

IDROCARBURI E SISMICITÀ IN ITALIA

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Via Veneto, Via Vittorio Veneto 89



Guidelines for the Monitoring – MiSE (seismicity, ground deformation and reservoir pressures)

Aldo Zollo

Università degli Studi di Napoli Federico II

Members of the Working Group:

Gilberto Dialuce (MiSE - coordinatore),

Claudio Chiarabba (INGV – Struttura Terremoti),

Daniela Di Bucci (Dipartimento della Protezione Civile),

Carlo Doglioni (Dipartimento Scienze della Terra, Università Sapienza di Roma),

Paolo Gasparini (Università di Napoli “Federico II”; AMRA),

Riccardo Lanari (CNR – Istituto per il Rilevamento Elettromagnetico dell’Ambiente - IREA),

Enrico Priolo (OGS – Sezione Scientifica Centro di Ricerche Sismologiche),

Aldo Zollo (Università di Napoli “Federico II” - Dipartimento di Fisica).

Outline

- Guidelines Aims & Content
- Monitoring of induced seismicity:
 - Discrimination between natural and induced/triggered seismicity
 - Characterization of the background seismicity level
- Guidelines MiSE:
 - seismic monitoring
 - Ground deformation
 - Pressure reservoir
- Control of induced seismicity and alert procedures (eg traffic lights)
- Definition and role of the “Structure For Monitoring”

Guideline's Aim & Content

Aim: To define the standard and criteria for the set-up of **high resolution monitoring systems**, to track the background seismicity, and **prevent/control effects of industrial activities** resulting from re-injection of fluids into the ground and extraction/storage of hydrocarbons.

TECHNICAL INFORMATION CONCERNING:

- ✓ Definition of volumes concerned by the monitoring
- ✓ Technical characteristics of the monitoring network
- ✓ Processing and data analysis strategies
- ✓ Publication of monitoring data and disclosure of information
- ✓ Design, implementation and maintenance of monitoring networks
- ✓ SPM - Structure Responsible for the Monitoring
- ✓ Activation of actions to be taken in case of anomalous parameters trend
- ✓ Management of production activities
- ✓ Traffic lights control system

The Guidelines will be tested by the MISE on some pilot sites. The results of these tests will be shared with the Ministry of Environment and Protection of Land and Sea, the Regions of concern, as well as made of public dominion.

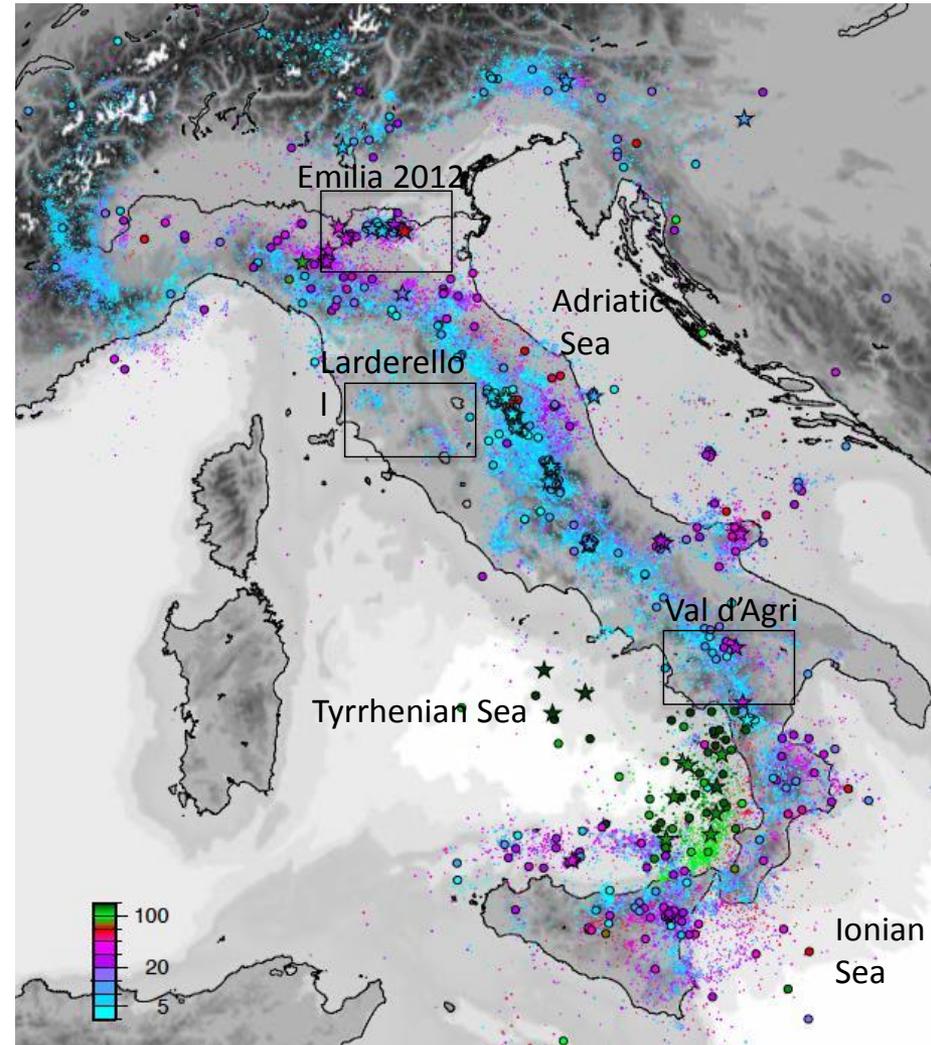
Areas of industrial interest and seismicity

Leases (UNMIG 30/04/2014)



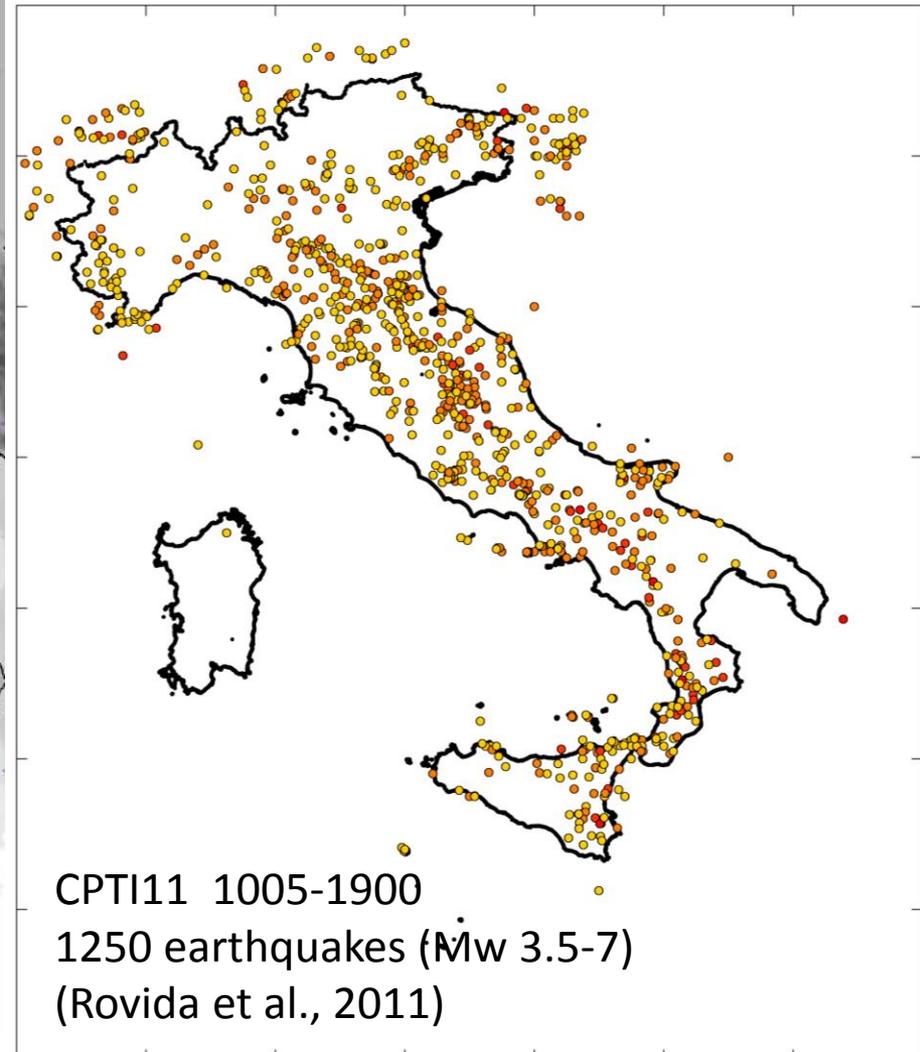
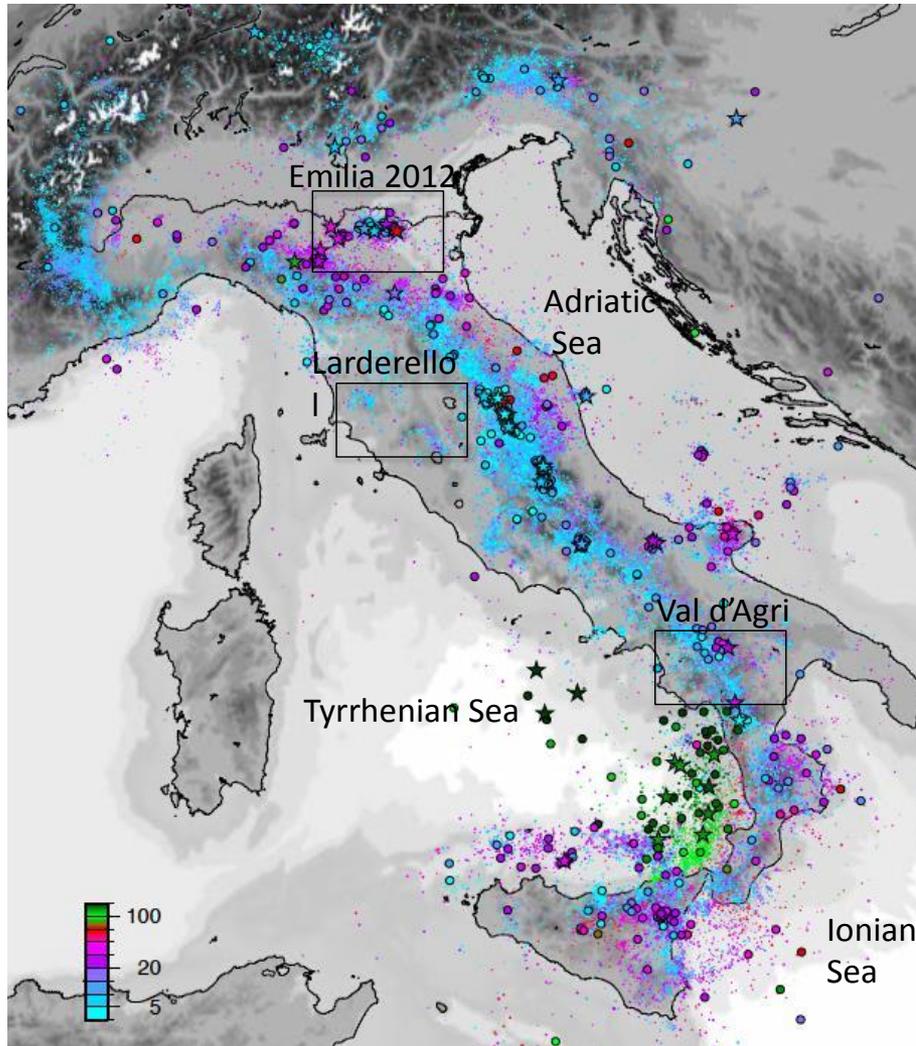
- Hydrocarbon concessions
- Storage concessions
- Geothermal wells
- Hydrocarbon exploratoin conc.

Recent Seismicity (1980-2013)



from Chiarabba, London, AAPG Induced Seismicity Meeting Feb, 13-14, 2014

Areas of industrial interest and seismicity



The current low-magnitude seismicity occurs along the fault zones which produced moderate/large earthquakes in the past

Natural and Induced/Triggered Seismicity in Italy.

- Problem 1: Discrimination between natural and induced/triggered* seismicity
- Problem 2: To characterize and define the seismicity background level in small areas (100 to 1000km²)

Criteria for Identifying Induced Events - Davis and Frohlich (1993)

In some cases it can be difficult to establish cause and effect relationships between injection and seismicity in order to determine that the seismicity was induced by the injection activity → seven questions which are often used as an objective test:

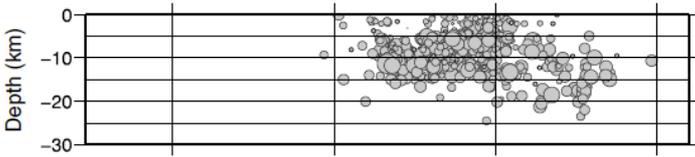
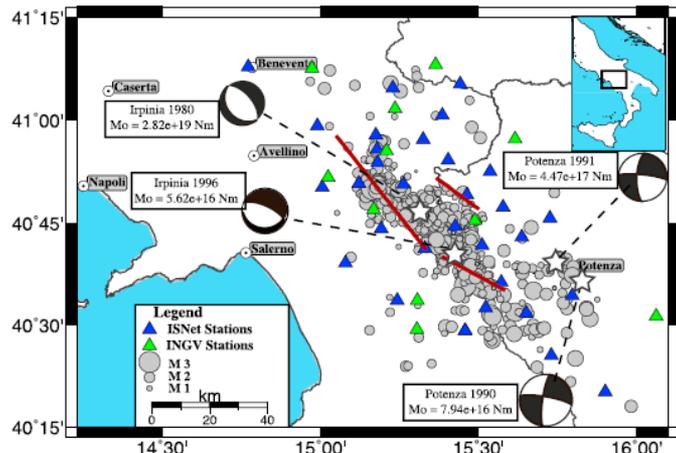
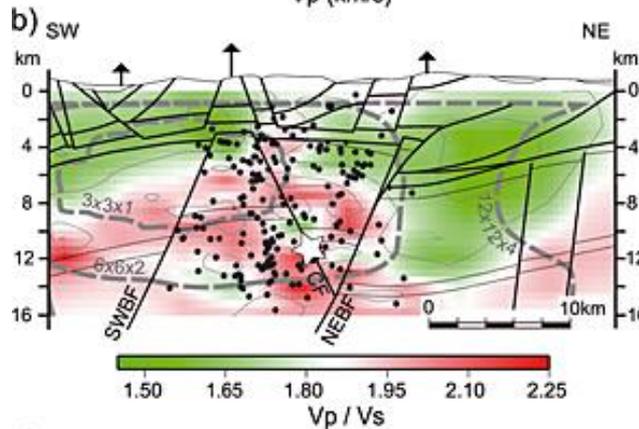
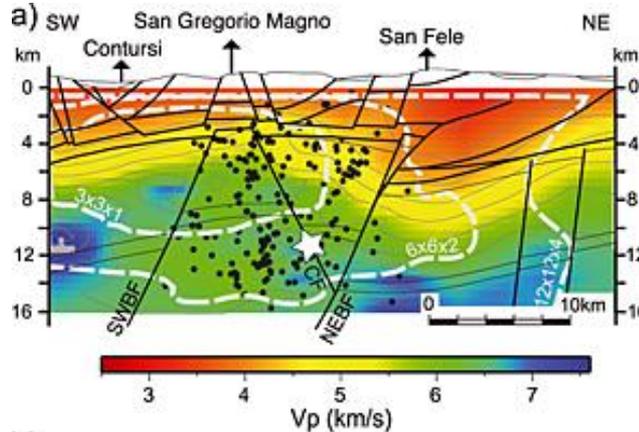
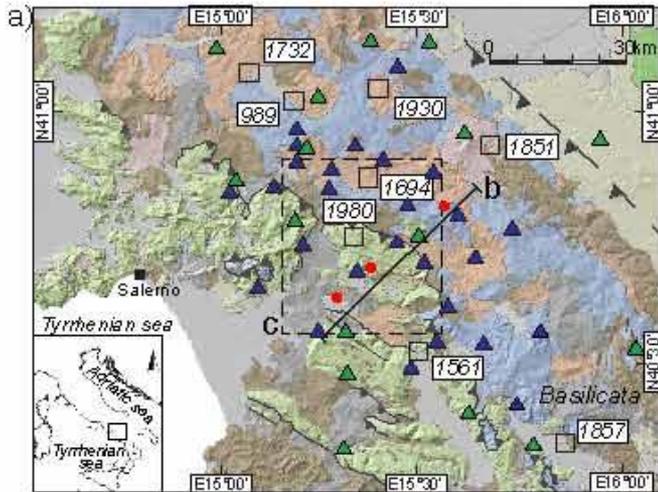
1. Are these events the first known earthquakes of this character in the region?
 2. **Is there a clear (temporal) correlation between injection and seismicity?**
 3. **Are epicenters near wells (within 5 km)?**
 4. **Do some earthquakes occur at or near injection depths?**
 5. **If not (similar depth) are the known geologic structures that may channel flow to sites of earthquakes?**
 6. Are changes in fluid pressure at well bottoms sufficient to encourage seismicity?
 7. Are changes in fluid pressure at hypocentral locations sufficient to encourage seismicity?
-
- The diagram uses blue brackets on the right side to group the seven criteria into three categories:
- Historical analysis**: This category includes criteria 1 and 2.
 - Observation**: This category includes criteria 3, 4, and 5.
 - Modeling**: This category includes criteria 6 and 7.

Discrimination between natural and induced/triggered seismicity

- **The natural background seismicity is already high and widespread, even in active fault zones (e.g. Irpinia)**
- Induced seismicity by low-pressure re-injection of fluids
 - generally confined in a volume of a few hundred meters around the borehole
 - can generate signals of amplitude similar or smaller than the seismic noise → high-resolution observational systems are needed
 - possible discriminants: stress-drop? Not pure double-couple mechanism?
- Triggered events have the same generating mechanisms of the natural seismicity
 - Triggered seismicity may develop on larger volumes, involving adjacent fault segments that can also communicate with each other (stress-transfer).
 - Possible discriminants: localization, stress-drop?

Seismic imaging of a fluid storage in the actively extending Apennine mountain belt, southern Italy

Amoroso et al., GRL, 2014



- High pore fluid pressure within the volume bounded by segments of the Irpinia fault system control background seismicity.
- The increase of pore fluid pressure in fluid-filled cracks around faults can episodically lead to the nucleation of moderate to large earthquakes

Discrimination between natural and induced/triggered seismicity

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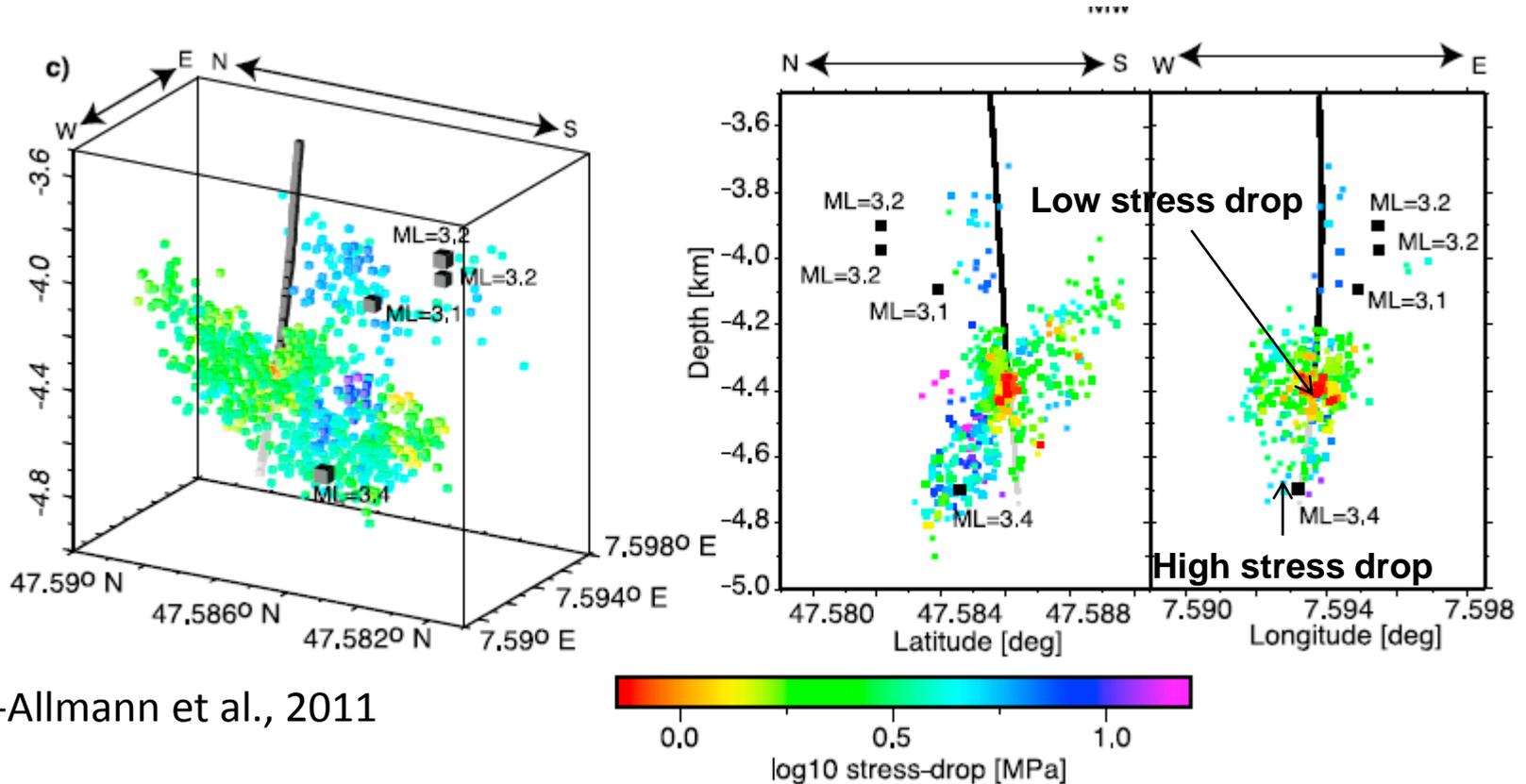
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The example of the induced seismicity at the Enhanced Geothermal System (EGS) of Basel (Switzerland)



Goertz-Allmann et al., 2011

The induced microseismic events focused around the well.

The study of microseismic events has allowed defining a model where the pore pressure, the differential stress and the stress drop of seismic events are related.

A reduction of the differential stress due to high pore pressures can reduce the stress drop of earthquakes.

Discrimination between natural and induced/triggered* seismicity

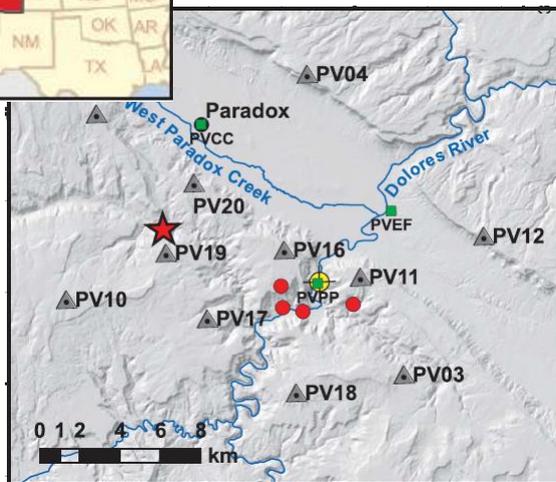
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* ICHESE terminology

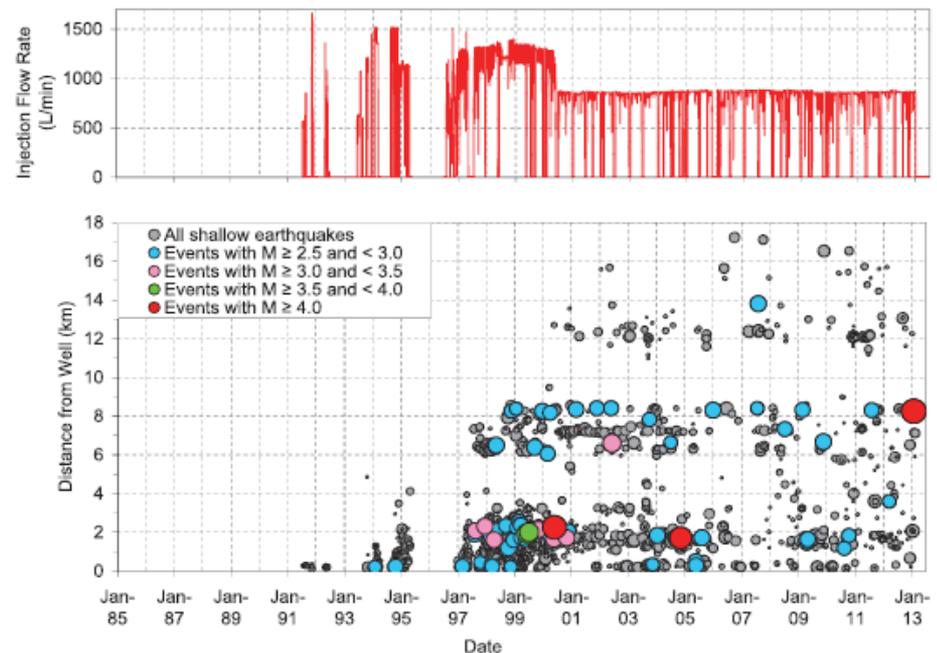
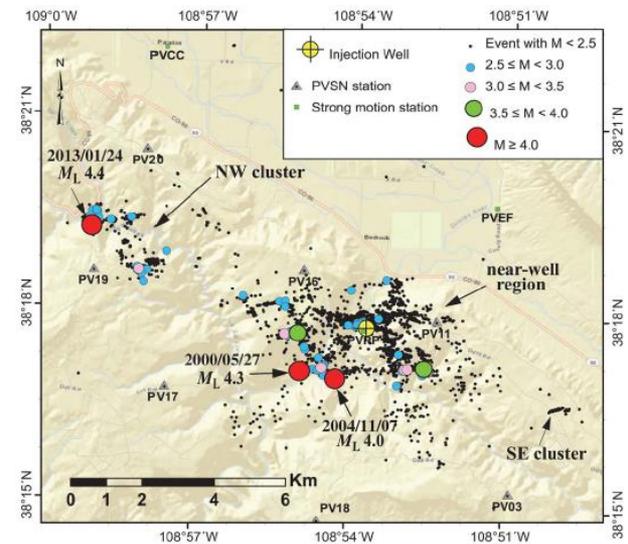
PARADOX Valley, COLORADO

The 24 January 2013 ML 4.4 Earthquake near Paradox, Colorado, and Its Relation to Deep Well Injection (Block et al, SRL, 2014)

Paradox Valley Unit (PVU) deep brine (salt water) disposal well.

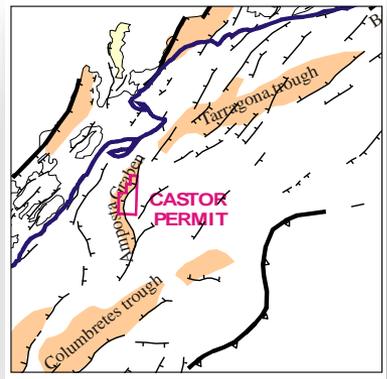


The Paradox Valley Seismic Network (PVSN), a local 20-station surface array of broadband three-component seismometers installed to monitor earthquakes induced by fluid injection



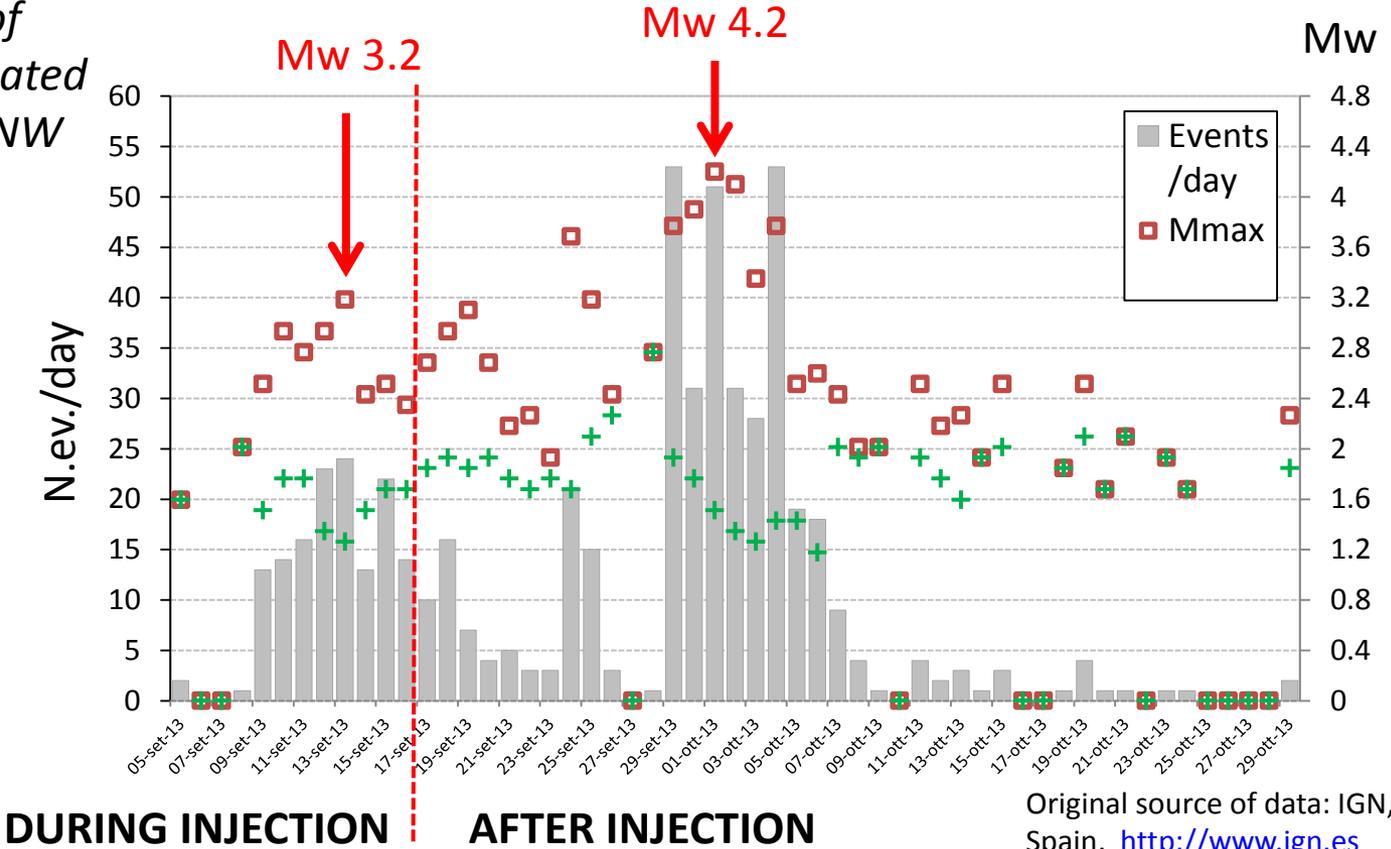
▲ Figure 6. Scatter plot of earthquakes having $M \geq 0.5$ and locating less than 8.5 km deep (relative to the ground-surface elevation at the injection wellhead), plotted as a function of date and distance from the PVU injection well (lower plot). Each circle represents a single earthquake, with the width of the circle scaled by the event magnitude. The upper plot shows the daily average injection flow rate over the same time period.

CASTOR PROJECT, offshore Spain



Castor is the biggest underground reservoir of natural gas in Spain, located in the Gulf of Valencia (NW Mediterranean)

After the beginning of injection on 16th September of 2013, a series of seismic events occurred, reaching maximum magnitudes of 4.2 and EMS intensities in coastal towns of grade III.



Original source of data: IGN, Spain. <http://www.ign.es>

Assessing the seismicity background level in small areas (100 to 1000km²)

- Estimation of the seismicity rate and the minimum magnitude of completeness (in time ...)
- Estimation of the Gutenberg-Richter (GR) magnitude distribution
- Estimation of the maximum expected magnitude
- Location / focal mechanism / stress-drop
- Definition of the observational time window (empirical approach vs. ETAS modeling, Reasenberg and Jones, Shapiro, ...)

→ Is the National seismic network adequate? (magnitude completeness threshold, location accuracy, ...)

→ The comparison of estimates made at regional and local scale is critical and often unfeasible

Is the National seismic network adequate? (magnitude completeness threshold, location accuracy, ...)

Map of Detection probabilities based on the INGV Network (2005-2008)

The magnitude completeness threshold of the national network has changed over time and is TOO HIGH to allow a proper monitoring seismic phenomena related to the fluids migration, and pore pressure increases at active faults

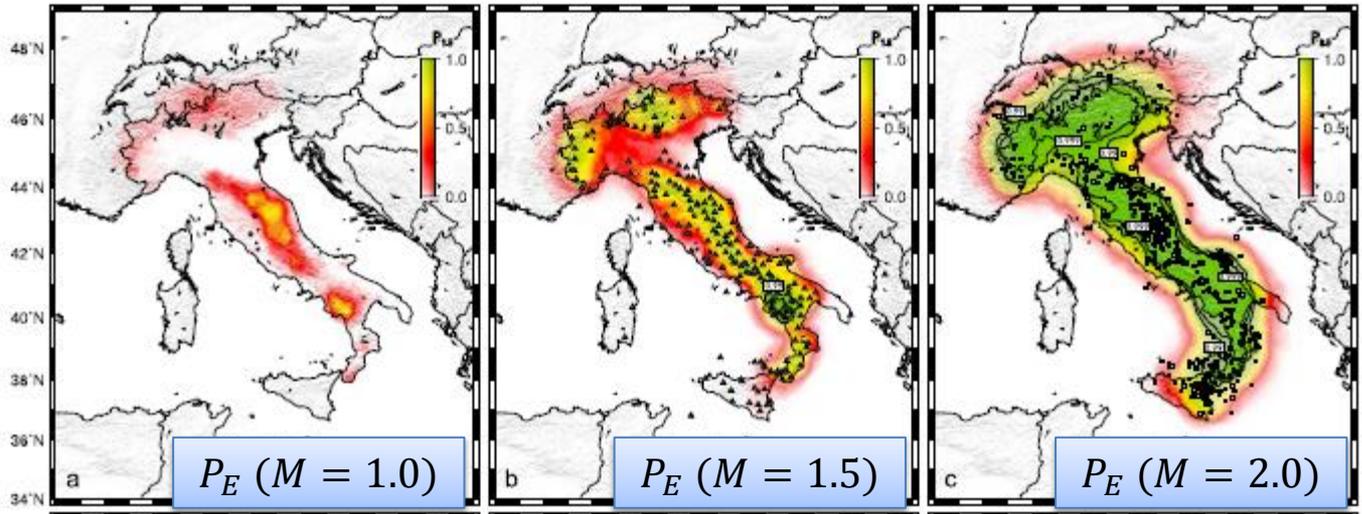


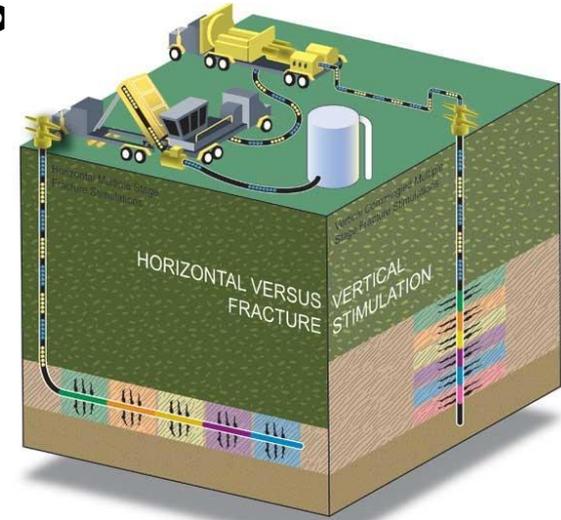
Figure 3. Map of detection probabilities, P_E , for different magnitudes on 1 January 2008 at a depth of 30 km. The black contour lines indicate the $P = 0.99$ and $P = 0.999$ level. (a) Map of P_1 . (b) Map of $P_{1.5}$. Gray triangles mark all stations that were in operation on 1 January 2008. (c) Map of P_2 . Gray boxes mark all earthquakes of magnitude $M = 2$ that occurred during the period 16 April 2005 to 1 January 2008. (d) Map of $P_{2.5}$. Magnitude $M_L = 2.5$ represents the reporting threshold level of the Italian Civil Protection. (e) Map of $P_{2.9}$. The catalog can be considered complete at the $M_p = 2.9$ level for the entire territory of Italy except for the islands of Sardinia, Pantelleria, and Lampedusa. (f) Map of M_p at the $P = 0.999$ level. The white contour lines show the $M_p = 2.5$ contour (inner line) and $M_p = 2.9$ contour (outer line).

Schorlemmer et al. (2010, JGR)

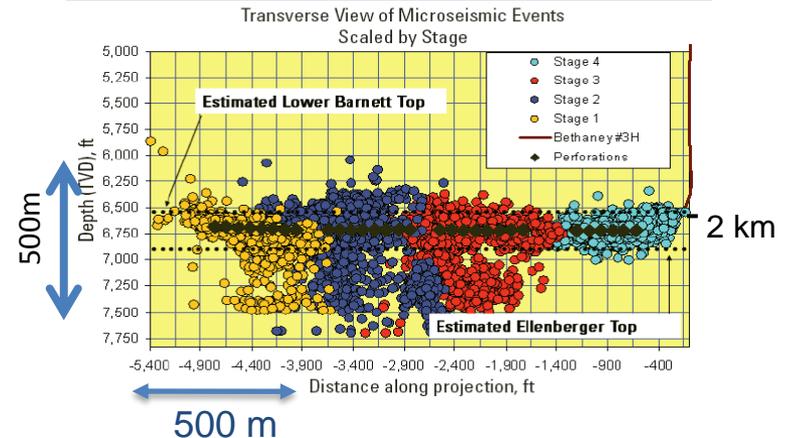
Seismic networks at exploitation sites must allow to detect, locate and estimate source parameters of microearthquakes with magnitude smaller than 1 !

Induced/Triggered Seismicity Monitoring

- **MiSE Hypothesis:** assuming the self-similarity of the GR, if we decrease the networks' detection threshold ($M \leq 1$), we improve its events detection/localization capability, which allows a more accurate estimate of the microseismic background
 - Development of new observational systems (Dense 2D arrays at the surface, 1D array of sensors in wells,...)
 - Use/Development of advanced techniques for the data analysis



Transverse view of microseismic locations from four-stage slickwater stimulation treatment orthogonal to the preferred fracture orientation.



MISE GUIDELINES → SEISMIC MONITORING

The Guidelines provide the technical information needed for the design of seismic monitoring networks

- ✓ **Inter-stations distance**
- ✓ **Hardware characteristics (sensor and data-logger dynamic)**
- ✓ **Acquisition mode and data telemetry**
- ✓ **Integration with geodetic stations**
- ✓ **Best practice for stations installation**
- ✓ **Operational requirements for a monitoring network**
- ✓ **Requirements for operation of seismic stations**

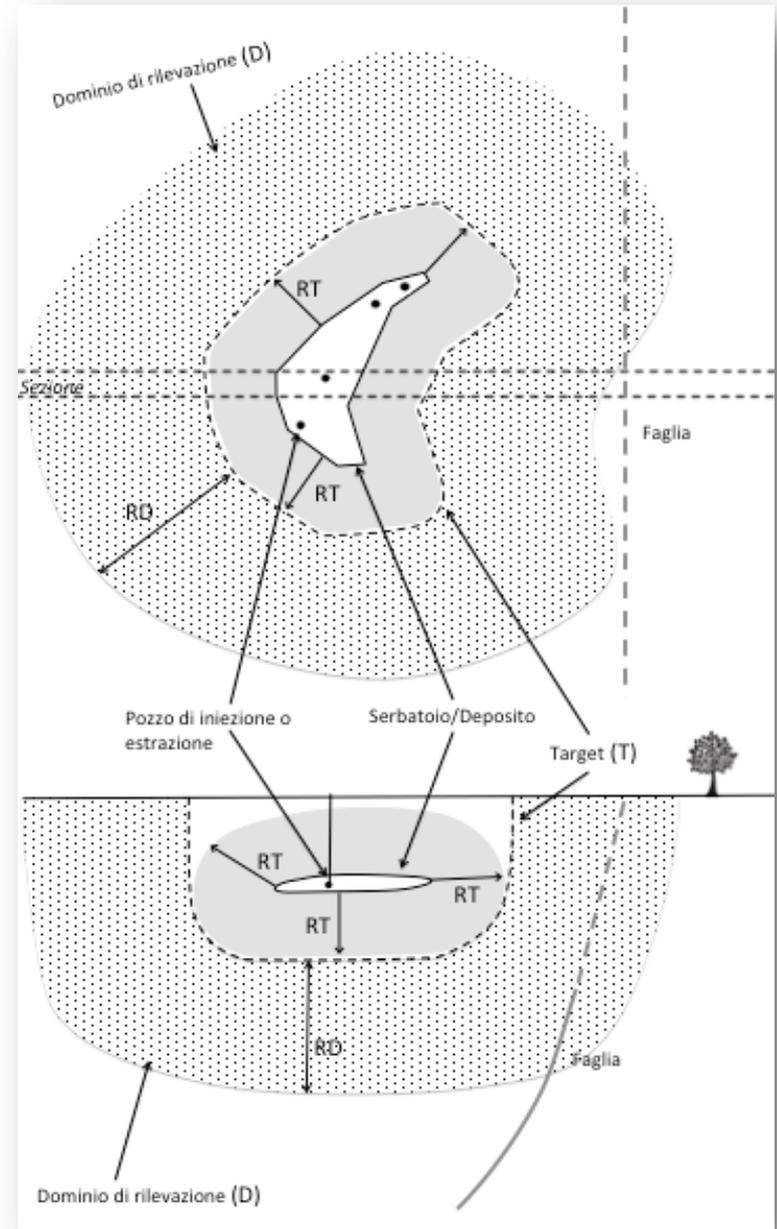
Both construction and maintenance of the monitoring networks compete to the Resource Permit Holders

Definition of volumes requiring the seismic monitoring

Internal detection domain (DI) - the volume within which the induced/triggered seismicity or the ground deformation associated with the industrial activity may occur.

DI's size varies between 2 km and 8 km depending on the activity.

TARGET – To detect and locate earthquakes from local magnitude ML between 0 and 1 ($0 \leq ML \leq 1$), and with hypocenter location uncertainty of few hundred meters

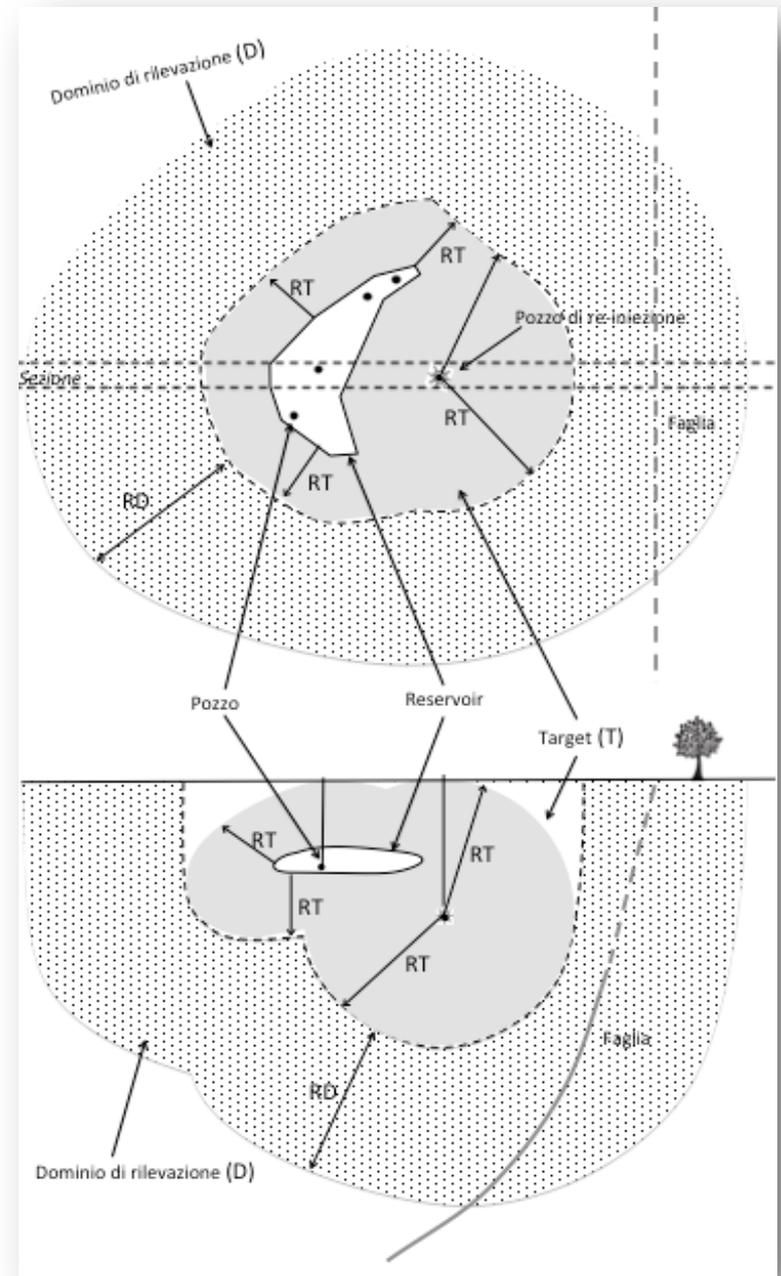


Definition of volumes requiring the seismic monitoring

Extended Detection Domain (DE) – volume surrounding the DI that includes a greater portion of the earth's crust, in order to better define and contextualize the monitored phenomena

> Between 5-10 km, taking into account the size of the reservoir and the type of activity.

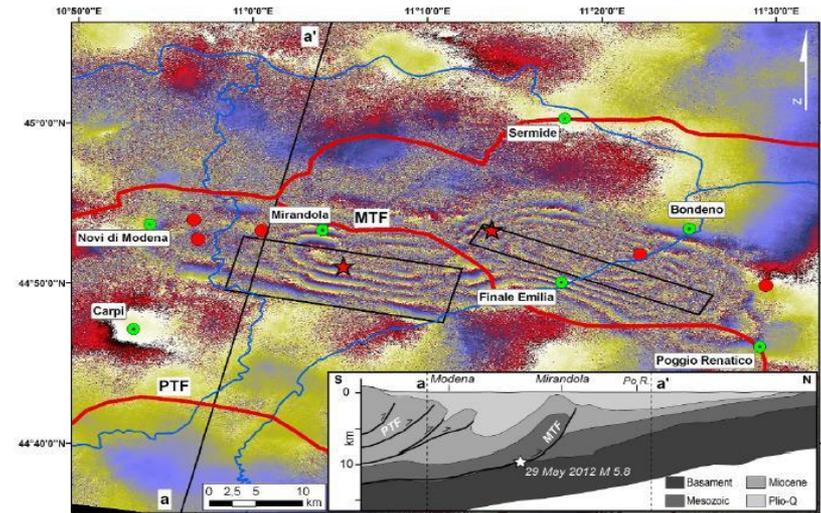
TARGET - Improving the magnitude of completeness from the national network of about 1 unit with uncertainty in locating the hypocenter contained within 1 km



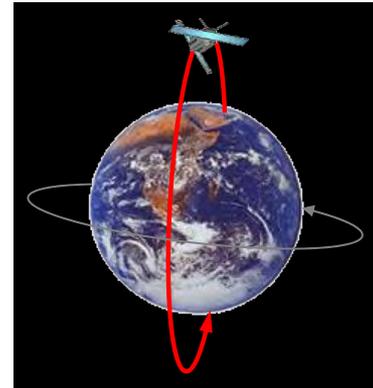
Ground Deformation & Reservoir pressure monitoring

Mirandola 2012 May 20 and 29 mainshocks

- Surface deformation phenomena typically have a **rather slow temporal dynamics and large spatial extension**.
- InSAR techniques integrated by continuous GPS → **Detect/Track the ongoing sub-surface phenomena**, as well their **evolution in time**
- The value of the reservoir pressure is a useful element **for updating and validate the storage and reinjection models**.
- New storage and reinjection wells (excluding production ones): **surface read-out bottom instruments**, → **real-time measures**.
- Existing wells: pore pressure measurements vs time by **memory gauges** placed at the bottom of the well.



Fantoni e Franciosi (2010, JGR)



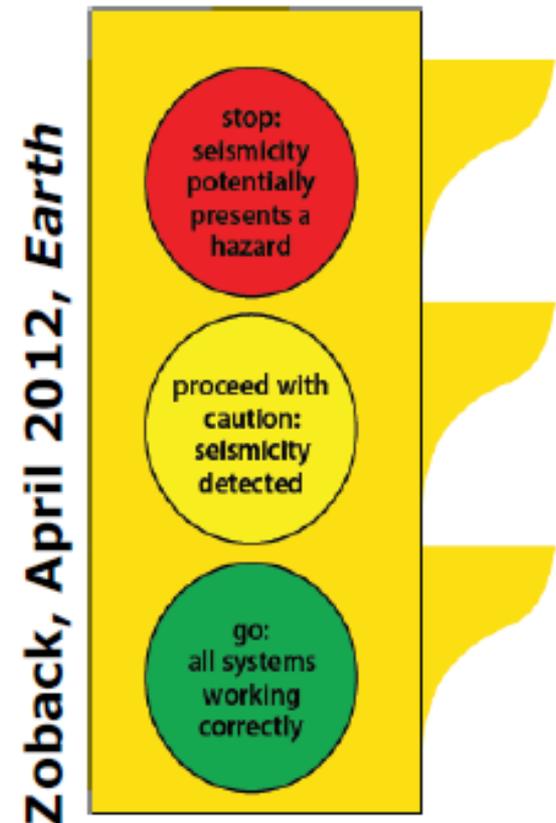
Induced seismicity control and alert procedures : Traffic- lights system

The ‘classic’ seismic risk analysis is aimed at assessing and mitigate

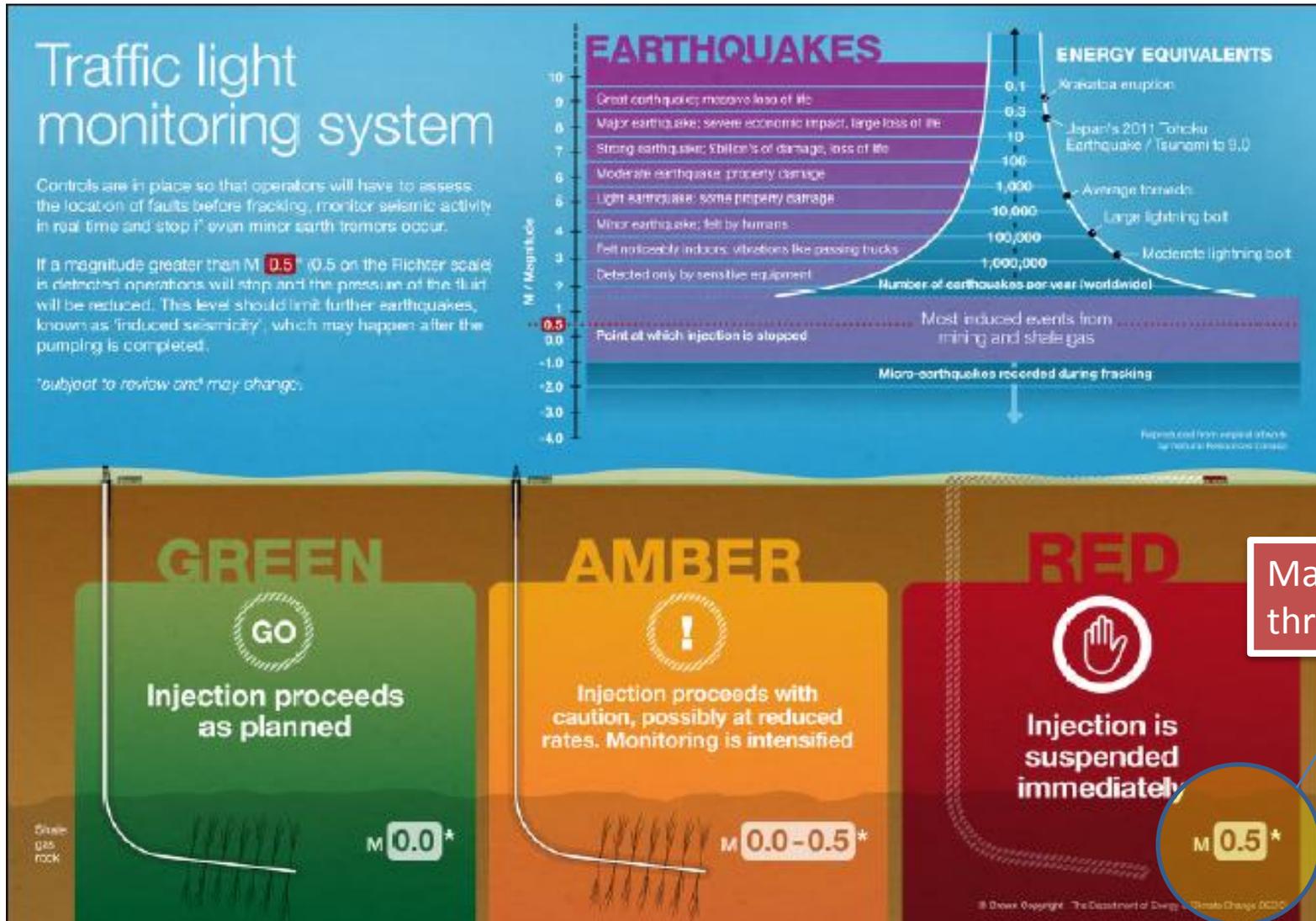
- Structural damages
- Non-structural damages

In the case of the induced seismicity is necessary to consider also the ‘human discomfort’, which requires:

- Control and definition of acceptable ground motion levels



Traffic-Light System to control hydro-fracturing activities in UK



MiSE Guidelines: Decision-Making System for Actions

Four levels of activation. The levels will be set considering the geodynamic model of the area, as well as the parameters monitored in the detection domains

Livello di attivazione	Stato corrispondente
0	Ordinarietà
1	Attenzione
2	Riduzione delle attività
3	Sospensione delle attività

Normal

Attention

Reduction

Halt

- ✓ Variation in the number and frequency of seismic events, as well as their magnitude and spatial distribution
- ✓ Observed peak ground acceleration and velocity
- ✓ Variation in the ground deformation rate
- ✓ Pore pressure variation

Observed
parameters

Test of a Traffic-Light System in areas with injection wells

The traffic light system will be applied to the parameters monitored in the internal detection (ID) domain.

- Decisional parameters are : maximum magnitude (M_{\max}), peak ground acceleration (**PGA**) and velocity (**PGV**).

Activation level	Traffic Light	M_{\max}	PGA (% g)	PGV (cm/s ²)
0	Verde	$M_{\max} \leq 1.5$	-	-
1	Giallo	$M_{\text{verde}} \leq M_{\max} \leq 2.2$	0.5	0.4
2	Arancio	$M_{\text{giallo}} \leq M_{\max} \leq 3.0$	2.4	1.9
3	Rosso	$M_{\max} > M_{\text{arancio}}$	6.7	5.8

PGA and PGV threshold s are taken from ShakeMap table used for Italy by INGV (Michellini et al., 2008)

- The thresholds are selected case-by-case depending on background seismicity level and tectonic context
- To activate a given level >0, just ONE of the indicated parameters must pass the threshold.
- Occasionally an anomalous increase of seismicity or significant variations of ground deformation/reservoir pressure can justify the activation of a level > 0

SPM - the Structure For Monitoring

- The SPM is a scientific/technical entity, consisting of universities and/or research organizations, responsible for **planning and management of the monitoring network, as well as the collection and analysis of data.**
- The SPM is appointed by MiSE as the responsible for the tasks of collecting and analyzing the monitoring data, and it will provide the technical support for decisions.

SPM Tasks:

- ✓ Supervision/Coordination/Validation of the Monitoring Project
- ✓ Under request of the *Resource Permit Holder*, the SPM can design and manage the monitoring (acquisition/analysis/interpretation of data)
- ✓ Evaluation of the monitoring network performance (it communicates and motivate any problems to the MISE)
- ✓ Data storage (ensure integrity, continuity and data security)
- ✓ Together with the Resource Permit Holder/UNMIG/Region, it take part to the activation of actions to be taken in case of critical situations (out of the ordinary variations of monitored parameters)

Summary

- Discriminating induced/triggered from natural seismicity in Italy is a difficult task.
- Need to improve the monitoring system around and at the exploitation sites → detect and track «anomalies» as fast and accurate as possible
- Set-up of a decision-making procedure for action → testing a traffic-light system
- Guidelines needs to be practiced and experimented → further adjustments & re-evaluation 2-years after their first application to pilot sites

Thank for your attention

ADDITIONAL SLIDES

**Migrazione di fluidi, incrementi di
pressione di poro & faglie attive:
criticità dei sistemi di osservazione per
la sismicità indotta/innescata**

Migrazione di fluidi e generazione di terremoti

- Teoria e meccanismi ben noti
 - L'iniezione produce incremento della pressione di poro su una faglia (o segmento di faglia) prossimo allo stato critico → dislocazione innescata dalla riduzione dello sforzo normale effettivo
 - L'estrazione di fluidi causa un decremento della pressione di poro e una conseguente contrazione del reservoir con relativa subsidenza e compattazione. Tale contrazione genera il trasferimento di stress poroelastico ed il possibile sviluppo di fratture sismiche

Iniezione di Fluidi

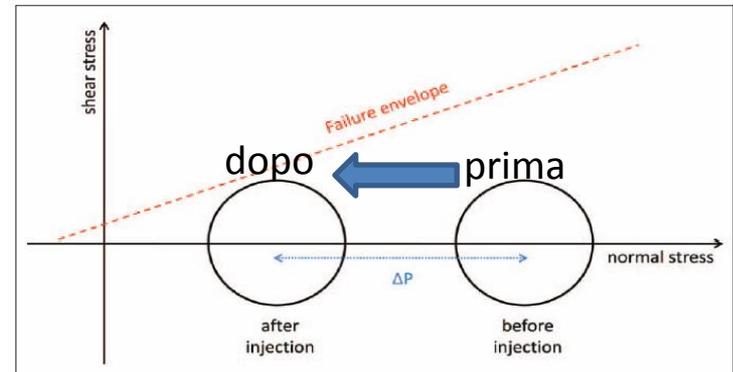
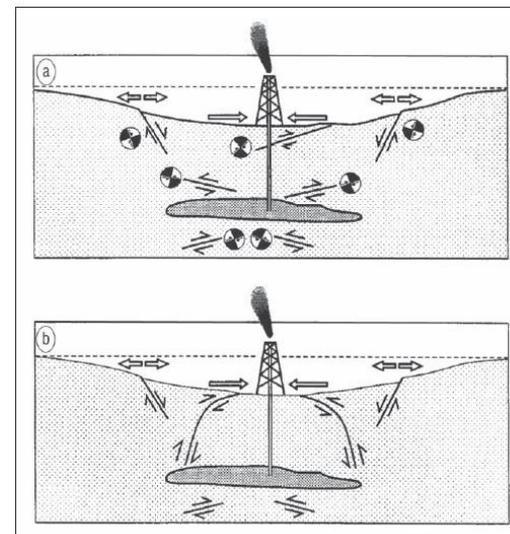


Figure 3. Mohr-Coulomb diagram illustrating how fluid injection lowers the normal stress and thereby brings rock closer to failure.

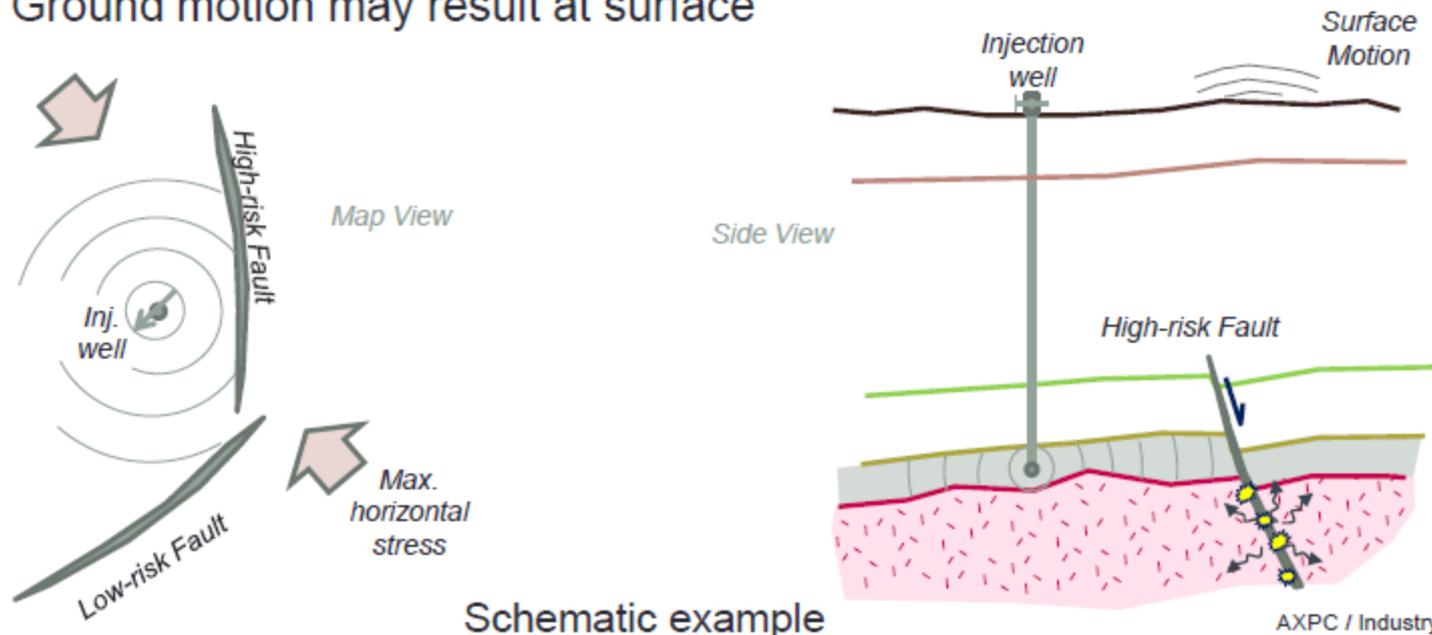


Triggered seismicity: The basic idea

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Induced Seismicity – Fluid Injection

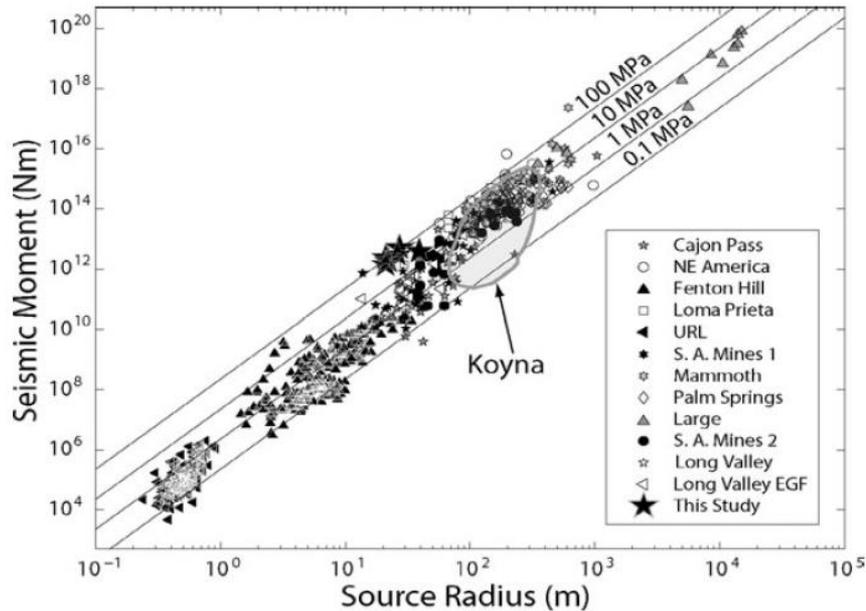
- Fluid injection: raises pore pressure in subsurface
- Increased pressure reaches a nearby critically stressed fault with a high-risk orientation
- Fault reacts: brittle deformation, especially in basement rock, radiates seismic waves
- Ground motion may result at surface



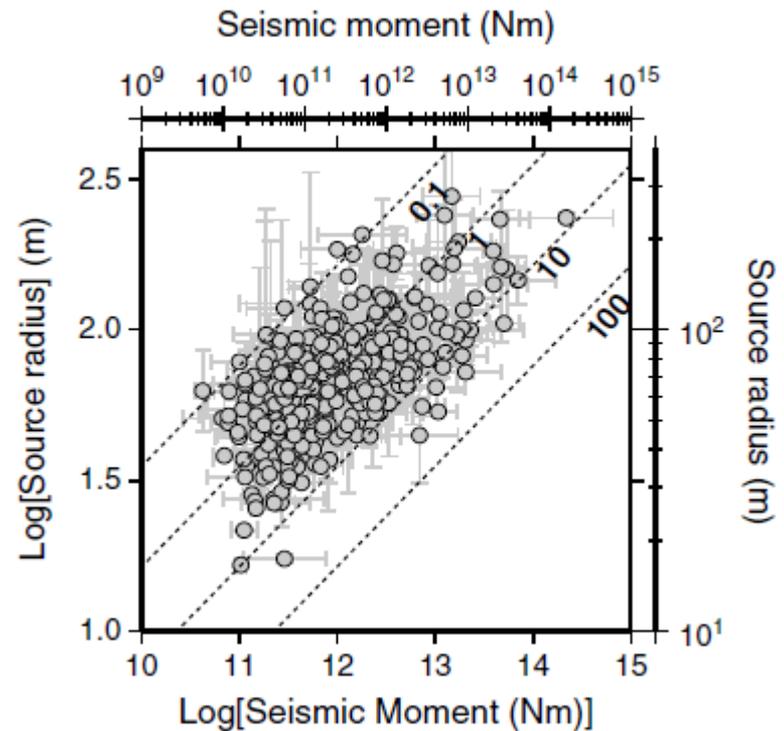
Schematic example

AXPC / Industry induced seismicity SME presentation

Fluids & stress drops



Induced (black symbols)/natural earthquakes (Tomic et al., 2009)



Microearthquakes at the Irpinia fault zone (Zollo et al., 2014)

- Induced earthquakes appear to have systematically lower (~ 1 MPa) stress drops than the tectonic earthquakes (Abercrombie & Leary, 1993).
- At the Irpinia fault zone, the evidence for massive presence of fluids /low stress drops suggests that ruptures occur at lower stress levels due to pore pressure increase.

**Controllo della sismicità indotta e
procedure di allerta (e.g. semaforo) in
aree di stoccaggio e coltivazione di
idrocarburi**

Managing the Seismic Risk Posed by Wastewater Disposal (M.Zoback, Earth, 2012)

- Step 1: Avoid Injection into Active Faults
 - Detailed mapping of nearby active faults
- Step 2: Minimize Pore Pressure Changes at Depth
 - Minimize (optimize) injection volumes
 - Use highly permeable regional saline aquifers to dispose of wastewater that can accommodate large volumes of injected fluids without experiencing significant pressure changes.
- Step 3: Install Local Seismic Monitoring Arrays
 - Follow possible migration
 - Detect small size faults capable of moderate eqks
- Step 4: Establish Modification Protocols in Advance
 - E.g. traffic-light regulator
- Step 5: Be Prepared to Alter Plans or Abandon Wells

Monitoring – Toolbox *

Proposal of Guidelines in US

- Data, resources and tools for **Monitoring** evaluation

Item		Data, Resources and Tools
Operations	Fluid parameters	<ul style="list-style-type: none"> Continuous monitoring and recording of injection rates, and pressures. Daily and cumulative injection volumes measured and recorded. Injectant properties noted: e.g. salinity, chemistry.
	Reservoir	<ul style="list-style-type: none"> Fluid levels, shut-in pressure, pore pressure, changes in conditions. Pressure transient behavior – e.g. falloff, step rate tests Well performance and reservoir flow behavior (Hall plots, Silin plot) Storage/transmissivity
Seismicity	Regional	<ul style="list-style-type: none"> Establish baseline conditions from USGS and other regional sources. Maintain catalog of events from USGS and other regional sources. Identify excursions from historical trends (temporal and spatial). Note surface effects from seismic events recorded.
	Local	<ul style="list-style-type: none"> (Level II) Install local array sufficient to locate events in the subsurface near the injection zone. (Level II) Deploy sensors capable of measuring peak ground acceleration and velocity in the vicinity of the injection site. Monitor possible "traffic light" events within 10 miles of well. Evaluate whether any observed seismic events are induced or naturally occurring. Report potentially induced threshold events established in the Risk Management plan that initiate mitigation steps.

In-situ

Reg:

* *Toolbox contains various scalable tools user can select to fit for purposes*

da Jeff Bull, Meeting on Assessing & Managing Risk of Induced Seismicity by Underground Injection” , GWREF Spotlight Series , February,2013

Example of a traffic-light system applied in the USA

Planning - Risk Management Plan: Traffic Lights

The occurrence of a single value of perceptible ground motion, even with high value of PGV or other parameter, can be less alarming compared to a longer series of events even if with lower levels of the ground motion.

- Green** Continue operations – no seismicity felt at surface (MMI I-II)*
- Amber** Modify operations – seismicity felt at surface (MMI II-III+)*
- Red** Suspend operations – seismicity felt at surface with distress and/or damage (MMI V+)*

Perceived Shaking	Not Felt	Weak	Light	Moderate	Strong	Very Strong	Severe	Violent	Extreme
Potential Damage	none	none	none	Very Light	Light	Moderate	Moderate Heavy	Heavy	Very Heavy
Peak Acceleration (%g)	<0.17	0.17 to 1.4	1.4 to 3.9	3.9 to 9.2	9.2 to 18	18 to 34	34 to 65	65 to 124	>124
Peak Velocity (cm/s)	<0.1	0.1 to 1.1	1.1 to 3.4	3.4 to 8.1	8.1 to 16	13 to 31	31 to 60	60 to 116	>116
Magnitude	1 – 2.9	3 – 3.9	4 – 4.4	4.5 – 4.9	5 – 5.4	5.5 – 5.9	6 – 6.4	6.5 – 6.9	7.0+
Modified Mercalli	I	II to III	IV	V	VI	VII	VIII	IX	X+

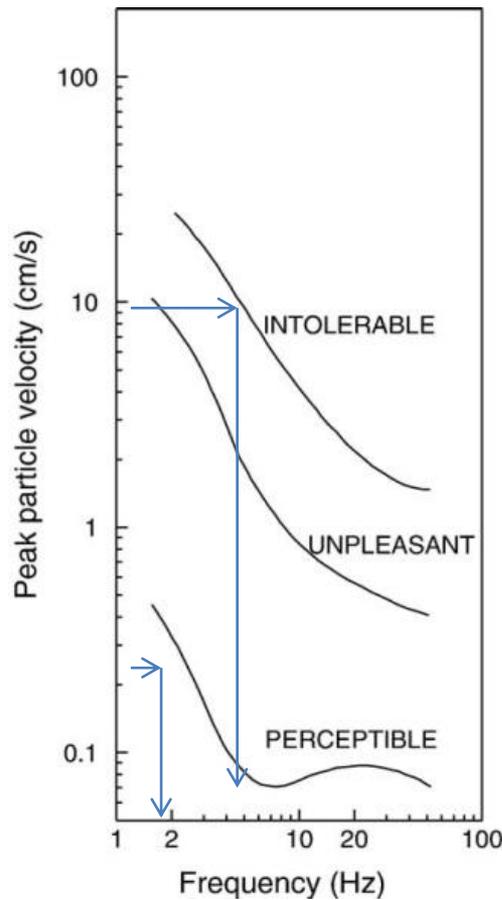
Traffic Lights *



Semaforo convenzionale

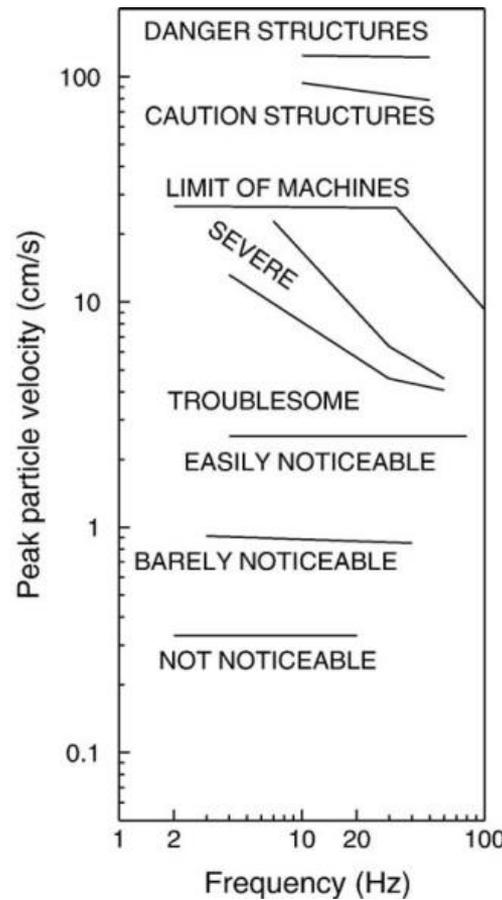
Sensibilità umana alle vibrazioni dovute a:

Esplosioni



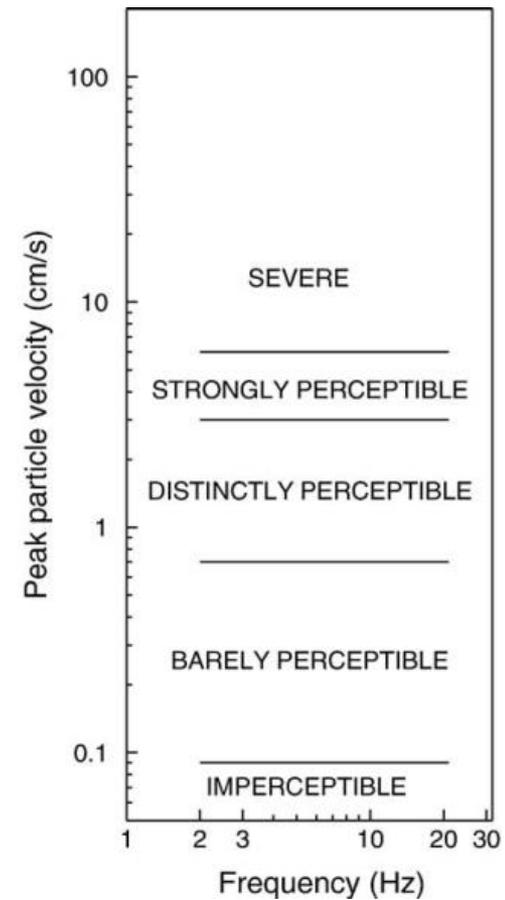
USACE (1972)

Traffico



Barneich (1985)

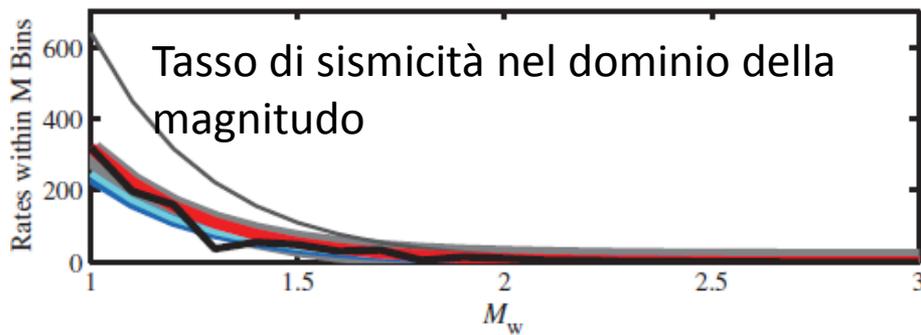
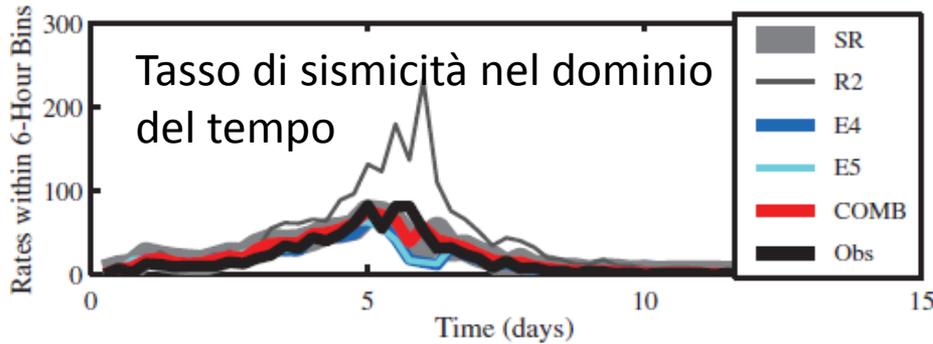
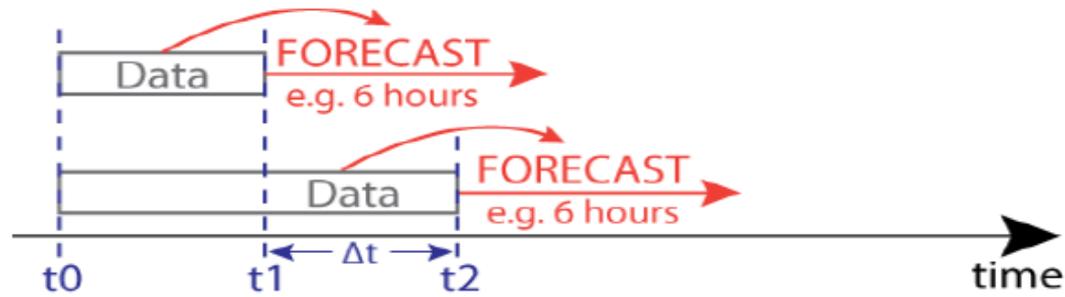
Batti-pali



Athanasopoulos and Pelekis (2000)

Semaforo avanzato

- Previsione della sismicità utilizzando i dati acquisiti dalla rete dedicata
- Approccio probabilistico
 - Combinazione di più modelli statistici di occorrenza degli eventi
 - Include incertezze aleatorie ed epistemiche
- Approccio dinamico
 - La previsione cambia nel tempo in base al livello di sismicità osservato



I modelli statistici per la previsione della sismicità possono essere utilizzati per calcolare la pericolosità sismica e quindi il danno atteso avendo a disposizione curve di vulnerabilità ed esposizione

Struttura preposta al monitoraggio

Information provided to the SPM

In order to have a detailed picture of the geological and seismotectonic characteristic of the lease, and thus put the SPM in the condition to design the best possible monitoring system, the Resource Permit Holder will provide the SPM with the following information:

- ✓ At least three geological sections
- ✓ Reflection seismic profiles – whenever available, the 3D seismic model
- ✓ 3D Stratigraphic/Structural Model
- ✓ Direct or indirect estimation of the primary and secondary porosity in the well's stratigraphy, also from analysis of samples
- ✓ Identification of eventual active faults nearby (within 3 km) or in the proximity (within 15 km) of the lease
- ✓ Simulations of the fluids migration within the DI monitoring domain
- ✓ 3D Geo-mechanical Model

SPM will protect the confidentiality of the industrial production data.

Operational time of the monitoring

- ✓ **The seismic monitoring should start at least one year before the start of production/storage, in order to measure the natural background seismicity in "unperturbed" conditions.**
- ✓ **The seismic monitoring will continue for the whole period during when the production/storage activities are ongoing, and it will last for at least one year after the completion of activities.**

After two consecutive years of activity, the Designed Monitoring Structure (SPM) evaluates the performance of the monitoring network, as well as any critical issue in the system or in the adopted analysis.

In the case the monitoring does not meet the expected performance due to technical limits, actions for its improvement should be rapidly adopted. Eventual objective reasons of the Resource Permit Holders must be documented by SPM reports to the MISE.