MONITORING OF NATURAL AND INDUCED SEISMICITY AT NATURAL GAS UNDERGROUND STORAGE FACILITIES

- Christophe Maisons (Magnitude)
- Jacques Grappe (Géostock)

Magnitude
A Baker Hughes & CGG Company

geostock

Outline

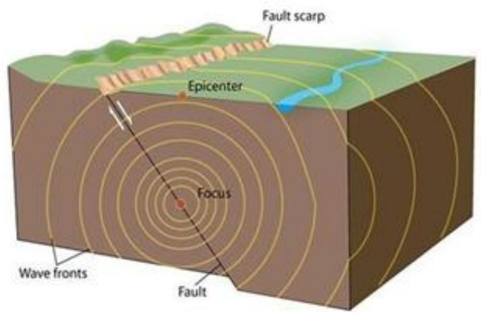
1. INTRODUCTION
2. BACKGROUND INFORMATION
3. SEISMIC MONITORING
4. CASE STUDIES - NATURAL GAS UGS
5. CONCLUSION

Range of seismicity

INTRODUCTION

A large range of seismic events

Natural and human activity related



- **Natural seismic events:**
  - Sumatra 2004 : magnitude 9.1-9.3
  - Coast of Honshu (Japan) 2011 : magnitude 9.0
  - Fukushima aftershock 2011 : magnitude 7
  - Aquila (Italy) 2009: magnitude 6.3
  - Kefalonia (Greece) 2014: magnitude 6.4

  ~14,450 earthquakes with magnitudes above 4.0 are measured globally every year.

  This number increases to more than 1.4 million earthquakes greater than M 2.0 (very small events most of which are only detected by instruments).

- **Events related (or suspected to be related) to subsurface human activity**
  - Lacq F (Gas Production) 2013: magnitude 4
  - Basel CH (Ehanced Geothermal System) 2009: magnitude 3
  - *Prague Oklahoma US (Water injection) magnitude 5.7*
  - *Blackpool UK (Gas Shale) 2011: magnitude 2.3*
  - *Castor Spain (Offshore Gas storage) 2013: magnitude 4.2*

  However, most of the induced seismicity are related to event magnitude below 1

  Industry has successfully dealt with induced seismicity issues for almost 100 years (mining)

Anthropogenic Seismicity

Induced / Triggered Seismicity

Two types of anthropogenic events :

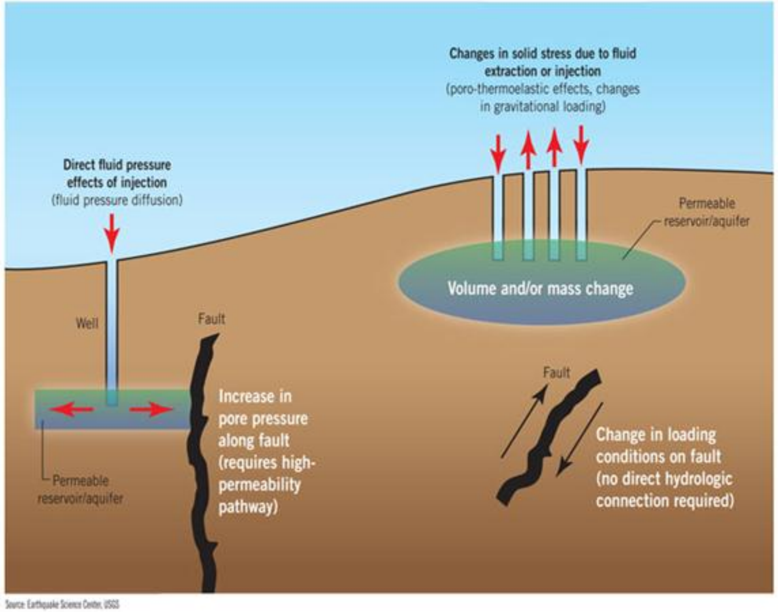
Induced Micro-seismic events, corresponding to an inherent part of the injection/production process. These are very small events considered as minor, not harmful and require very sensitive monitoring equipment to be detected. In this context, microseismic surveys are considered as means to understand the reservoir stimulated volume and/or the shear-enhanced permeability.

Seismicity can be useful as a resource management tool

Triggered earthquakes, resulting from injection or production of fluids interacting with existing geological faults. These lead to more significant ground accelerations, potentially felt by humans at the ground surface. The unintended events are connected to circumstances that could be avoided through site selection, injection design and permanent monitoring.

Seismicity must be addressed as a risk mangement tool.

Mechanisms for inducing, triggering Earthquakes



Schematic diagram of mechanisms for inducing earthquakes (B. Ellsworth)

In addition to the subsurface stresses, fluid volume and pressures play a key role in causing seismicity.

Thus, induced seismicity can be caused by injecting fluid into the subsurface or by extracting fluids at a rate that causes subsidence and/or slippage along planes of weakness in the earth.

Induced/Triggered seismicity

A few features

- An induced or triggered event, like a natural earthquake, occurs when a fracture or fault plane moves and releases energy.
- Induced seismicity generally releases a relatively small amount of energy, not entailing human perception (this explains why such events often go undetected when not monitored by a site specific microseismic monitoring network), but in some cases may trigger a higher level of stress release and be felt by the neighboring communities.
- A significant fault plane and specific pre-existing seismo-tectonic conditions are necessary to generate a large magnitude Earthquake. For a given seismo-tectonic context, a maximum natural earthquake likely to occur can be assessed. The characteristics of this maximum earthquake depend on the stress conditions (compressional, extensional ..) and the existence of potential “capable faults” (pre-existing geologic fault along which it is mechanically feasible for sudden slip (i.e., earth motion) to occur during the lifetime of a project under consideration).
- ***An induced or triggered earthquake cannot be higher than the maximum natural earthquake occurring on the capable faults of the area.***

Seismicity & Microseismicity

Feedback from few field experiments

Type of project	Seismicty		
	Induced events Injection/production process (Stimulation scale)	Triggered events on mappable faults (Reservoir scale)	Natural seismicity Tectonic context (Regional scale)
Hydraulic Fracturing			
Gas Shale US	[-3; -1.5]	Mw 2,3 Blackpool	NA
UGS – CCS			
Cerre-la-ronde & Germigny (F) - UGS (Aquifer)	[-2.5 ; -1.5]	NA	NA
Manosque (F) – UGS (Salt caverns)	[-2; 0.5]	NA	3.5
Weyburn (CDN) - CCS	[-3 ; -0.8]	??	NA
Rousse (F) – CCS	[-3 ; -0.8]	[-1 ; 1]	> 5
In-Salah (Algeria) - CSS	??	[-1 ; 1]	
Castor (S) - UGS (depleted field)	??	4.2	NA
Depleted field – EOR			
Lacq (F) – Withdrawal	[-3 ; 0]	Up to 4	> 5
Bergemeer (NL) – Withdrawal	[-2.5; 0]	Up to 3.5	NA
Groningen (NL) - Withdrawal	[-2.5; 0]	Up to 3	NA
Ekofisk (North Sea - UK) – Secondary Recovery	[-2.5; 0]	Up to 4	NA
../..			

Earthquake & Microseismic Domains

Seismological scaling law

Magnitude range / Microseismic domain

Magnitude range	Class	Length Scale	Displacement Scale
8 – 10	Great	100-1000km	4-40m
6 – 8	Large	10-100km	0.4-4m
4 – 6	Moderate	1-10km	4-40cm
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0 – 2	Micro**	10-100m	0.4-4mm
-2 – 0	Nano	1-10m	40-400μm
-4 – -2	Pico	0.1-1m	4-40μm
-6 – -4	Femto	1-10cm	0.4-4μm
-8 – -6	Atto	1-10mm	0.04-0.4μm

Bohnhoff et al., ILP, 2010 - Length and displacement approx.

Earthquake Seismic Hazard Domain (magnitudes 2 – 10)

Induced Microseismicity Domain (magnitudes -4 – 2)

Accoustic Emission (AE) Lab Test Domain (magnitudes -8 – -4)

Most of the negative aspects associated with induced seismicity are associated with the impact of Earthquake on the surrounding community (Seismic hazard domain with magnitude > 2 & vibration felt on surface).

Positive effects of induced microseismicity, such as shear-enhanced permeability characterization or monitoring of the reservoir performance, have not yet significantly impacted the cost-benefit ratio of industrial operations.

Human induced, - triggered or natural Seismicity?

BACKGROUND INFORMATION

Anthropogenic Earthquake

7 questions to assess whether an Earthquake as an anthropogenic origin

Since 1993, seven generally accepted criteria must be met before fault reactivation is considered to have an anthropogenic origin

(*Davis and Frohlich,1993 – under discussion / revision)

1. Are these events the first known earthquakes of this character in the region?
2. Is there a clear correlation between injection and seismicity?
3. Are epicenters near the wells (within 5 km)?
4. Do some earthquakes occur at or near injection depths?
5. If not, are there known geologic structures that may channel flow to sites of earthquakes?
6. Are changes in fluid pressures at well bottoms sufficient to encourage seismicity?
7. Are changes in fluid pressures at hypocentral distances sufficient to encourage seismicity?

What is "Induced Seismicity"?

General definition LBNL

- *Induced seismicity is earthquake activity resulting from human activity that causes a rate of energy release, or seismicity, which would be expected beyond the normal level of historical seismic activity. For example, if there is already a certain level of seismic activity before human activities begin, one would expect that this "historical" seismic activity would continue at the same rate in the future.*
- *If, however, human activity causes a concurrent increase in seismic activity, this increase in seismic activity would be considered "induced."*
- *In addition, if the seismic activity returns to background activity after the human activity stops, that would be another sign that the seismic activity was induced.*

As defined by « Lawrence Berkeley National Laboratory »

Induced seismicity is the more colloquial term, but triggered seismicity is the more accurate term for earthquakes inadvertently cause by anthropogenic activities

Proposed Definitions *(modified from LBNL)*

Human induced, - triggered or natural seismicity?

Human-induced micro-earthquake:

- ✓ Causative activity accounts for most of the stress change or energy to produce the micro-earthquakes. Micro-earthquake would not have happened without human action.
- ✓ Rupture nucleation and propagation both controlled by induced stress field.

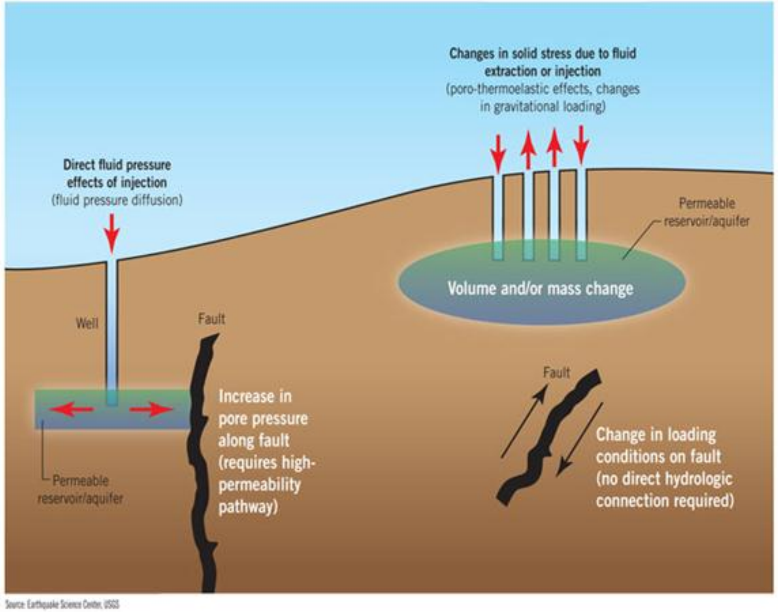
Human triggered earthquake:

- ✓ Causative activity accounts for only a small fraction of the stress change associated with the earthquakes. Earthquake occurrence advanced by human action.
- ✓ Nucleation triggered by human-induced stress, but rupture propagation driven by pre-existing tectonic stress rates. (Pre-existing tectonic stress play the primary role)

Natural earthquake:

- ✓ Both nucleation and rupture fully controlled / driven by tectonic stress rates.

Mechanisms for inducing, triggering Earthquakes



Schematic diagram of mechanisms for inducing earthquakes (B. Ellsworth)

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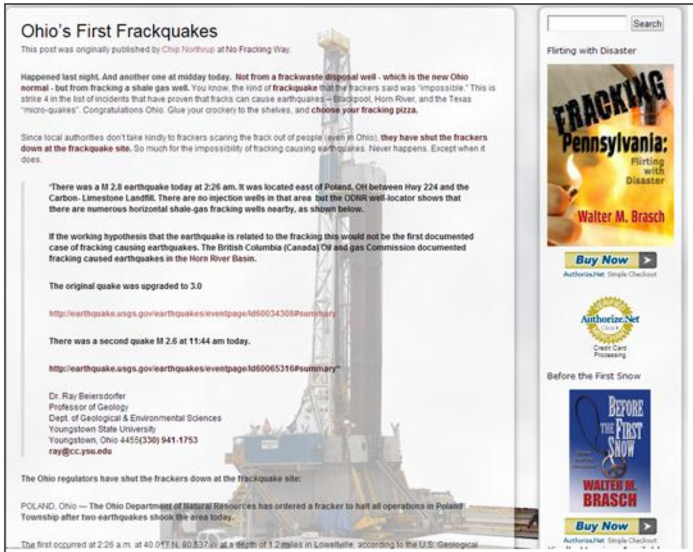
Induced/Triggered seismicity

What impact for the UGS industry?

- **Controversies and debates about shale gas and waste water injection have raised concerns among public and administrations about the risk of induced seismicity (and of seismic risk in general !)**



Ohio's First Frackquakes

This post was originally published by Chip Northrup at No Fracking Way.

Happened last night. And another one at midday today. Not from a frackwaste disposal well - which is the new Ohio normal - but from fracking a shale gas well. You know, the kind of frackquake that the frackers said was "impossible." This is strike 4 in the list of incidents that have proven that fracks can cause earthquakes – Blackpool, Horn River, and the Texas "micro-quakes". Congratulations Ohio. Glue your crockery to the shelves, and choose your fracking pizza.

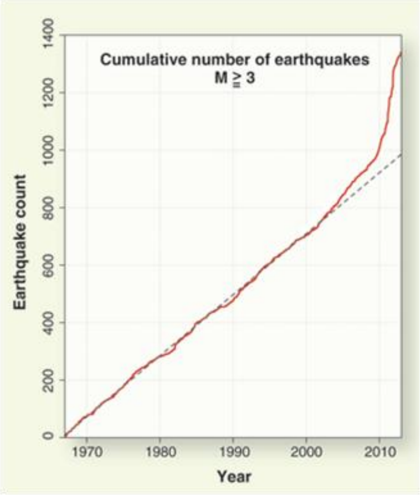
Since local authorities don't take kindly to frackers scaring the frack out of people (even in Ohio), they have shut the frackers down at the frackquake site. So much for the impossibility of fracking causing earthquakes. Never happens. Except when it does.

> "There was a M 2.8 earthquake today at 2:26 am. It was located east of Poland, OH between Hwy 224 and the Carbon- Limestone Landfill. There are no injection wells in that area but the ODNR well-locator shows that there are numerous horizontal shale-gas fracking wells nearby, as shown below.
>
> If the working hypothesis that the earthquake is related to the fracking this would not be the first documented case of fracking causing earthquakes. The British Columbia (Canada) Oil and gas Commission documented fracking caused earthquakes in the Horn River Basin.
>
> The original quake was upgraded to 3.0
>
> http://earthquake.usgs.gov/earthquakes/eventpage/id60034308#summary
>
> There was a second quake M 2.6 at 11:44 am today.
>
> http://earthquake.usgs.gov/earthquakes/eventpage/id60065316#summary"
>
> Dr. Ray Beiersdorfer
> Professor of Geology
> Dept. of Geological & Environmental Sciences
> Youngstown State University
> Youngstown, Ohio 4455(330) 941-1753
> ray@cc.ysu.edu

The Ohio regulators have shut the frackers down at the frackquake site:

POLAND, Ohio — The Ohio Department of Natural Resources has ordered a fracker to halt all operations in Poland Township after two earthquakes shook the area today.

The first occurred at 2:26 a.m. at 40.017 N, 80.537 W at a depth of 1.2 miles in Lowellville, according to the U.S. Geological



Injection-Induced Earthquakes
William L. Ellsworth

Earthquakes with magnitude (M) ≥ 3 in the U.S. midcontinent, 1967–2012.

After decades of a steady earthquake rate (average of 21 events/year), activity increased starting in 2001 and peaked at 188 earthquakes in 2011.

Human-induced earthquakes are suspected to be partially responsible for the increase.

- **Because the UGS industry hardly never experienced large magnitude induced seismic events, this risk was probably until a recent past underestimated by the storage operators**
- **If not addressed properly induced and triggered seismicity could unduly delay or cancel important energy applications**

Induced/Triggered seismicity

What impact for the UGS industry?

- **The risk related to <u>natural seismicity</u> (perceived as an external risk factor) is since long years both established, <u>considered and addressed</u> at the design and construction stage (and reassessed on a regular basis)**

- **The risk related to <u>induced seismicity</u> was until recently more <u>rarely considered</u>. R&D studies triggered by sequestration projects involving injection of massive quantities of CO2 into aquifers or strongly depleted Oil & Gas reservoirs and by the related risk assessment studies, contributed to develop knowledge and consideration of induced seismicity**

- **After the <u>Castor crisis</u> it is to be expected that <u>the question of induced seismicity will arise</u> for new projects but also for existing UGS; and the UGS Industry must be prepared to face that event**

What can be done to improve this situation?

Addressing Induced/Triggered seismicity

Proposed workflow

1. **Perform a preliminary screening evaluation (regulatory and public scrutiny).**
2. **Characterise the seismo-tectonic context: geological context, structural context with identification of major structures and faults, identification of active (or capable) faults and natural seismicity (historical and instrumental).**
3. **Quantify the hazard from natural and induced seismic events.**
4. **Seismic monitoring:**
   1. Use of the pre-existing network (national or regional)
   2. Establish a local dedicated and adapted seismic monitoring network
5. **Characterise the risks (effect and potential consequences) of induced seismicity**
6. **Establish a contingency and a communication plan**

Induced/Triggered Seismicity

MICROSEISMIC MONITORING

Earthquake & Microseismic Domains

Seismological scaling law

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Microseismic Domain

AE Lab Test Domain

Induced Micro-Seismicity

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Reservoir surveillance

Fracture characterization

Microseismic event

From rupture, seismic radiation, wave propagation to event recording

Source

Radiated Seismic Energy

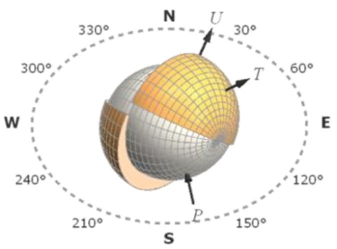
T0,X0,Y0,Z0,M0,τ a

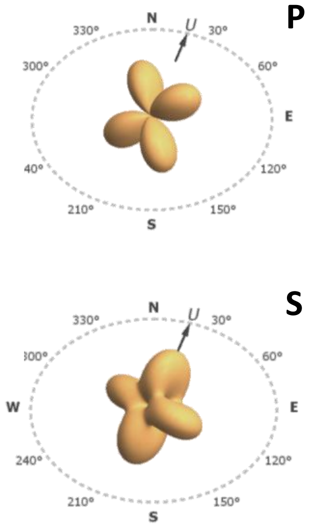
Failure mechanism

M0 -> ER

P and S

Radiation Pattern

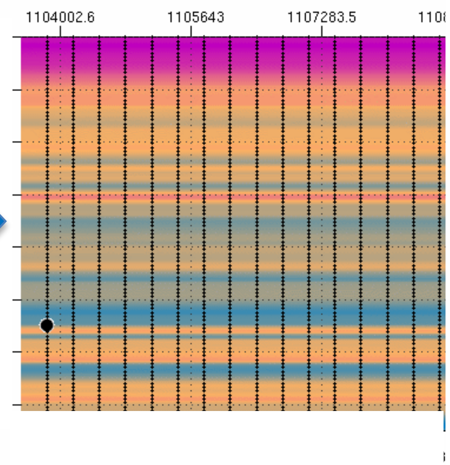




Propagation

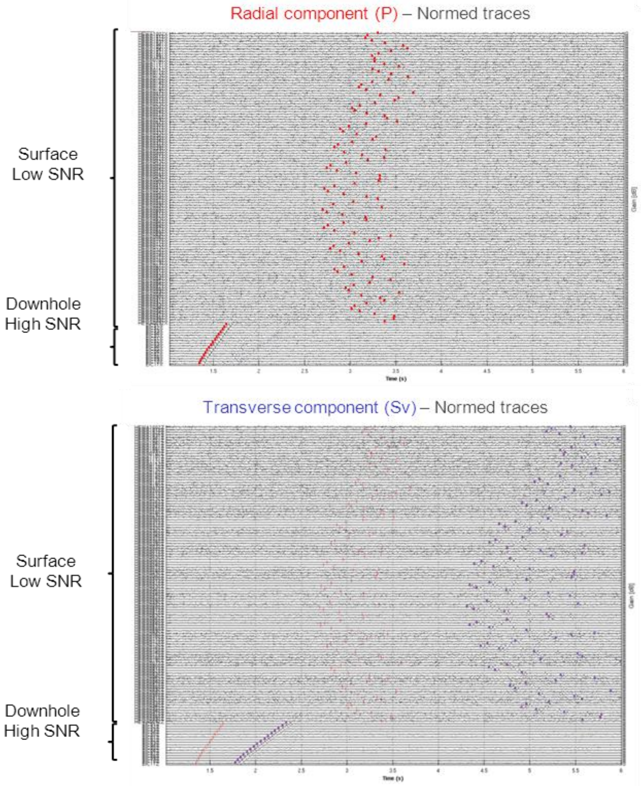
Geometrical spreading, wave scattering, anleastic attenuation..

P & S Seismic waves



Recording

Surface, downhole sensors



Microseismic Monitoring
Monitoring Technologies

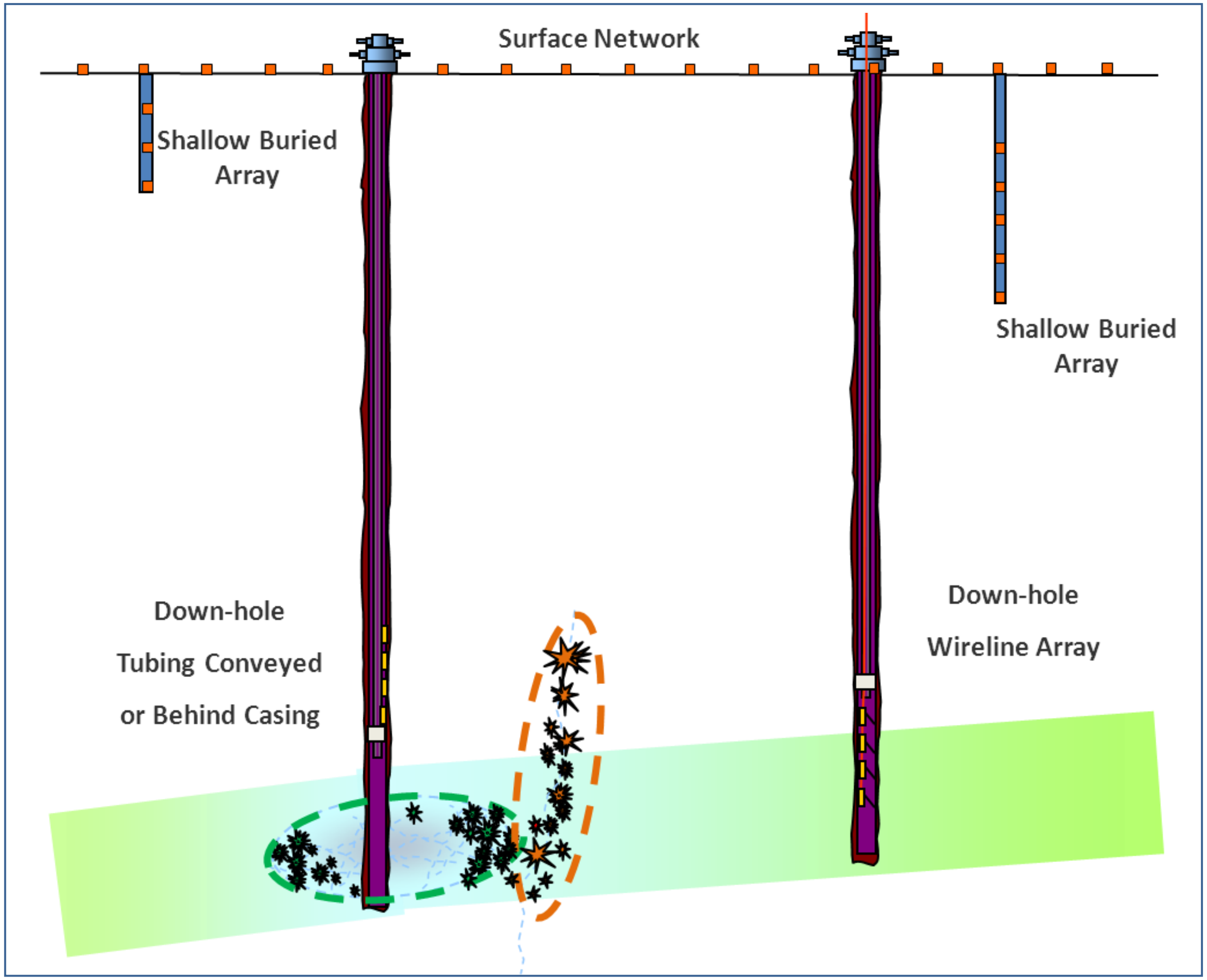
Typical frequency
- Micro-event: [0.1 -10 Hz]
- Nano-event : [10 – 1000Hz]

Type of sensors
- Velocimeter
- Accelerometer

Type of deployment
- Surface / Sea bottom
- Shallow buried array
- Observer well
- Live well

Type of network
- Sparse
- Dense
- Hybrid networks

Type of processing
- Vibration & spectral analysis
- Low SNR (Location)
- High SNR (Location)
- Focal Mechanism



Microseismic Monitoring

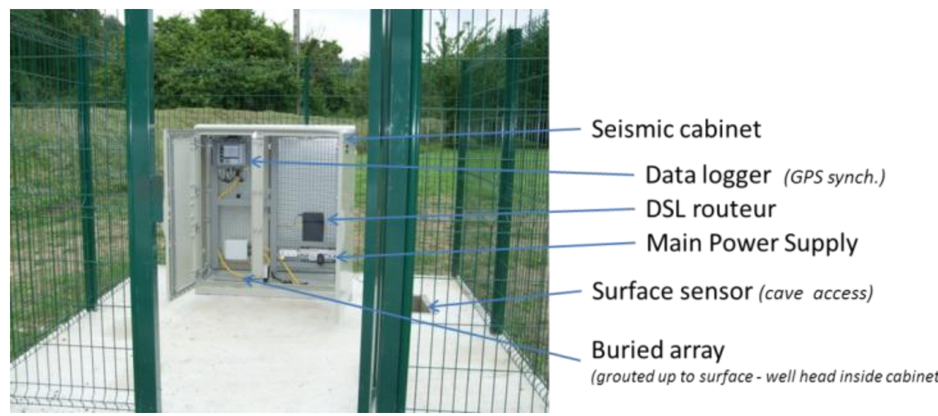
Monitoring System

Seismic sensors (Shallow well)

BroadBand Seismometer (surface)

Permanent deployment

Temporary deployment



Seismic & Microseismic monitoring

A tool of choice for the UGS Industry

- ✓ Complement the existing regional seismic array and gather information that may become relevant to any inquiry regarding claims associated to vibrations or structural damage.
- ✓ Improve the knowledge and understanding of natural and of triggered seismicity: detection above a given threshold, location of epicenters, event signature analysis, discrimination between natural and induced seismicity

- ✓ Check the absence of impact of events on the storage integrity.
- ✓ Early detect small events, if any, and provide data for understanding, interpretation and definition of mitigating actions as well as support to communication with the stakeholders.

- ✓ Additionally, recording of small events considered as minor, not harmful, microseismic activity (typically below magnitude 0) contributes to:
  - Identify relationship with storage movements and weakness areas if any
  - Monitor the response of the caprock to pressure cycling in the reservoir
  - Follow up the evolution of the gas bubble effects
  - Monitor stability of salt caverns : rock falls, dissolution of salt for cavern creation, salt pillar between adjacent caverns

Microseismic Monitoring

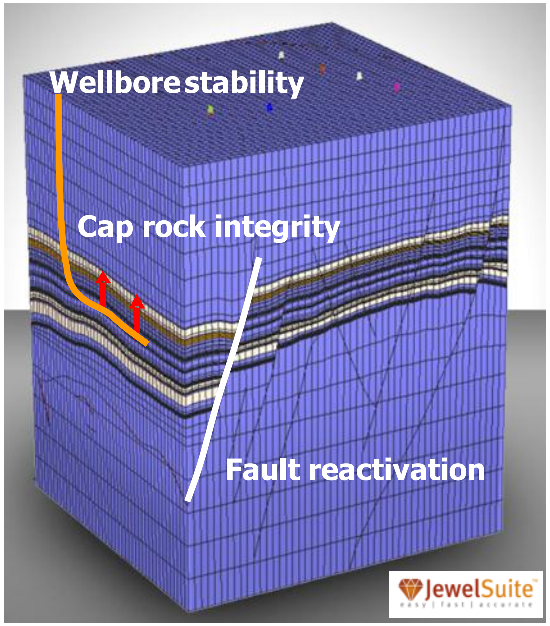
CASE STUDIES

Geo-hazard Surveillance

Business segment & Objectives

- **Segment**
  - Contingency monitoring
  - UGS & CO_2 sequestration

- **Objectives**
  - **Risk management, assess containment**
    - Identify active faults in reservoir
    - Early detect “fracture development”
    - Implement early warning system
  - **Insure integrity and sustainability of the field**
    - Identify active faults in overburden
    - Early detect “fracture development”
  - **Diagnostic system associated to Seismic hazard**
    - "traffic light" scheme established for halting operations in the event of unacceptable earthquake occurrences
    - Gather information that may become relevant to any inquiry regarding claims of structural damage



Seismicity & Microseismicity

Feedback from few field experiments

Type of project	Seismicty		
	Induced events Injection/production process (Stimulation scale)	Triggered events on mappable faults (Reservoir scale)	Natural seismicity Tectonic context (Regional scale)
Hydraulic Fracturing			
Gas Shale US	[-3; -1.5]	Mw 2,3 Blackpool	NA
UGS – CCS			
Cerre-la-ronde & Germigny (F) - UGS (Aquifer)	[-2.5 ; -1.5]	NA	NA
Manosque (F) – UGS (Salt caverns)	[-2; 0.5]	NA	3.5
Weyburn (CDN) - CCS	[-3 ; -0.8]	??	NA
Bayou Corne (USA) – UGS (Salt caverns)	[-2.5; 0.5]	2?	
Rousse (F) – CCS	[-3 ; -0.8]	[-1 ; 1]	> 5
In-Salah (Algeria) - CSS	??	[-1 ; 1]	
Castor (S) - UGS (depleted field)	??	4.2	NA
Depleted field – EOR			
Lacq (F) – Withdrawal	[-3 ; 0]	Up to 4	> 5
Bergemeer (NL) – Withdrawal	[-2.5; 0]	Up to 3.5	NA
Groningen (NL) - Withdrawal	[-2.5; 0]	Up to 3	NA
Ekofisk (North Sea - UK) – Secondary Recovery	[-2.5; 0]	Up to 4	NA
../..			

Gas Storage / Salt leached caverns

Gas storage in seismo-tectonic context

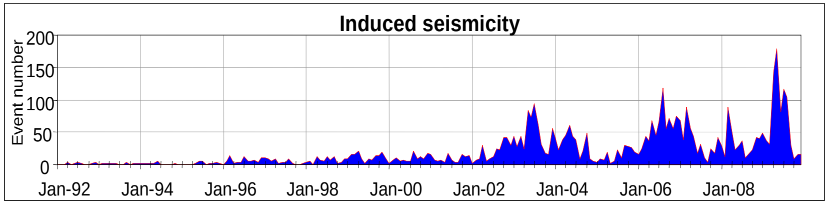
UGS Surveillance

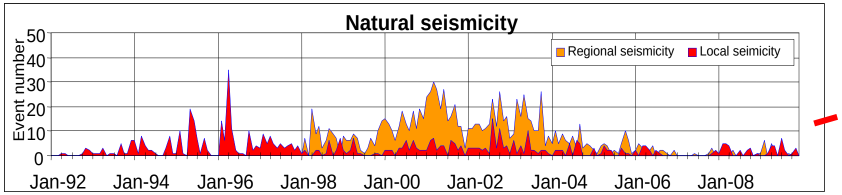
Surveillance Protocol

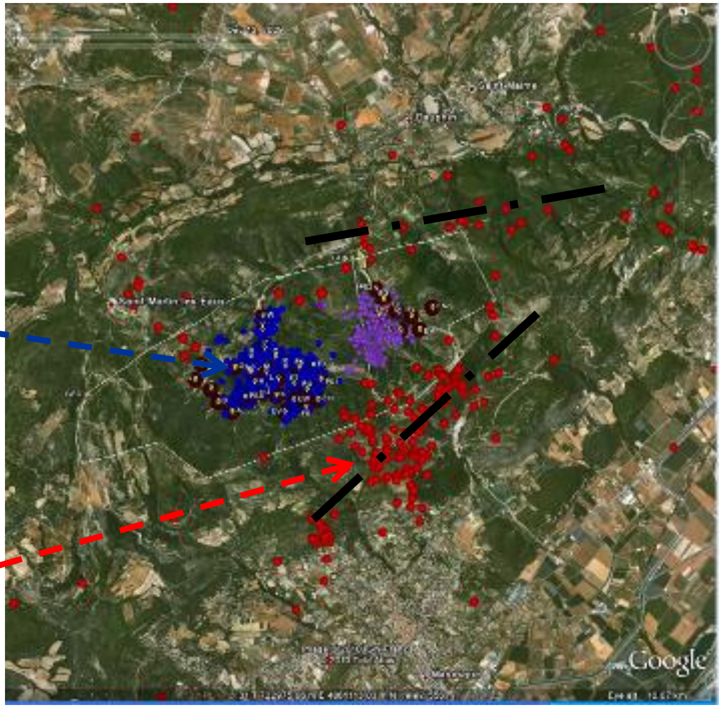
- Daily check
- Correlation with operation to alert on potential unexpected behaviour
- Correlation with seismological database
- « Watch » if seismicity & pressure anomaly
- « Watch » if event magnitude > 1
- « Watch » if critical microseismic migration
- « Warning » if event magnitude > 2

Event Clustering Analysis

- Intra-reservoir seismicity
- Seismicity at overburden interface
- Micro-seismicity along structural features (Reservoir scale)
- Seismicity associated to tectonic features (Regional scale)



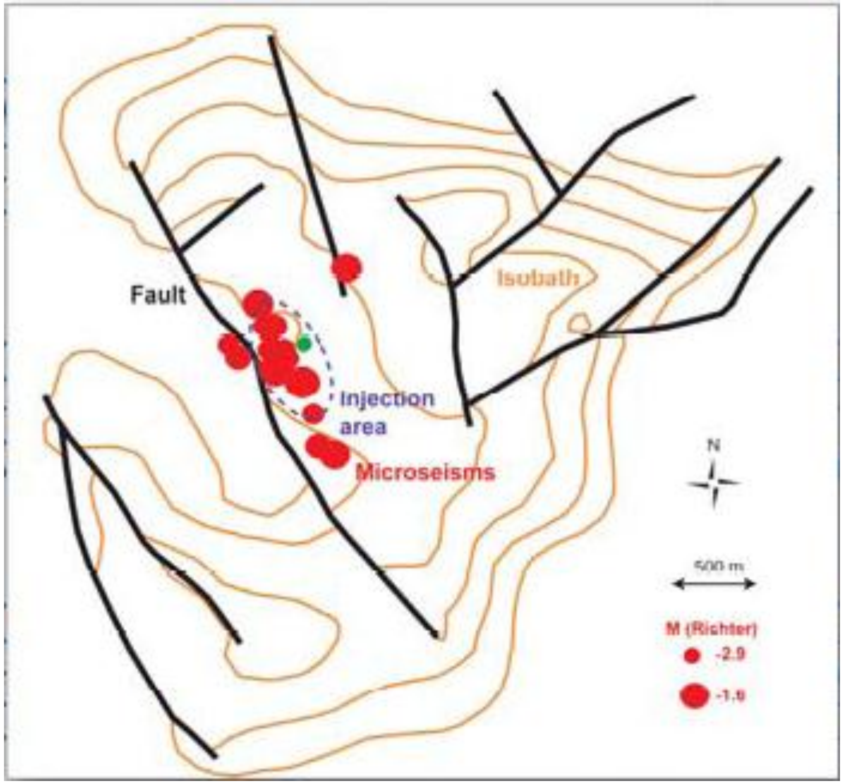




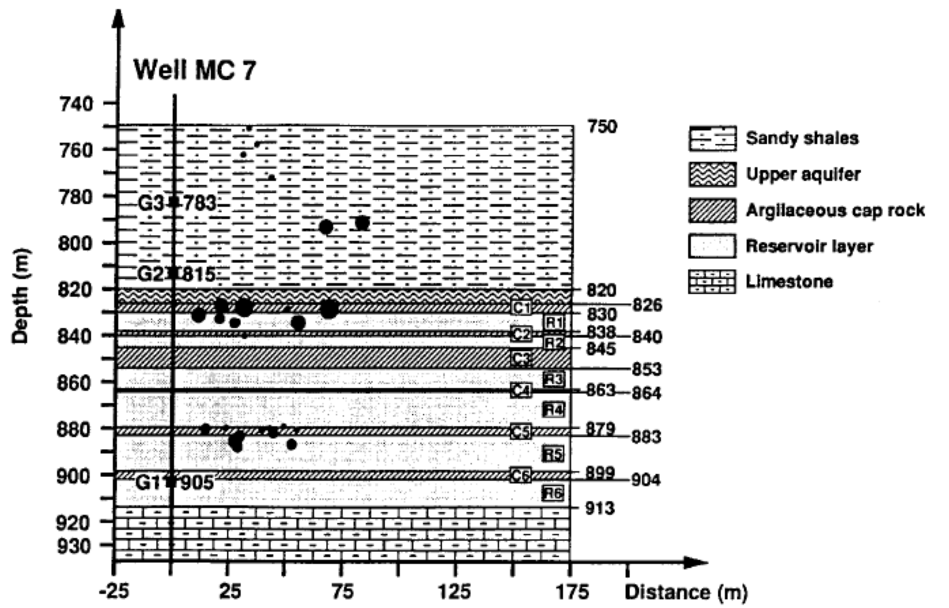
Gas Storage / Aquifer

Low injection rate / large volume – Cap rock integrity

Monitoring & Verification – Maximum injection pressure and cap-rock integrity pilot
Permanent downhole array (tubing conveyed)
Magnitude up to -1.5



IFP - Deflandre



Magnitude range [-2,5; -1,5]

Fig. 7: 2D location of microseismic events. G1, G2 and G3 are sensors (op. cit.)

Deflandre et al 1995 First Break Vol 13

CCS Pilot / Deep Reservoir

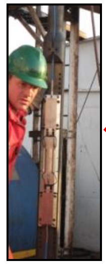
Depleted fractured reservoir – Confinement & Acceptability concern

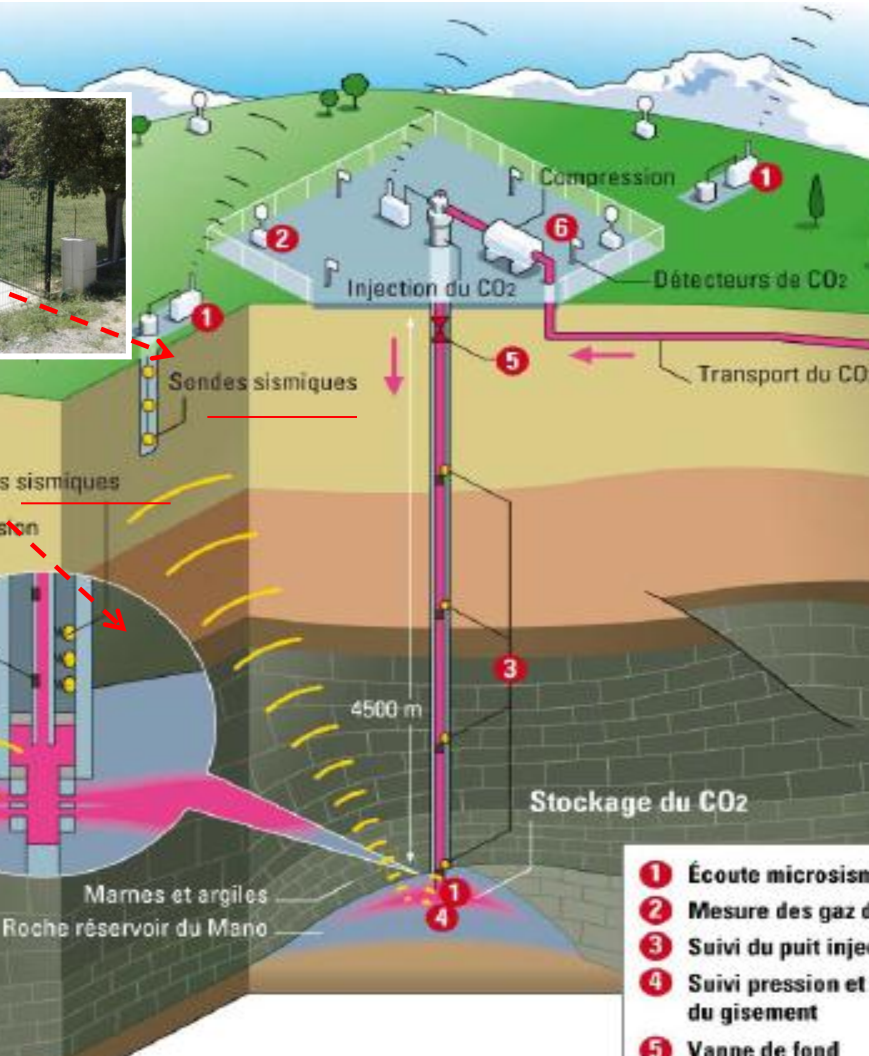
MS Monitoring system (1)

- 7 shallow buried arrays (4x3C)
- 1 tubing conveyed array (3x3C)

Monitoring services

- Daily acquisition system QC
- Real time data transfer
- Processing
  - On site (automatic detection)
  - Off site (daily remote processing)
- Live Reporting (Website)
- On demand expertise





Seismic surveillance network of geological CO_2 storage - Magnitude/Total
Deep saline aquifers for geological storage of CO2 and energy - IFP workshop – Rueil Malmaison (27 - 29 May 2009)

Gas cavern collapse

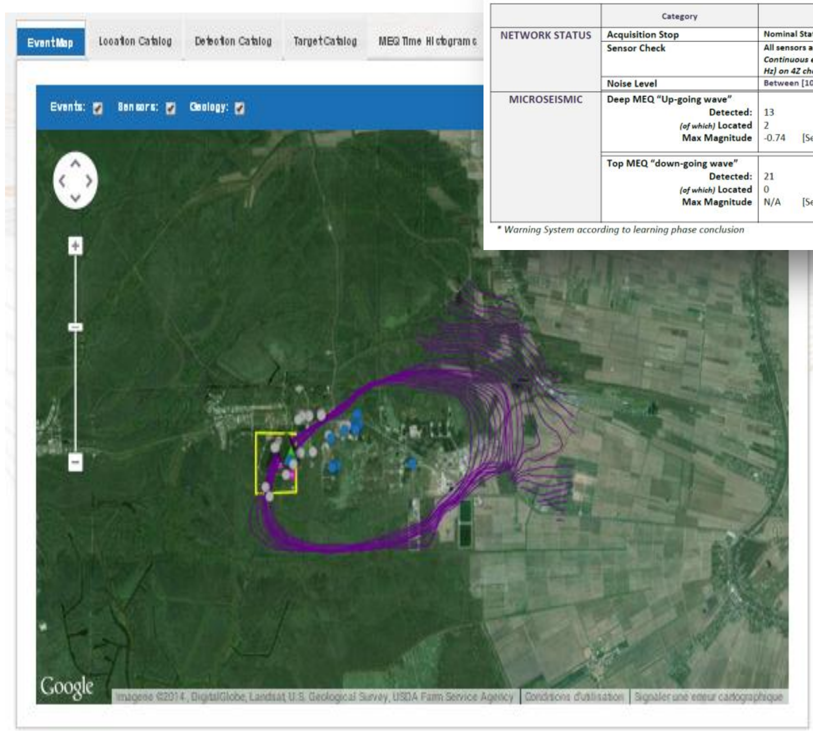
Traffic Light system / Risk-Based Mitigation Plan

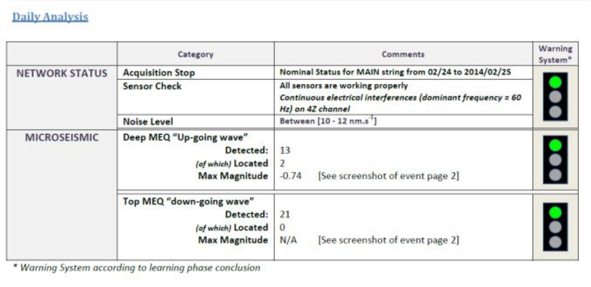
Traffic light system when applicable:

Green: No risk
→ operations proceed as planned.

Amber: Alertness
→ be prepared to alter plans. Operations proceed with caution, possibly at reduced rates. Monitoring is intensified.

Red: Warning
→ operations are suspended immediately

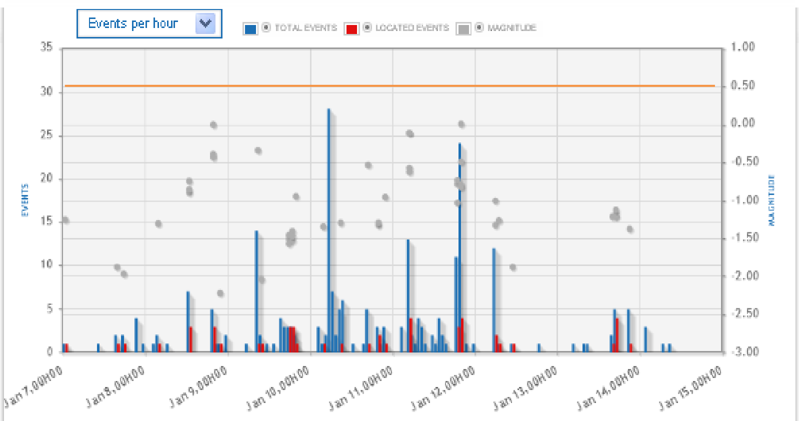




Daily Analysis

	Category	Comments	Warning System*
NETWORK STATUS	Acquisition Stop	Nominal Status for MAIN string from 02/24 to 2014/02/25	
	Sensor Check	All sensors are working properly *Continuous electrical interferences (dominant frequency ≈ 60 Hz) on 4Z channel*	
	Noise Level	Between [10 - 12 $nm.s^{-1}$]	
MICROSEISMIC	Deep MEQ "Up-going wave" Detected: (of which) Located Max Magnitude	13 2 -0.74 [See screenshot of event page 2]	
	Top MEQ "down-going wave" Detected: (of which) Located Max Magnitude	21 0 N/A [See screenshot of event page 2]	

* Warning System according to learning phase conclusion



Microseismic Monitoring

CONCLUSION

Addressing "Induced/Triggered Seismicity"

Natural Gas Underground Storage facilities

- Controversies and debates about anthropogenic seismicity have raised concerns among public and administrations .
- It is to be expected that the question of "induced/triggered seismicity" will arise for new projects (regulatory framework).
- UGS Industry must be prepared to face that event.
- Three main issues to address:
  - How does one assess risk associated to "Triggered Earthquake"
  - How does one minimize risk (Triggered seismicity)
  - How does one effectively utilize "Induced Seismicity"
- UGS industry can benefit from experience gained in Geothermal industry to propose a workflow.

Addressing Induced/Triggered seismicity

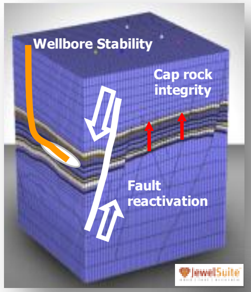
Proposed workflow

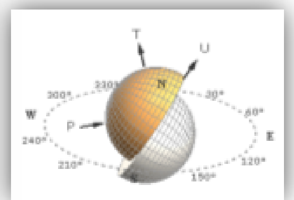
1. **Perform a preliminary screening evaluation (regulatory and public scrutiny).**
2. **Characterise the seismo-tectonic context: geological context, structural context with identification of major structures and faults, identification of active (or capable) faults and natural seismicity (historical and instrumental).**
3. **Quantify the hazard from natural and induced seismic events.**
4. **Seismic monitoring:**
   1. Use of the pre-existing network (national or regional)
   2. Establish a local dedicated and adapted seismic monitoring network
5. **Characterise the risks (effect and potential consequences) of induced seismicity**
6. **Establish a contingency and a communication plan**

Microseismic Monitoring

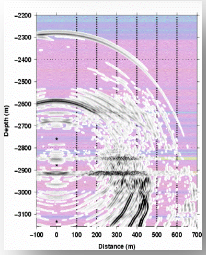
Typical Pre-survey planning

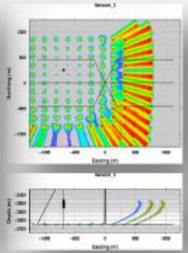
1. **Screening Evaluation** *(Geomechanical review)*
   - Rock properties / Critical stress regime
   - Identify most probable location and type of seismicity
   - Identify "by-product" and unintended seismicity

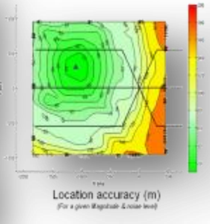




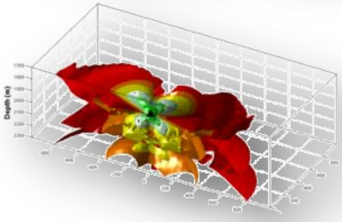
2. **Basic Feasibility** *(Explosive source)*
   - Site survey (Scouting/environmental context)
   - Preliminary modeling (Waveform complexity, sensitivity & location accuracy)
   - Compare network design options

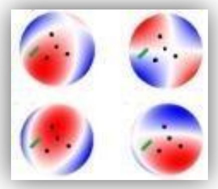




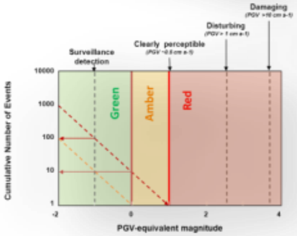


3. **Advanced modeling** *(Tensile / Shear source)*
   - Consider source complexity (Radiation pattern impact on sensitivity & location accuracy)
   - Assess moment tensor invertability





4. **Engineering design & Monitoring protocol**
   - Network design & Traffic light system
   - Monitoring protocol
   - Cost evaluation



THANK YOU

Magnitude
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