Geological maps: evolution and use of the precious knowledge hidden in a coloured landscape

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ABSTRACT

Since the first modern geological map published in 1815, geological maps represent the best way to store geological knowledge, available for different applications. As for all the other types of thematic maps, geological maps require a continuous update. For geological maps updating is critical, not because the geology of a territory is affected by significant, major changes at a human time scale (except for major catastrophic events, such as flooding, landslides, volcanic eruptions) but because the geological knowledge of a territory increases continuously. Actually, the increased understanding of geological processes and the development of new technological tools for analyses (both on rocks and minerals but also for geophysical investigations) greatly developed in the last century, continuously providing new data able to enhance the geological knowledge. Furthermore, the availability of digital tools able to store and process georeferenced data, improved the integration of geological elements with other types of geographic information (such as land use, urbanistic plans, infrastructure networks and so on), increasing the integration of different information for decision-makers. The classical process of geological mapping (starting from outdoor field work integrated with laboratory analyses) requires a major effort for the homogenization of the criteria when the systematic geological mapping of entire countries is planned to produce maps that represent with the same rules complex and wide areas. The need of the update of geological maps is documented by some examples of application of the Italian official geological map at 1:50,000 scale (CARG Project) as well as the innovations that this project represents with respect to previous maps at 1:100,000 scale in terms of definition of mappable units, criteria for representation of geological objects and presence of a digital database, promoting its use for different applications related to land management.

KEY-WORDS: geological maps, land management, history of geology, CARG project.

INTRODUCTION

Describing a territory with a map has been one of the first ways of storing and sharing geographical data. With the increased knowledge of geological processes, driven also by the need of knowing the territory to manage natural resources and the understanding of natural processes in a culture that abandoned the myth of the creation in six days, the representation not only of the morphology of a land but also its composition led to the production of the first scientific geological maps. The publication of the first modern geological map (Smith, 1815) dates back to the 1815 (the same year of the Battle of Waterloo): it contains all the basic elements that are still today present in modern geological maps, although resolution, conceptual elaborations, and analytical tools provide in modern maps richer and more elaborated details.

As the importance of geological maps immediately became evident, most of the scientifically advanced countries at that time applied this way of documenting the geological nature of a land, its resources and the environmental risks: geological mapping became fundamental within these countries but also in their colonies, where the knowledge of the territory was fundamental also to evaluate the economic value (and rewards) of controlling specific countries or regions.

Due to the nature of geology, the representation in a map of the geological elements of a territory may be realised with differences according to the scope of the representation and by the experience and sensitivity of the geologists involved in the field survey. This condition creates different possible geological maps from the same territory, each of them, for instance, stressing some aspects rather than others (e.g., Quaternary cover, tectonics, morphology, risks, resources and so on) and using different symbolic representations. Due to these potentially different ways of geologically describing a territory in geological maps, immediately became evident that for the production of geological maps at a national level, the definition of standards was fundamental. This awareness became evident in the second half of the XIX century, when different national geological surveys were created and were responsible for the definition of the rules required for a systematic, standard and homogeneous mapping of entire countries. This, for instance, was the case of the UK (Wilson, 1985), where the systematic geological survey started in 1832 when Henry de la Beche was appointed by the Board of Ordnance 'to affix geological colours to maps of Devonshire, with portions of Somerset, Dorset and Cornwall', shortly before the foundation of the UK Geological survey in 1835.

The kaiserlich königlichen Geologischen Reichsanstalt (kkGR) was founded a few years later (15 November 1849) and appointed to produce 1:75,000 scale geological maps (field mapping started in 1870) of the Austro-Hungarian Empire in the frame of the Geologische Spezialkarte der Österreichisch-Ungarischen Monarchie project (Console et al., 2016). Immediately after the unification of Italy, the need for a geological knowledge of this new country was highlighted by Quintino Sella, who also promoted the foundation, in 1873 of the *Servizio Geologico d'Italia* (Geological Survey of Italy): field mapping for the production of the first sheets of the 1:100,000 geological map of Italy started in 1877. Two years later (1879) the United States Geological Survey (USGS) was created. A coeval development of national geological survey is observed in most of the European countries: for example, the "Service de la carte géologique de la France" was funded in 1868 (Napoleon III, signing the act for the creation of this service, stated that the detailed geological map of France would be produced at the State's expense), the "Preussische Geologische Landesanstalt" in Germany was created in 1873; the Geological Survey of Finland dates back to 1885. The second half of the XIX century was the period of the birth of most of the geological surveys in Western countries indicating an increasing awareness of the importance of geological mapping for a correct management of the territories and their resources: the need of a systematic geological mapping of entire countries was one of the main triggers that promoted the institution of geological surveys in different nations.

Since then, the geological knowledge evolved rapidly, as well as the availability of analytical tools, techniques and procedures that improved the quality and detail of each generation of geological maps. Nevertheless, the definition of standards for systematic geological maps remained fundamental for the production of a homogeneous coverage of entire nations: recently, these standards also focus on the digital handling of the geological data stored in digital geological maps.

The awareness of the critical role of geological mapping for a correct land management is generally limited outside (but sometimes also inside) the geological community. The digital availability of geological maps represents an important element to disseminate outside of the scientific community the importance of knowing the geological nature of a specific area or of an entire country, to correctly exploit its resources and to manage natural risks. This contribution aims at documenting the conceptual nature and scientific content of geological maps, the striking evolution that geological knowledge experienced during the last two centuries and the importance of keeping the geological knowledge of the land we inhabit updated. Different examples of the contribution of geological maps to the everyday life are provided, as well as the importance of a common approach in representing geologically complex countries, as Italy is, with specific reference to the Italian situation. Geological maps are not only scientific and technical tools, but also cultural products available for citizens and indispensable as supports for political decision-making in a changing world.

CHARACTERISTICS, PRODUCTION AND USE OF GEOLOGICAL MAPS

A geological map is a thematic map describing the type of rocks that outcrop at the surface of the Earth. Geological maps show the anatomy of a territory, reporting rocks, recent deposits and their relationships, even by deducing their distribution below forests, soils, and urban areas. The distribution of rocks and geological deposits on the Earth's surface provides essential elements to reconstruct their distribution at depth. The rocks are represented with different colours, one for each type; line symbols represent different types of contacts among rocks; point symbols indicate specific observations or features of small size. The legend is the key to the colours, patterns and symbols and is fundamental for understanding the information stored in the map. Geological data are reported on topographic maps, so that the user can "read" both the shape of a territory (topographic map) and the distribution of rocks in it (coloured polygons). Geological maps are thus three-dimensional physical objects (actually, a fourth dimension, time, is implicitly represented by the nature, age and relationships of geological bodies and processes that can be "read" with basic geological knowledge from a geological map): the intersection between geological boundaries and the topographic surface (represented in the maps by contour lines) provides geometric constraints on the relationships among different rock bodies, helping the geologist in predicting the subsurface geology. The three-dimensional nature and use of geological maps are further demonstrated by the common presence, in the map itself, of geological cross-sections, which help the reader in understanding the subsurface geology.

Furthermore, geological maps are "user friendly" repositories for the storage of data regarding the type, nature and characteristics of the rocks outcropping in the mapped area, available for any type of user. The use of geological map is thus pivotal for land management: seismic zonation, natural hazards, engineering works (i.e., bridges, tunnels, dams…), and georesources.

Geological maps represent a shared international way to report geological information and to communicate worldwide the elements that help in resource exploitation, land management and use. Their use is common in all the countries (Fig. 1): since the first modern geological map by William Smith ("A delineation of the strata of England and Wales, with part of Scotland", 1815), most of the countries supported, frequently through their national geological survey, the production of official geological maps covering their territory. Official geological maps provide standardized maps (in terms of geological criteria and symbols used, as it happens for official topographic maps) that cover homogeneously the national territory.

Since geological maps are a mixing between observable and interpreted data of a science, geology, that is still evolving, they should be subjected to "ongoing maintenance" rather than to be considered a static and definitive product: that is why a periodical update of geological maps is essential.

To produce geological maps, three major steps are required (Fig. 2):

- Field survey: geological field survey is usually performed at a detailed scale (e.g., 1:10,000), then smaller scale geological maps are derived from these detailed surveys. Geologists produce the first draft of the geological map directly in the field, day by day (Fig. 3).
- Data analysis and elaboration: samples are carefully collected from different types of rocks and sediments to be analysed. Samples are characterised in a laboratory for texture, composition, and origin (chemical analyses and investigations in optical or electronic microscopes), age (fossils, microfossils or radiometric dating) and so on.
- Data management and storage, map production: results of field work and laboratory analyses are merged together in a database that is used to characterize and describe each geological unit (i.e., each colour on the map), place their distribution on the topographic map, produce a legend for the colours and symbols on the map, add schemes to improve the readability of the map and produce a technical and scientific document (explanatory notes) to store data that cannot be directly placed on the map.

Geological maps were produced for a long time as typographical products, through a long, handmade process. These maps reflect the geological knowledge at the time of the map production: they

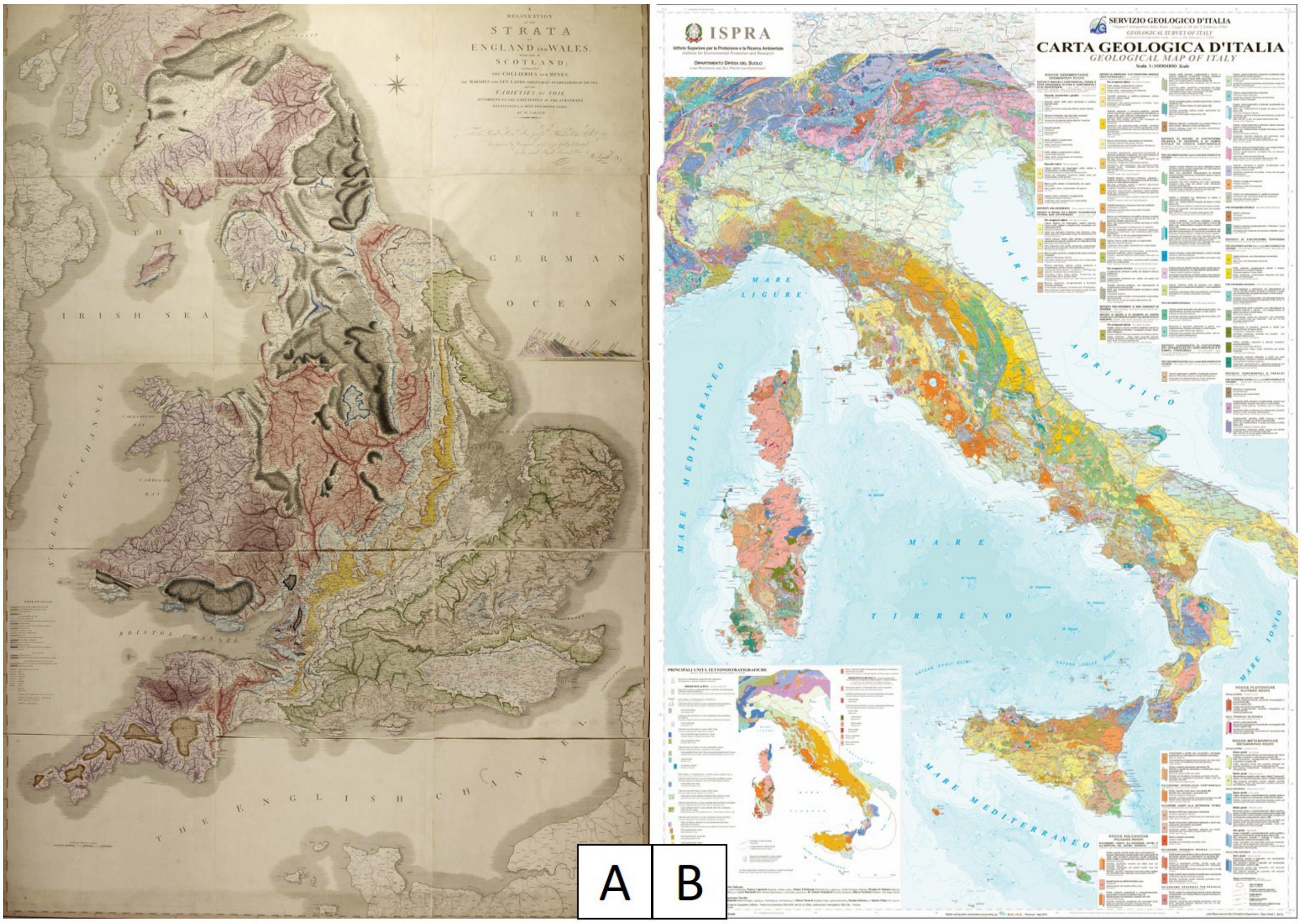

Fig. 1 - William Smith's 1815 geological map (A) and the 2011 geological map of Italy (Servizio Geologico d'Italia, 2011a) (B): geological knowledge and data resolution has changed, but the basic concepts still remain the same. Despite the difference in details, both the maps report the geological data with colour and the description of the units, organised according to their age, is provided by a coloured legend.

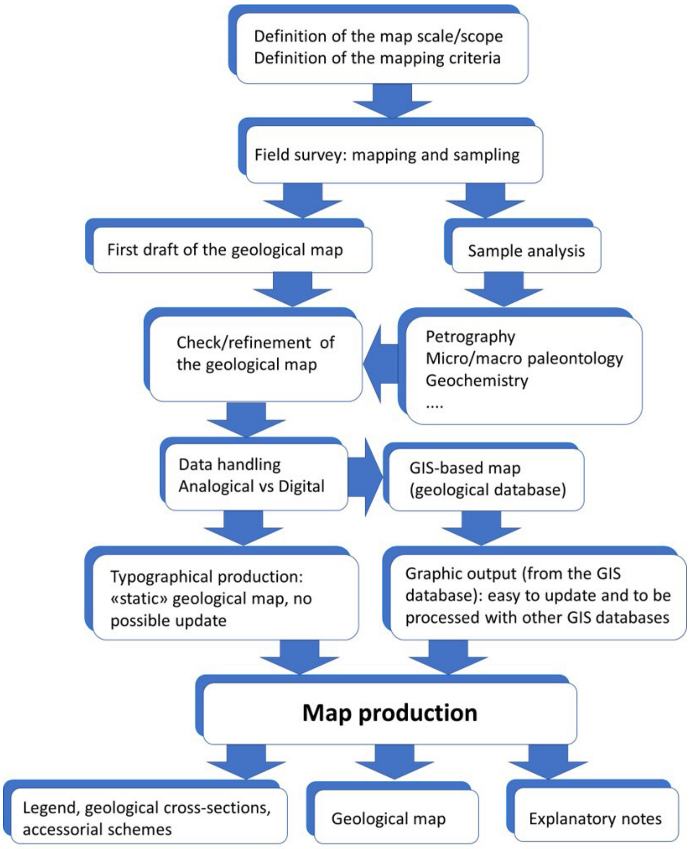

Fig. 2 - Typical workflow for the production of a geological map, with digital storage of the field data.

behave as a static product and their update required a complete redrawing. The recent availability of digital tools significantly changed the handling of geological data (Fig. 3). Today, geological maps are commonly produced as a graphical output of a digital GIS database: geological maps can be "personalized" according to their scope, easily updated, and can store more data than those shown on the map (digital database).

GEOLOGICAL MAPS: EVOLUTION THROUGH TIME AND THEIR USE

Geological maps are important for land management, as they describe specific geological settings and highlight situations and problems that cannot be understood without knowing the distribution of different rocks (for composition, genetic processes, and physical/mechanical properties) and their geometry. Geological knowledge is needed to deeply understand the data stored in a geological map, as these maps are not purely representative maps but contain important interpretative messages.

As geology is a "young" science (with respect to other classical sciences, such as physics or chemistry), the different generations of geological maps on the same area represent an update, in terms of details, data, and scientific improvement, of the previously existing maps. Geological maps need to be continuously updated, not, in general, due to changes in the local geology (that at the scale of human history remains stable, with the exception of catastrophic events such as landslides, earthquakes or volcanic eruptions), but to the improvement of the geological knowledge and the availability of new data (related to new investigations). Furthermore, beside the scientific improvement of geology, also the tools for geological data handling rapidly developed in the last decades: new geological maps couple the increased details and understanding of geological processes with digital tools for georeferenced geological data handling (typically GIS systems) and high-precision topographic survey tools (such as UAV, but also Lidar and other remote-sensing technologies).

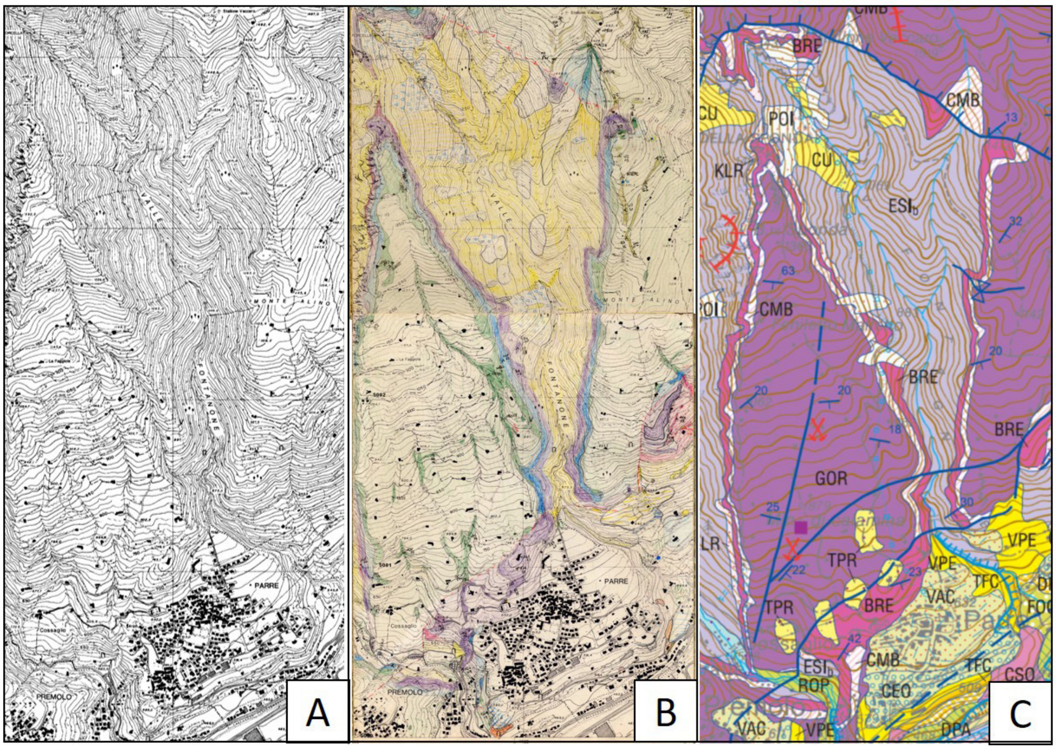

Fig. 3 - Example of the main processes in the production of a modern geological map, from topographic (A) to a digital geological map (C). Geological field survey is usually performed at a detailed scale (1:10,000) on a topographic map (A): smaller-scale geological maps are derived from these detailed surveys. Geologists walk across the study area reporting with coloured pencils the different rocks and their boundaries on the topographic map, producing the first draft of the geological map directly in the field (B). After fieldwork and laboratory analyses, a final, comprehensive, symbolic representation of the geology of the study area is produced, by typographic processes in the past, with a graphic output from a geological database in modern maps (C; Sheet 077 Clusone; Servizio Geologico d'Italia, 2012b): the obtained geological map is a fundamental database to understand the characteristics and the problems of the mapped area.

To illustrate the importance of geological maps to face specific territorial problems, examples of how geological maps illustrate the improvement of the knowledge of a territory, and may help in managing it, are described for five selected areas in Italy, a country characterised by different geological problems. The progressive increase in the understanding of local geology has important implications for the knowledge and use of our land.

To illustrate the evolution of the geological knowledge and its effects on the quality of the information stored in a geological maps and, as a consequence of the need of a continuous maintenance and update of existing geological maps, an example of the parallel evolution between geological mapping and evolution of the Earth sciences is presented, focussing on a sector of the Alps that was fundamental for the development of the role of tectonics in the structuration of orogenic belts: the Rhaetian Alps, at the border between Italy and Switzerland. This required updating of geological maps is than demonstrated by different types of application of the data in geological maps for land management, in different geological conditions for risks and resources. Examples of the use of geological maps in areas affected by seismic shocks are described, in terms of identifications of risks of soil liquefaction in alluvial plains and as support for studies of seismic microzonation. Furthermore, examples of the use of geological maps for the management of volcanic risk and for the geological knowledge of sea bottom in shallow submarine environments in a highly industrialized coastal area.

These examples of the application of geological maps for land management document their fundamental role, as well as the need of a continuous update, required to have reliable data as starting point for further analyses.

GEOLOGICAL MAPS IN THE ALPS: A VOYAGE THROUGH THE DEVELOPMENT OF A SCIENCE DISCIPLINE AND ITS INSTRUMENTS

A good example of how the advances in geological sciences have been reflected in geological maps is represented by a complex area of the Alps between Italy, former Austro-Hungarian Empire and Switzerland that since the end of the XIX century has been the subject of pioneering geological studies. These studies were performed in a complex tectonic setting, where, as we know today, different tectonic nappes of basement and sedimentary cover are overthrust along major faults.

Despite the tectonic complexity and the rough topography, one of the most striking geological maps of the Alps was realised by Albrecht Spitz and Günter Dyhrenfurth in 1914 (Fig. 4). Spitz & Dyhrenfurth (1914) produced this amazing document (for detail, precision, and complexity of the geological setting) before the First World War (Spitz died during the War, in 1918, while working as military geologist). Their work produced the first geological map of this complex part of the Alpine chain: most of their lithological subdivisions are still recognizable in more recent maps. At that time, the role of the faults in the orogenic processes was unclear, so that contacts between different kind of rocks in the geological maps are generally represented without tectonic structures. In terms of mapping criteria, Spitz & Dyhrenfurth (1914) considered these aspects 1) for Quaternary deposits, classification based upon the type of deposit; 2) for the metamorphic basement, lithological classification; 3) for sedimentary rocks, partly «lithostratigraphic», partly «chronostratigraphic» classification; 4) for tectonics, use of a reduced number of tectonic contacts with faults used only where anomalous contacts between rocks of different ages or between sedimentary and overlying metamorphic rocks were observed; folding was overestimated.

In the same area, the Servizio Geologico d'Italia promoted a national geological mapping project since the end of the XIX century, at 1:100,000 scale. The Sheet 009 "Monte Cevedale" was published in 1951 (field survey mostly dates back to a period before the end of the Second World War; Servizio Geologico d'Italia, 1951), the adjoining Sheet 008 "Bormio" in 1970 (Servizio Geologico d'Italia, 1970; Fig. 5).

The two maps follow significantly different mapping criteria. After the Second World War, geological knowledge greatly improved, and the way of mapping rocks changed. Apart from the increased detail, a new (lithostratigraphic) classification of mapped units was

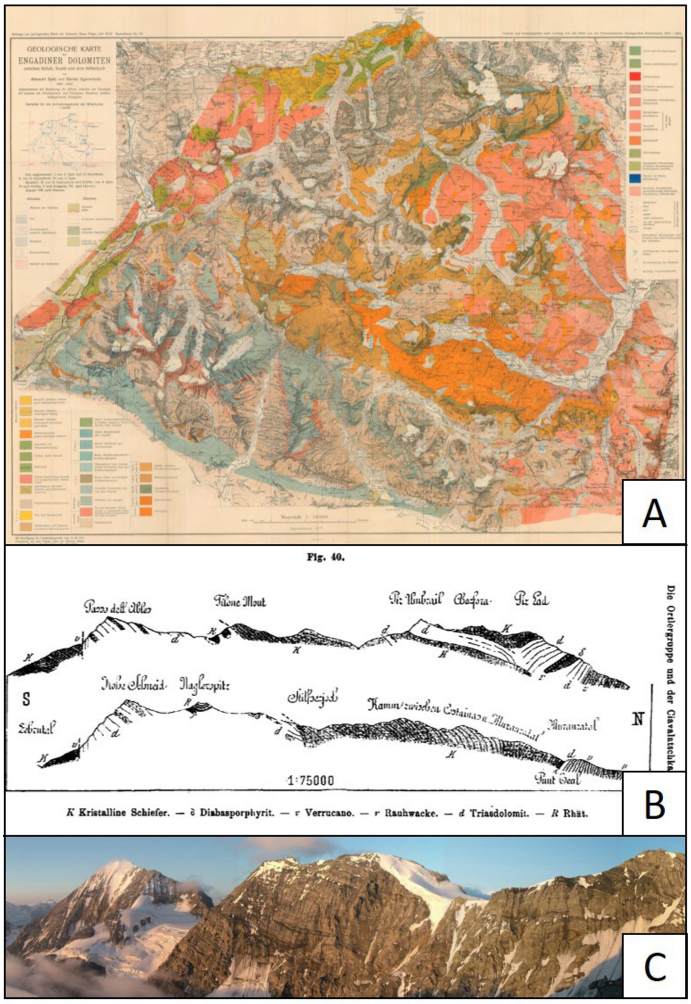

Fig. 4 - Geological map realised by Spitz and Dyhrenfurth (1914), one of the oldest detailed geological maps on part of the Alpine chain (A; Permission ISPRA library). The geological map benefitted from previous studies focussed on the understanding of the stratigraphic and tectonic studies, such as that by Hammer (1908) who represented the limestone intercalations (B) in the Hauptdolomit succession of the Ortles Nappe, that can be clearly observed in the picture underneath, from the summit of the Ortles (C).

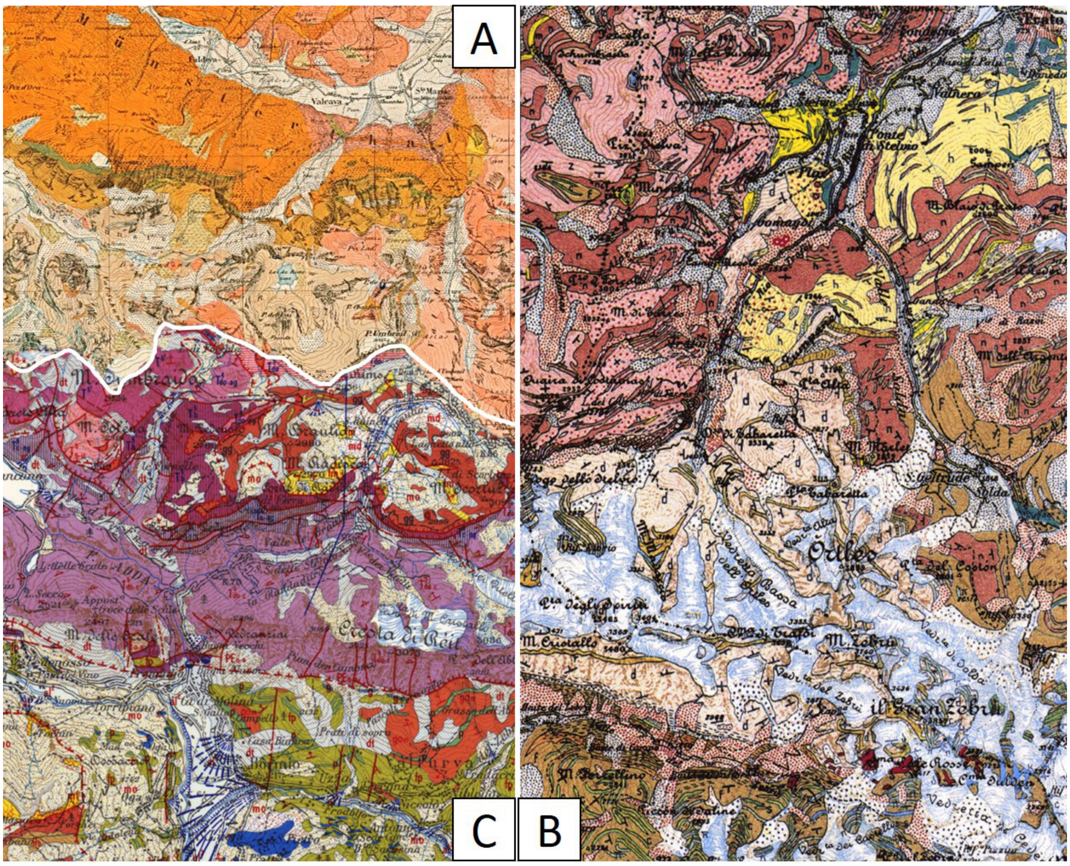

Fig. 5 - Composition of three different maps for age and development of geological knowledge, represented at the same scale (although originally published at different scale). Note, for example, the different detail in the representation of tectonic elements, testifying for the different degree of knowledge at different times. A) Geological map by Spitz & Dyhrenfurth (1914); B) Sheet 09 Cevedale 1:100,000 geological map, (Servizio Geologico d'Italia, 1951); C) Sheet 08 Bormio 1:100,000 geological map (Servizio Geologico d'Italia, 1970). A newer 1:50,000 geological map (Sheet 024 Bormio, Servizio Geologico d'Italia, 2012a) can be compared with these maps, to appreciate the increased detail and the improved geological interpretation (see Fig. 7).

introduced (for sedimentary and metamorphic rocks); furthermore, tectonic interpretation greatly improved thanks to the development of structural geological studies.

In summary, major conceptual differences are evident when comparing the Sheet 009 "Monte Cevedale", the Sheet 008 "Bormio" and the map of Spitz & Dyhrenfurth (1914): 1) basement: lithological classification (Cevedale) vs. lithostratigraphic classification (Bormio), also for the basement units; 2) tectonics: mostly folds in the Spitz & Dyhrenfurth (1914) map, prevalence of "mylonitic horizons" in the Cevedale, "modern" representation of tectonic surfaces in the Bormio Sheet (faults, overthrusts); 3) Quaternary deposits: based upon type and morphology in all the maps; 4) additional schemes (geological cross sections, tectonic sketch, stratigraphic schemes) in the Bormio Sheet, missing in the two previous maps. The difference in the geological knowledge at the time of the publication of the maps appears clear when comparing of the legends of these three maps (Fig. 6).

FROM PAPER MAPS TO DIGITAL DATABASES: UNDERSTANDING GEOLOGICAL PROCESSES IN THE XXI CENTURY

The development of digital tools for handling geological data promoted a new way of collecting and storing geological data to produce geological maps. In the Italian national geological mapping project 1:50,000 (CARG Project), the use of GIS digital databases was introduced. This modern approach has two major consequences: 1) scientific approach to data collection, storage and representation was updated; 2) geological data are stored in a standardised national database (homogeneous criteria for data collection), allowing many possible queries. The map (Fig. 7) is only one of the possible elaborations from the database.

In the 1:50,000 Sheet 24 "Bormio" (Servizio Geologico d'Italia, 2012a; Fig. 7) a new geological approach is followed: 1) Quaternary deposits are classified as Unconformity Bounded Stratigraphic Unit (UBSU) and not only according to their lithology; 2) tectono-metamorphic units are used for the basement; 3) lithostratigraphic classification of sedimentary rocks is more detailed (identification of different rocks and depositional environments within the same lithostratigraphic unit); 4) detailed classification of tectonic contacts (classification of faults according to kinematics); 5) the map is the graphic representation of data selected from the database, that can be subject of detailed queries for further geological elaborations.

The creation of a GIS database is also essential for 3D reconstruction of the geological architecture (Fig. 8), improving geologists' ability in identifying risks and resources of the territory.

GEOLOGICAL MAPS IN THE PO PLAIN: MAPPING THE SURFACE TO UNDERSTAND THE SUBSURFACE IN AN ALLUVIAL PLAIN

The wide plain areas, generally densely populated, were long considered not intriguing from a geological point of view, due to the lack of outcropping rocks and surficial and well-exposed and spectacular pieces of evidence of Earth's evolution (such as mountain chains, landslides, and so on). However, geologists accepted the challenge to understand and describe, through maps, the surface and subsurface geology of these areas, "where the essential is invisible to the eyes" (de Saint-Exupéry, 1943).

The Po Plain, one of the largest alluvial plains in Europe, represents a good example of the evolution of both geological mapping and knowledge related to plain areas also considering the geological hazards that characterise this region.

In the first generation of geological map of the Po Plain (Sacco, 1892) the "outcropping" rocks, represented mainly by Quaternary alluvial deposits, were very poorly differentiated (Fig. 9A). Only a few characteristics of these deposits were recorded by the colours used to distinguish and map them, and the tectonic contacts were not mapped at all. Terms such as "*Diluvium*", "*Terrazziano*", or "*Sahariano*" were used to indicate at the same time the age and the genesis of the sediments.

Forty years after his first field work and map, Federico Sacco mapped again the same area for the production of the first edition of the Geological Map of Italy at 1:100,000 scale (Sheet 87

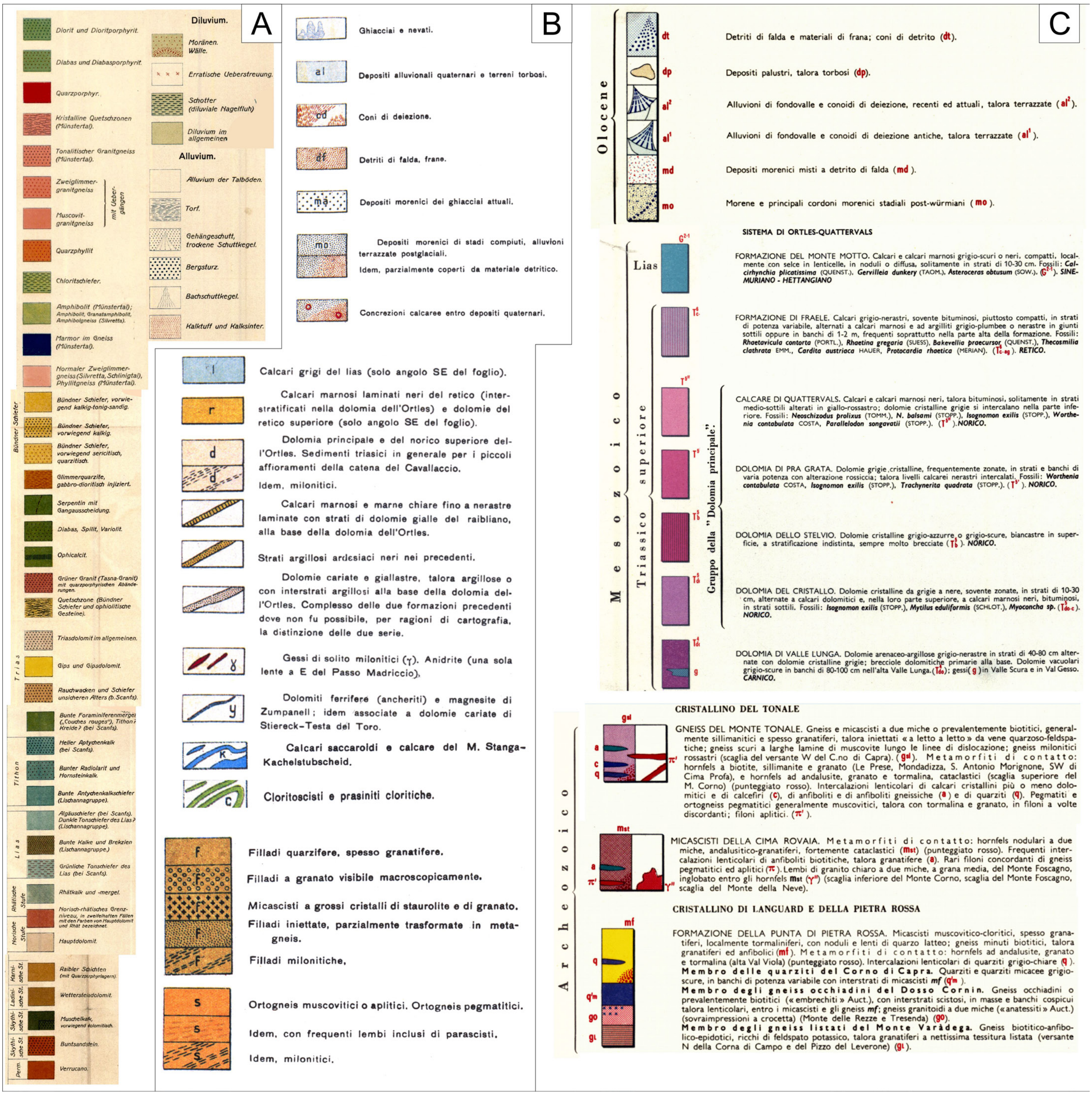

Fig. 6 – **The legends of three geological maps (A: Spitz & Dyhrenfurth, 1914; B: 1:100,000 geological map Sheet 09 Cevedale (Servizio Geologico d'Italia, 1951); C) 1:100,000 geological map Sheet 08 Bormio (Servizio Geologico d'Italia, 1970) highlight the different detail in the definition and description of the mappable units, reflecting the continuous improvement of the knowledge of the geological processes and of the analytical tools usable for the characterization of rock bodies.**

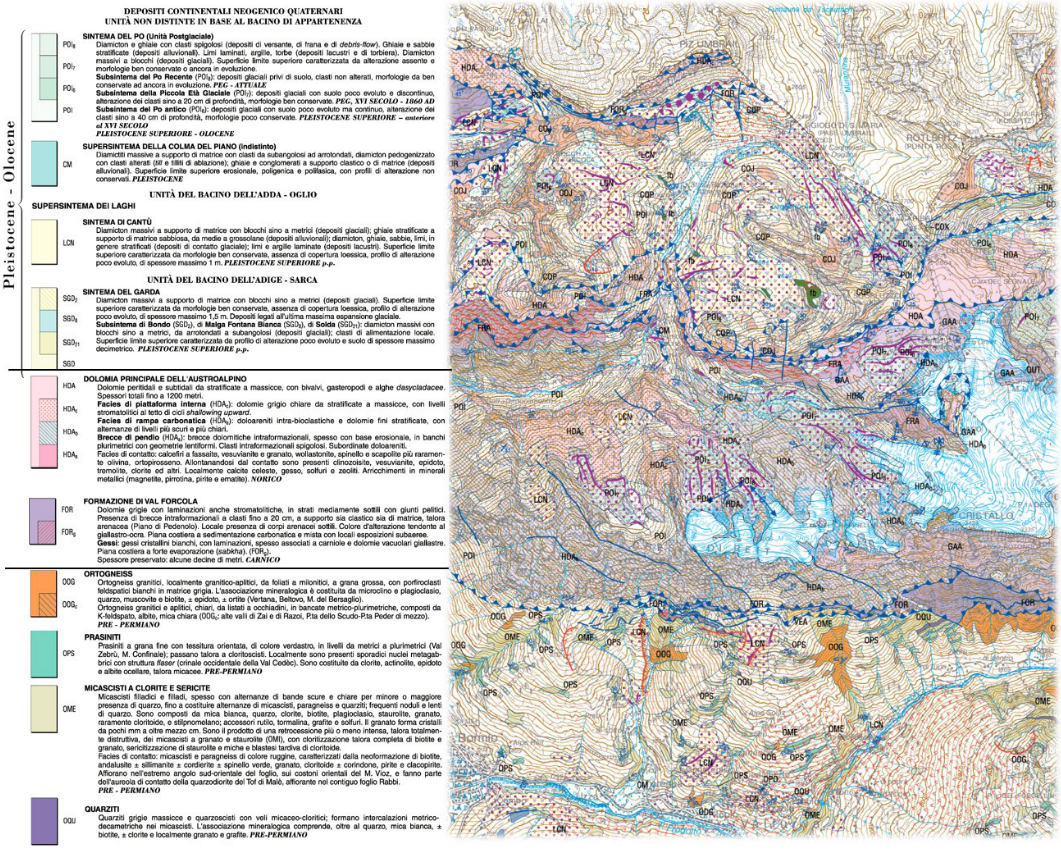

Fig. 7 - New 1:50,000 Geological Map of Italy, Sheet 024 Bormio (Servizio Geologico d'Italia, 2012a), obtained from a digital database.

"Bologna"; Servizio Geologico d'Italia, 1932; Fig. 9). Sacco added new field information with respect to its previous cartographic product (i.e, Sacco, 1892): in particular (Fig. 9B), the Quaternary deposits were subdivided into a larger number of units and "modern" chronological terms, such as "Pleistocene" ("*Plistocene*" in the legend) and "Olocene", were adopted.

The new series (II edition) of the Geological Map of Italy 1:100,000 scale introduced meaningful improvements in the mapping of the plain areas: the differentiation of the Quaternary units based on age, lithology, morphology, and sedimentation environment. Also, a first imagery of subsurface structures enriched geological maps thanks to data from Oil & Gas exploration activities.

Starting with the Geological Map of Italy at 1:50,000 scale new stratigraphic concepts (Unconformity Bounded Stratigraphic Unit) have been adopted as standard for the mapping of Quaternary units (Pasquarè et al., 1992) and additional information, derived from geophysical and geotechnical investigations, supported the knowledge of the subsurface architecture. New graphic elements have been introduced: patterns to distinguish depositional systems and lithologies, subsurface geological sheet, pairing the traditional surface geological map, to map the depth of specific units, and vertically-exaggerated geological cross sections to describe the geometries and the lateral variations of the deposits (Fig. 10A).

Earthquake liquefaction studies and subsurface geology

Soil liquefaction effects happen whereby a saturated or partially saturated soil loses strength and stiffness in response to an applied stress, usually earthquake shaking or other sudden change in stress condition, causing it to behave like a liquid (similar to quicksand).

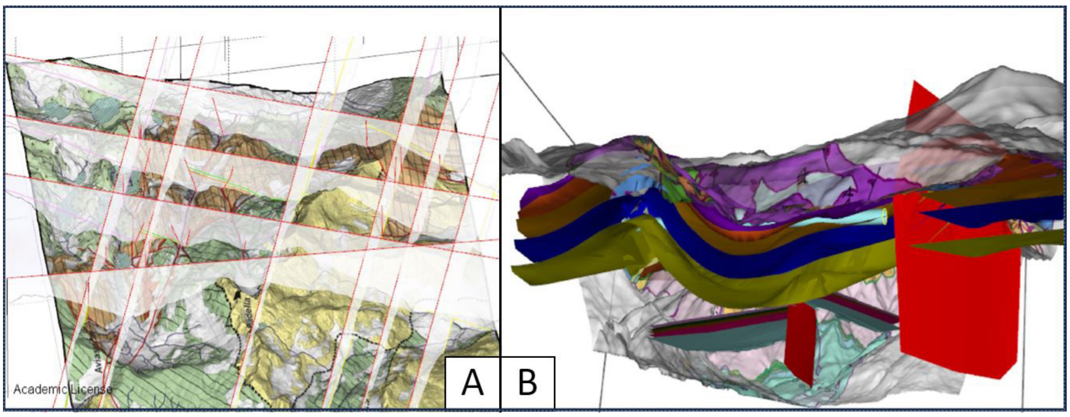

Fig. 8 – Examples of the potential of digital geological maps to provide constraints for 3D modelling. In A) it is possible to identify the network of geological cross-sections required to constrain the geological model and to reduce arbitrary forcing of the model; in B) a 3D geological model with the reconstruction of the subsurface geometry of geological bodies, starting from surface data.

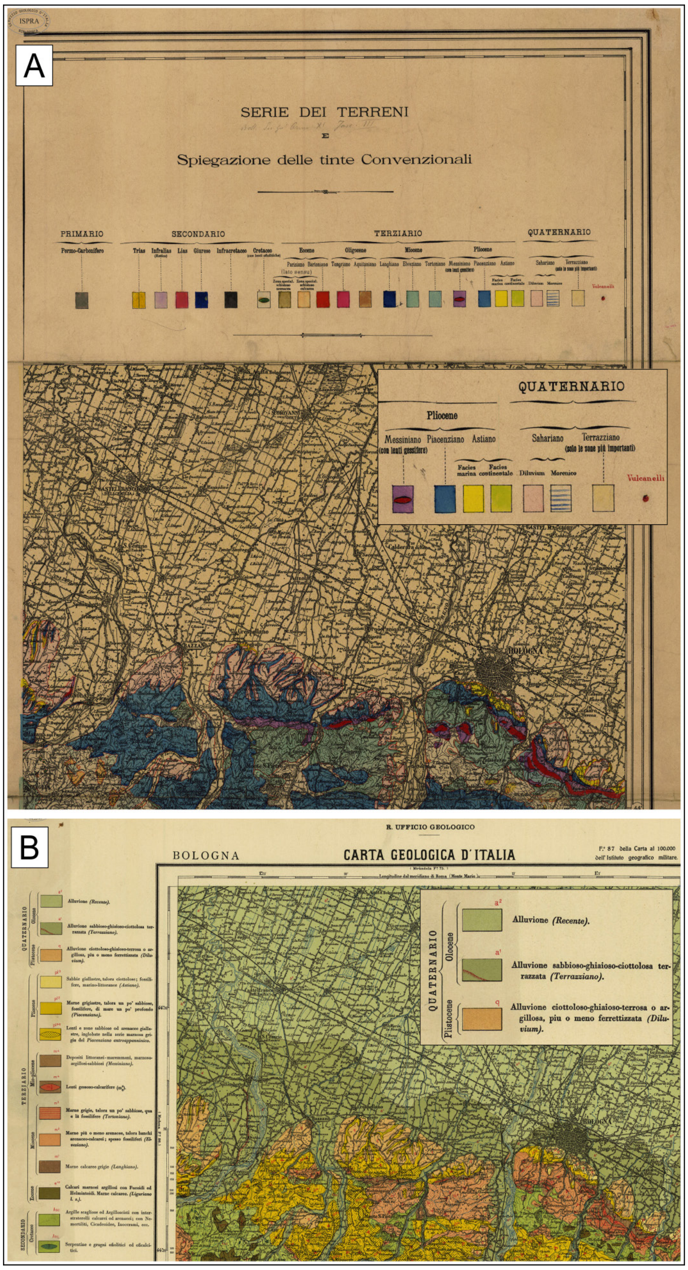

Fig. 9 - A) detail of the geological map realised by F. Sacco (1892) and related legend where the colours indicate a different type of geological units; B) a detail of the first edition of the Geological Map of Italy 1: 100,000 scale - Sheet 87 Bologna (Servizio Geologico d'Italia, 1932); the mapped area is the same as A).

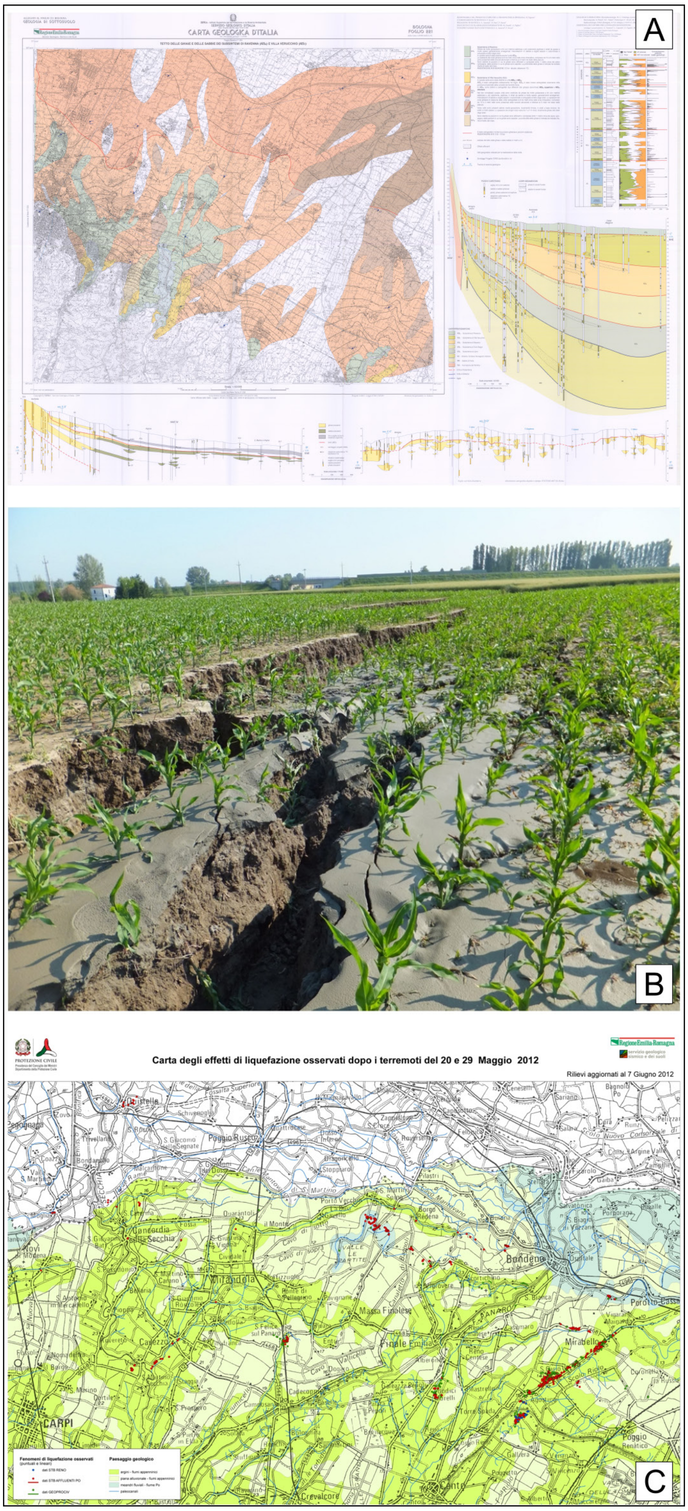

Fig. 10 - A) Subsurface geological map enclosed to Geological Map of Italy 1: 50,000 scale - Sheet 221 Bologna (Servizio Geologico d'Italia, 2009). Geological cross sections and schemes support the description of lateral variations of the Quaternary deposits; B) soil liquefaction effects observed near San Carlo after the earthquake (May 2012, photo: P. di Manna - ISPRA); C) map showing the position of soil liquefaction effects (coloured dots) in relation to the distribution of levee and channel sands (Gruppo di Lavoro Liquefazione – Italian Civil Protection Dept. and Regione Emilia Romagna, 2012).

During, and immediately after, the Emilia seismic sequence (May 2012), several soil liquefaction effects have been observed (Fig. 10B) and mapped (Fig. 10C) (Gruppo di Lavoro Liquefazione – Italian Civil Protection Dept. and Regione Emilia Romagna, 2012; Minarelli et al., 2022); they were in correspondence with levee or channel sands. Blast-induced liquefaction test was also performed in an area affected by extensive liquefaction, in order to provide a quantitative evaluation of the conditions required to produce the observed phenomena in a specific geological setting (Fontana et al., 2019).

These phenomena put in evidence the basic role of detailed geological mapping in plain areas; as a matter of fact, the needed soil information (e.g., texture, grain size) and the mapping of levee sand that may be prone to liquefaction are information included in the geological map at 1:50,000 scale.

CENTRAL APENNINES: THE FUCINO AND L'AQUILA AREAS

The geological mapping in the Central Apennines has a longstanding history: from the mid 1800's up to now. The maps of this region underwent an increasing degree of detail from poor differentiations up to a detail useful for seismic microzonation.

Since the mid 1800's geological knowledge and mapping of wide regions have been considered a strategic activity to discover the availability of natural resources.

The 14 October 1853 Ferdinando II di Borbone, King of the Two Sicilies, ordered Prof. Bonaventura Montani the realization of a geological map with the main purpose of not leaving unused the natural resources of the kingdom and to exploring the geology of the Abruzzi region, "looking for fossil fuels and mines" as stated in the printed version of the map (Montani, 1854b): "S.M. il Re Ferdinando II sempre intenta a non lasciare inerti le ricchezze naturali ond'è il suo Regno provveduto si degnò ordinare nel consiglio di Stato del 14 Ottobre 1853 la esplorazione geologica dell'Abruzzo Ulteriore I° in ricerca di combustibili fossili e di miniere. Il quale comando eseguito dal Prof. Bonaventura Montani ha dato luogo alla presente Carta Geognostica con gli analoghi spaccati di quel territorio da poter servire di elemento per la Carta Geologica del Regno e di base ai lavori Statistici per lo Stato Fisico" [His majesty King Ferdinand II, always intent on not leaving untouched the natural resources of which his Kingdom is provided, in the State Council of 14th October 1853 ordered the geological exploration of Abruzzo Ulteriore I° in search of fossil fuels and ores. This command, performed by Prof. Bonaventura Montani, gave rise to the present Geognostic Map with cross-sections of that territory, to be used as an element for the Geological Map of the Kingdom and as a basis for Statistical works for the Physical State.].

In its maps (Montani, 1854a, b) the rocks were distinguished mainly according to chronological criteria, coupled with bio-lithological details, and specific colours were used to identify the "resources" (e.g., lignite, iron, mines) (Fig. 11A). Montani's maps represent not only a first attempt of regional geological mapping but also record the evolution of the area : the Fucino Lake, represented in the Montani's map and cross-section (Fig. 11B), was artificially drained between 1855 and 1878 and now the area is a fertile plain (Fig. 11C).

A clear-cut change in the geological mapping of the Abruzzi region (Fucino and L'Aquila areas) is registered with the new geological map at 1:50,000 scale. A modern approach to the description and subdivision of the geological units, both for sedimentary cover and continental Quaternary deposits, is highlighted by the great number of mapped units, thereby providing users with a detailed reconstruction of the palaeogeographic and structural evolution (Fig. 12A). This latter theme is particularly significant in seismic areas; for this reason, several structural elements and related characteristics are mapped (e.g., cataclastic zones, inherited faults, active faults, buried faults).

From the CARG project to seismic microzonation

After the April 9th, 2009, earthquake, Mw 6.3, that hit the city of L'Aquila and its surroundings the official geological map at 1:50,000 scale proved to be a basic tool for several post-earthquake studies and applications (Sheet 359 L'Aquila, Servizio Geologico d'Italia, 2005).

Although having a different goal, a well-done field survey at 1:10,000 scale realised for the Geological Map of Italy at 1:50,000 scale turns out to be a basic starting point for the 1st level Seismic Microzonation: thematic maps (Fig. 12B) are derived from the geological one to support the delimitation of areas with different susceptibility to seismic local amplifications.

VOLCANOES IN ITALY: THE CASE OF VESUVIUS

Ancient mythology around the world is full of legends about volcanoes (Piccardi & Masse, 2007), and classic literature offers several poetic descriptions of volcanoes and volcanic phenomena (i.e., the anonymous poem "Aetna", quoted in: Hine, 2012), but is unanimously accepted that the "modern" volcanology was born in Italy, when Pliny the Younger, in his letters to Tacitus, described the 79 A.D. eruption of Vesuvius that buried the roman city of Pompeii (Bullard, 1962). Many researchers were attracted to Vesuvius, especially after the archaeological excavations that discovered the ancient towns buried by the Vesuvius eruption. For this reason, the first modern cartographic representation in the world of a volcano comes from Vesuvius, and the Vesuvius Observatory, responsible for monitoring of Vesuvius and now a branch of the National Institute of Geophysics and Volcanology (INGV), is the oldest volcanology observatory in the world. In the shadows of Vesuvius lies the town of Naples with its hinterland, that has one of the highest population densities in the world.

Early descriptions of Vesuvius mainly dealt with geomorphology, with some artistic/realistic pictures of the volcanic cone (Fig. 13.A), but since the beginning of the 19th century, maps of historical lava flows were realised, probably being the first modern cartographic products referred to an active volcano (Fig. 13.B).

Later, the first 1:100,000 edition of the geological maps of this area (Servizio Geologico d'Italia, 1910a, b) reported not only the historical lava flows but also the regional distribution and thickness of pyroclastic deposits. It is important to notice that the latter ones derive from pyroclastic flows, that represent the deadliest of all volcanic phenomena since they contain a mixture of hot lava blocks, pumice, ash and volcanic gas that move at very high speed (typically greater than 80 km per hour) down volcanic slopes (Fig. 14).

The second edition of the 1:100,000 Italian Geological Map related to the Vesuvius-Naples area (i.e., sheets 183-184 "Napoli" and 185 "Salerno") was realised in the early '60 following a volcanostratigraphic approach. Moreover, volcanic products were differentiated not only by composition and age but also considering volcanoclastic processes. The new geological survey of Italy (CARG Project) led to obtain 1:50,000 maps whose details come from 1:10,000 base maps (Fig. 15A).

The obtained database led researchers and Public Authorities to realize a very detailed geological map of Vesuvius, where the whole history of the volcano (born about 20,000 years ago) is recorded.

Fig. 11 - A) Geological maps of the Abruzzi region realised by B. Montani in 1854 (Montani, 1854a,b); colours and symbols indicate different types of rocks but also bridle paths and royal postal trails; B) the detail of the B. Montani map and related cross-section (Montani, 1854a) shows the Fucino lake before the artificial drainage occurred between 1855 and 1878; C) picture captured from the space (NASA – ISS Crew Earth Observations experiment, Earth Science and Remote Sensing Unit, NASA Johnson Space Center, ISS016-E-30337, https://eol.jsc.nasa.gov/SearchPhotos/photo.pl?mission=ISS016&roll=E&frame=30337) shows the present condition of the Fucino plain.

From the CARG project to volcanic hazard maps

Volcanoes monitored by observatory networks generally exhibit unrest phenomena that, when detected and analysed in time, allow eruptions to be anticipated and communities at risk to be forewarned.

Volcanic eruptions produce lava (flowing molten material) and tephra (ejected fragments of magma or of ancient rocks). Deaths caused directly by lava flows are uncommon because most move slowly enough that people can move out the way easily. About tephra, the largest fragments (bombs) are deposited near the eruptive vent; the smallest material, volcanic ash (<2 mm diametre), is both easily transported upward within the plume and carried downwind for very long distances. Ashfall rarely endangers human lives, but it can dramatically damage buildings, transportation means, water and wastewater, power supply, communications equipment, agriculture. Moreover, as a result of widespread distribution by wind, ash clouds are a major hazard to aviation. Volcanic products of an eruption may move also as a pyroclastic flow, that, as above described, represents the most dangerous volcanic process. In fact, since pyroclastic flows contain rock fragments, whose size range from ash to boulders and temperature from 200°C to 700°C, they run across the ground carrying away and/or burning all objects and structures in their path.

In the 2015, according to the distribution of volcanic products of Vesuvius, and moving from CARG geological data, the Italian Department of Civil Protection designed an emergency plan around Vesuvius that defined a red zone (the area that potentially could be involved by lava and/or pyroclastic flows) and a yellow zone (the area where buildings could collapse under an ash load of 300kg/m^2) (Fig. 15B).

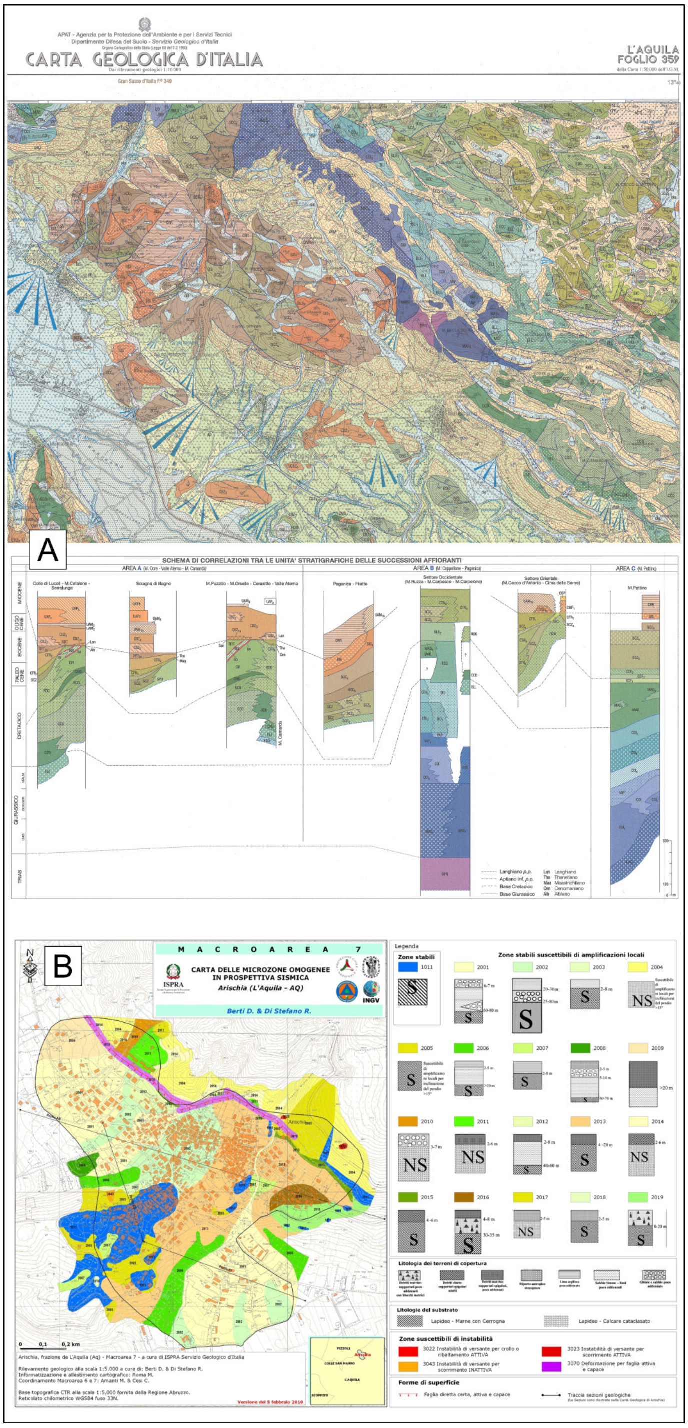

Fig. 12 - A) A detail of the Geological Map of Italy 1:50,000 scale - Sheet 359 L'Aquila (Servizio Geologico d'Italia, 2005) and the correlation scheme of the stratigraphic units; B) map of homogeneous zones in relation to their susceptibility to local seismic amplification; the different colours correspond to different types and thicknesses of soils and rocks. Map realised by Gruppo di Lavoro MS-AQ (2010).

GEOLOGY OF A COASTAL INDUSTRIAL AREA: THE CITY OF TARANTO

The history of the town of Taranto dates back to the 8th century BC when it was founded as a Greek colony. Since that time, the town protects an almost enclosed gulf (i.e., the Mar Piccolo) representing a natural harbour in the northernmost part of the Taranto Gulf in the Ionian Sea. Geology of the area reflects that of the western side of Murge, in Apulia. Apulia is the easternmost region of Italy and is characterised by a thick Mesozoic carbonate succession covered by thin Cenozoic deposits.

First geological maps of the Taranto area (Servizio Geologico d'Italia, 1904) highlighted the presence of Plio-Pleistocene covers (light colours) onto a Cretaceous basement (green) (Fig. 16.A). Apart from their small scale, these maps were very poor of data since they did not report tectonic structures, stratigraphic details of outcropping rocks, and geological sections.

All geological surveys made in the Murge area for the second edition of the 1:100,000 scale geological map of Italy were realised during the 60's (Servizio Geologico d'Italia, 1969; Fig. 16.B). For the first time geological sections were proposed, showing the distribution of Plio-Pleistocene deposits along the western flank of Murge, like in the Taranto area (Fig. 17).

Moreover, Cretaceous stratigraphy was detailed, and a geodynamic meaning was attributed to the Plio-Pleistocene succession cropping out in the Taranto area, considered a stratigraphic record of the Apennines foredeep migration on its foreland side (the Bradanic Trough). A staircase of marine terraces characterizes the top of the Plio-Pleistocene succession in the hinterland of the Taranto Gulf and represents one of the best stratigraphic records in the world of the Quaternary period. Within these terraces, one of those located around the Mar Piccolo of Taranto is considered the best record of the Late Pleistocene, and "Tarantian" is the name proposed for this interval of time (Gibbard & Head, 2009). No Global Stratotype Section and Point (GSSP) have been still formally defined for this interval, but stratigraphic sections around Taranto and the Mar Piccolo are among the best candidates to become the GSSP for the "Tarantian" stage.

Sea-bottom geology: a fundamental knowledge-requirement for seaside towns

Taranto is considered one of the most polluted towns in Italy and western Europe. The pollution is mainly factory-related, being produced by various heavy industries close to the urban area (Fig. 18). Many studies show that not only air and sea-water are polluted but also sediments are contaminated.

Since 1991, the Italian Ministry of Environment has declared Taranto a High Environmental Risk Area, but only with the recent designation of a Special Commissioner the geological knowledge of the area has been considered a fundamental requirement for developing the most appropriate remediation to pollution.

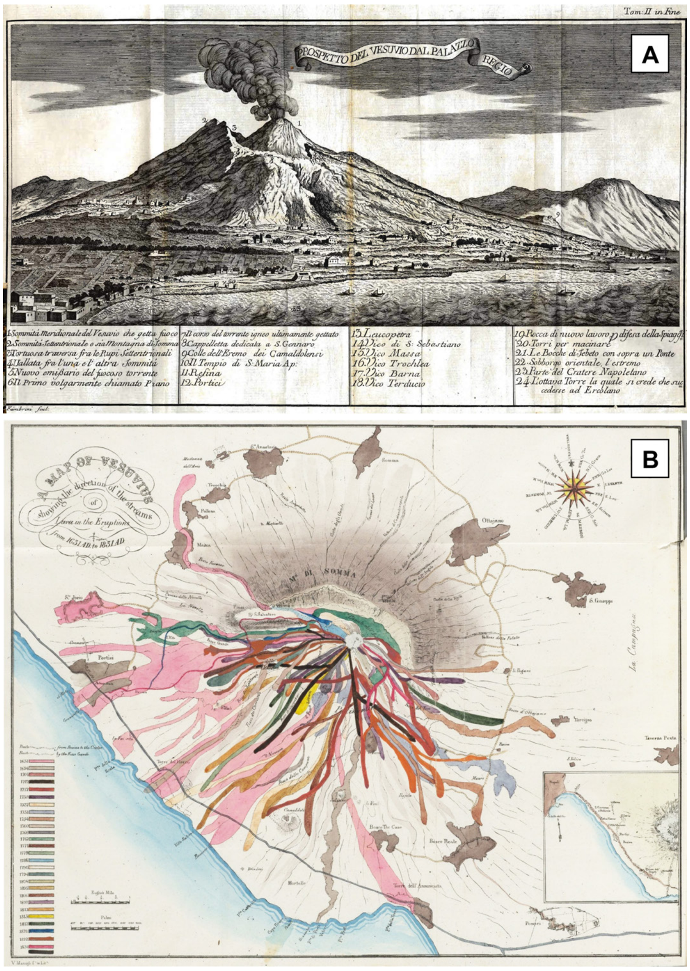

Fig. 13 - A) View of Vesuvius from the Royal palace (1779) (Permission ISPRA library). B) Lava map of Vesuvius (Auldjo, 1832) - https://www.flickr.com/photos/bibliodyssey/5912896472

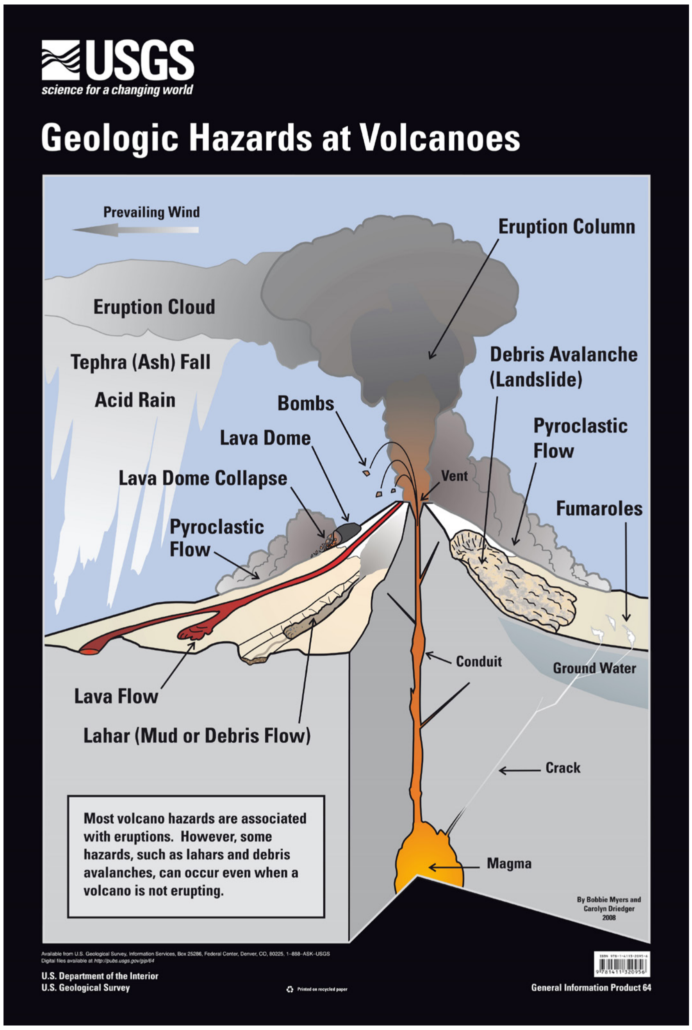

Fig. 14 - Geologic hazards at volcanoes (Myers & Driedger, 2008).

Unfortunately, the second Edition of the 1:100,000 Sheet 202 “Taranto” (Servizio Geologico d’Italia, 1969) still represents the official geological map of the area, but it is inappropriate for pollution-remediation scopes because its scale is too small, the reported stratigraphy of Quaternary deposits is poor, and the sea-bottom geology lacks.

In fact, seaside towns need geological base maps of land and sea like those realised for the new 1: 50,000 Geological Map of Italy (see for example: Sheet 128 “Venezia”, Servizio Geologico d’Italia, 2007, in Fig. 19; Sheet 593 “Castellammare del Golfo, Servizio Geologico d’Italia, 2011c). This kind of maps represents the base for much more detailed geological studies, like those required in the polluted area of Taranto.

At the time of writing this work, the new geological survey of the Taranto area financed by the CARG Project is in progress (sheet 493 “Taranto”).

DISCUSSION

The production of geological maps coordinated by national geological surveys follows well-defined standards that guarantee the homogeneous geological coverage of the national territory: as a consequence, these maps, covering both emerged and submerged areas, can be used as official reference documents for the different application of geology, as documented in this text. In the case of the Official Geological map of Italy at 1:50,000 scale (CARG Project) the detailed definition of the standards for the geological mapping and data representation (including the organization of the digital database) is continuously updated and documented by a set of reference documents (i.e., Quaderni del Servizio Geologico d’Italia, serie III) defined by the Servizio Geologico d’Italia in collaboration with the scientific community. They include: i) the methods and criteria for geological field survey at 1:10,000 scale (Pasquarè et al., 1992; Galluzzo et al., 2009), ii) the data model of the national geological database at 1:25,000 scale and related specialistic database (i.e. sample analysis, geological 3D models, geophysics) (Cara et al., 1995; Artioli et al., 1997; Battaglini et al., 2009a), iii) the standards for a common representation including symbols and chromatic rules (Cosci et al., 1996; Tacchia, 2007), iv) the catalogue of geological units: traditional (Cita et al., 2007a, 2007b) validated (Delfrati et al., 2000, 2002b, 2003b), non-validated (Delfrati et al., 2002a, 2003a) and the Italian guide to stratigraphic classification and terminology (Germani & Angiolini, 2003, produced in collaboration with the Italian Stratigraphic Commission) and v) the specific criteria

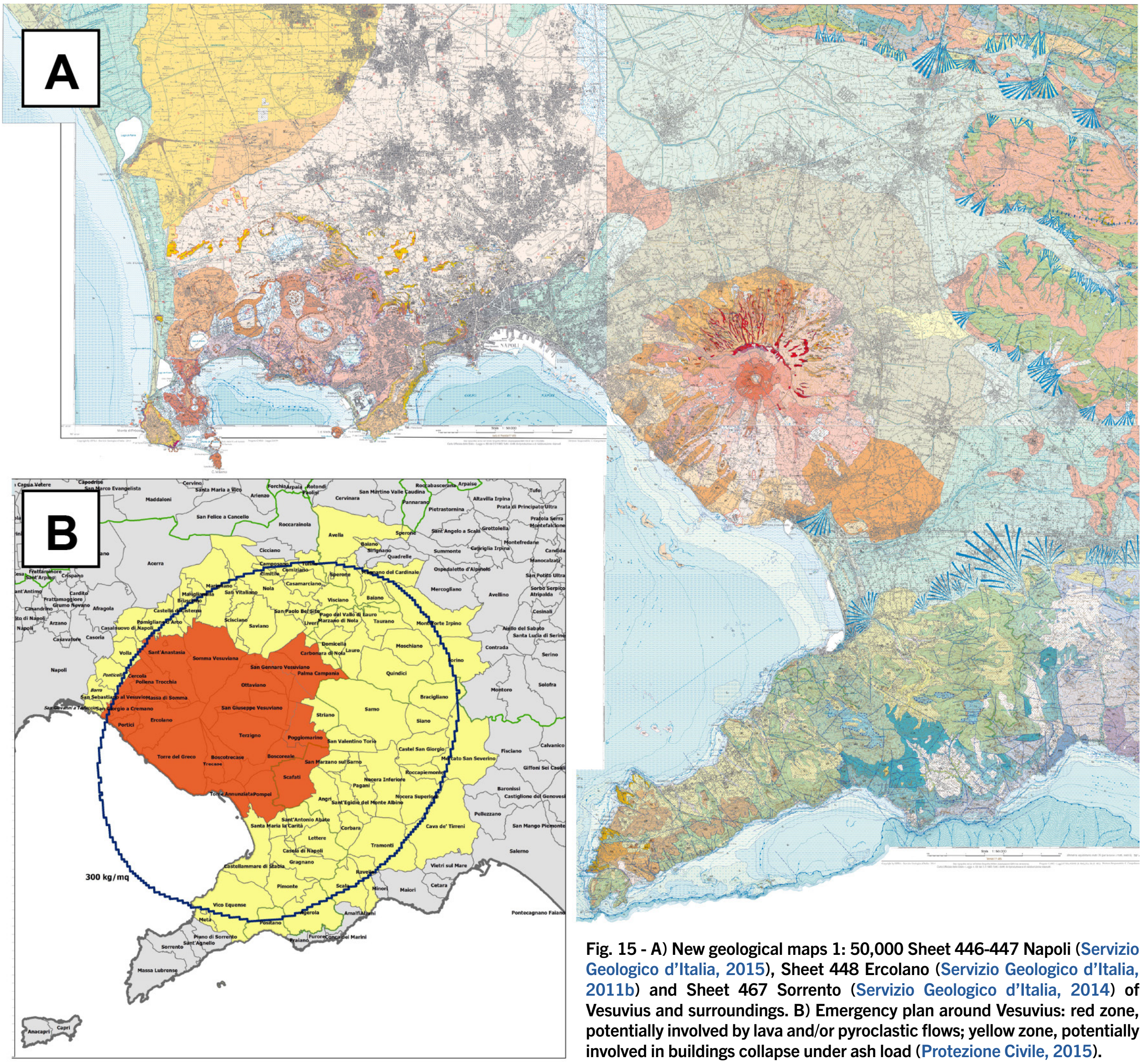

Fig. 15 - A) New geological maps 1: 50,000 Sheet 446-447 Napoli (Servizio Geologico d'Italia, 2015), Sheet 448 Ercolano (Servizio Geologico d'Italia, 2011b) and Sheet 467 Sorrento (Servizio Geologico d'Italia, 2014) of Vesuvius and surroundings. B) Emergency plan around Vesuvius: red zone, potentially involved by lava and/or pyroclastic flows; yellow zone, potentially involved in buildings collapse under ash load (Protezione Civile, 2015).

for survey, mapping and informatization of data in submerged areas (Battaglini et al., 2009b). Recently, a new and updated version of the standards has been published (Vita et al., 2022) which includes a complete online Glossary (Glossario 3.0) providing access to standardised shared terminology.

One of the main effects of this standardization of criteria for the production of geological maps within the CARG Project is related to the conceptual approach to the representation of different mappable units according to their nature. The systematic geological mapping of a geologically complex country, including its coastal marine and lake submerged areas, was coupled with a detailed definition of the most suitable criteria for representing geological bodies in the maps. The most important innovations involved all the types of rocks mapped. The Quaternary units were mapped as Unconformity Bounded Stratigraphic Units (UBSU) to frame them in a succession of events, whose identification is particularly important, for example, in glacial settings. To preserve useful information for the professional use of the geological maps beside the colour used to identify each UBSU, an additional pattern is added (and stored in the database) to provide information about the nature and texture of the deposits. This approach is thus able to provide data both about the time relationships among the units (important to reconstruct the recent geological evolution of a territory) and about the nature of the deposits, important for any application related to land management. Also, for metamorphic rocks the mappable units have been referred to tectono-metamorphic units, adding scientific information about the history of these rocks and not only to lithology (Vita et al., 2022). A new approach has been applied also to sedimentary units. The standard criteria for the definition

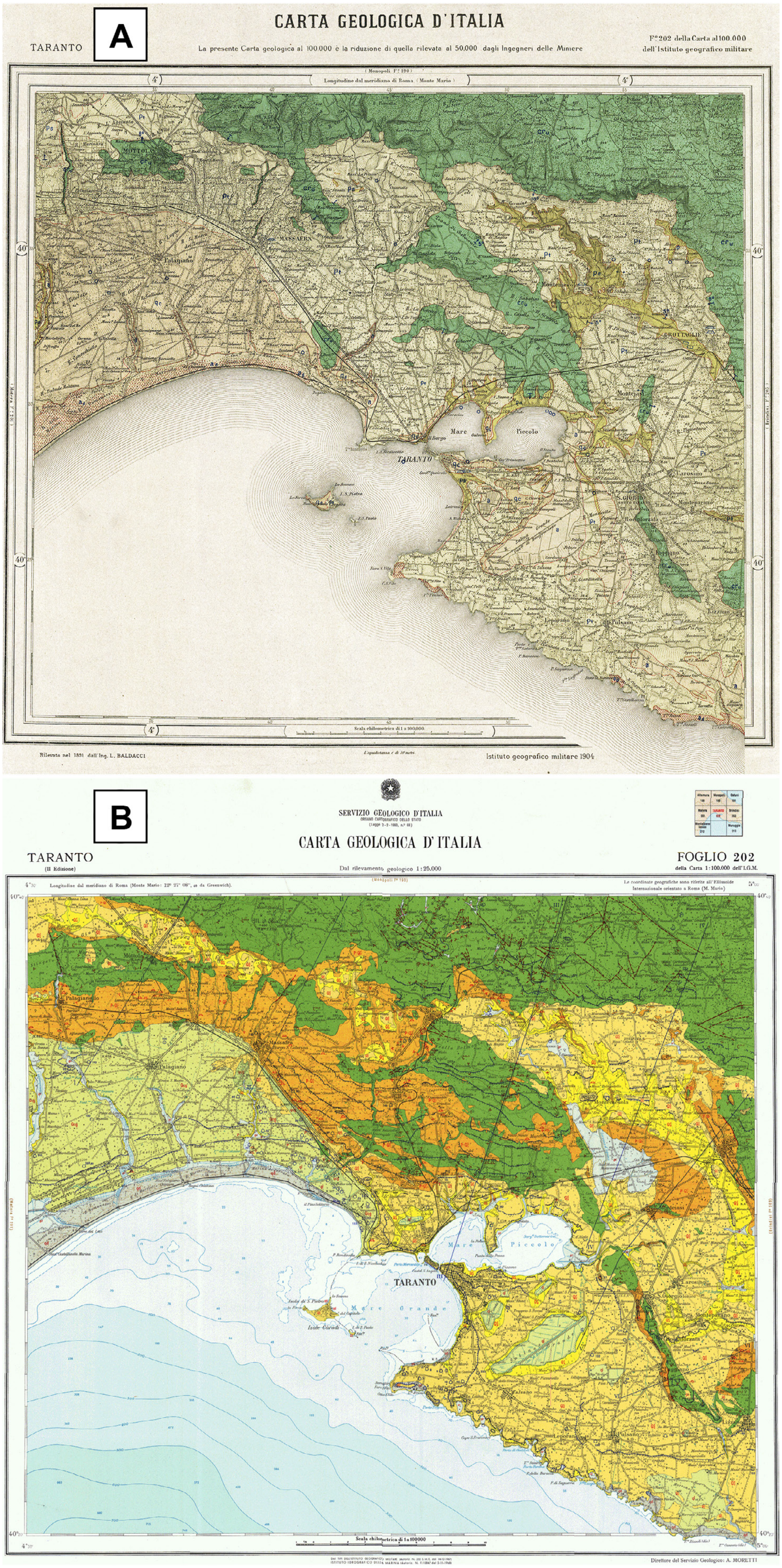

Fig. 16 - A) First edition (1904) of the 1:100,000 Sheet 202 "Taranto" (Servizio Geologico d'Italia, 1904). B) Second edition of the same map (Servizio Geologico d'Italia, 1969).

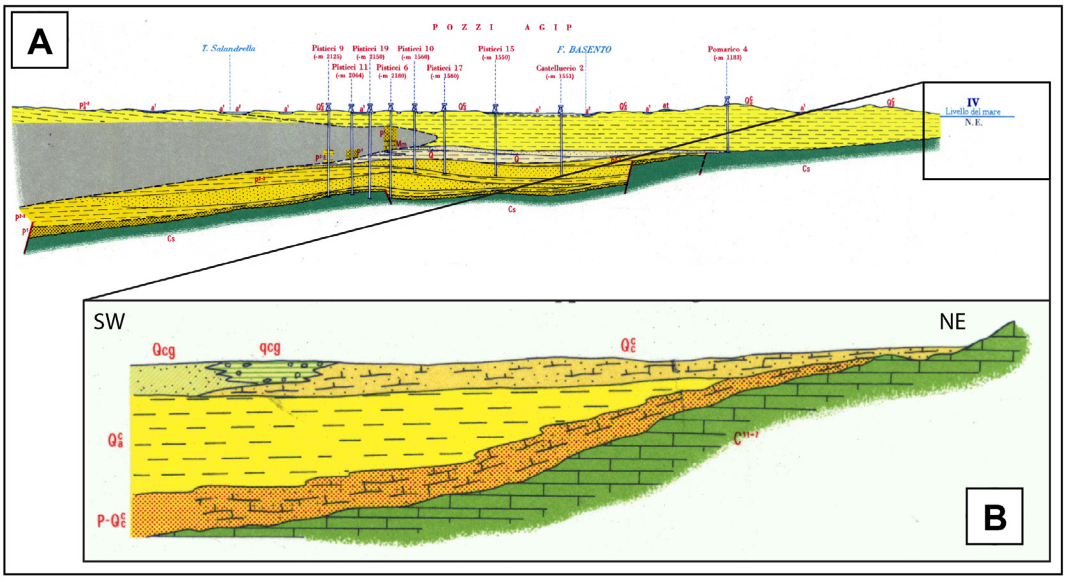

Fig. 17 - A) First detailed regional section cutting the South-Appennines Foredeep (1:100,000 Sheet 201 "Matera") B) Relationships between the Cretaceous bedrock and the Plio-Pleistocene deposits on the eastern side of the same foredeep in the Taranto area (1:100,000 Sheet 202 "Taranto").

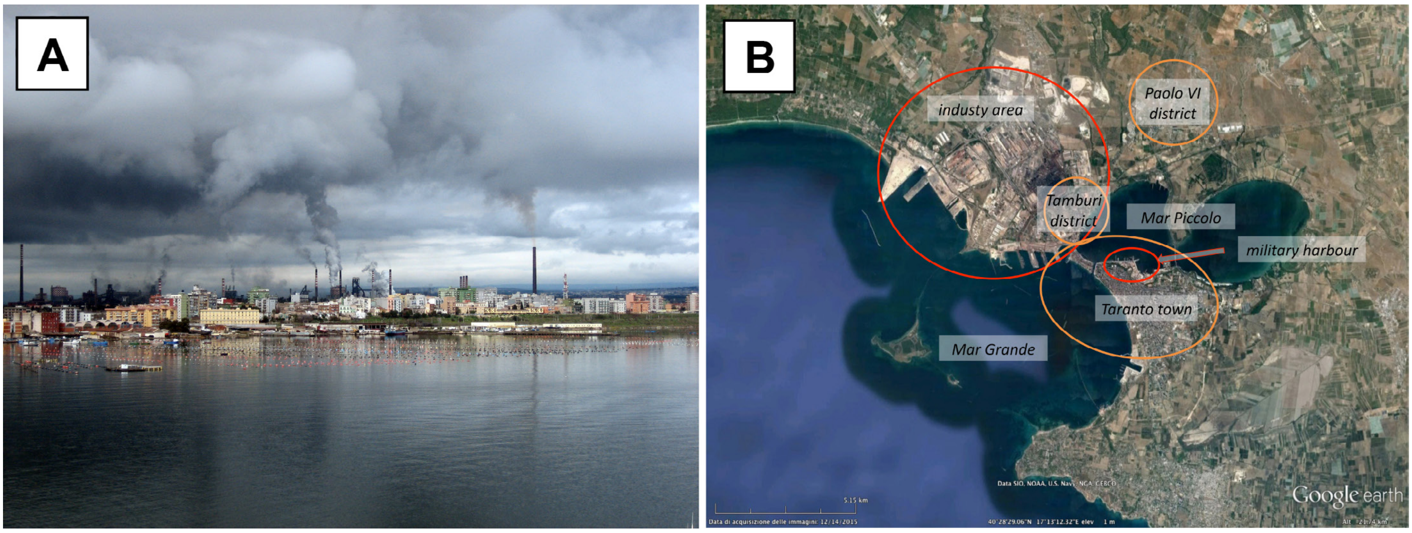

Fig. 18 - A) The industry area of Taranto (https://commons.wikimedia.org/wiki/File:ILVA_-_Unit%C3%A0_produttiva_di_Taranto_-_Italy_-_25_Dec._2007.jpg); B) location of the industries respect to the town districts (base map from Google Earth).

of lithostratigraphic units resulted not sufficient to represent in the map all the specific changes observed within a single unit. To avoid the excessive proliferation of lithostratigraphic units (with the risk of an excessive splitting of the nomenclature for the systematic geological map of a geologically complex country of more than 300,000 km^2) a new approach is followed in the CARG maps: in the case of significant lithological changes (reflecting changing depositional conditions and, different petrophysical properties), lithofacies can be distinguished to evidence these differences, important for the use of the map but not sufficient to define new formal lithostratigraphic units, with the risk of complicating the reading of the geological evolution of the mapped area. In addition, the CARG database includes a standardised hierarchical description for the lithology and texture of each mapped polygon according to international standards and existing classifications improving significantly further elaborations and the production of geothematic maps.

Finally, according to the increasing numbers of societal decisions and environmental challenges based on subsurface geological information, the Servizio Geologico d'Italia, as most of the Geological Survey Organizations in the world (MacCormack et al., 2019), promotes the definitive transition from static 2D surface geological maps to systematic subsurface mapping and 3D reconstructions paired to the official geological sheets of the CARG Project.

The technology facilitates not only this transition toward machine-readable geological products but also significantly accelerates the use of digital devices for the collection of geological field survey observations and data (Gencarelli et al., 2022), based on the data model of the national geological database, and allows for the application of the FAIR (Findable, Accessible, Interoperable, Reusable) data principles to geological data (i.e., metadata catalogue, compliance with international standards, DOI, open data license) to strengthen their dissemination and use.

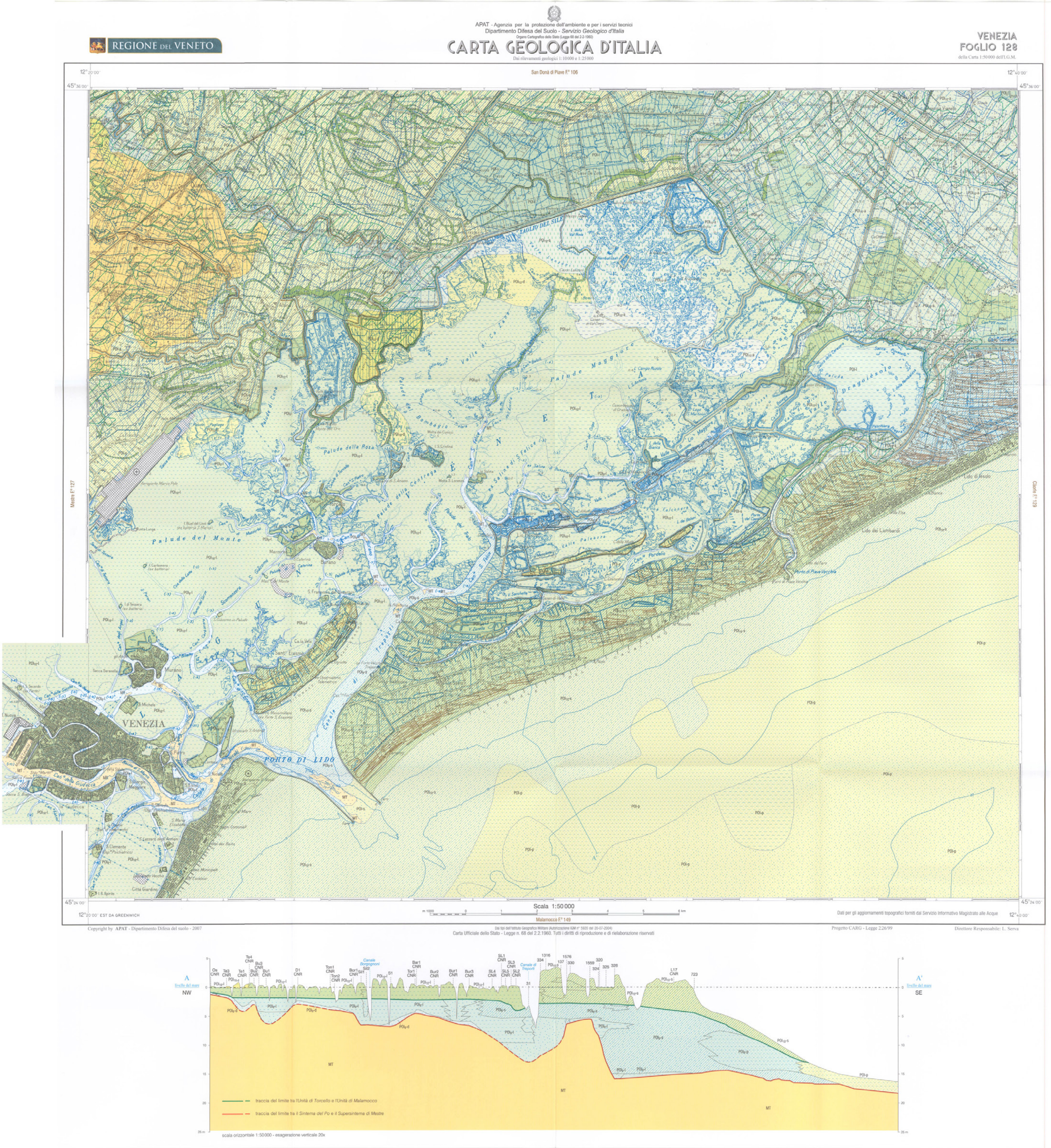

Fig. 19 - Example of a new geological map of land (onshore) and submerged areas (offshore; Sheet 128 "Venezia", Servizio Geologico d'Italia, 2007) recently realised within the 1:50,000 Italian official cartography (CARG) project.

The definition of these new approaches to the geological mapping of the different types of rocks and sediments can provide (and store) both scientific information (such as age relationships, genetic processes, geological history, and palaeogeography) and practical data describing the properties of the rocks and sediments present in a specific territory. The decision to use this approach at a national scale is strictly related to the possible use of geological maps, linking geological knowledge with useful information for everyday life. Geological maps thus represent, for geological science, the best way to demonstrate the importance of a scientific approach for the understanding of natural environments and to correctly drive human interactions, breaking the illusionary separation of applied and basic science. Citing Pasteur, geological maps are one of the best demonstrations of what this important scientist wrote in 1871: “There does not exist a category of sciences to which we can give the name of ‘applied sciences.’ There are science and the applications of science”. Geological maps are the result of scientific research, recording the improvement of the geological knowledge through the years: the need for this knowledge, fundamental for correct land management, requires a strategic definition of the representation criteria (and of a digital database definition for modern maps), to deliver the results of scientific research to everyone who needs to use them for applications.

The production of a national geological coverage (i.e., geological maps), such as in the example of the Italian CARG Project, provides thus the basic knowledge for any activity related to land use (from resources to risks). A national program of geological mapping requires several years: during this period, it is fundamental that this process never stops, in order to keep homogeneous standards for the entire duration of the project. The interruption of the funding for about 20 years (from 2000 to 2020) of the CARG Project caused a stop in the process of production of geological maps, with a gap in the activities and, as a consequence, a dispersion of the teams and experiences acquired in the previous years. The recent reprise of the project is positive, but it is important that the public funding will continue until the entire coverage of the Italian territory with these modern geological maps. Of course, once the project will be finished, the first maps will be “old” and new geological data will be continuously available: the update of existing geological maps will be the next challenge. The digital format of the CARG maps will guarantee the possibility to update the existing maps without the need of a new project, but with the definition of a standardised procedure for the controlled updating of the existing geological database. This interaction between geology and IT tools provides, for the first time in the history of geological mapping, a more efficient way to continuously keep up-do-date the geological knowledge of entire countries.

CONCLUSIONS

Storage and description of geographical properties of any land are at best provided by maps. Among the diverse maps that can describe an area, geological maps have the peculiarity of requiring a detailed survey in the field, needed to intercept all the natural variations of forms, deposits, rocks, and events that record the story of a territory. Geological mapping, although performed with a common background, may differ according to the scope, the competences of the geologists involved, detail, and resolution. As a consequence, when a systematic mapping of wide areas (such as an entire nation) is planned, the definition of standards and criteria is fundamental to obtain a homogeneous product.

The definition of these standards is critical because any choice implicates consequences on the type of information delivered to the users: the best solution is the one that permits to store both scientific (thanks to updated analyses) and practical data (e.g., information able to provide indications on the petrophysical properties of sediments and rocks), and to widely disseminate and promote the use of these data.

The need of a shared standard approach to geological mapping is even more important when the data of a geological map are stored in digital form, typically on GIS systems. The availability of digital geological data and more and more detailed digital topographic models provide important constraints for the reconstruction of geological bodies in the subsurface: the 3D nature of geology and of geological maps is increasingly evident but everything starts for the detailed study of the surface of our planet, in a never-ending continuous update. We can mention a sentence from the Palomar novel by Calvino (1983): “it is only after you have come to know the surface of things, that you can venture to seek what is underneath.... But the surface of things is inexhaustible”: this is absolutely true for geology.

ACKNOWLEDGEMENTS

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https://www.socgeol.it/N956/la-carta-geologica-d-italia-molto-piu-di-un-immagine-a-colori.html (in Italian and in English).
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ISPRA library is warmly acknowledged for providing and making freely accessible geological historical maps (here displayed) from its outstanding geological map collection. The sheets of the Geological Map of Italy 1:100,000 and 1:50,000 (CARG) can be freely accessed, respectively, at these web addresses:
http://sgi.isprambiente.it/geologia100k/
http://www.isprambiente.gov.it/Media/carg/
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