Geological map, balanced and restored cross-sections, and 3D geological model of the Monte Fema area, Umbria-Marche Apennines (Italy)

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ABSTRACT

The Mt. Fema area is located within the 1:50,000 scale Sheet 325-Visso of the CARG project, in the Umbria-Marche Apennines. Here, inherited pre-orogenic deformation and multi-layered mechanical stratigraphy affect mountain belt evolution and cause along- and across-strike changes in structural architecture. Further complexity is caused by post-orogenic extensional tectonics dissecting the fold and thrust belt. In this work, we combined classical field methodologies with digital mapping and drone surveys to produce a 1:10,000 geological map of the Mt. Fema area. The resulting map was integrated with a 10 m-cell size DEM in a 3D environment to construct four balanced cross-sections that were used to document structural style and stratigraphic variations. One section was restored to quantify the amount of deformation related to both Neogene orogenic shortening and multiple extensional phases affecting the area. Ultimately, we built a 3D geological model to investigate the subsurface geometrical arrangement of strata and faults of different generations, thus the overall structural architecture of the fold and thrust belt. According to our interpretation, the Mt. Fema thrust system is characterised by relatively limited displacement (cumulative dip separation ranging from ~100 m to the north in Val di Tazza to ~500 m to the south in Valnerina). Reactivation of inherited normal faults was likely precluded because of their unfavourable orientation with respect to W-dipping thrusts. Inherited basin structure and mechanical stratigraphy govern folding by buckling mechanism, which in turn controls the locus of thrust propagation. Normal faults dissect the crestal region of the Mt. Fema anticline. These structures do not show evidence of surface faulting during recent seismic sequences, although earthquake epicentres fall within the study area. Our work provides new insights into the 3D structural architecture, timing, and kinematics of a key sector of the Umbria-Marche Apennines, with implications for a better understanding of the role of structural inheritance and subsequent extensional tectonics in the evolution of fold and thrust belts.

KEY-WORDS: balanced geological sections, fold and thrust belts, 3D model, Northern Apennines, extensional faulting.

INTRODUCTION

The study of orogenic systems can shed light on their dynamics and evolution by examining the modes and timing of development of fold and thrust belts (Coward, 1983; Davis et al., 1983; Butler & Mazzoli, 2006; Poblet & Lisle, 2011; Lacombe & Bellahsen, 2016; Pfiffner, 2017; Butler et al., 2018). Since the early 1900s, our understanding of orogenic systems has evolved from detailed surface investigations (i.e., classical geological mapping, structural, stratigraphic, and sedimentological analyses) to incorporating subsurface data through geophysical surveys (e.g., Bally et al., 1986; Coward et al., 1999; Mele & Sandvol, 2003; Sepehr & Cosgrove, 2004; Calamita et al., 2012; Butler et al., 2018). However, subsurface data in fold and thrust belts is often incomplete due to difficulties in seismic acquisition and interpretation, as well as limited deep well data. These limitations commonly result in gaps in cross section interpretations, leading to uncertainty in tectonic styles and evolutionary scenarios (e.g., Tozer et al., 2002; Shiner et al., 2004; Butler et al., 2006, 2018). Alternative techniques or methodological approaches have been developed to address these limitations and reduce uncertainty in the interpretations. Deformation history of fold and thrust belts is typically reconstructed using analogue models, balanced geological sections, and numerical models. These approaches focus mainly on the amounts, modes, and shortening rates through time. The development of the step-by-step evolution of orogenic wedges through balancing and restoration techniques started with Chamberlin (1910). Advances have been made through multiproxy-based computer simulations (e.g., Schönborn, 1999; Tozer et al., 2002; Watkins et al., 2014; Jourdon et al., 2014; Tavani et al., 2018; Balestra et al., 2019) and laboratory analogue modelling (e.g., McClay, 1995; Bellahsen & Daniel, 2005; Di Domenica et al., 2014; Santolaria et al., 2022), making balancing and restoration techniques faster and more precise. However, most of these efforts are limited to 2D reconstructions that do not fully capture the geometry of the orogenic belt and the shortening rates and structural style variations along the strike of the domains (e.g., Mazzoli et al., 2005; King et al., 2010; Caricchi et al., 2015; Castelluccio et al., 2016; Molli et al., 2018; Heydarzadeh et al., 2022).

This paper focuses on the Apennines fold and thrust belt, where several complexities hinder the understanding of its geometric and kinematic evolution, such as (i) across- and along-strike changes in structural style, (ii) inherited pre-orogenic deformation along with facies differences and lateral thickness variations affecting the belt evolution, and (iii) post-orogenic extensional tectonics dissecting the fold and trust belt structure (e.g., Calamita et al., 1994; Coward et al., 1999; Marchegiani et al., 1999; Deiana et al., 2002; Mazzoli et al., 2002, 2005; Butler et al., 2004, 2006; Bigi & Costa Pisani, 2005; Scisciani, 2009; Tavarnelli et al., 2019). In the Apennines, however, detailed balanced (and restored) cross-sections are limited so far (Lavecchia, 1979; Barchi et al., 1988; Mazzoli et al., 2005; Santini et al., 2021), as are also 3D models depicting the (local) structural architecture (Borraccini et al., 2004), since existing models are commonly of regional significance (Barchi et al., 2021; Di Bucci et al., 2021).

This study aims to investigate the structural style, timing, and amount of deformation occurring from the Pliocene to Present in the Mt. Fema area (Umbria-Marche Apennines), within the 1:50,000 scale geological Sheet 325-Visso of the Italian CARG (Geological CARtography) project (Fig. 1). We integrate classical field methodologies with digital mapping and drone surveys to define the local stratigraphic and structural framework and to create a geological map. The amount of deformation related to both contractional and multiple extensional regimes (pre- and post-thrusting) acting in the area was quantified through the restoration of balanced geological cross-sections. Ultimately, the overall structural architecture was investigated through the construction of a detailed 3D geological model. Our results provide new insights into the three-dimensional structural architecture of a sector of the Umbria-Marche Apennines, with particular emphasis on the role of structural inheritance and subsequent extensional tectonics in the evolution of fold and thrust belts.

GEOLOGICAL BACKGROUND

The Apennines are an arc-shaped fold and thrust belt characterised by a series of NW-SE trending and NE-verging asymmetric folds bounded by thrusts (Fig. 1). The evolution of the Apennines orogenic wedge followed the orogenic collapse of the Alpine belt of Corsica that formed during the Late Cretaceous to Late Eocene collision between Adria microplate (African plate) and Europe. From the Oligocene onwards, the rollback of the Adriatic slab triggered the fragmentation of the European continental margin with the formation of back arc basins and the drift of continental blocks (e.g., Corsica-Sardinia block). The progressive E-NE migration of the Apennines thrust front above foredeep deposits (Ricci Lucchi, 1975) is followed by extensional exhumation in the internal region since the Miocene. A slab rollback - upper (Tyrrhenian) plate retreat model has been invoked to explain the contemporaneous crustal shortening, in the mountain front, and extension, in the inner portion of the chain (e.g., Elter et al., 1976; Malinverno & Ryan, 1986; Royden, 1988; Faccenna et al., 1996; Vai & Martini, 2001; Marroni et al., 2017).

The crustal shortening shaping the fold and thrust belt has started during the Late Oligocene and, nowadays, has migrated toward NE in the external sectors of the orogen and the adjacent foreland (Calamita et al., 1994; Coward et al., 1999; Di Bucci & Mazzoli, 2002; Scrocca et al., 2007; Bonini et al., 2014; Mazzoli et al., 2015; Antonellini et al., 2020; Pezzo et al., 2020). The orogenic stage has been preceded by multiple phases of normal faulting: (i) Jurassic rift-related extensional tectonics affecting the passive (Adria) continental margin (e.g., Marchegiani et al., 1999; Tavarnelli et al., 2019), (ii) Cretaceous-Eocene syn-sedimentary faulting, and (ii) Miocene pre-thrusting normal faulting induced by the Neogene flexure of the foreland (Apulian) plate (e.g., Deiana et al., 2002; Mazzoli et al., 2002). The post-orogenic extensional regime has established since Late Miocene and is responsible for the presently active normal faulting affecting the axial zone of the chain (e.g., Cello et al., 1997; Barchi et al., 2000; Tondi & Cello, 2003; Pondrelli et al., 2006; Mariucci & Montone, 2020). Here, instrumental and historical seismicity is characterised by moderate to strong earthquakes (http://cnt.rm.ingv.it; Rovida et al., 2022). Several normal-faulting seismic sequences recently struck the Umbria-Marche Apennines, i.e., Colfiorito 1997 - Mw 6.0 - and Gualdo Tadino 1998 - Mw 5.3 - (Cello et al., 2000; Deschamps et al., 2000; Vittori et al., 2000; Chiaraluce et al., 2003; Barchi & Mirabella, 2009) and Central Italy 2016 (Mw 6.5; Chiaraluce et al., 2017; Galli et al., 2017; Civico et al., 2018; Villani et al., 2018).

Stratigraphy

The Umbria-Marche stratigraphic succession (Fig. 2) consists of Mesozoic-Paleogene sedimentary units deposited above the basement of the Adria plate, i.e., crystalline basement and overlying Permo-Triassic continental siliciclastic deposits commonly referred to as ‘Verrucano’ (VRR). The latter is constituted by sandstones and phyllites (Aldinucci et al., 2008; Cassins et al., 2018). Neither these units crop out in the study area, but they are documented in the surrounding areas and through seismic studies and deep wells

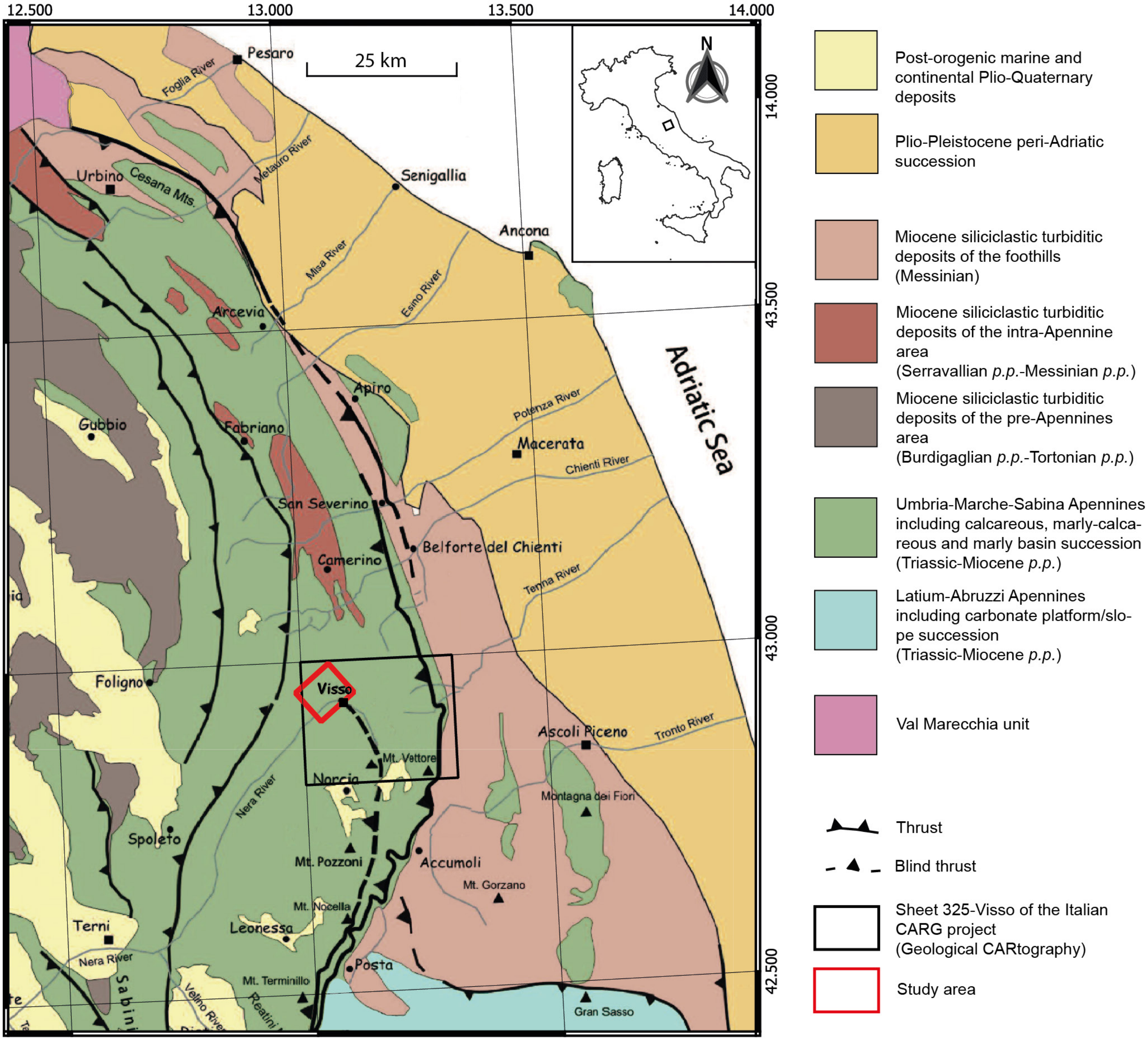

Fig. 1 - Geological sketch map of the Umbria-Marche Apennines (modified after Pierantoni et al., 2013). Black and red boxes show location of Sheet 325-Visso of the geological map of Italy and the study area, respectively.

(Boccaletti et al., 1969; Trevisan et al., 1971; Anelli et al., 1994; Mele & Sandvol, 2003). The deformed passive margin succession includes Upper Triassic evaporites (referred to as Anidriti di Burano, BUR) and a Jurassic-Oligocene carbonate multilayer consisting of shallow water carbonate platform deposits and of calcareous-marly pelagic basin units. Anidriti di Burano is mostly made of anhydrites and dolostones and, subordinately, limestones and marls. The calcari e marne a *Rhaetavicula Contorta* fm. (RET, Norian *p.p.* - Rhaetian) commonly mark the passage with the overlying carbonate multilayer, and they are constituted by alternating black limestones and marls. Calcare Massiccio (MAS, Hettangian – Pliensbachian *p.p.*) is mainly constituted by c. 800 m-thick massive white limestones and represents a peritidal platform developing in a shallow water environment (Centamore et al., 1971; Pierantoni et al., 2013).

Extensional faulting during the Sinemurian age fragmented the Jurassic depositional environment in structural highs (i.e., PCP, Santantonio, 1993, 1994) and lows (i.e., basin). This morphotectonic setting induced the deposition of three different types of (pelagic) successions: (i) condensed, (ii) complete, and (iii) composite (Colacicchi et al., 1970; Centamore et al., 1971; Deiana et al., 2002; Pierantoni et al., 2013). The *complete succession* is calcareous-siliceous and continuous, and generally onlap Jurassic fault scarps. It consists of several units deposited from the Sinemurian *p.p.* to Tithonian age. Corniola (COI) is the oldest in the complete succession (Sinemurian *p.p* – Toarcian *p.p.*), and it consists of grey to dark brown micritic limestones with nodules of white and grey chert. Its thickness is highly variable, ranging from a few tens of metres to 500-600 m (in the Mt. Vettore

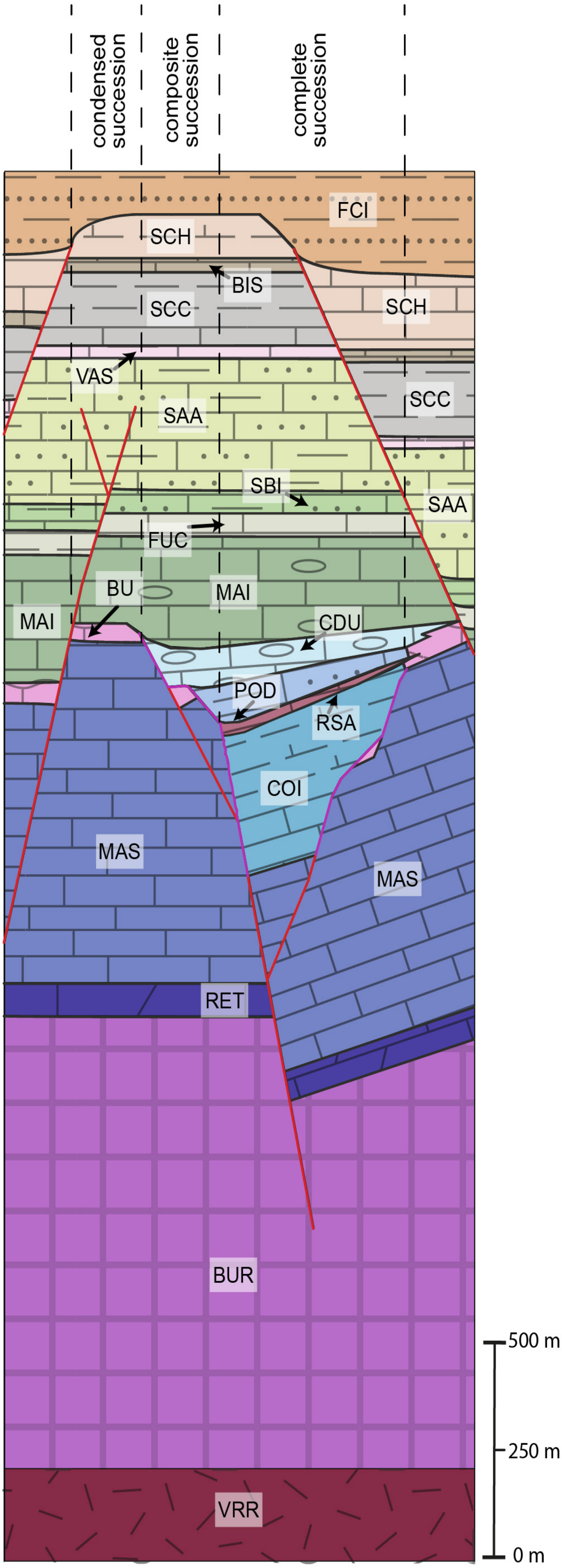

Fig. 2 - Stratigraphic scheme of the Umbria-Marche succession showing the complete, condensed, and composite successions (modified after Pierantoni et al., 2013). Red lines represent faults related to multiple phases of extension; purple lines are Jurassic fault scarps. Stratigraphic units are identified according to the following abbreviations (Cita et al., 2007): VRR, 'Verrucano'; BUR, Anidriti di Burano; RET, calcari e marne a Rhaetavicula Contorta fm.; MAS, Calcare Massiccio; COI, Corniola; RSA, Rosso Ammonitico; POD, Calcari e Marne a Posidonia; CDU, Calcari Diasprigni; BU, Bugarone Group; MAI, Maiolica; FUC, Marne a Fucoidi; SBI, Scaglia Bianca; SAA, Scaglia Rossa; VAS, scaglia variegata fm.; SCC, Scaglia Cinerea; BIS, Bisciaro; SCH, Schlier; FCI, Camerino fm.

area; Pierantoni et al., 2013). This is overlain by Rosso Ammonitico (RSA), which is made by 25-40 m-thick, dark red, pink, or green nodular limestones and marly limestones deposited during the Toarcian age. Next, there is Calcari e Marne a Posidonia (POD), which is constitute of brown limestones and marly limestones (Toarcian *p.p.* – Bajocian *p.p.*). Its thickness ranges from a few tens of metres to 150-200 m. The complete succession ends with Calcari Diasprigni (CDU, Bajocian *p.p.* - lower Tithonian), made by green siliceous calcilutites alternated with green cherts and few marly levels. The complete succession may be thicker than 400 m (Chiocchini et al., 1976; Pierantoni et al., 2013). The *condensed succession* is predominantly calcareous and discontinuous and consists of only the Bugarone Group (BU, Lower Pliensbachian - Lower Tithonian) that was deposited directly above Calcare Massiccio. It is made of grey, brown, or pink nodular limestones and marly limestones. The deposition of the condensed succession occurred on the PCPs and on the submarine palaeo-escarpments in the form of epi-escarpment deposits (Santantonio et al., 1996) resting unconformably on the horts-block Calcare Massiccio, and being unconformably overlain by the Sinemurian-to-Thithonian hanging wall basin succession (Galluzzo & Santantonio, 2002), and it does not exceed 40 m in thickness (Centamore et al., 1971; Santantonio, 1993, 1994; Pierantoni et al., 2013). The *composite succession* is constituted by Calcari Diasprigni overlaying by the deposits of the condensed succession (BU). The composite succession is limited to relatively narrow areas close to palaeo-escarpments of Calcare Massiccio (Centamore et al., 1971; Santantonio, 1993, 1994; Ciarapica & Passeri, 2001; Donatelli & Tramontana, 2010; Pierantoni et al., 2013).

All types of succession are overlaying by Maiolica (MAI, upper Tithonian-lower Aptian *p.p.*), which sutures the rift-related extensional tectonics affecting the passive margin of Adria during the Lower Jurassic. Maiolica is made of white and ivory micrites containing nodules and lenses of black chert. Its thickness ranges from 150-200 m when placed over the condensed succession, up to 400 m when it is above the complete one. Above, there is Marne a Fucoidi (FUC, lower Aptian *p.p.* - upper Albian *p.p.*), which is composed of grey, green, and red marls, clayey marls, and marly limestones, and its thickness ranges from 40-50 up to 80-100 m. It contains a bituminous level named 'Livello Selli', which constitutes a regional marker (Cecca et al., 1994; Pierantoni et al., 2013). Scaglia Bianca (SBI, upper Albian *p.p.*

- Turonian *p.p.*) overlies Marne a Fucoidi. It is made of c. 60-70 m-thick, white limestones and marly limestones with black chert in the upper part. It contains a bituminous level named 'Livello Bonarelli' (c. 1.5 m thick; Bonarelli, 1891), which is located close to the passage with Scaglia Rossa (SAA). The latter was deposited from the Turonian *p.p.* to the Lutetian *p.p.* age, and its thickness in the study area varies from 150 to 450 m (e.g., Pierantoni et al., 2013). It has been divided in three members: the lower one (SAA_1) is made by pink marly limestones and cherts nodules. The middle member (SAA_2) is characterised by red limestones without chert. The upper one (SAA_3) is made of red limestones and marly limestones with red chert in nodules. The latter member may have a minimum thickness down to a few metres. Several normal faults terminate within this unit, indicating a phase of extensive faulting (besides the Jurassic one) that ended during the Late Cretaceous - early Paleogene (Chiocchini et al. 1976; Marchegiani et al., 1999; Shiner et al., 2004; Pierantoni et al., 2013). The scaglia variegate fm. (VAS) was deposited above Scaglia Rossa from the Lutenian *p.p.* to Bartonian *p.p.* age, and it is usually composed of red, grey, and green limestones and marly limestones, alternated with grey and red marls and calcareous marls. Its thickness ranges from 10 to 50 m. The younger Scaglia Cinerea (SCC; Bartonian *p.p.* to the Aquitanian *p.p.*) represents the last unit of the 'scaglia' succession. It consists of green and grey calcareous marls, marls, and clayey marls. The thickness is 150-200 m. The Bisciaro (BIS; Aquitanian *p.p.* - Burdigalian *p.p.*) consists of dark grey marly and siliceous limestones, limestones with black cherts nodules alternated with grey calcareous marls and clayey marls. The thickness ranges from 50 to 150 m. This formation marks the end of the pelagic basin succession. The Mt. Fema area lies in the Camerino foredeep basin controlled by forebulge normal faults, in which the Schlier (SCH, Burdigalian *p.p.* - Tortonian *p.p.*) was deposited. This is constituted by an 80 to 250 m-thick alternation of grey marls, clayey-silty marls, with calcareous marls and shallow water carbonate environment located within the basin. Here, pre-thrusting normal faults are associated with the flexure of the (Adriatic) foreland (Ricci Lucchi, 1975; Calamita et al., 1979; Cantalamessa et al., 1980; Deiana et al., 2002; Mazzoli et al., 2002; Pierantoni et al., 2013). This calcareous-marly pelagic basin succession is stratigraphically overlain by Neogene deposits. The sedimentation of large amounts of siliciclastic turbidites during the Miocene suggests proximity to exposed lands. The Camerino fm. (FCI; Tortonian *p.p.* - Messinian *p.p.*) is a turbiditic unit thick up to 500 m, consisting of arenaceous, arenaceous-pelitic, and pelitic-arenaceous lithofacies (Calamita et al., 1979; Pierantoni et al., 2013). The orogenic phase shaping the fold and thrust belt occurred during Miocene to the Early Pleistocene, with the thrust front and related foredeep progressively migrating eastward over time (in the Adriatic Sea), with extension following. In the study area, the youngest thrust activity is Early Pliocene. The currently active extensional regime affecting the axial zone of the chain is reflected by the unconformable deposition of Quaternary continental deposits over the peri-Adriatic marine succession (Ricci Lucchi, 1987; Menichetti et al., 1991; Barchi, 2010; Bigi et al., 2011; Guerrera et al., 2015).

Deformation Style

The geodynamic evolution of the Apennines fold and thrust belt was interpreted, over time, using different styles of deformation, which reflect different definitions of thin-skinned (detachment-dominated) and thick-skinned (ramp-dominated) tectonics (e.g., Mazzoli et al., 2005 and references therein). The earliest models envisioned that the basement is not involved in the deformation (thin-skinned) with multiple thrust-related repetitions of the sedimentary cover above the "undeformed" basement (e.g., Baldacci et al., 1967; Decandia & Giannini, 1977; Bally et al., 1986; Calamita & Deiana, 1986; Hill & Hayward, 1988). The ground behind this interpretation was the presence of evaporites (décollement level) at the base of the sedimentary cover, together with the absence of crystalline basement in the outer part of the Apennines. These models predicted displacements of several tens of kilometres for the major thrusts (i.e., Umbria-Marche-Sabina thrust zone), in accordance with a model of continuous and hundreds of km-long faults. However, the CROP03 deep seismic reflection experiment (Barchi et al., 1998) led to the interpretation that the basement is involved in thrusting, later supported by data on the magnetic basement (Speranza & Chiappini, 2002), thus questioning the validity of pre-existing deformation models. Balanced and restored cross-sections that followed supported a thick-skinned model, at least in the outer portion of the central-northern Apennines (e.g., Coward et al., 1999; Butler et al., 2004; Tavarnelli et al., 2004; Mazzoli et al., 2005). These interpretations have led to a much lower orogenic shortening, i.e., c. 7.5 km (Scisciani et al., 2014) and c. 8.5 km (Butler et al., 2004), than that estimated by applying a thin-skinned model, i.e., c. 50 km (Bally et al., 1986; Calamita et al., 2012). This shortening range is consistent with the claim that the main thrusts are composed of multiple, partially overlapping fault segments rather than a single, continuous structure (Mazzoli et al., 2005).

It is now clear that both thin- and thick-skinned styles contribute to defining the overall architecture of the Apennines belt (e.g., Coward et al., 1999; Barchi and Tavarnelli, 2022). Efficient décollement levels are found at various structural levels in the Apennines sedimentary succession (Triassic evaporites - BUR, Marne a Fucoidi - FUC, Scaglia Cinerea - SCC). This produces a multi-layered mechanical stratigraphy characterised by multiple weak décollements horizons cut by thrusts involving part of the succession, favouring thin-skinned compressional structures (e.g., Koopman, 1983; Massoli et al., 2006; Barchi and Tavarnelli, 2022). A thick-skinned style prevails, instead, where compressional structures are ramp-dominated and thrusts reactivate pre-orogenic normal faults deeply rooted within the basement (e.g., Tavarnelli, 1996; Barchi et al., 1998; Coward et al., 1999; Barchi & Tavarnelli, 2022). In addition to across- and along-strike changes in structural style, other factors hinder the comprehension of the geometric and kinematic evolution of the Apennines fold and thrust belt. The most critical are linked to multiple events of extensional faulting that preceded the thrusting and have caused structural inheritance along with facies differences and lateral thickness variations (e.g., Colacicchi et al., 1970; Centamore et al., 1991; Alvarez, 1990; Coward et al., 1999; Marchegiani et al., 1999; Deiana et al., 2002;

Mazzoli et al., 2002; Butler et al., 2006; De Paola et al., 2007; Scisciani et al., 2014, 2019; Tavarnelli et al., 2019). Moreover, the post-orogenic extensional regime established since Late Miocene, and still active, dissect the axial zone of the fold and trust belt (e.g., Cello et al., 1997; Tondi & Cello, 2003; Pierantoni et al., 2013).

METHODOLOGY

Fieldwork and Photogrammetric survey

High-resolution geological mapping is the basic tool to shed light on the subsurface in areas where seismic lines, deep wells, or recorded seismicity are limited. Fieldwork was carried out in the Mt. Fema area from April to December 2022 based on the 1:10,000 scale '*Carta Tecnica Regionale*' from the *Regione Marche* database (available at https://www.regione.marche.it/, last accessed December 2022) integrated with Google Earth satellite imagery. Specifically, the mapping allowed to define the local stratigraphic units and their spatial relationships, including thickness and lateral facies variations, the structural elements (e.g., faults, folds) and their features, i.e., orientation, geometry, kinematics, and crosscutting relationships, as well as geomorphic phenomena. In this work, classical field methodologies were integrated with digital mapping and drone surveys. The attitude of bedding and structural elements was collected using the FieldMove Clino app (Petroleum Experts) installed on reliable smartphones and tablets (e.g., Whitmeyer et al., 2010; Allmendinger et al., 2017). The magnetic declination in the study area is 3° 54' E, and it has been verified at each survey.

When outcrops are made inaccessible by the considerable height of rock walls, vegetation, or rivers, they were occasionally studied using photogrammetric surveys. The resulting virtual outcrop models allow, in fact, to obtain additional information regarding the architecture of strata and structural elements (e.g., Corradetti et al., 2017; Del Sole et al., 2020; Volatili et al., 2022). Unmanned Aerial Vehicle (UAV) imagery was collected using a DJI Mini 2 drone, which is equipped with a 12Mp onboard camera, and 1/2,3-inch image sensor. In the field, the UAV flew at distances between 150 and 200 m from the rock walls. The general Structure from Motion (SfM) processing procedure used to construct the virtual outcrop model follows the methods described by Volatili et al. (2022). The virtual outcrop was created using the Agisoft Metashape software (Agisoft LLC) and it consist of high-resolution surface meshes built using 304 overlapping photos.

Balanced Cross-section Construction and Restoration

The resulting geological map of the Mt. Fema area was integrated with a 10 m-cell size digital elevation model (Tarquini et al., 2007) and located in a 3D environment using Move software (Petroleum Experts Ltd) to construct a series of balanced geological cross-sections. Four sections were traced perpendicular to the trend of major folds, that is according to the best-fit great circle approximating the distribution of the poles to bedding (i.e., folded layers attitude data) and the related pole (i.e., π statistical fold axis; Fig. 3). This allows for computing the thickness of outcropping rock units along the section (e.g., Tavani et al., 2018; Mazzoli et al., 2022), when the possibility to calculate the thickness of some rock formations was not available, we based on Pierantoni et al. (2013). The stratigraphic and tectonic contacts were projected onto the section trace using structural contours provided from the geological map and dip-angle data (and dip domains).

The balancing procedure was performed using the balancing analysis tool in Move. It basically follows the classical approach of Dahlstrom (1969); however, the suite allows to check the quality of the interpretation and identify locations where horizons are missing or incorrectly interpreted, thus reducing uncertainty in the resulting geological model. Specifically, the balancing analysis tool automatically unfolds all the horizons in the section to horizontal lines and calculates the difference in area between fault blocks. Geological units of the Umbria-Marche succession were reconstructed, even when they are not cropping out because of erosion, under the assumption of constant thickness.

Once the balanced cross-sections were built, a representative one was selected for sequential restoration. This is a widely applied procedure to validate the cross-section balancing and to reconstruct tectonic scenarios. The restoration procedure allows to quantify the amount of shortening and/or extension related to different tectonic events occurring in the study area. The polylines of the restored section were constructed by linking the restored cut-off points by applying a smoothing to avoid zigzag effects and, in any case, never exceeding 0.5% of the original cut-off point position (e.g., Tavani et al., 2018; Santini et al., 2020; Basilici, 2021; Mazzoli et al., 2022). In this work, the algorithms *Flexural slip*, *Fault Parallel Flow*, and *Simple Shear* were used to restore folding of beds over thrust planes, movement on the thrusts, and on the normal faults, respectively. *Flexural slip* mimics the well-known mechanism of folding defined by Ramsay (1974) and Tanner (1989). It is generally used to restore folds in sedimentary successions (unfolding), which requires constant layer thickness and line-length preservation of horizons (e.g., Castelluccio et al., 2016; Tavani et al., 2018; Masrouhi et al., 2019; Santini et al., 2020; Basilici, 2021; Verwater et al., 2021; Mazzoli et al., 2022). Widespread occurrence of striae and calcite shear fibres on fold limb bedding surfaces, trending roughly perpendicular to fold axis, supports the adoption of this folding mechanism and algorithm. *Fault Parallel Flow* (Egan et al., 1999; Kane et al., 1997) is based on the principle of particulate laminar flow over a fault ramp. It permits to preserve the line-length and the forelimb area, keeping the footwall undeformed. It is generally used to restore movement on thrusts (e.g., Castelluccio et al., 2016; Santini et al., 2020; Basilici, 2021; Mazzoli et al., 2022) because, when a suitable angle of angular shear is constrained, it allows the best estimation of the amount of shortening. *Simple Shear* (Gibbs, 1983; Verral, 1981; Withjack &Peterson, 1993) is generally used to model penetrative deformation that occurs throughout the hanging wall rather than a discrete slip vector between bedding planes. Applying a vertical Simple Shear, it is possible to deform back the hanging wall along a normal fault with a well-constrained geometry. It permits to preserve the area of the hanging wall and the length between the fault plane and a marker horizon (e.g., Castelluccio et al., 2016; Basilici, 2021; Mazzoli et al., 2022).

3D Geological Modelling

According to Dahlstrom (1969), out-of-plane movements are not considered in a 2D balanced cross-section. This assumption makes 2D balanced geological sections generally inadequate to discriminate which geometry and kinematics are the most appropriate and to reconstruct a reliable structural architecture (Roure & Sassi, 1995; Deville & Sassi, 2006; Castelluccio et al., 2016; Tavani et al., 2018; Balestra et al., 2019; Basilici et al., 2020b; Santini et al., 2020, 2021; Mazzoli et al., 2022). In recent years, several attempts have been made to construct geological models allowing to display the subsurface geometric arrangement of rock formations and faults in a three-dimensional space, thus considering out-of-plane movements (e.g., Royer et al., 2015; Balestra et al., 2019; Basilici et al., 2020b; Basilici, 2021; Di Bucci et al., 2021; Santini et al., 2021).

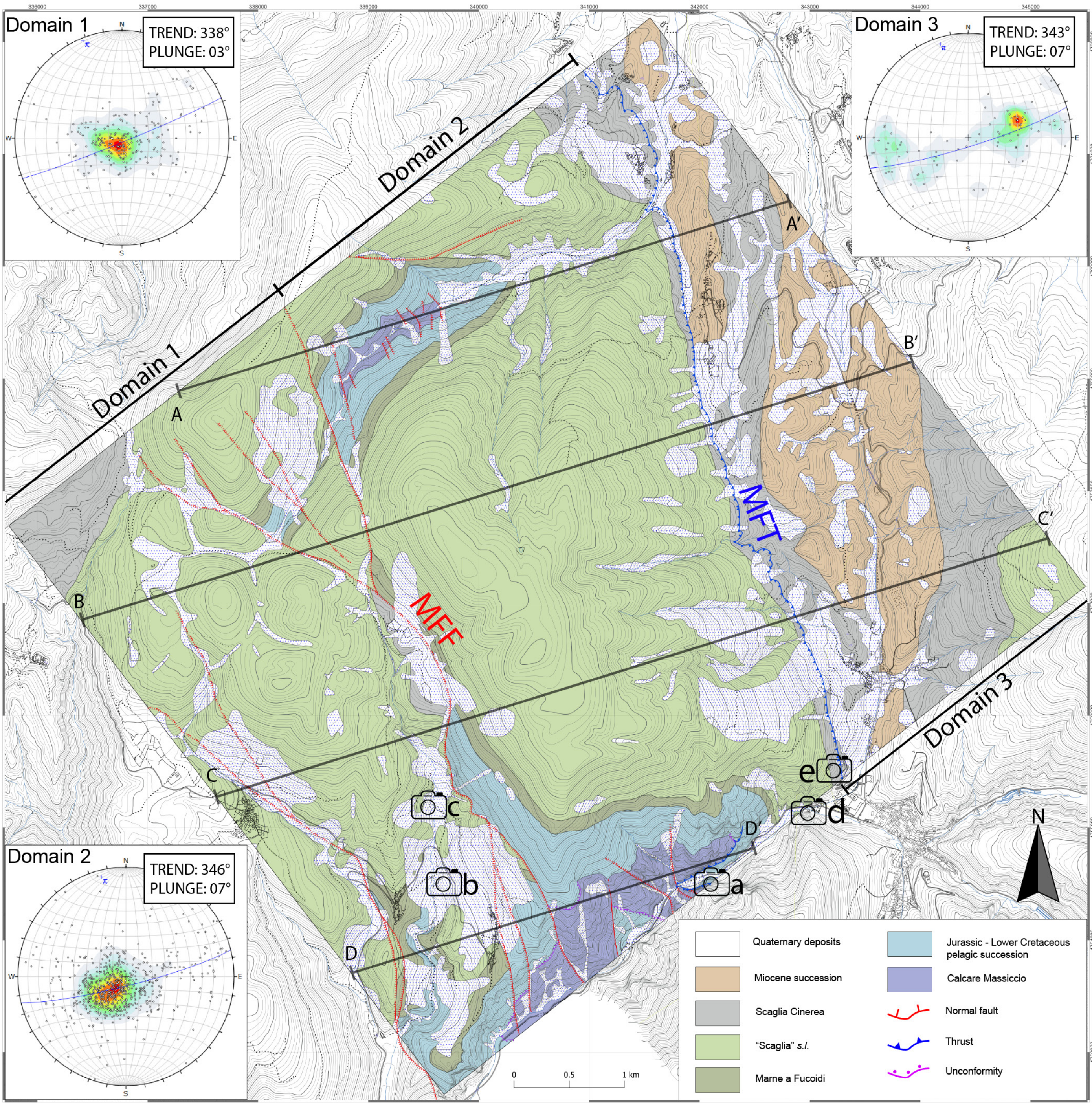

Fig. 3 - Schematic geological map of the Mt. Fema area. See Fig. 1 for location. Lower-hemisphere equal-area projections of poles to bedding refer to the following three structural domains: (1) hanging wall of the Mt. Fema Fault (MFF; backlimb and part of the crestal region of the Mt. Fema anticline, (2) footwall of the Mt. Fema Fault (part of the crestal region and forelimb of the Mt. Fema anticline), and (3) footwall of the Mt. Fema Thrust (MFT). Plots show best-fit great circle approximating the distribution of poles to bedding and the related pole (i.e., π statistical fold axis). Location of field pictures (Fig. 4) and traces of the balanced cross-sections (Fig. 5) are also shown. The 1:10,000 scale geological map can be found in the Supplemental Materials S1.

In this work, 29 projected cross-sections were built in Move software under the constraints of the geological map, the digital elevation model, and the four balanced geological cross-sections. Then, the surfaces identifying the faults and the top of the BUR, MAS, MAI, and SAA formations were created using a spline interpolation between a series of linear horizons. Once a suitable 3D digital model is created, different structural hypotheses can be tested and quantified by manipulating the model. The 3D structural model allows to display, at high-resolution, the subsurface arrangement of strata and faults of different generations (pre-, syn-, and post-thrusting), providing useful insights into the understanding of the structural architecture, timing, and kinematics of the fold and thrust belt in the Mt. Fema area (Umbria-Marche Apennines).

RESULTS

Geological Map

Three structural domains may be identified on the geological map (Fig. 3; Supplemental Material S1). These are separated by the main extensional structure (Mt. Fema Fault) and the more continuous NNW-SSW-striking, WSW-dipping thrust (Mt. Fema Thrust) of the study area. The resulting domains are the following: (1) hanging wall of the Mt. Fema Fault (backlimb and part of the flat top of the Mt. Fema box fold), (2) footwall of the Mt. Fema Fault (part of the crestal region and forelimb of the Mt. Fema anticline), and (3) footwall of the Mt. Fema Thrust. The sector outcropping east of the Mt. Fema Thrust (Domain 3) is essentially constituted by Schlier, Bisciaro, Scaglia Cinerea, and scaglia variegata formations. Their strata are arranged in approximately N-S trending, adjoining synclines and anticlines. The Mt. Fema Thrust trace is roughly straight and continuous throughout the study area, from the locality of Capodacqua (north) to Visso (south). Except when it is covered by Quaternary alluvial deposits which are found, in slopes, on top of all other units. The Mt. Fema Thrust, at surface, mostly cuts through strata of Scaglia Cinerea and shear zones developing therein facilitate the identification of the thrust surface (Fig. 4e). The thrust also juxtaposes Scaglia Cinerea against Bisciaro. Further west, in the southern sector, a (internal) blind thrust poses the E-dipping beds o Calcare Massiccio against the pelagic units of Calcari Diasprigni and Maiolica (Fig. 4a). In the hanging-wall (west) of the Mt. Fema Thrust, there is a broad and asymmetric, ENE-verging anticline (Mt. Fema anticline). This fold is characterised by a steep, ENE-dipping forelimb and a wide crestal area (Domain 2). The hinge line trends NNW-SSE. The Mt. Fema anticline essentially consists, at outcrop, of the Scaglia Rossa pelagites. The older units are exposed along two NE-SW trending valleys, the Val di Tazza, in the north, and the Valnerina, in the south. Here, the core of anticline is constituted by Calcare Massiccio and above, a composite Jurassic succession (Bugarone and Calcari Diasprigni; Fig. 4a). The west limb of the Mt. Fema anticline (Domain 1) is characterised by a system of high-angle (60-80°) NW-SE to N striking normal faults, the main of which is referred to as Mt. Fema Fault (Fig. 4b, c). These faults are roughly parallel to the thrusts to the east. Most faults belonging to this system dip towards SW to W, with minor NE-dipping antithetic faults. These faults crosscut the Jurassic rift-related fault scarps delimiting the transition to the complete succession, thus bordering the Jurassic structural high of Mt. Fema towards SSW (i.e., Valnerina; Fig. 3). In map view, normal fault traces are anastomosing, and they bend and branch in multiple segments with an en-echelon geometry along strike, NW-ward and SE-ward. They develop tip splays, both synthetic and antithetic. Steep morphological scarps are commonly associated with these faults and, in their proximity, the units older than Scaglia Rossa are exposed, i.e., Scaglia Bianca, Marne a Fucoidi, and Maiolica.

Balanced and Restored Sections

Balanced cross-sections show a ramp-dominated deformation style, characterised by low-angle (15-30°) reverse fault planes (Fig. 5). These planes become steeper (up to c. 50°) upward, whereas they tend to flatten downward. Here, they probably become thrust flats reaching a basal detachment level. The thrust is exposed along the forelimb of the major anticlinal structure, which has a WSW-dipping axial plane. Generally, a syncline is found in the immediate footwall of the thrust ramp. This is followed by a roughly symmetric anticline that most probably grow above a blind thrust (i.e., buried tip line) propagating, in the subsurface, up to Rosso Ammonitico (Fig. 5a, b). The blind thrust is most probably rooted in the same structural position as the Mt. Fema Thrust, and they seem to branch out, down-dip, from the same décollement level. The succession in the footwall of the thrust is dominated by the complete type, whereas the condensed one dominates in the hanging-wall. High-angle, mostly ENE-dipping, normal faults and fault scarps, located in the hanging wall of the thrust, mark this transition. These features are crosscut, down-dip, by the thrust, whereas their upper tip lines are confined within the Upper Jurassic basin units (i.e., they are blind faults).

Our interpretation suggests limited displacement (cumulative dip separation) related to the thrusting, especially when considering the sections in the northern (A-A': 90 metres, Fig. 5a) and central (B-B': 47 metres, Fig. 5b; C-C': 61 metres, Fig. 5c) part of the Mt. Fema area. The southernmost section, D-D' (Fig. 5d), cuts along the Valnerina, and it shows a composite succession. Here, the blind thrust juxtaposes the gently E-dipping beds of Calcare Massiccio against the pelagic units (Calcari Diasprigni, Maiolica) of the overturned forelimb, suggesting the higher displacement in the area, i.e., 440 metres. Here, the displacement along the Mt. Fema Thrust has not been calculated since the section D-D' do not cross the thrust at surface, however it has been later estimated to be ~65 m, directly from the 3D model.

Balanced section C-C' (Fig. 5c) was selected as the most representative of the overall structure of Mt. Fema. Sequential restoration along section C-C' (Fig. 6) shows the progressive development of the Mt. Fema anticline, from present-day configuration (t0) back to the late stage of post-thrusting normal faulting (t-1), and the early stages of fold and thrust belt development (t-2 and t-3). At stage t0, a starting horizontal distance of 5915 m is defined by two fixed pin lines. At stage t-1, the movement along the most recent normal faults was restored, and the horizontal distance becomes 5725 m (3.3% elongation). The movement along the thrust was restored at stage t-2. Here

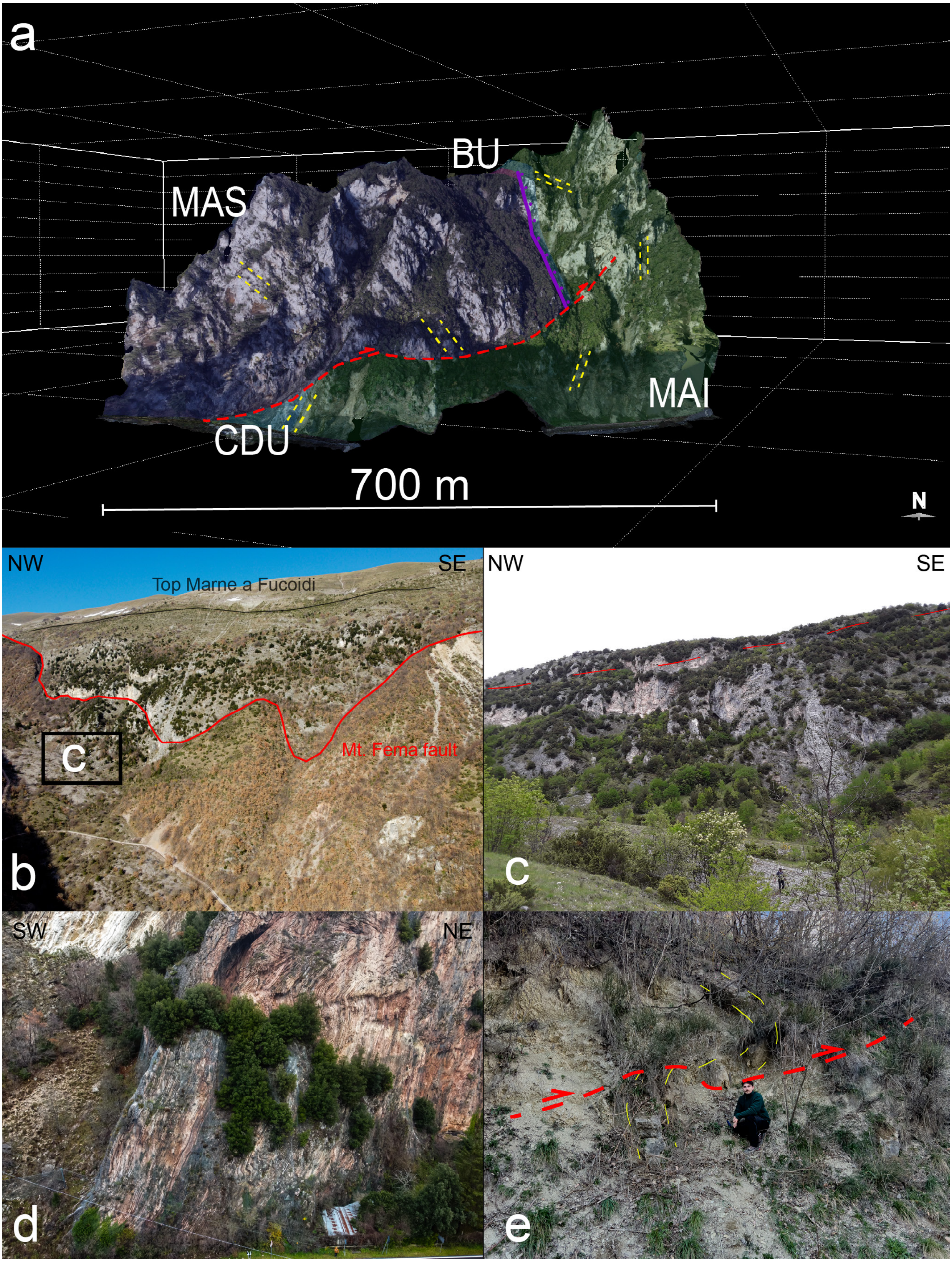

Fig. 4 - Virtual outcrop model of the northern slope of Valnerina (Nera River Valley) and field pictures (located in Fig. 3). (a) Blind thrust superposing the Calcare Massiccio (MAS) and Bugarone Group (BU) onto overturned strata of the Calcari Diasprigni (CDU) and Maiolica (MAI) formations in the core of the Mt. Fema anticline. Yellow lines show bedding traces. Panoramic (b) and detailed (c) view of the main extensional structure of the study area (Mt. Fema Fault). (d) Chevron and kink folds in the Scaglia Rossa. (e) Thrust (red line) and associated tectonic fabric in the Scaglia Cinerea in proximity of the main thrust (yellow lines show a faulted calcarenite bed). (Move Petroleum Experts academic licence, not for commercial use).

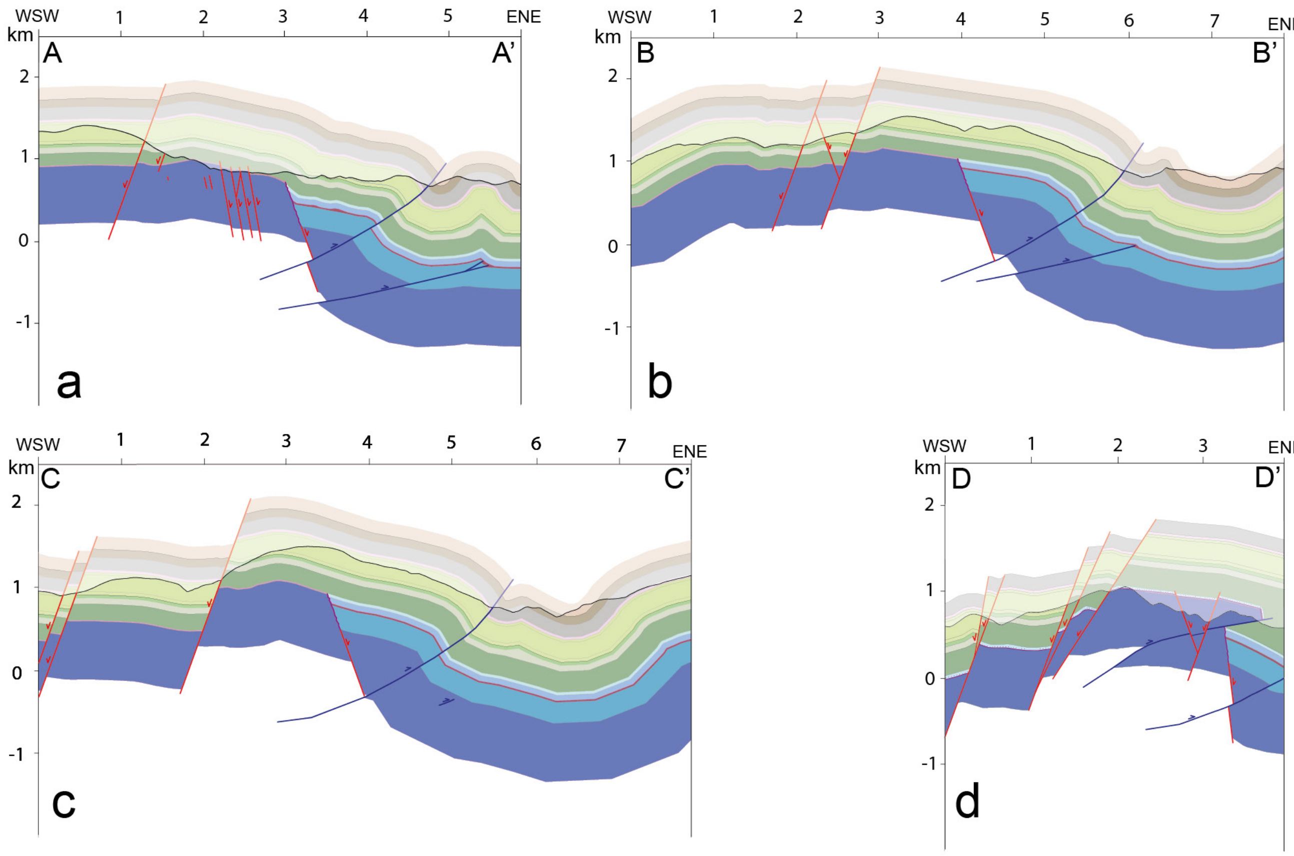

Fig. 5 - Balanced geological cross-sections. From north to south: (a) A-A'; (b) B-B'; (c) C-C'; (d) D-D'. The balancing error for each cross-section is the following: A-A' = 1.7%, B-B' = 1.0%, C-C' = 0.6%, D-D' = 0.4%. Eroded geological units are shown in transparency above the topographic surface. Refer to Fig. 2 for the stratigraphy.

the horizontal distance becomes 5785 m, corresponding to a 1% shortening. After unfolding (t-3) the horizontal distance becomes 6100 m, corresponding to a shortening of 5.1%. The configuration at t-3 indicates the presence of a ENE-dipping, pre-thrusting normal fault and fault scarp. The restoration validates the cross-section balancing.

High-angle normal faults dissect the crestal region of the anticline, up to the scaglia variegata fm. (Fig. 5c). They have also been interpreted to crosscut the thrust and they do not necessarily reach the surface (e.g., Fig. 5d). The displacement of normal faults was analysed along the Mt. Fema Fault and other minor segments, by means of a displacement-distance diagram (Fig. 7). Normal fault displacement has been measured as the distance, along the fault surface, between the hanging-wall and footwall cutoffs of a selected marker horizon. Then, this value is plotted against the strike-parallel distance. Maiolica was chosen as marker horizon because it is well defined in the subsurface dataset, and it is quite laterally continuous in outcrop. The displacement profile related to the Mt. Fema Fault is overall bell-shaped, showing a maximum in the central area (630 m at c. 4929 m of distance; 550 m at c. 3974), while it diminishes rapidly (i.e., steep displacement gradient) toward the southeast and less abruptly toward the northwest (Fig. 7). Toward the northwest, the Mt. Fema displacement profile shows, after a local minimum of 107 metres (at c. 2236 m of distance), another (albeit smaller) sort of bell-shaped portion with local maxima of 242 metres (at c. 1672 m of distance) and 190 metres (at c. 968 m of distance). Minor fault segments have smaller displacements, which reach c. 275 m in the SW sector and c. 220 m in the NE one. These splays are located toward the NW and SE terminations of the Mt. Fema Fault; hence they contribute only to the ends of the cumulative profile (Fig. 7). The latter mimics, in the central part, the trend of the Mt. Fema displacement profile, whereas it shows two peaks at the extremities (681 m at c. 5960 m of distance and 710 at 968 m of distance) because of the presence of splays.

3D Geological Model

The 3D geological model shows the overall structural architecture of the fold and thrust belt in the Mt. Fema area. The model portrays the outcropping geology and the subsurface geometrical arrangement of main horizons of the Umbria-Marche succession and major faults of different generations and their mutual crosscutting relationships (Fig. 8; Supplemental Material S2). The stratigraphic surfaces are (from top to bottom): top Scaglia Rossa, top Maiolica, top Calcare Massiccio, and top Anidriti di Burano. The most apparent feature of the 3D model, as seen from SE or NW, is the fold and thrust structure affecting the Jurassic-Lower Miocene carbonate multilayer and the overlying Miocene siliciclastic deposits. The model shows the gentle and open anticlinal structure of the Mt. Fema, which has a WSW-dipping axial plane. Except for the presence of small-wavelength morphological variations, the overall trend of the horizons is quite

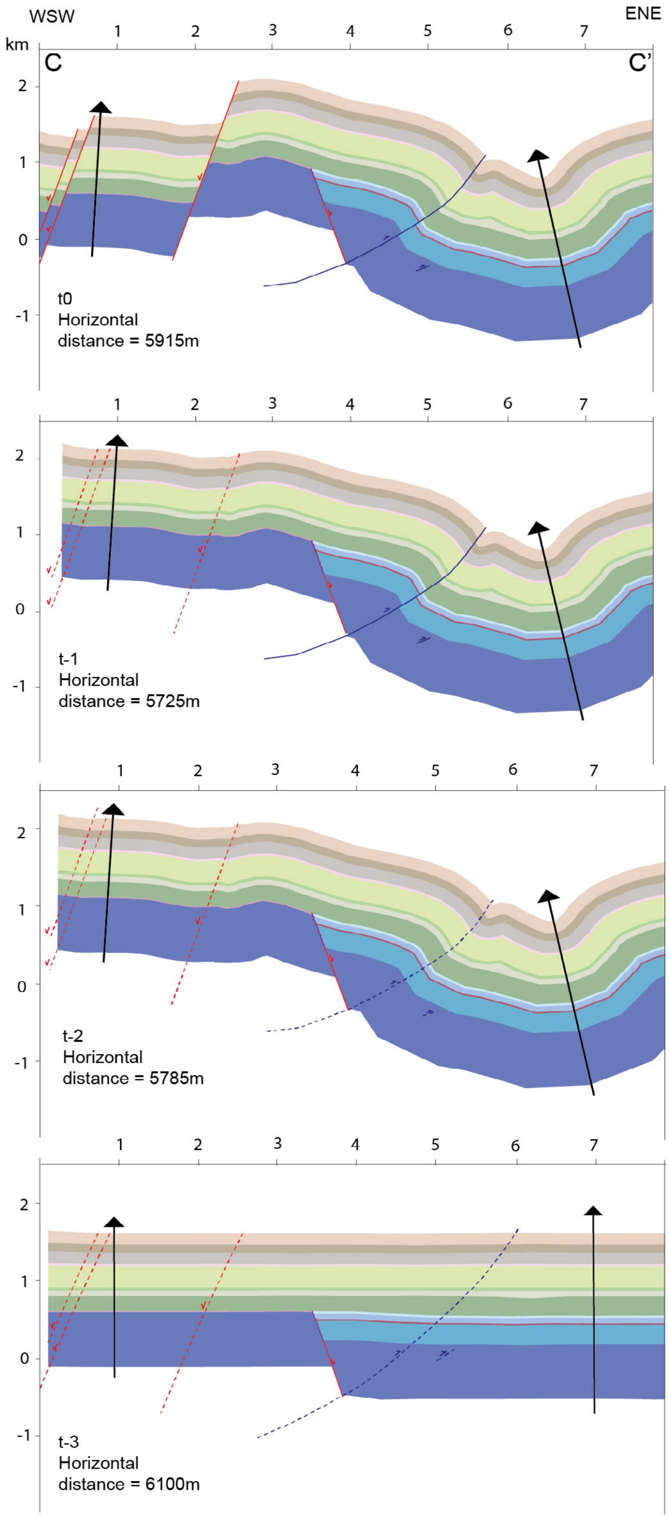

Fig. 6 - Sequential restoration of section C-C' (Fig. 5c) showing the main deformation stages affecting the study area. Horizontal distances were measured between pin lines (black). Refer to Fig. 2 for the stratigraphy.

homogenous. The anticline is bounded by a NNW-striking thrust along its ENE-dipping forelimb. The Mt. Fema Thrust surface is roughly straight, continuous, and homogenously dipping toward WSW at low angle (c. 20-30°) throughout the considered volume. However, it becomes steeper (up to c. 50°) near the surface. In the northern sector, a minor blind thrust segment splays out from the Mt. Fema Thrust, in its footwall block, towards the foreland. The blind thrust tip likely terminates at Rosso Ammonitico, propagating a fold upward. This minor thrust converges with the Mt. Fema Thrust towards the south, suggesting that they may laterally connect. Moreover, in the SW sector of the study area, there is a minor thrust located more internally than the Mt. Fema Thrust (i.e., in its hanging wall block), but having a similar direction. This thrust crops out in Valnerina. Generally, thrusts tend to flatten down-dip, where they probably merge at a basal décollement level. The topography mimics well the overall strata architecture, particularly in the central sector of the study area. In the thrust hanging wall block the beds dip gently towards ENE as does the relief. The lowest topography is found in the footwall syncline. However, the crestal region is dissected by a set of normal faults that displace and lower the strata toward the SW. This fault system is constituted, just at the back of the relief, by a major fault (Mt. Fema Fault) with sinuous surface, from which multiple synthetic and antithetic fault strands branch off, developing tip splays at its NW and SE terminations. Toward the SW, a minor fault segment parallel to the Mt. Fema Fault exhibit similar features. In the proximity of these faults, the rock horizons increase their roughness. Faults belonging to this system do not necessarily reach the surface. In fact, in the southern sector (Valnerina), two normal faults crosscut the thrust, though they end in the Maiolica fm. (Fig. 5d). Moreover, from the model is apparent an E-dipping high-angle normal fault that runs throughout the study area, exhibiting with a sinuous surface. This fault is covered by the Upper Jurassic to Lower Cretaceous units (Fig. 5a, d) and towards south it is crosscut by the thrust.

DISCUSSION

Hereafter, we discuss our results in terms of structural geometry, kinematic, timing, and the role of structural inheritance and subsequent extensional tectonics in the evolution of the fold-thrust belt in the Mt. Fema area (Umbria-Marche Apennines).

The overall structure of the Mt. Fema area reflects the structural style of the Umbria-Marche Apennines (e.g., Barchi et al., 1998; Butler et al., 2004). Our reconstruction goes all the way to the base horizon of Calcare Massiccio (Figs. 5 and 8), then we cannot discuss whether the basement is involved (thick-skinned) or not (thin-skinned) in the fold and thrust belt. Based on our sections, we can only argue that thrusts tend to flatten down-dip, where they probably merge at a basal décollement level (Fig. 5). However, it has become clear that thin- and thick-skinned tectonics coexist in this region (e.g., Barchi & Tavarnelli, 2022). Along-strike variations of the geological structures have been long recognised in the Umbria-Marche Apennines (e.g., Mazzoli et al., 2005) and in other fold-and-thrust belts (e.g., Mazzoli et al., 2022). For instance, in the Mt. Fema area thrust displacement and shortening varies from north to south (Fig. 5). According to our interpretation, the Mt. Fema thrust system is characterised by relatively limited displacement, i.e., the cumulative dip separation ranges from ~100 m to the north in Val di Tazza to ~500 m to the south in Valnerina; unlike other interpretations in which multiple (carbonate) thrust

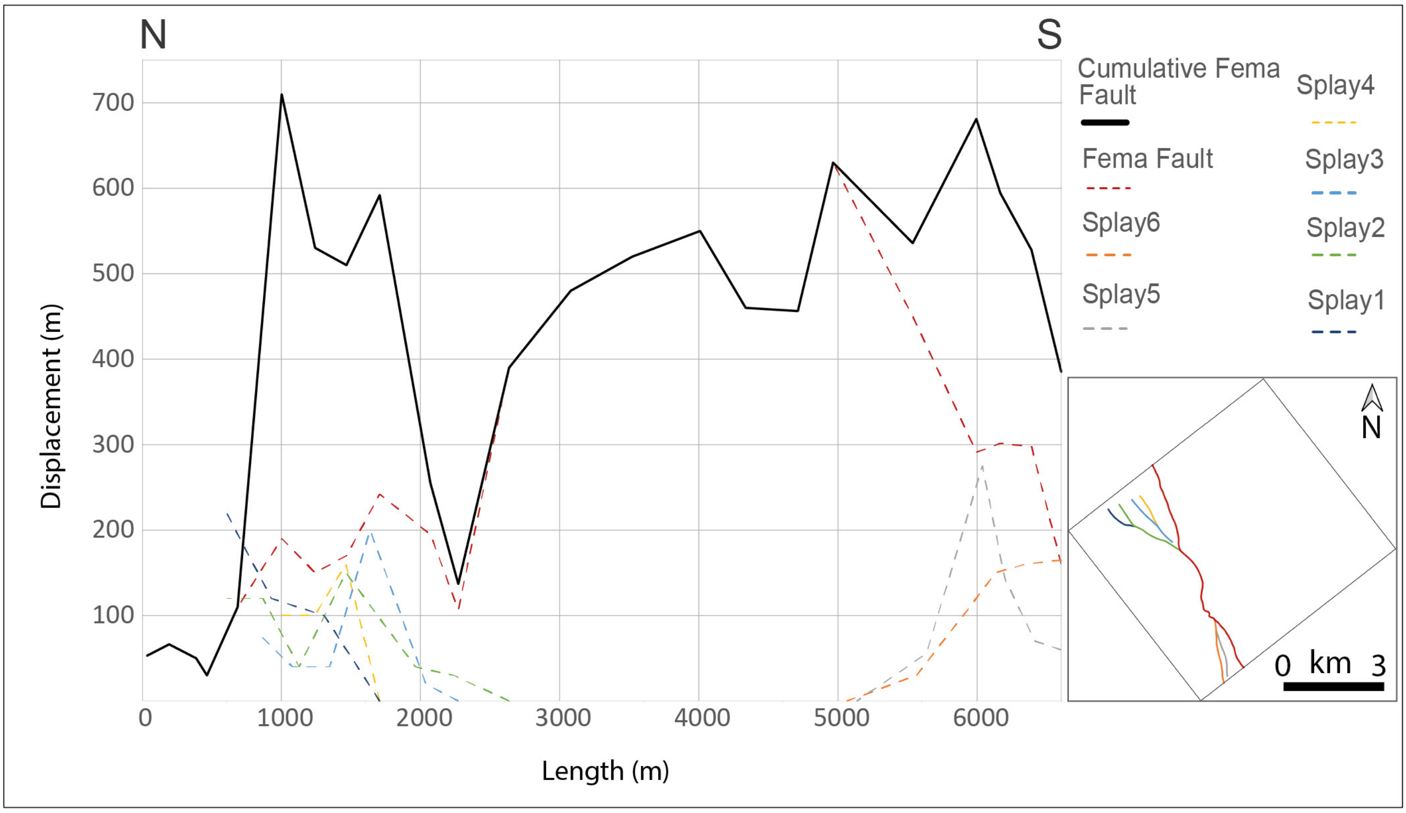

Fig. 7 - Displacement-distance profile along the Mt. Fema Fault and associated splays (lower right inset shows map view).

sheets without basement involvement and defined by 'ramp-on-ramp' structures accommodate larger amounts of contraction (e.g., Bally et al., 1986; Calamita et al., 1994; Calamita et al., 2012). An interpretation similar to the latter is made by Mirabella et al. (2008), however, according to their model the thrust roots into the basement westward. Instead, the solution proposed by Tavarnelli et al. (2004) considers the involvement of basement in the main thrust structure and limits the inferred amount of orogenic contraction but considers the re-activation of pre-orogenic normal faults by most thrust.

Thrust geometry also varies towards the south, where the blind thrust in Valnerina cuts through the core of the anticline with a concave downward geometry (i.e., slope decreases upward), at the back of the Mt. Fema Thrust (Fig. 5d). These observations demonstrate that along-strike variations may occur even at short distances. An additional complexity is given by inherited pre-orogenic deformation along with facies differences and lateral thickness variations. The Umbria-Marche Apennines has recorded multiple phases of extensional tectonics, including the Jurassic rift-related normal faulting fragmenting the passive (Adria) continental margin (e.g., Marchegiani et al., 1999; Tavarnelli et al., 2019). In the Mt. Fema area, inherited E-dipping normal faults and fault scarps once separating different palaeogeographic domains (e.g., condensed vs. complete succession), presently produce across-strike changes (e.g., Colacicchi et al., 1970; Centamore et al., 1971; Deiana et al., 2002; Pierantoni et al., 2013). These may profoundly affect fold-and-thrust belt development, since the inherited basin conformation and the resulting competence contrast produce the mechanical stratigraphy of the deforming multilayer that, in turn, govern folding by buckling mechanism (e.g., Lavecchia, 1981; Price & Cosgrove, 1990; Tavani et al., 2021; Mazzoli et al., 2022). Recent studies (e.g., Butler et al. 2020) emphasised buckling as a primary generator of fold patterns in thrust belt. These authors have argued that too much emphasis has been put on kinematic models (e.g., Jamison, 1987) which often overlook the importance of mechanical strength of layers. For many years, these ideas were largely disregarded, but in recent times there is a renewed appreciation of the importance of understanding of folding mechanism of fold and thrust belts (e.g., Butler et al., 2018). The mechanically dominant member (Calcare Massicio in this instance) played a fundamental role in regional fold development as a result of buckling processes (Morley, 1994; Mazzoli et al., 2001; Mazzoli et al., 2022) with fold wavelengths normally determined by the thickness of the stalwart 'control units' (Cobbold, 1975; Price & Corgrove, 1990). The calcareous strata of the Umbria-Marche succession show a spaced disjunctive pressure-solution cleavage generally perpendicular or at very high angle to bedding. Often observed striae and calcite shear fibers on bed surfaces are normally positioned to the bedding-cleavage intersection lineation, which usually corresponds to fold hinges. The field data shows that parasitic folds is dominant in the area, caused by polyharmonic folding, which is based on the dissimilar levels of mechanical viscosity and active layering on varied scales (Ramsay & Huber, 1987). The development of cleavage at a high angle relative to the bedding, leading to convergent cleavage fans in folds, is an indication of the tangential longitudinal strain that is present in strong layers and only minimum or no alteration of the primitive cleavage produced by the initial layer-parallel shortening

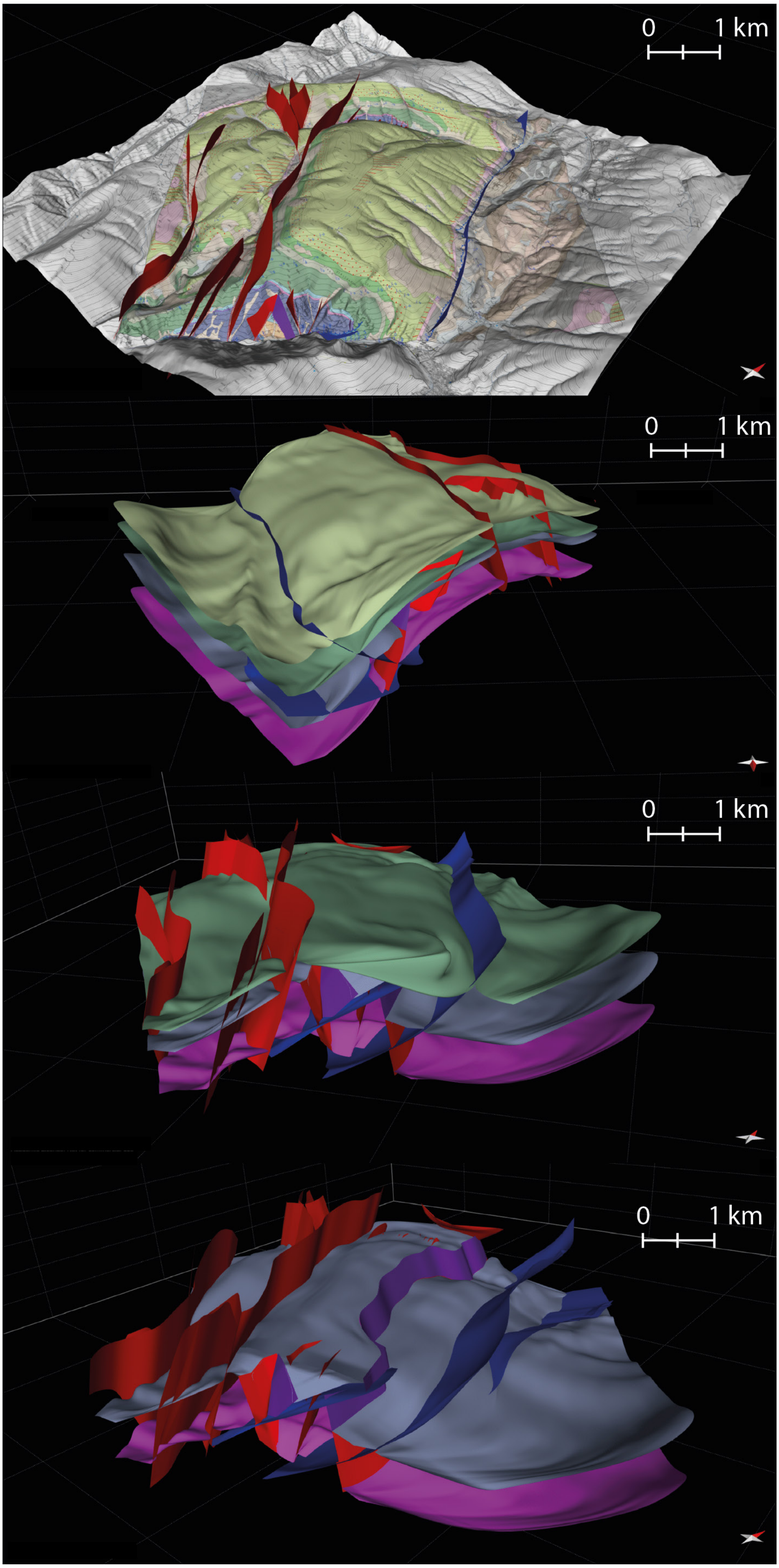

Fig. 8 - Snapshots of the 3D geological model (Supplemental Material S2). Red surfaces are normal faults, blue surfaces are thrusts, and purple surfaces are Jurassic fault scarps. The maximum interpolation error between 3D surfaces and horizons traced in cross-sections and maps is 30 m where structures increase complexity. stratigraphic surfaces are (from top to bottom): top Scaglia Rossa, top Maiolica, top Calcare Massiccio, and top Anidriti di Burano (Move Petroleum Experts academic licence, not for commercial use).

that occurred prior to the amplification of the mechanically active multilayers in the fold (Ramsay, 1967). Cleavage patterns (I.E., finite strain trajectories) and layer thickness variations in beds of differing competence are all indicative of buckle folding (Ramsay, 1981). Thus, the buckling may be favoured just at the transition among condensed (westward) and complete (eastward) succession, and more precisely in the immediate footwall block of the pre-existing Jurassic normal fault (Fig. 5). Eventually, the fold controls the locus of thrust propagation (e.g., Morley, 1994; Butler et al., 2020). In the Umbria-Marche Apennines, others have already suggested that buckles nucleate at pre-existing Jurassic normal faults (e.g., Tavarnelli, 1996). In the Mt. Fema area, E-dipping Jurassic normal faults are not favourably oriented for re-activation by the thrusts, that rather crosscut them (Fig. 5). Normal fault reactivation would be enabled if they were W-dipping, the same as the thrusts (e.g., Butler, 1989; Barchi & Tavarnelli, 2022).

Here, we present one of the few available detailed 3D geological models of the Apennines (e.g., Borraccini et al., 2004). The high-resolution 3D model of the Mt. Fema area allows to display the subsurface arrangement of strata and faults of different generations (pre-, syn-, and post-thrusting), providing useful insights into the understanding of the structural architecture. In particular, it enhances the visualisation of along- and across-strike variations of faults and folds characteristics, such as their geometry, splays pattern, and zones of overlap and linkage. For example, the overall trend of the surfaces representing the top of the geological formations is quite homogeneous and laterally continuous (Fig. 8). Except for the presence of small-wavelength morphological variations, the folds that are found within the Structural Domains 1 and 2 may be termed as sub-cylindrical, following the classification by Ramsay and Huber (1997). In fact, more than 90% of data point (poles to bedding) fall within the 20° of the π-circle (Fig. 3). Folds that are found in the Domain 3, instead, are non-cylindrical (i.e., less than 90% of the poles lie within the 20° of the π-circle). Small-wavelength roughness of the surfaces in the 3D model (Fig. 8) may be explained by the variability of folded layers attitude (Fig. 3; Supplemental Material S1). A three-dimensional visualisation of the geological model of the area also allows non-specialist users, including decision-makers and engineers, to access the geological information in support of planning and management of new infrastructures. In this work, the construction of the 3D geological model was carried out using field data, such as maps and cross sections, as primary data source. The integration of geophysical data (e.g., seismic, gravimetric, etc.) and well logs to the current 3D model can be used to validate and improve our interpretation. The next stage will be to extend this workflow to build a 3D geological model for the entire area of the geological Sheet 325-Visso.

The normal faults observed in the western (back)limb of the Mt. Fema anticline are post-orogenic since they crosscut much of the contraction structures (e.g., Fig. 5d), as well as pre-orogenic ones (Fig. 3). These normal faults are consistent in trend and kinematics with post-orogenic structures dissecting the axial zone of the chain and they were formed in the frame of a NE-SW trending extensional regime established since Pliocene. These fault systems control the Quaternary seismicity and active tectonics of the area (e.g., Cello et al., 1997; Barchi et al., 2000; Tondi & Cello, 2003). In particular, the post-thrusting structures observed in the study area belong the Norcia-Mt. Fema system, that further south also displaces the western limb of the Mt. Patino anticline, and in a few cases, they exceed 1000 m in throw (i.e., Mt. Vettore and San Pellegrino-Collescille faults, e.g., Calamita & Pizzi, 1993; Calamita et al., 1993; Porreca et al., 2020). The faults located within the study area, instead, have a few hundred metres of displacement (Figs. 5 and 7). The shape of the Mt. Fema Fault displacement profile shows that this fault is constituted by two portions, each having a (local) maximum (Fig. 7). A major strand is placed toward the SE and a minor one toward the NW, the two being 'separated' by a local minimum displacement. This shape may suggest that the Mt. Fema fault growth occurred through segment linkage, i.e., fault interactions between two isolated neighbouring faults, that may allow a rise of the displacement gradient (e.g., Nicol et al., 2016). The contribution of the minor fault segments to the cumulative displacement is visible only at the ends of the aggregate displacement profile, whereas the latter match the trend of the Mt. Fema Fault profile in its central portion. The splays have variable amounts of overlap with the Mt. Fema Fault and their displacement seems to increase away from the it. This may suggest that minor fault segments branching from the Mt. Fema Fault terminations are tip splays propagating away from the parent fault (e.g., Peacock et al., 2017). However, we cannot rule out with certainty that these segments are, instead, faults that approach and intersect the Mt. Fema Fault. No evidence of surface fault reactivation has been found during our fieldwork or others (Cello et al., 2000; Vittori et al., 2000; Civico et al., 2018; Villani et al., 2018) despite several normal-faulting seismic sequences recently struck this sector of the Apennines (Cello et al., 2000; Deschamps et al., 2000; Vittori et al., 2000; Chiaraluce et al., 2003, 2017; Barchi & Mirabella, 2009; Galli et al., 2017), and several epicentres of weak earthquakes (M_w < 3.5) fell in the vicinity of our study area (http://cnt.rm.ingv.it).

If on one hand post-orogenic extensional tectonics dissect the Umbria-Marche fold and trust belt, hindering the understanding of its geometric and kinematic evolution (e.g., Calamita et al., 1994; Butler et al., 2004), the presence of pre-existing tectonic discontinuities may in turn affect the development and geometry of subsequent normal faults. In this work, the geometrical and crosscutting relationships among Quaternary normal faults and pre-existing reverse structures have not been investigated in depth. However, we recognise that the Mt. Fema area may offer interesting insights to elucidate (i) if normal faults do not displace the thrust and are detached at depth on its low-angle portion (e.g., Bally et al., 1986; Calamita et al., 1994), (ii) if the normal faults crosscut the pre-existing fold and thrust belt (e.g., Mazzoli et al., 2005), (iii) if inherited reverse structures are reactivated with extensional kinematics (e.g., Bonini et al., 2016) and control the segmentation of the seismogenic normal faults (e.g., Pizzi et al., 2017) or if, instead, (iv) more than one scenario is valid at the same time. This issue is still subject of debate since recent studies propose either that the seismogenic normal faults displace the thrusts (e.g., Porreca et al., 2020) or that thrust portions could be reactivated with extensional kinematics (Scognamiglio et al., 2018; Stendardi et al., 2020; Barchi et al., 2021; Di Bucci et al., 2021).

CONCLUSIONS

In this work we present a geological map, balanced and restored cross-sections, and a 3D geological model of the Mt. Fema area located within the 1:50,000 scale Sheet 325-Visso, in the Umbria-Marche Apennines. The most striking element of the area is an ENE-verging asymmetric anticline bounded by the NNW-SSE striking Mt. Fema Thrust. The anticline core is constituted by the Calcare Massiccio fm. outcropping in Val di Tazza and Valnerina. The fold and thrust belt in this area was shaped during the Late Miocene-Early Pleistocene orogenic phase. The cumulative dip separation along the Mt. Fema thrust system ranges from ~100 m in the northern sector (Val di Tazza) to ~500 m in the south (Valnerina). According to our interpretation, the thrust system is characterised by relatively limited displacement, unlike other interpretations where multiple thrust sheets, defined by 'ramp-on-ramp' structures, accommodate larger amounts of orogenic contraction. Whether the basement is involved or not in the main thrust structure will be clarified in a future study. The Mt. Fema area represents a key place to appreciate the Jurassic-age configuration of the passive (Adria) continental margin and its effects on the fold and thrust belt development. We do not find evidence of re-activation of inherited (E-dipping) normal faults, most likely because they were not favourably oriented with respect to the W-dipping thrusts. However, we believe that thrust location is not coincidental. Pre-existing normal faults and fault scarps produce across-strike changes in the mechanical stratigraphy of the deforming multilayer that, in turn, govern folding initiation by buckling mechanism. Eventually, the fold controls the locus of thrust propagation. Cross-section balancing and restoration highlights a phase of post-orogenic (Quaternary) extensional faulting which is recorded by a system of normal faults dissecting the flat top of the Mt. Fema box fold. Their displacement reaches a maximum of 630 m in the central area. No evidence of recent fault reactivation has been found at surface, despite recent seismic sequences hit central Italy. The 3D model of the Mt. Fema area enhances the visualisation of the subsurface structural architecture, clarifies structural geometries and kinematics of this sector of the Apennines, and may allow non-specialists to access the geological information in support of infrastructure planning and management. This work presents among the few available balanced and restored cross-sections and 3D geological models of the Apennines.

ELECTRONIC SUPPLEMENTARY MATERIAL

This article contains electronic supplementary material which is available to authorised users.

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