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RETRACE-3D project: a multidisciplinary collaboration to build a crustal model for the 2016-2018 central Italy seismic sequence

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ABSTRACT The RETRACE-3D project (centRal italy EarThquakes integRAted Crustal model) focused on the revision of all the available geological and geophysical data in the area interested by the 2016-2018 seismic sequence of central Italy, with the final aim to reconstruct a reliable and consistent 3D geological model of that area. It is based on a collaboration, which was framed into a formal agreement, between Dipartimento della Protezione Civile (the Italian Civil Protection Department), Istituto di Geologia Ambientale e Geoingegneria, and Istituto per il Rilevamento Elettromagnetico of the Consiglio Nazionale delle Ricerche, Istituto Nazionale di Geofisica e Vulcanologia, and Istituto Superiore per la Protezione e la Ricerca Ambientale. The agreement purpose was to develop a project aimed at the geological and seismotectonic characterisation of the crustal volume hosting that seismic sequence. We present and discuss the approach, methodology and results of the project. The 3D geological model of the study area is developed in detail down to a depth of about 12 km, and extended to the Moho based on available regional-scale information. The model is available on the RETRACE-3D project website (www.retrace3d.it).

Key words: earthquake, seismogenic faults, inherited faults, 3D geological model, central Apennines.

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1. Introduction

This contribution aims to present the methodological approach designed and implemented to carry out the RETRACE-3D project (centRal italy EarThquakes integRAted Crustal model, www.retrace3d.it) and to show its main results. We describe and discuss the experience acquired on how to pursue a profitable collaboration, share existing data from a public-private partnership, and make vast expertise available for seismic hazard estimate and risk reduction and for civil protection aims.

The idea of the RETRACE-3D project was born in the immediate aftermath of the 24 August 2016 Amatrice earthquake (moment magnitude M_W 6.0). The initiative originated from the President of the Istituto Nazionale di Geofisica e Vulcanologia (hereafter INGV). It was promoted during the first days of emergency in the Direction of Command and Control (DICOMAC), issued in Rieti by the National Civil Protection Department (hereafter DPC) for the *in situ* emergency management.

The Italian civil protection system has a long-lasting collaboration with research institutes and Academia, established by law (L. 225/1992, 1992; D. Lgs. 1/2018, 2018). In particular, DPC has on its side the so-called Competence Centres. These are scientific institutions (such as research institutes, academic consortia, universities) that provide knowledge and scientific products that are the result of research and innovation, and that can be integrated into civil protection activities. In this way, the scientific community is involved in all the different phases of risk management, being an integral part of the system (Dolce, 2008; Dolce and Di Bucci, 2015). Some of these Competence Centres are usually present in the DICOMAC to ensure a 24/7 technical and scientific support to emergency management. It was the case also after the Amatrice earthquake, the first mainshock of the 2016-2018 central Italy seismic sequence [Dolce and Di Bucci (2018); see Table 1 for the parameters of the mainshocks].

The initial proposal included, along with DPC, the Consiglio Nazionale delle Ricerche - Istituto di Geologia Ambientale e Geoingegneria (hereafter CNR-IGAG), the Istituto Superiore per la Protezione e la Ricerca Ambientale - Servizio Geologico d'Italia (hereafter ISPRA) and INGV, because these Competence Centres have more than others expertise in geology and earthquake geology. It was essentially an invitation for a collaboration to realise a geological and

Table 1 - 2016-2018 central Italy seismic sequence: earthquakes with moment magnitude $M_W \geq 5.0$ (data from INGV; http://cnt.rm.ingv.it/).

yyyy-mm-dd	Time CET	M_W	Zone	Depth (km)	Latitude N	Longitude E
2016-08-24	03:36:32	6.0	1 km W Accumoli (RI)	8	42.70	13.23
2016-08-24	04:33:28	5.3	5 km E Norcia (PG)	8	42.79	13.15
2016-10-26	19:10:36	5.4	3 km SW Castelsantangelo sul Nera (MC)	9	42.88	13.13
2016-10-26	21:18:05	5.9	3 km NW Castelsantangelo sul Nera (MC)	8	42.91	13.13
2016-10-30	07:40:17	6.5	5 km NE Norcia (PG)	9	42.83	13.11
2017-01-18	10:25:40	5.1	3 km NW Capitignano (AQ)	10	42.55	13.28
2017-01-18	11:14:09	5.5	2 km NW Capitignano (AQ)	10	42.53	13.28
2017-01-18	11:25:23	5.4	3 km SW Capitignano (AQ)	9	42.50	13.28
2017-01-18	14:33:36	5.0	2 km N Barete (AQ)	10	42.47	13.28

seismotectonic characterisation of the crustal volume hosting the seismic sequence. Later, the Consiglio Nazionale delle Ricerche - Istituto per il Rilevamento Elettromagnetico dell'Ambiente (hereafter CNR-IREA) was involved too, because of its expertise in satellite interferometry and finite element modelling.

DPC always promotes and supports collaborations among its Competence Centres for civil protection scopes, even more during the emergencies. In this case, the Department played a coordinating role both among the Competence Centres and among them and the Ministry of Economic Development, Eni and Total hydrocarbon exploration and production (E&P) companies.

We notice that private companies, such as the two just mentioned, are part as well of the National Service of Civil Protection inasmuch they serve a purpose that is useful to achieve civil protection aims [art. 13 in D. Lgs. 1/2018 (2018)]. Therefore, Eni and Total, who had worked in the study area mainly during the 1970s and 1980s, were invited by DPC and warmly agreed to contribute to the project by providing a considerable amount of data accompanied by their technical support. Data included seismic reflection profiles, deep well logs, gravity and magnetic data, scientific and technical reports.

All of the involved research institutes made available the contents of their databases in a way compatible to implement the project workflow.

The main goal of the RETRACE-3D project is to build up a high-quality 3D model of the crustal volume affected by the seismic sequence, which accurately defines the three-dimensional subsurface distribution of the geologic units and main faults, including the seismogenic faults.

In the project design, this model was thought to represent both the starting point and a reference for several further applications, which include, among others: i) the possible improvement of velocity models used to locate the seismicity in the crustal volume, ii) the elaboration of dynamic models of the recognised seismogenic faults, based on a multiparametric optimisation of the surface deformations obtained by satellite interferometry analyses, and iii) the detailed definition of the overall subsurface setting down to seismogenic depths and the related seismic wave velocities, to back the seismic input definition for future microzonation studies.

2. Project organization

2.1. Organization

DPC, CNR-IGAG, CNR-IREA, INGV, and ISPRA framed their collaboration into a formal agreement. More than 50 scientists, not only from the mentioned institutes but also from universities associated with them, volunteered to contribute to the project. Therefore, we needed a well-structured organisation to suitably favour collaboration among different research groups with a broad spectrum of expertise. The entire project was implemented voluntarily: although no funds were allocated to finance it, the participant institutions committed their human, instrumental, and data resources to achieve the project goals.

Scientists and DPC experts, appointed by their institutions, formed the working group (Fig. 1a), organised in work-packages (Fig. 1b) and tasks, depending on the expertise. The overall coordination was in charge of four representatives of the institutions, that signed the agreement. A working plan was drafted, including a set of intermediate and final products.

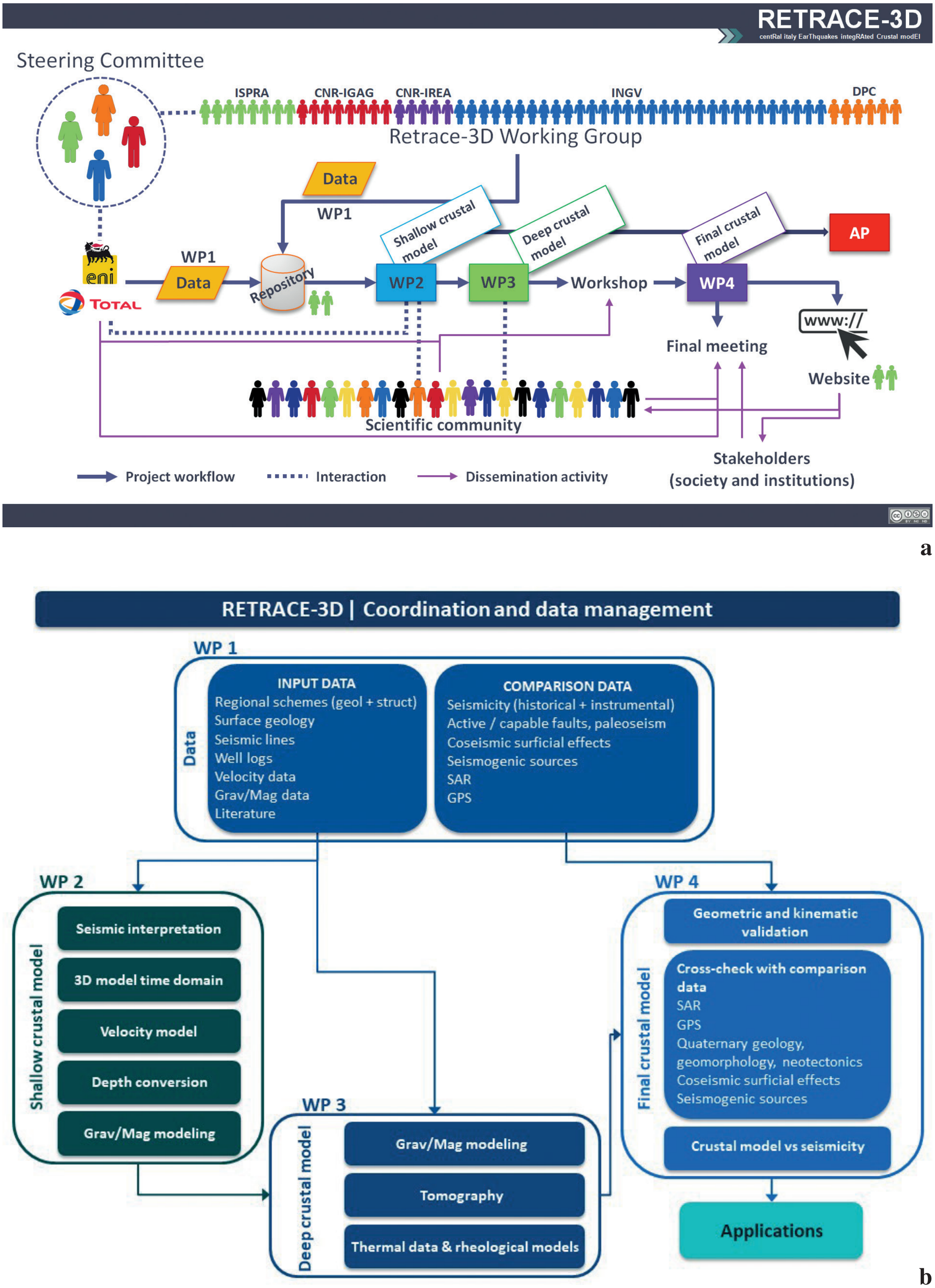

Fig. 1 - RETRACE-3D: a) organisation of the RETRACE-3D working group; b) work-packages and tasks. The overall coordination was in charge of four representatives of the institutions, that signed the agreement.

2.2. Activities and products

The work activities led to the construction of a preliminary 3D crustal model (WP1 and WP2, Fig. 1b), mainly based on seismic reflection profiles and deep well logs interpretation, which also took the surface geology into strong consideration, as well as gravity modelling and gravity map interpretation constraints. A further step was the integration of the preliminary model with independent information coming from Local Earthquake Tomography (LET), thermal and rheological data, gravity and magnetic crustal modelling, which led to the extension at seismogenic depths of the 3D model (WP3, Fig. 1b).

The final step was a geometric and kinematic validation (e.g. balancing and analogical modelling) and a cross-check against comparison data sets (e.g. Synthetic Aperture Radar-SAR, Global Positioning System-GPS, coseismic surficial effects, seismogenic sources characteristics, Quaternary geology-geomorphology-neotectonics, seismic catalogues) not used on purpose during the 3D modelling phases (WP4, Fig. 1b).

The main products are:

- a 3D model of the crustal volume hosting the Amatrice earthquake and the following seismic sequence. This model (i.e. key horizons and faults) is delivered in common ASCII (American Standard Code for Information Interchange) file format through the project webpage (www.retrace3d.it), to be used by the scientific community, and as 3D pdf file format, for a more comprehensive communication;
- deformation maps and dynamic models of the seismogenic faults;
- a report, which illustrates the model content and related information, the constraints and interpretations behind it, including a discussion on the different interpretations considered, and the way to chose the final one.

2.3. Data

The starting point of the project was collecting, harmonising, and sharing data and information, mainly derived from institutional databases of the involved research institutes, in suitable formats, among the participants. Data included geological maps, cross-sections, stratigraphic logs, deep well logs, seismic reflection profiles, gravimetric and magnetic data, bibliographic references.

The project relies on a shared repository, developed and hosted by ISPRA with controlled access for the project participants, where all data and information, as well as official documents, meetings minutes, and reports, are stored and organised. We divided data into two groups: the Input Data to build the 3D model, and the Comparison Data to verify its coherence.

The collection and predisposition of the first group of data, in particular, represented a huge effort. Based on maps available in literature (Servizio Geologico d'Italia, 1941, 1955, 1959, 1963, 1967, 1968a, 1968b, 1969, 1970, 2020a, 2020b; Centamore *et al.*, 1991, 1992a, 1992b; Servizio Geologico d'Italia - ISPRA, 2011; Pierantoni *et al.*, 2013), an *ad hoc* geological map (Fig. 2a) and a tectonostratigraphic model were prepared. Here, the stratigraphic units (Fig. 2b), describing crucial steps in the evolution of the area, have been summarised and harmonised to support the well logs and seismic profiles interpretation, therefore keeping in mind the most recognisable seismic facies and reflectors. ISPRA led this activity.

The preparation of the subsurface data set was quite demanding. Just to mention one criticality that we solved, the integration of data coming from different oil companies, acquired dozens of years ago, poses problems of datum plane alignment. Moreover, data have been provided

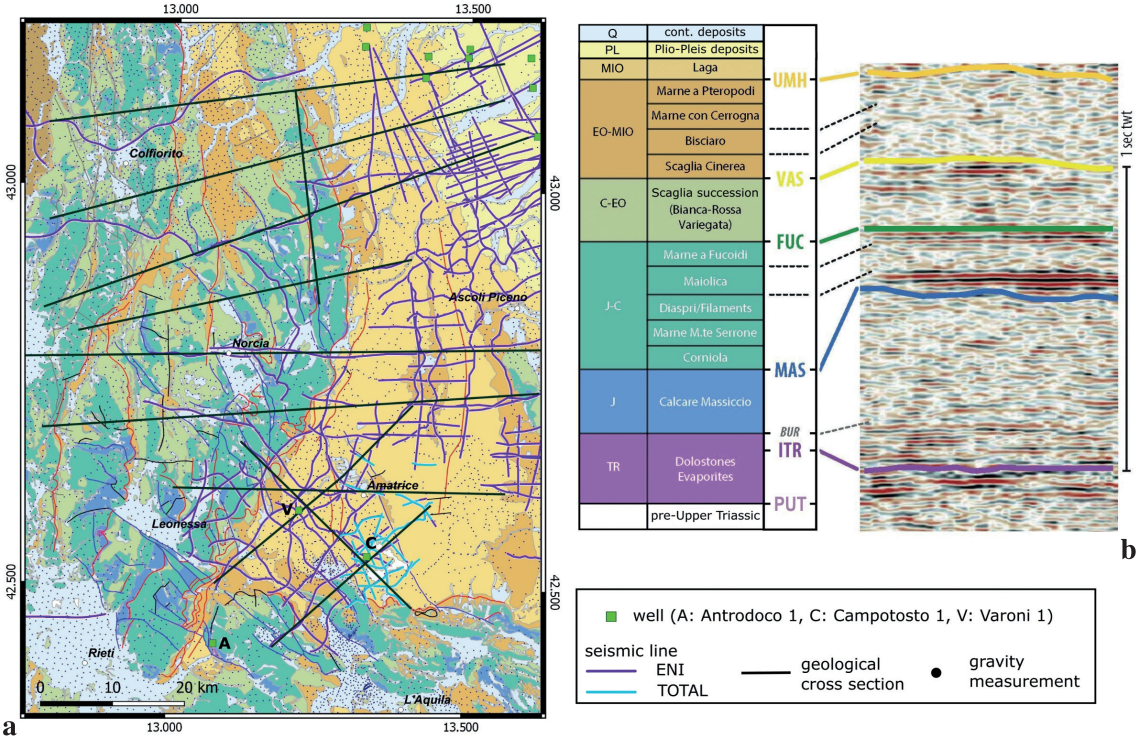

Fig. 2 - a) Geological scheme and full data set used in the RETRACE-3D project. b) Stratigraphic units, corresponding to key reflectors and related signature in seismic profiles.

on paper, as digital raster or in vector format. We acquired and fixed all of them to interpret these data within a 3D workspace by using different software packages, such as Move (https://www.petex.com/products/move-suite/move/) and Petrel E&P software platform (https://www.software.slb.com/products/petrel). This activity was jointly carried out by CNR-IGAG, INGV, and ISPRA.

The Input Data also included velocity data, analysed to provide a velocity model to be applied for time-depth conversion; this activity was carried out by INGV.

Finally, as mentioned before, a variety of data sets were used only after the 3D model completion, in order to compare it with independent information.

We remark that the public-private partnership that characterises the RETRACE-3D project also relies on the fact that confidentiality agreements signed by each participating research institute cover the data provided by Eni and Total. Only the researchers mentioned in the agreements were allowed to enter the repository folders where these data were stored.

3. Geological framework of the study area

The study area lies within the Apennines fold-and-thrust belt of peninsular Italy, which forms part of the Africa-verging mountain system in the Alpine-Mediterranean region. In particular, the Meso-Cenozoic sedimentary successions of the central Apennines belong to the paleogeographic domains developed since the Triassic along the southern passive margin of the Neotethys Ocean. In the area of interest for this study, the most relevant paleogeographic domains are the Latium-Abruzzi Carbonate Platform and the Umbria-Marche Pelagic Basin, the latter including basin-platform transition and Jurassic intrabasinal structural highs, bounded by normal faults that formed in Early Lias and conditioned the next Mesozoic basinal sedimentation (among many others: Parotto, 1980; Koopman, 1983; Lavecchia, 1985; Bally *et al.*, 1986; Centamore *et al.*, 1992a, 1992b; Damiani *et al.*, 1992; Vezzani *et al.*, 1998; Cosentino *et al.*, 2010; Bigi *et al.*, 2013; Pierantoni *et al.*, 2013; Scisciani *et al.*, 2014; and references therein).

Within the framework of the slow convergent motion between the African and European plates, the thrusting process then involved these Meso-Cenozoic sedimentary successions. It happened when the eastward retreat of the Apennines west-directed subduction zone caused the progressive migration of the related accretionary prism from west to east (e.g. Malinverno and Ryan, 1986; Patacca and Scandone, 1989; Doglioni *et al.*, 1999; Carminati *et al.*, 2004).

Since Middle Miocene, the central Apennines underwent a compressional phase characterised by a mainly E- to NE-directed thrusting and associated foredeep/thrust-top basin sedimentation and flexural (mostly Miocene) normal faulting. This tectonic wave progressed towards the Adriatic coastline, where contractional deformations are presently still active (e.g. Patacca *et al.*, 1990; Cosentino *et al.*, 2010; DISS Working Group, 2018). Miocene and Pliocene hemipelagic, evaporitic, and turbiditic sediments deposited on top of the Mesozoic-Paleogene marine successions.

Thrust sheets involving Meso-Cenozoic, mostly carbonate marine successions characterise the study area (Deiana and Pialli, 1994). The pre-thrusting Mesozoic and Cenozoic normal faults were detached from their substratum and passively transported within these thrust sheets that are now piled in the Apennines stack (e.g. Di Francesco *et al.*, 2010; Casero and Bigi, 2013; Scisciani *et al.*, 2014).

Several alternative hypotheses have been proposed concerning the tectonic style of the Apennines, ranging from thin- to thick-skinned with different amounts of basement involvement and shortening (e.g. Bally *et al.*, 1986; Ghisetti *et al.*, 1993; Barchi *et al.*, 1998; Coward *et al.*, 1999; Butler *et al.*, 2004; Tavarnelli *et al.*, 2004; Scrocca *et al.*, 2005; Cosentino *et al.*, 2010; Scisciani *et al.*, 2014; Bonini *et al.*, 2016, 2019; Porreca *et al.*, 2018).

Thrust accretion across the Adriatic continental margin was then followed by extensional faulting, which progressively cross-cut the thrust pile, affecting the core of the central-northern Apennines since Pleistocene (e.g. Barchi *et al.*, 1998; Cavinato and De Celles, 1999; Galadini, 1999; D'Agostino *et al.*, 2001). Extensional tectonics is still active in the axial ridge of the Apennines, where it is responsible for the main seismicity of the area (e.g. Barchi *et al.*, 2000; Chiarabba *et al.*, 2009; Montone and Mariucci, 2016; Chiaraluce *et al.*, 2017; Guidoboni *et al.*, 2018, 2019; Rovida *et al.*, 2019, 2020; Chiarabba *et al.*, 2020). High-angle, mainly W-dipping, active normal faults likely interact with deep parts of pre-existing faults, possibly reactivated within the current extensional regime (Calamita *et al.*, 2011; Scisciani *et al.*, 2014; Pizzi *et al.*, 2017; Buttinelli *et al.*, 2018; Scognamiglio *et al.*, 2018). The whole thrust pile seems to be floored by a low-angle E-dipping normal fault or detachment level at a regional scale (Barchi *et al.*, 1998; Boncio *et al.*, 2000; Chiaraluce *et al.*, 2017; Lavecchia *et al.*, 2017).

4. Results

The 3D geological model of the area hosting the 2016-2018 central Italy seismic sequence has been completed in detail down to a depth of about 12 km, while extended down to the Moho based on regional-scale information (e.g. Piana Agostinetti and Amato, 2009). The model was developed initially in Two Way travel Time (TWT) as a direct result of the interpolation of 2D seismic profiles interpretation. The depth conversion was, then, carried out based on a careful review of rock seismic velocities obtained by the analysis of well log data, compared with literature information (Barchi *et al*., 2012; Scisciani *et al*., 2014; Montone and Mariucci, 2015, 2020; Latorre *et al*., 2016).

The interpretation of the seismic profiles was also constrained by data from Varoni-1 and Campotosto-1 exploration wells drilled in the area (see Fig. 2 for location), as well as by surface data coming from the geological survey carried out by the Servizio Geologico d'Italia. Data acquired during recent field surveys for the Geological Map of Italy 1:50,000 [Foglio 348 Antrodoco and Foglio 337 Norcia: Servizio Geologico d'Italia (2020a, 2020b)], along with *ad hoc* surveys for specific key sites, allowed the fault displacements at the surface to be constrained for different periods through accurate stratigraphic and tectonic analyses. Geologists from all the scientific institutes involved in the project participated in the *ad hoc* surveys.

The north-western area, which hosts the Mount Vettore fault system, located at the Sibillini Thrust hanging-wall, is unfortunately crossed by few seismic profiles (Fig. 2). Although these seismic profiles provide some information on the relationships between high angle faults and thrusts at depth, we modelled the 3D key surfaces based mainly on geological cross-sections. On the contrary, a more dense grid of seismic profiles covers the central and southern areas; thus the 3D key surfaces from the infra-Triassic deposits up to the top of the Miocene siliciclastic foredeep succession have been mapped with unprecedented detail. In the model, these surfaces correspond to the infra-Triassic marker (ITR), the Jurassic top-Massiccio limestone (MAS), the Cretaceous top-Fucoidi marl (FUC), the Cretaceous-Eocene top-Scaglia limestone (VAS), and the Miocene bottom-Laga siliciclastic deposits (UMH, Figs. 2 and 3).

Moreover, we reconstructed the 3D geometry of several principal faults. These faults include: i) Mesozoic extensional faults, controlling the formation of pelagic basin and carbonate platform domains; ii) Miocene normal faults, formed during the flexural stage of the foreland, or inherited from previous tectonic phases and reactivated in this epoch; iii) thrust faults responsible for the build-up of Apennines fold-and-thrust belt; and iv) Quaternary/active normal faults, both newly formed and reactivated, being inherited from previous tectonic regimes.

The 3D model resulting from these activities is a comprehensive and consistent representation of the complex geology of this sector of the Apennines, allowing for a full 3D analysis of the relationship between extensional and thrust faults.

The primary outcomes of this analysis can be summarised as follows:

1) the tectonic stack forming this part of the Apennines chain is mostly due to the superposition, repeated at least three times, of the Meso-Cenozoic stratigraphic succession that characterises the study area. It possibly includes part of the Permo-Triassic succession at the bottom, for a total thickness of about 10 km. Below the Meso-Cenozoic succession, we recognised high reflectivity layers that we ascribed to a thick sedimentary succession that is part of the Permo-Triassic units. The interpretation of the seismic profiles highlights

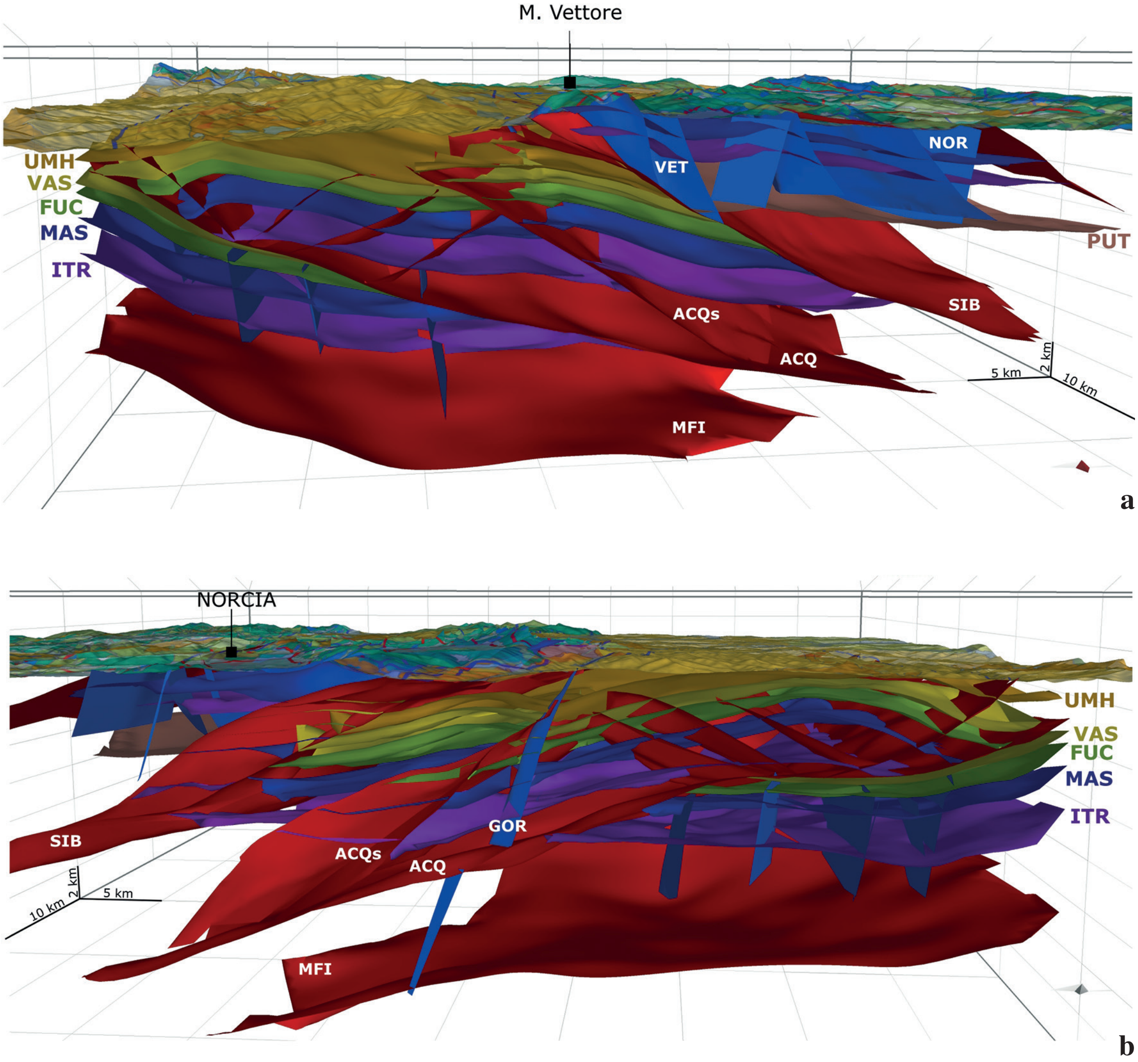

Fig. 3 - Excerpts from the 3D model: a) view from the north; b) view from the south. See Fig. 2 for horizon codes. Thrust systems: SIB - Sibillini, ACQ/ACQs - Acquasanta, MFI - Montagna dei Fiori. Normal fault systems: VET - Mount Vettore, NOR - Norcia, GOR - Gorzano.

the involvement of these deposits within the thrust pile. Later, some of the related thrust faults could have experienced negative tectonic inversion;

2) the development and reactivation of normal fault systems, both at depth and surface, as well as the reactivation of thrusts at depth, is quite complex to be fully unravelled. At depth, we mainly observe inherited normal faults, which either remain confined within single thrust sheets or are segmented through more than one thrust sheet. Throughout the whole study area, the normal faults are organised in a recurrent structural pattern, characterised by the juxtaposition of deep and confined inherited faults with both deeper and shallower normal faults. Some of the latter faults are well exposed at surface and develop down to the very first few kilometres of the crust, showing evidence of having been transported into

the sizeable regional thrust sheets. The occurrence of normal faults cut by thrust faults is a recurrent feature in the study area;

3) the total amount of displacement observed on all these normal faults, both at surface and depth, is strictly related to the age of inception of fault activity. In some cases, due to syn-sedimentary activity of the fault, it has been possible to discriminate the Mesozoic displacement from the Miocene and Quaternary ones. In particular, according to surface stratigraphic data, some of these faults follow Mesozoic paleogeographic boundaries such as the transition between pelagic carbonate platforms and basins (Santantonio, 1993, 1994). They show a prevalent Mesozoic and possibly Miocene activity, whereas minor activity occurred during the Quaternary. A more detailed reconstruction of each fault geometry and its Quaternary displacement rate is essential to carry out a reliable assessment of the seismic potential of that fault;
4) the comparison between seismicity and the identified structural pattern sheds new light on the interpretation of the fault architecture in the study area. It is especially true when trying to relate coseismic displacement detected on exposed shallow portions of faults (e.g. Villani *et al.*, 2018) with alignments of hypocentres observed at depth (e.g. Chiaraluce *et al.*, 2017; Improta *et al.*, 2019; Michele *et al.*, 2020). Intriguingly, many of the faults reconstructed in the 3D model correspond to trends of seismicity distribution.

To obtain a broader perspective, crustal sections based on anomalies of potential fields (gravity data: courtesy of Eni, ISPRA and CNR-IGAG - ISPRA reprocessed the whole data set; magnetic data: of courtesy Eni; Fig. 2) have been drafted to explore the crustal setting down to the Moho, which has also been constrained taking into account the results of other geophysical studies (e.g. Chiarabba *et al.*, 2005; Piana Agostinetti and Amato, 2009; Di Stefano *et al.*, 2011; Carannante *et al.*, 2013).

We finely tuned some details of the 3D reconstruction and integrated into the model some general information on the deeper part of the crust. We then checked the model with independent data, acquired at the beginning of the activity but not used to implement the model. In particular:

- the seismicity distribution within the modelled crustal volume, acquired or relocated using the INGV national seismic network observations (Chiaraluce *et al.*, 2017; Improta *et al.*, 2019; Michele *et al.*, 2020);
- the surface deformation associated with the central Italy 2016-2018 main shocks (Table 1), provided by DinSAR and GPS data and analyses (Lavecchia *et al.*, 2016; Cheloni *et al.*, 2017, 2019);
- the surface distribution of coseismic effects along several fault splays and secondary fractures activated by the considered seismic sequence (EMERGEO Working Group, 2016; Civico *et al.*, 2018; Villani *et al.*, 2018).

The final results listed in the agreement are publicly available on the project website: http://www.retrace3d.it/.

Following the model completion, future activities derived from the RETRACE-3D project envisage, among others: i) the implementation of a finite elements geo-mechanic model, to test from a dynamic point of view the coherence of the 3D static model in terms of stress and strain propagation through space and time; ii) the relocation of the 2016-2018 central Italy seismic sequence hypocentres using geometry and velocity distribution from the RETRACE-3D model.

This relocation would allow checking the discrepancies with the best relocation available, but based on models that do not take into account the geological setting of the crustal volume hosting the earthquakes; and iii) the development of detailed models of the shallower geological deposits in the Amatrice area for defining the seismic input in the microzonation studies.

Further analysis could be carried out on the different processes that may or may not contribute to the surface deformation, such as primary faulting or gravitative ground motion (EMERGEO Working Group, 2016; Huang *et al.*, 2017; Civico *et al.*, 2018; Villani *et al.*, 2018; Di Naccio *et al.*, 2019; Delorme *et al.*, 2020).

5. Discussion

The RETRACE-3D project focused on the revision of all the available geological and geophysical data in the area interested by the 2016-2018 seismic sequence of central Italy, with the final aim to reconstruct a reliable and consistent 3D geological model of that area. This challenging task was fundamental since a comprehensive geological model and a robust 3D picture of the crust, in particular the shallow crust, of those areas were lacking. From the very first days of the seismic sequence, it was somewhat clear that a certain degree of difficulty would have been experienced by the entire scientific community when trying to relate the structures at the surface with the alignments of seismicity observed at depth.

As stated at the beginning of this paper, the reason why we are presenting this work is two-folded. Besides showing the methodological approach and the main project results, we would also stimulate a fruitful discussion within the journal audience, which broadly represents our scientific community.

We would stress, in particular, some elements that we consider strength points, concerning:

1. the need to achieve shared products;
2. the involvement of a broad geological and geophysical community, represented by three among the leading Italian research institutes and associated academic scholars. All these contributors started from different viewpoints, both for cultural background and scientific expertise, and, therefore, they reciprocally provided constraints for the model interpretation;
3. the decision to address more than one interpretation model to produce, on one side, a final consensus model that is based on contributions accepted by all and, on the other side, to leave the floor to different interpretations, especially (but not only) where constraints are not enough. The numerous researchers agreed to confront each other to reach a shared final model;
4. the commitment to interact with that part of our scientific community that was not involved in the project but it is working on the same topic (for instance, we organised a workshop at the end of 2018, and we presented intermediate results during congresses).

Concerning points 1 and 2, we have to consider that we conceived the project in a civil protection framework, where the decision-makers need to rely on scientific products that “have reached a level of progress and consensus recognised by the scientific community” (D. Lgs. 1/2018, 2018). Scientists do have to conduct scientific discussions, of course, but the final product has to be one and the best on which a scientific agreement can be reached. Therefore, the broader is the involved scientific community, and the higher is the value of the final product.

This approach implies that different research groups may develop different interpretation models, which represent a desirable starting point. These models might have parts in common and parts less constrained that, therefore, can differ among them. For instance, in our case, the quality and number of the reflection seismic lines are lower in the north-western part of the study area and higher in the eastern and southern ones. This occurrence can leave room for different interpretations where, for instance, there are few constraints, and there is a broader uncertainty about the position of some key horizons, the thickness of some stratigraphic units, or the geometry of faults from the surface to depth. In any case, the work confirmed once again the need for a 3D approach, especially in areas with a highly non-cylindrical structural setting, to fully capture the existing tectonic complexity avoiding possible misinterpretations caused by a simplified approach. As summarised in point 3, the final model is an integration of the common parts of the different models, whereas the rest of the interpretations remains separated and will hopefully represent the inception of future scientific reasoning.

As regards the aims summarised in point 4, since the beginning of the activity we established that, once we had reached a sufficient level of confidence on interpretation models and limits of our information, we would open the discussion to other scientists who are working on the same issues and are willing to share comments, critical observations, and interpretative ideas reciprocally. We are aware of the limits of our work, mainly because data have been acquired for different aims (mostly hydrocarbons exploration), and they are not homogeneously distributed in the study area. Nevertheless, due to the complete 3D analysis of all the available data and to the check of some geological key points in the field, we consider the result obtained to be entirely satisfactory considering the available data. Therefore, we think that the remarkable effort made by all the participants represents a real added value to the final model, especially considering that no budget was allocated for further data acquisitions or analyses. Although uncertainties accompany our results, we believe that the RETRACE-3D project has obtained original results that shed new light on some significant elements regarding the seismotectonics of the study area.

In addition to the scientific results, the value of the collaboration and its potential future prospects, there is an achievement of RETRACE 3D that we want to emphasise. Rarely such high-quality data sets, significant expertise level, and integration of information and multidisciplinary know-how were made available to study an area like the one hit by the 2016-2018 central Italy seismic sequence. This achievement represents a key point that one should consider for other analogous cases that may happen on the Italian territory.

For instance, consider the following questions:

- which kind of relationship may exist between faults at the surface and at depth, where large earthquakes are mostly generated?
- how much a simplified location of the hypocentres differs from a location based on a 3D tectonic model?
- what pre-existing faults (if any), inherited from previous tectonic regimes, maybe reactivated or not in case of major seismic events?

Answering these questions allows considering a wide range of geological/seismological uncertainties that one may take into account, especially during the first phases of an analogous seismic crisis. Keeping in mind the uncertainties that accompany the available scientific knowledge is fundamental from a decision making perspective, because it helps to understand better, the event scenario decision-makers are dealing with.

6. Final remarks

To conclude, we would finally mention the social value of this kind of work that one might think exceeding its scientific value. People who freely decided to participate in this project were aware of being part of the National Service of Civil Protection, thus serving the Italian system of civil protection. They have put passion and knowledge for a goal that was not only scientific. Intriguingly, the research institutions joining the RETRACE-3D project have decided to work together forming a network precisely as indicated by the Italian law, which states that "the DPC coordinates the activity to establish networks of Competence Centres aimed at developing specific topics on integrated issues and in multi-risk perspective" [art. 21 in D. Lgs. 1/2018 (2018)].

As above mentioned, the idea of the RETRACE-3D project was born during a seismic emergency. For this reason, we conceived the structure of the project as easily reproducible and, therefore, it represents a successful working scheme that one can rapidly activate in case of similar emergencies. As an example, in case of a seismic crisis in areas where subsurface data are usually not public, they might be rapidly released and made available thanks to ongoing collaboration between governmental administrations, research institutions, and private companies. We think that such a scheme could be put in place for any future seismic emergency, establishing a strong collaboration among research institutes, each having yet an individual role and relationship with the Italian DPC. Moreover, this experience and the applied methodology could be easily adopted also in ordinary times, to study some key areas of potential interest in terms of seismic scenarios (e.g. referred to active faults not related to any earthquakes, or historical earthquakes without seismotectonic characterisation). For instance, ad hoc projects could be promoted and funded to apply this approach in specific areas that are known to be exposed to a high seismic hazard, to be prepared in advance with well-constrained geological models that support more reliable inferences regarding faults activation and related hazard.

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