SUBSURFACE GEOPOTENTIALS VS GEOLOGICAL RISKS: ENHANCEMENTS FROM 3D MODEL ANALYSIS

C. D'Ambrogi* & F.E. Maesano*
* Geological Survey of Italy – ISPRA. Rome. Italy chiara.dambrogi@isprambiente.it; francescoemanuele.maesano@isprambiente.it

1. INTRODUCTION

Since the gold rush to the recent shale gas exploitation, the history of natural resources and geopotentials has evolved together with the evolution and advancements of geological knowledge. 3D modelling techniques are the most advanced frontiers of geological representation and analysis and are key tools in the understanding of the subsurface geological structures.
The 3D modelling of buried geological structures, especially in large plains (e.g. Molasse and Po Plain basins) become, now more than ever, a strategic objective for the evaluation and sustainable management of the subsurface in terms of resources (water, geothermal energy, oil and gas) and potential usages (storage activities, i.e. CO_2 and CH_4). At the same time, despite the common perception that *plain* is equivalent to *stable*, the societal and industrial activities in these areas have to face also with geological hazards. As a matter of fact some of the geological structures hosting geopotentials can generate earthquakes or can be affected by vertical soil movements.
To dispose of 3D geological models and of consistent tools of analysis for these areas become strategic to assess resources, to analyze structures, to quantify and parameterise their behaviour.
This contribution describes the 3D modelling strategies and the analysis workflows supporting the evaluation of potential risks developed in the last years by the Geological Survey of Italy (ISPRA), and its ongoing activities within the EU funded GeoMol Project (Diepolder et al. 2014).

2. GEOPOTENTIALS AND RISKS: AN ITALIAN EXAMPLE

The Emilia seismic sequence of May-June 2012 (M_W max 6.1) hits the central part of the Po Plain, one of the biggest plain areas in our continent, highly populated, with important industrial facilities; its underground hosts the Southern Alps and the Emilia-Ferrara thrust systems, that are the geological structures related to the evolution of the Alps and Apennines chains, which contain one of the main hydrocarbon provinces in Italy and 17 natural gas storage sites.
The coseismic effects induced by the 2012 seismic sequence were widespread liquefactions related to overpressure of surficial aquifers. The major damages were observed in the old and monumental buildings in the historical centers, but also in buildings of reinforced concrete, and in industrial facilities and farmhouses.
The blind thrusts which generated the earthquake sequence are associated with anticline structures hosting exploited hydrocarbon plays (e.g. Cavone) or interested by *debated* research concession for gas storage (Rivara).
The possible interaction between these anthropic activities and the seismic sequence were the object of an animated international scientific (Cartlidge, 2014) and political debate during the last two years in Italy as already happened elsewhere in documented cases of induced and/or triggered seismicity all around the world
This case points out the basic need of a publicly available 3D geological infrastructure to support decision-makers and facilitate the public acceptance of subsurface uses.
Therefore the geopotential assessment cannot be separated from the understanding and analysis of the geological structures; the geological knowledge, as much as the engineering and technical solutions, become strategic for the sustainable use of natural resources.

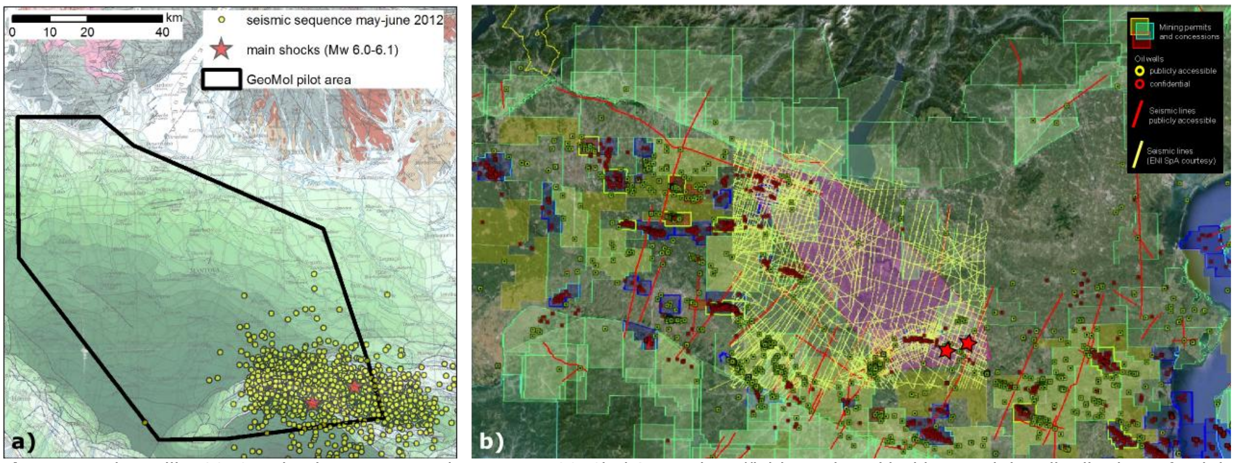

Figure 1: a) Emilia 2012 seismic sequence (May-June 2012) (ISIDE, http://iside.rm.ingv.it); b) Po Plain: distribution of mining permits and concessions and related seismics and wells data. The red stars indicate the main shocks of the Emilia 2012 seismic sequence.

3. 3D MODELLING WORKFLOW

The Italian Geological Survey has as main institutional activity the collection, harmonization, analysis, storage and dissemination of earth, mainly geological, data and observations (ISPRA, http://sgi.isprambiente.it/geoportal/catalog/main/home.page).
The collection of geological data, especially of those needed for the 3D modelling of strategic geological structures, in areas with high geo-potentials and characterized by many geological risks, is facilitated by the occurrence of large amount of subsurface information, such as seismic reflection dataset or boreholes for oil and gas exploration, (unfortunately, these data are not always or completely publicly available depending on the national laws).
Also the occurrence of earthquakes or vertical soil movements, and the presence of buried seismogenic structures can contribute to the improvement of geological knowledge. The huge amount of information acquired by the national seismic network, the seismological data, the information derived from GPS or SAR measurements supports the characterization of the geometry of geological bodies and the understanding of the behaviour of the faults at depth.
All these data, stored and managed at national scale, are the fundamental bricks of 3D geological models produced by the Italian Geological Survey following a workflow further implemented in the framework of the EU funded GeoMol Project (Maesano et al. 2014).
The workflow is designed to be widely applied in various geological contexts, integrating data characterized by different domain of the vertical axes: time (e.g. seismic lines, velocity data, time-depth or time velocity curves of wells) or depth (e.g. published geological maps, cross sections, isobath and isopach maps).
The modelling workflow processes data, in time and depth domain, in parallel; however an iterative process occurs during seismic interpretation: depth-domain data (e.g. wells stratigraphies) are used to check the depth of the digitized key seismic reflectors.
Some critical aspects related to data should be considered and further addressed:

- seismics: seismic resolution (≥ 30 m for the available industrial seismic reflection profiles provided by the oil companies);
- stratigraphy: chronological methods, age definition, depositional relationships;
- structural elements: identification of growth strata, correct identification of fault tip position.

The further steps in construction of 3D model depend on the type of available data, on the geological context, and on the final use of the elaboration.
In the GeoMol Project we define the following two steps (Fig. 2):

i. construction of a "raw" 3D model using only data in time domain, by interpolating the interpreted seismic horizons and faults. This "raw" 3D model in time is depth-converted as a whole to quickly test different 3D velocity models;
ii. depth-conversion of the horizons and faults digitized in time domain and integration with the depth domain dataset (Fig. 2). In this case the best 3D velocity model available for the area is used to run the time-depth conversion. At this point it is crucial to check the consistency of the time-depth conversion results with the constraints in depth domain. If important misfits are observed, the process must be reiterated changing the interpretation or the velocity model. The data can be then used to build surfaces and the depth 3D model.

Two general aspects should be considered:

i. the availability of petro-physical parameters for the 3D modelled objects;
ii. the definition of uncertainties for each of different dataset.

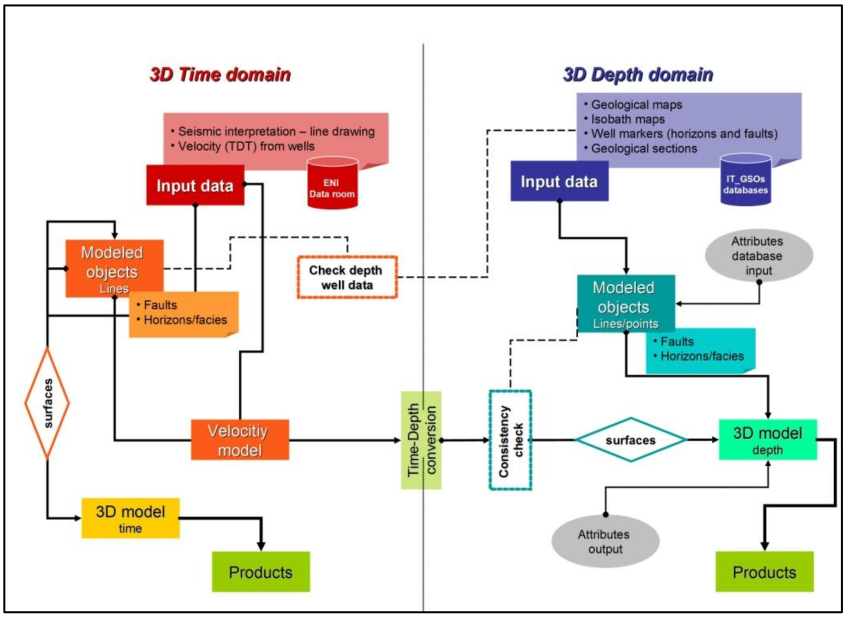

Figure 2: 3D modelling workflow adopted in the Italian pilot area of the GeoMol Project (after Maesano et al. 2014).

4. RESTORATION WORKFLOW

One of the main applications of 3D models to evaluation of risks is the identification and analysis of tectonic structures deemed to be active. The identification of these structures is often difficult in plain areas where the sedimentary processes are generally predominant on the tectonic effects.
The 3D models provide us an imagery of 3D fault planes that is more accurate and geometrically constrained compared to regional 2D cross sections.
The 3D restoration of deformations gives quantitative information on the kinematic (e.g. slip rates) and mechanical behaviour of faults and folds (e.g. fractures distribution) and contributes to the building of complex hazard scenario.
The criteria for the identification of active faults take into account orientations compatible for a reactivation in the present day stress field and the deformations in the horizons younger than 1.6 Myr, including both dislocation and/or folding (Fig. 3). The evidences of folding and growth strata are often elusive (e.g. mild folding with low amplitude and high wave length) and are better imaged in a 3D framework instead of a single seismic profiles in which they are difficult to detect.

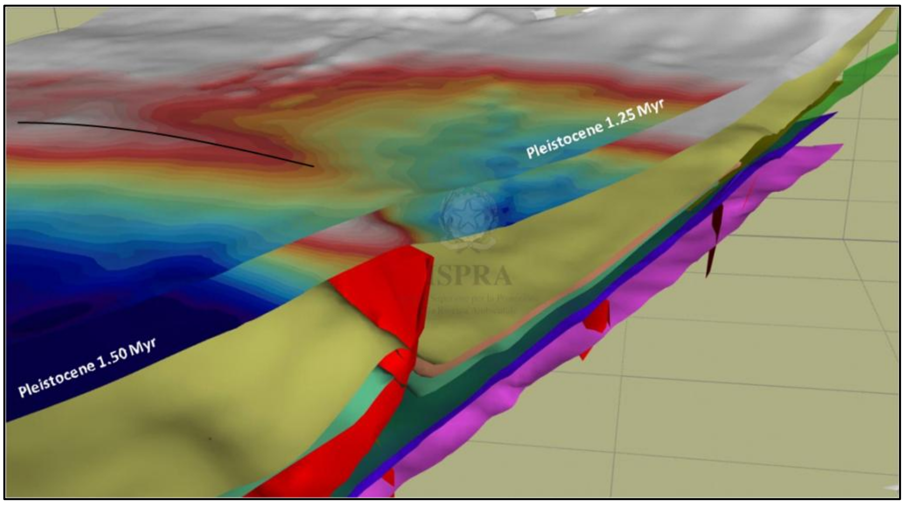

Figure 3: 3D model of the Italian pilot area of the GeoMol Project; it highlights the deformation in the horizons younger than 1.6 Myr related to the fault activity. The black line is the anticline axis.

A comprehensive slip rate calculation on the faults that join these criteria must take into account the differential compaction effects on the syntectonic sediments.
The general workflow (Fig. 4) for the slip rate calculation, that will be applied also in the Italian pilot area of the GeoMol Project, has been proposed by Maesano et al. (2013). It can be summarized in the following steps:

- 3D modelling;
- decompaction on the target horizon;
- restoration with appropriated algorithm (trishear, fault parallel flow, simple shear) based on the type of deformation observed;
- slip rate calculation and uncertainties estimation.

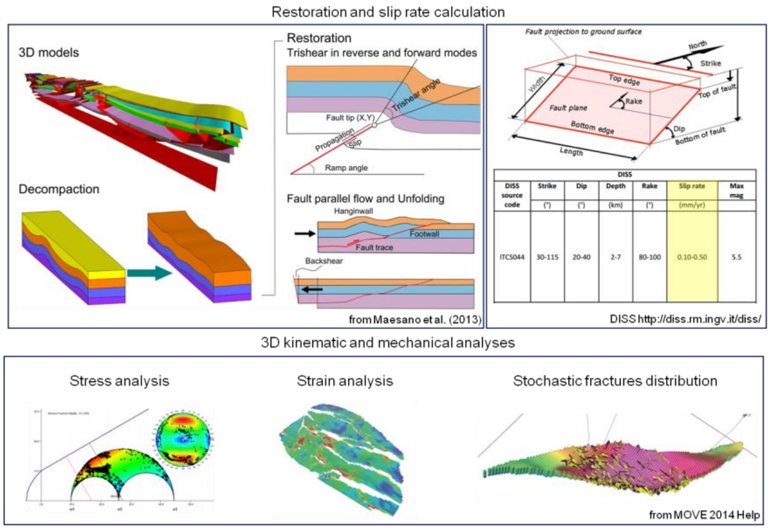

Figure 4: Workflow for 3D restoration and analysis.

The 3D modelling techniques, as opposed to the 2D, allow to consider the full spatial variability of input parameters both in the reconstruction and restoration of the geological structures (e.g. strike and dip of faults, fold geometry) and in the geomechanical behaviour of the geological bodies (e.g. velocity in the depth conversion, porosity in the decompaction).
The uncertainties estimation in the slip rate values is related both to the resolution of the model (and of the relative input data), to the goodness of the 3D velocity model used for the depth conversion of seismic profiles and to the dating of the target horizons.
The slip rate uncertainties and their lateral variability are key parameters to allow a better definition of the fault kinematics and give the possibility to build more detailed models for hazard assessment.

5. CONCLUSIONS

The 3D modelling techniques are commonly recognized as the best synthesis to understand, characterize and describe the geological structures, thanks to the integration of various types of data (e.g. geological, geophysical, geochemical, etc.); collectively, this information provide the foundation in analyzing and monitoring the geological structures, both for their possible geopotential usage and for the risks they can generate.
3D models are the starting points for specific analyses and applications:

i. structural history of sedimentary basins;
ii. move on fault restoration and decompaction for calculation of long term slip rates;
iii. identification of data inconsistency and support to the model validation;
iv. thickness maps for key stratigraphic horizons.

In plain areas, such as the Alpine foreland basins (GeoMol Project), 3D geological modelling can support the analysis of buried thrusts, as those responsible for the 2012 Emilia earthquake, allowing the quantification of the long-term slip rates of these faults. These results are basic input data for predicting the possible conflicts between subsurface usage and hazards and their likely consequences for human activities.

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For further information please refer to www.geomol.eu