Chapter 9: Institut Cartogràfic i Geològic de Catalunya: Synopsis of Three-Dimensional Geological Mapping and Modelling

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Introduction

The Earth is three-dimensional (3D) and heterogeneous as a consequence of the succession of different geological processes throughout time. For this reason, to understand Earth's nature and processes, as well as to predict the effects of human activities on the ground, it is necessary to study it from a 3D/4D perspective. Therefore, one of the main challenges for geological survey organizations (GSOs) is to gather subsurface data and predict the nature and behavior of the subsurface from the available data.

The Cartographic and Geological Institute of Catalonia (ICGC), as a public organization of the Government of Catalonia, aims to provide formally homogeneous geological and geothematic information, appropriate to support territorial and urban planning, the execution of civil engineering works, the reduction of risk, as well as other activities of public management that require knowledge of subsurface structures and compositions.

3D geological mapping and modelling has been embraced at the ICGC during the past 10 years as data collection, analysis, visualization, and presentation methods have evolved with the advent of personal computers equipped with fast video cards, vast storage capacity, and 3D software programs (CAD, GIS, and other specific applications). As a result of this work, a series of 3D geological models have been developed at different resolutions, and with varying approaches, geographical areas, and objectives.

This contribution describes the state of the art of 3D geological mapping and modelling at the ICGC. This overview will help us to explain the organizational challenges that we hope to achieve in the coming years as 3D modelling and visualization will allow us to best assess the benefits of the ICGC to the society that it serves.

Organizational Structure and Business Model

The ICGC represents a public organization whose purpose is to promote and carry out actions related to knowledge, exploration, and information on the soil and the subsoil, within the scope of the competencies of the Government of Catalonia (Figure 1).

The ICGC was created in 2014 from the merger of the Institut Cartogràfic de Catalunya (the national mapping agency) and the Institut Geològic de Catalunya (the geological survey organization). In accordance with article 152 of Law 2/2014 of the Government of Catalonia, the ICGC adopted the legal form of a public entity; it has its own legal status, as well as administrative, technical, and economic autonomy, and it maintains a full capacity to perform functions congruent with its goals and mission. The ICGC reports to the Ministry of Territory and Sustainability that is responsible for territorial policy and urbanism.

At the time of drafting this document (November 2018) the ICGC has a staff of 267 employees. About 20% of the staff focus scientific-technical tasks specific to a Geological Survey Organization. This group of Earth science professionals roughly is organized into 11 teams addressing regional geology, geological mapping, earth surface processes, hydrogeology and geothermal energy, geotechnics and geological engineering, geological hazards and risk assessment, urban geology, soil science, avalanche prediction, seismology, geophysical exploration, environmental geology and geological heritage.

Apart from these activities, the ICGC performs other tasks related to geodesy, topography, cartography, remote sensing, and geographic information systems, all of which support the geological survey. In particular, are tasks

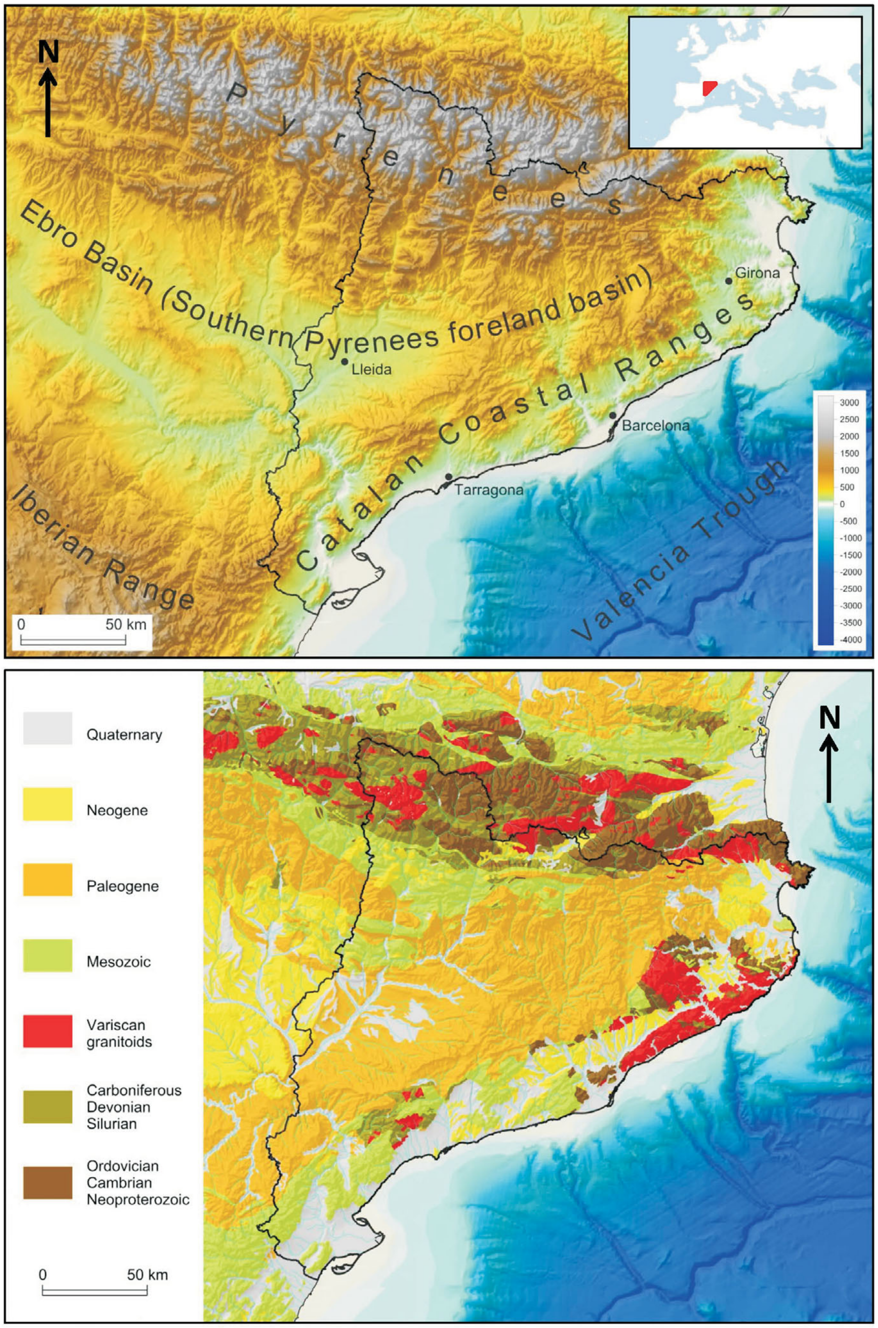

Figure 1. Physiography (top) and geology (bottom) of Catalonia and neighboring areas.

related to 3D geological mapping and modelling.

Some ICGC tasks within geological projects are outsourced, while other activities are carried out in collaboration with the academic community and other public and private institutions.

The production and technical objectives of the ICGC are defined in a contract established with the Government of Catalonia. This contract covers ~85-90% of the annual budget and includes tasks that the ICGC plans to execute in order to comply with its functions as established by law. The remainder of the budget comes from commissioned work from the public and private sectors.

Overview of 3D Modelling Activities

Over the past 10 years, a very significant part of the 3D geological modelling activity at the ICGC has been conducted within the framework of a specific project called the 3D geological model of Catalonia. Its main objective was the development of a 3D geological model of Catalonia at a resolution of 1:250,000 scale, and it was based on the collection, classification, homogenization, and reinterpretation of available surface and subsurface geological information. This 3D geological model of Catalonia was developed through collaboration with the Geomodels Research Institute of the Universitat de Barcelona (Gratacós et al. 2012). The first version of the 1:250,000-scale 3D geological model of Catalunya was completed in 2013 (Figure 2).

In addition to the 3D geological model of Catalonia, the ICGC has performed other 3D geological modelling endeavors for specific geographic regions. Two representative examples of these activities are:

- The 3D geological modelling related to the development of the 1:5,000-scale Urban Geological Map of Catalonia (Pi and Vilà, 2013). A pre-Quaternary basement map, cross-sections, and an isopach map of surficial materials (Vilà et al. 2015) were components of the 3D modelling and portrayed on geological map sheets that covered 8 km^2.
- The 3D reconstruction of the architecture of the Holocene deposits of the Ebro delta plain (Figure 3). This model was developed within the framework of a larger project called LIFE EBROADMICLIM (http://www.lifeebroadmiclim.eu), which advocates for pilot actions related to adaptation to and mitigation of climate change in the Ebro Delta

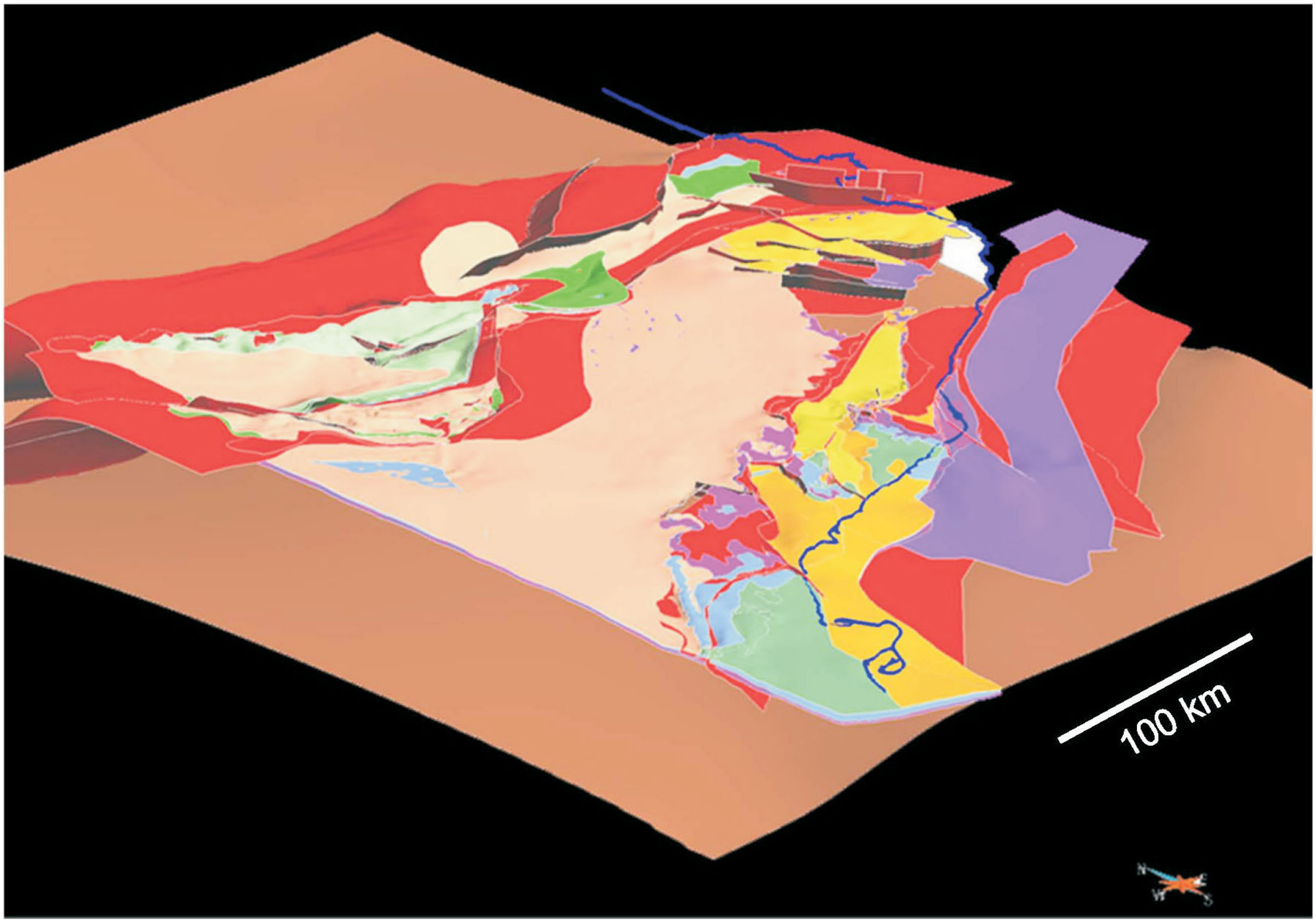

Figure 2. General view of the 3D geological model of Catalonia (version 1.0).

(south Catalonia), an area vulnerable to sea level rise and subsidence. The main objective of this 3D model was to evaluate the distribution of areas susceptible to subsidence (Rodríguez et al. 2018).

In addition, 3D geological modelling in recent years also has concentrated on the development of methods and techniques, as for example:

- Programing CAD applications for the 3D analysis of geological traces, outcrop data, and borehole logs to facilitate the reconstruction of geological surfaces and cross sections.
- Determination of soil-rock boundaries and some Quaternary sedimentary horizons from the analysis of passive seismic data (e.g., Macau et al. 2015).
- Development, most recently of specific tasks of ICGC projects related to geo-resources, natural hazards, and engineering geology.

Resources Allocated to 3D Modelling Activities

The 3D geological model of Catalonia project represents one of the 33 lines of work included within the strategic programme 2014-2018 (and the 40 of the 2019-2022 programme). The total yearly budget of this project is ~150,000 €. These annual resources allow for the dedication of ~3,200 hours related to 3D modelling (approximately equivalent to the full dedication of two geologists) and the outsourcing of some specific work.

These resources are relatively small compared to those dedicated to overall geological mapping projects. However, the development of 3D models is dependent upon and benefits from traditional 2D geological mapping. Broadly speaking, in the last 5 years, about 10-14 geologists have been dedicated, full time, on the development of traditional 2D geological maps. Their efforts mainly have been focused on constructing and publishing geological maps at 1:25,000-scale, as well as, associated thematic maps (Figure 4). From an administrative point of view, the development of these maps has not been explicitly considered to be related to 3D geological modelling.

Despite advances in the development of specific software for depicting the 3D geology, activities related to digital geological mapping in the ICGC have been done using standard CAD and GIS tools (basically Microstation

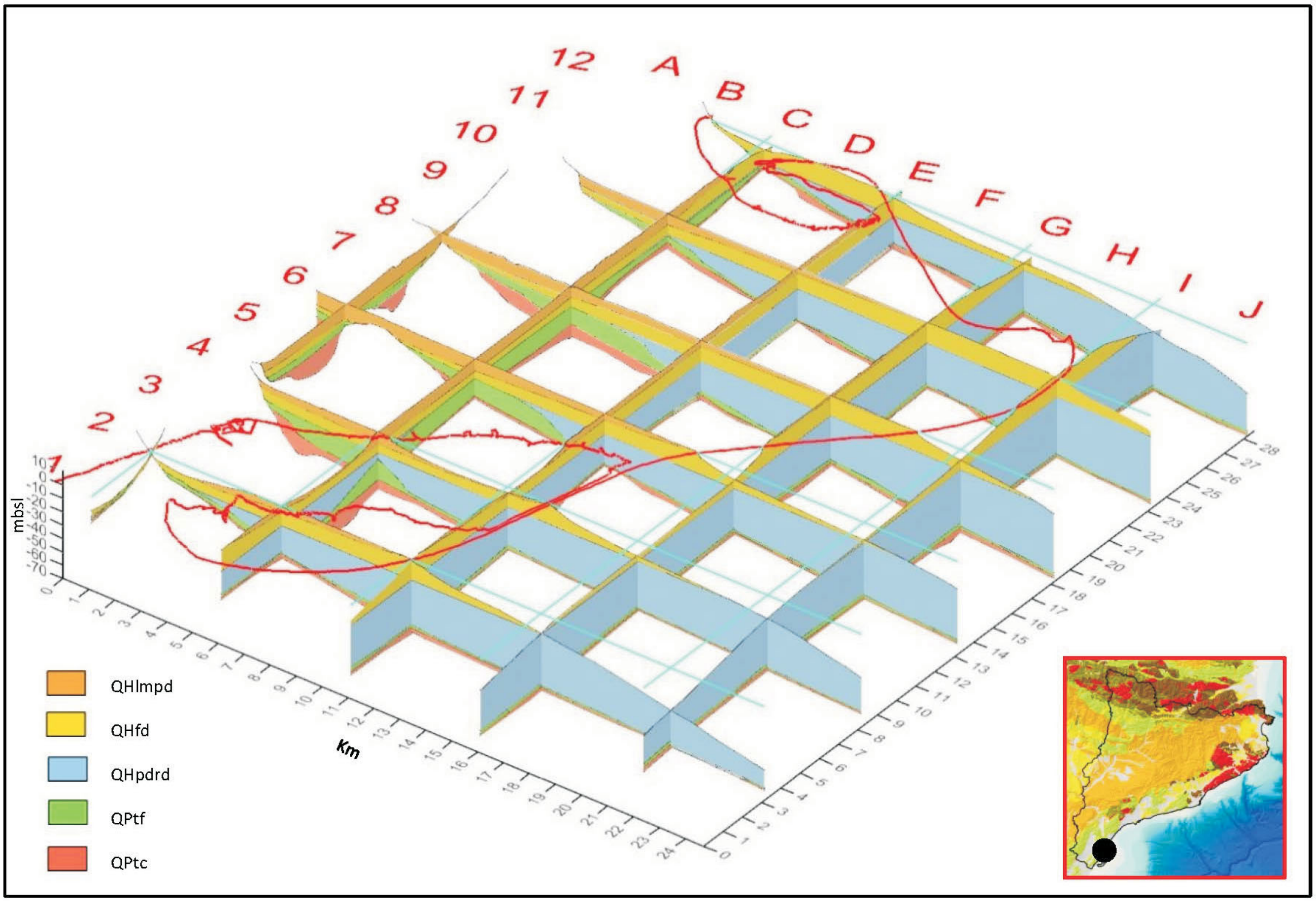

Figure 3. 3D view WNW-ESE cross sections (2, 4, 6, 8, 10 and 12) and SSE-NNW cross sections (A, C, E, G and I) showing the structure of the Holocene and Upper Pleistocene deposits of the Ebro delta plain. QHlmpd: Holocene lagoon, marsh, and alluvial plain deposits; QHfd: Holocene delta front deposits; QHprd: Holocene prodelta deposits; QPtf: Upper Pleistocene fine grained transgressive deposits; QPtc: Upper Pleistocene coarse grains transgressive deposits.

and ArcGIS). The investment in 3D geological modelling software and associated training has been low. Currently the ICGC has 9 GOCAD licenses, 2 Move licenses and 1 GeoModeler license. Over the last 10 years the ICGC has offered only one generic training course (2015) for 3D geological modelling. It involved 35 hours of teaching and 10 ICGC geologists participated by initially learning GOCAD and Move. However, since then, there has not been continuity in the systematic use of these softwares, and geologists have been training on their own.

It is difficult to quantify the total resources that the ICGC commits to 3D modelling activities. Broadly speaking, it is estimated that the resources allocated to the 3D geological model of Catalonia project represented approximately 25% of the total resources that the ICGC dedicates to 3D geological modelling activities. It is important to note that a significant part of the results related to 3D geological modelling has been performed mostly based on individual initiatives, where modelling has been used as a tool to solve specific aspects of projects, but not explicitly labeled as 3D.

Overview of Regional Geological Setting

Covering an area of 31,895 km^2, Catalonia has significant physiographic diversity that directly reflects the underlying geology (Figure 1). The geomorphology reflects Cenozoic events linked to the Alpine Orogeny and the subsequent opening of the Valencia Trough in the western Mediterranean (Losantos and Berástegui, 2010).

The territory of Catalonia can be subdivided into three main morphostructural domains: (i) The northern do-

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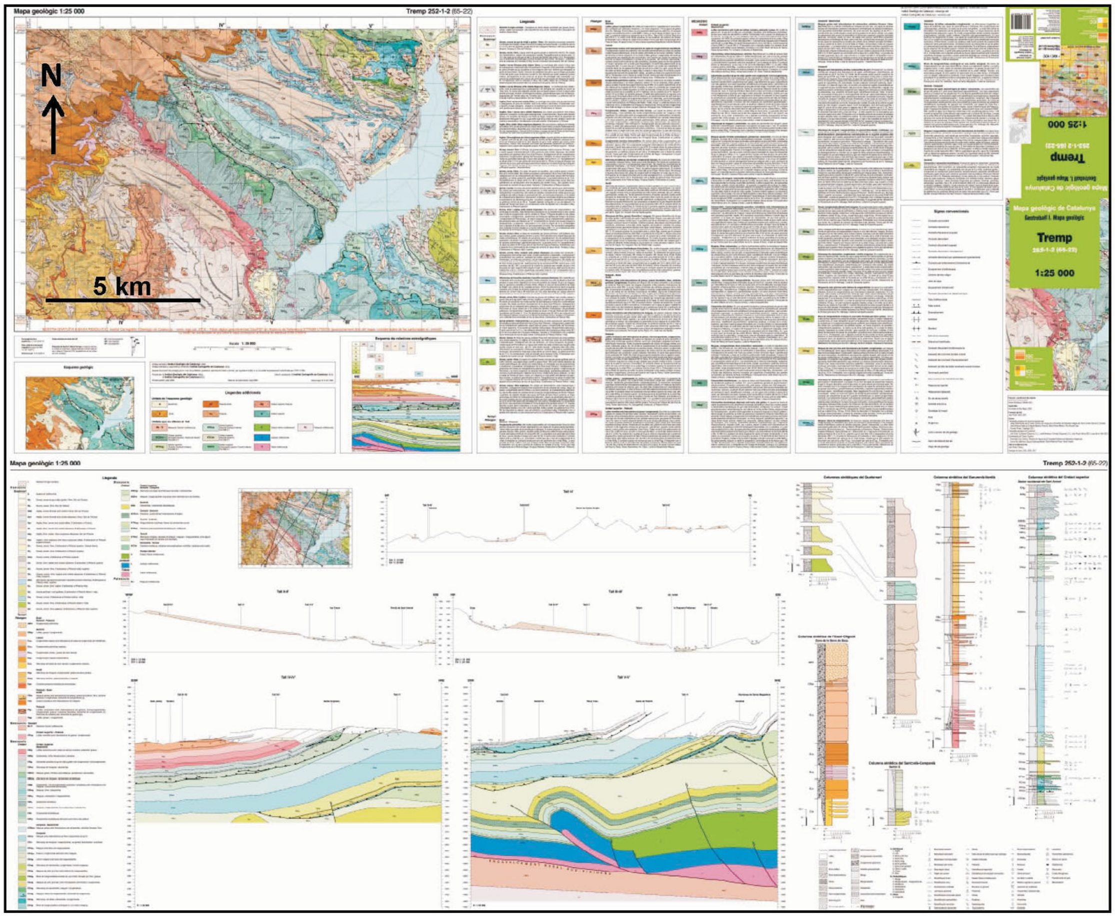
Figure 4. Top: Example of a printed map sheet of the 1:25,000-scale Geological Map of Catalonia series, the Tremp map sheet (Cirés et al. 2009) from the Central Pyrenees. Bottom: 3D reconstructions of pre-Campanian Mesozoic horizons (I), Campanian reference horizons (II), Maastrichtian reference horizons (III) and Paleogene reference horizons (IV) of the Tremp area developed after the publication of the Tremp geological map sheet 1:25,000-scale (Institut de Recerca Geomodels, 2012).


Mapa geològic 1:25 000
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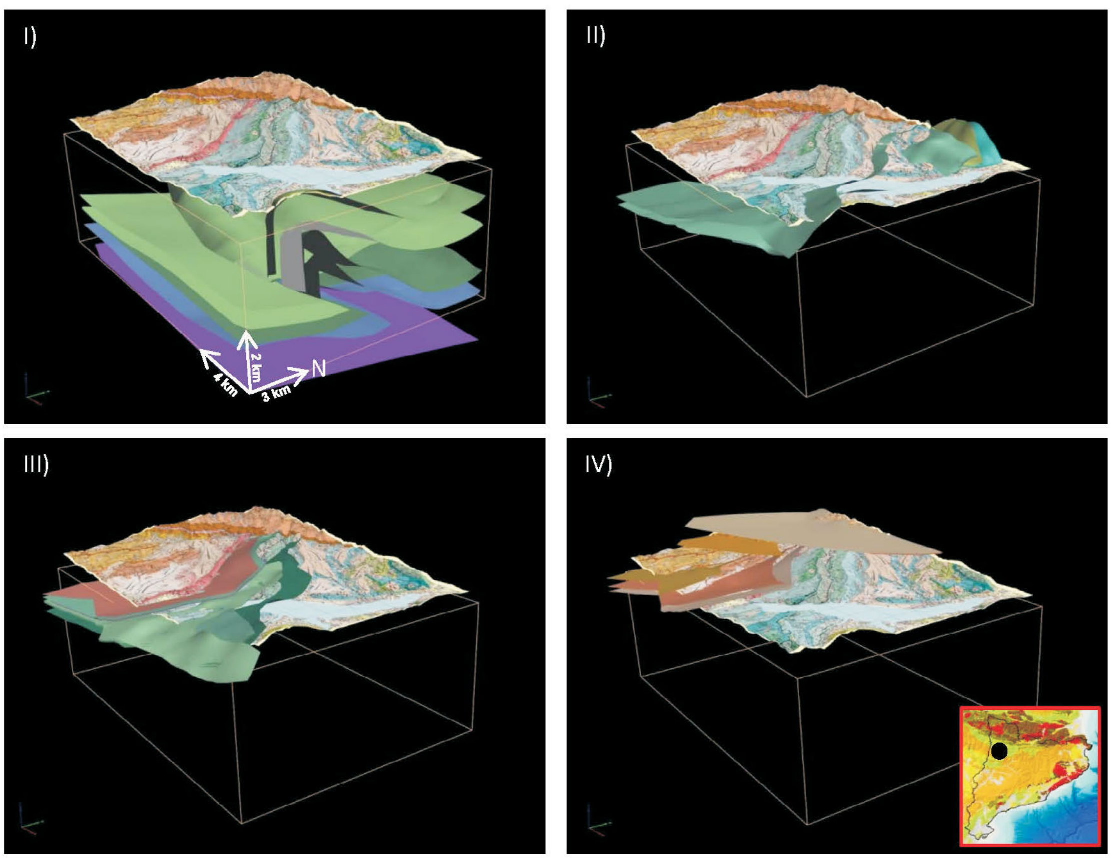
I)
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main, is a mountainous region that belongs to the southern limb of the central and eastern part of the Pyrenees; (ii) the coastal domain, named the Catalan Coastal Ranges, includes a system of mountain ranges separated by basins parallel to the present coastline, and (iii) the central domain, a relatively depressed region that defines the eastern sector of the Ebro Basin, represents the Cenozoic foreland basin of the Pyrenees, the Iberian Range, and the Catalan Coastal Ranges.

The Variscan basement has a sedimentary cover outcrop in the Pyrenees and the Catalan Coastal Ranges. The Variscan basement includes Lower Palaeozoic clastic-dominated sedimentary sequences, Upper Palaeozoic carbonate-dominated sequences, and late-Variscan intrusions of granitoids. The sedimentary cover primarily consists of Mesozoic carbonates, terrigenous red beds and Triassic evaporates, and Palaeogene clastics and carbonates. The general structure of the materials outcropping in the Pyrenees and the Catalan Coastal Ranges is governed by several systems of folds and faults related to the Alpine Orogeny. In addition, the basement rocks are affected by ductile structures and metamorphism related to the Variscan Orogeny.

Generally, the fill of the eastern Ebro Basin consists of a composite succession (up to 5 km thick) of alternating continental deposits of Palaeocene and late Eocene-lower Miocene age and marine sediments of early-middle Eocene. The Palaeogene deposits located at the margins of the current day Ebro Basin were affected by compressive structures related to the Alpine Orogeny.

In the eastern Pyrenees and the Catalan Coastal Ranges, the Alpine structures have been overprinted by Neogene extensional structures related to the opening of the NW Mediterranean margin. As a result of this extensional period, a series of basins were formed, which were gradually infilled by continental and marine deposits. In NE Catalonia, at the intersection of the eastern Pyrenees, the Ebro Basin and the Catalan Coastal Ranges, there is a volcanic province also related to the development of these young extensional basins.

The Quaternary record in Catalonia encompasses many environments, including alluvial, fluvial, colluvial, lacustrine, glacial, aeolian, coastal, estuarine, and marsh deposits. In the coastal and fluvial plains, there are outcrops of upper Pleistocene-Holocene deposits that are related to the last global sea level rise. Also present are the Pleistocene alluvial-colluvial deposits related to the climatic cycles previous to the last glacial period that cover many plains and foot slopes.

Apart from the geological configuration, throughout history, the territory of Catalonia has undergone intense landscape modifications related to human activity (agrarian, urban, etc.). It is important to note that since the Classical Greek period, Catalonia represents an important strategic crossing point that links the western Mediterranean region with the rest of Europe. Urban zones represent the areas where anthropization has a significant impact on the ground. Catalonia has a population of 7,534,813 inhabitants spread over 947 municipalities (www.idescat.cat retrieved 1 January 2018), and 131 of these municipalities have more than 10,000 inhabitants, mainly located in the coastal area. The Barcelona Metropolitan Area, including Barcelona City and 35 neighbouring municipalities (~3.3 million people in an area of 636 km^2) is the most heavily populated region. Other urban areas with more than 100,000 inhabitants include Terrassa-Sabadell, Tarragona-Reus, Lleida, Mataró and Girona.

Data Sources

Catalonia has had a geological map at 1:250,000 scale since the mid 1990s. Associated with this map and the associated database are 228 cartographic units differentiated as follows: 22 Quaternary, 24 Neogene, 56 Paleogene, 55 Cretaceous, 4 Jurassic, 9 Triassic, 1 Permian, 5 Carboniferous, 15 Devonian, 1 Silurian, 7 Cambrian-Ordovician, 15 Variscan plutonic rocks, and 14 metamorphic rocks. This geological map represents the basic geological conceptual reference for the initial construction of associated more detailed models.

In 2007, the ICGC completed a geological map at 1:50,000-scale for the whole territory of Catalonia. The map, which is available in shp format, was derived from synthesizing and harmonizing the geological information of the MAGNA project (geological maps sheets 1:50,000 scale made by the Geological and Mining Institute of Spain), that was conducted between 1997 and 2007. This larger-scaled geological map homogenized 84 map sheets, and it covered an approximate area of about 500 km^2 for each 1:50,000-scale map. The 1:50,000-scale geological map of Catalonia, and its associated database, have not been updated since 2007. The map includes 1047 cartographic units. The distribution of these units undoubtedly represents an essential source of geological data of reference to build 3D reconstructions throughout Catalonia.

The geological database associated with the 1:50,000-scale mapping represents a detailed source of information covering the entire territory of Catalonia. However, the ICGC has more detailed information that covers a considerable part of the territory. Much of this information derives from the development of a 1:25,000-scale geological map of Catalonia. Currently (November 2018) there are 92 published map sheets of this cartographic series that cover a total area of ~10,000 km^2. These map sheets include a considerable number of structural measures, geological cross sections, and stratigraphic columns. The development of this 1:25,000-scale project entails the compilation and homogenization of a large volume of data from outcrops and boreholes. In parallel to this effort, the ICGC also has conducted other regional mapping projects, but oriented towards the inventory of geothematic data (e.g., geomorphological, hydrogeological). These products have also been useful contributions to the 3D modelling effort.

In urban areas, in general, there is a considerably higher density of available data, especially geotechnical. The 1:5,000-scale geological map sheets from the Urban Geological Map of Catalonia project include a large volume of geological information (Pi and Vilà, 2013). At present (November 2018), 38 map sheets have been published, covering 310 km^2.

In addition to the information related to geological maps, the ICGC has other sources of geological information that have been useful to build 3D geological models. Currently the ICGC's document management system stores 11,046 technical reports that can be consulted upon request. The ICGC also hosts a borehole database with ~31,000 logs and a geophysical database that includes the results from various surveys (gravity, electric, magnetotellurics, active seismic, passive seismic, well-logging) that have been conducted during the last 40 years.

Apart from the geological information, it should be noted that the ICGC is the national mapping agency of Catalonia. Through the Vissir application (http://www.icc.cat/vissir3/), a large number of layers of topographic information useful for the development of 3D geological models can be viewed and downloaded:

- Topographic maps of the entire territory up to 1:5,000 scale.
- Topographic maps at 1:1,000 scale for urban areas.
- Current orthophotos up to 25 cm pixel size of the entire territory.
- Digital elevation model with a 5-meter grid size of the entire territory derived from the 1:5,000-scale topographic database.
- Digital elevation model with a 2-meter grid size of the entire territory derived from LiDAR data. The point cloud, in las format, is also provided.

It should be noted that topographic cartography is available in 3D formats (e.g., 3D dgn files). This facilitates the reconstructions and the integration of buildings and other topographic features in 3D geological models.

Apart from these cartographic data sources, which are periodically updated, the ICGC makes available a large volume of historical topographic maps, photogrammetric frames, and satellite derived images that can be used to identify ground surface changes over time and landscape evolution.

3D Modelling Approach

As described in the Overview of 3D Modelling Activities section, the main objective of 3D geological modelling has focused on the geometric reconstruction of geological structures. Recently, the ICGC began to develop more sophisticated models, with physicochemical parameters, in order to make more realistic simulations and predictions. These advanced models are in a preliminary stage, and can be envisaged as one of the current challenges of the ICGC.

The reconstructions carried out to date are basically deterministic, and most of them have been obtained by applying explicit methods. Broadly, the explicit method reconstructions imply (1) establishing 3D geometric relationships between initial data, (2) the use of the initial data in its original xyz position, (3) and applying geological knowledge in the data analysis. The explicit reconstructions have the disadvantage that they are laborious, and by contrast provide greater control and understanding over each reconstruction step. On the other hand, it is important to emphasize that by means of the explicit method, any type of geologic structure can be reconstructed regardless of it complexity. In addition, explicit reconstructions can be obtained using current CAD tools, as they do not require the application of very specific software. This is important because the reconstructions easily can be merged with many kinds of specific projects (e.g., ground and environmental engineering, natural hazards, municipal operations, reality modelling, roads and other types of infrastructure).

As has been discussed in the previous section, the nature of the primary geological surfaces that divide the subsurface of Catalonia are very diverse. This fact influences the way that the ICGC has reconstructed surfaces. Some of the more common methods are:

1) Comparing digital terrain models. The comparison of topographical documentation of different periods highlights the impact of human activities on the ground through time (Vilà et al. 2015). Thus, from a 3D geological modelling perspective, it is possible to define the geometry of certain artificial deposits by comparing detailed pre- and post-urbanisation digital terrain models, such as infilled river channels. This method is also useful to detect 3D landscape evolution related to natural processes such as coastal or alluvial dynamics.
2) Surface contouring. This method basically consists in interpolating the locations of selected contour elevations honouring the information at a number of places (e.g., Groshong 2006). For a long time, surface contouring has been widely applied to 3D geological modelling as it allows for the re-

construction of the geometry of surfaces in an easy way. The surface contouring method is especially useful to model the geometry of near surface deposits that are relatively thin (e.g., Anthropocene, Quaternary and Neogene units).
3) Dip domain. The segmentation at different scales of geologic surfaces into planar domains using the dip domain method (e.g., Fernández et al. 2004, Carrera et al. 2009) is one of the most useful strategies to build internally consistent geological models of multilayer sequences, especially where extensive surficial exposures exist (e.g., the Paleogene and the Mesozoic units in the Pyrenees).
4) Interpolation of 2D sections. The interpolation between closely spaced 2D data, such as seismic sections or geological cross-sections (e.g., De Donatis 2001, Kessler et al. 2009) is one of the most applied methods of 3D reconstruction of geological surfaces from field and subsurface data.
5) Gridding structural orientation data. The interpolation of spatially distributed measures of regional planar geological structures allows for obtaining of the continuous distribution of such structures on a grid cell basis (e.g., Meentemeyer and Moody 2000, Günther 2003). The application of this method, based on regionalisation of structural orientation data, is useful, for example, for predicting the orientation in the near surface of the Variscan regional foliation of the Cambro-Ordovician successions.

The reconstruction of 3D subsurface structures that represent the diverse types of environments of Catalonia can be obtained by applying and utilizing the above methods. These methods were used for the development of the 1:5,000-scale Urban Geological map of Catalonia (Vilà et al. 2015). However, other methods of reconstruction have been used and, often the most effective way to build a particular surface is applying a hybrid procedure by combining different methods. The ICGC's modelling approach is to build 3D models that involve applying a combination of explicit methods.

Clients

Major users of ICGC data and information include the ministries and agencies of the Government of Catalonia, and the councils and other public organizations that focus their activity on the management Catalonia's municipalities.

Because of the national scope of the ICGC functions, land management agencies use its surveys in developing policies that help them meet their administrative responsibilities. For example, the Ministry of Territory and Sustainability rely on ICGC geothematic information to develop the land-use policies that are within its jurisdiction. The ICGC also provides information that helps other government organizations develop and enforce regulations. For example the Catalan Water Agency relies on ICGC assessments of groundwater levels and quality across the territory. The ICGC provides information that helps develop policy and provides warnings or mitigation strategies related to hazards such as landslides, floods, subsidence and collapses, avalanches, and earthquakes. The ICGC is focused on providing geoinformation to the citizens of Catalan, and it also provides impartial advice to academia and industry.

Usually, the general customers of the ICGC information do not directly use 3D geological models, but they use the results. Academic users are usually collaborators in 3D modelling helping to improve modelled resolutions and checking the correct shapes of the modelled structural features.

Concerning the prioritization of the modelled regions, for the general 3D model of the whole territory, the ICGC continues to improve its spatial resolution in the areas where there is new available information.

Recent Jurisdictional-Scale Case Study Showcasing Application of 3D Models

As previously stated, in 2013 the ICGC, in collaboration with the Geomodels Research Institute of the Universitat de Barcelona, finalized version 1 of the 3D geological model of Catalonia at 1:250,000-scale (Figure 2). According to Gratacós et al. (2012), the methodology used to generate the 3D geological model of Catalonia is summarized as follows:
- Adequacy of information. Collecting information from different sources involved different data formats. All this data was transformed in a common digital format for its use in a common 3D graphic environment.
- Database. A database was generated including some properties (type, quality, format, authors, etc.).
- Information was added in a common 3D graphic environment. Collecting and visualizing of all available information was accomplishing using a single software (GOCAD).
- 3D reconstruction. A deterministic geological surface and 3D reconstruction was made honoring all available data and incorporating geological constrains.

The 3D geological model of Catalonia covers the entire territory and differentiates 11 main stratigraphic discontinuities:
- Base of the Triassic
- Base of the Jurassic
- Base of the Lower Cretaceous
- Base of the Upper Cretaceous
- Base of the Upper Santonian (initiation of the Pyrenean deformation)
- Top of the Garumnian materials
- Base of the Lower Eocene

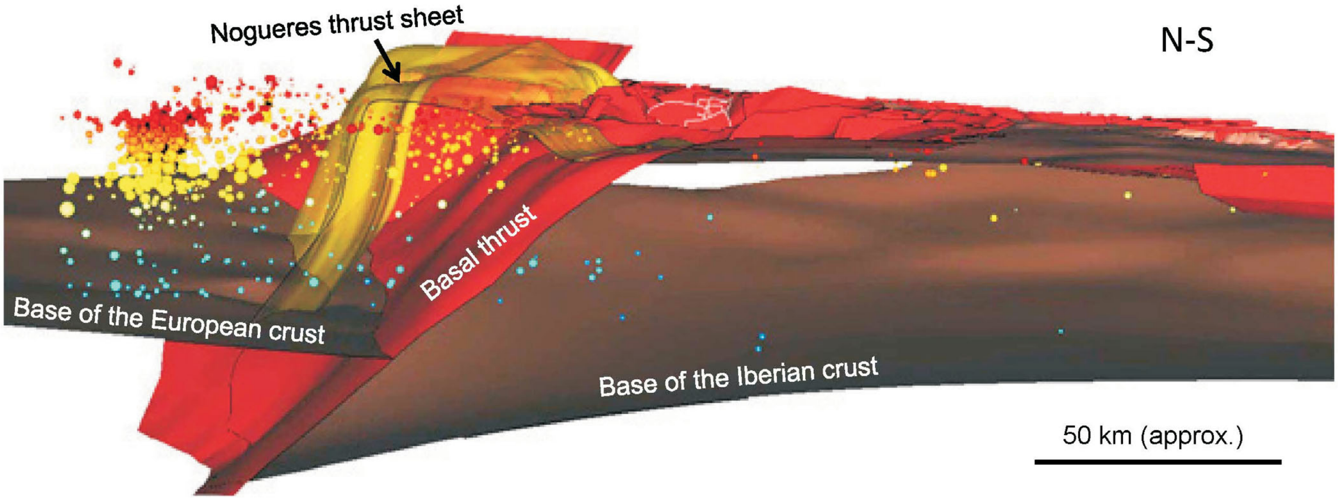

Figure 5. N-S view of the 3D geological structure of west Catalonia, with accompanying earthquake hypocenters.

- Base of the Lower Priabonian
- Base of the Neogene
- Base of the Middle Miocene
- Top of the Paleozoic basement (Variscan unconformity)

Moreover, the realization of the model involved the reconstruction of 30 major structural discontinuities (individual faults and fault systems) as well as the base of the crust of the Iberian plate and the European plate (Figure 5).

The 3D geological model of Catalonia only includes the reconstruction of the most important surfaces (stratigraphic and structural discontinuities), leaving the volumes between them as empty spaces. This model, which can be downloaded in 3D pdf format from the ICGC web page (www.icgc.cat), represents an important improvement in the visualization of the structure and the composition of the subsurface of Catalonia and allows for an improved disclosure of geological knowledge. Over the last 5

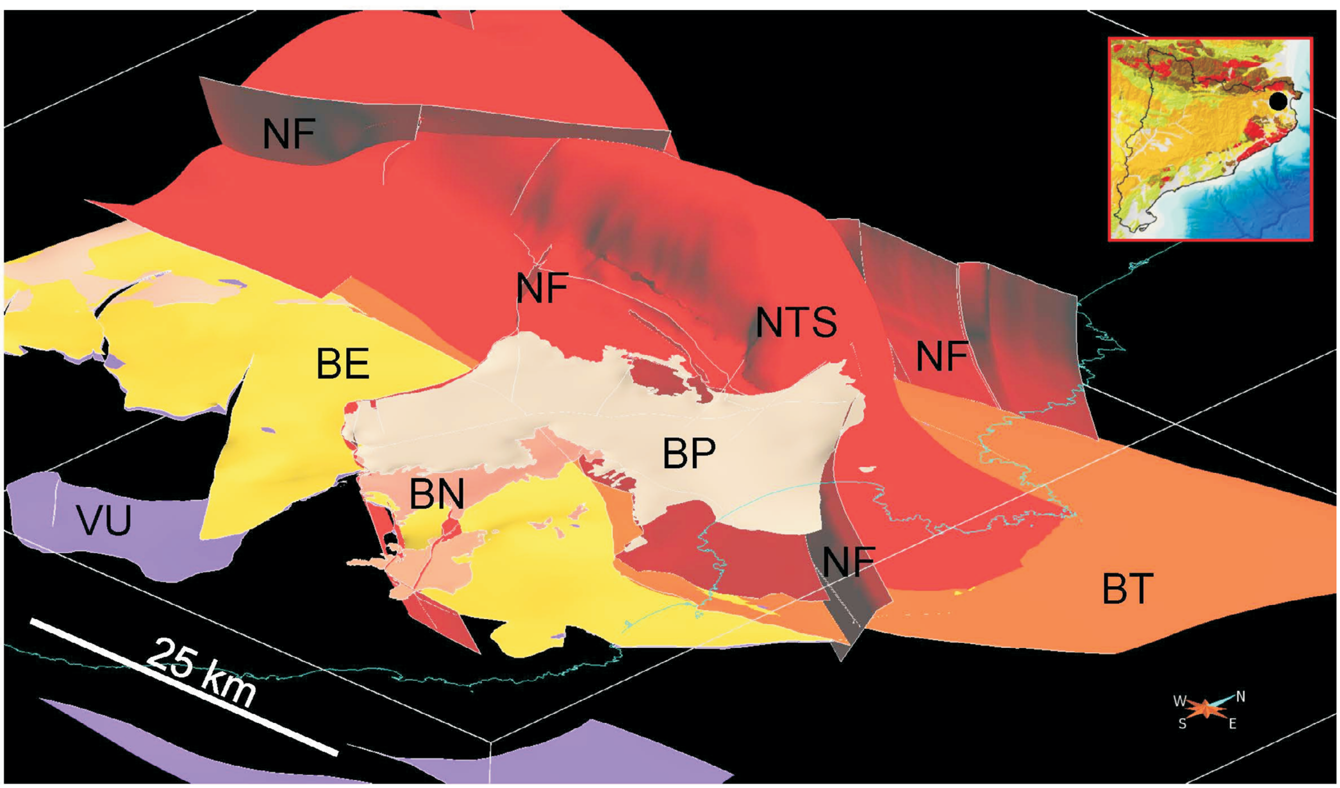

Figure 6. Detail of the geological structure of the Empordà Basin (NE Catalonia). BP: Base of the Pliocene deposits; BN: Base of the Neogene deposits; BE: Base of Paleogene deposits; VU: Variscan unconformity; NTS: Nogueres thrust sheet; BT: Pyrenean basal thrust; and NF: Neogene normal faults.

years, the model has served as a basic geological reference in numerous specific studies.

Since its completion, the 3D geological model of Catalonia (version 1) has been improved in the Neogene Empordà Basin (Gratacós et al. 2015), taking into account data from 1:25,000-scale geological maps and new available data (Figure 6). The Institute foresees the update of the model. However, during the last 3 years it has not had significant modifications.

Current Challenges

The primary current challenges that the ICGC must face regarding 3D geological mapping and modelling are:

- Fostering the use of 3D geological modelling tools by geologists engaged in geological mapping projects. There are currently a large number of 3D geological modelling tools that can facilitate the development of many common tasks in geological mapping projects (e.g., making geological cross sections). However, the available tools commonly are underutilized, although their use in the near future would be very beneficial. Encouraging 3D geological modelling is a challenge for those geologists that have been engaged with traditional 2D geological mapping.
- Taking advantage of the technological infrastructure and 3D topographic databases. Over the last few years, the ICGC has devoted considerable effort to the generation of high resolution 3D topographic geoinformation for the management and sustainability of the territory (e.g., LiDAR surface model with a minimum density of 0.5 m^2), and in particular urban and peri-urban areas (e.g., topographic cartography of urban areas at a scale of 1:1,000). The acquisition of this information and the know-how generated should be used in the development of 3D geological models.
- Ensuring that the 3D geological models that are being developed have maximum interoperability with topographic information and subsurface infrastructures (e.g., transportation tunnels or commodity storage caverns). If geological models can visualize subsurface structures and allow for predictions in areas of sparse data, it is essential that the models be able to integrate into the information system used for planning and territory management.
- Implementing 3D reconstructions in applied projects. Regardless of the types of models that are constructed, it is the duty of the geological survey to use them and be able to apply them in more specific projects related, for example, to hazard management and safety, sustainable development, geo-resource management, adaptation and mitigation to climate change, archaeology/cultural heritage, environmental pollution, underground storage, and integral planning.
- Fostering the realization of models that incorporate physical and chemical parameters. To date, the ICGC's 3D geological models have basically corresponded to geometric models of the subsurface. The ICGC has begun developing projects that foresee the realization of more sophisticated 3D geological models that incorporate physical and chemical parameters of geological units. These more advanced models will allow obtaining more robust subsurface reconstructions from adjusting geophysical potential fields, simulating geodynamic processes and/or performing more accurate predictions (Figure 7). For the ICGC, it is a challenge to foster lines of work focused on the development of more robust 3D geological models that not only adjust the geometry of the units, but also the physicochemical conditions of the subsurface.

Lessons Learned

The development of the 3D geological model of Catalonia represents an important improvement in the visualization of the structure and the composition of the subsurface. For the ICGC, the completion of this innovative model was considered a milestone. However, the geological survey projects over time are varied; therefore, 3D geological modelling should not be considered as an end but rather as a tool that serves to improve the knowledge of the structure of the subsurface or to support projects for which knowledge of the subsurface structure is important. Apart from this general reflection, other lessons that the ICGC has learned while developing 3D modelling products or programs are:

- To plan the models taking into account the regional geological setting. The regional geological knowledge in the technical body of the ICGC is the main asset for developing 3D geological models.
- To develop models that integrate and honor information derived from different techniques, as far as is practical. For example, combine data from outcrops, boreholes, and geophysical techniques. In this way the models will be more robust and consistent.
- To avoid relying excessively on specific software and computer formats. The developed models must be easily exportable and able to integrate into standard systems. The GSO must have sufficient infrastructure to effectively disseminate the models that are constructed.
- The realization of 3D geological models often requires a multidisciplinary approach. For this reason, collaboration between different groups of experts must be encouraged. It is not necessary for all members involved in the real-

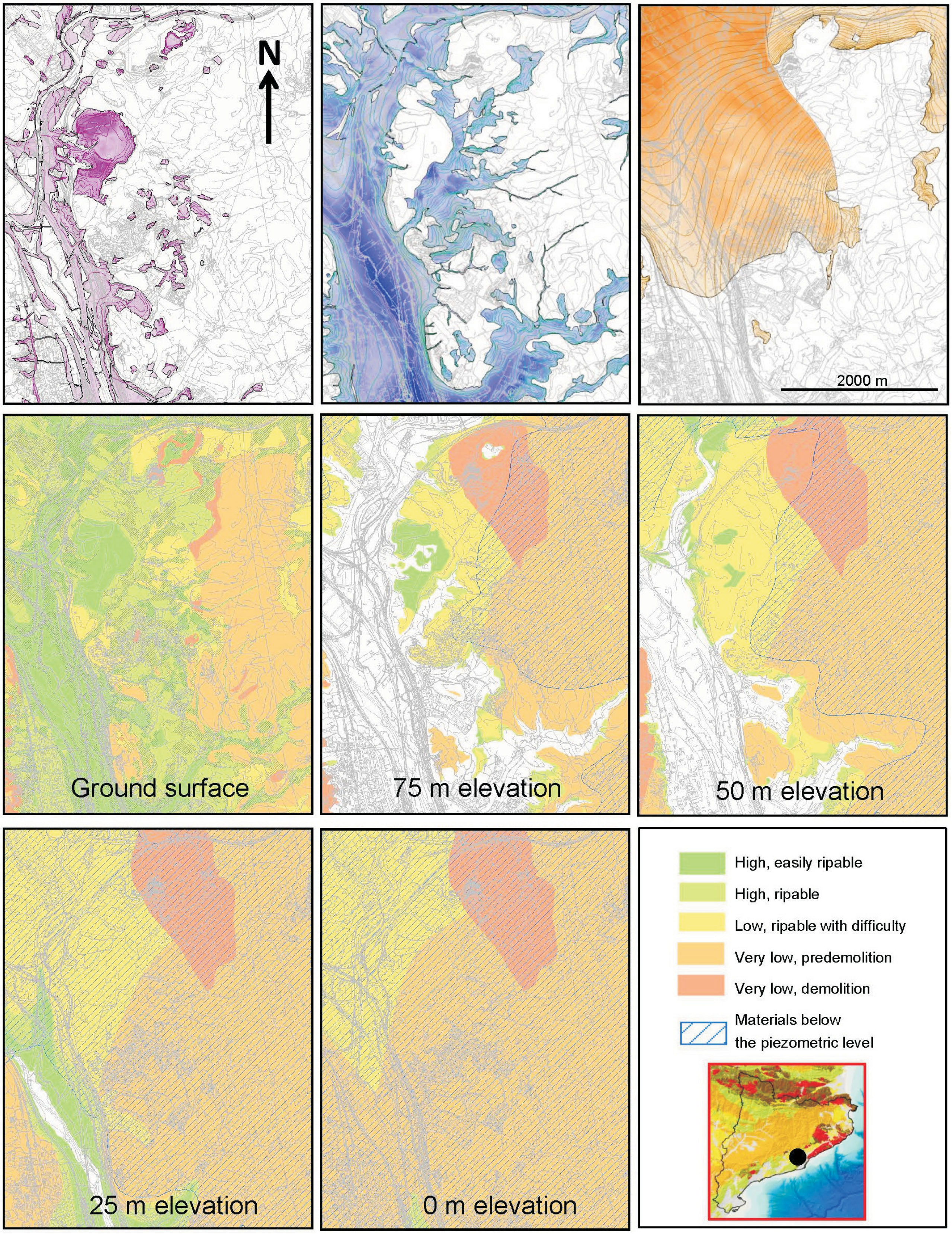

Figure 7. Example of 3D geological reconstructions used to predict terrain excavatability conditions. Isopachites of the Anthropic deposits (I), Quaternary deposits (II) and Miocene deposits (III); and excavatability conditions at ground surface (IV), 75 m (V), 50 m (VI), 25 m (VII) and 0 m (VIII) elevation above sea level. These predictions come from the urban geology pilot project of el Papiol municipality of the Metropolitan Area of Barcelona (ICGC, 2016).

ization of a 3D geological model to master computer tools, to have a thorough knowledge of the geological structure of the region or to be experts in geo-resources or ground engineering. This works, just so long as the person who is responsible of the reconstruction has the geological background to assess the geology as the model is being developed.

- In the ICGC, there should be a formal work group for 3D geological modelling that promotes the implementation and use of modern 3D geological modelling techniques.
- For each model it is important to make clear its objective, the methodology used, and to explain its virtues and weaknesses. The utility of the model will depend on these characteristics.
- When planning jurisdictional-scale models, it is important to decide whether these will be updated and, if so, how the update will be conducted.

Next Steps

In the future, the ICGC will continue to concentrate on improving the geological knowledge of Catalonia. In the next four years, specifically in the field of geological mapping, there is a plan to focus the work around three main activities:

- To update the 1:250,000-scale and 1:50,000-scale geological databases.
- The geological characterization of specific morphodynamic domains.
- The detailed geological characterization of specific urban areas.

On the part of the technical team, there is the commitment for 3D geological modelling to play an important role in the development of these activities, specifically to:

- Improve the 3D geological model of Catalonia at 1:250,000-scale. This means modifying the geometry of existing surfaces, adding new horizons, generating the volumes of the units and introducing the petrophysical parameters of the units.
- Reconstructing in 3D the sedimentary deposits associated with recent dynamics (since the last glacial maximum) of the main Catalan coastal-plains.
- Developing a methodological guide for the agile reconstruction of 3D geological structures based on the 1:50,000-scale geological database.
- Building the 3D geological models of 3 morphostructural domains (of the order of 100 km^2 of horizontal plan and few kilometres of depth).
- Building detailed 3D geological models of the near surface (of the order of 1 km^2 of horizontal plan and depths of the order of 100 m) of urban areas of interest (mainly from the Metropolitan Area of Barcelona) integrated with the 3D topographic databases and the available information related to subsurface infrastructure.

It is expected that 3D geological modelling will also have an important role in the development of other activities: geophysical, hydrogeology, geothermal, geotechnical, subsidence, surface geodynamic processes and the dissemination of geological knowledge. But, today, it is difficult to establish its weight. For this reason, it is recommended to set up an ICGC working group to collect the information related to the 3D geological modelling activity at the Institute and, ultimately, optimize resources and offer a better geological survey.

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