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Abstracts Volume

34th Course of the International School of Geophysics on DENSELY POPULATED SETTINGS: THE CHALLENGE OF SITING GEOLOGICAL FACILITIES FOR DEEP GEOTHERMICS, CO_2 AND NATURAL GAS STORAGE, AND RADIOACTIVE WASTE DISPOSAL

Underground Coexistence and Synergies for a Sound Energy Mix in the Post-Kyoto Era

Ettore Majorana Foundation and Centre for Scientific Culture

Erice, September 25 | 30, 2010

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Istituto Nazionale di Geofisica e Vulcanologia

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ABSTRACTS VOLUME

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ETTORE MAJORANA FOUNDATION AND CENTRE FOR SCIENTIFIC CULTURE

ERICE, SEPTEMBER 25 | 30, 2010

Edited by
Fedora Quattrocchi, Giuliana Mele, Barbara Cantucci, Monia Procesi, Alessandra Sciarra, Silvia Nardi and Enzo Boschi

INGV (Istituto Nazionale di Geofisica e Vulcanologia)

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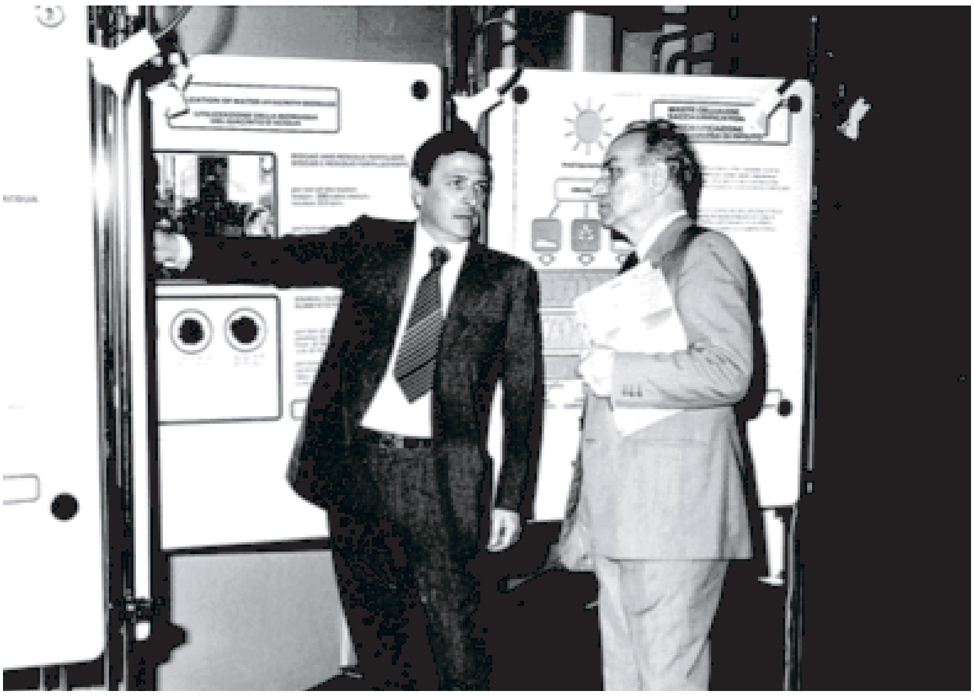
Tribute to Mario Mittempergher (1930 – 1989)

The 34th Course of the International School of Geophysics, held in Erice (Italy) from 25-30 September 2010, and the abstracts collected in this volume are dedicated to the memory of Mario Mittempergher, one of the fathers of geological disposal in Italy, who started building up and arousing, in the 1960's, our knowledge, passion and scientific curiosity about this strategic topic in Italy.
Mario was indeed the first scientist in Italy to conceive of radioactive waste disposal as the final obvious phase of electric power generation by nuclear fuel, as well as of the industrial and medical uses of radionuclides.
The strategic road map he developed was focused on sustainable energy production and on the safety of the natural geosphere, considered as the main receptor for these kinds of waste. The geosphere includes natural barriers that have both the capacity to dilute and disperse and/or to contain radionuclides. Both properties were considered for low-level, short-lived radionuclides, hosted in a near surface repository. On the other hand, the final disposal, also known as the "total containment" in deep suitable geologic formations, i.e. "geological disposal", was taken into account only for the isolation of long-lived radionuclides with high level activity (HLW).
As for the confinement capacity of a geological barrier, Mario was explicit: "Any radionuclide migration from a deep repository sited in a well selected geological formation to the surficial environment is null".
Such a strong statement was necessary to clear up the doubts expressed by the great variety of scientists and technologists engaged in studying the geological disposal of nuclear waste. Indeed, most of them were lacking in the basic knowledge of the natural environment.
Several years later, the development of systematic studies on "natural analogues" led to the correct conclusion drawn by Mario in the 1970's. The concept of "natural analogues" was also reintroduced 20 years later for CO_2 geological storage: at that time Mario had disappeared from the Italian Earth Sciences scene, but his teachings are still topical and widely used as a reference today.
At the end of the 1970's and during the 1980's, running his research labs at ENEA (former CNEN), Mario engaged his laboratory staff in some of the first EU funded projects (i.e. Project PAS-SGRIF, laboratory LRRR and geochemical laboratory AMB-MON-PAS in the 1980's) according to cooperation plans aimed at exploring the isolation potential of clay formations in Italy, with regard to harmful elements, possibly confined in them. The scientific research carried out by Mario was independent from facility siting application and useful for the selection of the Italian final nuclear waste disposal site, not yet defined.
Mario approved and encouraged the adoption of "geological analogue studies" as the most productive method for achieving reliable scientific results. At the end of the 1980's (the referendum on nuclear energy was held in Italy in 1987), the scientific results obtained studying geological analogues were quite positive and were disseminated and recognized worldwide [Benvegnù F., Brondi A., Polizzano C., 1988. "Natural analogues and evidence of long-term isolation capacity of clays occuring in Italy". Contribution to the demonstration of geological disposal reliability of long-lived wastes in clay. Directorate-General Science, Research and Development. Commission of the European Communities. EUR 11896 EN. Office for Official Publications of the European Communities, L-2985, Luxembourg; see also the foreword written by Serge Orlowsky acknowledging Aldo Brondi and his colleagues].
Was Mario endowed with prophetic vision? No! He was simply a deep-rooted and tenacious expert in Earth Sciences. He was a true geologist!

Ciao Mario.

Aldo Brondi and Fedora Quattrocchi



Mario Mittempergher (left) with a colleague at a scientific congress in the 1970's.

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presented by Fedora Quattrocchi at the 182nd session of the 13th Standing Committee (Territory, Environment and Environmental Assets) of the Senate of the Italian Republic, held in Rome on June 8, 2010 (in Italian) 93

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Introduction

The abstracts herein – collected for the 34th Course of the International School of Geophysics, held in Erice, Italy ("Ettore Majorana" Foundation and Centre for Scientific Culture, 25-30 September, 2010) – focus on geophysical, geological and geochemical methods applied to the planning of the soundest energy mix in densely populated countries, where the coexistence of different technologies requires unique underground facilities and resources. In the framework of IEA and EU programmes, where the concepts of "smart grids" and "smart cities" are prevailing, we rather propose the concept of "smart region" planning the use of both underground and surface areas in a new social-energetic paradigm of "zero kilometer" life. The coexistence of geological storage of CO_2 and natural gas, geothermics and, possibly, nuclear waste temporary storage (near surface or geological) is today necessary owing to the progressive decrease of space and resources.

In this context, the following technologies turn out to be very important: renewables (geothermal energy), nuclear power, clean coal technologies via CO_2 Capture and Storage (CCS), Enhanced Oil Recovery (EOR), Enhanced Coal Bed Methane (ECBM), non-conventional gas exploitation, and seasonal storage of natural gas (also for strategic reserves). These technologies have been recently emphasized in Italy by the Ministry of Economic Development and by the Ministry of the Environment and Territory, as well as by research institutions such as INGV and CNR.

Key topics addressed during the Course were:

- Geological storage and disposal: assessment of available volume and structures.
- Subsurface geological resources: management of potential conflicts among various technologies.
- Geological site characterization and risk assessment for policy makers and regulators: the role of the energy industry.
- New high tech frontiers for geothermal power production.
- New concepts in nuclear waste disposal.
- Numerical simulation software for geothermal exploration, geological storage and nuclear waste disposal.
- Sharing subsurface data coming from oil & gas and geothermal exploration.
- High resolution characterization of shallow aquifers and reservoirs: multi-strata exploitation by different energy technologies.
- Case histories and natural analogues: "learning by doing" and "acceptable risk" concepts.

The 34th Course of the International School of Geophysics is dedicated to students and young contract researchers starting their carreers in a period of energetic-environmental global crisis. Although their scientific contribution is of high quality, they are usually underpaid in public research institutions with respect to volatile staff of some international organizations who, making use of the results of government-funded research, make final decisions on low-carbon energy technologies.

Fedora Quattrocchi and Enzo Boschi

The issues herein, along with the announcement of the 34th Course of the International School of Geophysics, were reported by Fedora Quattrocchi at the 182nd session of the 13th Standing Committee (Territory, Environment and Environmental Assets) at the Senate of the Italian Republic in Rome on June 8, 2010. The full-length text of the report (in Italian) is available at page 93.

Underground Gas Storage between Safety and Efficiency

Claudio Alimonti

Sapienza Università di Roma, Dipartimento Ingegneria Chimica Materiali Ambiente - Roma, Italy
claudio.alimonti@uniroma1.it

Underground gas storage (UGS) can be approached using the "4W" method: What, Why, Where and When. The first item to be taken into account is: What kind of gas will be stored? The larger part of underground storages concerns natural gases, some of them are industrial gases like propylene or butylene. CO_2 storage represents a new frontier in the control of GHG emissions from big production plants. The second item is Why. For industrial gases there is only shortage control on the contrary for natural gas there are regulation and strategic storage. The third element to be considered is: Where. Underground sites can be distinguished based on their origin: natural or anthropogenic. The last element is When. How long must a gas be stored? Is the storage cyclic or not? Answering the four questions is the primary way to understand how gas can be stored underground.

Gas can be stored in three principal types of underground structures: hydrocarbon reservoirs, aquifers and salt caverns. The main features of hydrocarbon reservoirs are the availability of a geological structure, high capital immobilization (cushion gas), working to cushion gas ratio between 0.5 and 2, large capacity volumes and deliverability rates, long lead time to increase capacity (3-7 years). Aquifers are an alternative to hydrocarbon reservoir and are somewhat similar. Aquifers basic features are the identification of confining layers, selective completion for water and sand management, high capital immobilization, similar working to cushion gas ratio of depleted reservoir as well as lead time for developing capacity.

In Italy, the gas storage know-how resulted from the modulation needs in the various activities linked to the production and distribution of natural gas. The first gas field was located at Cortemaggiore and at present, some other UGS are running. The gas national market characterized by a monopoly situation, has led to a single type of storage: in depleted fields. Gas reservoirs are quite widespread and are hosted mainly in terrigenous formations with porosity between 10-30% and an extremely variable permeability between 1 to 1000 mD. Most of gas reservoirs are hosted in Miocene and Pliocene formations constituted by more or less consolidated sand and clay. The onset of the transformation process of the energy system in our country has been setup on a natural gas basis. The big idea was to play a very important role as a hub of the European gas network. But geopolitics highlights the importance of storing gas to safeguard security of gas supply.

The control on GHG emissions is becoming more and more important and should be the final way to get into. A lot of companies have undertaken studies on the underground storage of CO_2, but few of them are real case studies. Serious gaps in the knowledge on CO_2 sequestration must be filled in order to meet safety requirements.

From an engineering point of view it is important to understand the real possible way to use a storage site and to recognize its optimal use. First of all the capacity of a site must be studied, particularly the two main systems hosting fluids in rocks: pores and fractures. The fraction of pores (porosity) ranges from a few percent to 30-40 percents of the structure total volume. Terrigenous formations are characterized by larger pore volumes while limestones present smaller volumes. Limestones are constituted by small pores connected in a network strongly affected by capillarity. The volume of fractures accounts for a few percent maximum of the reservoir bulk volume, with low or without capillary effects. The strong point of fractures is their permeability. Pores and fractures may form different types of reservoir depending on their volume ratio and can be represented by a single porosity or dual/double porosity model.

From an engineering point of view the reservoir efficiency is the main goal to be pursued. The injection/production efficiency is closely related to heterogeneities in media as well as to phase mobility in the media itself. Porosity, permeability and capillary pressure are the principal parameters controlling injectability/deliverability. Permeability is a key issue in media characterization. Are fractures more permeable than pores? How much are fractures and pores permeable to gas? These are the most common questions to be answered in order to understand reservoir behavior. Capillary pressures act on the pores system and have a significant influence on relative permeabilities. Capillary pressure is at the origin of residual gas saturation and connate water saturation. In gas-liquid multiphase flows an important parameter giving an idea of the displacement behavior is mobility, obtained from the ratio of relative permeability and viscosity of the two phases.

These aspects at pore scale affect the behavior at reservoir scale. The overpressure obtained injecting gas in an underground structure depends on how fast the gas is injected and on the total volume injected. The faster a gas injected, the higher the pressure increases. Thus, reservoir engineers are asked to plan the programme of injection and production in order to reduce overpressure and to inject the prescribed volume of gas. It will depend on the number of wells, the flow rate per well, the type of well, the location and the water activity. The last aspect is very important to distinguish the gas injection in depleted reservoirs from aquifers. If the water activity is low then the gas injection can be easily performed and the depleted reservoir can be refilled without any problems. When the water activity is high the pressure reservoir tends to increase rapidly and the injection can be quite difficult. In this case the injection in aquifers is similar to the one in depleted reservoirs. This is far more evident if the depleted reservoir is inactive from a long time. The aquifer tends to invade the pore space by increasing its pressure. In the long term the depleted reservoir will become an aquifer.

Optimizing the storage efficiency should be associated with an accurate risk assessment in order to guarantee the safety of the storage activity. Risk factors include natural events as seismic activity or accidental events as leakage from the reservoir or induced microseismicity. From an engineering point of view accidental leaks are the most important occurrences to be avoided. To prevent leaks from the structure due to overfilling, it is important to have a detailed structural model and to know the proper volumes to be injected and an inventory of both the injected and produced gas. The installation of monitoring wells is important to guarantee to correct storage activity. Wells and caprocks represent potential leakage points. Well cementing has to be executed following rules and best practices and be verified by leak testing. The caprock integrity should be ensured at small and at large scale. Small scale integrity concerns the entry of gas in the caprock and its migration to the surface. The entry of gas can take place if the local pressure is higher than the hydrostatic pressure plus the threshold pressure. Large scale integrity deals with caprock fracturing. Obviously it is necessary to know the fracture gradient in the caprock through leak testing. It will be used to estimate the maximum pressure in the reservoir before fracturing occurs. Risk studies [Evans, 2008] have demonstrated that failures in gas storages are highly rare (event failure rate $> 10^{-5}$) worldwide.

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Insight into Modern Geothermal Reservoir Engineering and Management Practice

Miklos Antics

GPC Instrumentation Process - Roissy CDG, France
m.antics@geoproduction.fr

Owing to the exhaustible nature of geothermal resources, sustainable heat mining is of utmost importance in designing and implementing relevant exploitation strategies aimed at reconciling users' demands with reservoir longevity concerns.

Sound and effective reservoir engineering allows developers to optimize energy extraction from a geothermal field and extend its commercial life.

The application of reservoir engineering begins during the exploration phase of the project with the analysis of the initial geophysical measurement data that indicate a promising geothermal system, and it continues throughout the operational life of the geothermal resource. It is the reservoir engineer's task to test wells, monitor their output, design new (make up, step out) wells, and predict the long-term performance of the reservoir and wells. This design and prediction is accomplished by studying field and operational measurement data and using computer models to project the field operation into the future in order to secure reservoir management. During operation of a geothermal field, the reservoir engineer will be able to compare the actual performance to the predicted performance. Whenever, the engineer can modify the exploitation strategy for the geothermal field to obtain more efficient operation.

Geothermal reservoir simulation is a technology that contributes to the important problem area of sustainable heat mining, and has become standard over the past decade. If sufficient information on the field is available then it is possible to construct numerical models of the reservoir and use these models to simulate field performance under a variety of conditions. Perhaps the most important and most challenging part of this process is the integration of information gathered by all the geoscientific disciplines leading to the development of the conceptual model. The success of any reservoir modeling exercise is dependent upon the flow of high quality information from the basic data collection phase, through the conceptual modeling phase, to the simulation process. This flow of information must go both ways, as the modeling process is an interactive one, often requiring numerous reconstruction and reinterpretation.

Once a geothermal resource has been identified and the reservoir assessed leading to a conceptual model of the geothermal system, reservoir development and relevant management issues come into play.

In the broad sense, reservoir management is an extension of reservoir engineering. Whereas the latter addresses key issues such as heat in place, reservoir performance, well deliverabilities, heat recovery, water injection and reservoir life, reservoir management aims at optimized exploitation strategies in compliance with technical feasibility, economic viability and environmental safety requirements.

Nowadays reservoir engineers are required to construct a realistic conceptual model of the field including sub surface temperature and pressure distributions in both vertical and horizontal planes, the distribution of chemicals and gases, field boundaries, reservoir storage and transmissivity, and the flow of fluids both within the reservoir and across the boundaries. The sources of information from which the model is deduced address well test results and down-hole measurements. The reliable interpretation of field measurements is therefore a major consideration for the reservoir engineer. The conceptual model of the field often provides sufficient understanding of the reservoir to enable informed and logical decisions on the field development and reservoir management issues.

Micro-Seismicity Monitoring for a Cushion Gas Storage Project in Italy

Paolo Augliera[1], Ezio D'Alema[2], Gianlorenzo Franceschina[1], Simone Marzorati[2], Marco Massa[1], Ernesto Marchesi[3] and Daniele Marzorati[4]

[1]*Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Milano/Pavia - Milano, Italy*
paolo.augliera@mi.ingv.it
[2]*Istituto Nazionale di Geofisica e Vulcanologia, Centro Nazionale Terremoti- Ancona, Italy*
[3]*Stogit S.p.A., Polo Operativo Cortemaggiore - Piacenza, Italy*
[4]*Stogit S.p.A., Sede Operativa di Crema - Cremona, Italy*

A Pilot Project for CO_2 injection and storage was proposed for a gas storage area located at Cortemaggiore (Piacenza), in northern Italy. This project is conducted both to verify the injection techniques and to analyze the potentiality of CO_2 as a cushion gas. Starting from 2004, a series of analysis has been conducted to verify suitability and feasibility of this operation. The injection phase will be preceded by a passive seismic monitoring in order to measure the background seismicity of the area. Seismic monitoring will be carried out during the 3 years of the injection phase and will continue also for a control period of 2 years, following the working phase.

The Milano - Pavia Department of the Istituto Nazionale di Geofisica e Vulcanologia is in charge of the surface seismic monitoring. To study the background seismicity a microseismic network composed by 7 seismic stations has been realized. On February 2010, a first test phase has been conducted for 3 sites. The network was completed with 4 more stations on May 2010. All stations are composed by a 24-bit digital recorder (Lennartz M24/NET) with GPS time signal. The study area is characterized by a very high anthropic and industrial noise. In order to improve the quality of the seismic signals, 4 stations have been installed in a 100 m deep borehole.

The seismic sensors (Lennartz LE-3D/BH for the borehole and LE-3Dlite MKI for the installation at the surface) have similar technical characteristics with 1 Hz free period, cutoff frequency at 80 Hz and dynamic range of 136 dB. In this first stage we analyzed the microseismic noise level and evaluated the detection capability of the network. Using the RMS measurements the borehole stations indicate a reduction on the noise by a factor of 2.5. A more detailed analysis, performed using the density function distribution of the power spectra, evidences a 10 dB gain for the borehole stations in the frequency band 1 - 10 Hz. Noise measurements have been used also to determine the minimum magnitude for the events detection. Using a point source model to simulate seismic events, we verified the expected detection levels by comparing the estimates obtained with the simulation and the local events recorded by the seismic network.

Acknowledgments

The installation of the borehole stations has been performed by Lennartz Electronics. Thanks in particular to D. Stoll for the useful suggestions in the test phase of the digital seismic recorders. Many thanks to the Stogit staff and personnel for the collaboration during the installation phases and in the following periodical field operations.

Probabilistic Seismic Hazard Analysis for Nuclear Waste Disposal Sites: Not Only Ground Motion

Simone Barani[1,2]

[1]*Università degli Studi di Genova, Dipartimento per lo Studio del Territorio e delle sue Risorse - Genova, Italy*
[2]*GEAmb S.r.l. - Genova, Italy*
barani@dipteris.unige.it

The definition of sites for nuclear waste storage and disposal, as well as the design of facilities like nuclear power plants and pipelines, require detailed geohazard studies necessary to quantify the level of risk to which facilities are exposed. For example, the identification of fault activity is of great importance for the evaluation of the risk that facilities could be subjected to displacements caused by tectonic movements along a fault during their life. Similar considerations apply to landslides and ground shaking levels induced by seismic activity. Given this premise, the study will focus on earthquakes hazard, describing probabilistic methods and approaches to seismic hazard assessment.

The term "Probabilistic Seismic Hazard Analysis" (PSHA) is commonly used to indicate a probabilistic method to assess the ground motion level expected at a site during a given period of time. However, a more general and correct definition of PSHA should take into account a variety of earthquake characteristics, such as fault displacements, earthquake-induced slope displacements, and, obviously, shaking levels. A schematic diagram illustrating the main stages of a generic PSHA is shown in Figure 1.

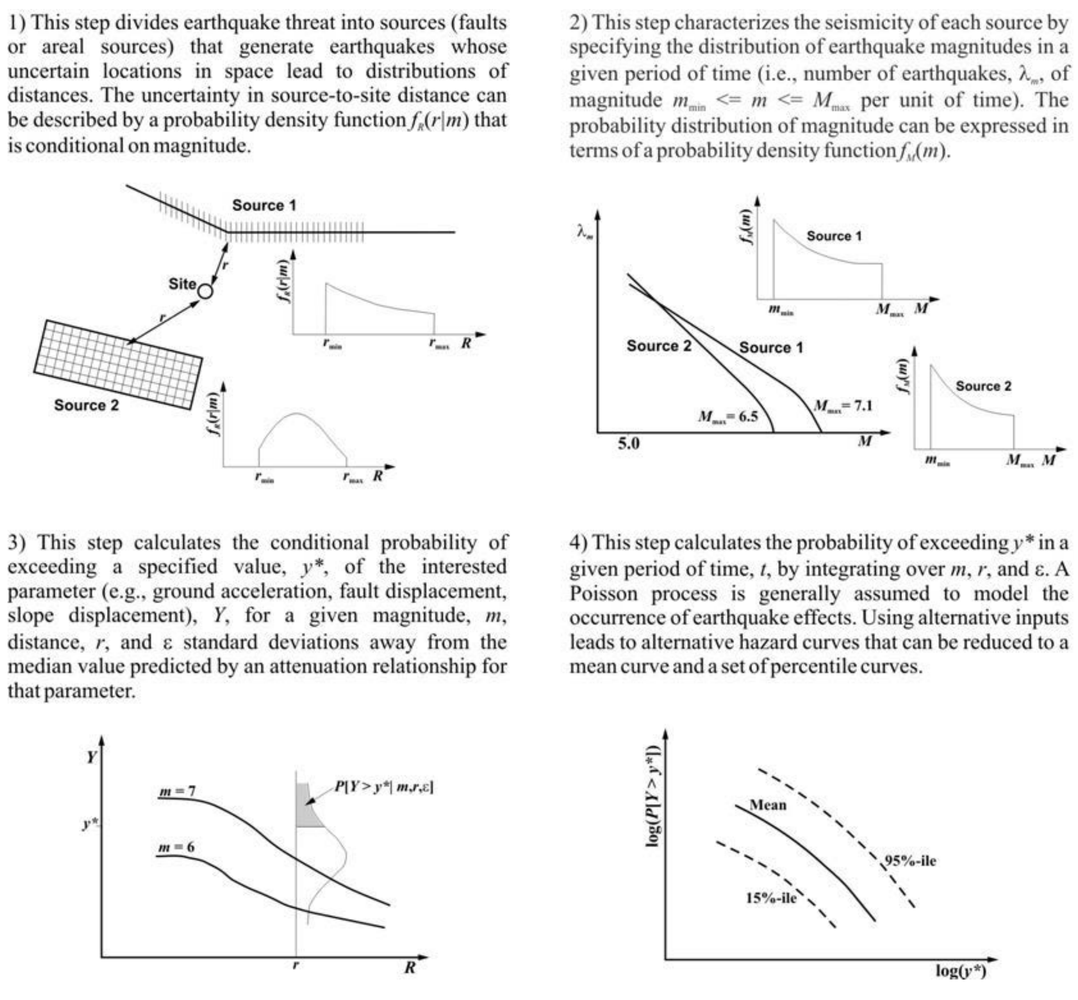

Figure 1. Four steps of a PSHA. Modified from McGuire [2004].

Therefore, a PSHA can be defined as a process that calculates the likelihood of occurrence (or, alternatively, the probability of exceedance) of a characteristic earthquake at a site during a given period of time. The aim of this work is to present advanced approaches for a comprehensive hazard evaluation at sites where to place nuclear waste disposal facilities. To this end, the following geohazards should be taken into account and evaluated: ground motion, slope displacement, and fault displacement. Contextually, ground response studies (numerical and experimental) cannot be neglected, as they allow the evaluation of possible amplification effects related to local geological features. The quantification of these effects is of first importance for a reliable site-specific ground motion hazard assessment that includes nonlinear soil effects.

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New Technologies for the Sustainable Development of the Geothermal Energy

Fausto Batini

Coordinator of EERA_Joint Programme on Geothermal Energy - Pisa, Italy
f.batini@sssup.it

Geothermal energy is a non-carbon-based renewable energy source, able to provide base load power for electricity and heat generation in many countries around the world. In continental Europe the geothermal potential is estimated to be over 50.000 MW, but only in Italy, Iceland, and Portugal is it harnessed for the generation of electricity (over 1.400 MW). In several European countries it is also used on a small or district scale, mainly for heating supply and heat/chill storage. The development scenarios foresee about 5 - 6000 MW of installed geothermal electric capacity within 2020 and between 15.000 and 30,000 MW within 2030.

To realize such an increase is beyond the scope of available mature technology and requires the development of new cost-effective technologies for:

- significantly enhancing the production from already identified and utilized resources;
- exploring at large scale new untapped deep seated (up to 6 km) hydrothermal systems;
- making Engineered Geothermal ready for large scale deployment,
- accessing new extreme “high potential” resources such as Supercritical fluids and Magmatic systems.

Beside the technological challenges other aspects of relevance for the further development of geothermal energy require to be addressed with innovative approaches and tools to:

- improve the risk assessment and management for a reliable evaluation of the technical, environmental and economical sustainability of the projects;
- secure the social acceptance of geothermal projects by ensuring that potential site and technology specific side effects are typically relatively minor compared to the benefits;
- provide the guidelines to the Regulatory Authorities and Policy Makers for sustainable development of geothermal initiatives.

To face these challenges the EERA (European Research Alliance) launched a strategically oriented Joint R&D Programme on Geothermal Energy (JPGE) aimed at accelerating the development of next generation geothermal technology in order to provide industry with all the elements required for its large-scale and cost-effective deployment.

The main areas of research and technological innovation which requires major efforts to made available new geothermal resource suitable for increasing electricity and heat/chill generation are:

- Resource Assessment.
- Accessing and Engineering of the Reservoir.
- Process Engineering and Design of power systems.
- Operation and Management of Geothermal Systems.
- Environmental sustainability.

The milestones to meet these challenges and the expected results for a cost-effective geothermal project development will be discussed as wells barriers and obstacles, which avoid a faster growth of this clean and efficient base-load power supply.

Geological Storage of CH_4 and CO_2 in Deep Saline Aquifers

Roberto Bencini

Independent Resources plc - Roma, Italy
rbencini@ir-plc.com; www.ir-plc.com

Storage of methane (CH_4) and carbon dioxide (CO_2) in deep saline aquifers is a proven technique and a promising strategy to respectively address mitigation of climate change and energy security regarding additional methane demand during cold weather. These themes are attracting growing interest within both scientific and industrial communities.

According to one of the leading scientific research foundations in geosciences in Italy [Donda et al. 2010] "Deep saline aquifers offer the largest storage potential among all the geological CO_2 storage options, and are widely distributed throughout the Earth".

Moreover, according to the International Gas Union [IGU, 2010] "The sciences and technologies that Underground Gas Storage (UGS) operators use for methane storage, especially for aquifers storage, are a solid basis for CO_2 sequestration projects", highlighting, in an authoritative way, the strong technical interconnection between these two industrial sectors.

The reservoirs most commonly considered for CH_4 and CO_2 underground storage are the sandy type, often in semi-depleted hydrocarbon fields. Sandy porous reservoirs can provide relevant total volumetric capacities although often associated with limited permeability.

An interesting alternative is given by large and thick, massive carbonates sedimentary bodies (e.g., shallow water carbonate platforms in the peri-Tethys realms), which are usually intensively and pervasively fractured. In this reservoir type, the apparently limited volumetric capacity (due to limited primary and secondary porosity) is compensated by the usually large trap size. At the same time, well connected fracture systems can provide very high permeability (i.e., 20 - 50 Darcy).

Therefore, in industrialised areas without enough semi-depleted hydrocarbon fields, but where carbonate platform are well developed, aquifers in fractured carbonate reservoirs are primary targets for both CH_4 seasonal storage and CO_2 geological sequestration.

Noteworthy, the high permeability provided by extensive fracture systems guarantees significant deliverability which is a key-issue for the commercial viability of storage projects. In CO_2 storage, the higher the permeability the less the number of required injection wells. In CH_4 projects, the high deliverability is essential to effectively inject and produce gas during the seasonal cycles, while the strong water drive minimizes the need of cushion gas. In addition, aquifers are less likely to have suffered the density of drilling associated with depleted hydrocarbon fields and are therefore less prone to the problems typically related to integrity issues at old wells.

In Italy, several storage projects in fractured carbonate aquifers are underway. A major underground methane storage site (Rivara Project) is being planned by ERG Rivara Storage srl (ERS) in a fractured carbonate reservoir in the Italy's Po Valley. Rivara's working capacity is estimated at approximately 3.2 billion cubic metres (bcm), which would make it one of the largest and potentially best performing gas storage facilities in Italy and in Europe.

Additionally, several sites in naturally fractured carbonate aquifers are being evaluated for potential CO_2 storage, including an off-shore site in the continental platform of the Tyrrhenian Sea.

Major efforts are in progress to properly characterise these storage sites and to plan their safe operation ahead of the beginning of the construction phase, including reservoir and caprock stratigraphy and structure, geomechanics, reservoir engineering, geochemical and seismological monitoring. These research activities are carried out by integrated teams involving, among others, industry members (e.g., ERS and Schlumberger) and research institutions (e.g., IGAG-CNR, Sapienza Università di Roma, Università degli Studi di Catania, Università degli Studi di Bologna, and Istituto Nazionale di Geofisica e Vulcanologia).

Worldwide, some 600 underground natural gas storage sites are in operation, of which approximately one half have been in operation for more than 40 years. Around 85 sites are hosted in deep aquifers, while the rest are hosted in other types of structures (mostly former gas fields). Considering the 483 natural gas storage sites hosted in a reservoir rock (either aquifers or former gas fields), some 133 are making use of fractured carbonate rocks (limestone and dolomite naturally fractured), corresponding to 27% of this group.

Only a handful of underground CO_2 storage projects are today in operation at industrial scale, worldwide. Of these, most use deep saline aquifers (Sleipner, Snohvit, Gorgon), while one (Weyburn), the most studied, uses naturally fractured carbonates.

An innovative, multidisciplinary and integrated work flow has been identified (Figure 1). The work programme is designed to determine the feasibility and the safety of the gas storage project, either CH_4 or CO_2. This includes two main phases, namely:

- Initial Phase;
- Appraisal Phase, which repeats the cycle in more details.

Each phase involves the following integrated sequential stages:

- Analysis of pre-existing data (wells, exploration seismology);
- 3D geologic modelling;
- 3D reservoir modelling;
- 3D geomechanical modelling.

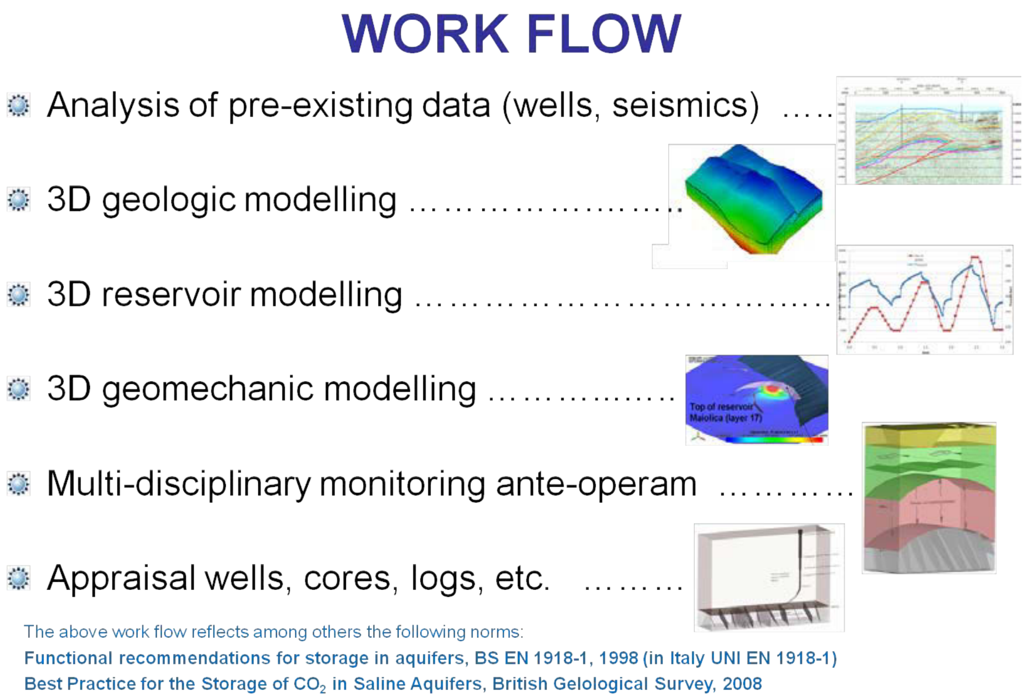

Figure 1. Integrated multidisciplinary work flow for the exploration and appraisal of underground storage sites for methane or CO_2.

The Initial Phase involves all the data gathering activities that can be implemented without a specific licence, while during the Appraisal Phase the activities include the acquisition of geophysical data and the drilling of wells, which require specific authorization and license. The key elements of the Appraisal Phase, in fact, are the acquisition of a new 3D reflection seismic survey and the drilling of explorative wells with the associated specialized activities (cores, logs, reservoir test). Before the beginning of the construction phase, it is also important to implement a multidisciplinary monitoring programme ante-operam, in order to have the basic elements for detecting any change that may occur after the beginning of the site operations.

While underground methane storage activities are fully regulated in Italy, underground storage of CO_2 is not yet currently regulated. Italy is however about to adopt the European Directive 2009/31/CE of 23 April 2009 on the geological storage of carbon dioxide. Figure 2 shows the comparison between the UGS licensing system and the CO_2 storage licensing system likely to be implemented in Italy.

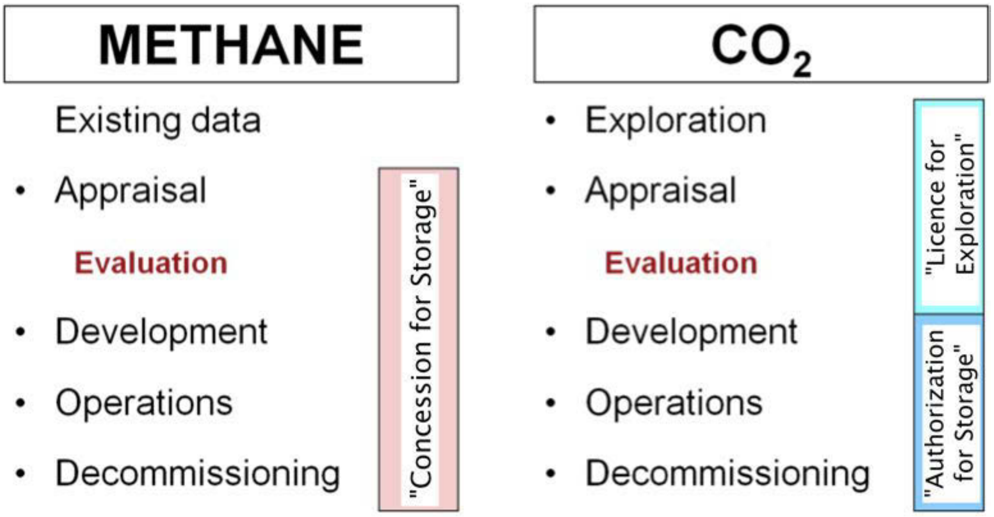

Figure 2. Comparison between the current licensing system for CH_4 underground storage and the draft licensing system for CO_2 underground storage in Italy.

The adopted work flow includes the following sub-phases:

a) Acquisition of all available geological and engineering data from previous hydrocarbon explorations and production activities, surface geological surveys, deep boreholes for industrial or drinkable water. This includes 2D geophysical prospecting (seismic reflection), oil and gas well profiles, deep stratigraphy, rock composition and age, electric and special logs and the results of their analysis, petrophysical analyses on cores, flow test results, fluids temperature, pressure and composition, geomechanical data, and other specialized subsurface data.

b) Seismological study of the area of interest, in order to determine earthquake hypocenters and focal mechanisms, and assess historical seismicity. This study aims at identifying all the active or potential seismogenic sources in a vast area providing fundamental data to understand the geodynamic framework of the structure. These data represent the basis for the microseismic study of the project area and the safe engineering of the surface facilities.

c) Interpretation of the seismic reflection data (2D and 3D, where available), including well-to-seismic ties by using time-depth curves for the wells located along the available seismic sections. The interpretation is quality controlled from the structural geology standpoint by balancing in 2D (and 3D if possible) the geological cross-sections resulting from geophysical interpretation. The goal of this sub-phase is to reconstruct and model in detail the subsurface geometry of as many layers and horizons as possible, particularly the top of the reservoir, and at the same time the geometry of all the active or extinct faults that are likely to be located within the volume of pore pressure change due to storage operations (Figures 3 and 4).

d) Construction of a static reliable 3D geologic model of the subsurface, including as many layers as possible from the surface to reasonably below the bottom of the hydrologic unit that comprises the reservoir earmarked for gas storage. Each layer and cell of the model is to be characterized by relevant geologic and petrophysical properties. Data coming from the petrophysical analyses of well logs and cores will be used to populate the matrix section of each cell. Available natural fracturing attributes and properties, such as fracture spacing in the three direction in space, fracture aperture and length, will be used to characterize the fracture system of the reservoir. The analysis will be integrated within an appropriate sedimentological facies distribution model. Alternatively, data from analogue reservoir rocks or from fracture models based on analysis of look-alike structures and reservoir rocks in outcrop will be used (Figures 3 and 4).

e) Verification of the hydrological properties of the cover rocks through the exam of the permeability of the sediments based on lithology (claystone, marl, etc.) and on scarcity and vertical discontinuity of natural fractures. Available formation test data are important in this context, because a tight test (no flow, no fluid recovery) represents a strong element to establish the impermeability of the tested formation. Also, any information on the density of the drilling mud is important, as well as data on mud losses (with a given mud weight), and water or gas inflow into the borehole (knowing the mud density during the occurrence of the phenomenon). The density of drilling mud indicates, with a high degree of certainty, the presence or absence of overpressure in the formations drilled by relevant wells. Leak-off data in the cover series are important too, as they represent a high quality indication of the pressure at which the cover rock would fracture under fluid pressure, and therefore of the maximum pressure that the stored gas can apply to the roof of the storage reservoir. Additionally, the combination of rock density, mud weight, borehole break-out direction and leak-off data may indicate the orientation of the stress ellipsoid in the subsurface, helping with the evaluation of the geomechanical stability at different depth. In summary, documenting a thick and laterally continuous series of clay-rich sediments, particularly if overpressured, is equivalent to documenting the existence of an excellent impermeable cover rock above the reservoir of interest (Figure 5).

f) 3D reservoir simulation and numeric hydrodynamic modelling. This is done by characterizing each grid cell representing the reservoir rock with pressure, temperature, fluid composition, fluid saturation and relative permeability data (initial data), and assuming well number, well geometry and flowing data such injection or extraction (dynamic data). The simulation obtains fundamental indications about the behaviour of the injected gas and of the formation water within the reservoir rock during the operational cycles. Results include the maximum static and dynamic pressure at the top of the reservoir during the injection and extraction cycles, the likely amount of working gas and cushion gas, injectivity and productivity of each well, the aquifer volume likely affected by pressure variations (Figures 6 and 7).

g) 3D geomechanical modelling of the structure, based on geomechanical properties derived from lab data or directly from well logs (Figure 8, left). Each layer and cell of the 3D grid is populated with such properties (Figure 8, right). The model documents the stress ellipsoid in the subsurface and calculates the strain in each cell of the model during the injection and extraction cycles, including the strain along each segment of the faults within the model volume (Figure 9). The main result of the 3D geomechanical model is the ability of estimating if the gas storage operations are able or not to create or reactivate any fault in or around the storage structure. The model, in other words, documents the degree of geomechanical and seismological stability of the structure under operational conditions.

h) Monitoring of environmental parameters (air quality; emissions; noise) and of subsurface parameters, both before the start of the construction works (soil gas; temperature, pressure and chemistry of near surface aquifers; precision altimetry from satellite interferometric techniques; high precision GPS; natural seismic activity monitored with surface stations), and during the gas storage activities (same parameters as ante-operam; plus possible induced seismicity monitored with geophones at the bottom of the wells; gas temperature, pressure and saturation inside the reservoir rock and possibly also above the reservoir rock; flow rate, temperature, pressure and composition of injected and produced gas).

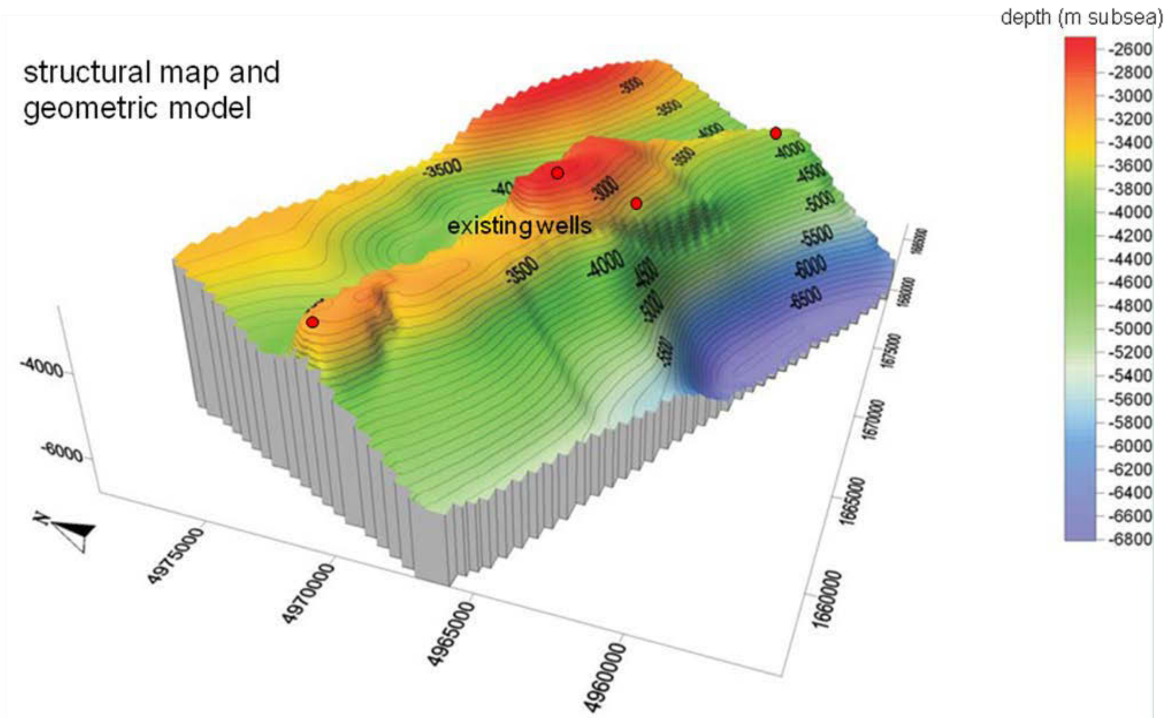

Figure 3. 3D geometric model (top reservoir, subsea depth) of a geologic structure earmarked for methane underground storage in deep saline aquifer with naturally fractured carbonate reservoir (northern Italy).

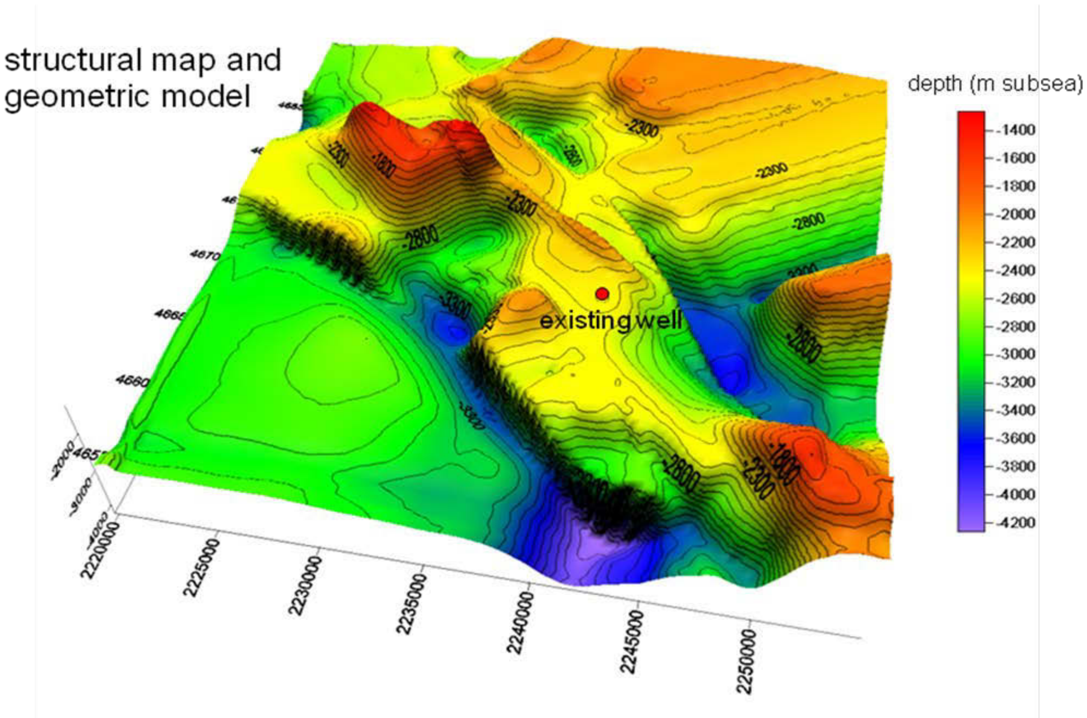

Figure 4. Preliminary 3D geometric model (top reservoir, subsea depth) of a geologic structure earmarked for CO_2 underground storage in deep saline aquifer with naturally fractured carbonate reservoir (Tyrrhenian Sea).

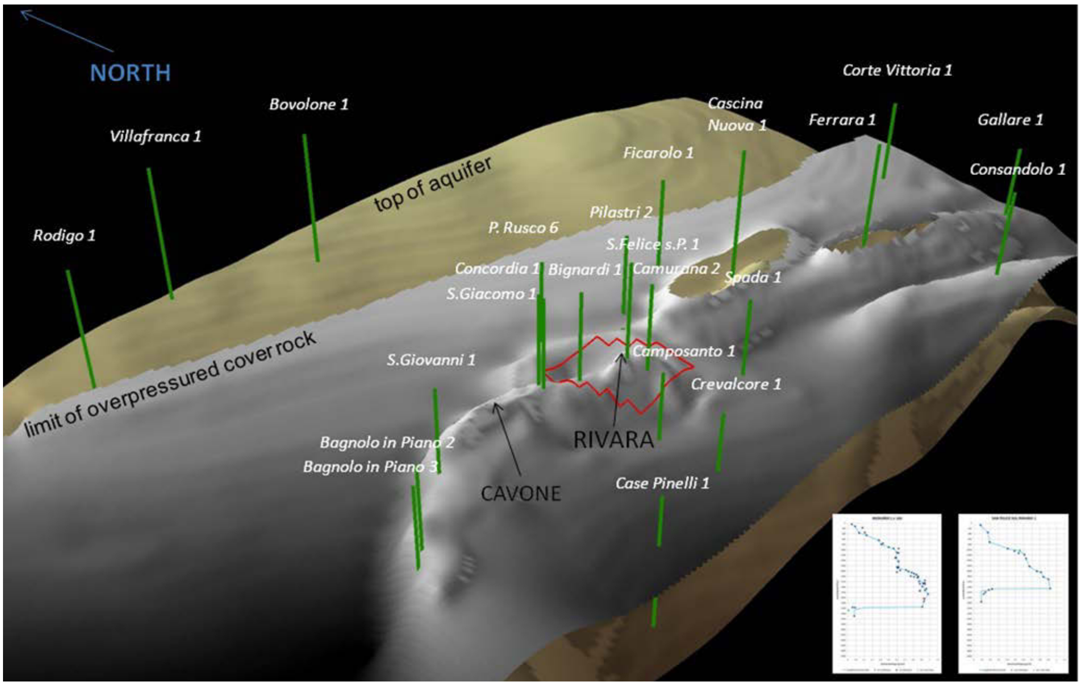

Figure 5. 3D rendering of the surface that limits upward the laterally unconfined aquifer of the Mesozoic carbonates (top of aquifer), and of the surface that limits upward the laterally continuous claystone and marl sequence with overpressure (totally impermeable rocks) that acts as cover to the underlying reservoir rock, northern Italy. The status of overpressure is demonstrated by the heavy mud necessary during drilling operations (see for example the two inserts at bottom right of the Figure).

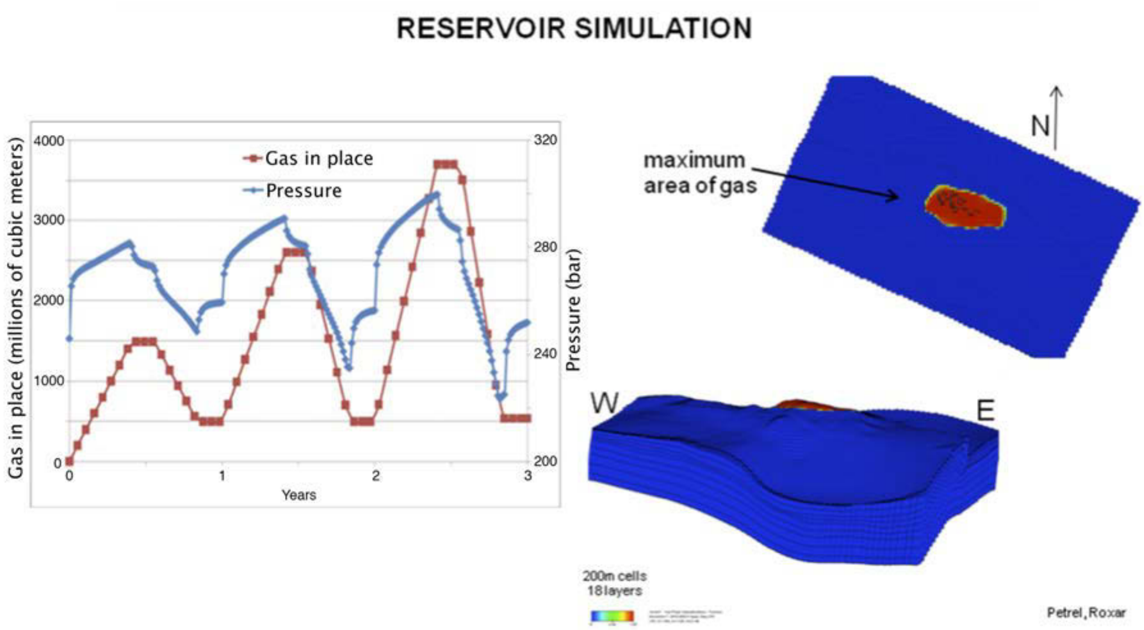

Figure 6. 3D reservoir simulation for a geologic structure earmarked for methane underground storage in an unconfined deep saline aquifer hosted in a naturally fractured carbonate reservoir (northern Italy). The graph on the left shows the gas inventory during the three initial annual cycles of methane injection and withdrawal, and the quantity of gas that remains in the reservoir as cushion gas (red curve, scale on the left). The blue curve (scale on the right) shows the modest cyclical oscillations of the formation pressure at the apex of the structure (much below the possible maximum according to UNI norms).

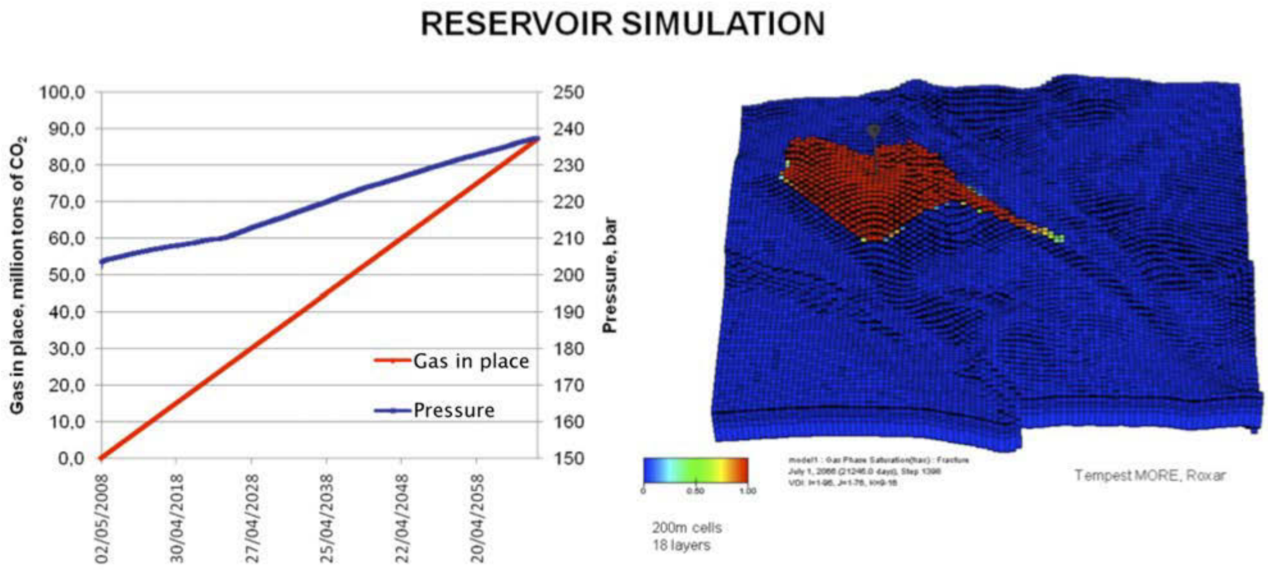

Figure 7. 3D reservoir simulation for a geologic structure earmarked for CO_2 underground storage in an unconfined deep saline aquifer with naturally fractured carbonate reservoir (Tyrrhenian Sea). The graph on the left of the figure shows the gradual filling of the reservoir during 58 years of CO_2 injection (87 million ton of CO_2 capacity to the spill point of the structure, red curve, scale on the left). The blue curve (scale on the right) shows the modest gradual increase of the formation pressure at the apex of the structure during the filling process (up to 18%, much below the possible maximum according to UNI norms).

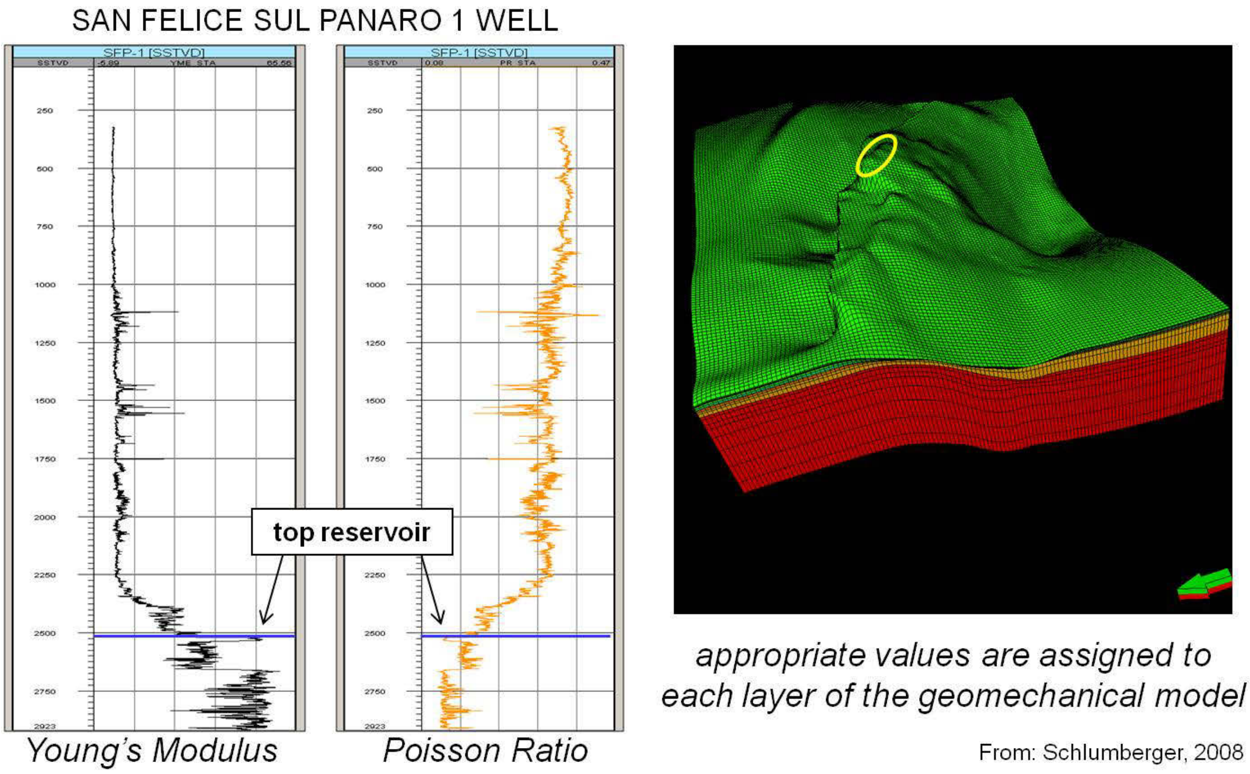

Figure 8. 3D geomechanical modeling of a geologic structure earmarked for methane underground storage in an unconfined deep saline aquifer with naturally fractured carbonate reservoir (northern Italy). The geomechanical properties of the cover rock and the reservoir rock have been derived directly from petrophysical measures taken in the most relevant well (left), and were assigned to each layer of the 3D geomechanical model (right).

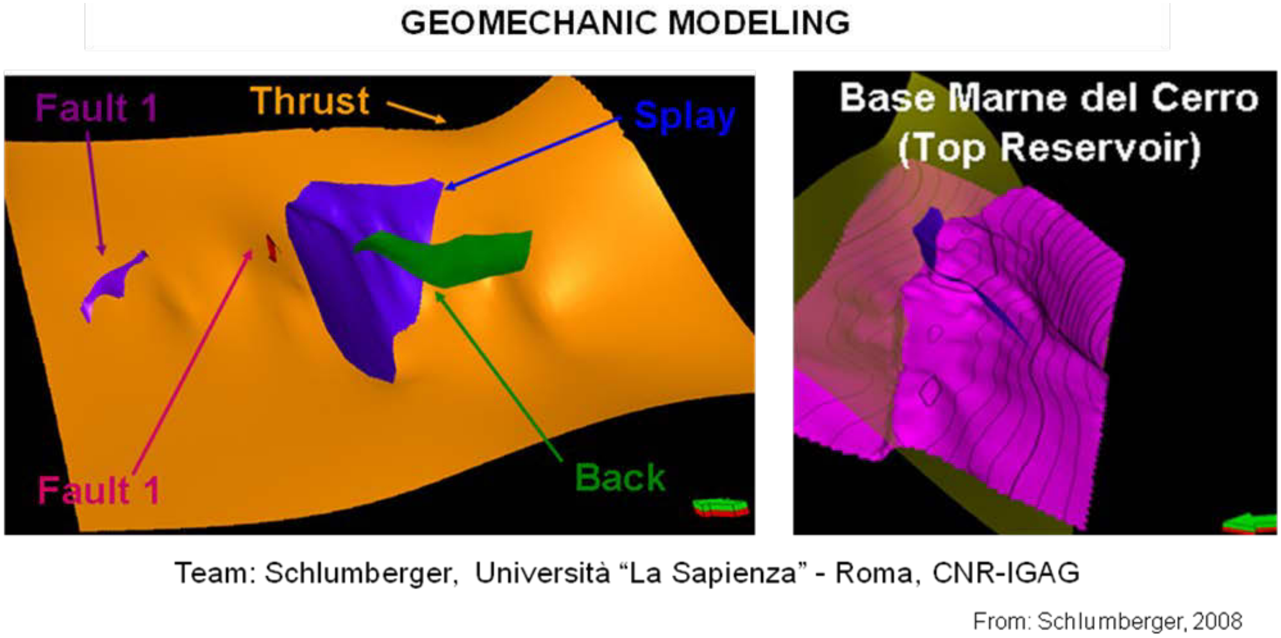

Figure 9. 3D geomechanical modeling of a geologic structure earmarked for methane underground storage in unconfined deep saline aquifer with naturally fractured carbonate reservoir (northern Italy). The seismological stability of all the relevant faults during the injection and withdrawal cycles have been confirmed. The fluid phase is not geomechanically coupled to the rock matrix because of the large permeability of the natural fracture system.

During each phase of the work flow all the available data are used. This means that the second phase, the Appraisal Phase, is intentionally redundant and complete, and results of this phase are able to guarantee safety and feasibility of the storage project, in the interest of all stakeholders (industrial operator, awarding and control Authorities, local Administration and the public).

Independent Resources plc poses itself, through its companies in Italy (Erg Rivara Storage srl, and Independent Gas Management srl) as a competent specialized operator for the safe development of CH_4 and CO_2 underground storage sites in deep saline aquifers hosted in naturally fractured carbonate rocks.

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The Outlook for Energy: A View to 2030

Piero Biscari

Exxon Mobil Corporation, Esso Italiana - Roma, Italy
piero.biscari@exxonmobil.com

In our "Outlook for Energy – A View to 2030" study, as ExxonMobil we see many hopeful things: economic recovery and growth, improved living standards and a reduction in poverty, and promising new energy technologies. Furthermore we see a tremendous challenge: how to meet the world's growing energy needs while also reducing the impact of energy use on the environment.

ExxonMobil expects that global energy demand in 2030 will be almost 35 percent higher than in 2005, even accounting for the recession that dampened energy demand in 2009, going from 470 to 630 quadrillion of British Thermal Units (QBTU's).

To fully understand the energy outlook in coming decades, we need to examine what's going on in the OECD (Organization for Economic Cooperation and Development) countries (like the United States and European nations) and non-OECD nations (such as China and India), because the trends in these two groups can be starkly different.

Through 2030, the economies of non-OECD countries, while still relatively smaller, will grow at a much faster rate than those of the OECD. By 2030, these developing economies will have reached close to 40 percent[1] of global economic output. In non-OECD countries, rapid economic growth is expected to produce a steep climb in energy demand. In fact, ExxonMobil expects that between 2005 and 2030, non-OECD energy demand will grow by about 72 percent. However, even with this rapid growth, per-capita energy demand in non-OECD countries still will be much smaller than in OECD countries.

By contrast, in OECD countries, energy demand is expected to be slightly lower in 2030 versus 2005, even though their economies will be more than 50 percent larger on average.

How is this possible? The main reason is energy efficiency. ExxonMobil continues to project substantial improvements in energy efficiency both in OECD and non-OECD countries. But in non-OECD countries the faster growth in Gross Domestic Product (GDP) and personal incomes will continue to drive higher energy demand.

Broken down by the end-use sectors, the biggest demand for energy comes from electric power generation – a fact that might surprise some people, who may think that transportation is the largest. Power generation is not only the largest energy-demand sector, but also the fastest-growing.

Through 2030, this sector will represent 55 percent of the total growth in energy demand going from 16.000 to 28.000 TeraWatt/hour (TWhr). 80 percent of total growth in electricity demand is non-OECD countries which will have exceeded OECD power generation demand by 2015 and more than doubled electricity demand through 2030.

Transportation is one of the fastest growing energy demand sectors rising from 44 MBDOE (Million Barrels per Day Oil Equivalent) in 2005 to almost 60 MBDOE in 2030. Over the same period light-duty vehicles (cars, SUVs and light pickup trucks) demand flattens as more efficient vehicles enter the market, while heavy-duty vehicles (trucks and buses) grow the most, becoming the largest transportation demand segment.

We can classify transportation into two basic categories: personal and commercial. In both of them, but especially in personal vehicles, today energy consumption in OECD countries is higher than non-OECD. By 2030, the OECD personal transportation demand is expected to drop by 25 percent, while non-OECD demand will be more than doubles (from 4 to 8.5 MBDOE). Commercial transportation demand will grow in

[1] The projections and Figures provided in this article are ExxonMobil's internal estimates and forecasts based upon internal data and analyses as well as publicly available information from external sources including the International Energy Agency.
Actual future conditions (including economic conditions, energy demand and energy supply) could differ materially due to changes in technology, the development of new supply sources, political events, demographic changes, and other factors discussed herein and under the heading "Factors Affecting Future Results" in the Investors section of our website at: www.exxonmobil.com.

all regions, but far more rapidly in non-OECD countries. By 2030, these fast developing nations will have overtaken the OECD as the largest source of commercial transportation demand.

Efficiency improvements in each sector will add up to significant energy savings each year – reaching 300 quadrillion BTUs per year in 2030, which is about twice the growth in global energy demand through 2030. Most of the energy saved through efficiency will be in OECD countries.

What types of supplies will we use to meet this rising need for energy through 2030?

Fossil fuels (oil, natural gas and coal) will continue to meet most of the world's needs during this period, accounting for nearly 80 percent of demand. Among them the fastest-growing fuel will be natural gas, since it is the cleanest-burning. By 2030, global demand for natural gas will be about 62 percent higher than it was in 2005.

Nuclear power will also grow significantly to support increasing needs for power generation.

Wind, solar and biofuels will grow sharply through 2030, nearly 10 percent per year on average. However, since they are starting from a small base, their contribution by 2030 will remain relatively small at about 2.5 percent of total energy.

No single fuel can meet the energy challenges. To satisfy projected increases in global energy demand to 2030 – and ensure reliable and affordable energy – we will need to expand all economic fuel sources. But all of this work doesn't come without a price. The International Energy Agency predicts that the total investment needed in the world's energy sector from 2007 to 2030 is about $26 trillion. Spending devoted to oil and gas is estimated to be about 45 percent of the total, close to $500 billion per year.

From 2008 - 2012, ExxonMobil anticipates investing 125 billion dollars across the globe – an average of 25 billion dollars annually. Significantly more than what invested in 2004 - 2009 period (20 billion dollars annually).

Rising emissions of anthropogenic CO_2 and other greenhouse gases expose society and ecosystems to significant risks. Since most of these emissions are energy-related, any integrated approach to meeting the world's growing energy needs over the coming decades must incorporate strategies to curb emissions and tackle risks associated to climate change. These strategies will need to be implemented by both OECD and non-OECD countries.

The outlook for energy-related CO_2 emissions is linked directly to the types and amounts of energy required around the world. By 2030, global CO_2 emissions are likely to be about 25 percent higher than they were in 2005. While this is a significant increase, it is substantially lower than the projected growth in energy demand over the period. This positive development is the result of expected gains in efficiency, as well as a shift over time to a significantly less carbon-intensive energy mix – mainly natural gas, nuclear and wind, gaining share as fuels for power generation.

Natural gas used for power generation can result in up to 60 percent less CO_2 emissions than coal, currently the most widely used fuel for power generation.

Broken down by end-use sector, power generation accounts for the largest share of the growth in CO_2 emissions through 2030. This is not only the fastest-growing demand sector, but also the one that relies most heavily on coal.

From 1980 to 2005, OECD energy usage became both more efficient and less carbon intensive.

Growth in CO_2 emissions through 2030 will be dominated by China, India and the other non-OECD countries. Non-OECD emissions surpassed OECD emissions in 2004; by 2030, non-OECD countries will account for two-thirds of the global total.

Meanwhile, OECD emissions will decline by about 15 percent, and by 2030 will be down to 1980 levels. Beyond 2030, further gains are likely as OECD countries continue to pursue efficiency and shift to less-carbon intensive fuels to help mitigate risks associated with CO_2 emissions.

Managing GHG emissions and meeting growing energy demand is indeed an enormous challenge. But, thanks to technology and innovation, it is not an insurmountable challenge. As history has shown, the way in which we produce, deliver and use the world's oil and natural gas endowment constantly changes.

Natural gas will provide a growing share of the world's energy through 2030 and since it burns cleaner than oil and much cleaner than coal, natural gas is a powerful tool for reducing the environmental impact of energy use. Natural gas used for electricity can reduce CO_2 emissions by up to 60 percent versus coal, which today is the most popular fuel for power generation. It also has fewer emissions of sulfur oxides and nitrogen oxides. ExxonMobil produces more natural gas than any other public company in the world. We also develop breakthrough natural gas technologies that make more of this cleaner burning fuel available to consumers around the world. In the United States, ExxonMobil technologies have unlocked vast new resources of natural gas that previously were trapped in dense rock formations, as well as other types of so-called "unconventional" natural gas.

ExxonMobil is a leader in the development and use of component technologies essential for carbon capture and storage (CCS), which we have focused on in our oil and gas operations for many years. The ability to capture, transport, and store CO_2 safely and efficiently represents an important opportunity for reducing global GHG emissions.

Through projects in Australia, Norway, the United States, and other areas of the world, ExxonMobil engineers and scientists are developing and validating leading-edge technologies that could help to expand opportunities for the use of CCS over time. Our LaBarge Shute Creek facility in Wyoming has been capturing, transporting, and selling CO_2 since 1987. We are currently expanding this capability by nearly 50 percent and significantly reducing overall emissions.

ExxonMobil is committed to develop and test an improved natural gas treating technology for CO_2 removal called CFZ™. The technology is undergoing commercial-scale qualification in a new demonstration plant at our LaBarge facility. The CFZ™ technology more efficiently separates CO_2 and other impurities from natural gas, and discharges the CO_2 as a high-pressure liquid, ready for injection into underground storage.

ExxonMobil believes that biofuels from photosynthetic algae could someday play an important role in meeting the world's growing need for transportation fuels, while also reducing CO_2 emissions.

In July 2009, ExxonMobil announced a significant new project to research and develop algae biofuels. The partner is Synthetic Genomics Inc (SGI), a California-based biotech firm founded by genome research pioneer Dr. J. Craig Venter. The goal of the program: to produce a commercially scalable, renewable algae-based fuel compatible with today's gasoline, diesel and jet fuel.

ExxonMobil is developing an innovative technology called "*on-board* hydrogen-powered fuel cell system". This system converts conventional hydrocarbon fuels, such as gasoline or diesel, into hydrogen for a fuel cell right under a vehicle's hood. No new power plants or service stations required. The benefits are clear. Measured on a "well-to-wheels" basis, this on-vehicle hydrogen fuel system could be up to 80 percent more fuel-efficient and emit 45 percent less carbon dioxide than today's internal combustion engine.

Using our expertise not only in fuels and lubricants, but also in chemicals and plastics, we are advancing new technologies to make vehicles more fuel efficient. Conventional vehicle efficiency improvements will be a key in reducing personal transportation fuel demand in the OECD by 2030.

Working with major tire manufacturers, ExxonMobil developed a new tire-lining technology that uses up to 80 percent less material in the manufacturing process, making tires lighter and keeping them properly inflated. A car with underinflated tires burns up to an extra tank of gasoline every year.

ExxonMobil believes that meeting future energy needs while also reducing environmental risk will require an integrated set of solutions that includes:

- accelerating energy efficiency, which tempers demand and saves emissions;
- expanding all economic energy sources, including oil and natural gas;
- mitigating emissions through the use of new technologies and cleaner-burning fuels such as natural gas, nuclear and other renewable sources.

This multidimensional approach will need trillions of dollars in investment, and an unwavering commitment to innovation and technology that evolves over years and decades. It will require sound, stable government policies that enable access to resources and encourage long-term investments and technological development. And it will require the global energy industry to operate on a scale even larger than today.

Updated each year, The Outlook for Energy is a comprehensive look at long-term trends in energy demand, supply, emissions and technology. The report is built upon detailed analysis of data from about 100 countries, incorporating publicly available information as well as in-house expertise.

The Outlook for Energy is available on our Web site at www.exxonmobil.com.

CO_2 Capture and Geological Sequestration: The First Italian Experience

Bruno Boiardi

eni exploration & production - San Donato Milanese (Milano), Italy
bruno.boiardi@eni.com

On 21 October 2008, eni and Enel signed a Strategic Cooperation Agreement to develop technologies for CO_2 capture, transport and geological sequestration and to accelerate the deployment of Carbon Capture & Storage (CCS). Among other goals, the cooperation program includes the construction of the first integrated CCS pilot project in Italy, combining the Enel's CO_2 post-combustion capture plant in Brindisi and the eni's pilot CO_2 injection plant in a depleted gas field at Cortemaggiore (Piacenza).

The different phases of the project will be described, and particular evidence will be given to the description of the injection site, together with the preparatory studies and the monitoring plan that were developed for the proper evaluation of all technical issues related to injection and monitoring of CO_2.

The start of the CO_2 injection is scheduled for mid of 2011.

The Long Term Isolation Capacity of the Geological Barriers as Demonstrated by Natural Analogues

Aldo Brondi

Università degli Studi della Tuscia - Viterbo, Italy
fabio.bro@tiscali.it

When it comes to assessing the safety of geological disposal for radioactive waste, one of the major causes of uncertainty is the very long period of time under consideration (many hundred thousand years). The world scientific community has from many years realized that “natural analogues” offered by nature are the best, if not the only, support to the long term conclusions of safety assessments. They are processes similar to those thought as operating around a repository and also active over long time span under different evolutive conditions.

These natural analogues are progressively providing confirmation for the majority of scientists of various disciplines involved in radioactive waste disposal research and development of safe disposal options. Natural analogues are also providing clear evidences of the reliability of the geological disposal useful also for regulators and for public acceptance.

Since 1982, natural analogues have been an important theme of European Community research in the framework of the CEC R&D programs. Successively major national and international programs regularly have focused the demonstrative role of natural analogues as the main confirmation tool for the experimental and modeling activities. Every countries have referred the results deriving from the studies on the analogues to the geological formations of their own interest. Generally speaking the formations under consideration have been hard rocks, mainly granitic rocks, salt and clay. All these formations appear as possessing good aptitude with regard to the long term isolating capacity of dangerous wastes. However clay formations may play at least two roles with regard to the different options considered for waste disposal: a) direct waste isolation, b) isolation of different host rocks containing waste.

Repository safety is prevalently determined by tectonic evolution. With regard to clay, perturbation processes have been studied extensively for clay especially in Italy as analogues of processes that could affect the long term safety of geological radioactive waste repositories. The evolutionary state of recent Italian clays is particularly indicated for studies in this sector. Parts of recent Italian clay formations are spectacularly exposed on hills and morphological slopes. Traces of early and late genetic and evolutionary phenomena can be “read” in three dimensions in these landscape morphologies. This is a real advantage over small-scale observations and experiments in boreholes and tunnels and on samples. The general results demonstrate that the original isolation conditions of a repository in clay eventually undergone to tectonic uplift and consequent erosion are lost only at a depth of few meters from the final topographic surface.

A summary of the most significant results of the study on analogues carried out in the world are here reported together with a presentation of the positive results achieved in Italy whit regard to clay formations.

As a general conclusion the “analogues” demonstrate that the “geological disposal” of high-level long lived radioactive waste assures the long term safety to future generations. They also offer an effective tool for models development according to a realistic and not to a fanciful approach.

The Disposal of Radioactive Wastes

Aldo Brondi

Università degli Studi della Tuscia - Viterbo, Italy
fabio.bro@tiscali.it

Many types of radioactive wastes are generated in nuclear power plants. They deeply differ with regard to the emitted radioactivity and decay times. Other sources of nuclear wastes are originated from military use and from industrial, medical applications and scientific researches.

On the whole two main waste categories are classified in the perspective of their management and final accommodation or disposal.

High level long lived waste (HLW - III category), including spent fuel. They are highly radioactive and very hot. They must be disposed off (Geological Disposal) in deep parts of well selected geological formations characterised by high isolation capacity (granite, salt, clay). The complete isolation from the biosphere must be accomplished for a very long time (on order to hundreds thousands years). Complementary technological barriers contribute to the repository security at least for the period of the emplacement of conditioned wastes into the geological formations. Once sealed, the repository can be abandoned and its memory could be lost.

Low level short lived wastes (LLW - II category). They must be isolated from the biosphere for some hundreds years. They can be accommodated in repositories above or below the topographic surface, in pre-existing tunnels or underground cavities. A continuous institutional control is foreseen.

Safety Assessment and Public Perception of Nuclear Waste and CO_2 Geological Disposal/Storage: Differences and Similarities in the Approaches

Jordi Bruno[1,2]

[1]*Enresa - Amphos Chair on Sustainability and Waste Management - Barcelona, Spain*
[2]*Amphos 21 Consulting SL - Barcelona, Spain*
jordi.bruno@upc.edu; jordi.bruno@amphos21.com

The objective of this lecture will be to compare the differences and similarities in the approaches about the description, calculation and prediction of the performance and the safety of geological storage of nuclear waste and CO_2 and the consequences for the perception and acceptance of the implementation of these environmental infrastructures.

This work derives from more than 25 years of experience in the implementation of the geological disposal of spent nuclear fuel together with more recent advances on the geological storage of CO_2.

The differences in the safety assessment approaches, in terms of time scales and safety requirements will be described and analyzed and the implications for the social perception of these related technologies will be discussed.

The outcome of this lecture should be useful to draw some lessons from the different perspectives in the two related technologies that may be applied to improve public perception and enhance social acceptance. These complementary technologies requires to decrease atmospheric CO_2 levels and mitigate potential global climate impacts.

3D Reconstruction of the Structural Setting, Reservoir Modeling and Simulation of an Off-Shore Area from Available Seismic Reflection Data Interpretation: Evidences and Constraints in the Research of Potential Structures for Geological Storage of CO_2

Mauro Buttinelli[1], Giuseppe Vico[2], Elio Bianchi[2], Davide Scrocca[3], Lorenzo Petracchini[3] and Fedora Quattrocchi[1]

[1]*Istituto Nazionale di Geofisica e Vulcanologia, Sezione Sismologia e Tettonofisica - Roma, Italy*
mauro.buttinelli@ingv.it
[2]*Independent Energy Solutions S.r.l. - Roma, Italy*
[3]*Consiglio Nazionale delle Ricerche, Istituto di Geologia Ambientale e Geoingegneria - Roma, Italy*

A re-interpretation of available seismic reflection surveys dataset in an off-shore area has been performed to unravel the shallow structural setting and to identify potential geological structures for CO_2 storage.

The stratigraphic succession of this area is constrained by a deep well, and is characterized by sedimentary rocks constituted by terrigenous marine units resting above marly-sandy-calcarenitic flysches, which are tectonically superimposed above calcareous units and evaporites.

Seismic reflection data interpretation shows that this area was affected by several deformational stages, which caused firstly the formation of compressional (thrusts, back-thrusts and fold structures) and then extensional features (horst, graben and half-graben structures, bordered by normal faults).

These tectonic phases in turn contributed to isolate portions of rocks that could be considered as structural traps potentially suitable for geological storage of CO_2. Both compressional (anticlines and thrust-related anticlines) and positive extensional structures (horst) could be targets of this research.

The marly-sandy-calcarenitic succession (and the terrigenous mostly clayey marine units above it) can be considered as caprock, whereas calcareous fractured formations (with promising petrophysical characteristics and hosting a regional deep aquifer) can be considered as reservoirs.

The original raster seismic reflection data have been transformed into SEG-Y vectorial data format. The SEG-Y files were loaded in a digital database and a three-dimensional reconstruction of the structural setting of the area has been accomplished via dedicated software. The interpretation was carried out through manual picking of the relevant seismic horizons and discontinuities. Principal surfaces of top caprock and top reservoir units have been computed taking into account normal faults and thrusts surface geometry, also reconstructed.

The reconstruction of top reservoir surface have been checked via cross correlation between units signals on seismic lines (two-way time in ms) and the analogue measured thickness in the well stratigraphy (in meters).

This workflow allowed to identify and map a high standing reservoir trap structure completely surrounded by caprock lithologies.

A depth conversion from time (ms) to depth (meters below sea level) of all the computed surfaces have been then performed by construction of isopach maps for each seismic units, even referring to the geological literature on seismic velocities of rocks.

This methodology led to the reconstruction of a reliable three-dimensional geometry of the reservoir potentially suitable for CO_2 injection. Moreover, this process also allowed the calculation of the trap volume. After this process, a simulation of the CO_2 behavior in the reservoir after injection has been performed, considering the fluid flow through the pore, volume of the reservoir, the injected gas properties and the petrophysical characteristics of reservoir rocks.

CO_2 Reactive Transport Simulations in Deep Saline Aquifers

Barbara Cantucci[1], Giordano Montegrossi[2], Federico Lucci[3],
Mauro Buttinelli[1] and Fedora Quattrocchi[1]

[1]*Istituto Nazionale di Geofisica e Vulcanologia, Sezione Sismologia e Tettonofisica - Roma, Italy*
barbara.cantucci@ingv.it
[2]*Consiglio Nazionale delle Ricerche, Istituto di Geoscienze e Georisorse - Firenze, Italy*
[3]*Università degli Studi Roma Tre, Dipartimento di Scienze Geologiche - Roma, Italy*

CO_2 Capture & Storage (CCS) is presently one of the most promising technologies for reducing anthropogenic emissions of CO_2. Among the several potential geological CO_2 storage options, saline aquifers are estimated to have the highest potential capacity. In these sites CO_2 can safely be retained at depth for long times, as follows: *a)* physical trapping into geological structures; *b)* hydrodynamic trapping where $CO_{2(aq)}$ slowly migrates in an aquifer, *c)* solubility trapping after the dissolution of CO_2 and *d)* mineral trapping as secondary carbonates precipitate.

The fate of CO_2 once injected into a saline aquifer can be predicted by means of numerical simulations of multiphase flow and reactive transport, these theoretical calculations being one of the few approaches for investigating the short-to-long term consequences of CO_2 storage. Significant uncertainty may exist for chemical-physical parameters due to the difficulty in collecting data and carry out an adequate site characterization. Uncertainty related to fluid properties exists due to a general lack of data on the behavior of supercritical CO_2 in the subsurface and the drastic changes in transport of CO_2 caused by variation in pressure, temperature, density or chemical composition of fluid phase.

In this study numerical simulations of reactive transport in an off-shore deep saline aquifer for the geological sequestration of carbon dioxide are presented and discussed.

Stratigraphic data from a deep well show that below a 1,800 m thick caprock, constituted by allochtonous marly calcarenites and clayey marls, a regional deep saline aquifer is present. This aquifer consists of porous limestone (mainly calcite) and marly limestone deposits at 1,900 - 3,100 m b.s.l. Available site-specific data include only basic physical parameters such as temperature, pressure, and salinity of the formation waters.

Bulk and modal mineralogical composition were obtained after sampling each formation in contiguous on-shore zones. Mineralogy was determined by X-Ray diffraction analysis coupled with Rietfield refinement. The latter was performed using Maud v2.2. The surface reactive area of minerals was assumed as geometric area of a truncated sphere calculated on the basis of Scanning Electronic Microscopy analysis. Porosity and permeability were inferred by the well log data along with the use of boundary conditions such as surficial measurements and temperature profiles.

The chemical composition of the aquifer formation water is unknown. As a consequence, this was calculated by batch modeling, assuming thermodynamic equilibrium between minerals and a NaCl (0.45 M) equivalent brine at reservoir conditions (up to 118 °C and 300 bars).

The reconstructed dataset represented the base of numerical simulations to evaluate the potential geochemical impact of CO_2 storage and to quantify water-gas-rock reactions. Three-dimensional simulations were performed by the TOUGHREACT via the implementation to the source code and the correction of the thermodynamic parameters at the theoretical CO_2 injection pressure.

A reinterpretation of the available seismic reflection data was carried out to define the 3D geometry. Reactive transport simulations were conducted under multiphase advection, aqueous diffusion, gas phase participation in multiphase fluid flow and geochemical reaction in non-isothermal conditions. Feedbacks between flow and geochemical processes were taken into account to evaluate changes in porosity and permeability as kinetic reactions were proceeding.

Twenty years of CO_2 injection at the rate of 1.5 Mt/year were simulated, whereas water-gas-rock interactions between CO_2-rich brines and minerals, over a period of 100 years, were performed. Preliminary results suggest that injected CO_2 can safely be retained in the reservoir by mineral trapping, mainly due to the formation of secondary calcite deposits. This barrier reduces the outflow velocity of the CO_2–displaced water, thus reflecting in a lower CO_2 injectivity.

From Pore Space to Public Outreach: Overview of Canada's CCS Policy and Project Activities

Rick J. Chalaturnyk[1] and William D. Gunter[2]

[1]University of Alberta, Department of Civil and Environmental Engineering - Edmonton, Alberta, Canada
rjchalaturnyk@ualberta.ca
[2]G BACH Enterprises Incorporated, Alberta Innovates - Technologies Futures - Edmonton, Alberta, Canada

As with most countries, Canada has been working towards the development of a greenhouse gas emissions policy/regulatory framework to guide its commitments towards reducing CO_2 emissions into the atmosphere. As part of this work, both the federal government and provincial governments have invested in projects ranging from basic science, such as understanding mineral reactions for CO_2-brine mixtures, to pilot/demonstration scale field projects, such as the IEA GHG Weyburn - Midale CO_2 Storage and Monitoring Project. Most recently, the province of Alberta's $2B commitment to four CCS projects has garnered worldwide attention on the potential deployment of CCS technology. This study will provide an overview of CCS policies, programmes and projects in Canada and will focus on the R&D and demonstration projects have been completed, are underway or are in the design stages. The Table 1 provides only a subset of the projects that will be discussed in the study.

PROPONENTS	PROJECT NAME	PROV.	PROJECT TYPE / SOURCE OF CO2	CAPTURE TECHNOLOGY	CO2 CAPTURED (Mt/y)	STORAGE	TOTAL PROJECT COST	ANNOUNCED PUBLIC FUNDING ($M)
EnCana Corp	Weyburn EOR Project	SK	Commercial EOR CO2 from coal gasification plant in North Dakota	Methanol-based physical solvent (Rectisol)	2.4	EOR	$1.3 B	None
Apache Canada	Midale EOR Project				0.5	EOR	$120 M	None
SaskPower	Boundary Dam Integrated CCS Demonstration Project	SK	Coal-fired electricity generation (retrofit)	Post-combustion amine	1	EOR	$1.4 B	240 (GOC, Mar 2008)
Shell Canada (on behalf of the Alberta Oil Sands Project Joint Venture)	Quest CCS Project	AB	Oil sands upgrading (SMR of natural gas)	Activated amine technology (ADIP-X)	1.1	Saline aquifer	$1.35 B	865 (GOC, AB Oct 2009)
TransAlta Corp.	Project Pioneer	AB	Coal-fired electricity generation (retrofit)	Alstom post-combustion chilled ammonia process	1	Saline aquifer and/or EOR	~ $1 B	779 (GOC, AB Oct 2009)
Enhance Energy Inc.	Alberta Carbon Trunk Line	AB	CO2 trunk pipeline to carry CO2 from multiple industrial sources	Fertilizer plant: pure CO_2 Gasification: acid gas removal/Rectisol process	Initially 1.6 with potential to grow to 14.6	EOR	$1.1 B	558 (GOC, AB Nov 2009)
Spectra Energy Transmission	Fort Nelson CCS Project	BC	Natural Gas Processing	Conventional acid gas separation technology	1.0-2.0	Saline aquifer		3.4 (BC)

Table 1. Subset of the Canadian projects on CCS. SK: Saskatchewan. AB: Alberta. EOR: Enhanced Oil Recovery.

Containment and Biosphere Risk Assessment at the IEA Weyburn CO_2 Storage and Monitoring Project

Rick J. Chalaturnyk

University of Alberta, Department of Civil and Environmental Engineering - Edmonton, Alberta,Canada
rjchalaturnyk@ualberta.ca

The Weyburn - Midale CO_2 Project was launched in 2000 with the mandate to study CO_2 injection and storage in depleted oil fields. The first phase of the Weyburn - Midale CO_2 Project (2000 - 2004) was to predict and verify the ability of an oil reservoir to securely store and economically contain CO_2. This was done through a comprehensive analysis of the various process factors as well as monitoring/modeling methods designed to measure, monitor and track the CO_2 in the enhanced oil recovery environment. The final phase continues the technical studies initiated in the first phase, with research objectives refined based on the findings of the first phase. The major areas of focus, based on technical and non-technical considerations, including technical components (site characterization, monitoring and verification, wellbore integrity, and risk/performance assessment) and policy components (regulatory issues, public communication and outreach, business environment). A more detailed outline of the project and links to other relevant sites can be found on the PTRC website: www.ptrc.ca.

The ultimate objective of the long term risk assessment research is to evaluate the performance and ability of the Weyburn reservoir to securely store CO_2. The ultimate deliverable is a credible assessment of the permanent containment of injected CO_2 that will help to answer questions by regulatory bodies and community stakeholders as to the security of large volume CO_2 storage in the Williston Basin. For the Weyburn - Midale CO_2 Project the risk assessment comprises quantitative evaluation of potential technical risks associated with CO_2 leakage from geologic containment and a semi-quantitative assessment of potential risks to the biosphere resulting from the CO_2 leakage. This methodology was found to be an appropriate approach to deliver a transparent risk assessment process that can interface with the wider community and allow stakeholders to assess whether the CO_2 injection process is safe, measurable and verifiable and whether a selected alternative delivers cost effective greenhouse benefits.

This study will review the process followed for conducting a “containment” risk assessment and “biosphere” risk assessment with the Weyburn project. The reservoir (geosphere) risk assessment provides a basis for understanding the risk of containment within the geosphere - the risk related to the potential pathways, likelihoods and rates of CO_2 flow from the geosphere into the overlying biosphere. The outputs from the reservoir risk assessment are key inputs to subsequent environmental (biosphere) risk assessment as shown in the flowchart on Figure 1.

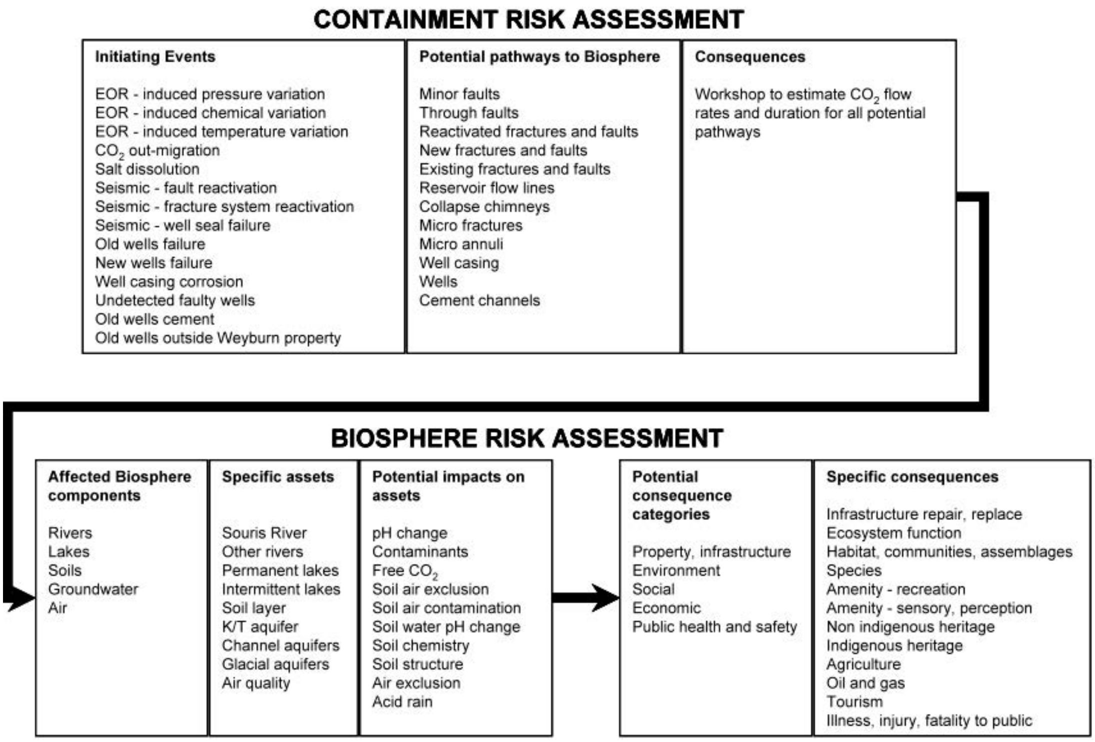

Figure 1. Flowchart of containment and biosphere risk assessment.

The flowchart also shows that the outputs from the biosphere risk assessment are used to communicate the risks to key stakeholders (community, regulators, and industry).

Assessment of the risk to the biosphere requires an understanding of the nature and value of key assets within the biosphere that need to be protected. The risk assessment process can then evaluate the risk by defining the potential impacts on these assets due to interaction with CO_2 originating from the identified containment risk events. The study will also discuss the challenges of stakeholder engagement conducted to assess the risk to assets that are important to the community, such as property and infrastructure, ecosystem function, habitat, communities, assemblages, species, amenity (recreation), amenity (sensory, perception), non indigenous heritage, First Nation heritage, agriculture, industry, tourism, and public health.

Well Integrity Research for Geological Storage of CO_2 and Engineered Geothermal Systems Well Technology

Rick J. Chalaturnyk

University of Alberta, Department of Civil and Environmental Engineering - Edmonton, Alberta,Canada
rjchalaturnyk@ualberta.ca

The potential for CO_2 leakage from wells is one of the key risks identified in the geological storage of CO_2. The long-term integrity of wellbore systems is of particular concern because of the potential for CO_2 to react with and degrade wellbore materials, principally Portland cement and carbon steel casing [Crow et al. 2010]. Some of the key questions include:

- What are the possible migration pathways for CO_2 along well systems?
- What components in the well system are most susceptible to degradation and lead to enhancement of leakage potential?
- What are the major degradation mechanisms that occur over the long term, which for geological storage can be defined as hundreds of years?
- How can permanence of storage with respect to well systems be monitored and verified?

The study will discuss a methodology to assess the transport properties of wells used in the geological storage of CO_2. The methodology provides a framework that systematically identifies and estimates the effect of each of the physical and chemical processes responsible for the response of active and abandoned wells, on their transport properties. Based on the physics involved in these permeability alteration mechanisms, a four-group classification is proposed: geomechanical damage, hydro-chemical damage, mud removal and deterioration damage (cement and casing). These mechanisms can occur during the various phases of a well life, namely, drilling, completion, production, and abandonment. Challenges associated with integrating real operational data into the performance assessment are discussed within the context of a performance assessment methodology.

For the full life cycle of geothermal energy developments, however, their overall environmental impacts are markedly lower than conventional fossil-fired and nuclear power plants because a geothermal energy source is contained underground, and the surface energy conversion equipment is relatively compact, making the overall footprint of the entire system small. Enhanced or engineered geothermal systems (EGS) power plants operating with closed-loop circulation also provide environmental benefits by having minimal greenhouse gas and other emissions. With geothermal energy, there is no need to physically mine materials from a subsurface resource, or to modify the earth's surface to a significant degree. However, there still are impacts that must be considered and managed if this energy resource is to be developed as part of a more environmentally sound, sustainable energy portfolio for the future. The major environmental issues for EGS are associated with groundwater use and contamination, with related concerns about induced seismicity or subsidence as a result of water injection and production. And with respect to well integrity and the geological storage of CO_2, it is within this realm of unintended subsurface movement of fluids along or within wellbores that is perhaps a common theme for both disciplines.

For the long-term performance prediction of well systems in the geological storage of CO_2, many of the issues listed above are common elements for both technologies. The study will review current well integrity research in the area of CO_2 storage and identify common areas where synergistic research will provide value added knowledge for both engineered geothermal systems and CO_2 geological storage.

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A GIS-DSS for CO_2-ECBM Project Feasibility Study: Case of Sulcis Coal Basin (Sardinia, Italy)

Raimondo Ciccu[1], Paolo Deiana[2], Alessandro Mazzella[1] and Caterina Tilocca[1]

[1]*Università degli Studi di Cagliari, Dipartimento di Geoingegneria e Tecnologie Ambientali - Cagliari, Italy*
amazzella@unica.it
[2]*Agenzia Nazionale per le nuove tecnologie, l'energia e lo sviluppo sostenibile - S.M. Galeria (Roma), Italy*

The correct identification of the potential sites for geological storage of greenhouse gases (i.e. CO_2) is the most important operative step to assure the success of the project. It is obvious that, in this field, the achievement of a geological storage project can be reached only if, in addition to the technical and the economical accomplishment, it is always guaranteed the safety for the people and the ecosystems directly exposed.

The geological reservoir evaluation must take into account a large amount of parameters, often very heterogeneous, mainly concerning: the coal seam features, the hosting formations properties, the environmental restrictions and the human/administrative constrains. The variety and variability of these parameters make each evaluation unique and, for this reason, it is impossible to give "*universally valid*" guidelines to help the *Decision Makers* in the planning procedure. For these reasons it is not advisable for the *Decision Maker to use* only his own experience suggesting, instead, the use of a *Decision Support System*.

In the CCS field, the combination of DSS and GIS technology allows the realization of very powerful tools able to identify and solve technical problems (like the location of geological reservoirs able to contain safely large quantities of gases) and to technically/economically evaluate different alternatives (like the environmental monitoring system planning) in order to assure the right balance between the technical/economical success of the project and the safety for the people and the ecosystems directly involved.

This research work concerns the first results accomplished by our research team in the development of a GIS-DSS for the pre-feasibility study of a CO_2-ECBM within the Sulcis Coal Basin (Italy, Sardinia, SW) [Ciccu et al. 2010].

The Sulcis coalfield extends over an area of about 200 square kilometers and includes proven reserves for about 130 million tonnes of coal. The *Produttivo* system is formed by at least 16 seams with variable thickness (40 - 100 meters) and depth (0 - 800 meters below sea level) which are related to 16 different genetic events. Three of the seams have historically been mined for over 100 years to provide materials for economic development of industries in Sardinia and the rest of Italy. Currently, because of the energy and climate crisis, this ore body is at the center of a great number of studies about its alternative uses, such as geological storage of Carbon Dioxide.

The GIS-DSS has been completely implemented using the ArcGIS Model Builder 9.3. The available data concerning: the basin DTM [Mazzella, 2009], the coal bed 3D model [Mazzella and Mazzella, 2010], the geological data, the soil use maps and the environmental constraints have been combined using the Weighted Overlay Process (WOP), also known as Multi-Criteria Evaluation (MCE). The WOP applied produced an output grid by combining the values in the input grids by using a relative importance scale and weighting them to produce a basin suitability map. This procedure allowed to define, within the basin area, the most suitable zones where more detailed studies will be carried out.

The created GIS-DSS, still in development and validation, can be simply modified to take into account more input grids and/or to produce different results varying the weighting values for each input theme.

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Volcanological and Geothermal Studies in Southern Italy in the Framework of the 'Campi Flegrei Deep Drilling Project': Towards a Geothermal Renaissance in Italy

Giuseppe De Natale and Claudia Troise

Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Vesuviano - Napoli, Italy
denatale@ov,ingv.it

The geothermal electric technology was born in Italy more than one century ago, in Tuscany region, and in the same area it has grown to the actual power of almost 800 MWe, which is comparable to a medium/large nuclear plant. However, since more than 100 years, no other area of Italy has been exploited, although very favourable geothermal conditions are common along the whole southern Tyrrhenian margin, both on-land and off-shore. Since 2005, INGV started to elaborate a large International, interdisciplinary project which, mainly aimed to give innovative solutions to the study and mitigation of highest volcanic risk area in the World, namely the Neapolitan area, could also favour the economic exploitation of the huge amount of geothermal energy stored in Italian volcanic areas. The Campi Flegrei Deep Drilling Project (CFDDP), endorsed and partially funded by ICDP (Continental Drilling Program) is devoted to study in detail, by direct drilling, the volcanic structure of the Campi Flegrei caldera. Large collapse calderas, which include other renewed volcanoes like Yellowstone and Long Valley (USA), Santorini (GR), Rabaul (PNG), Ywo-Jima (J) and many others, represent, at the upper limit of their eruption spectra, the most explosive volcanism on Earth, namely the ignimbritic eruptions, the only ones able to generate global natural catastrophes, similar to large meteoritic impacts.

The CFDDP has, furthermore, a broader aim to install, in this area, a natural laboratory for leading experiments on volcanic risk mitigation, innovative borehole monitoring and innovative geothermal exploitation. This area, in fact, is characterized by a very high geothermal gradient, around 150°C/km in many sites, then ideal to test innovative solutions for geothermal exploitation from very shallow low-medium enthalpy up to supercritical temperatures at depths generally lower than 3 km. The activities aimed to geothermal studies and experiments will be carried out in the framework of several research projects someway linked to CFDDP, the main ones being the EU-VIIFP GEISER, aimed to understand and mitigate the induced seismicity at EGS sites and the MIUR-PON TIGRE (Italian Ministry for Research), with industrial participation, aimed to set up innovative technologies and methods for geothermal exploration and exploitation. Such projects, with related involvement of industry and private companies in research aimed to optimize geothermal exploration and exploitation with innovative technologies, are leading to a new deal for geothermal in Italy, which can give a solution to the big energetic problems in this country. In fact, the huge amount of geothermal energy stored in volcanic and tectonic areas of Italy, exploited by innovative technologies set up by applied geophysical and engineering research, represents a clean and sustainable answer to the energetic needing of Italy, potentially representing an invaluable economic benefit, in agreement with all the International environmental targets.

Strain Rate Changes and Seismic Cycle

Claudio Eva[1,2] and Simone Barani[1,2]

[1]*Università degli Studi di Genova, Dipartimento per lo Studio del Territorio e delle sue Risorse - Genova, Italy*
eva@dipteris.unige.it
[2]*GEAmb S.r.l. - Genova, Italy*

Understanding the nature of earthquakes in a region and evaluating the associated hazard requires a detailed knowledge of the geodynamic and tectonic processes relative to that area. Hence, seismic strain rate and moment rate evaluations are of paramount importance for a more complete understanding of the earthquake process which, in turn, is fundamental for reliable earthquake forecasting and, possibly, prediction. Moreover, the analysis of strain rates is of great importance for the development of finer seismic-hazard source models, usually needed for a careful characterization of sites for CO_2 and nuclear waste storage and disposal.

In this study, strain rates for different Italian areas are calculated from historical and instrumental seismicity by using a smoothed seismicity approach [Barani et al. 2010]. This method does not require the delineation of area or fault sources but implicitly incorporates them through the seismic catalogue. Results are presented in terms of maps showing the geographical distribution of strain rate values calculated for different period ranges and diagrams presenting the variation of the moment rate as a function of time.

Figure 1 shows the running averages of the (smoothed) seismic moment release rate as a function of time for a site in southern Umbria (central Italy). Moment rates are calculated accounting for the contribution of earthquakes with magnitude $M_w \geq 5.0$ since 1700.

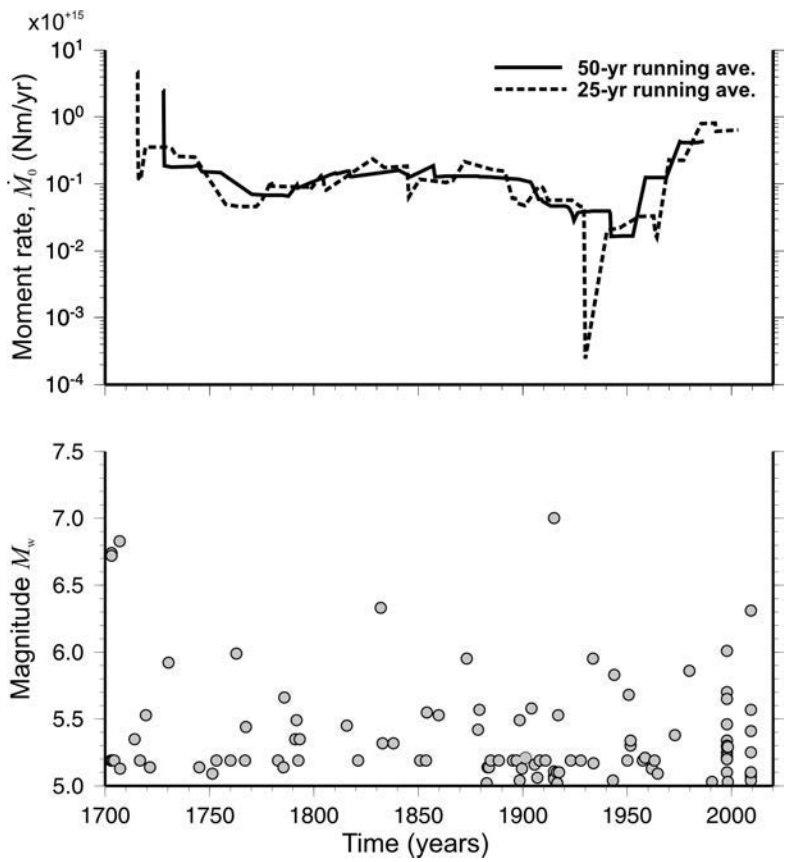

Figure 1. 25 and 50 year running averages of the seismic moment release rate for a site in southern Umbria (central Italy) and evolution of seismic activity ($M_w \geq 5.0$) within the study area. Data points in the running average curves are plotted in the middle of each time period sampled.

Figure 1 evidences that the moment rate tends to decrease to a variable value after a strong earthquake (e.g., $M_w \geq 6.0$), reaching its minimum some years before the occurrence of the next large shock. This stage may correspond to a quiescence period characterized by a sporadic seismic activity (particularly of earthquakes of $M_w \geq 5.0$). This pattern is clearly observable before the period including the 1979 Valnerina earthquake ($M_w = 5.9$) and the 1997 Umbria-Marche sequence which produced a significant moment rate increase. Thus, it is possible to define a rise and fall pattern compatible with a seismic cycle model where a seismically quiet period precedes a stage of increased activity, then followed by a period including a major event, its foreshocks and aftershocks.

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Issues Related to the Shallow, Superficial and Deep Geological Radioactive Waste Repositories

Giuseppe Forasassi

Consorzio Interuniversitario per la Ricerca Tecnologica Nucleare, Università di Pisa - Pisa, Italy
forasassi@ing.unipi.it

The peaceful use of nuclear energy and industrial and medical applications of radioisotopes generates waste products and materials, that may be classified into three categories (I, II and II category) depending on the level of radioactivity produced.

In relation to the radiological characteristics of the radioactive wastes (RW), the required repositories for the storage and disposal of RW should be different, according to the following categories: superficial or sub-superficial interim repositories for medium to low activity wastes (requiring storage time of the order of the century), and deep geological repositories for higher activity and half-life wastes, that require a very long and deep geological confinement.

The latter RWs typically correspond to residues of the back-end of the fuel cycle (waste from reprocessing fuel elements and their solidification in suitable arrays and containers).

The choice of sites and the design of suitable installations depend obviously on the RWs nature and must be carried out in close connection with the design and construction of the containers required for their storage. In most of the Countries that developed and are employing nuclear energy, are available repositories of both the two mentioned types (e.g. Figure 1). They are suitable to ensure the safety of the storage and conservation in time, with no uncontrolled releases of radioactivity in compliance with the present rules, in all the possible normal and accident conditions, due to natural events (earthquakes, floods, hurricanes, etc.) and malicious human actions (attacks, impacts of aircraft, fires and/or explosions, etc).

Even in Italy, the possible “renaissance” and the public acceptance of the nuclear energy deployment depend on the sites and storage technologies choices (in particular superficial or shallow and/or deep geological repositories) for the RWs resulting from the operation and decommissioning of past nuclear plants and laboratories, as well as those expected to be deployed in the near future.

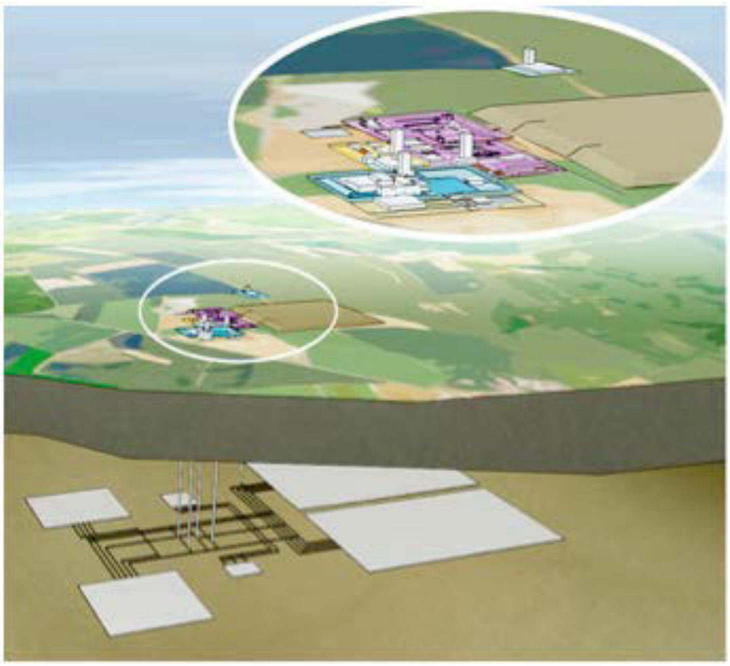

Figure 1. Possible HL/IL - LL RW repository configuration.

Reflection Seismic Imaging and Characterization of Subsurface Reservoirs for Resource Exploitation and Fluid Storage

Roberto G. Francese

Istituto Nazionale di Oceanografia e di Geofisica Sperimentale - Sgonico (Trieste), Italy
rfrancese@inogs.it

Exploitation of subsurface natural resources and, more recently, underground storage of a variety of fluids (water, oil, methane, carbon dioxide, etc) is nowadays a key issue for the future development of the modern countries. Fully addressing this problem requires knowledge in many different forms. The subsurface reservoirs must be first characterized in order to understand their structure and how fluids may flow through them. Such knowledge is necessary to allow for proper modeling of the underground flow that is required to reduce the potential impacts both of fluid exploitation and storage. The comprehensive understanding of the depositional framework of the sediments and of the geological structure became then vital for a successful simulation and prediction and this is particularly so in complex environments.

Modern geophysical methods are excellent tools for the characterization of such reservoirs. Among the variety of geophysical techniques suitable in imaging the subsurface, high-resolution reflection seismic profiling can play a major part due to its vertical and horizontal resolution and the potential information on acoustic impedance, shale fractions, or porosity, to name only a few, carried back by the seismic wavelet.

Anyhow a successful reflection survey requires a careful “state of the art” design and attention to details during acquisition, processing and interpretation. Minimal requirements are an adequate selection of the recording system and parameters, the choice of the source, of the detectors and of the spread geometry and the application of proper data processing and interpretation techniques. The present contribution focuses on a general overview of the reflection seismic technique highlighting potentials and analyzing pitfalls in the characterization of subsurface reservoirs.

Site Selection for Critical Infrastructures in Switzerland: Coping with Natural and Induced Seismicity

Domenico Giardini

Swiss Seismological Service, ETH - Zürich, Switzerland
giardini@sed.ethz.ch

Like other European countries, Switzerland also has a very advanced technological infrastructure. The production of electricity in Switzerland covers the national needs entirely, and is based on a 60:40 partitioning between hydro and nuclear, with only minor fossil fuel burning. Five reactors are located in four plants, and licensing applications for three new power plants are being evaluated. The selection of appropriate sites for two deep geological repositories (high- and medium-grade) started three years ago, and it is now restricted to a short list of six suitable sites. Geothermal energy is also being strongly developed, and several deep boreholes have been drilled or are planned, using deep hot aquifers or reservoirs in crystalline rock; the site of Basel (EGS at 5.5 km depth) has produced significant induced seismicity and has been stopped one week after injection initiation.

Switzerland is characterized by a moderate tectonic activity and rare damaging earthquakes. Earthquakes with magnitude exceeding 6 are recorded every 80 - 100 years, and the 1356 M6.6 earthquake destroyed the city of Basel. Assessment of seismic hazard in Switzerland is based mostly on historical and geological data, as active faults are hard to identify and geodetic deformations are low. Earthquakes pose the largest natural threat to critical infrastructures, accounting for up to 90% of the core damage frequency in existing reactors.

We will review the present knowledge and experience on the assessment and mitigation of natural and induced seismicity, as well as the potential for surface faulting, in relation to the siting of nuclear power plants, deep geological repositories and the use of deep aquifers and the Basel Geothermal (EGS) Project in Switzerland.

Power Tube Geomagmatic Technology for Power Generation

Claudia Gramaccia and Doyle Brewington

Power Tube Inc. - Houston, Texas, U.S.
claudia.gramaccia@gmail.com

Geomagmatic energy represents a new technological frontier for power generation entirely developed by Power Tube Inc. It is an integrated closed loop system based on direct use of the natural heat of the underground (temperature range between 105 and 210 °C, within 1,500 meters of depth). This technology does not need water, steam or steam pressure in any phase of the process.

The installation consists of a down-hole system (Figure 1) with a very small surface footprint. It fits perfectly in densely populated areas as well as in zone with high touristic attractiveness since it only uses 100 square meters surface area.

Geomagmatic technologies are currently designed in three size models: 1, 5 and 10 MW installed electrical power, each providing continued baseload capacity during the year.

Since geomagmatic technology uses neither water nor fractured rock systems, it could also be a valuable answer in terms of compatibility between different technologies (as power generation and CCS), giving an important contribution for the climate change problems resolution and for the carbon dioxide emissions decrease.

Power Tube geomagmatic technology will become commercially available in Europe during 2011 as soon as the industrialization process will be completed in the USA.

The main targets of this technology are electrical companies, especially those located close to high geomagmatic resources, in order to support a sustainable growth and CO_2 emissions abatement.

In this line of convergence with policies of CO_2 emissions control, Power Tube would welcome common initiatives and development of zero emissions energy mix projects. In particular, geomagmatic technology could provide the necessary power at zero emission and at lower costs for the operation of carbon sequestration and storage systems. This integration of the processes could be particularly effective for all partners and allows faster and more effective models of zero emission power production.

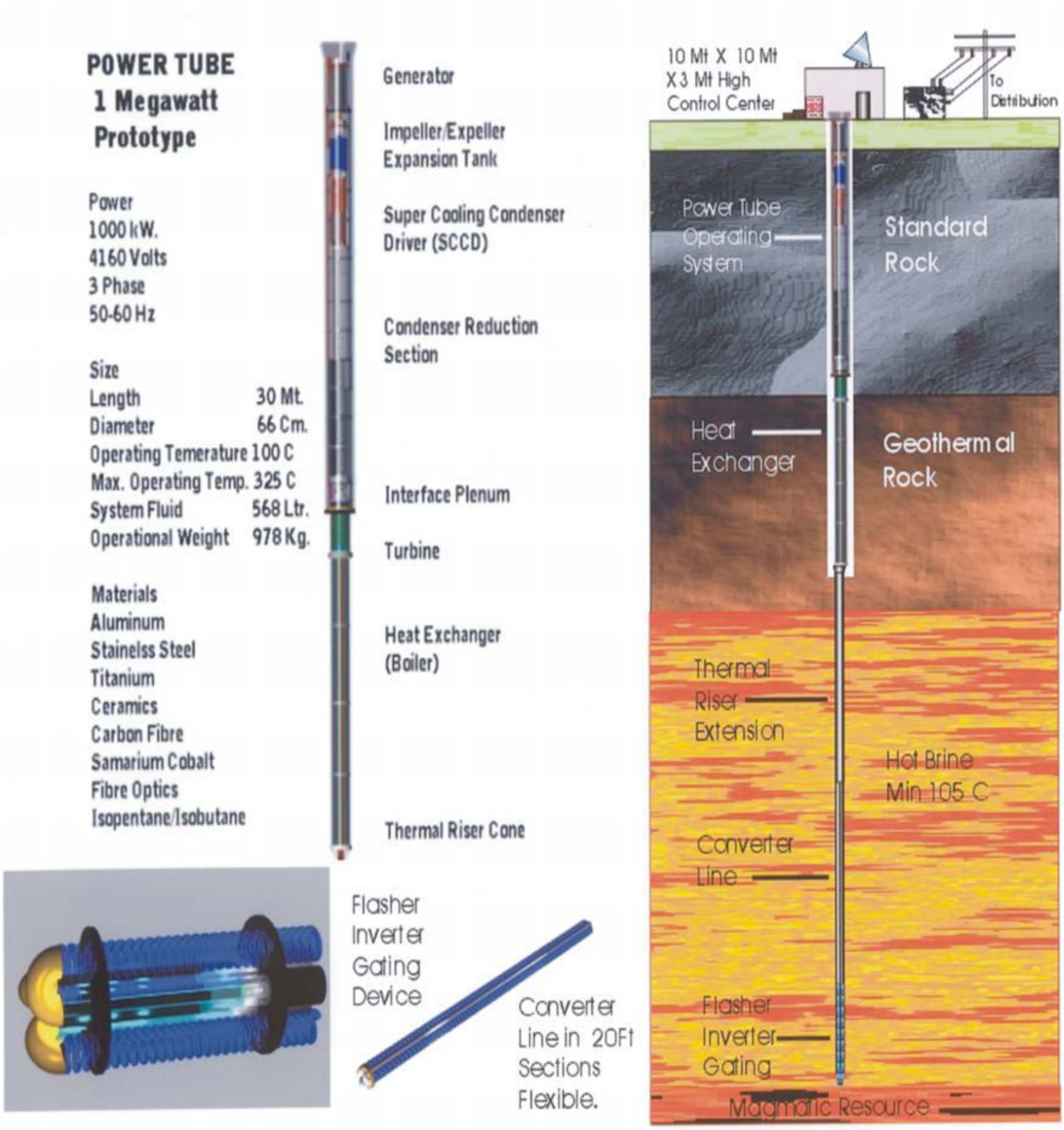

Figure 1. Illustration of a geomagmatic power plant.

4D Hybrid Microgravity Measurements: Two Case Studies of Monitoring at Mt. Etna Volcano and at a Gas Storage Reservoir in Northern Italy

Filippo Greco[1], Antonio Pistorio[1,2], Gilda M. Currenti[1], Ciro Del Negro
Rosalba D. Napoli[1] and Danila Scandura[1,2]

[1]*Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Etneo - Catania, Italy*
filippo.greco@ct.ingv.it
[2]*Università degli Studi di Catania, Dipartimento di Ingegneria Elettrica, Elettronica e Informatica - Catania, Italy*

Detection of clear gravity signals associated with the renewal of the volcanic activity and the emerging need of characterizing the dynamic changes of subsurface systems have led to increased application of the microgravity method in time-lapsed monitoring, also known as 4D gravity approach. Conventionally, microgravity measurements have been carried out using relative gravimeters, which measure spatial changes with respect to a fixed reference site. Since 2007, with the aim of comparing relative microgravity measurements routinely acquired on Etna with absolute gravity observations, we performed repeated surveys using transportable absolute gravimeters.

We applied the combined use of absolute and relative gravimeters as hybrid method [Furuya et al. 2003] to extend the potential of gravity measurements for investigating the Etna volcanic area. The hybrid approach allows us to optimize techniques and strategies of the microgravity surveys of the Etna's network, ensuring an improvement in the quality of the data. On large volcanoes such as Mt. Etna, operators using an absolute gravimeter are not obliged to reach "stable" reference stations that are generally far from the active areas (the Etna reference stations, unaffected by volcano-related gravity changes, are about 20 km away from the summit zone) with the effect of propagating-measurement errors and greatly increasing the measurement time. Thus, the time required to accomplish discrete surveys drastically decreases and the reliability of discrete data increases.

Absolute gravity variations and gravity data recorded by the Etna relative network were combined and contoured over the July 2008 – July 2009 interval (Figure 1).

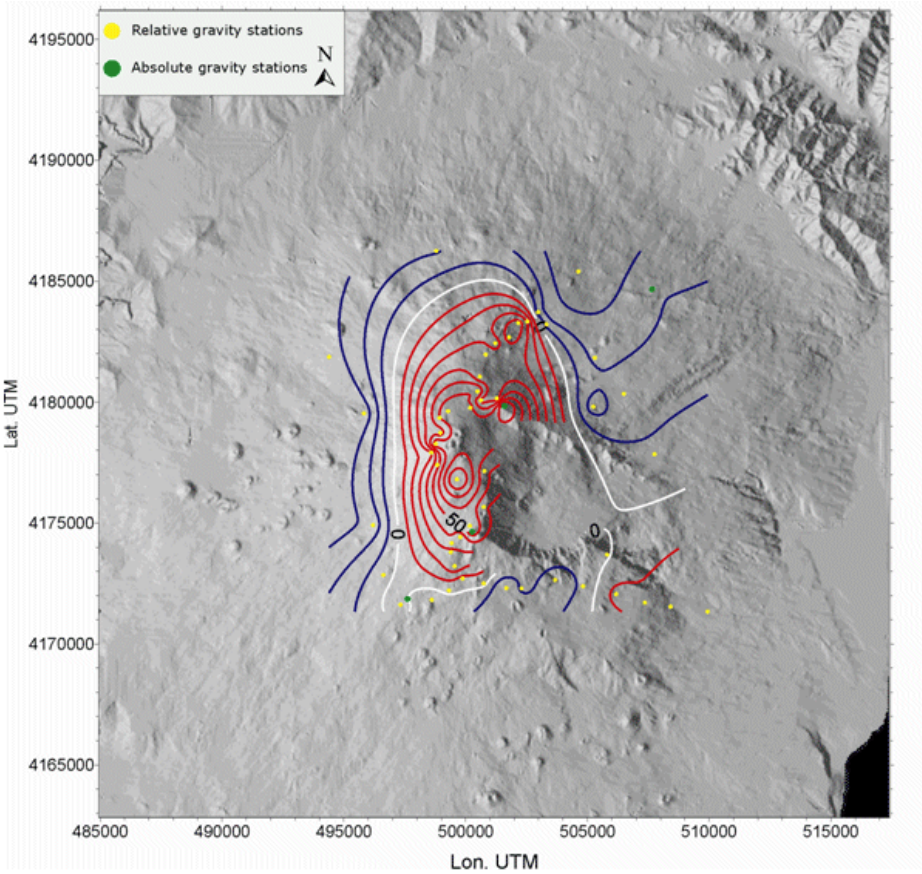

Figure 1. The annual absolute gravity variations and the gravity data from the entire Etna network (relative measurements) were combined and contoured over the July 2008 – July 2009 time interval (at 10 μGal intervals). Errors affecting relative gravity changes are typically of 10 μGal; larger errors (within 15 μGal) affect gravity changes along the Summit Profile.

The combined gravity contour map is mainly characterized by a positive variation involving the summit area of the volcano. The annual gravity variation shows a wavelength of about 10 km elongated in the North-South direction with a maximum amplitude of about 80 μGal and absence of important gravity variations elsewhere at the scale of the volcano. No significant vertical ground movements are evidenced by GPS measurements in this sector of the volcano in the same time interval. The source volume that produced such a variation can be approximated with a simple ellipsoidal source embedded in an elastic homogeneous medium; the gravity change produced by this source, computed using the analytical equations given by Clark et al. [1986], could reflect mass accumulations into the shallow magma storage system of the volcano identified at a depth of 1 - 2 km.

The measurement of the time varying (4D) gravity field as a method of observing subsurface fluid flow in a hydrocarbon reservoir is a more recent application [Hare et al. 1999; Sugihara and Ishido, 2008]. Using the expertise developed on the Etna volcano, the hybrid microgravity surveys were later expanded to investigate also natural depleted gas fields. Even though inversion of gravity data is not unique, reservoir geometry is usually well known, making time-lapse gravity measurements a highly sensitive, powerful, and relatively inexpensive monitoring technique to investigate the relatively low-amplitude of the spatio-temporal evolution of gravity associated with gas/fluids circulation.

We preliminarily carried out a feasibility study to estimate the expected time-lapse gravity signal both in terms of amplitude and extent of the anomaly. Several tests have been performed under different conditions and assumptions. An example is shown in Figure 2.

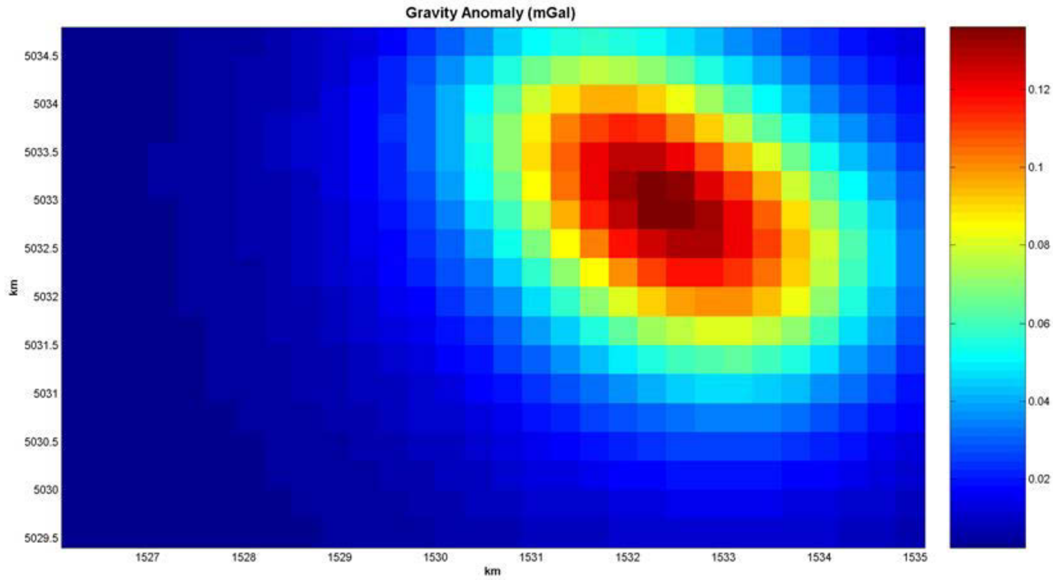

Figure 2. Time-lapse gravity map expected by switching from a filling state to a complete emptying of the gas storage field. The expected amplitude of the gravity signal detectable at the surface is of the order of 0.15 mGal.

For this synthetic calculation we considered the two opposite stages when the storage field is full (autumn) and when it is empty (spring). Switching between the two phases leads to a gravity signal at the surface of the order of 0.15 mGal, detectable using a currently available instrumentation.

The feasibility study has also been used to design the survey layout, positioning the stations in the areas where the maximum gravitational change is expected . Up to now, the storage reservoir was monitored by an absolute station only, located approximately in the center of the reservoir. The objective of this study was to investigate if time-varying gravity measurements can be correlated to the gas storage activities or not.

Figure 3 shows 2 months of continuous absolute readings performed during the summer 2009. The negative trend is due to a misalignment of the instrument during the recording period. At the end of August, the sequence is affected by man-made noise due to the presence of personnel in the site where the instrument was installed. As expected in this period, no significant gravity changes due to the gas storage/withdrawal occurred.

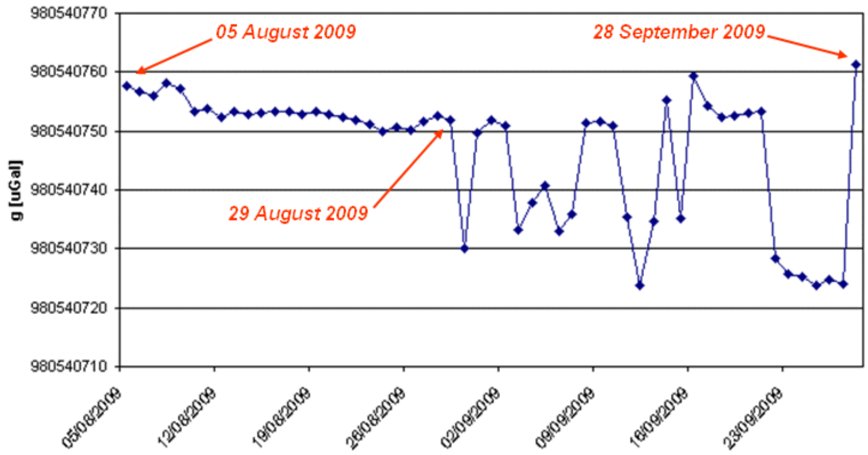

Figure 3. Continuous absolute readings (1datum/24h) performed on a storage gas field in northern Italy between 5 August and 28 September 2009.

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Geochemical Modeling of CO_2 Fate to Assess the Caprock Stability and Containment

William D. Gunter[1] and Rick J. Chalaturnyk[2]

[1]*G BACH Enterprises Incorporated, Alberta Innovates - Technologies Futures - Edmonton, Alberta, Canada*
Bill.Gunter@albertainnovates.ca
[2]*University of Alberta, Department of Civil and Environmental Engineering - Edmonton, Alberta, Canada*

Static geological, geochemical, hydrogeological, geomechanical, and well models are the fundamental models needed for Carbon Capture and Geological Storage of CO_2 (CCS) and when combined are generally referred to as a shared earth model. The quality of the shared earth model is directly related to the quality and quantity of the data and forms a fundamental platform upon which the accuracy of any dynamic modeling (e.g., equilibrium, kinetic, and transport models) for CCS depends. The uncertainty in the time variable for these models is largest with the longest time intervals. Consequently, it is convenient to split the modeling applications into short- and long- term. Short-term applications can be verified in the laboratory while the longer-term applications need additional evidence from natural analogues for verification. Table 1 shows the relation between the various model types for trapping and well, caprock & regional leakage which need to be used to evaluate the technical issues around the quantification of CO_2 storage reserves.

	Model			
	Static	Equilibrium SOLMINEQ	Kinetic PATH	Transport GEM & MODFLOW
Short- term Applications				
Residual Trap	R	–	–	many grid blocks
Solubility Trap	R	–	–	many grid blocks
Sweep	R**G**	QC/SI/Mixing	1 grid block	many grid blocks
Long- term Applications				
Ionic Trap	R**G**	QC/SI/Mixing	1 grid block	many grid blocks
Mineral Trap	R**G**	QC/SI/Mixing	1 grid block	many grid blocks
Leakage - caprock	R**G**M	QC/SI/Mixing	1 grid block	many grid blocks
Leakage - regional	HM**G**	QC/SI/Mixing	1 grid block	many grid blocks
Leakage - well	WM**G**	QC/SI/Mixing	1 grid block	many grid blocks

Table 1. Modelling Geochemical Trapping. R = Geological Reservoir; **G** = Geochemical; M = Geomechanical; H = Hydrogeological (regional); W = Well. QC/SI/Mixing = Parameters determined by the program.

Formation water analyses, together with formation mineralogy, can be used to assess their equilibrium status in the CCS reservoir and in the overlying caprock using geochemical codes such as SOLMINEQ. Once these equilibrium criteria are established, then kinetic codes such as PATH can be used to assess the reactivity (geochemical trapping potential) over time when CO_2 is injected into a depleted oil or gas reservoir or saline aquifer (considering only one grid block) and transport codes such as GEM and TOUGHREACT can be used to assess the distribution of CO_2 in time and space (considering a large number of grid blocks) over different phases. Then, hydrogeological codes such as MODFLOW, MOFAT or STOMP can model the regional implications due to displacement of saline water in the aquifer. Geochemical trapping of CO_2 in CCS is an important mechanism for secure trapping of CO_2. Once CO_2 is injected into the reservoir, the trapping mechanism progresses through residual gas trapping, solubility trapping, ionic trapping and finally to mineral trapping over 1000's of years. At each step, the CO_2 is trapped in a more stable form. At any time during this trapping progression, the effect of geochemical reactions and induced seismicity may also affect the stability of the well and the caprock.

Field Testing - The Laboratory for Validating Geologic Storage of CO_2 in the USA

Neeraj Gupta

Battelle Energy Technology - Columbus, Ohio, U.S.
gupta@battelle.org

Research and commercial-scale deployment of geologic storage of CO_2 will require consideration of numerous technical and logistical aspects, including regional and local scale geologic mapping, understanding of CO_2 behavior in the subsurface, permitting and social acceptance, site characterization, operations, monitoring strategies, and site closure. Conducting tests of CO_2 injection in the field conditions provides an opportunity to test all key facets of CO_2 storage under realistic conditions. Several such field projects are underway in the Midwestern United States, an area that could be adversely impacted by CO_2 control regulations due to its strong dependence on coal for energy production. These tests are being used for validation for the storage potential in Appalachian and Michigan Basins and one in the uplifted Cincinnati Arch region. All the field projects were conducted in a series of steps that contribute towards development of best practices for CCS validation, applicable to the Midwestern region and elsewhere in the world. These steps include initial geologic data compilation, permitting, stakeholder outreach, site characterization through seismic surveys and drilling of test wells, development of CO_2 supply system, injection and monitoring operations, and post-injection site closure. The tested formations include sandstone and carbonate layers and the sources of CO_2 include post-combustion capture from coal fired power plant, gas processing plant, and commercial supply. The concurrent regional mapping indicates that the tested layers are likely to be continuous over a large area and therefore have potential for large-scale, long-term injection operations for CO_2 sources in the region. Overall, the tests show that the exploration and deployment strategies for CCS infrastructure in the region will be different based on the geologic setting. Furthermore, information on the stakeholder interactions also highlights the need for development of site-specific outreach efforts for differing stakeholder perspectives across the region. All these lessons are being used in development of larger-scale storage tests in the region to demonstration commercial deployment potential.

Technological Feasibility of CCS: Where Does India Stand?

Priyank Jain[1] and Malti Goel[2]

[1]*Indian Institute of Technology, Departement of Mining - Kharagpur, West Bengal, India*
priyankjain.iitkgp@gmail.com
[2]*Jawaharlal Nehru University, Centre for Studies in Science Policy - New Delhi, India*

Carbon capture and storage (CCS) can play a major role in reducing future world's CO_2 emissions. In major economics like USA, China, Poland, India there is heavy reliance on coal power and the large coal reserves. The CO_2 emissions are predicted to be on a constant rise. CCS is an effective means for reducing atmospheric CO_2 concentration, either through reduction of emissions using advanced clean technology or capture of excess CO_2 from the atmosphere. Across the globe, research studies are presently going on geologic sequestration modeling techniques. Various numerical simulators like STOMP, FEHM, PFLOTRAN, NUFT, and TOUGH have been developed to predict the ability of a geological formation to store CO_2. There still remains considerable uncertainty about reaction sequences and the coupling of the processes that ultimately determines the fate of CO_2 in the reservoir. For example, experiments at PNNL have demonstrated the importance of reactions mediated by the supercritical CO_2 phase and suggested the need for mixed wettability simulation capabilities in sequestration modeling.

In India, a significant portion of the country's energy needs (over 70%) are met from coal burning power plants. In view of forecasts made for use of cool, CCS technology assumes particular importance in the economic development path of the country as a climate change mitigation option. The research in CCS has been given priority through government and industry support and the focus has been on development of CO_2 capture techniques. The technical feasibility of CO_2 storage in India is yet to be examined and some initial attempts have been made through pre-feasibility studies. The CCS technology has not been proven worldwide and the cost of its adoption is extremely high. There is need for developing a framework for joint collaborative research among different organizations.

Underground Siting of the Nuclear Facilities in Japan - Case Histories in Japan

Yoshihiro Kinugasa

Tokyo Institute of Technology, Interdisciplinary Graduate School of Science and Engineering - Yokohama, Japan
king@depe.titech.ac.jp; king@8f.adep.or.jp

Japan is the one of the most distinct examples of the densely populated countries where many nuclear facilities are located. However, this is not a unique situation on our Earth, but it will soon become a more common situation in rapid economic developing countries. Nowadays, many rapid economic developing countries are step forward to utilize nuclear power for their energy source. Moreover, many of such countries are located along active geologic regions. Earthquakes, volcanic eruptions, landslides, ground deformations are the major concerns for the safety of the nuclear facilities in such regions. One of the solutions to overcome such geological risks is underground siting of such critical facilities. However, there are still many issues remained to ensure the safety of underground critical facilities.

Long-term ground uplift rate in Japan reaches a few mm/year. This means that the present sea level horizon becomes a few hundred meters above sea level within the next hundred thousand years that is the necessary time duration for decay of high-level radioactive waste.

Seismic phenomena are another major concern for the safety. Though, shaking intensity itself decreases with depth, fault dislocation disrupts the underground facilities. Even without dislocation, newly formed cracks may change the underground water system and therefore the safety scenario of the facilities.

Volcanic phenomena are also major concerns in the active geologic regions. Of course, we can avoid the siting of such critical facilities in the active volcanic regions. However, 'Volcanic Front' changes its location through geologic time. Also, it is very difficult to identify the location of future eruption of monogenetic volcanoes.

It should be noted that our knowledge on nuclear science and technology derives from a study started by Marie Curie and continued during recent one hundred years or so. Furthermore, our knowledge on geological phenomena is based on the researches in recent era. By contraries, high-level radioactive waste should be kept away from human reaches for many hundreds of thousands years until it decays to the safety level.

Geophysics Contributing Geological Description of the Olkiluoto Repository Site in Finland

Mari Lahti

Posiva Oy, Olkiluoto - Eurajoki, Finland
mari.lahti@posiva.fi

Posiva Oy is responsible for implementing the programme for geological disposal of spent nuclear fuel in Finland. The Olkiluoto site in western Finland has been studied for this purpose for over two decades. Construction of ONKALO, the underground research facility, started in 2004 and will reach the planned disposal level of -420 m during 2010. Currently Posiva is preparing to submit the application for the construction license for the repository. An important part of the licensing is the development of the criteria to classify suitable host rocks for the final disposal. Posiva has set the Rock Suitability Criteria programme for developing a classification scheme both to be applied for the repository layout design and to define suitable rock volumes for the deposition holes.

In the Olkiluoto rock environment consisting mainly of migmatite gneisses and occasional pegmatite granites, the bounding lineaments, deformation zones and single extensive fractures are expected to have geophysical reflectivity that has been confirmed during the site investigations and the ONKALO construction. The task is to develop simple, practical and economic ways for implementing the techniques for characterising the rock volume at required detail. Geophysics has been in an important role throughout the investigations, from the early site selection studies to the construction of detailed geological and hydrological model of Olkiluoto, including rock units, brittle and ductile deformations zones as well as hydrogeological zones. Moreover, geophysics contributes the Rock Suitability Criteria by providing methods describing the unknown rock volume between investigation drillholes and the rock mass behind the tunnel walls. Geophysics provides a tool for imaging the bedrock volume that cannot be comprehensively drilled because of long-term safety reasons.

During the early site investigations the airborne geophysical mapping provided valuable data for lineament interpretation. Lineament data is a basis for locating deformation zones and the so called bounding lineaments are used for delineating the planned repository volume. Most of the bounding lineaments are over 8 km long and travelling below the sea. They are expected to be deformation zones and potential weakness zones for earthquakes. The airborne geophysical data has been complemented by ground measurements at the Olkiluoto Island. High resolution reflection seismic studies have been implemented to study the existence and geometry of the deformation zones. During 2010 the 55th deep drill hole will be drilled from the ground surface to confirm the modelled geological structures. All the drill holes have been logged by comprehensive geophysical methods that are providing in situ information of the geophysical properties.

The classification scheme developed within the Rock Suitability Criteria programme considers long-term safety and engineering aspects. The practical criteria consist of three different scales: repository, tunnel and deposition hole scale. In the repository scale the bounding lineaments define the repository volume. The layout determining features and their respect distance volumes are avoided when locating deposition tunnels. The zones defined as layout determining features are potentially mechanically instable in the current or future stress field or they are major groundwater flow routes that can transport solutes and alter chemical stability at the site. The brittle fault zones that are considered as layout determining features are established at high level of confidence. They are based on geophysical observations and drillhole intersections. Many of the gently dipping main deformation zones have been studied using 2D and 3D reflection seismic measurements and their extension can be followed towards eastern investigation area that is not comprehensively drilled yet. In the deposition hole scale even single extensive fractures are important for the local mechanical and hydrological stability. For the application of the rock characterization process, the ability to predict the occurrence of brittle fault zones and single extensive fractures that are potentially able to slip more than 5 cm, is essential.

Deep Geothermics and Possible Synergies with CCS

Adele Manzella

Consiglio Nazionale delle Ricerche, Istituto di Geoscienze e Georisorse - Pisa, Italy
manzella@igg.cnr.it

Geothermal energy is one of mankind's major global resources that is used in heat and electricity markets in many industrial and developing countries through predominately mature technology. New technology has the potential to significantly increase the yields and lifetime of the available geothermal energy recovery, but needs further research in various fields, among which exploration and investigation techniques.

Two main goals should be addressed by exploration and investigation: to reduce the mining risk by cutting the exploration cost and increasing the probability of success in identification of geothermal prospective areas, and to provide all necessary subsurface information to guarantee the best exploitation efficiency, the sustainability of the resource and the lowest possible environmental impact.

Technological challenges targeted to these goals are mainly aimed to: 1) find improved and newly developed methodologies able to map reservoir condition suitable for geothermal exploitation, in particular at local scale; 2) provide data integration (static and dynamic) and uncertainty analysis. Integration of technology and multidisciplinary evaluation of data, such as the one speeding up in the last 10 - 15 years for hydrocarbon exploration, must become a core competency also in the geothermal world; 3) find tools able to improve imaging between existing wells and performing real time measurements: some of these tools might be borrowed from oil and gas exploration but adapted to meet unique geothermal conditions, such as high temperature and pressure and possibly aggressive chemical composition.

Among other issues, that will be discussed during the presentation, there is the need to calibrate stratigraphy, reservoir fluid circulation and thermal history in underexplored areas. Measures to be taken need to involve a critical screening of thermal data, developing baseline temperature models, and investigating the modification through the time of reservoir exploitation, providing the essential thermal rock properties, and combining the temperature field properties with reservoir properties. Analogue sites should be studied and results incorporated in the workflow in order to help the interpreters to take advantages from known similar conditions. Other investigation programmes like nuclear waste storage, CCS and oil and gas field development may also provide useful information and experiences.

A share of experience with CCS research activities would be beneficial not only for improved exploration techniques, but also in other fields, such as in the research addressed to improve knowledge of the processes and rates of change in the permeability development of reservoir rocks due to scaling and precipitation of minerals by short- and long-term fluid-rock interaction.

First Demonstration of CO_2 Underground Sequestration in an Italian Depleted Storage Gas Field

Daniele Marzorati and Christian Coti

Stogit S.p.A., Sede Operativa di Crema - Cremona, Italy
daniele.marzorati@stogit.it

The CO_2 injection project in Cortemaggiore, a depleted natural gas storage field, represents the first pilot project in Italy.

The project started after a strategic agreement of cooperation eni-Enel, featuring Ministry of Environment to favour the development of CCS technologies.

Since in Italy there are no regulations or laws on such activity, the project has been presented as “upstream operation”, joining to the objective of defining a methodology for injection and control on the field of the carbon dioxide injected in the reservoir. The study permits also to provide new information on the practical aspects of storing CO_2 from power generation and the possibility to improve the efficiency of storage fields using the CO_2 as cushion gas instead of methane, as indicated in the existing law on gas storage activity.

The project consists of the injection of about 24,000 tCO_2, throughout 3 years, into a consolidated sand level at 1,500 m depth, previously used for natural gas storage (since 1964) and therefore considered suitable and safe to confine CO_2.

Engineering studies outline the possibility to perform the pilot test in safe conditions for the environment, ensuring the integrity of the system reservoir/well/surface plant. A monitoring plan has been proposed to guarantee these conditions during and after the project implementation.

Given the strategic meaning of the project, that is part of a much wider eni plan, and considering its experimental nature, the authorization process has been joined with an information campaign, both at local and regional level, with the aim of obtaining that “public acceptance” necessary to avoid territorial contrasts and opposition to the beginning of the project.

Public meetings also with engineers and consultants of public administrations contribute to create a “positive climate” and provided all the elements clearing up the major doubts over safety of the plant, integrity of the reservoir and possible risk of accident during both transportation and injection phases.

A complete process approval of the project is going on from the Ministry of Economic Development and the Ministries of Environment and Cultural Heritage.

Low-Temperature Geothermal Power: A Welcome Neighbor in Densely Populated Regions?

Pete B. McGrail

Pacific Northwest National Laboratory - Richland, Washington, USA
pete.mcgrail@pnl.gov

Low-temperature geothermal systems offer the potential to significantly expand areas where economic power production from the earth could occur. Operating with a reservoir temperature between 175 and 100°C, much shallower wells are needed relative to conventional geothermal systems, an especially important consideration in areas with moderate geothermal gradient. Shallower wells lower capital costs but also lessen risk of induced seismicity during pumping operations, and important consideration anywhere but especially in densely populated areas. This work will provide an overview of modern low-temperature geothermal power systems and highlight the critical technical and cost barriers that currently inhibit installation of these systems. Recent discoveries regarding nanofluids will be discussed including how their physical and thermodynamic properties could be exploited in both the surface power plant and in the subsurface to foster geothermal power development.

Adapting Integrated Sequestration System Design for Densely and not so Densely Populated Areas

Pete B. McGrail, E. Charlotte Sullivan and Mark D. White

Pacific Northwest National Laboratory - Richland, Washington, USA
pete.mcgrail@pnl.gov

Introduction

Use of fossil fuels for electric power generation and industrial processes is not going away anytime soon. However, as described in the International Panel on Climate Change special report [IPCC, 2005], stabilization of global atmospheric CO_2 concentration anywhere between 450 and 650 ppm will require CO_2 emissions to peak and then decline over the balance of this century. As illustrated in Figure 1, deployment of multiple new technologies for energy production and energy efficiency are needed to achieve these targets. Capture and geologic storage of CO_2 (CCS) represents one of the big technology levers that engineers could use to reduce CO_2 emissions from industrial sources and avoid economic harm to these businesses from future greenhouse gas regulations. However, numerous technical, legal, and public acceptance challenges remain to be met before commercial developments are realistically feasible. This paper will discuss several of the key technical and non-technical barriers that must be overcome for deployment of CCS, especially highlighting issues in densely populated areas that make siting CCS projects even more challenging.

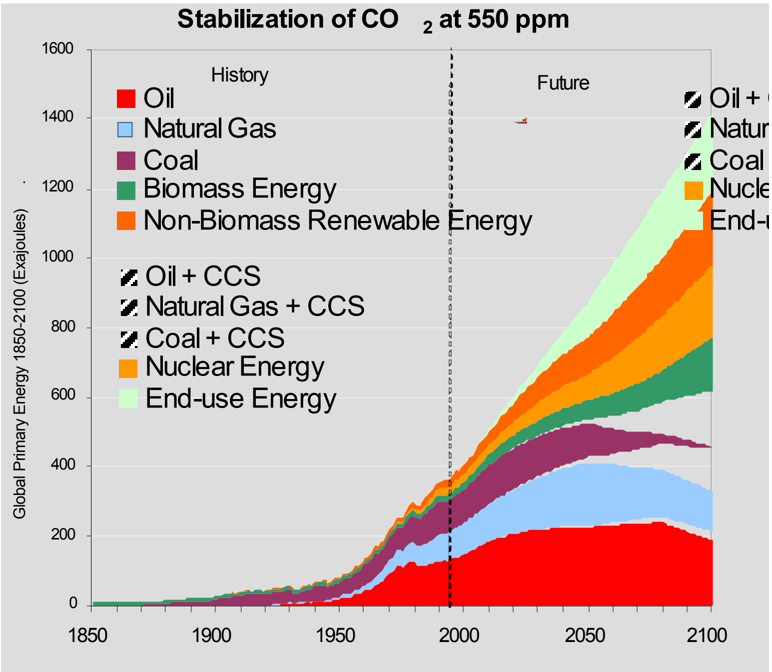

Figure 1. Impact of technology options for reducing global CO_2 emissions and stabilizing atmospheric CO_2 concentration at 550 ppm relative to 385 ppm today.

Strategic Barriers

Strategic barriers for CCS projects consist of overarching national and/or international policy, legal, and business issues that individual CCS projects cannot address on their own. These include:

- No agreed U.S. national or international drivers to cut emissions.
- No recognized national or international market mechanism to monetize credits for stored CO_2.

- No nationally-recognized standards for permitting leaving untried, untested, and differing approaches in each State or country.
- Landowners require full indemnification and set terms for royalties, access, and storage fees.
- Engineers solving a problem (climate change) that a large segment of the public believes does not exist or if it does, human activities are not the cause.

There are some actions, however, that regions and individual CCS projects can engage in that will help mitigate some of these strategic barriers:

1. Enact legislation for regional Emissions Performance Standards (EPS) targets that provide State-level and regional-level incentives for emissions reduction projects.
2. Work alternative business models that introduce plant upgrades or efficiency improvements to offset costs and leverage Federal seed funding.
3. Draft national EPA regulations for geologic sequestration are in the review process.
4. Utilize insurance companies that have announced offerings for liability insurance for CCS projects.
5. Have CCS scientists and engineers engage with the public at more opportunities.

Over time, these actions, taken at the local and regional level, could influence national and international policy such that fewer of these strategic barriers exist or at least minimize their impact on deployment of CCS projects. However, densely populated regions present additional challenges including:

- Technical difficulties with performing standard monitoring methods such as surface seismic, InSAR, and groundwater monitoring.
- Securing subsurface rights (U.S.) is much more involved.
- Complicated rights-of-way for pipelines.
- Permit applications will cost more to prepare and almost certainly take much longer to approve.
- Liability coverage costs will increase significantly.
- Higher probability of legal challenges and organized opposition.

Given the current very early stage of CCS demonstration projects, overcoming these additional challenges in densely populated regions seems unlikely. Projects in densely populated regions will almost certainly deploy later when the technology is proven and public acceptance of the risks/benefits better established.

Cost of CO_2 Capture

The cost of separating CO_2 from a combustion gas stream using conventional amine stripping technology represents approximately ¾ of the total cost of a CCS system [Woods et al. 2007]. Hence, the greatest potential for cost reduction associated with CCS is presently with new technologies that could dramatically reduce the energy penalty and capital costs associated with current capture systems [Freeman and Rhudy, 2007; McGrail et al. 2008; D'Alessandro et al. 2010]. For example, solid sorbent materials such as illustrated in Figure 2 exhibit some intriguing properties including 25 wt% CO_2 uptake at 1 bar and room temperature (4X amine solvents), no uptake of N_2 at 1 bar, absorbs SO_2 without degradation of material, and a heat of regeneration <40 kJ/mol-CO_2 versus 150 kJ/mol-CO_2 for monoethanolamine. It remains to be seen whether large volume throughput systems can be engineered to take advantage of these thermophysical properties and whether manufacturing such advanced sorbents can be done at low enough cost. In densely populated settings, space to accommodate another unit operation of the scope and scale required for CO_2 capture also will be an issue.

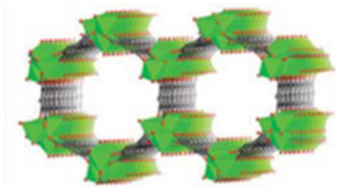

Figure 2. Metal-organic framework material based on dihydroxyterephalic acid organic linker.

Sequestration System Design

Design of CCS systems is an emerging area that requires knowledge and input from an extraordinarily wide range of disciplines. A convenient pictoral construct is the sequestration system design "Pentagon" illustrated in Figure 3. The five major disciplines, Monitoring, Control and Data Acquisition, Permitting, Cost Estimation, and Infrastructure all reside with the "walls" of Legal & Liability constraints that dictate feasibility of activities in each discipline and filter communication of work product and conclusions to the technical community and public. The filtering step is critical because technical feasibility of a particular system design component is rarely a constraint – legal or liability constraints for deployment though almost always are.

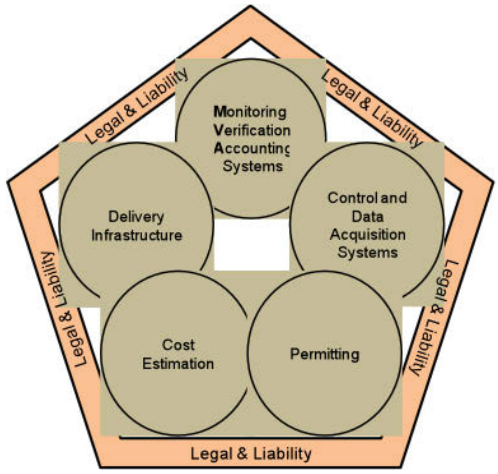

Figure 3. Sequestration system design pentagon.

Monitoring technologies are an example, within a single discipline, that requires an extraordinary range of technical expertise. Techniques include atmospheric monitoring, eddy covariance, soil gas flux accumulation chambers, LIDAR, color infrared orthoimagery, aerial photography/spectroscopy, tiltmeter, gravimetric interferometry, laser induced breakdown spectroscopy (LIBS), isotope mass spectrometry, GC/MS, electromagnetic induction, high resolution electrical resistivity, and seismic reflection to name just a few. Sequestration system designers must be reasonably cognizant of each of these technologies to ensure adequate treatment and evaluation in an integrated monitoring program plan for a site.

Design of individual components of sequestration systems, including the pipeline transporting CO_2 from the plant to the sequestration site and the injection well or wells, requires close communication between the plant operators and sequestration system engineers. Although analysis of pipeline flow behavior of CO_2 is well established, surprisingly little analysis has been done of a fully-coupled system linking the compression requirements at the plant all the way to pressure requirements at the bottom of the injection well(s) at a sequestration reservoir. To ensure that proper pipeline sizes are selected and appropriate sizes for injection wells are designed, a coupled pipeline-wellbore thermo-hydraulic analysis is required. A simple, steady state, one-dimensional flow model can be used to calculate the pressure drop along a series of segments of the pipeline or well. Pressure changes from frictional loss, gravity head, and acceleration of the flow are included in the model. The CO_2 density is calculated from the pressure and internal energy from the carbon dioxide state equation of Span and Wagner [1996]. The carbon dioxide is assumed to be a liquid or supercritical fluid and the calculation stops if two-phase conditions occur. The internal energy at the end of a pipe length segment is calculated from the energy equation accounting for the heat transfer from or into the carbon dioxide stream from the surrounding soil or rock, change in potential energy due to pressure, and kinetic energy of the flow. Using a thermo-hydraulic modeling to match appropriate pipeline size to the plant peak output is important because pipeline costs run in excess of $410,000 per cm-km. Over specifying a pipeline diameter can be very costly to a CCS project. Likewise, drilling and well completion costs are directly related to the size of the wellbore. Wellbore sizes need to be designed large enough so that frictional losses do not result in inadequate pressures for injection at depth or worse, a non-functioning well where CO_2 flashes to gas before reaching reservoir depth.

Sequestration system designers must also account for important coupled processes in geologic reservoirs including coupled flow, heat, chemical, and geomechanical processes [Ferronato et al. 2010; Rutqvist et al. 2010] such as illustrated in Figure 4.

Also, it has only very recently been discovered that water-wet supercritical CO_2 is very reactive with well construction materials and certain reservoir rocks [McGrail et al. 2009; Schaef et al. 2010]. These chemical reaction processes in the supercritical phase are potentially very important in certain geological settings [Gaus, 2010] and reservoir simulator development is needed so that the long-term implications of these reactions can be understood.

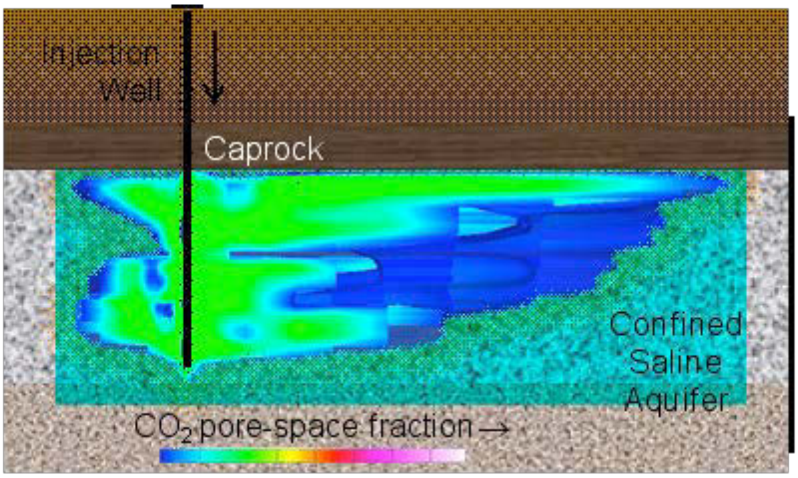

Figure 4. Multiphase flow and reactive transport of supercritical CO_2 in a deep geologic reservoir.

Conclusion

The sequestration system designer is faced with an extraordinary range of technical, legal, and permitting challenges associated with CCS projects. Engineering tools are being developed that allow integrated design of CO_2 capture systems, pipeline, and wells for CO_2 injection at a sequestration site. Legal and permitting challenges face all geologic sequestration projects and are even more complex in densely populated settings. Good sequestration system design employs technical strategies that reduce legal and liability risk to the maximum extent possible at reasonable cost. By integrating processes across the molecular, pore, and reservoir scale, the sequestration system designer provides the project developer, permitting agency, and the public with a comprehensive view of how the CCS system is expected to perform, and a monitoring program designed to verify the projections - ultimately the key to successful CCS projects.

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CCS Natural Analogues and Public Perception. A Case Study

Beatriz Medina, Daniela Russi and Irene Kopetz

Amphos 21 - Barcelona, Spain
beatriz.medina@amphos21.com

CCS natural analogues and public perception

CCS is still mostly unknown by the general public, due to the fact that it is an emergent technology, and only a very small share of the society has an opinion on it [Shackley et al. 2004; den Best-Waldhober et al. 2009; Ha-Duong et al. 2009; Kamishiro and Sato, 2009]. In 2007 in the Eurobarometer survey a question on CCS was introduced. The outcome revealed that only 21% of the sample had heard about CCS.

Information is therefore crucial in helping people to form an opinion on CCS, and make informed opinion on it.

Natural analogues proved to be useful to explaining to the wide public the CCS technology [Tokushige et al. 2007; Itaoka et al. 2009] because they represent phenomena directly observable in the environment and people have experiences on it (e.g. Figure 1).

Figure 1. Natural analogue in northern Spain.

Some insights from a literature review:

The most important factors that influence the public perception of CCS are the following:

- Giving information on CCS mostly increases acceptance, but in some cases it decreases. The outcome of providing information depends on the targeted public and on the characteristics of the provided information.
- CCS, when compared with other energy options, is generally considered more acceptable than nuclear energy, but worse than renewable energies.
- The NIMBY (Not In My Back Yard) effect can be observed with regard to the CO_2 geological storage.
- Trust in the implementing organisations, increases acceptance and decreases the risk perception.
- A possible increase of the energy prices associated with CCS implementation may decrease its acceptance.
- The concern that CCS financing may reduce the available resources for renewable energy and energy saving is one of the main reasons for being against CCS.

Case Study

Scope

In a CO_2 enriched aquifer located in an old volcanic area in the Campo de Calatrava region (Castilla la Mancha, Spain), natural gas leak is a common occurrence. This natural effect is well known by the local population. In 2000 in such area, a case of anthropogenic perturbation in a CO_2- rich aquifer (a well illegally drilled at 200 m depth, Figure 2) was caused by a private farm. The consequence was the emission of water, gases (mainly CO_2) and solids during 176 days. The event had broad media coverage, mainly by means of regional media.

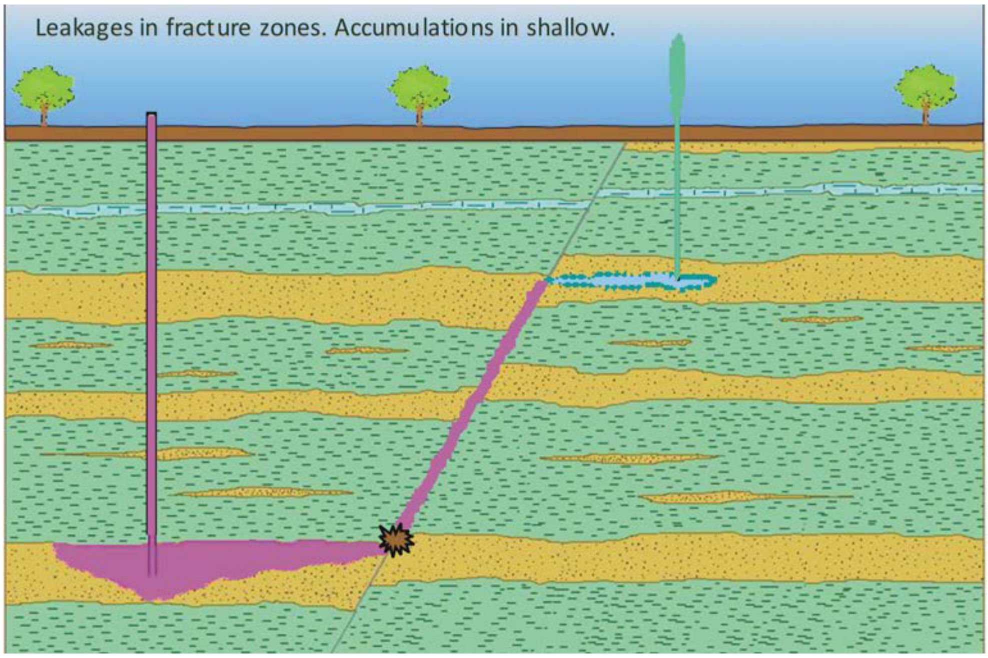

Figure 2. The geological section shows a hypothetical CO_2 injection in a geological storage site, with CO_2 leakages (in pink) through fractures and CO_2 accumulations in shallow formations. Drilling field (in green) can induces a CO_2 leakage to the atmosphere from the shallow formations. This example has similarities with the incident in 2000 in Campo de Calatrava, where a CO_2 enriched aquifer (in blue) was perturbed by a farmer and caused the above mentioned spectacular emission of water and gasses.

The evaluation of the risk perception of this incident is important because its consequences may be similar to those caused by a possible leakage in a CO_2 storage site. Analysing this natural analogue is also interesting because CO_2 repositories are expected to be located in regions with a socioeconomic context similar to that of Campo the Calatrava, i.e. an economy mainly based on the agricultural sector and the local tourism, as well as a low population density and an ongoing process of rural depopulation.

This research is based on three approaches: 1) Literature review on public perception of CCS; 2) qualitative and quantitative analysis of media coverage related to the incident in Campo de Calatrava (regional, local and national newspapers, and TV documents); and 3) 11 semi-structured in-depth interviews carried out in May 2010 in order to analyse local stakeholders' opinion about the incident and about CCS in general.

The interviewees were key representatives of some identified stakeholder groups (i.e., local politicians, neighbours, experts, local opinion leaders and directly affected people).
The interview was structured in three sections: 1) Perceptions of the incident; 2) Opinions on climate change; and 3) Attitudes towards the CCS (a stimulus material was distributed before third part of the interview, in order to inform the interviewees about the technology).

Main results

1. *Attitudes of the local population towards the incident occurred in 2000:*
   - Population did not perceive a significant risk associated with the incident. One of the reasons may be the generalized positive attitude towards water phenomena, particularly strong in areas characterized by water shortage.
   - A feeling of satisfaction and pride was observed with regards to this incident, due to the increased popularity of the municipality.
   - Most population had a positive perception of the event impact on the local economy, due to the massive affluence of visitors. However, the real impact was insignificant, because tourists spent only some hours watching the incident.
   - However, the incident produced significant physical damages to the field where it occurred and to the neighbouring ones. The perception of the directly affected families was therefore negative.

- The control measures carried out by the public authorities were not perceived to be sufficient.
- The population did not perceive significant environmental impacts. Moreover, media did not focus on possible environmental impacts. However, the incident produced a degasification in the perturbed aquifer, with a consequently slight field subsidence. In addition, leaks water with high CO_2 concentrations was mixed with freshwater into the surface water reservoirs.

2. *Local knowledge on CO_2 and on the characteristics of the area.*
   - People are generally aware of the past volcanic activity in this region, owing to the characteristics of the area (natural springs CO_2-rich). Water raisings in this area are well identified.
   - Local population has traditionally attributed medicinal properties to water with high CO_2 concentration.
   - Local population requires more control on illegal drilling of wells for water irrigation. In addition, population is aware of the potential risk of illegal drillings which might increase the probability of similar incidents.
3. *Opinions on CCS*
   - None of the interviewees was aware of CCS.
   - People do not perceive impacts related to the climate change in their context (local level). However, they recognise the existence of climate change at the global level. Some of them accept the need for mitigation measures, but only in densely populated areas.
   - Interviewees showed a positive attitude towards CCS after giving the stimulus material.
   - People would require more institutional responsibility in the case of a possible incident in an industrial CCS plant compared to a natural analogue system, even though the consequences were similar.
   - Opinions on risks associated with CCS were influenced by the current debate on the location of a radioactive waste repository in Spain. However, all interviewees were aware of the difference between nuclear waste and CO_2.

Recommendations on the use of natural analogues for communication on CCS

- Different information material on natural analogues should be prepared for the different target groups, i.e. public, policy makers, communicators, safety assessment specialists, experts (Figure 3).
- Information on natural analogues should be complementary to other kinds of information. Natural analogues should not be directly compared with CCS, because the inherent cognitive naturalness of an analogue is different from the artificiality of an industrial system. The results of the interviews showed that a direct comparison might not favour the CCS understanding.
- Natural analogues should be used to fill knowledge gaps of the public on CCS, rather than try to influence the public opinion on it.
- In general, natural analogues are useful for knowledge dissemination on CO_2 behaviour and not only in the framework of CCS (e.g. physical characteristics, properties, toxicology, industrial uses, etc.).

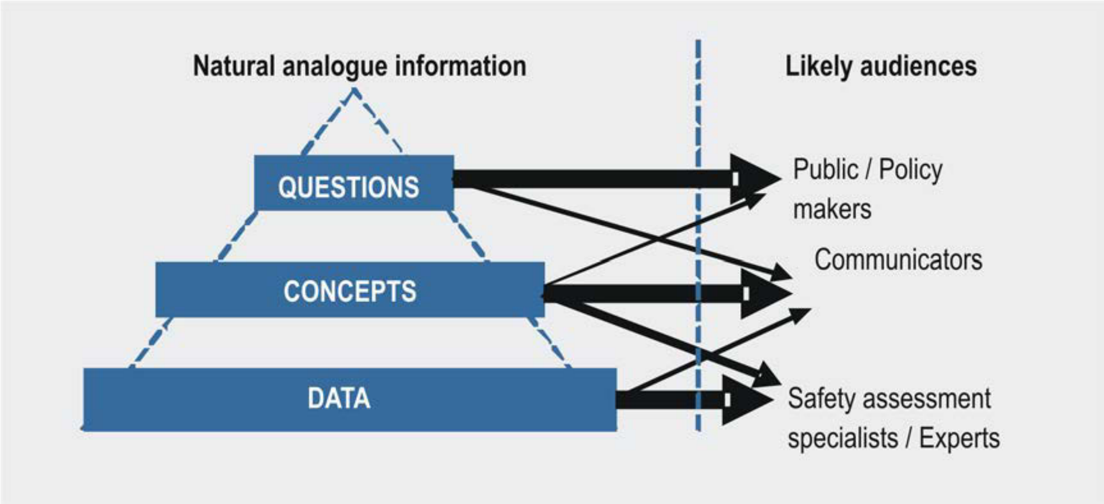

Figure 3. Information on natural analogues can be given through different kind of sources (data, concepts and answered questions). Every type of information is more interesting for some audiences than others. The thickness of the arrow shows the use intensity of every type of information by the different audiences.

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Solute Precipitation in Exploitation of Geothermal Reservoirs: Modeling Examples of Calcite and Halite Precipitate Formation

Giordano Montegrossi

Consiglio Nazionale delle Ricerche, Istituto di Geoscienze e Georisorse - Firenze, Italy
Giordano.Montegrossi@igg.cnr.it

Halite precipitation processes in low permeability geothermal reservoirs, containing saline water, where vaporization of the solution occurs at a sharp front because of vapor extraction at constant pressure, were investigated both analytically and numerically. An analytical solution to this problem was given by Tsypkin and Woods [2005]. They found that two branches for the self-similar solution are possible and these two branches coincide at a critical value of the liquid flux. For liquid fluxes above this value, the self-similar solutions cease to exist and this was attributed to sealing of rock with solid salt. The TOUGH2-EWASG [Battistelli at al. 1997] code was then used by Tsypkin and Calore [2007] to verify this hypothesis and predictions from the analytical model, and investigate the precipitate formation for conditions around the critical point. Three groups of regime of precipitate formation were individuated:

i) First group includes precipitation regimes when quasi-stationary state can be reached quickly (reservoir pressure lower than the critical pressure).
ii) Second group describes transient regimes when mass of precipitate at the vaporization front slowly increases for a long time (reservoir pressure slightly lower than the critical pressure). In this case non-stationary regime can go on for hundred years or even more to reach quasi-stationary regime or reservoir sealing.
iii) Third group consists of sealing regimes, which are characterized by comparatively fast filling of porous space with solid salt (reservoir pressure higher than the critical pressure). The point in the system at which sealing occurs becomes closer to the extraction well with increasing initial reservoir pressure.

The molecular diffusion process of NaCl in the brine is now considered in the above model Rock-fluid interaction studies suggest that mineral dissolution and precipitation effects could have a major impact on the long-term performance of geothermal well. Since it is common to have geothermal well drilled in carbonate formations, the precipitation and dissolution of calcite in geothermal reservoir has been here considered. Calcite relates to the carbon dioxide behavior, as governed by boiling, dilution and condensation processes [Simmons and Christenson, 1994].

Reactive transport modeling, as TOUGHREACT [Xu et al. 2004], was used to simulate fluid production from a well located at the center of a 2D radial carbonate reservoir and calcite deposition/dissolution processes.

Calcite dissolution gradually decreases along the flow path from the recharge inflow of fresh water toward the extraction well, whereas a depositing phase may occurs in the neighborhood of the extraction well. The deposition of calcite is mainly related to two effects: a) evaporation of the brine, which leads to calcite precipitation due to the consequent increase of calcium and carbonate concentrations, and b) forced CO_2 ex-solution, which leads to an increase of the saturation index of calcite. The above effects have been investigated modeling extraction from the well both at fixed and variable bottom-well pressure.

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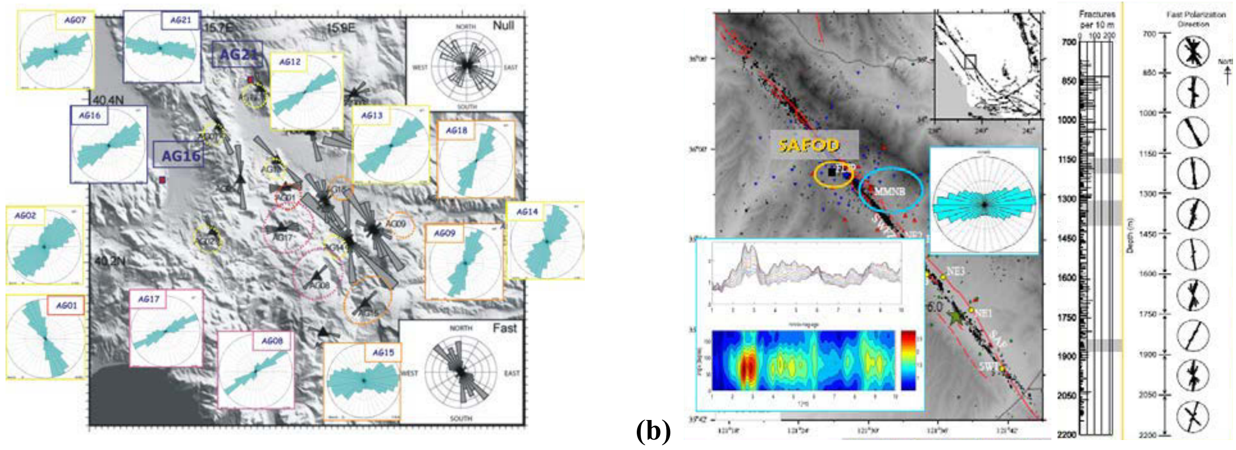
Ground Motion Polarization in Fault Zones: Its Relation with Brittle Deformation Fields

Marta Pischiutta[1], Antonio Rovelli[1] and Francesco Salvini[2]

[1]*Istituto Nazionale di Geofisica e Vulcanologia, Sezione Sismologia e Tettonofisica - Roma, Italy*
marta.pischiutta@ingv.it
[2]*Università degli Studi Roma Tre, Dipartimento di Scienze Geologiche - Roma, Italy*

Recent studies have found that ambient noise and seismic signals in fault zones tend to be polarized on the horizontal plane with a predominant orientation [Rigano et al. 2008; Di Giulio et al. 2009; Cara et al. 2010; Falsaperla et al. 2010; Pischiutta, 2009; Pischiutta et al. 2010]. Here we present a summary of past experiments as well as new case studies showing evidence of this effect. The approach combines the H/V technique in the frequency domain with the covariance matrix diagonalization method [Jurkevics, 1988] in the time domain. Common features are: *i)* a high stability of results at each site, independently of the nature and location of the source of seismic signals, *ii)* a predominant polarization that is characteristic for each fault, and *iii)* polarization is not parallel to the fault strike as it would be expected for fault-trapped wave generation.

In previous papers, a role of fluid-filled micro-cracks in the damage zone was hypothesized [e.g., Di Giulio et al. 2009]. If this is true, a correlation is expected between seismic anisotropy and polarization. In the studied faults, when anisotropy results are available, the horizontal ground motion polarization is found to be perpendicular to the fast wave splitting component, confirming the role of fluid-filled micro-cracks in the damage zone. In Figure 1 the orientation of horizontal polarization and the direction of the S wave fast component are shown for two case studies: the Val d'Agri basin (southern Italy) and the San Andreas fault.



(a) **(b)**

Figure 1. Perpendicularity relation between seismic anisotropy and the orientation of horizontal ground motion polarization on seismic events recorded in two studied areas. (a) Val d'Agri extensional basin (southern Italy): the horizontal polarization at each station site (cyan rose diagrams) is calculated from up to 30 seismic events and compared to the S wave fast component direction (grey rose diagrams) obtained from the S-wave splitting [Pastori et al. 2009]. (b) San Andreas fault, Parkfield sector. Comparison between the horizontal polarization of 2,000 earthquakes recorded in 2004 at the borehole station MM (cyan rose diagram) and the S wave fast component direction calculated by Boness and Zoback [2004] in the SAFOD pilot hole.

We have checked this interpretation in terms of the fracture field orientation in the damage zone by applying the package FRAP3 [Salvini, 2002] to model the brittle deformation field expected in the damage zone of the studied faults. We have found that the observed polarization azimuths are consistently orthogonal to the orientation of the predicted fracture systems.

As an example we report in Figure 2 the Pernicana fault case study (Mt. Etna), where Di Giulio et al. [2009] found a strong directional effect around 1 Hz. The polaritazion azimuth varies from N160 at stations installed on the fault hanging wall (# 7, 9, 10, 11, 12 and 13) to N120 at stations on the footwall (#3, 4, 5 and 6). In order to explain the observed variation, the brittle deformation in the fault damage zone was analytically computed through the package FRAP3. We explained the observed variation of the polarization azimuth in terms of a differential probability to develop different brittle deformation fields. The synthetic cleavage (N75) is more diffuse on the fault hanging wall while extensional fractures (N40) dominate the fault footwall. A perpendicularity relation between polarization and the most diffuse fracture field is again recognized.

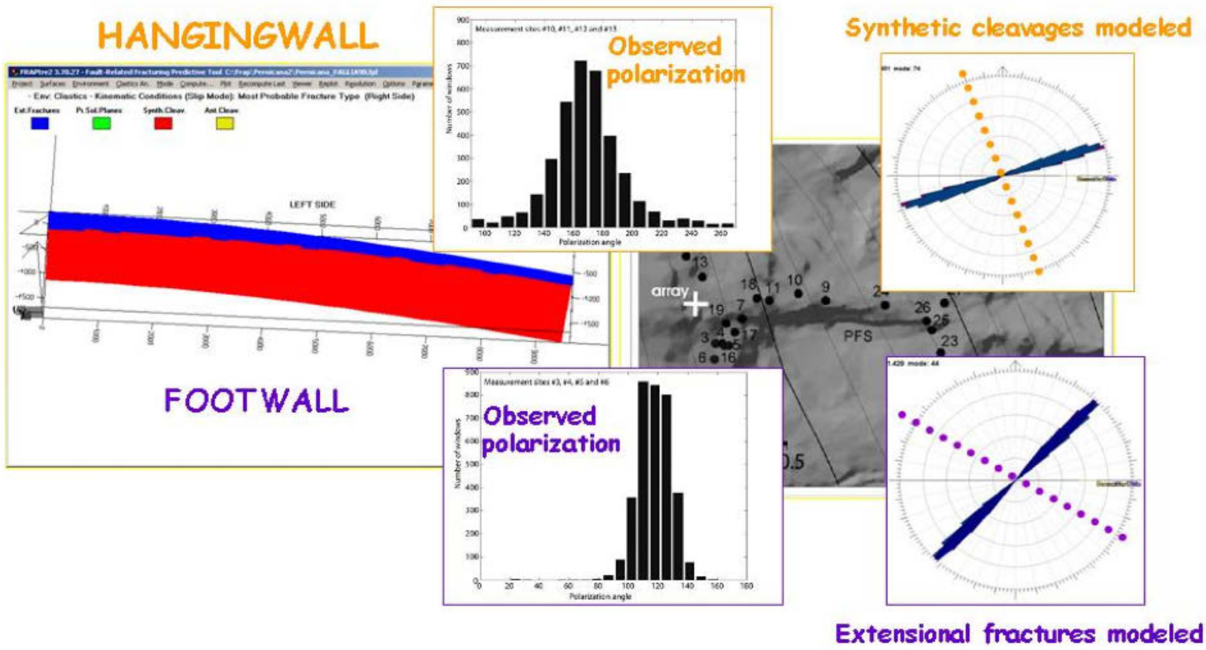


Figure 2. Most probable fracture field on the fault surface and rotation of polarization from the hanging wall to the footwall. Perpendicularity relation between polaritazion and the orientation of the most probable fracture fields (rose diagrams) both in the hanging wall (synthetic cleavages) and in the footwall (extensional fractures).

The quick and relatively inexpensive polarization method encourages to further tests for an extensive application to many fields of theoretical and applied geophysics, where indications about the orientation of fracture fields are required. In fact, polarization method yields the same information as S waves anisotropy allowing lower costs and faster measurements.

This method could be tested in geothermal areas where hydrofracturing is caused by water high-pressure injection. It could be also interestingly applied to CO_2 injection sites along with studies of focal source mechanisms, in order to detect seismicity variations due to fluid injection.

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Fluid Geochemistry and Geothermometry in the Northern Province of Rome (Latium, Central Italy): Implication for Geothermal Exploitation

Monia Procesi[1], Daniele Cinti[1], Franco Tassi[2,3], Giordano Montegrossi[3]
Orlando Vaselli[2,3] and Fedora Quattrocchi[1]

[1]*Istituto Nazionale di Geofisica e Vulcanologia, Sezione Sismologia e Tettonofisica - Roma, Italy*
monia.procesi@ingv.it
[2]*Università degli Studi di Firenze, Dipartimento di Scienze della Terra - Firenze, Italy*
[3]*Consiglio Nazionale delle Ricerche, Istituto di Geoscienze e Georisorse - Firenze, Italy*

Geothermal exploration started in Latium at the beginning of 1970s till 1990s. Environmental problems and unfavorable characteristics of the discovered hydrothermal reservoirs discouraged the exploitation in this region. Nevertheless, some areas as the northern province of Rome are still under-exploited.

A geochemical survey of about 200 fluid discharges (cold and thermal waters and bubbling pools) from the northern province of Rome was carried out in 2007 - 2008. The chemical and isotopic compositions of the fluids discharges indicate the occurrence of two main sources: 1) relatively shallow aquifers trapped in volcanic and sedimentary formations; 2) a liquid-dominated CO_2-rich deep reservoir, hosted in the Mesozoic carbonate sequence, showing a Ca-SO_4(HCO_3) composition.

The CO_2-CH_4-H_2 system seems to equilibrate at temperatures ranging between 150 and 200 °C and R_H values between -3.4 and -3.6. This temperature range is significantly lower than those recorded in deep boreholes of the area (up to 290 °C) [Cavarretta and Tecce, 1987] probably because H_2 rapidly readjusts at decreasing temperatures related to the ascent of deep-originated fluids to the surface. On the other hand, geothermometric evaluations based on chemical equilibrium between CO_2 and CH_4 and, separately, H_2S suggest that the reservoir equilibrium temperature is up to ~ 300 °C.

Fluid geochemistry, in agreement with gravimetric data and tectonic assessment, supports the idea that significant contributions from a deep-seated geothermal brine are present in the Stigliano thermal fluid discharges [Cinti et al. 2011]. The presence of thermal waters, the anomalous heat flow and reservoir temperature >150°C, coupled with the demographical growth of the last years, make this site a suitable location for medium-to-low enthalpy applications of the geothermal resource.

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Need to Plan Regionally a Strategic Use of Underground Reservoirs in Densely Populated Countries: Synergies and Conflicting Issues in Storing CO_2, Natural Gas, Nuclear Waste and Exploiting Deep Geothermics. The Problem of Public Perception and Risk Assessment

Fedora Quattrocchi

Istituto Nazionale di Geofisica e Vulcanologia, Sezione Sismologia e Tettonofisica - Roma, Italy
fedora.quattrocchi@ingv.it

Besides the Earth Science disciplines more traditionally related to seismology and volcanology, that INGV as other scientific institutions have developed in the last decades, other disciplines came out recently in response to the urgency of solving the ongoing energetic-climatic crisis (rapid exhaustion of fossil reserves, fast CO_2 rise in the atmosphere, etc). This made necessary to rework the monitoring and modeling tools commonly used by research institutes worldwide, to adapt them to new strategic and security-addressed purposes. The new energetic-climatic-environmental issue, that represents the object of this 34th Course of the International School of Geophysics, has important connections with numerous research fields, with the public perception and acceptance of new energetic technologies such as "CO_2 Capture and Storage" (CCS) and safe nuclear waste disposal, as well as deep geothermics exploitations, understating the need for "natural gas garages" underground. With 7 billion people living on our planet, the use of the geological underground will be increasingly important, and geophysical and geochemical risks assessment, mostly concerning induced seismicity and leakage of industrial fluids at surface, is a prerequisite. Unfortunately, the time left to face climate changes and exhaustion of reserves is short and we have to adopt a "learning by doing" approach.

Especially in densely populated countries it is growing and impelling the coexistence of different technologies to produce clean and CO_2-no emissive energy, such as 1) clean coal combustion, jointed to CCS; 2) last generation nuclear power and safe HLW (High Level Waste) nuclear waste geological disposal; 3) low "space consuming" renewables (hundreds of Megawatts in few hectares possibly!); 4) safe natural gas (CH_4) consumption without pipeline reserves.

All these draw-plate technologies, yet stated and well defined by the IEA (International Energy Agency) as priorities for worldwide security, together with the "energy efficiency" draw plate and the upstanding use of "energy saving", are urgent and strategic up to 2050 also for the IPCC (Intergovernmental Panel of Climate Change), G20, European Platforms (as "Zero Emissions Fossil Fuel Power Plant EU-ZEP platform), and CSLF (Carbon Sequestration Leadership Forum): all agree about the need of synergies and a shared use of the underground for geological storage of CO_2, CH_4, nuclear waste and geothermics exploitation. The geological underground storage and the exploitation of deep geothermics are really challenging multidisciplinary research fields not only within the Earth Sciences; an example is the integration among mass-transport, geochemical and geomechanical numerical modelling, that actually is the main gap to fill for underground reservoir characterization.

In summary, it is necessary to find soon synergies, compatibilities, conflicting issues, positive and negative interferences among the different use of deep underground (500-5,000 m of depth) for the different energy producing technologies in our industrial but densely populated countries. This new approach to the problem tentatively joins and not divides the different lobbies and scientific communities linked to the different draw-plates up to now, i.e., the nuclear one, the clean coal one or the hydrocarbons production enterprises, and the geothermal energy community. One example is the "Position Paper" of EGEC (European Geothermal Energy Council) published on December 15, 2009, which recognized the need to search synergies and conflicting issues between CCS and geothermics, trying to build up constructive cooperation among different communities on common areas of interest, to decrease the costs and resolve the environmental issues jointly.

However, as demonstrated by the fires spread around Moscow in summer 2010, it is necessary to plan safely the nuclear waste disposal taking into account alternative, possibly close, underground storages.

The first step of this planning is in the regulatory schemes, such as the European Directives (i.e., ANNEX 1 of the European Directive for CO_2 geological storage, where the criteria for sites selection are reported). A lot of questions have arisen, e.g., whether a regional or a national planning is preferable. Postponing this underground planning country by country, region by region, as it must be done for potable groundwater reservoir, is irrational and irreversible as well.

Integrated Infrastructure for CO_2 Transport and Storage in Western Mediterranean

Abdelkrim Rimi[1], Yassine Zarhloule[2], Dulce Boavida[3], Júlio F.Carneiro[4] and Roberto Martinez[5]

[1]*Université Mohammed V Agdal, Institut Scientifique - Rabat, Morocco*
rimi@israbat.ac.ma; rimi_krimo@yahoo.com; rimikrimo@gmail.com
[2]*Université Mohammed Premier, Faculté des Sciences - Oujda, Morocco*
[3]*Laboratorio Nacional de Energia e Geologia - Lisboa, Portugal*
[4]*Geophysical Centre of Evora (CGE), Geosciences Department - Evora, Portugal*
[5]*Instituto Geológico y Minero de España - Madrid, Spain*

Background

The need for developing a common strategy for CCS deployment in the West Mediterranean (Morocco, Portugal and Spain) is related not only to the geographical proximity but also to:

1. the increasing connections between the energy and industrial sectors in this area;
2. the spatial continuity of sedimentary basins that can act as potential storage reservoirs;
3. the existing experience in managing a large gas transport infrastructure.

Spain and Portugal emitted about 484 Mt CO_2eq in 2008 and, together, they accounted for nearly 10% of the European Union (EU - 27) GHG emissions. Drastic reductions are necessary to meet the commitments prepared within the EU and worldwide. Because of its increasing economic growth and energy demand Morocco's emissions were about 75 Mt CO_2eq in 2004 and these are expected to grow, in a "business as usual" scenario. On the one hand, Morocco, Portugal and Spain already cooperate in terms of transport of natural gas. The pipeline that supplies the Iberian Peninsula with natural gas from the Algerian fields crosses Morocco for a large extent.

COMET - Integrated infrastructure for CO_2 transport and storage in the west Mediterranean- is a join research Project co-financed by the European Seventh Framework Programme (FP7), which started on January 2010.

Methods

The overall strategy of COMET comprises four fundamental tasks, subdivided in seven work packages:

1. Harmonized inventory of present and future CO_2 sources and storage capacities in the region.
2. Least cost modeling of national and regional energy systems.
3. In-depth assessment of selected transport networks.
4. Dissemination of information.

Statement of Purpose

COMET is a three-year (2010-2013) join research Project co-financed by the European Seventh Framework Programme (FP7). COMET is aiming to identify and assess the most cost effective CO_2 transport and storage infrastructure able to serve the West Mediterranean area, namely Portugal, Spain and Morocco. This is achieved considering the time and spatial aspects of the development of the energy sector and other industrial activities in those countries as well as the location, capacity and availability of potential geological formations for CO_2 storage. Special attention is given to a balanced decision on transport modes, matching the sources and sinks, addressing safety and lifetime objectives, meeting optimal cost-benefit over time for a CCS network infrastructure as part of international cooperation policy.
Morocco, Portugal and Spain are at different stages of evaluating the local possibilities for implementing CCS.

Spain has been involved in CCS R&D projects for several years, having characterized its main point sources and identified its storage potential. Portugal and Morocco have only recently started characterizing their local possibilities.

Major stationary sources and the potential geological formations for storage were identified in the study area, namely Gharb, Essaouira, Doukkala, Tadla and Guercif sedimentary basins in Morocco, Porto, Lusitanian and Algarve basins in Portugal; Cantabrica, Duero, Madrid depression, Iberica, Ebro, Guadalquivir and Beticas basins in Spain (Figure 1).

Conclusions

COMET project will generate insights into the potentials and constrains of developing a common regional strategy to design and rationalize a CCS network infrastructure of carbon transport and storing, in order to help a group of countries to reduce their CO_2 emissions without compromising energy supply and economic development. Of particular relevance is the focus on placing together two industrialized countries, Spain and Portugal, and one developing country at fast economic growth, Morocco, which all ratified the Kyoto Protocol.

COMET is conceived to be the first concerted effort to the deployment of CCS in the West Mediterranean area, with common energy and development interests. COMET aims to be an important step towards the safe and commercial deployment of large scale near zero emission power plants in SW Europe and North Africa.

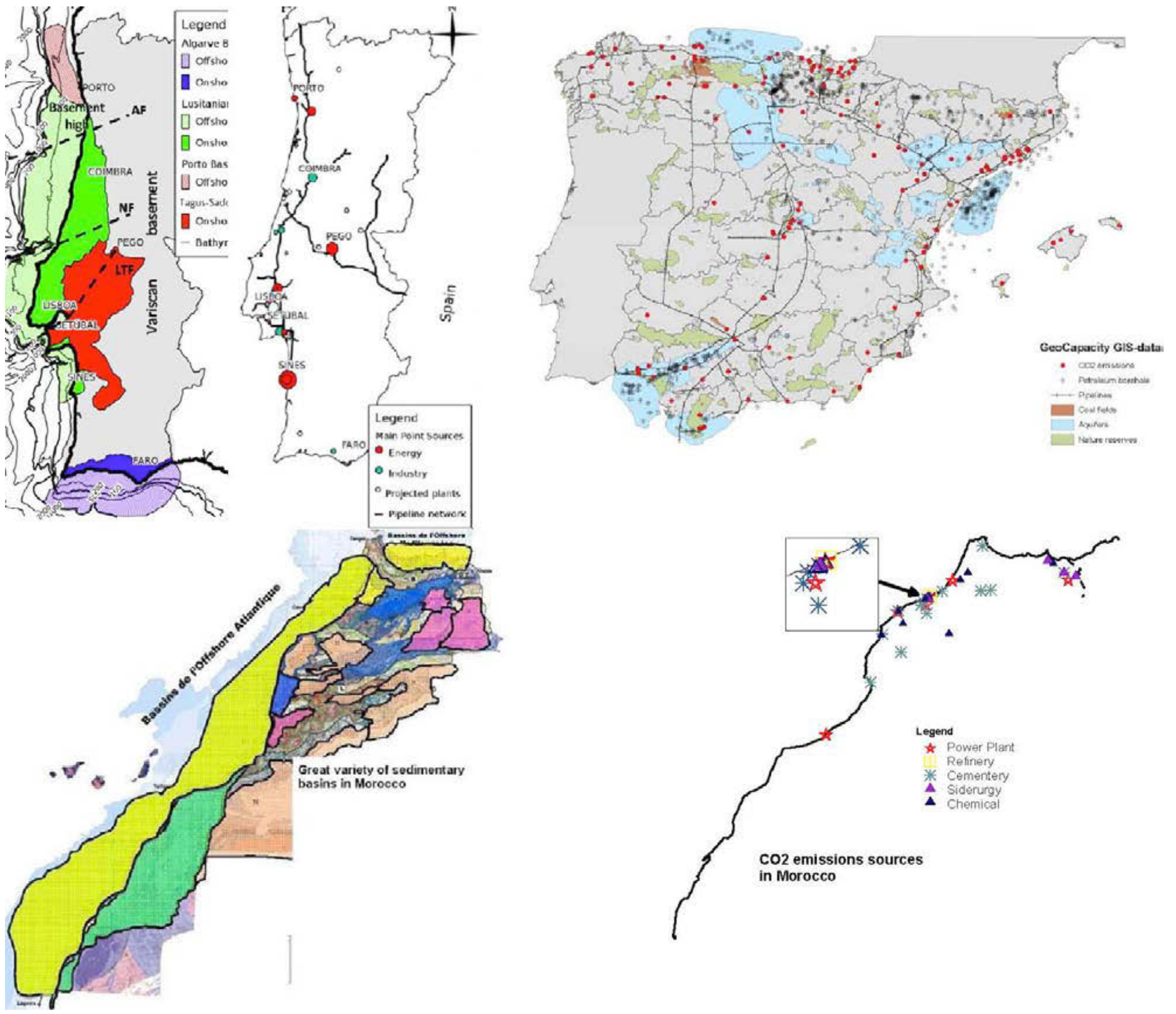

Figure 1. Present-day inventory of CO_2 emission sources in Spain, Portugal and Morocco and potential sedimentary basins for CO_2 sequestration in the three countries.

Methods to Access CO_2 and CH_4 Leakage from Natural Gas Storage and CO_2 Geological Storage: Case Histories from Italy

Alessandra Sciarra and Fedora Quattrocchi

Istituto Nazionale di Geofisica e Vulcanologia, Sezione Sismologia e Tettonofisica - Roma, Italy
alessandra.sciarra@ingv.it

Near surface gas geochemistry is the study of the physical and chemical behaviour of gas species in the vadose zone ("soil gas") and their exchange between the soil and the atmosphere ("flux"). Soil gas survey consists in collecting gas from the soil and analysing them for a wide range of species or isotopes to understand their origin, migration mechanisms and attenuation processes.

Flux measurements typically involve the measurements of CO_2 and CH_4 over time by using an accumulation chamber placed on top of the soil.

Within the field of CO_2 geological storage and natural gas storage, near surface gas geochemistry can give critical information regarding potential migration pathways, travel times, and attenuation processes, and can be used for monitoring storage sites giving early warnings in the unlikely event of a CO_2 or CH_4 leak. The first thing to know in detail is the presence/absence of geogas in geological strata closer to the surface, in soils and groundwater surface, both quantitatively and spatially georeferenced to define the baseline / background of the content of CH_4 and other gas source more or less deep.

Our work takes into account different studies conducted in various areas of Italy, with particular regarding to fault and fracture markers, like ^{222}Rn, He, H_2, CO_2, CH_4, in the soil gas concentration, and CH_4 and CO_2 flux measurements. These studies represent a good example of applying geochemistry techniques of fluids useful to define quantitatively gaseous species contents in the interstitial pores of soil and the flow measurements associated with it. This information allows to estimate the soil degassing potential of an area. Indeed, defining and delimiting the possible escape routes related to the normal processes of "leakage" (gas leakage from underground) and "seepage" (leakage of gas underground in the lower atmosphere) of geogas of deep origin is crucial to get a real vision of the natural degassing structures (CO_2, CH_4, ^{222}Rn, etc.).

From the Integrated Interpretation of Subsurface Datasets to 3D Geological Models: Applications and Case Studies

Davide Scrocca

Consiglio Nazionale delle Ricerche, Istituto di Geologia Ambientale e Geoingegneria - Roma, Italy
davide.scrocca@igag.cnr.it

In the last decades, the increasing availability of digital geophysical and geological datasets has been coupled by the developments of powerful 3D modeling applications. These tools represent a challenge to build reliable and consistent 3D subsurface geological models where data and knowledge are fully combined. 3D model may also contribute to overcome several of the existing limitations that are inherent in the traditional 2D methods of analysis and representation (e.g., maps and cross sections). Furthermore, by reconstructing 3D models, geoscientists are stimulated to check data consistency and to understand the spatial relationships among structural and stratigraphic features.

Building 3D subsurface models requires the integration of multi-scale and multi-source georeferenced dataset, generally including the following typologies.

- Surface data: digital elevation model, geological maps (faults, geological boundaries, dip data), and imagery (satellite, aero photos, etc.).
- Subsurface data: borehole data (stratigraphy, well logs, core measurements, etc), geophysical information (e.g, 2D/3D seismic reflection data, magnetotelluric surveys, etc).

These different datasets may be usefully integrated in a single 3D environment where the final interpretation and modeling will be carried out.

Data density and quality influence the way data are elaborated and modeled. Of course, the availability of high-density and high quality subsurface datasets (e.g., 3D seismic surveys or dense 2D seismic grids) makes 3D modeling a relatively straightforward procedure. In areas where only sparse subsurface constraints are accessible, the construction of a consistent 3D model requires the optimization of the use of surface information and a special care in data interpolation.

The modeling procedure often involves, as a first step, the reconstruction of the fault network. In this way the modeled volume is subdivided in blocks by fault surfaces. Geological surfaces are then interpolated separately within each block.

In complex geological settings (e.g., thrust belt, salt dome), a validation of the structural interpretation may be appropriate. 2D/3D software tools for structural restoration and analysis can help in building more robust structural models.

When seismic reflection data are used, the model is usually built in the time domain. To depth convert a model reconstructed in the time domain, a 3D subsurface velocity model needs to be elaborated interpolating the available information about seismic velocity of geological formations (usually derived from well measurements such as sonic logs, check-shot surveys and vertical seismic profiles).

3D geological models may be populated with specific properties including both geological features (e.g., facies or fracture modeling) and other attributes (e.g., porosity, permeability, temperature, etc.) derived from well measurements or from other geophysical surveys. As an example, when modeling a reservoir, knowledge about the depositional characteristics of a given geological formation will suggest rules concerning the geometries of the associate lithofacies and their possible relationships. These rules can be used to drive the geostatistical interpolation of the available subsurface information (e.g., well data or seismic attributes). The resulting facies model can be used to distribute within the 3D volume reservoir properties such as porosity.

Reliable 3D geological models are usually required as input to a variety of other tools such as reservoir simulators which are able to predict the behavior of the rocks under various scenarios (e.g., fluid flow, geomechanical behavior, geochemical reactions, etc.).

These techniques, originally developed by the oil industry, are now applied in a wide variety of contexts, including CO_2 and CH_4 geological storage, geothermics, and radioactive waste disposal.

The French Geological Disposal Project for HL Radioactive Waste: From the Underground Laboratory to a Global Territorial Development Plan

Nicolas Solente

ANDRA - Agence Nationale pour la Gestion des Déchets Radioactifs - Châtenay-Malabry, France
nicolas.solente@andra.fr

On December 1991, the French National Assembly passed the French Waste Management Research Act, authorizing and initiating a 15 year research program along three options for HLW long-term solution: separation and/or transmutation, long-term storage, and geologic disposal.

On June 2006, the "Planning Act on the sustainable management of radioactive materials and waste" sets a new framework and new aims to the above mentioned options.

Focusing only on the geologic disposal research program, the R&D program has been broken down into three phases, in a step by step approach. Each phase has intermediate objectives: site selection for an Underground research Laboratory (URL), disposal feasibility demonstration, reversible disposal design.

The first step of the research program aimed at URL site selection. From 1994 to 1996, Andra carried out geological characterization surveys in four French districts, leading to the Request for Licensing and Operation of laboratory facilities on three sites. During this phase, boreholes, 2D seismic surveys and geological outcrops studies were the main sources of data. The result was the selection of Bure area, the most suitable site for the implementation of an underground laboratory.

In the second phase, the research program targeted the safety and technical feasibility of a reversible disposal site, located in Meuse or Haute Marne districts, as selected by the government in 1998. Andra conducted geologic survey during the URL shaft sinking and experiments in drifts at depths of 445 and 490 m. This program allowed consolidating the knowledge already acquired: geological environment, stability of the rock and the regional geology, and containment properties. The 2005 Progress Report presents the results of this phase. The main conclusion is that a potential disposal facility may be safely constructed over a zone with geological characteristics similar to those investigated at the URL, called transposition zone (about 250 km^2). From 2006, in the third phase of the program, the activities were oriented, inside the transposition zone, to determine a smaller zone in which a potential disposal facility could be located. In 2009, Andra issued a proposal for such a zone to the French authorities.

Andra has a clear roadmap to prepare the next steps of the project, as they were defined in the 2006 act, eventually leading to the licensing process (2015), the first phase of the site construction (2017) and the repository commissioning (2025). The repository project is a key component of both the regional development plan and the national radioactive waste management plan. The consultation process initiated this year with waste producers, followed in 2013 by a public debate, will help shaping the project with national and local stakeholders.

Territorial and Infrastructural Risks Mitigation for Large Scale Deployment of Deep Geothermics and CO_2 Transport and Storage Technologies. Barriers to be Removed and Costs Analysis

Angelo Spena

Università degli Studi di Roma "Tor Vergata", Dipartimento di Ingegneria dell'Impresa
Laboratori di Fisica Tecnica Ambientale - Roma, Italy
spena@uniroma2.it

According to the EU Commission Set-Plan-Final Document COM [2007] 723, where "focus on the whole system requirements, including efficiency, safety and public acceptance to prove the viability of zero-emission fossil fuel power plants at industrial scale" is recommended, in this work a comprehensive review of the main barriers to kick-start an efficient transfer of both material and immaterial tools for either CCS and Deep, High Enthalpy Geothermics practice is attempted.

CCS is a bridge technology. A fully carbon free technology fit to replace fossil fuels (nuclear included) is far from any foresight. Governments could utilise CCS not only to meet emission targets, but to offset costs by using the CO_2 to increase oil production. Their involvement could also reduce risks at all levels of the CO_2 value chain by promoting it in its developmental phases, by supporting the implementation of new capture technologies and by facilitating contracts between companies.

Deep Geothermics (DG) is a promising technology. It allows to subtract power or heat from the ground, but costs evaluation is subjected to either scale factor and externalities assessment. If widely deployed, Deep Geothermics could contribute to cover energy demand without additional CO_2 emissions.

DG and CCS technologies present a common feature: a great impact both on ground and underground, and consequently relevant territorial and infrastructural risks analysis and mitigation. Given the urgency of the situation, deployment of CCS and of DG must begin with the most promising technologies available today. The oil and gas industry already run large chemical plants similar, although in scale, to some types of CO_2 capture facilities fit for power generation. DG could start exploring extensions of geothermal heat pumps well known technologies.

An inverse correlation between the relevance of environmental taxes and emission patterns for the overall economy is widely recognized, so that macroeconomic links and constraints need also to be considered and evaluated. This requires to implement modelling tools aimed to afford accurate sensitivity studies so that optimal infrastructure layouts could be defined. In order to process the available data in a global scenario and to give first approach results about links and related effects, an original nomogram is proposed. Several quantities are considered: costs of power installation, of energy generation, of CO_2 removal with CCS processes, power generation and CO_2 removal efficiencies, ETS evaluation reference levels. Social costs are also taken into account. In this lecture the case study of Italy and China is stressed with respect to two scenarios: year 2005 and year 2030. CCS technologies appear more beneficial in developing countries, as departures between China and Italy appear timely decreasing but only in absolute value.

This lecture will then deal mainly with CCS perspectives. A fully developed CCS system will reproduce on CO_2 pipeline grids several well known problems of electrical or hydrocarbons grids (dispatching, logistic, locational signals, operational problems). Studies are then needed to determine the best infrastructure routing, and to minimize internal and external (environmental and social) costs.

Most analyses of the Kyoto flexible mechanisms show that mitigation costs are lower in a global permit market than in regional markets or in permit markets confined to Annex I countries. And recent studies suggest that banking could not only increase the economic efficiency, but also the environmental effectiveness of climate policy, especially in the short-term. Then laws and treaties regulating the economics involved are needed. This also implies to compound policies for planning investments in either oriented economies and in market economies (or hybrid ones, like in China): as a matter of certainty, investors convinced that CCS or DG technologies could have robust, long-term perspectives, with the right incentives can deliver solutions. Otherwise, delay would be costly and maybe dangerous. It means establishing a clear, stable fiscal and regulatory framework, to create a level playing field for all industrial actors within a common legislative framework as broad as possible, avoiding over-regulation. This framework should also have a long lifetime - of the order of 30 years. This gives the necessity of long-term investors, regardless their public or private nature, rather than venture capitals and private equities.

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The Calatrava Volcanic Province (Central Spain): CO_2 Hazard versus CCS (Carbon Capture and Storage)

Orlando Vaselli[1,2], Barbara Nisi[3], Franco Tassi[1,2], Luciano Giannini[1,2], Giordano Montegrossi[2], Fidel Grandia[4], Robert J. Poreda[5], Luis Pérez del Villar[6] and Jordi Bruno[4]

[1]*Università degli Studi di Firenze, Dipartimento di Scienze della Terra - Firenze, Italy*
oralndo.vaselli@unifi.it
[2]*Consiglio Nazionale delle Ricerche, Istituto di Geoscienze e Georisorse - Firenze, Italy*
[3]*Consiglio Nazionale delle Ricerche, Istituto di Geoscienze e Georisorse - Pisa, Italy*
[4]*Amphos 21 Consulting SL - Barcelona, Spain*
[5]*University of Rochester, Department of Earth and Environmental Sciences - Rochester, NY, U.S.*
[6]*Centro de Investigaciones Energéticas, Medio Ambientales y Tecnológicas - Madrid, Spain*

In the present study, new original geochemical and isotopic data of the CO_2-rich gas discharges from the late Miocene-Quaternary Calatrava Volcanic Province (CVP) are presented. Such fluid emissions, often accompanied by mineral waters with temperature generally <30 °C, are the marker of the past volcanic activity characterizing this extended area. The CVP consists of a series of scattered vents, outcrops of mafic lava flows and pyroclastic deposits of alkaline composition, likely formed in two different periods. The first stage (8.7 - 6.4 Ma) is referred to ultra-potassic mafic extrusives whilst the second stage (4.7 - 1.75 Ma) is characterized by an alkaline and ultra-alkaline volcanism. These two main phases were followed by some volcanic activity that extended between 1.3 and 0.7 Ma. Maar craters in the CVP are lined up according to NW–SE and NE–SW tectonic trends in central Spain. The CO_2-rich gas manifestations have a deep (mantle-related) origin, as indicated by the relatively high helium isotopic ratios (up to 2.7 R/Ra) and those of carbon in CO_2 that are ranging between -6.8 to -3.2 ‰ (V-PDB), i.e. within the carbon mantle interval. The hypothermal waters are mainly $Mg(Ca)\text{-}HCO_3$ and are occasionally Fe- and Mn-rich, with pH and electrical conductivity values down to 5.5 and up to 6500 µS/cm, respectively. The gas discharges are largely dominated by CO_2 that in some cases is up to 999,000 µmol/mol, while N_2 and Ar (both atmospheric origin) are comprised between 709 and 11,849 and 7 and 313 µmol/mol, respectively. H_2S and CH_4 are present in all the analyzed samples up to 71.4 and 81 µmol/mol, respectively.

The CVP represents a natural analogue of CO_2 escape from a deep-seated reservoir and different geochemical monitoring activity, including soil CO_2 flux measurements and IR thermal imaging, can be carried out to identify the main areas of CO_2 leakage. The CVP is particularly interesting because Spain is preparing a pilot well into which liquid CO_2 will be injected at the depth of 1,000-1,500 m. The CVP and the Selva-Emborda field (Cataluña) are the only places in the Iberian Peninsula where abundant CO_2 leakage is occurring and, consequently, their study may allow to develop appropriate monitoring techniques before the first Spanish pilot well will be operating. It is worthwhile to mention that in July 2000, a relatively cold (17 °C) gas jet occurred in Granatula de Calatrava (central Spain) during the drilling of a 200 m deep well as a semi-confined CO_2-rich aquifer was reached. The gas eruption lasted 176 days and about 1 hm^3 of CO_2 was released at a peak rate of 75 L/sec. These gas blasts induced by well drilling are quite common in volcanic and non-volcanic areas, where CO_2-rich reservoirs are present (e.g. central Italy, where a similar gas blast, though at lower extent, occurred in July 2010 in Tuscany). Carbon dioxide accumulation within lacustrine water bodies may suddenly be released, causing gas blasts such as those occurred at Lake Nyos (Cameroon) in 1986, when approximately two thousand people died. These events, sometimes extreme, represent an important feature to be considered when dealing with CCS (Carbon Capture and Storage), as CO_2 leakage from anthropogenic CO_2 reservoirs. Weakness zones, as faults and fractures, can represent preferential pathways of CO_2 leakage at surface. CO_2-rich gas pockets may also form at shallow depth if an impervious caprock acts as a sealing cover. Hence, understanding CO_2 natural analogues is a fundamental step to minimize the risk of CCS system.

Thermo-Hydro-Mechanical Processes in Rocks: From Natural Hazard to Reservoir, CO_2 Sequestration and Waste Disposal

Sergio Vinciguerra

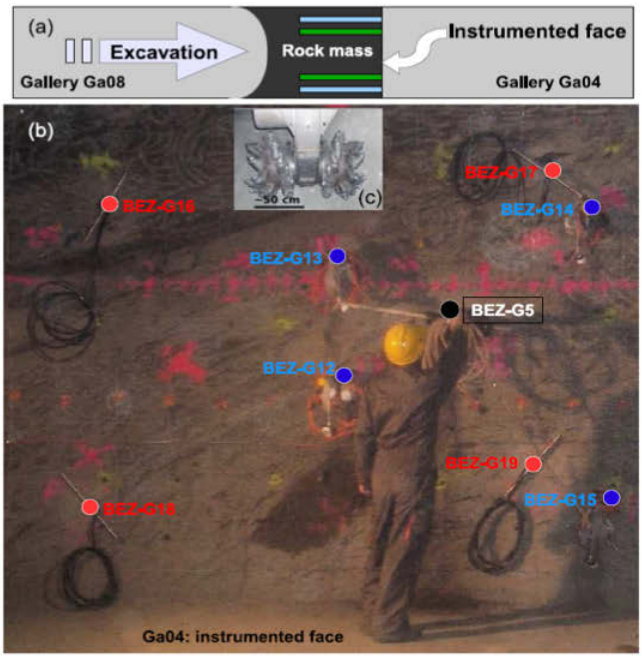
Istituto Nazionale di Geofisica e Vulcanologia, Sezione Sismologia e Tettonofisica - Roma, Italy
sergio.vinciguerra@ingv.it

Detailed understanding of the composition, structure and evolution of the Earth's crust which provides all life-sustaining materials, is essential for sustainable, science-based management of Earth's environment and resources. Importantly, rising global population and urbanization increases vulnerability from natural hazards such as earthquakes, volcanic eruptions and anthropogenic climate change.

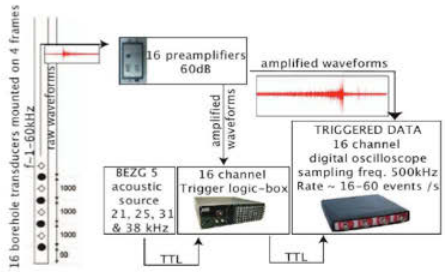
Natural hazard events such as earthquakes or volcanic eruptions and the geomechanical controls on underground storage of CO_2 and nuclear waste, and the production of oil, gas and geothermal involve activation of coupled thermo-hydro-chemo-mechanical processes in rocks.

While for structural materials (e.g., steel), the relevant properties in an application (e.g., a beam in a large structure) can reliably be determined, this is not valid for rocks.

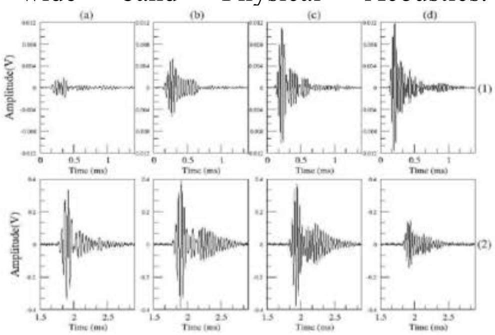
Unfortunately, rock masses can be accessed directly only at the surface or through tunnels (Figure 1) and boreholes, and thus uncertainties about material and transport properties are inevitable.



Monitoring of Excavation Damage Zones (EDZ).



Acoustic set up, which consists of 16 wide band Physical Acoustics.



Acoustic signals received at 20, 25, 31 and 38 kHz.

Figure 1. (a) Principle of the experiment: monitoring of the excavation damage zones (EDZ) from the end-face Ga04 during the excavation from gallery Ga08. (b) End-face Ga04 as seen when instrumented: black circle is for the borehole where the acoustic source was introduced, blue and red circles are for the near- and far-field acoustic measurements, respectively. (c) Illustration of the tunnel borehing machine: a road header was used for the excavation.

Rock physics laboratory experiments allow determination of how intrinsic properties of rocks (e.g., microstructure, composition, fabric, microcracks, strength, seismic properties and attenuation) vary as a function of extrinsic variables (pressure, temperature, pore fluid pressure, differential stress).

In order to simulate conditions at depth in the Earth's crust, it is necessary to conduct rock deformation experiments inside a pressure vessel. A jacketed rock sample is placed inside the pressure vessel, and the vessel is then pressurised (using silicone oil) to simulate the lithostatic stress at depth. A separate pressurisation system is then used to provide water pressure in the internal pore space of the rock sample (known as the pore fluid pressure). The specimen jacket acts to keep the two fluids apart. The sample assembly may then be heated via an internal furnace to simulate the temperature at depth, and finally an axial stress is applied via a loading ram to simulate the tectonic stress (Figure 2a).

The sample jacket is made of a synthetic rubber compound and contains inserts for the location of up to 12 piezoelectric transducers that are used for the measurement of elastic wave velocities (both compressional and tangential) and microseismic (acoustic) emission output. A schematic diagram of this arrangement is given in Figure 2b. Two pore fluid ports in the sample end-caps allow for fluid flow through the sample for the measurement of permeability.

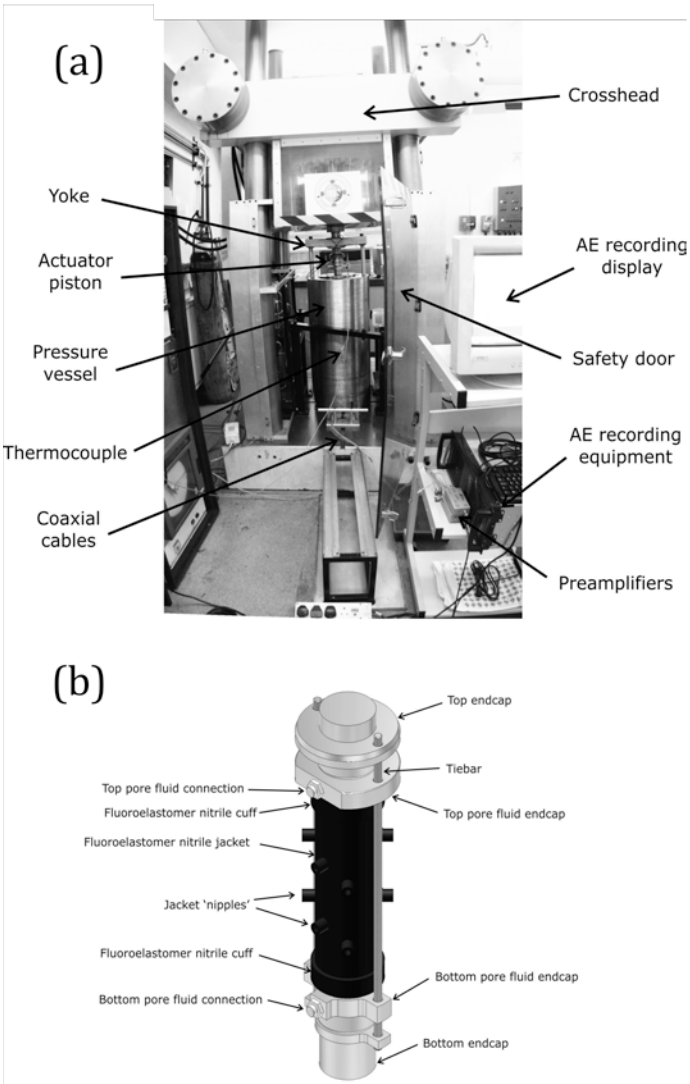


Figure 2. (a) Photograph of the servo-controlled 400 MPa triaxial rock deformation apparatus at the Rock & Ice Physics Laboratory, UCL (b) three-dimensional Autodesk Inventor picture of the jacketed sample setup.

In recent years the development of new experimental, analytical and modelling techniques has generated substantial progress. Theoretical modelling helps validating experimental observations and is used to extrapolate laboratory observations to the field scale.

For example it has been shown that for bulk rock deforming in a brittle manner, stress corrosion will lead to highly nonlinear time-dependent deformation.

This allows rocks to deform even under a constant applied differential stress over extended periods of time; a phenomenon known as brittle creep [Atkinson and Meredith, 1987]. This style of deformation can be described as exhibiting an apparent trimodal behaviour when axial strain is plotted against time (commonly known as a *creep curve*). The three stages of the creep curve have conventionally been described as: (1) primary or decelerating creep, (2) secondary or steady-state creep, and (3) tertiary or accelerating creep (Figure 3).

Despite the smaller length and time scale of laboratory experiments compared to nature, field observations can be quantitatively reproduced and modelled [Ventura et al. 2010], thus significantly contributing to the understanding of the dynamics of tectonic and transport processes.

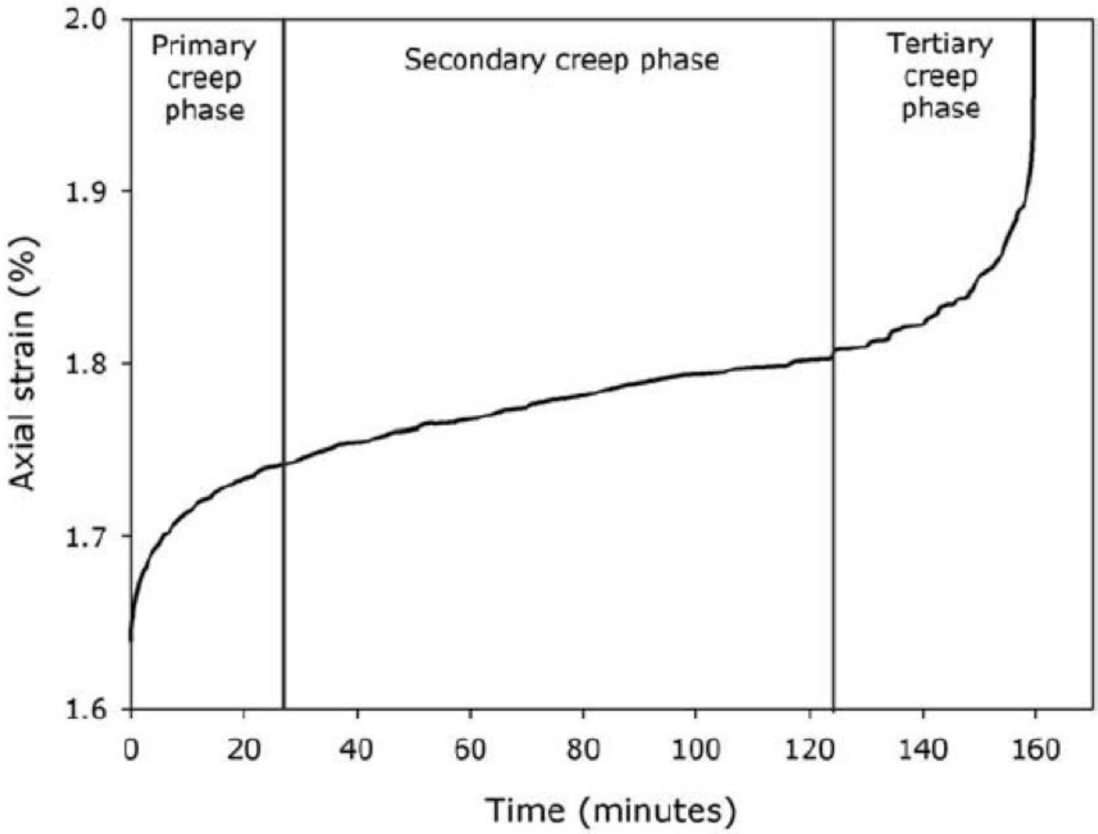


Figure 3. The classic trimodal creep curve for brittle material at a constant applied differential stress. The curve shows the three stages of brittle creep: (1) primary or decelerating, (2) secondary or steady-state, and (3) tertiary or accelerating. The secondary creep phase is where creep strain rates are calculated.

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Study of Natural Analogues for the Comprehension of Gas Migration Mechanisms

Nunzia Voltattorni[1], Daniele Cinti, Gianfranco Galli[1], Salvatore Lombardi[2], Luca Pizzino[1], Alessandra Sciarra[1] and Fedora Quattrocchi[1]

[1]*Istituto Nazionale di Geofisica e Vulcanologia, Sezione Sismologia e Tettonofisica - Roma, Italy*
nunzia.voltattorni@ingv.it
[2] *Sapienza Università di Roma, Dipartimento di Scienze della Terra - Roma, Italy*

Introduction

Soil gas anomalies are useful to recognize influences of surface features on natural gas migration. The study of the association of different gases (with different origin and physical/chemical behavior), the collection of a large number of samples during periods of stable meteorological and soil moisture conditions (e.g., during dry season) and the use of appropriate statistical treatment of data are fundamental in the comprehension of gas migration mechanism.

Gas geochemistry has been proven to be a reliable and simple technique to apply, at different scales, to many geological scenarios [Quattrocchi et al. 2001; Baubron et al. 2002; De Gregorio et al. 2002; Pizzino et al. 2002; Lewicki et al. 2003; Voltattorni et al. 2009; Lombardi and Voltattorni, 2010]. The study of spatial distribution of soil gas anomalies, at the surface, can give important and interesting information on the origin and processes involving deep and superficial gas species. This information can be applied and studied in different frameworks, for example:

- Geological sequestration of anthropogenic CO_2 to reduce the amount of greenhouse gases released to the atmosphere. Natural gas emissions represent extremely attractive surrogates for the study and prediction of the possible consequences of leakage from geological sequestration sites of anthropogenic CO_2 (i.e., the return to surface potentially causing localized environmental problems).
- Radionuclide migration in the study of high-level radioactive-waste isolation systems. The main approach is to study the natural migration of radiogenic particles or elements throughout clay formations that are considered an excellent isolation and sealing material due to their ability to immobilize water and other substance over geological timescales.

Sampling and analytical procedures

Soil gas surveys can be performed at both regional (e.g., sampling grid: 1 sample/km^2) and local scale (detailed sampling grid including profiles and/or transects) on the basis of the research goal. The surveys should be performed during summer or dry periods to avoid climatic factors which may affect soil gas values [Hinkle, 1994].

Shallow soil gas samples are obtained using a 1 m stainless steel probe fitted with a brass valve: this system enables soil gas to be collected and stored in metallic containers (with a vacuum 10^{-2} atm) for laboratory analysis or to be pumped for on-site Radon (Rn) analysis. Radon determination is accomplished in the field with an EDA Instrument RDA-200 Radon Detector.

Generally, the studied gases include major (N_2, O_2, CO_2) and trace (^4He, H_2) gases and light hydrocarbons (C_1 to C_4) that are analysed using a Fison Instrument GC-8000 Series gas-chromatograph.

A specific technique has been developed to collect submarine samples [Caramanna et al. 2005] in proximity of gas vents. In order to collect free/dry gas samples, a plastic funnel is inverted (30 cm diameter with 12 kg ballast around the lower ring) and placed precisely on the gas vent to be sampled. The funnel is connected, through a silicon hose, to a Pyrex glass flask with twin valves. This flask is pre-filled with air at a pressure above that of the hydrostatic pressure expected at the sampling depth in order to stop seawater from entering the sampler.

Results: study of natural gas emissions

An area in proximity of Panarea Island (Aeolian Islands, southern Italy) was interested by a huge submarine volcanic-hydrothermal gas burst during November, 2002. The submarine gas emissions chemically modified seawater causing a strong modification of the marine ecosystem causing the death of mainly benthonic life forms and serious damage to the sea-grass *Posidonia oceanica* [Voltattorni et al. 2009].

Gases have been collected from the seafloor at variable depths (depending on gas emission point depth). The temperatures of leaking fluids are variable at the different gas emission points (Figure 1): highest temperature measurements refer to Black point ranging between 110 °C and 137 °C, excepting the first measurement. Lower temperatures (mean value: 86.7 °C) have been measured at the Sink point and at Vent 8 (mean value: 52.11 °C). According to Capaccioni et al. [2007], a possible explanation for the temperature variability at the different gas emission points is related to an inferred magmatic system centred on or closer to Black point and whose diameter probably does not exceed a few hundred meters.

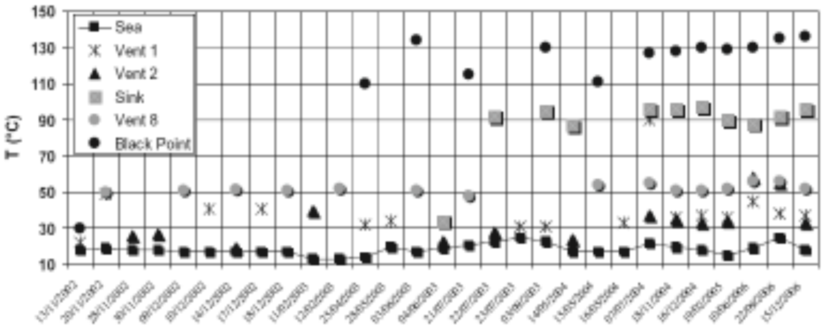

Figure 1. Temperature measurements at Panarea vents. Fluids from vents are very hot (especially from Sink and Black point with temperatures >90 °C) but due to their low flow, they do not affect temperatures of the surrounding seawater.

All of the collected gases are CO_2-dominant (the content varies from a minimum of 83.64 vol. % to a maximum of 98.43 vol. %). The CO_2 leakage varies at the different vents being higher at the Black point and lowest at the Sink point. However, median values are very similar for each vent suggesting a common degassing input linked to local tectonic features. In fact, all the gas emission points are located along N–S, E–W and NE–SW oriented active faults controlling the Aeolian Volcanic District.

Another natural degassing area is the Phlegraean Fields magmatic system that is still active, as the last eruption occurred in 1538 A.D. at Monte Nuovo. Faults affecting the Phlegraean Fields caldera follow two preferred strikes, NW-SE and NE-SW, that also affect the Campanian Plain and the inner sectors of the Apennine belt [Orsi et al. 1996].

The Phlegraean Fields Caldera has been investigated, during November 2006, by means of a detailed soil-gas survey in the inter crater sector, during which 54 soil gas flux measurements (1 sample/50 100 m) have been performed through the method of the accumulation chamber.

The Φ_{CO2} values range from 0 to 5500 gr/m^2*d with an average of 1127.32 gr/m^2*d. The highest flux values were found in the "La Fangaia" and near the "Bocca Grande" and "Bocca Nuova" fumaroles. The same area was investigated during June 2002 [Voltattorni et al. 2006] and a comparison of the two surveys (Figure 2) performed in different years and seasons, has highlighted that the highest Φ_{CO2} values are always within an area bordered by faults and fractures, confirming that the degassing process is strictly related to local tectonic structures.

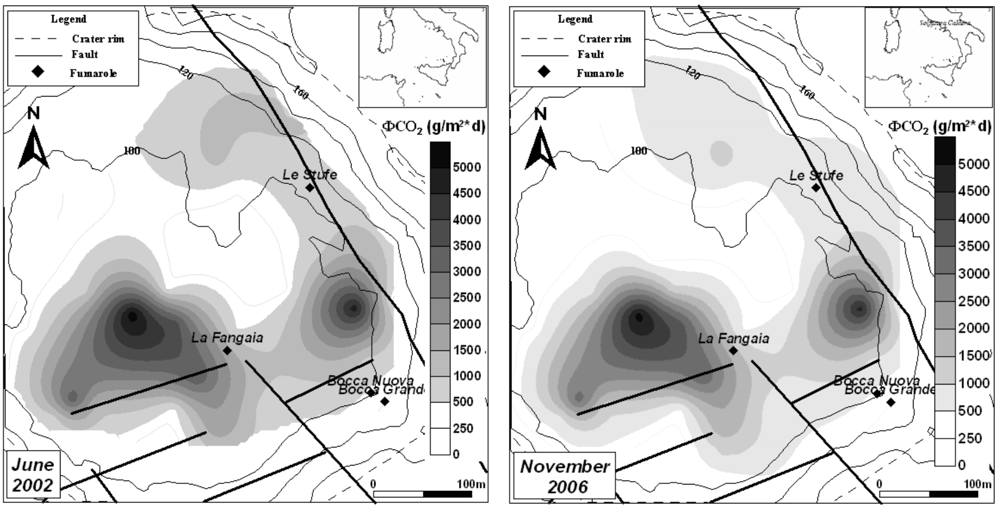

Figure 2. Contour maps of CO_2 fluxes at Phlegraean Fields Caldera. The results from two surveys performed in different years (June 2002 at the left and November 2006 at the right) and seasons highlights that the highest Φ_{CO2} values are always within an area bordered by faults and fractures.

Results: study of natural radionuclide migration

The physical properties of thermally altered clays of the Orciatico area (Tuscany, Central Italy) were studied as they could act as geological barriers to radionuclide migration in high-level radioactive-waste isolation systems. The study was performed through detailed soil gas surveys in order to define the gas permeability of the clay unit [Voltattorni et al. 2010].

A total of 1,086 soil gas samples was collected in the Orciatico area. Highest soil gas values (^{222}Rn> 25 Bq/l, CO_2>2 %,v/v) occur in the southwestern part of the studied area (characterized by the presence of the igneous body outcrop named Selagite) and along a narrow belt, with direction NNW-SSE, where metamorphosed clays (named Termantite) are present. All over the northeastern sector, in non metamorphosed clays, radon and carbon dioxide values are very similar to background values reported in literature (Rn: 10 - 15 Bq/L, CO_2: 0.5 %,v/v). As radon and carbon dioxide values seem to decrease gradually from the Selagite outcrop towards un-metamorphosed clays, soil gas data set were projected along one longitudinal line coinciding with a performed geoelectrical profile. Figure 3 shows polynomial regression (3° degree) of radon and carbon dioxide values plotted against the distance from a reference point. The overlapping peaks in the radon-carbon dioxide plots should confirm that the soil gas distribution is linked to clay alteration degree. In fact, highest CO_2 and Rn values were found between the Selagite outcrop and the first resistive limit, in a narrow belt characterized by a high alteration degree and, probably, by an intense shallow fracturing. On the other hand, after the second resistive limit, where clays did not undergo the effects of the intrusive body, radon and carbon dioxide values are in agreement with the mean values reported in literature excepting in the last 200 m of the profile where values increase again slightly.

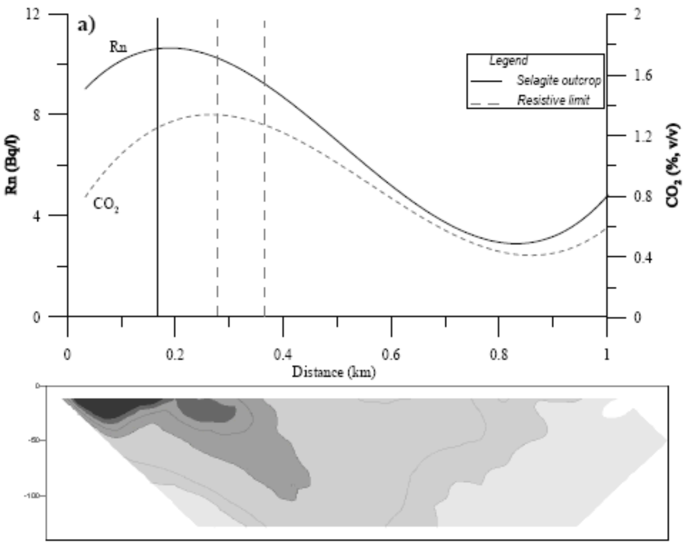

Figure 3. Comparison between polynomial regression (3° degree) map and geoelectrical profile. Rn and CO_2 graphs highlight slightly decreasing trends of soil gas values towards the NE, from the Selagite outcrop towards un-metamorphosed clays.

Conclusions

On the basis of the many achieved results, it can be said that soil gas prospection constitutes a powerful tool to identify complex phenomena occurring within the crust. The comprehensive approach followed in this study has provided insights on the spatial influence of tectonic discontinuities and geology on gas migration toward the surface. Soil gas measurements, performed at different scales, involved gaseous species with very different geochemical behaviour. Soil gas surveys yielded different features of the anomalies, reflecting the different gas bearing properties of the pathways along which gases can migrate.

As soil gas distribution can be affected by some phenomena related to the climatic factors, soil moisture and gas behaviour (mobility, solubility, and reactivity), a multivariate study including a large number of gaseous species has been considered.

However, independent from gas origin, all the results show that gases migrate preferentially through zones of brittle deformation and enhanced permeability. In order to quantify the spatial influence of fault geometry and geochemical properties on the distribution of soil gases, the geostatistical approach (i.e., variograms) is necessary.

Because of the very high variability of gas concentrations at the surface, soil gas prospection appears necessary in order to select potential optimum sites for surveillance to identify, for example, regional changes of strain fields or variations in toxic emanation. Due to the complex relationship between geology and local phenomena, a network of geochemical stations would be much more useful.

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State of CCS in Germany and the Question of How to Use the Underground

Gabriela von Goerne

CCS Consultant, Ansbach Str. 60 - 10777 Berlin, Germany
Gabriela@Geogoerne.de

Efforts in Germany are big to increase the share of renewable energies and energy efficiency. However, there is still a share of fossil fuelled power plants as well as energy-intensive industries with process-related emissions contributing 372 Mt, respectively 81 Mt CO_2 annually (data from 2008) to the global greenhouse gas budget. Such emissions need to abate soon if an emission reduction of 80 to 95 percent is to be achieved by 2050 compared to 1990 levels. The recently published energy concept of the German Government outlines the pathway to achieve that goal. Carbon dioxide capture and storage (CCS) is part of it.

CCS is regarded as a possible CO_2 mitigation option for industrial facilities (such as iron and steel, cement, or chemistry) and the energy sector (i.e. coal-fired power plants). Moreover CCS could also be used in combination with biomass thus achieving negative emissions. The technology is still under development and first demonstration projects are planned to test its feasibility and environmental safety. Two issues are seen as critical for a demonstration start in Germany that is transposition of the European CCS directive into German law in a timely manner, and public acceptance. Public opposition against storage of CO_2 in geological formations is on the rise in regions selected for further detailed geological investigations. Most exploration activities or demonstration plans had already to be postponed or have been cancelled. Just one project from Vattenfall at Jänschwalde in the state of Brandenburg, is currently proceeding.

Public concerns include a number of issues, such as potential leakage of CO_2 or brine, pollution of drinking water, degradation of soil (farmers) and loss of property value. In addition to these more direct storage related concerns there is also the view that CCS ties up "business as usual" and coal mining, which means increasing impact of open-cut lignite mining, and continued use of coal-fired power plants.

Regarding storage capacity the potential for CO_2 storage is estimated between 6.3 and 12.8 Gt CO_2 (data BGR). Wuppertal Institute gives an average effective storage capacity of 5 Gt (range 4 to 15 Gt). This seems to be convenient numbers if CCS is seen as a bridging technology. However saline aquifers, the most interesting rock formations for CO_2 storage and predominantly located in northern Germany, may not only be used for this scope. They are also used for liquid waste disposal from salt mining and underground natural gas storage. Beyond that there is also growing interest for renewable energy storage (e.g. air, synthetic natural gas from wind or solar, hydrogen), as well as geothermal energy use. While the latter activities may cover a rather small area, CO_2 storage will influence larger areas. Injection of CO_2 results in displacement of brine and an extending pressure front. Leakage of CO_2 or brine through faults, fractures or wells must be avoided. This has to be taken into account when planning a CO_2 storage project. If there are neighbouring activities it might be useful to define a "safety zone" between the different activities, based on the modelled distribution of the pressure front, pressure thresholds and brine displacement. To make safe and proper use of the underground a comprehensive planning is needed. Competition between existing or planned underground activities and CO_2 storage might not necessarily be an imperative. There might even be synergies or options for coexistence that need to be researched and further assessed under legal, safety, and environmental aspects.

Report of Dr Fedora Quattrocchi, Senior Technologist at the Istituto Nazionale di Geofisica e Vulcanologia presented at the 182nd session of the 13th Standing Committee (Territory, Environment and Environmental Assets) of the Senate of the Italian Republic, held in Rome on June 8, 2010 (in Italian)

Necessità di pianificazione regionale e nazionale dell'uso del sottosuolo per un congruo e strategico *mixing* energetico

Carbone super-pulito, nucleare di ultima generazione, rinnovabili poco "*space consuming*" e riserve strategiche di metano

Quattrocchi. Signor Presidente, l'Istituto che rappresento si occupa di stoccaggio geologico di CO_2 per tutte le tecnologie CO_2 *Capture & Storage* ed ora, insieme alla SOGIN, del sito per le scorie nucleari, della ricerca geotermica su tutto il territorio nazionale ed anche di riserve strategiche per ampliare la possibilità di utilizzo del metano nel nostro Paese. Insieme al professor Boschi, presidente dell'Istituto Nazionale di Geofisica e Vulcanologia (INGV), abbiamo predisposto una relazione che consegno agli atti della Commissione.

Accanto alle discipline più tradizionalmente legate alla ricerca sismologica e vulcanologica che l'Istituto Nazionale di Geofisica e Vulcanologia porta avanti da anni e con successo internazionale «*peer review*», negli ultimi anni si sono affermate altre tematiche legate alla crisi energetico-ambientale in corso, in cui l'INGV è impegnato in prima persona, con grandi ripercussioni in tutti i campi della scienza e nella percezione pubblica e politica del consenso alle tecnologie energetiche (si pensi, ad esempio, anche agli eventi pubblici INGV al Festival della Scienza 2008 e 2009, specificamente quello del 2008 sul CO_2 *Capture & Storage* e quello del 2009 sulla geotermia).

In particolare, ci si riferisce alla necessità, soprattutto in Paesi densamente popolati, di far coesistere diverse tecnologie di produzione energetica «pulita»: quindi nucleare di nuova generazione, rinnovabili poco «*space consuming*» (molte centinaia di megawatt in pochi ettari), centrali a gas naturale con relative riserve strategiche e, infine, centrali a carbone pulito senza emissioni serra (quindi con cattura e stoccaggio di CO_2, noto ormai come CCS).

Tutte queste filiere tecnologiche sono strategiche da qui al 2050 ed oltre, come ormai decretato da tutti i principali organismi di governo internazionali: per la IEA (*International Energy Agency*), per il G20, per l'IPCC (*Intergovernmental Panel on Climate Change*, di cui sono stata *peer reviewer* per il *report* 2005) e debbono – a parere di tutti – poter coesistere, soprattutto per quel che riguarda l'uso del sottosuolo: unico, peculiare, limitato e non rinnovabile, soprattutto in Paesi densamente popolati come l'Italia.

È necessario, quindi, trovare sinergie, compatibilità, interferenze positive e negative sull'uso del sottosuolo ai fini energetici e strategici per i nostri Paesi industrializzati e densamente popolati: utilizzo come stoccaggio geologico di CO_2, metano (gas naturale), scorie nucleari ad alta attività e per la geotermia profonda.

Questo campo della ricerca è estremamente multidisciplinare e *challenging* dal punto di vista dell'applicazione di tutta una serie di metodiche geofisiche e geochimiche sperimentali e teoriche sviluppate negli ultimi 40 anni dalle Scienze della Terra, in Italia soprattutto dall'INGV, come ad esempio il monitoraggio multidisciplinare, la modellazione 3D e la tomografia sismica 4D di settori della crosta terrestre, fino alla profondità di 2-3 km, studiando le interazioni sismo-tettoniche fino alla scala delle strutture sismogenetiche (che, come è noto, si possono osservare molto in dettaglio).

È da dare particolare enfasi ai possibili rischi geofisici e geochimici, *in primis* la sismicità indotta e il rilascio verso la superficie di contaminanti gassosi o liquidi, in interazione con le diverse barriere geochimiche associate a ciascuna geosfera.

Qualsiasi tecnologia ha rischi connessi con il proprio utilizzo ed in particolare le tecnologie di stoccaggio e di uso geotermico del sottosuolo. Si tratta però di stabilire il rischio accettabile ed il rischio massimo in un regime di acquisizione di conoscenza particolare: il cosiddetto «*learning by doing*» (cioè imparo facendo).

È altresì urgente da parte della politica italiana, possibilmente in modo *bipartisan*, approvare la realizzazione di un sito di stoccaggio geologico delle scorie radioattive ad alta attività (HLW), e questo indipendentemente dall'avvio o meno di nuove centrali nucleari in Italia. Quindi, oltre al Parco tecnologico nucleare (PNT) di superficie già avviato dalla SOGIN, anche con il contributo ormai costante del mio gruppo, occorre superare gli ultimi ostacoli per avviare anche quello nel sottosuolo in sinergia con il PNT.

È con tale ottica di sinergie – e non competizione – ai fini di un *mixing* energetico ottimale, finalizzato a combattere la crisi energetica e quella climatica, che l'INGV ha organizzato, dal 25 al 30 settembre 2010, invitando anche esponenti governativi e tecnocrati statali, una *International School of Geophysics* dal titolo: «*Densely populated settings: the challenge of siting geological facilities for deep geothermics, CO_2 and natural gas storage, and radioactive waste disposal*» e sottotitolo: «*Underground coexistence and synergies for a sound energy mix in the post-Kyoto era*», sponsorizzata dall'INGV *in primis* e secondariamente dal CNR e dall'ambasciata USA (*Department of Energy*). È prevista la partecipazione di relatori provenienti dai principali Paesi europei (Gran Bretagna, Francia, Germania, Svezia, Spagna, Italia e Norvegia) ed extra-europei (USA, Canada, Australia, Giappone e Russia) che vantano, insieme all'Italia, la maggiore esperienza e tradizione nella tematica.

L'INGV ha svolto il 14 aprile 2010 – in particolare con il mio contributo – un «*Public Hearing*» organizzato dall'onorevole Salvatore Tatarella al Parlamento europeo su queste tematiche, con grande spirito di collaborazione con i nostri parlamentari europei in modo *bipartisan*.

Sicuramente la novità più importante nella rivoluzione energetico-climatica in corso è l'avvio anche in Italia dell'insieme di tecnologie denominate CCS (CO_2 *Capture & Storage*), con i Progetti EEPR ENEL Alto Adriatico ed il Progetto ENI-GHG Cortemaggiore, in cui l'INGV è coinvolto *in primis*, soprattutto per la parte riguardante i rischi.

Esse includono lo «stoccaggio geologico della CO_2» (internazionalmente «CO_2 *geological storage*»), che è diventato un filone strategico della letteratura scientifica e delle discussioni in ambiti di politica energetica ed ambientale. Ciò accade da tempi recentissimi, ma con peso esponenzialmente crescente di mese in mese, per il suo potenziale straordinario di abbattimento delle emissioni serra. Stime globali della capacità di stoccaggio di CO_2 nel pianeta si basano essenzialmente su studi fatti per i bacini sedimentari già produttivi (petrolio e gas naturale). Per i bacini di petrolio «depleti», già sfruttati con tecniche tradizionali di stoccaggio di CO_2 per il recupero di petrolio (dicasi *Enhanced Oil Recovery,* EOR) si è calcolata una capacità di stoccaggio di circa 130-350 giga tonnellate di CO_2 e gli acquiferi salini italiani sono almeno 200 sparsi lungo la fascia peri-adriatica. La capacità di stoccaggio in *reservoirs* a gas naturale «depleti» (dove effettuare *Enhanced Gas Recovery*, quindi il recupero di metano iniettando CO_2 nel sottosuolo, in pratica quello che farà l'ENI a Cortemaggiore) è significativamente più elevata ed è stimata in circa 800 giga tonnellate di CO_2. C'è da dire che al momento attuale la tecnica CO_2-EOR non è ingegnerizzata per massimizzare lo stoccaggio di CO_2, ma per produrre la massima quantità di petrolio. Molto lavoro è in corso per una co-optimizzazione dei due scopi, energetico ed ambientale.

Nel prossimo futuro, se verrà imposta – come tutti auspichiamo - una «*carbon tax*» semplice e diretta, al posto o a fianco al farraginoso meccanismo degli «*Emission Tradings*», lo stoccaggio di CO_2 avrà un valore economico e la co-optimizzazione di CO_2-EOR e CO_2-*storage* che può aumentare anche la produzione di idrocarburi sarà una realtà anche in Italia, come in America dove, ad esempio, esistono già circa novanta progetti del genere.

I dati relativi ai bacini sedimentari produttivi europei (e non ultimi quelli italiani «depleti») sono estremamente confortanti nello stabilire gli enormi volumi di stoccaggio geologico di gas, sia esso CO_2 o metano (quindi riserve strategiche qualora vengano chiusi i metanodotti dalla Russia come, ad esempio, nel caso dell'Ucraina).

La capacita di stoccaggio di CO_2 può essere calcolata usando le banche dati INGV (lavoro in corso di pubblicazione su *Energy Conversion and Management* da parte del mio gruppo) negli acquiferi salini profondi e, volendo, rapidamente anche nelle riserve ENI della perforazione/produzione passata, soprattutto se i dati ENI vengono condivisi con i centri di ricerca italiani in sinergia per il Paese.

Il progetto IEA-EC Weyburn, finanziato dalla Comunità Europea e sponsorizzato dalla IEA, dove l'INGV ha svolto il ruolo di *partner* italiano principale, può a tutt'oggi essere ancora considerato come il più eclatante esempio al mondo di CO_2 *geological storage* contemporaneo a produzione petrolifera, aumentata da iniezione di CO_2 nel sottosuolo (EOR). Esso è concepito per conciliare gli interessi di aumento produttivo di idrocarburi con interessi «climatologici», di fatto venendo incontro ai due aspetti della crisi del nostro tempo, quello climatologico e quello energetico. L'INGV ha pubblicato importanti articoli «*peer review*» (ad esempio su *Chemical Geology*) ora considerate pietre miliari della tecnologia CCS.

I risultati scientifici in siti reali di stoccaggio ed in siti di «modellazione» sono estremamente rassicuranti riguardo l'effettivo stoccaggio definitivo geologico (ordine delle centinaia di migliaia di anni) della CO_2 iniettata (migliaia di tonnellate al giorno su aree di circa 15 chilometri quadrati, quindi aree molto piccole).

L'INGV è in Europa l'ente di ricerca più impegnato nella valutazione dei rischi dello stoccaggio geologico della CO_2 che sono prioritariamente: rischio sismico associato eventualmente a iniezione di fluidi nel sottosuolo (rischio assai remoto) e rischio di degassamento in superficie della CO_2 precedentemente iniettata, essenzialmente lungo faglie permeabili fino ai suoli in superficie.

L'INGV studia, anche per il dipartimento di Protezione Civile in convenzione (che si spera non venga decurtata con la «manovra 2010» viste queste ricerche strategiche da portare avanti) i sistemi naturalmente degassanti di CO_2 - definiti

CO_2 *analogues* –, in tutti i suoi aspetti geologici, geofisici e geochimici. Circa una cinquantina di persone, la metà delle quali precarie, già lavorano su questo progetto.

Il pubblico ed i *policy maker* devono assimilare il semplice concetto che l'anidride carbonica è un gas anzitutto naturale, di origine geologica, emesso dal sottosuolo, soprattutto nelle zone vulcaniche ben note all'INGV, così come lungo le faglie ormai tutte catalogate (anche quella di L'Aquila, già precedentemente al terremoto) nel DISS, il nostro catalogo *on-line*, come in realtà naturale è il gas metano, naturalmente stoccato nel sottosuolo, e naturali sono le scorie radioattive, dove la natura arricchisce spontaneamente le rocce di uranio.

Per tornare allo stoccaggio di gas naturale nel sottosuolo (sia esso CO_2 o metano, CH_4), non tutte le faglie sono comunque permeabili da parte di gas in risalita da strati profondi e molto influisce la presenza di acquiferi superficiali che tamponano la CO_2 (che renderebbero le acque solo più frizzanti e quindi gustabili al bere, allertando inoltre con largo anticipo di eventuali fughe future di gas al suolo ed avviando rapidamente i rimedi ai pozzi di iniezione gas) e una roccia di copertura impermeabile sopra il *reservoir* di stoccaggio (per esempio sotto gli 800 metri di *default* per la CO_2). Tutte cose ben note all'INGV e ad altri centri di ricerca italiani in proficua collaborazione, come le *International School* di Erice sia nel 2007 che nel 2010 dimostrano e dove è invitata tutta la Commissione. L'INGV spera che qualcuno di voi sia presente alla tavola rotonda del 29 settembre 2010 proprio per parlare apertamente con la comunità scientifica e le industrie presenti su questi temi.

Per concludere, faccio presente quindi la necessità, accanto al nucleare di ultima generazione già deciso dal presente Governo e alle rinnovabili «vecchie» già sufficientemente incentivate dal precedente Governo, di aiutare le sinergie di uso del sottosuolo per il nucleare, per le rinnovabili di nuovo tipo (come la produzione di energia elettrica da sonde «geomagmatiche» – filone che sto approfondendo con la Fondazione sviluppo sostenibile - e affini, cicli binari e quant'altro), per la tecnologia «ponte» dello stoccaggio geologico della CO_2 nel sottosuolo (fino ad esaurimento di combustibili fossili).

Di fatto tali iniziative risolvono il problema energetico dovuto ad uno stato disastroso delle riserve di petrolio e gas naturale del pianeta a seguito di un tuttora spregiudicato e sproporzionato uso dei *fossil fuels* che ancora rimangono (ad esempio il petrolio da tenere invece per usi più nobili, come la chimica e le plastiche) di fatto incentivando economicamente le tecniche EOR (*enhanced oil recovery*), EGR (*enhanced gas recovery*) e ECBM (produzione di metano da letti di carbone tramite iniezione di gas). Gli australiani dello Stato del Queensland, ad esempio, producono il 70% del loro metano con sistema CBM. Tale problema viene di fatto ridotto, anche perché tali tecniche utilizzano soprattutto l'anidride carbonica per recuperare idrocarburi sepolti altrimenti non recuperabili.

Inoltre verrebbe risolto il problema climatologico, dovuto allo stato di degenerazione del clima per uso dei combustibili fossili e conseguenti emissioni di CO_2 e metano (CH_4). Solo le tecniche CCS riescono a seppellire volumi di anidride carbonica di ordini di grandezza compatibili con una effettiva riduzione dell'effetto serra, come ormai confermato da tutti gli organismi internazionali (IEA, IPCC, Comunità Europea). A risolvere la complessa crisi energetico-climatica in corso riescono solo però la sinergia di CCS, nucleare e rinnovabili poco *space consuming* e la ricerca finalizzata all'aumento dell'efficienza energetica e del risparmio energetico.

Attualmente il problema più pressante ed urgente è la *public acceptance* delle tecniche di stoccaggio geologico nel sottosuolo, oltre che di metano anche della CO_2, cioè di un gas che è considerato ancora un rifiuto e non un «clima-alterante» naturale (solo lo 0,5% della popolazione sa cosa è la tecnologia CCS). Per non parlare della *public acceptance* del deposito geologico delle scorie nucleari, tutta da costruire, ed ora anche dei parchi delle rinnovabili, poco produttivi e devastanti il panorama per quanto riguarda l'eolico. Spesso il grande pubblico, inoltre, ignora il concetto di megawatt per ettaro o di megawatt prodotto per megawatt installato, o il concetto di «ore di produzione di una centrale installata», diversa da tecnologia a tecnologia. Si dovrebbe cominciare ad insegnare nelle scuole questo ABC dell'uso del territorio, sempre meno a disposizione.

L'INGV sta operando a tutto campo in questo senso, anche con il suo ufficio didattica e divulgazione, anche con personale precario e non strutturato: in queste strategiche discipline, invece, sarebbe necessario creare un sistema Paese duraturo, con ricerca pubblica non ricattabile, severa, decisa, non rammollita dai contorni del caso (precarietà, destrutturazione, delocalizzazione, futuro incerto, non pianificazione a lungo termine, e quant'altro). Cosa hanno fatto fino ad ora i Ministeri preposti alla divulgazione e all'incentivo di queste nuove e strategiche tecnologie energetico-climatiche e cosa hanno fatto per l'avvio effettivo di *test-sites* CCS? Poco o niente per lo «stoccaggio geologico della CO_2», nulla per il *nuclear waste disposal*, qualcosa nel campo della «cattura di CO_2» reflua industriale (progetti ministeriali MUIR-MATT-MINAGR approvati soltanto nel 2002): insomma fino ad ora si sono mossi solo i privati, soprattutto ENEL, e non il «sistema Paese», come sarebbe richiesto soprattutto a seguito del riavvio del nucleare.

Ma non basta.

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Via di Vigna Murata, 605
00143 Roma
Tel. +39 06518601 Fax +39 065041181

http://www.ingv.it

Istituto Nazionale di Geofisica e Vulcanologia