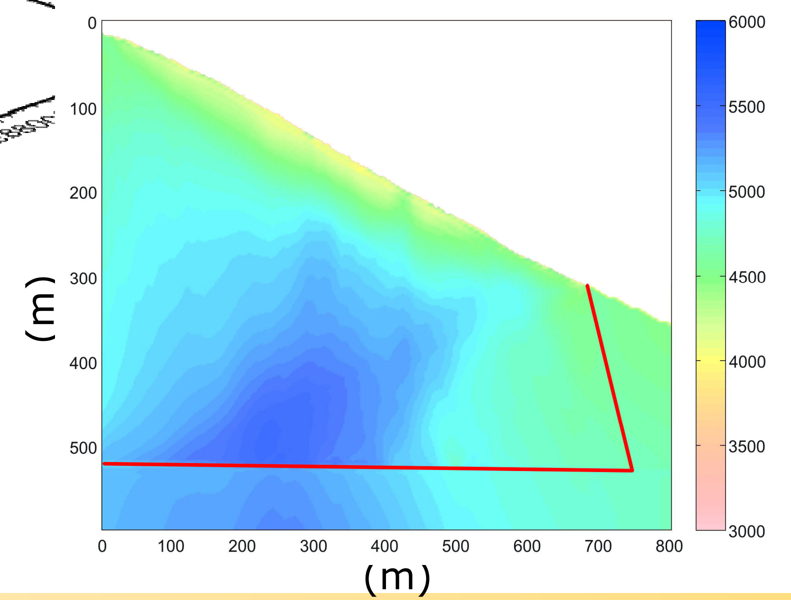
Size: 189 seismometers
Gallery: 150 geophones
103 shots (150 g TNT)





Maufroy et al. (2008)



- Area of high attenuation (geological faults?)
- Low speed (green) very porous limestone (> 7%)
- High-speed (Blue) Compact Limestones

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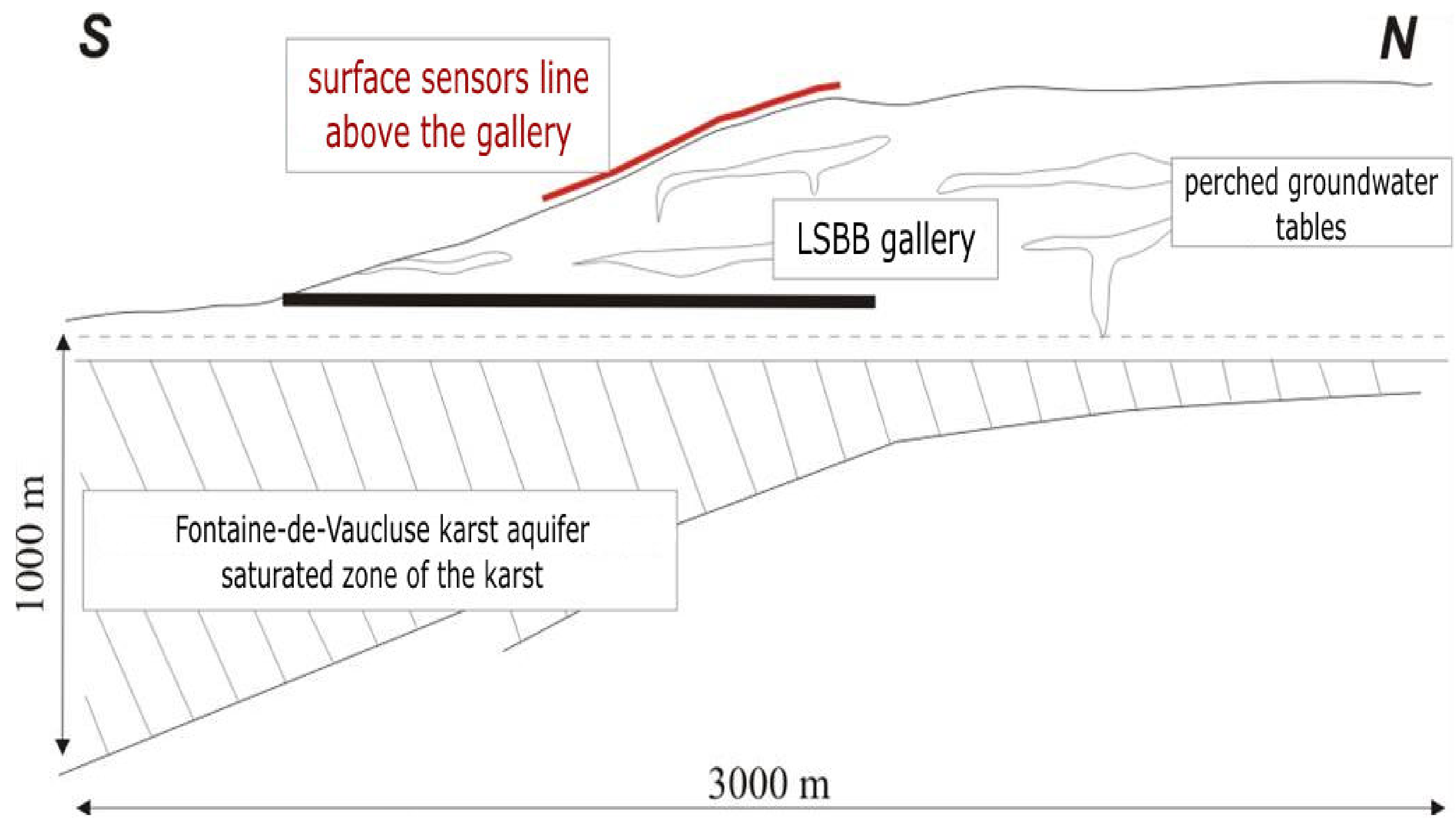
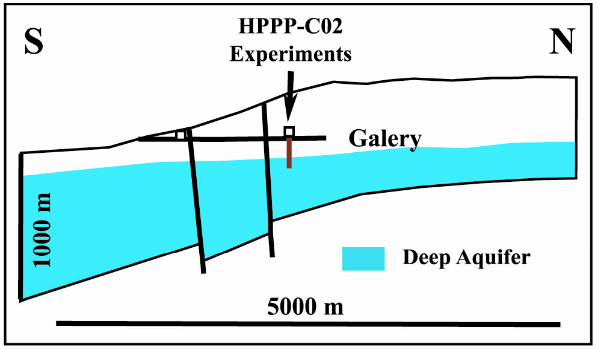


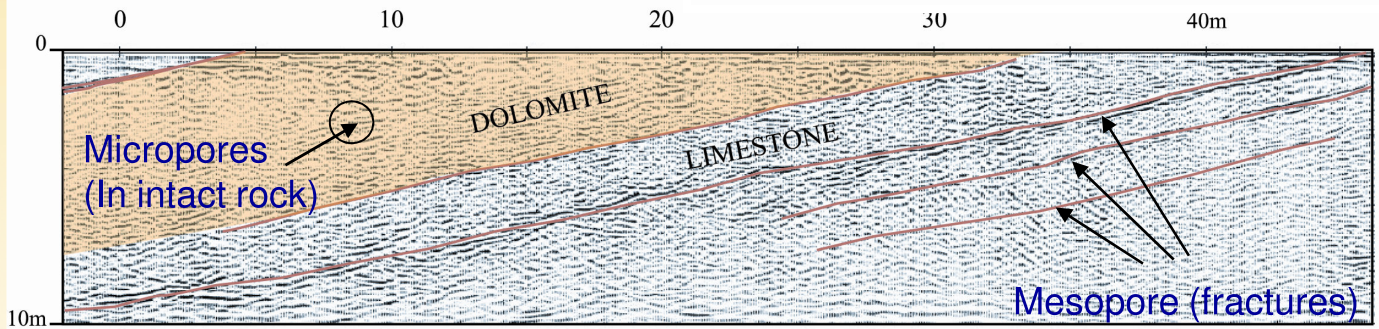
IMAGERIE DE LA DYNAMIQUE DES PROCESSUS PORO-ELASTIQUES

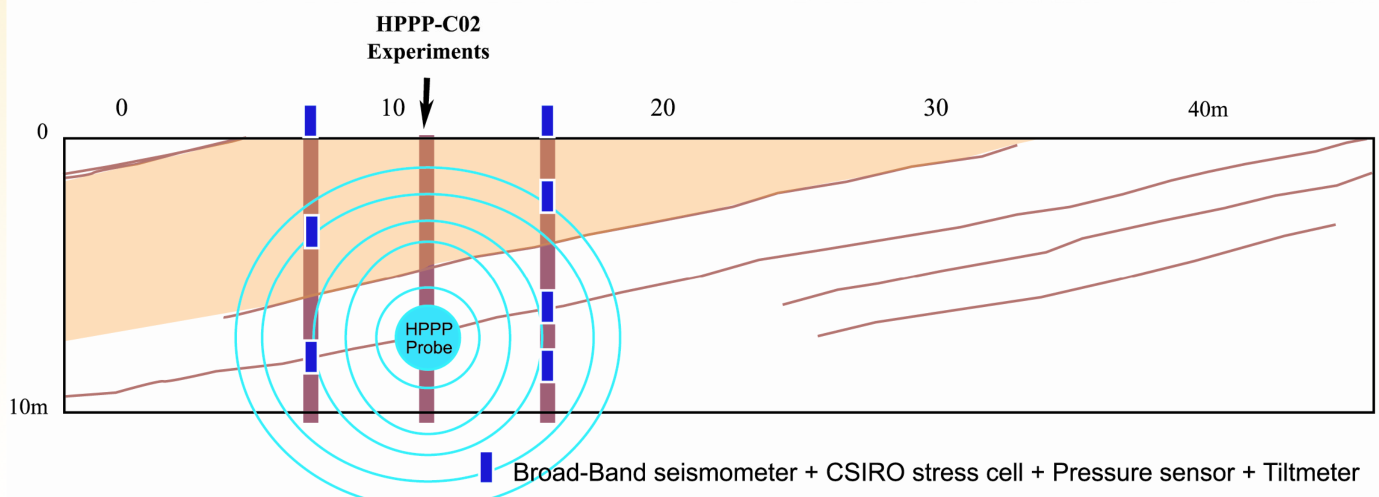
dans un milieu fracturé, partiellement saturé avec une porosité mésoscopique

Coll. ANR HPPPCO2 (in situ), ANR 2008 MAXWELL (EM), ANR 2009 LINES (Gravimétrie)



Projets associés thématiquement ANR HPPPCO2, MAXWELL et LINES. Investigation in-situ en forage de la réponse poro-élastique du milieu aux injections fluide (échelle métrique) – Imagerie EM en galerie et variation de la permittivité (pénétration 10-50m) – Variation du champ de pesanteur suivant l'infiltration météorologique (échelle 100-1000m)





METROLOGICAL DEVELOPMENTS

The High Pulse Poroelasticity Protocole (HPPP)

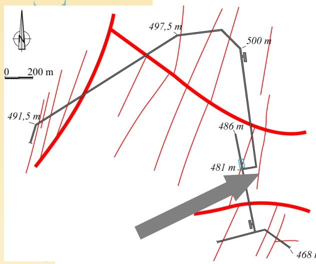
PI Y. Guglielmi – **Coll.** GSRC, Géosciences Azur, LBL, Standford

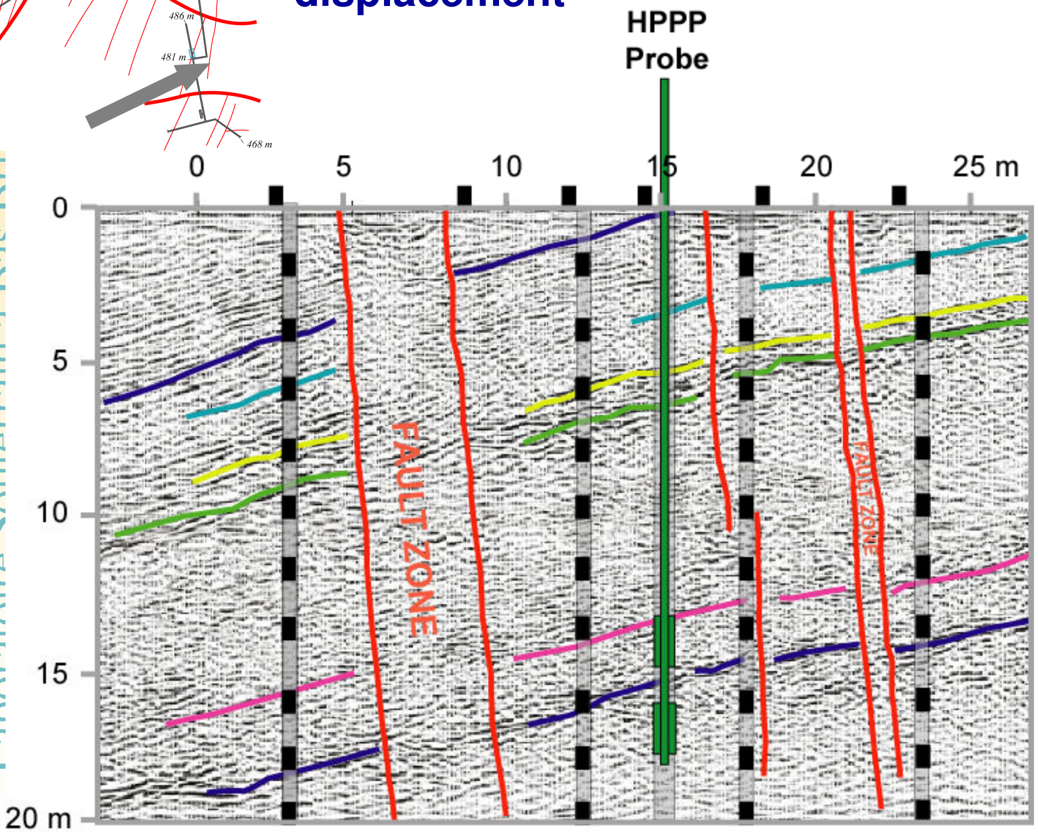
ANR HPPPCO2 (http://hppp.unice.fr/)

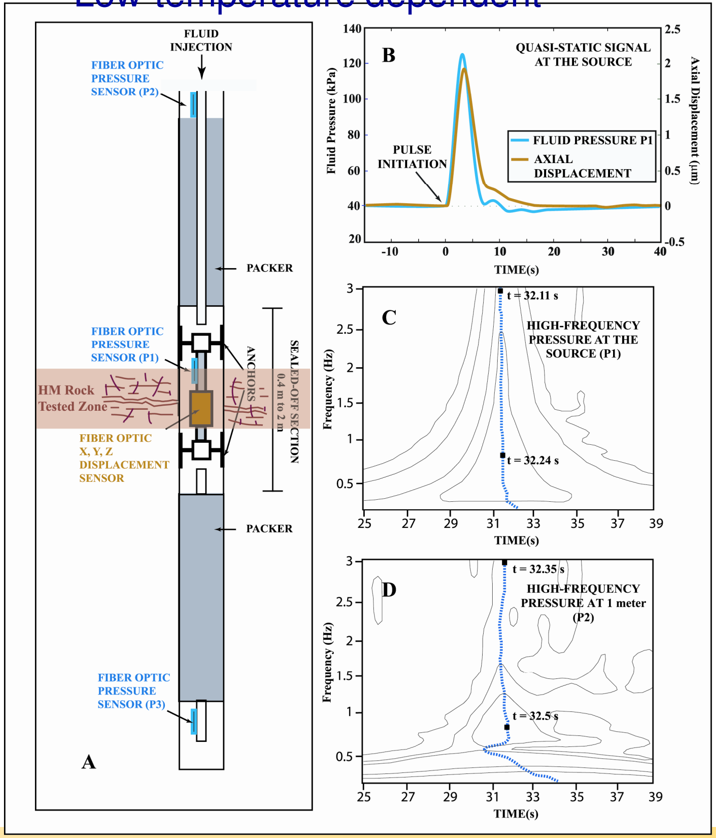
Development of innovative protocol for synchronous measurements of fluid pressure, mechanical displacement

Pulse Test:

Test duration: 0 - 20 secondes
Injected volume: 0 – 10 liters
Induced pressure: 0 – 20 MPa
Sampling frequency: 0.01 – 1 kHz
Accuracy : 10-7 m
Maximum depth operability: 1 km
Low-temperature dependent







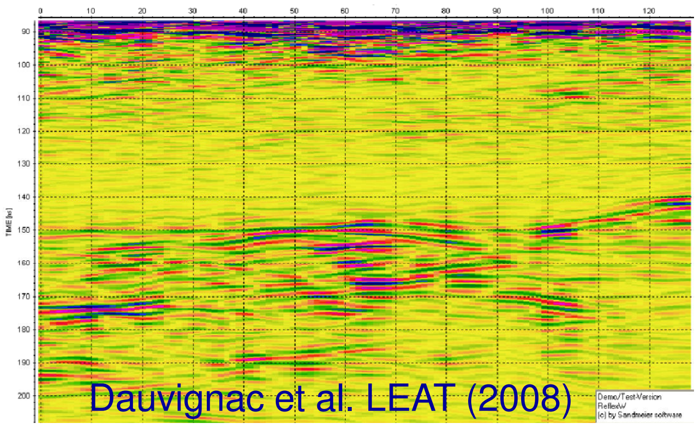
BROADBAND ELECTROMAGNETIC IMAGING

Methodology for imaging (broadband metrology, forward modelling & inversion)

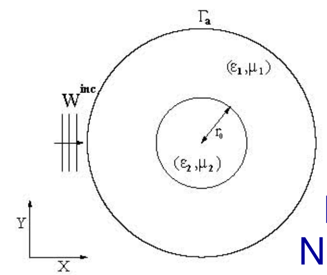
PI C. Pichot – **Coll.** LEAT**,** UBC, MIGP, Géosciences Azur, INRIA

ANR MAXWELL (http://leat.unice.fr/pages/anr-maxwell/anr-maxwell.html)

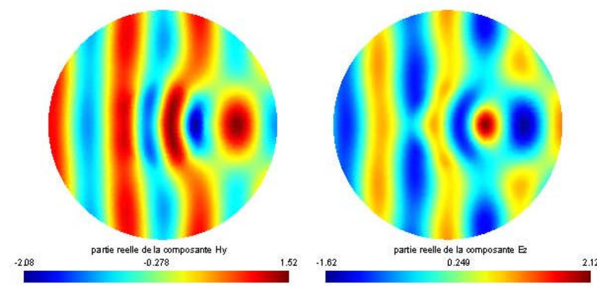
Ultra-wideband (0.1-2 GHz), bistatic, multipolarization, wide offset, microwave data acquisition, microwave imaging, and inversion for permittivity

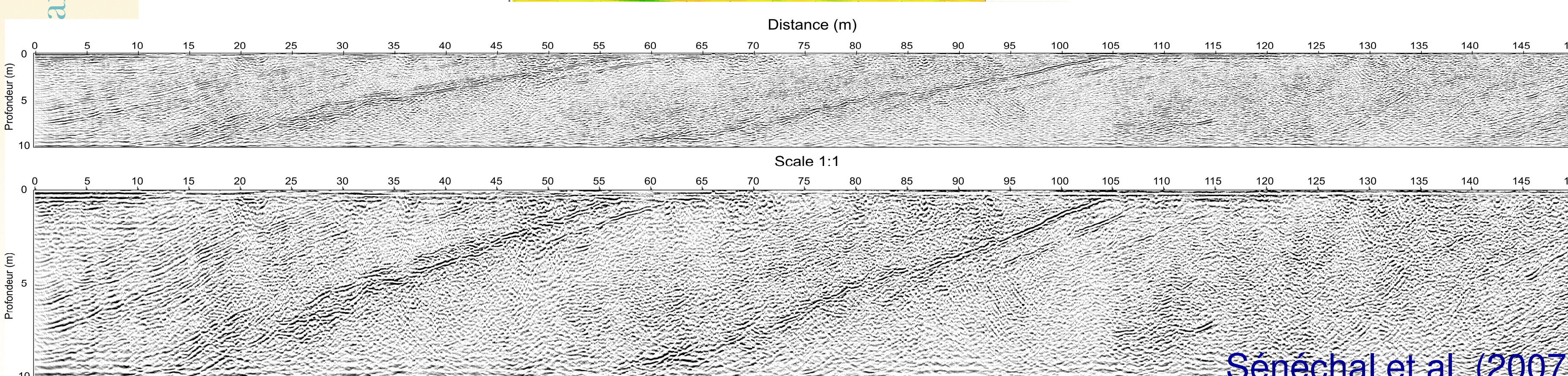


Dauvignac et al. LEAT (2008)



El Bouajaji, Nachos/INRIA (2008)





Séneschal et al. (2007)

Section radar 250 Mhz migrated (V=8,2 cm/ns, 82000 km/s) - Scale 1:2

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CONCLUSION / DISCUSSION

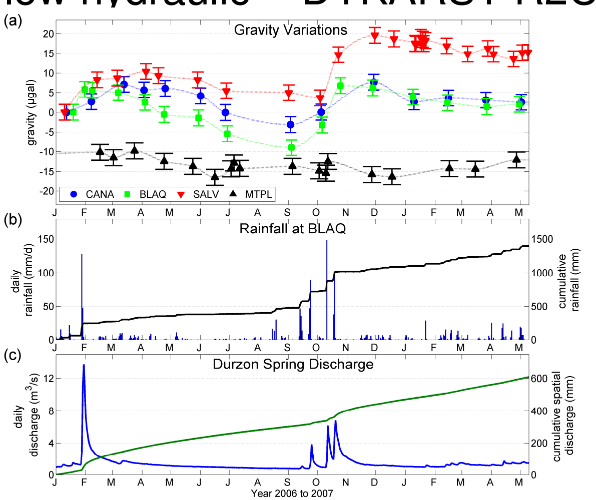
An interdisciplinary association for the realization of a new measure Geoscience in the knowledge of mechanical properties of subsurface

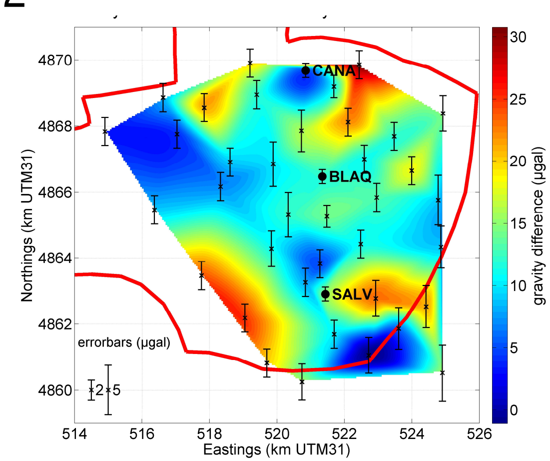
Muoscopy : Measurement of spatio-temporal density $\rho(t)$
Geology : Atomic description of the geology
RESULT : Tomography densitometry (simulation + inversion) (ρ)

Sismic : Velocimetric Mapping seismic waves (α, β)
Tomography ρ : Mapping tomography densitometry of the medium (ρ)
RESULT : Mechanical solid state $\Rightarrow$ E & ν

Hydro-geology : Quantification of water flow
Gravimetry : Gravity Modeling spatio-temporal distribution of masses
Tomography ρ : Mapping tomography densitometry of the medium (ρ)
RESULT : Dynamic flow hydraulic - DYKARST-R2C2

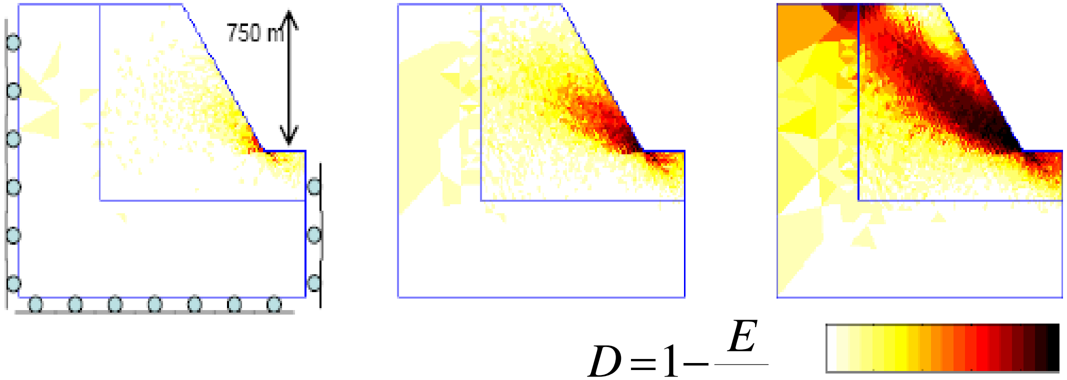
Economic recovery with industrial partners :
- ANDRA
- Association française des tunnels et de l'espace souterrain (AFTES)





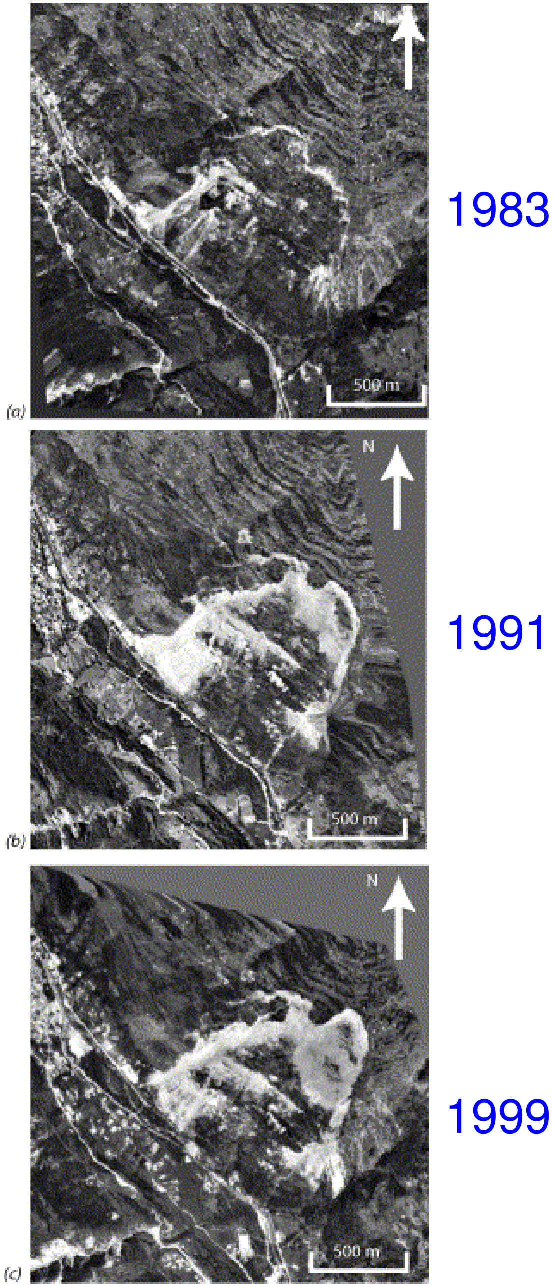
Jacob et al. (2008) Merlet et al. (2008)

How damage affects mechanical propreties vs depth and time



$$D = 1 - \frac{E}{E_0}$$

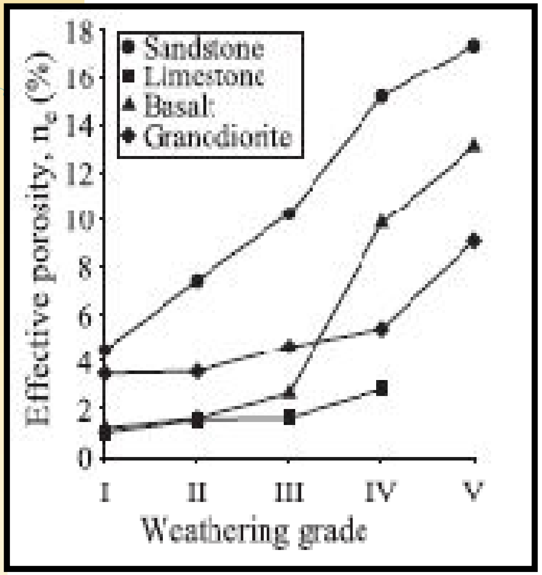
[Amitrano, 2005]

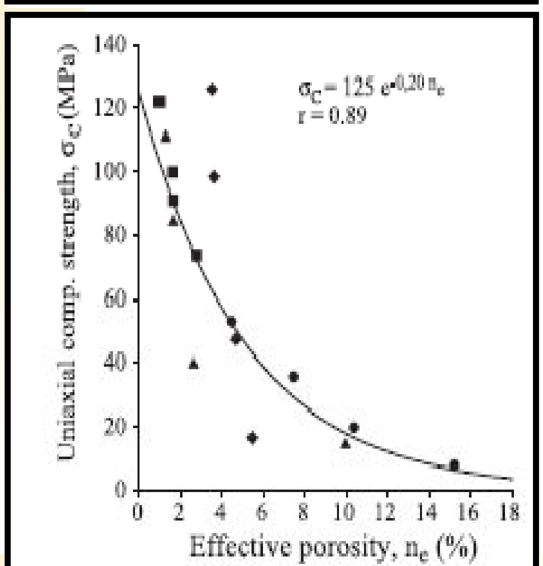


[Casson et al., 2003]

How weathering affects mechanical propreties vs depth and time

- Effects on compressive strength





[Tùgrul, 2004]

- Effects of weathering and hydrothermal alteration on granite

Weathering grades	UCS [MPa]	TS [MPa]	E [GPa]	UCS/SPZ [-]	W_d [kJ/m³]	D_d [g/cm³]	P [%]	φ [°]	c [kN/m²]	
VI - 7 Residual soil	Not possible to obtain data					1.3 - 1.8	50 - 30	40° - 30°	35 - 15	
V - 6 Completely weathered	Not possible to obtain data					1.8 - 2.3	30 - 13	30° - 20°	20 - 10	
IV - 5 Highly weathered	0.5 - 25	0.05 - 2 (estimated)	10 - 20 (estimated)	5 - 12 (estimated)	10 - 100 (estimated)	2.3 - 2.52	13 - 5	20° - 10°	50 - 25	Joint only!
III - 4 Moderately weathered	25 - 50	2 - 5	20 - 30	8 - 10	50 - 100	2.50 - 2.56	6 - 3.5	20° - 10°	50 - 25	Joint only!
II-III - 3 Slightly - moderately weathered	50 - 120	5 - 15	30 - 40	10 - 12	100 - 150	2.54 - 2.58	4.5 - 2.5	Not possible to obtain data		
II - 2 Slightly weathered	120 - 250	10 - 25	40 - 60	12 - 25	150 - 550	2.58 - 2.62	2.5 - 1	Not possible to obtain data		
I - 1 Fresh rock mass	No obtained data					2.62 - 2.64 (estimated)	1 - 0.5 (estimated)			

Soil material

Rock material

[Thuro & Scholtz, 2004]

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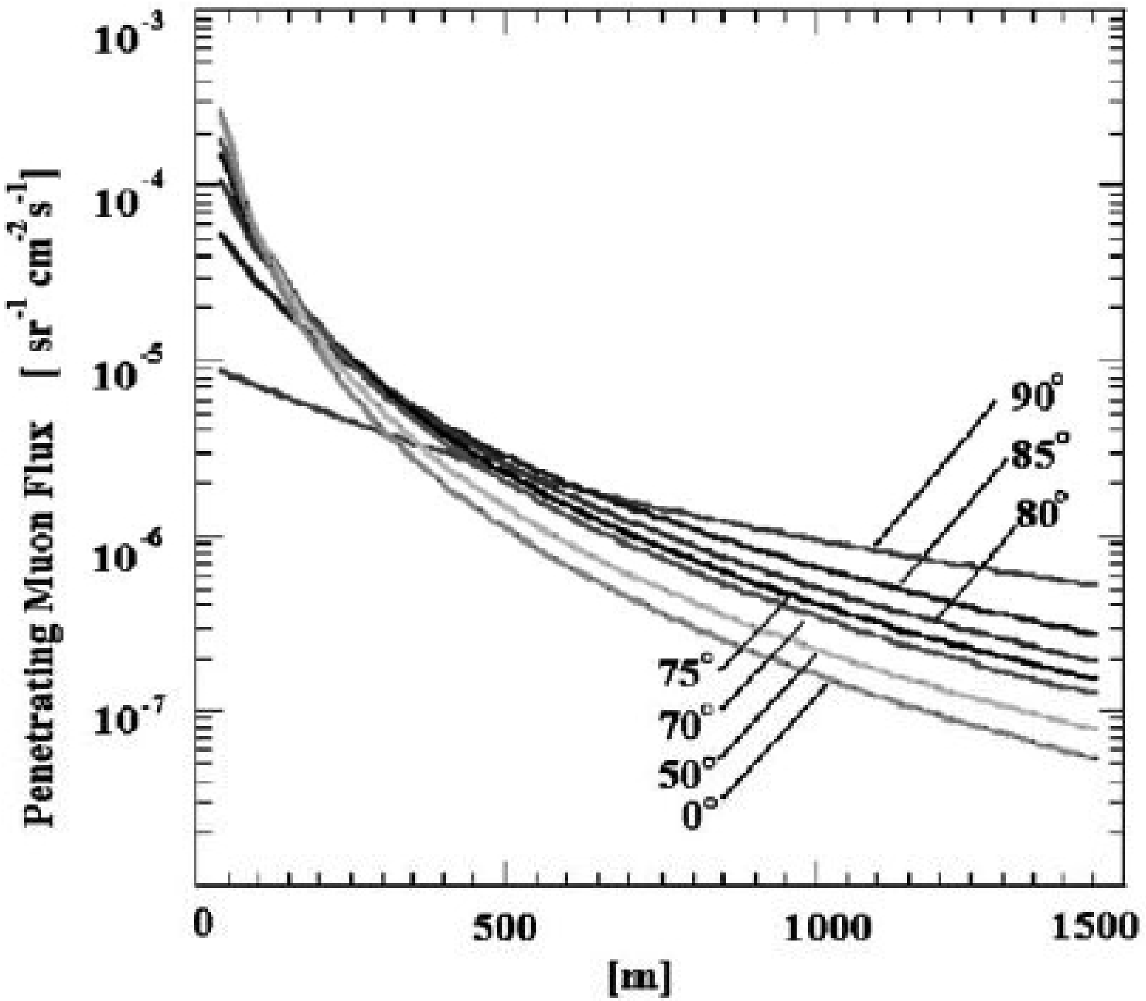

Fig. 1. Integrated flux of cosmic-ray muons at various angles penetrating through a given thickness of rock (*m*) with a density of 2.5 g/cm^3, as obtained with Eqs. (1) and (2). The vertical axis of Ref. [1] was corrected.

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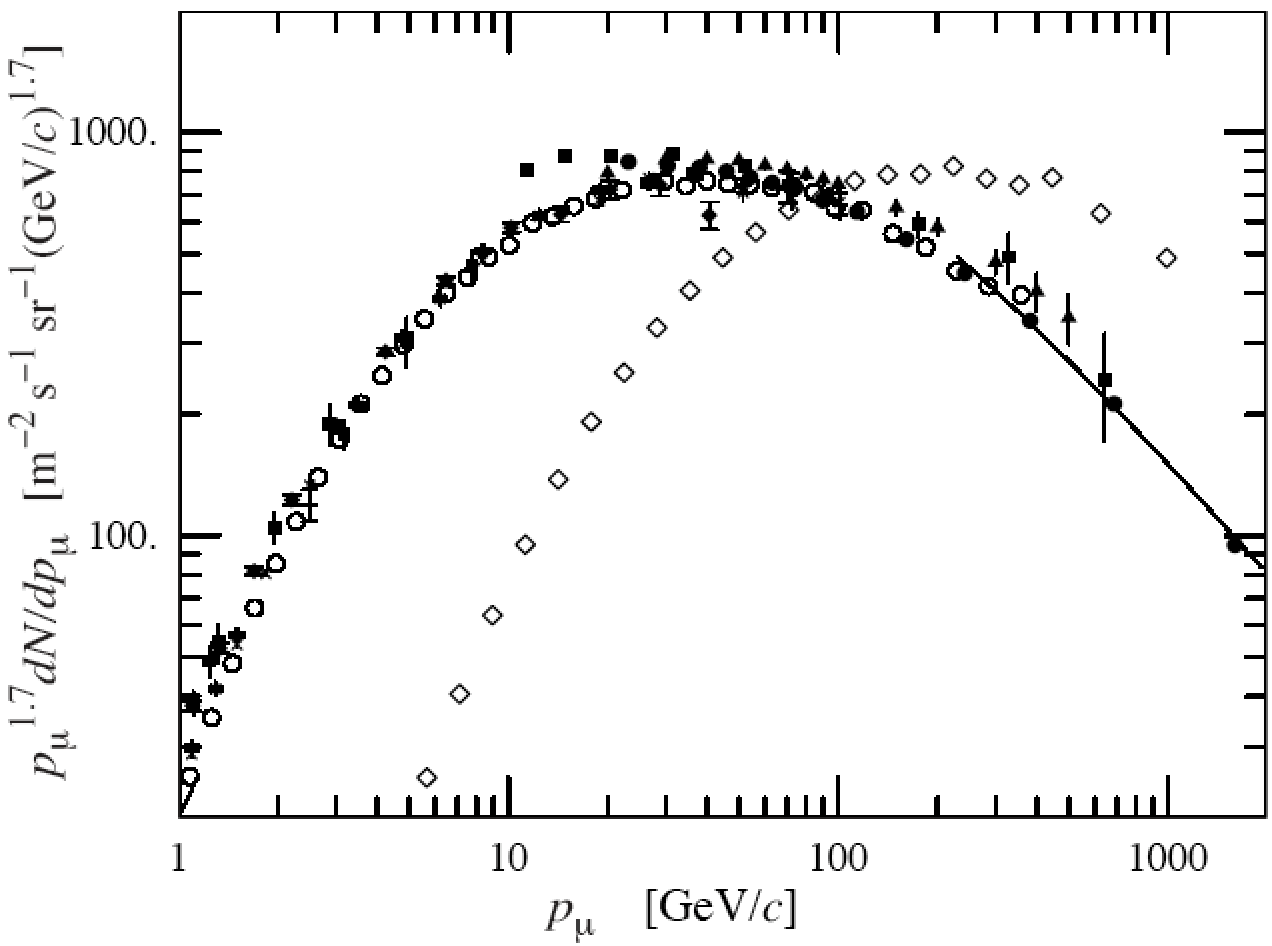
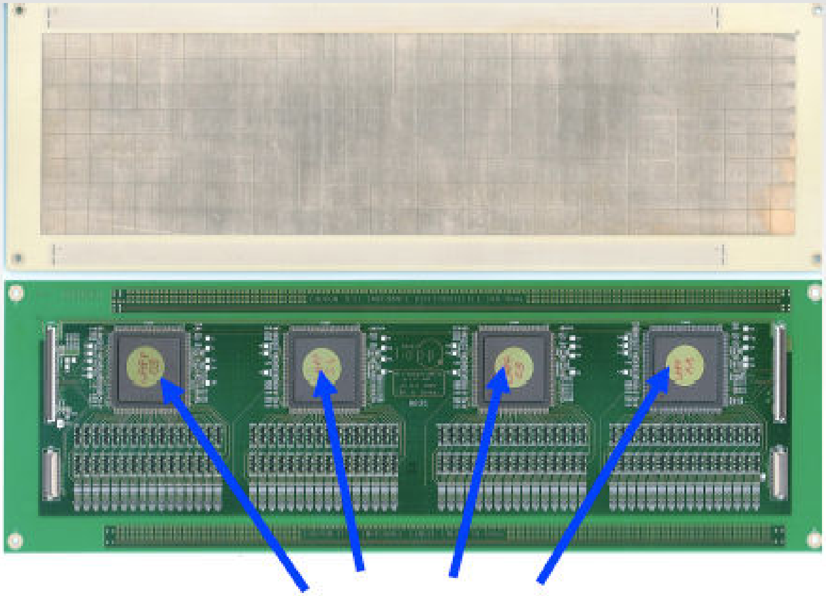


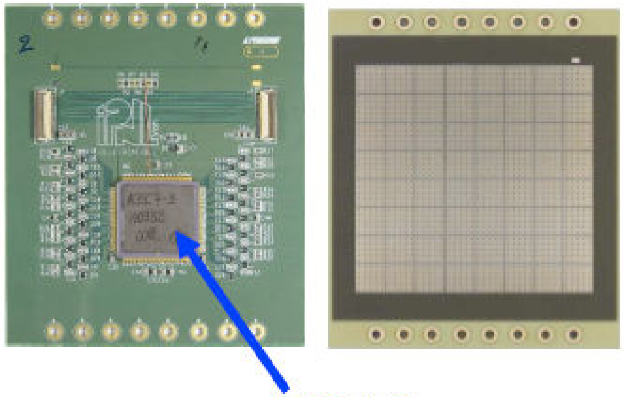
HARDROC 1 (2) (LAL)

- Analog and digital readout
- 1 chip (16 mm², 19 mm²) - 64 channels
- 2 (3) thresholds in 10 bit precision
- Digital memory for 128 events
- Gain - 10 fC to 1 pC (5 pC to 10 pC)
- Low consumption - < 10 μW/channel



DIRAC (IPNL)

- Digital readout
- 1 chip (7 mm²) - 64 channels
- 3 thresholds in 8 bit precision
- Digital memory for 8 events
- 2 gains - 3 fC to 200 fC
  (100 fC to 10 pC)
- Low consumption - < 10 μW/channel



Ensemble de développement et d'acquisition HARDROC

à droite en bas, 4 HARDROC au dos d'une µMégasBulk

DIF board (LAPP):

- Independent board to have more flexibility
- It provides the communication with PCs and HARDROCs (DIRACs) through the intermediate board (InterDIF)
- It allows ASICs configuration and performs analog and digital readout
- Also compatible with SPIROC and SKYROC