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Special Section:
The 2016 Central Italy Seismic Sequence: Insights, implications and lessons learned

Key Points:
- The seismic data set provides new constraints on the subsurface geology of the area affected by the 2016–2017 earthquake in Central Italy
- The main reflector below the Norcia area corresponds to the top of the acoustic basement and coincides with the cutoff of the seismicity
- The seismogenic normal faults have steep dip angles (65°–70°) close to the surface and lower (45°–50°) at hypocentral depths

Supporting Information:
- Supporting Information S1

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Seismic Reflection Profiles and Subsurface Geology of the Area Interested by the 2016–2017 Earthquake Sequence (Central Italy)

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Abstract Starting from 24 August 2016, a long seismic sequence, including nine $M_w > 5.0$ earthquakes, struck a wide area of the Central Italy. A large amount of geological, geodetic, and seismological data envisages a complex system of NNW-SSE trending, seismogenic normal faults. These active tectonic structures are well known at the surface and consistent with previous seismotectonic studies. In order to improve the comprehension of the seismotectonic framework of this seismic sequence, we provide a novel reconstruction of the subsurface geology of the area close to the Norcia M_w 6.5 mainshock (30 October 2016), based on previously unpublished seismic reflection profiles and available geological data. All the data have been synthesized along a 47 km long, WSW-ENE trending geological cross section, interpreted down to a depth of 12 km. Comparing the subsurface geological model with the available seismological data, we find that the majority of seismicity is confined within the sedimentary sequence and does not penetrate the underlying basement. The basement has been constrained at depths of 8 to 11 km and coincides with the cutoff of the seismicity. We have also traced the trajectories of the seismogenic normal faults activated during this seismic sequence, reconciling the high-angle (dip>65°) normal faults exposed at the surface, with their angle (dip < 50°) at hypocentral depths. The results of this study may be useful for better understanding the rheological properties of the seismogenic rock volume, as well as the coseismic deformations of the topographic surface observed by geodetic techniques and field mapping.

Plain Language Summary The 2016–2017 seismic sequence of the Central Italy has attracted many researchers specialized in different topics of Earth Sciences. An impressive amount of data have been collected by these researchers from field geological to deep seismological data. Despite the large number of data, a reconstruction of the deep structures from the surface to the hypocenter depths of the earthquakes is still lacking. Here we present a new geological reconstruction thanks to the interpretation of seismic data kindly provided by the Italian oil company (Eni). Even if these data have been acquired with different aims, they prove to be of great support in seismotectonic research, since the targets of oil explorations are typically located at a depth that is similar to that of the seismogenic sources. Our results confirm that seismic reflection profiles can give important insights on the subsurface geology of the seismically active areas and on the geometry of the seismogenic faults. We have identified the geometry of the main faults related either to the old compressive tectonics, responsible of the formation of the Apennines, and to the most recent extensional seismogenic tectonics.

1. Introduction

On 24 August 2016, an earthquake of M_w 6.0 (Tinti et al., 2016) struck a wide area of Central Italy, giving rise to a several months long seismic sequence, which included nine earthquakes with $M_w \geq 5$ (Figure 1). After 2 months, on 30 October 2016, a M_w 6.5 earthquake nucleated at about 7 km depth close to Norcia town (Chiaraluce, Di Stefano, et al., 2017). In this case a N151°, 47° normal fault was activated during the earthquake as indicated by focal mechanism solution (Chiaraluce, Di Stefano, et al., 2017; http://cnt.rm.ingv.it/). The seismological data (i.e., epicentral distribution and focal mechanisms of the mainshocks) clearly show that the sequence activated a 60 km long system of NNW-SSE trending normal faults, including two major WSW dipping normal faults, that is, the Mount Gorzano fault (hereinafter, Gf) and Mount

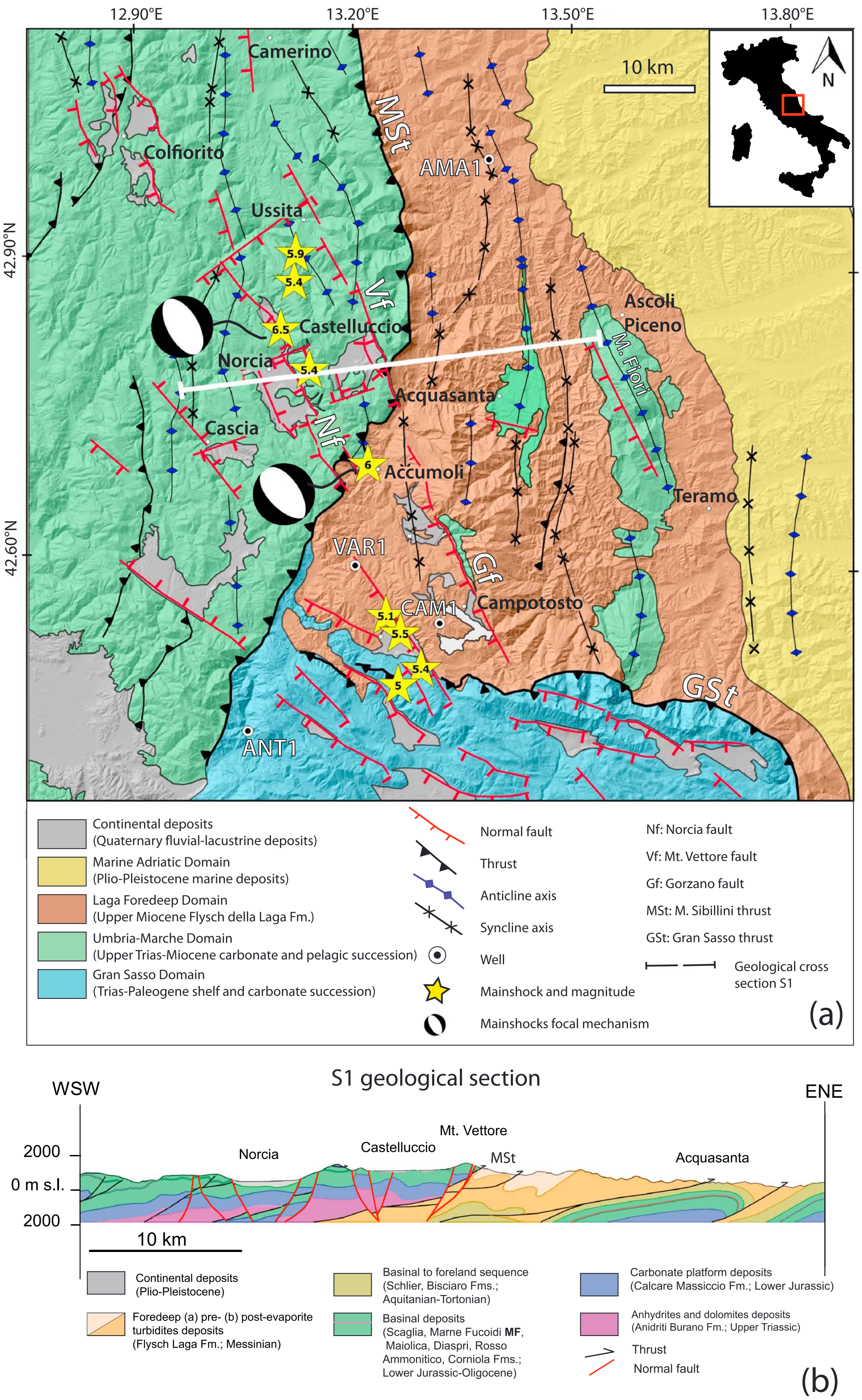

Figure 1. (a) Structural sketch of the area affected by the 2016–2017 seismic crisis with the nine mainshocks from 24 August 2016 to 30 January 2017. The trace of the geological section S1 is also reported; (b) geological cross section from north to Cascia to Montagna dei Fiori. The geological map and the section were built by means of the integration of literature data of several authors (see text for references).

Vettore fault (hereinafter, Vf), previously recognized as major seismogenic faults (Chiaraluce, Di Stefano, et al., 2017; Lavecchia et al., 2016; Pucci et al., 2017; Tinti et al., 2016). A complex set of impressive coseismic ruptures were clearly identified and described by Emergeo Working Group (2016), Livio et al. (2016), and Pucci et al. (2017). Most of the ruptures are WSW dipping with dip ranging from 55° to 70° and can be interpreted as synthetic and antithetic splays of the Vf. On contrast, along the Gf, the evidences of surface rupture are by far less outstanding.

The overall 2016–2017 seismic sequence developed along the axial ridge of the Apennines, characterized by active NE-SW extension as deduced by both seismological and geodetic data, at a rate of about 3 mm/year (Bennett et al., 2012; D'Agostino et al., 2011; Frepoli & Amato, 1997; Hunstad et al., 2003; Mariucci & Montone, 2016). The active extensional belt covers the whole Apennines from Tuscany to Calabrian arc, triggering several important earthquakes ($M > 5.5$) in the last 40 years, such as 1979 Norcia, 1980 Irpinia, 1997 Colfiorito, and 2009 L'Aquila earthquakes. For most of them, complex systems of highly segmented, NW-SE to NNW-SSE trending normal faults were identified as responsible of the mainshocks. The geometry, kinematics, and rates of some of active tectonic systems in adjacent areas of Central Italy, such as L'Aquila and Fucino Basins, have been investigated by several authors (e.g., Benedetti et al., 2013; Roberts & Michetti, 2004).

The Vf, activated during the M_w 6.5 mainshock of the 30 October 2016, is a well-known active NNW-SSE trending normal fault mapped by geologists (Boncio et al., 2004; Brozzetti & Lavecchia, 1994; Boncio & Lavecchia, 2000; Lavecchia, 1985; Pizzi et al., 2002), studied by paleoseismological approaches (Galadini & Galli, 2003), and through GPR prospections (Ercoli et al., 2013, 2014). All these studies have highlighted its seismogenic potential, even though no major historical earthquake was associated to this fault before 2016 (Galli et al., 2017). However, the area around Norcia town has been interested by several historical earthquakes, such as the 1328 M_w 6.5 and the 1703 M_w 6.8 destructive earthquakes, and the more recent the 1979 Ms 5.9 event (Deschamps et al., 1984; Rovida et al., 2016).

A first geometrical description of the main seismogenic faults activated during the 2016–2017 crisis was inferred by mainshocks and aftershocks distribution with depth by Chiaraluce, Di Stefano, et al. (2017), imaging a complex normal fault system, consisting of WSW dipping master faults and antithetic (i.e., ENE dipping) normal faults, both merging at depth along a subhorizontal (or gently east dipping) "shear zone," that also represents the cutoff seismicity layer, located between 10 and 12 km depths.

In a few months after the events, a huge amount of data has been collected and published, describing and characterizing the activated seismogenic faults: geological observations collected at the surface (see Mount Vettore seismic reactivation fault, Emergeo Working Group, 2016; Emergeo Working Group et al., 2016; Emergeo Working Group, 2017; Livio et al., 2016; Pucci et al., 2017), geodetic data (differential interferometric synthetic radar, Lavecchia et al., 2016; Global Navigation Satellite Systems and Global Positioning System, Wilkinson et al., 2017; Cheloni et al., 2017; Liu et al., 2017; De Guidi et al., 2017), and seismological data, describing the fault geometry and kinematics at hypocenter depths (Chiaraluce, Di Stefano, et al., 2017; Pizzi et al., 2017; Tinti et al., 2016). In spite of this great advance in knowledge, poor constraints are still available about the subsurface geological setting and in particular about the deep geological structures, connecting the surface ruptures to the hypocenter depths. The study of the relationships between coseismic evidence at the surface and deep tectonic structures may be complicated due to the lacking of clear subsurface images. In particular, a strong debate exists in literature about the geometry of the seismogenic faults and its relationships with inherited tectonic structures (e.g., Bonini et al., 2016; Lavecchia et al., 2016; Valensise et al., 2016), such as thrusts or reverse faults developed during the Miocene compressional phase.

In this work, we try to improve the subsurface seismotectonic reconstruction of this area by means of geological interpretation of seismic reflection profiles. Though conceived for oil exploration, recent works have demonstrated that the use of seismic reflection profiles can help to unravel the depth geometry of the seismogenic faults, as well as the rocks involved in the seismic ruptures (Barchi & Mirabella, 2009; Bigi et al., 2013; Bonini et al., 2014; Fuis et al., 2003; Maesano et al., 2015; Mirabella et al., 2008). In particular, in the area of the 1997–1998 Colfiorito seismic sequence, the seismic profiles have been useful to demonstrate how the complex mechanical stratigraphy of the region plays a relevant role in controlling the earthquake distribution (Barchi & Mirabella, 2009; Mirabella et al., 2008). In this case, most of the seismicity was distributed in the Mesozoic-Early Tertiary carbonates and evaporites, whereas the seismicity cutoff was controlled by the underlying acoustic basement.

A detailed reconstruction of the subsurface geology has also strong implications on the definition of the velocity models, used to localize the hypocenters. Recent studies performed in northern Umbria (Latorre et al., 2016) demonstrated that geologically constrained 3-D velocity models can provide a more accurate earthquake location, as well as constraints on the relationship between lithology (and rheology) and earthquake nucleation.

Here we present a preliminary, 2-D deep geological reconstruction of the area interested by the M_w 6.5 event, along a 47 km long WSW-ENE section crossing the Norcia Basin, the Vf, and the Mount Sibillini thrust (hereinafter, MSt) (Koopman, 1983; Lavecchia, 1985, Figure 1). This section was constructed by means of integration of surface geology and subsurface data, such as seismic profiles and wells data. The seismic profiles used in this work represent a small portion of the entire data set and show subsurface structures down to a maximum depth of 5 s (Two-Way Time, TWT), corresponding to 12–14 km. The results of this work propose to give new insights on the subsurface structure of the area affected by the seismic sequence, focusing on

- the along-dip geometry of the main faults activated during the 2016–2017 sequence,
- their relationships with preexisting faults (thrusts and normal faults), and
- the lithologies where the mainshocks are nucleated.

2. Geological Setting

The area interested by 2016–2017 seismic sequence is located in a tectonically complex region, at the boundary between the northern and central Apennines of Italy (Figure 1). Here three major structural domains interact: the Umbria-Marche Domain, that is, the southeastern part of the Umbria-Marche fold and thrust belt (e.g., Barchi et al., 2001; Pauselli et al., 2006); the Gran Sasso Domain, representing the transition between the pelagic basinal area and the southernmost Latium-Abruzzi Platform (Ghisetti & Vezzani, 1991); and the Laga foredeep Domain, where Upper Miocene–Pliocene syn-orogenic siliciclastic deposits extensively crop out (Flysch della Laga Fm.; Centamore et al., 1992).

The structural evolution of this region is characterized by Late Miocene-Early Pliocene compressional phase, followed by Late Pliocene-Quaternary extension (e.g., Cosentino et al., 2010, 2017; Pauselli et al., 2006). The compressional structures show a very complex pattern: both Umbria-Marche and Gran Sasso Domains overthrust the Laga Domain, through arc-shaped major thrusts, namely the MSt (Koopman,1983; Lavecchia, 1985) and the Gran Sasso thrust (Ghisetti & Vezzani, 1991), with eastward or northward convexity, respectively. The Umbria-Marche Domain overthrusts the Gran Sasso Domain along the southern part of the MSt (the Olevano-Antrodoco alignment, sensu Salvini & Vittori, 1982; Cipollari et al., 1997). The fold axes associated to these thrust systems mainly trend N-S in the Umbria-Marche and Laga Domains, WNW-ESE in the Gran Sasso Domain.

Despite this complexity, the later normal faults seem to crosscut the compressional structures, maintaining a regular, NNW-SSE alignment, at least across the Umbria-Marche and Laga Domains. Since Late Pliocene-Lower Pleistocene, the activity of these extensional faults promoted the formation of continental basins (Calamita et al., 1994; Cavinato & De Celles, 1999; Lavecchia et al., 1994, 2002). These basins are generally controlled by WSW dipping normal faults and are filled by hundreds of meters thick of fine to coarse grain sediments deposited in lacustrine and fluvial paleoenvironments (Blumetti et al., 1993; Boncio et al., 1998, 2004; Porreca et al., 2016).

Within this geologically complex region, the geological section constructed in this work, is localized in the easternmost part of the northern Apennines fold and thrust belt, including both the Umbria-Marche and the Laga foredeep Domains (Figure 1). The Umbria-Marche fold and thrust belt involve the rocks of the sedimentary cover, which consists of three major lithological groups (Figure 2). From top to bottom, these are

- foredeep and foreland sequence (Late Miocene–Pliocene, up to 3000 m thick) made from alternating layers of sandstones and marls;
- carbonates (Jurassic-Oligocene, about 2000 m thick), consisting of an Early Jurassic carbonate platform (Calcare Massiccio Fm.), overlain by pelagic limestones with subordinated marly levels;
- evaporites (Late Triassic, 1500–2000 m thick) made from alternating layers of anhydrites and dolomites (Anidriti di Burano Fm.; Martinis & Pieri, 1964).

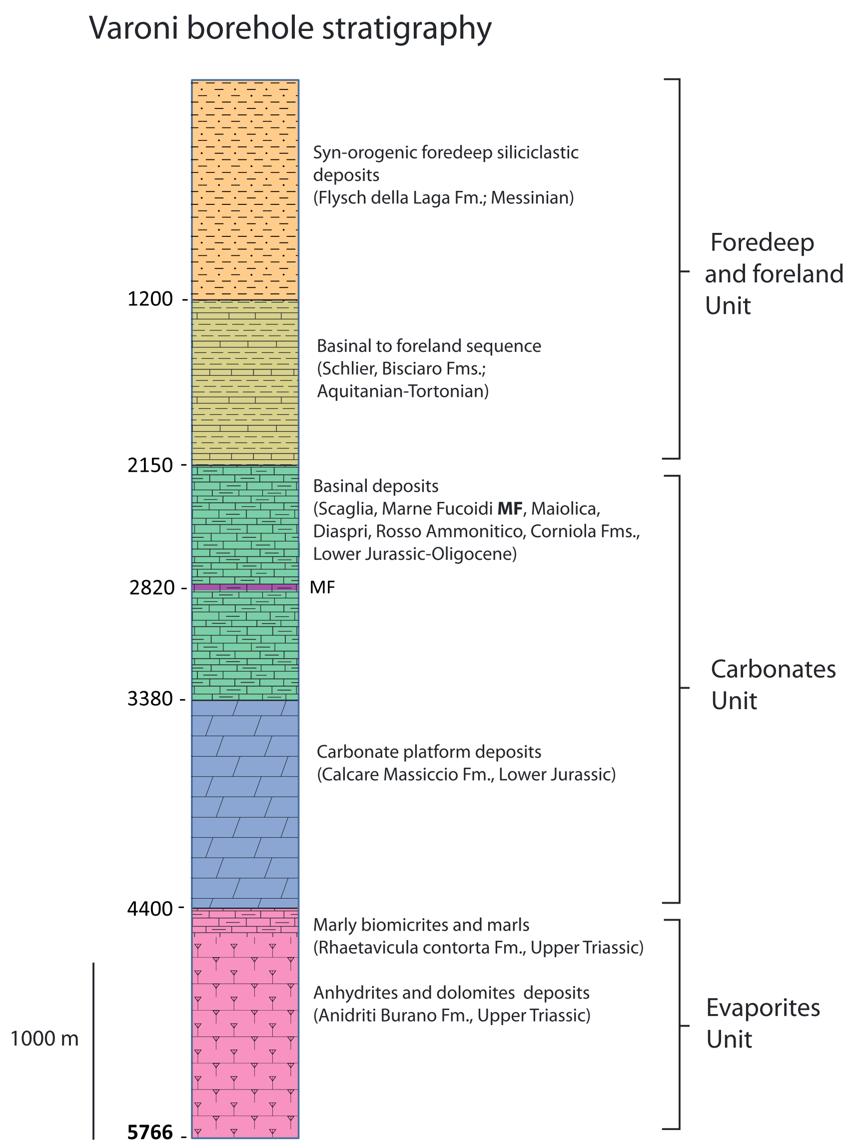

Figure 2. Stratigraphic columns of the Late Triassic-Upper Miocene sedimentary succession in the Amatrice-Norcia area as inferred by the Varoni1 well (see the location in the map of Figure 1a).

The Triassic evaporites act as an important regional detachment, separating the sedimentary cover units from the underlying basement s.l. (sensu Bally et al., 1986). Other secondary detachment levels are localized in the upper part of the sedimentary sequence, that is, at the base of the Miocene Flysch della Laga Fm. and within the Cretaceous Marne a Fucoidi Fm. (Barchi et al., 1998; Koopman, 1983; Massoli et al., 2006). The basement never crops out, is penetrated only by a few deep wells, all located far away from the study area, and shows an accentuated lithological variability (e.g., Alessandra1 and Puglia1; Bally et al., 1986; Patacca & Scandone, 2001).

The geological section of Figure 1b, along which the seismic interpretation was carried out, shows the main tectonic and sedimentary characters as described in previous works and geological maps (Bally et al., 1986; Centamore et al., 1992; Koopman, 1983; Pierantoni et al., 2013; Carta Geologica Regionale 1:10000 – Regione Marche, 2014; Carta Geologica Regionale 1:10000 – Regione Umbria, 2016). Here it is possible to recognize four tectonic units, separated by major thrusts. From east to west they are

- Montagna dei Fiori (MDF) and Acquasanta (ACQ) units, at the footwall of the MSt;
- Mount Vettore (VET), Norcia (NOR) and Cascia unit (CAS), at the hanging wall of the MSt.

Table 1
Main Geometrical Parameters and Depth Values of the Geological Sections Interpreted by Different Authors and This Work

			Compressional structures			Extensional structures		
Regional sections	Section length (km)	Basement depth (km)	Style	Detachment depth (km)	Shortening (km)	Max depth (km)	Max throw (km)	Elongation (km)
Bally et al. (1986)	133	10–12	TnS	11	130 (53%)	2–5	1.5	3.2 (2.5%)
Calamita & Pizzi (1994)	42	8–13.5	TnS	9	90 (68%)	2–13	1.7	2.0 (10%)
Lavecchia et al. (1994)	148	4–12	TkS	11	42 (22%)	8–11	1.3	10 (7%)
Bigi et al. (1999)	114	11	TkS[a]	11	60 (40%)	2–5	1	1.7 (2%)
Bigi et al. (2011)	63	n.a.	TnS	11	12 (19%)	7	0.8	0.6 (1%)
Scisciani et al. (2014)	61	6–11	TkS	5[b]	7.7 (10%)	2.5–9	1	2.5 (3%)
This study	47	7–10	TkS	9	65 (60%)	7–9	1.4	2.2 (5%)

Note. Section length: the length of the section as published in literature; basement depth: the depth range of the basement along the section. Compression - Style: TnS and TkS, thin and thick-skinned tectonic style, respectively; detachment depth: the depth of the detachment measured under the MSt (with its lateral variations). Extension - max depth: the maximum detachment depth of the normal faults; max throw: the maximum throw of the normal faults; elongation: the cumulative faults heave in absolute values (km) and in percentage. n.a. = not available.
[a]In the interpretation of Bigi et al. (1999) the basement is involved in the belt, but most of the shortening appears to be related to a thin-skinned doubling of the sedimentary cover. [b]This interpretation does not consider a regional basal detachment, so the depth range is referred to the maximum depth of the Paleozoic-Triassic sedimentary sequence.

The tectonic style is characterized by important amount of shortening along the main thrusts with a progressive nucleation of the compressional structures toward the foreland (i.e., toward ENE). The main detachment is localized at the base of the evaporites sequence and involves the whole sedimentary sequence deformed in a NE verging anticlines. These anticlines are characterized by overturned forelimb and gently west dipping backlimbs, associated with outcropping or blind thrusts. The siliciclastic foredeep sequence outcrops only to east of the MSt and is strongly deformed with frequent low-amplitude folds detached with respect to the carbonate sequence. The whole investigated sector is in turn interested by extensional tectonics with both WSW and ENE dipping normal faults, which control the deposition of important continental basins such as Norcia and Castelluccio Basins. Such NNW trending faults are still active as demonstrated by historical and instrumental seismicity.

3. Previous Studies

The Umbria-Marche Apennines and Laga Basin have been studied by several authors since more than one century. During the 1980s and 1990s, this area was actively investigated for hydrocarbon resources detection, mainly by means of seismic reflection prospections and explorative wells.

Koopman (1983) performed a detailed structural analysis of the external part of the Umbria-Marche Apennines, interpreting the thrust imbrication as controlled by thin-skinned tectonics with two main detachment levels: a lower detachment at the base of the sedimentary cover (within the Anidriti di Burano Fm.) and an upper detachment below the Flysch della Laga Fm. (Laga detachment zone). He also noted the occurrence of important normal faults dissecting the thrust belt, such as the Mount Gorzano (Gf) and Mount Vettore (Vf) faults.

The subsurface data coming from hydrocarbon exploration were considered for the first time by Bally et al. (1986), who performed balanced cross sections between the Adriatic Sea and the Umbria-Marche Apennines. Their thin-skinned interpretation includes a series of east verging imbricate thrust sheets, producing tectonic repetitions of the Umbria-Marche pelagic sequence. According to a long-lasting opinion (e.g., Baldacci et al., 1967; Koopman, 1983), they recognized the main detachment level at the base of the Triassic evaporites of the Anidriti di Burano Fm., at ~ 11 km of depth (Table 1). A series of subsequent, listric normal faults were interpreted, detached above the uppermost thrust splays at depth comprised between 2 and 5 km.

Calamita and Pizzi (1994) used geological sections constructed by Boccaletti et al. (1990) and Calamita et al. (1994) in order to understand the relationships between the compressional structures and the superimposed extensional faults. Their interpretation of the compressional structures does not differ significantly from that of Bally et al. (1986); however, they recognized some normal faults (e.g., the Vf) cutting the entire tectonic pile down to the seismogenic depths of 10–12 km, close to the basal detachment at the base of the Triassic evaporites (top basement s.l.).

In the same year, Lavecchia et al. (1994) proposed a geological section from Umbria region to Adriatic Sea integrating geological (Barchi, 1991) and subsurface data. The proposed structural style is characterized by basement-involved tectonics with a multiple detachment system. The section also depicts graben-bounding high-angle faults that at shallow levels dislocate preexisting fold and thrust belt structures. In this case the basement is located between 3 and 8 km of depth, whereas the main normal faults are detached at depths of 8 to 10 km (Table 1).

Bigi et al. (1999) proposed a geological section through the Umbria-Marche Apennines admitting a partial involvement of the basement, which was identified at ~11 km of depth (Tab. 1). In their interpretation, the sedimentary cover is internally doubled by duplex systems, which are in turn dissected by thrust faults splaying out from the underlying basement. The normal faults, characterized by listric geometry, all dip toward SW and are detached at relatively shallow depths comprised between 2 and 5 km. After this work, the same authors (Bigi et al., 2011) proposed a different geological interpretation, based on seismic interpretation of 200 km of seismic profiles and well data, where the compressional structures produce a much more limited shortening and the involvement of the crystalline basement is questioned. The normal faults, such as the Gf, are detached at ~ 4 km of depth.

In more recent years, Scisciani and Montefalcone (2006) and Scisciani et al. (2014) have constructed geological balanced cross sections from the Umbria-Marche Apennines to the Adriatic foreland using fieldwork data, existing geological maps, new seismic data, and well information. Their interpretation of the Apennines is extremely different from the previous ones. The basement is strongly involved into the compressional phase, as inversion of Permian-Triassic major normal faults: consequently, a much lower amount of shortening is proposed (Tab. 1), whereas the top basement depth significantly varies laterally across the section, between 6 and 11 km. The authors also speculated that the Plio-Quaternary extensional faults would be the reactivation of precompressive extensional structures inherited from the foreland flexure. Their expression is represented by high-angle normal faults responsible of intermontane basins and seismicity, reaching depths comprised between 2.5 and 9 km.

Table 1 reports a synthesis of the tectonic style (thin-skinned versus thick-skinned tectonics), main geometrical parameters, and estimation of shortening and extension as deduced by the cross sections of the different authors and this work. Summarizing, most of the interpretations agree on the maximum depth of the basement (10–12 km) and about the role of the Triassic evaporites as the main regional detachment at the base of the Umbria-Marche fold and thrust belt. On the contrast, several differences concern the structural style (i.e., thin-skinned versus thick-skinned tectonic style), the magnitude of shortening, and the depth and dip of the normal faults, which, in many cases, do not reach the seismogenetic depths. The supposed, shallow detachment depth of the normal fault is also not reconcilable with observed, limited amount of tilting in the hanging wall blocks. Moreover, their steep geometry is not always consistent with that provided by the solution of the focal mechanisms. In this work, we try to clarify the geometrical features of the seismogenic normal faults, activated during the 2016–2017 sequence, and the involved lithologies.

4. Methods and Data

Central Italy has been extensively explored by the Italian Agip (presently Eni S.p.A.) since the 1930s by using different geophysical prospections and boreholes. In this work, we use a new data set of previously unpublished 2-D seismic reflection profiles, provided by ENI S.p.A. Additional seismic sections and boreholes log were extracted from the public database "Visibility of petroleum exploration data in Italy" (Videpi Project, 2017; www.videpi.com).

The entire data set consists of 97 seismic reflection profiles and 4 boreholes (Varoni1, Campotosto1, Antrodoco1, and Amandola1) (Figure 3). The data set encompasses both stack and time-migrated seismic reflection lines, characterized by a variable quality, due to several factors. First, their acquisition spanned the period 1970–1998, so different equipment and technologies have been used. Among them, some were recorded by using Vibroseis sources, while many others through dynamite, that generally generated higher-quality images. Commonly, the total number of samples, common depth points (CDPs), is different due to variable directions and lengths (from less than 2 km up to ~50 km); the time window varies between 5.0 s and 7.0 s (TWT), grossly corresponding to maximum depths of about 12–20 km; and the datum planes are different as well, varying from 0, 100, 200, to 500 m above sea level. Issues regarding coordinates accuracy and amplitudes were also found in some lines and have been progressively fixed, in order to obtain

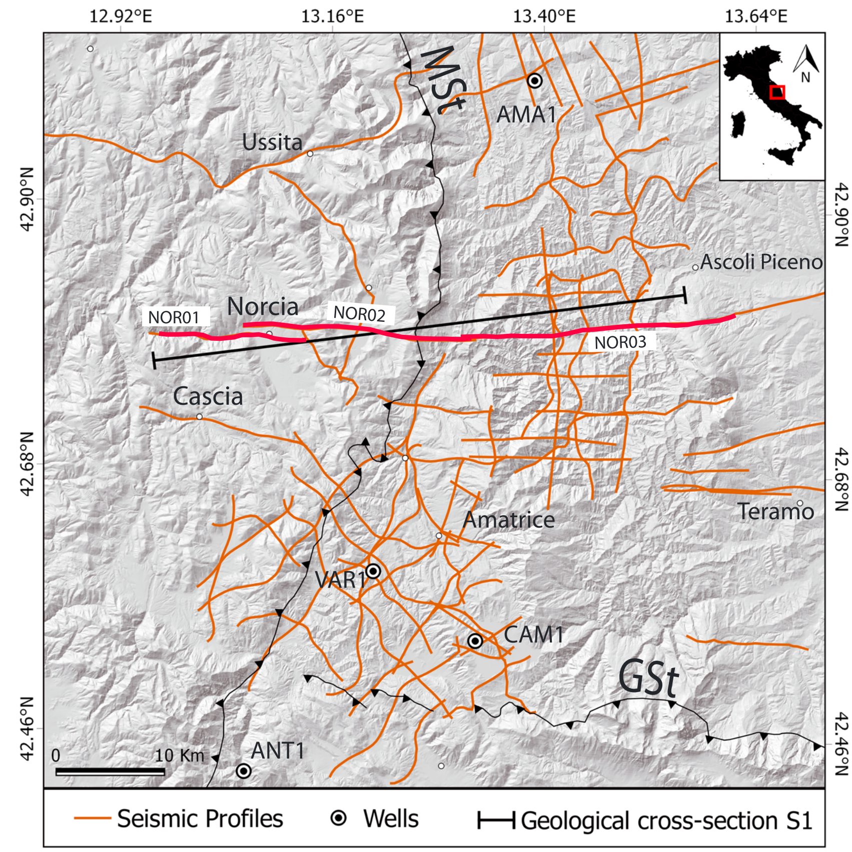

Figure 3. Location map of the seismic reflection profiles and wells used in this study. The red lines indicate the seismic profiles projected along the trace of the geological section S1. MSt = Mount Sibillini thrust; GSt = Gran Sasso thrust; AMA1 = Amandola1; CAM1 = Campotosto1; ANT1 = Antrodoco1; VAR1 = Varoni1.

accurate and coherent intersections among lines. Finally, the unpublished profiles are in SEG-Y format (http://seg.org/Publications/SEG-Technical-Standards), while the VIDEPI sections are available only as digital images.

For all the above listed reasons, the data integration on a unique seismic project was a challenging task, due to inhomogeneous characteristics of such seismic files. To accomplish this objective, we loaded and interpreted the entire data set by using the Midland software MoveTM (https://www.mve.com/), accurately accounting for crooked paths and for datum time shifts (here fixed at 500 m above sea level). In the same georeferenced database we also included additional data encompassing published geological sections and maps (Bally et al., 1986; Centamore et al., 1992; Koopman, 1983; Pierantoni et al., 2013); the National and Regional Official Cartography (Carta Geologica Regionale 1:10000 – Regione Marche, 2014; Carta Geologica Regionale 1:10000 – Regione Umbria, 2016); a digital terrain model of the area (Tarquini et al., 2007; Tarquini et al., 2012); and earthquakes hypocenters distribution from Chiaraluce, Di Stefano, et al. (2017) covering the period of interest (24 August 2016 to 29 November 2016). Such workflow enabled us to build an integrated pseudo-three-dimensional project of the study area, providing a novel and multidisciplinary working environment for the imaging of the geologic subsurface structures.

5. Seismic Interpretation

5.1. Seismic Stratigraphy and Velocity Model

The correspondence between the main lithological units of the regional stratigraphy and the seismic stratigraphy recognizable in the profiles is established on the basis of previous experience in the same region (e.g., Bally et al., 1986; Barchi et al., 1998; Bigi et al., 2011; Mirabella et al., 2008, 2011) and through the calibration of the deep wells (i.e., Varoni1, Campotosto1, Antrodoco1, and Amandola1 wells; Figure 3). We identify four seismostratigraphic units subdivided in function of their seismic facies and considering the presence of

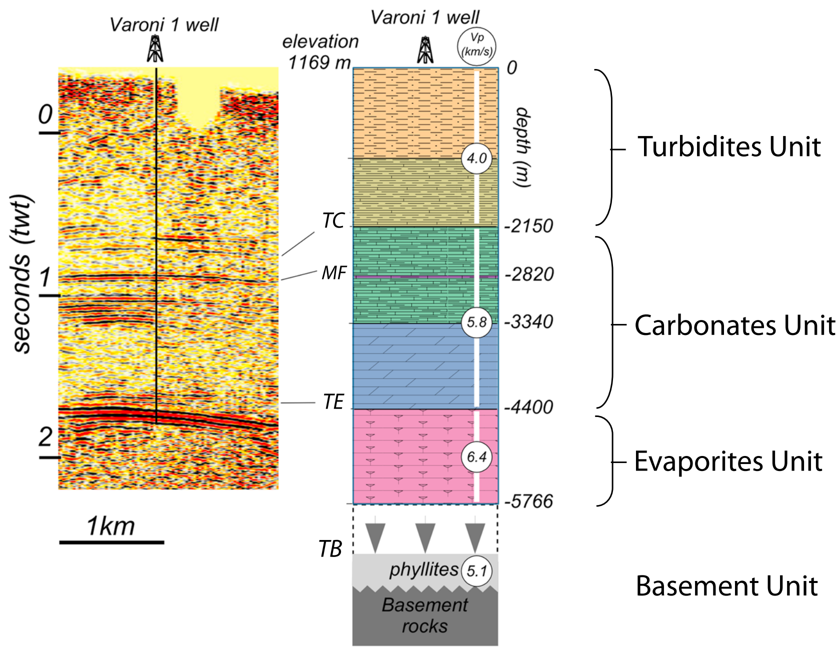

Figure 4. Seismic stratigraphy of the study area calibrated with Varoni1 well (see the map of Figure 1 for well location). The main reflectors of the sedimentary sequence used in this work are TC, top of the Scaglia group, that is, top of the carbonates unit; MF, top of the Marne a Fucoidi Formation; TE, top of the Triassic evaporites (Anidriti di Burano Formation); TB, top of the acoustic basement (basement s.l.). Vp, *P* wave seismic velocity. See text and Figure 2 for further details on the stratigraphy.

significant markers within or bordering them. From top to bottom, these seismostratigraphic units are turbidites, carbonates, evaporites, and basement s.l. (Figure 4).

The turbidites unit includes the Messinian-Lower Pliocene sandstones (Flysch della Laga Fm.) and the underlying, thick marly succession (Tertiary Marly Group, sensu Cooper & Burbi, 1988). This seismostratigraphic unit was penetrated for over 2 km by the Varoni1 well (Figure 4): the uppermost part (Flysch della Laga Fm.) is characterized by low-frequency, medium-amplitude reflectors, while the lower part is a relatively transparent seismic facies, signed by a stronger and continuous reflector in correspondence of its base.

The carbonates unit corresponds to the Umbria-Marche Meso-Cenozoic sequence, including a pelagic multilayer and the underlying Lower Jurassic thick carbonate platform (Calcare Massiccio Fm.). The carbonates unit is signed by some continuous and well recognizable reflectors, the most prominent of which are related to the top Scaglia Fm. and to the Marne a Fucoidi Fm. (Aptian-Albian), regional horizons well traceable in the seismic reflection profiles. This unit is about 2.3 km thick in the Varoni1 well, corresponding to about 0.75 s (TWT) (Figure 4).

The evaporites unit (mainly corresponding to the thick, Late Triassic Anidriti di Burano Fm., Martinis & Pieri, 1964) is generally characterized by a seismically transparent facies, locally topped by stronger, layered reflectors. These latter can be representative of the stratified dolomites and marls on top of the Anidriti di Burano Fm. (Calcari e Marne a Rhaetavicula Contorta Fm., Figure 2).

The top of the basement s.l. unit is signed by a group of high-amplitude, low continuity, often oblique reflections, with very good evidence below the VET and the ACQ anticlines. This prominent reflector is linked to a remarkable event of velocity inversion, passing from more than 6 km/s (evaporites unit) to about 5 km/s (basement unit), as also described by previous authors in other areas of the Umbria-Marche regions (e.g., Bally et al., 1986; Mirabella et al., 2008).

The depth conversion of the interpreted seismic profiles was performed using interval velocity data, measured in the deep boreholes of the region, and considering the data sets compiled in previous studies of the Umbria-Marche Apennines stratigraphy, reported in Table 2 (Bally et al., 1986; Barchi et al., 1998; Bigi et al., 2011; Latorre et al., 2016). The velocity values adopted for our simplified velocity model are summarized in Figure 4.

5.2. Description of the Seismic Profiles

The seismic interpretation has been performed along a 47 km long, WSW-ENE trending, composite seismic section obtained by a set of three seismic reflection profiles, here labeled as NOR01, NOR02, and NOR03 (Figure S1

Table 2
Seismic Interval Velocities (m/s) of the Main Lithostratigraphic Units of the Apennines

	Bally et al. (1986)	Barchi et al. (1998)	Bigi et al. (2011)	Latorre et al. (2016)[a]
Plio-Pleistocene	2400	2500	-	-
Miocene turbidites	3600	4000	3600	3900
Marly group	3400	4000	4500	-
Scaglia group	4500	-	5800	-
Carbonate multilayer	5200	5500	6100	5700
Calcare Massiccio Formation	6100	-	6400	-
Evaporites	6300	6200	6040	6300
Basement s.l. (phyllites)	3900	5000	-	5300

[a]Average velocities from in situ and laboratory measurements.

in the supporting information), from west to east (Figure 3). The section runs from the area west to Norcia Basin, crossing the Mount Vettore, to the western flank of the Montagna dei Fiori anticline, south of Ascoli Piceno (Figure 1). The interpretation of the seismic data has been supported by comparison with other seismic profiles, both parallel and orthogonally oriented with respect to the three above mentioned profiles (Figure 3). The quality of the seismic data is quite variable, generally increasing from west to east, depending on many factors, including the acquisition technologies and processing strategies (cf. Chapter 4) and the lithology exposed at the surface. It is common knowledge that seismic exploration in the Apennines is hampered by several factors, such as the complex tectonic setting, outcropping lithology, and poor accessibility: low signal penetration often characterizes these data, particularly in the mountainous

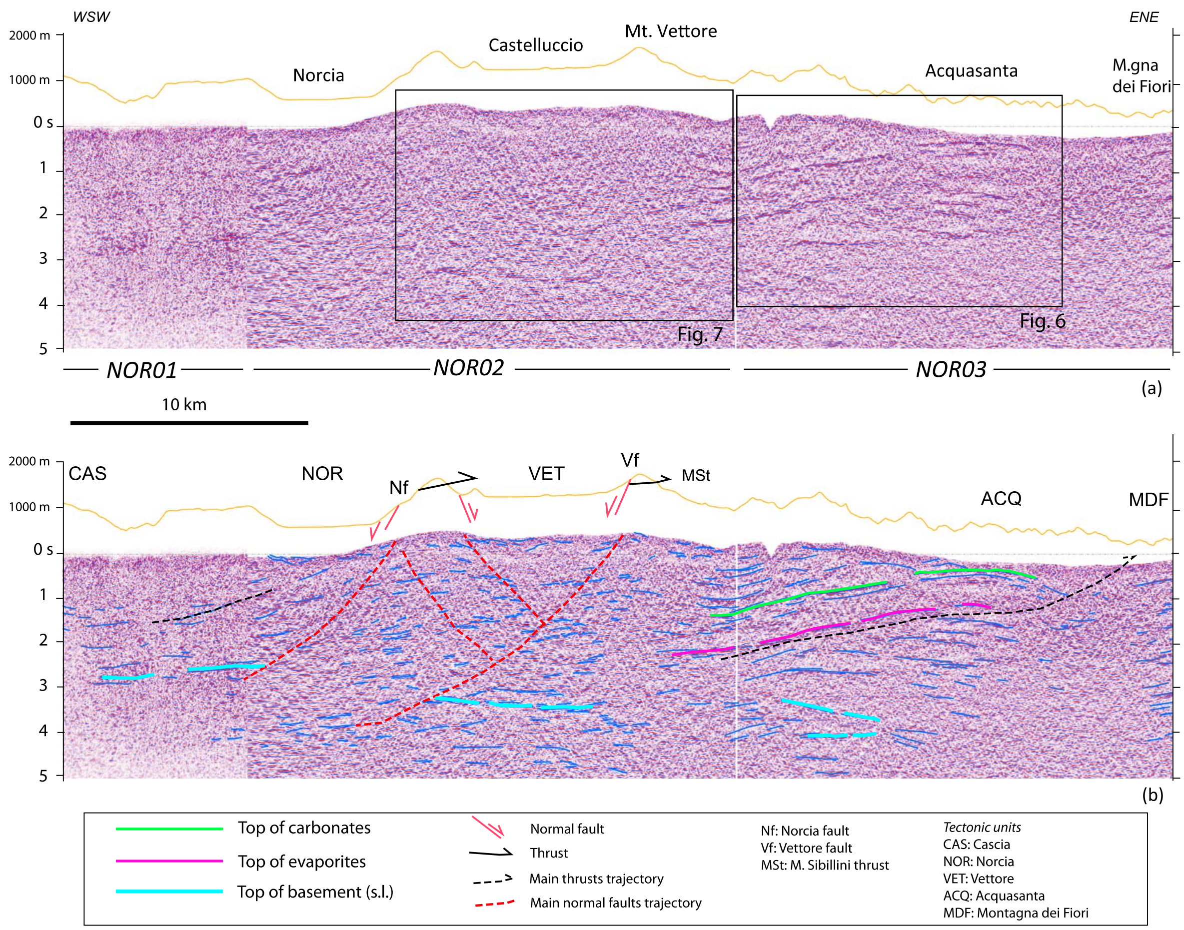

Figure 5. Composite seismic reflectors scheme. (a) Composition of three seismic profiles (NOR01, NOR02, and NOR03) and (b) scheme of the main reflectors. The topographic profile is also reported in the upper part of the seismic profiles.

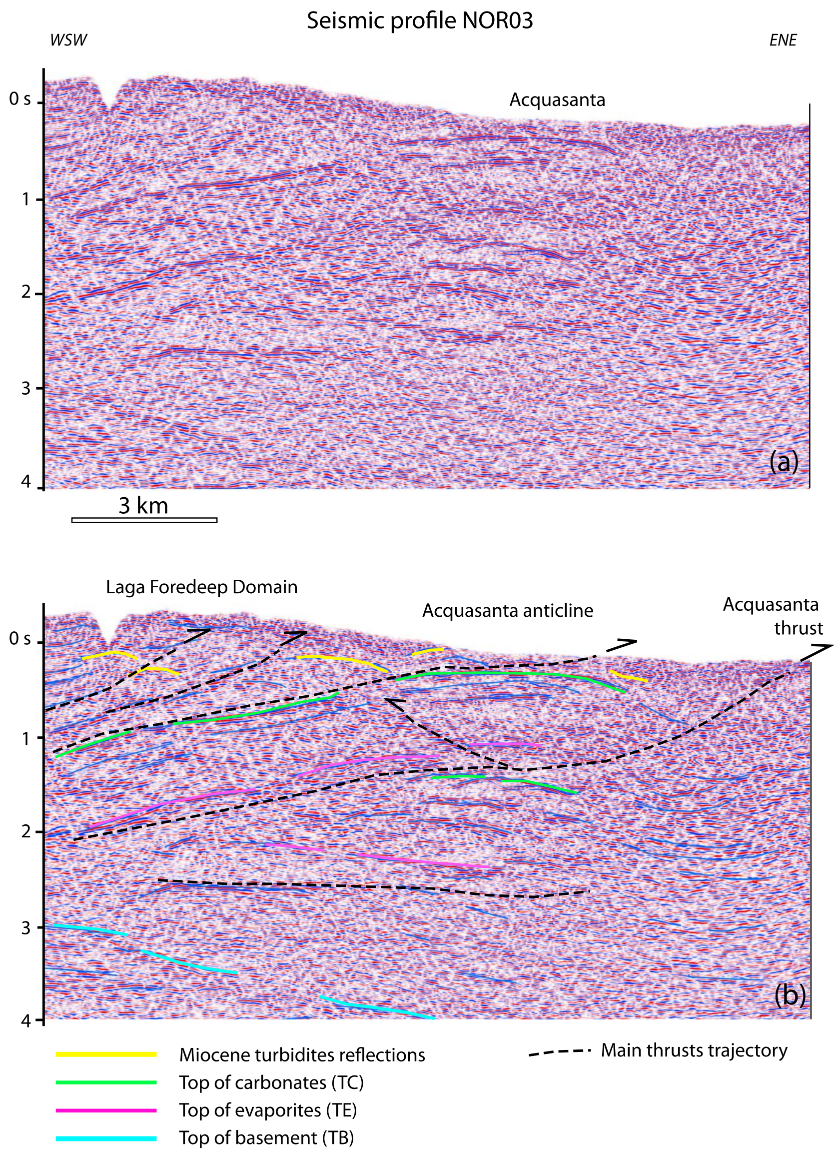

Figure 6. Seismic reflection profile (NOR03) from the external part of the Mount Sibillini thrust to the Acquasanta town. Continuous reflectors are visible in the upper part depicting an anticline structure in proximity of Acquasanta. Deep reflectors are evident up to 4.0 s (Two-Way Time).

areas where the carbonates (and/or the gravels infilling the recent intermountain basins) are exposed at the surface (Mazzotti et al., 2000). Consequently, the area at the footwall of the MSt (i.e., the Laga Domain, NOR03 in Figure 5a) is well resolved by the seismic data showing a better signal-to-noise (S/N) ratio with respect to the area at the hanging wall (i.e., the Umbria-Marche Domain, NOR01 and NOR02 in Figure 5a).

The details of the subsurface structures of the Laga Domain, that is, east of the MSt, are shown in the seismic profile NOR03 (Figure 6). This profile is dominated by the east verging ACQ anticline, a box-shaped fold, with a major west dipping forethrust (the ACQ thrust) and a steeper back thrust. The anticline involves the carbonates and the evaporites, whose geometry is clearly imaged by the attitude of the Top Scaglia reflector and by other subparallel reflections, including the top evaporites. Toward the western end of the profile, the west dipping top Scaglia can be easily traced down to 1.2 s (TWT). Above this major reflector, the overlying turbidites reflectors are intensely deformed, imaging a complex pattern of asymmetric, NE verging, low-wavelength folds, related to a set of imbricated, west dipping blind thrusts. The basal detachment of this shallow thrust system was mapped at the surface by Koopman (1983), who described this major décollement level as the “Laga Detachment Zone”. Just beneath the axial zone of the ACQ anticline, a group of gently east dipping reflections images the carbonates and evaporites down to a depth of at least 2.5 s (TWT), at the footwall of the ACQ thrust, whose trajectory at depth is effectively imaged by the different attitude of the carbonate reflectors at its hanging wall and footwall, respectively (Figure 6). This structural setting implies that a considerable amount of shortening (several km) is accommodated by the ACQ thrust, in contrast with previously proposed interpretations (Bigi et al., 2011), where the structural style of the Laga Domain is characterized by relatively high-angle thrust planes (40–45°), with limited displacement.

Summarizing, the profile NOR03 offers an excellent example of the structural style of the region, characterized by the presence of a system of multiple detachment, as previously described by Barchi et al. (1998) and Massoli et al. (2006). In fact, the ACQ structure is characterized by the presence and activity of at least two major decollements: the upper one is located above the top of the carbonates (Laga Detachment Zone, sensu Koopman, 1983; shallow imbricates, sensu Barchi, 2010); the deeper one is located within the evaporites and represents the basal detachment of the ACQ anticline.

The central profile NOR02 mainly crosses the Umbria-Marche Domain, at the hanging wall of the MSt (Figure 7). Compared to NOR03, this seismic profile is characterized by scattered reflectivity and by a relatively poor resolution. Notwithstanding, it still offers some significant points of interest for understanding of the subsurface structure. The most important feature of the profile is the prominent, gently east dipping package of reflectors, characterizing the central part of the profile, just beneath the Castelluccio Basin, at a depth of 3.2–3.5 s (TWT). These high-amplitude, low-frequency reflectors are continuous for at least 8 km and are sharply interrupted, at their western edge, below the eastern sector of the Norcia Basin, while toward the east, they may be continued along a deeper and steeper trace. Their attitude, amplitude, and depth are similar to analogous events, recognized in adjacent, northernmost sectors of the Umbria-Marche Apennines, and interpreted as corresponding to the top of the acoustic basement (e.g., Ciaccio et al., 2005; Mirabella et al., 2008). Above this major event, several west dipping reflectors can be observed, tracing the attitude of deep carbonates units. The distribution of these packages of near-parallel reflectors suggests the presence of stacked tectonic units of carbonates and evaporites, down to a depth of at least 3 s (TWT). The low quality of the seismic data hinders a precise tracing of the normal faults, widely outcropping in the area between Norcia and Castelluccio extensional basins. Their recognition in the seismic data is also hampered by their relatively steep geometry and by the fact that they separate rocks with similar seismic behavior at hanging wall and footwall. Similar problems limited a reliable interpretation of extensional tectonics in other mountain areas of the Apennines, such as the Colfiorito area (Mirabella et al., 2008). However, below the Castelluccio Basin we recognized a triangle-shaped zone where short, well-defined reflections are sharply interrupted and/or displaced along relatively steep discontinuities, with both east and west dipping attitude. We interpret these geometries as evidences of conjugate systems of opposite dipping normal faults. By comparison with topography and surface geological setting (see geological profile of Figure 1b), two of these discontinuities may be reasonably associated to the major west dipping normal faults, bordering the Castelluccio and Norcia Basins. In particular, the trace of the normal fault controlling the eastern flank of the Castelluccio Basin (i.e., the seismogenic Vf) can be connected at depth to a clear low-angle westward dipping discontinuity that interrupts the reflectors at 3.2 s below the Norcia Basin.

Similar to NOR02, the profile NOR01 is also characterized by an overall poor quality, as shown in the westernmost part of the merged seismic section (Figure 5). In the deeper part of the profile, a set of flat or gently west dipping reflectors image the position and attitude of the deeper carbonates and evaporites Units, down to a depth of about 3 s (TWT). Steeper reflections recognizable in the upper part of the profile can be related to thrust ramps and, in the shallower portion, may be connected with the intensely folded/faulted strata of carbonate rocks, exposed at the surface in the area west to Norcia Basin (Figure 1b).

The three interpreted seismic profiles NOR01, NOR02, and NOR03 have been merged and projected into a vertical section, supporting the interpretation of the geological section S1 (see trace in Figure 3), described in the next section. In the shallower part of the merged section, at the front of the MSt, we observe a deep synclinorium, where intensely deformed strata of the turbidites unit (up to 1.5 s TWT thick) are detached over the inner flank of the ACQ anticline. Below the synclinorium, the merged section shows the westward continuation of the ACQ carbonate unit, reaching a depth of about 1.5 s (top Scaglia) and 2.4 s (top evaporites) beneath Mount Vettore (Figure 5). Considering the depth, thickness, and attitude of this unit, it is evident that an intermediate tectonic unit is to be hypothesized, filling the available space between the MSt and the top of the ACQ unit. Evidences of this intermediate tectonic unit have been recognized by

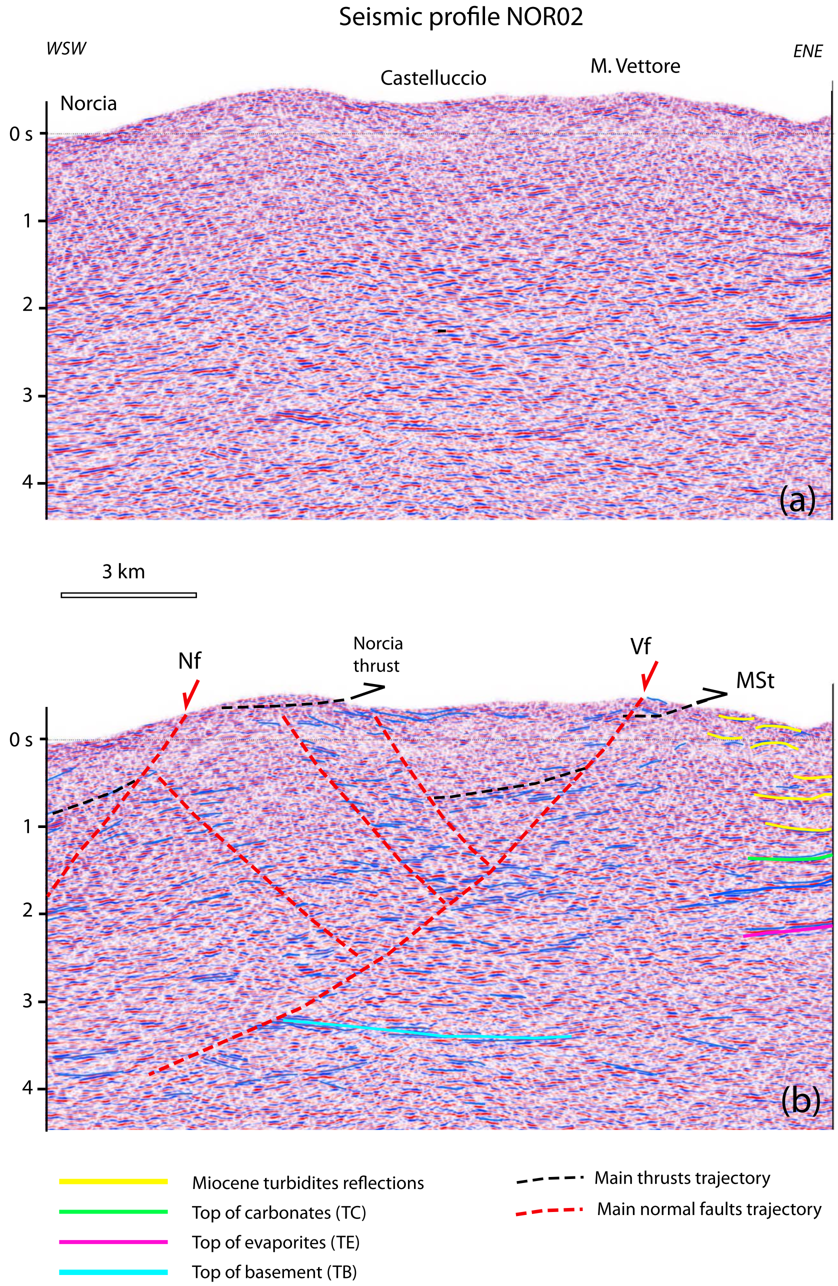

Figure 7. Seismic reflection profile (NOR02) crossing Norcia-Castelluccio-Mount Vettore. Good reflectors are visible in the external front of the Mount Sibillini thrust up to 2.3 s (Two-Way Time). Note the deep, strong, and continuous group of reflectors at about 3.2 s (Two-Way Time) that corresponds to the east dipping low-angle shear zone (here called Fault F3) described by Chiaraluce, Di Stefano, et al. (2017). The Castelluccio Basin is characterized by discontinuous and small reflectors from 0.3 to 2 s, whereas it is visible in the main discontinuity on the eastern flank of the Norcia Basin.

previous studies both at the surface and in the seismic profiles (e.g., Cooper & Burbi, 1986, Bally et al., 1986). This interpretation implies that several kilometers of shortening occur between the hanging wall of the MSt and the ACQ anticline, as also suggested by the large difference in structural elevation and by the presence of thick successions of syn-tectonic, foredeep deposits.

Locally, deeper reflections are also present in our seismic profiles, whose interpretation will require careful consideration of the whole data set. For example, below the previously described ACQ anticline, deeper, high-amplitude reflectors are present at 4.0 s (TWT), possibly representative of the top basement or of intra-basement reflections. These reflectors are apparently affected by a major thrust fault, indicating that at least the uppermost part of the acoustic basement is involved in the major thrust sheets.

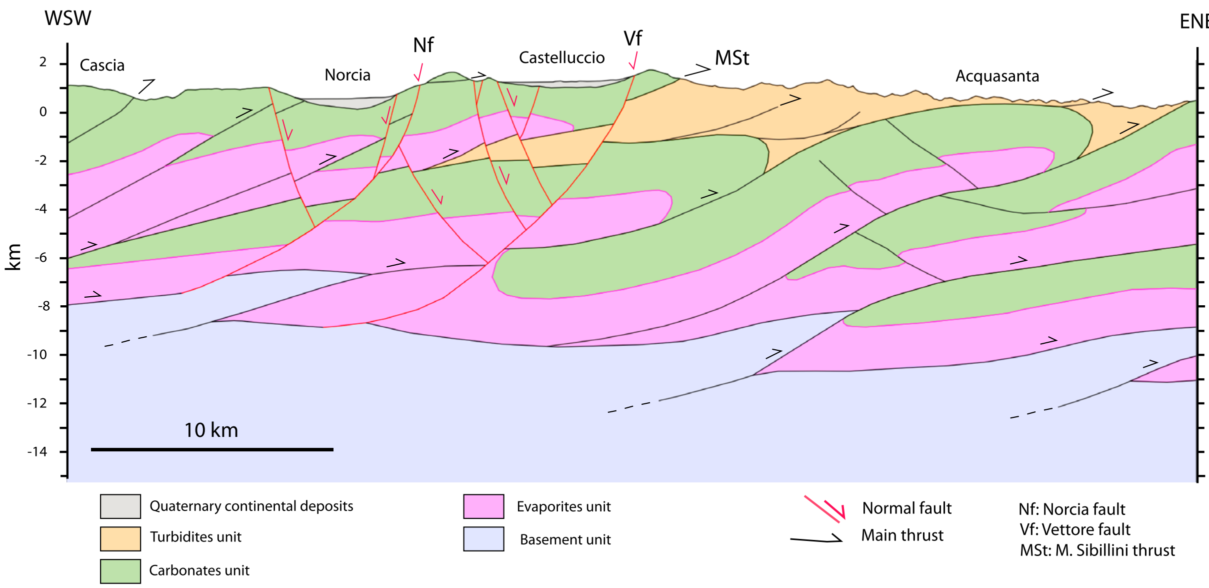

Figure 8. Geological interpretation of the composite section S1 integrating geological data at surface and subsurface data.

6. Integration of Surface Geological and Subsurface Data

Starting from the geological interpretation of the seismic profiles, described in the previous section we drew the geological cross section S1 (Figure 8), running about 5 km south of the M_w 6.5 Norcia mainshock. The section is traced obliquely with respect to the NNE trending compressional structures of the MSt and roughly perpendicular to the NNW-SSE striking extensional structures (see the trace in Figure 1).

To produce the S1 section, the interpreted seismic profiles were

- projected into a straight line, fitting the crooked path of the seismic profiles from west to east (Figure 3);
- converted into depth, using the simple velocity model, illustrated in section 5.1 (Figure 4);
- integrated with surface geological data derived from previously published maps and papers, as synthetized in the geological section of Figure 1b.

The resulting geological cross section offers a comprehensive view of both compressional and extensional structures of the region affected by the seismic sequence, extrapolated down to a depth of about 12 km.

6.1. Compressional Structures

The structural style of the Umbria-Marche region has been intensely debated in the literature, proposing both thin-skinned and thick-skinned alternative models, implying significantly different amounts of shortening (e.g., Bally et al., 1986; Scisciani et al., 2014, see chapter 3 for a synthesis). Our section shows that thick- and thin-skinned tectonics coexist in this region, which is characterized by a system of multiple detachment, where different sets of tectonic structures are generated at different structural levels. Three major detachments have been observed, in correspondence of progressively shallower structural levels: within the basement, within the evaporites, and at the top of the carbonate units (Barchi, 2010, and references therein).

The major constraint offered by the seismic data concerns the depth of the acoustic basement. The top basement is marked by groups of deep, high-amplitude reflectors, testifying the occurrence of low-Vp clastic and/or low-grade metamorphic rocks, as also described by Mirabella et al. (2008), in adjacent sectors of the Apennines. In depth converted section the top of the basement is located between 8 and 11 km, in agreement with most of the previous seismic studies performed in this region (e.g., Bally et al., 1986; Bigi et al., 1999; Calamita & Pizzi, 1994, see chapter 3 for an extensive discussion). The amplitude of the basement reflections is magnified in the central part of the section, between Norcia and Castelluccio, at a depth of 9 to 10 km.

Along the S1 section, the top basement has been identified at different depths. These steps suggest that at least the upper part of the basement is involved in the major thrust sheets (Barchi et al., 1998). These deep thrusts branch out upward, forming a complex pattern of long-wavelength, east verging anticlines, involving both carbonates and evaporites, extensively exposed at the surface. In the eastern part of the section, this kind of folds are also present, with similar geometry, at intermediate depth, as effectively imaged by the seismic data (ACQ anticline). In the Umbria-Marche Domain, stacked tectonic units consisting of carbonates and evaporites fill the space above the top basement, up to the surface. The relatively low-angle trajectory of the thrusts (whose dip is generally in the range 20°–30° and never exceeds 40°) is supported by the attitude of the stratigraphic reflections within the carbonates unit (top Scaglia and Marne a Fucoidi, Figures 5 and 6). Also at the surface, where the level of erosion is deep enough to show the thrust attitude, low-angle thrusts are systematically observed (e.g., Mount Sibillini thrust, Lavecchia, 1985; Patino thrust, Pierantoni et al., 2013).

The uppermost detachment, located in the Tertiary Marly Group overlying the carbonates, is effectively imaged in the eastern part of the section, where the turbidites are intensely and disharmonically shortened, forming the system of short-wavelength imbricates of west dipping thrusts and related asymmetric folds, detached on the western limb of the ACQ anticline (Figure 6).

In our interpretation, the stacking of carbonates and evaporites results in relatively large shortening, in substantial agreement with the reconstructions proposed by Bally et al. (1986) and Calamita and Pizzi (1994) (see Table 1). Seismic data offer a good support to these high values of shortening, at least for the eastern part of the S1 section, at the footwall of the MSt and the ACQ thrust.

6.2. Extensional Structures

Regarding the extensional tectonics, section S1 crosses two major west dipping normal faults, which are the Mount Vettore and the Norcia (Nottoria-Preci fault sensu Brozzetti & Lavecchia, 1994) faults (Vf and Nf, respectively), driving the subsidence of the intermountain basins of Castelluccio and Norcia At the surface, the geometry and kinematics of these well-known Quaternary normal faults have been extensively described in the literature (e.g., Blumetti et al., 1993; Boncio et al., 1998; Brozzetti & Lavecchia, 1994; Calamita & Pizzi, 1994; Pierantoni et al., 2013). Previous studies univocally indicate that they are high-angle normal faults, dipping 60°–70°, cumulating large displacement, in the order of 1.5–2 km. At the hanging wall of both Vf and Nf, complex systems of conjugate, synthetic, and antithetic splays have been mapped.

As described in the previous section 5 (Figure 7), these major extensional faults affect the carbonates of the Umbria-Marche Domain, where the quality of the seismic data offers poor constraint for their geometry at depth. However, we were able to trace these faults, as marked by alignments of interrupted stratigraphic reflections. The reconstruction of the extensional faults in section S1 was obtained by connecting these seismic discontinuities with the well-known position of the major normal faults at the surface.

The proposed reconstruction of the extensional Vf system can be tested by comparison with seismological data (focal mechanism of the mainshocks and aftershock distribution), collected during the 2016–2017 seismic sequence, which provide new insights on the geometry of the activated faults, as well as of their synthetic and antithetic splays, at depth ranging from 1 to 12 km (Chiaraluce, Di Stefano, et al., 2017). The comparison between our 2-D subsurface model and the hypocenter distribution will be illustrated in the following section.

7. Comparison Between Seismicity Distribution and Deep Structural Setting

Comparing the subsurface structures, recognized through the interpretation of seismic reflection profiles (“geological faults”), with the seismicity distribution, given the attitude of the faults activated during a seismic sequence (“seismological faults”), is not an easy task. An extensive discussion of this problem, focused on the seismogenic faults of the Umbria-Marche region, has been developed by Barchi and Mirabella (2009).

In our case, particular caution is due, since both the seismicity distribution and the subsurface structure represent the result of preliminary analyses. In fact, the seismic distribution derives from the locations published by Chiaraluce, Di Stefano, et al. (2017), using an approach based on a simple, 1-D velocity model. Previous experience suggests that the earthquake locations may be significantly improved, as far as more sophisticated velocity models and relocation algorithms are adopted, as observed for the case of 2009 L’Aquila (Chiaraluce, 2012; Valoroso et al., 2013) or of the 1997–1998 Colfiorito earthquakes (Latorre et al., 2016). Similarly, our proposed geological model is the result of a preliminary interpretation of a small part of the available seismic

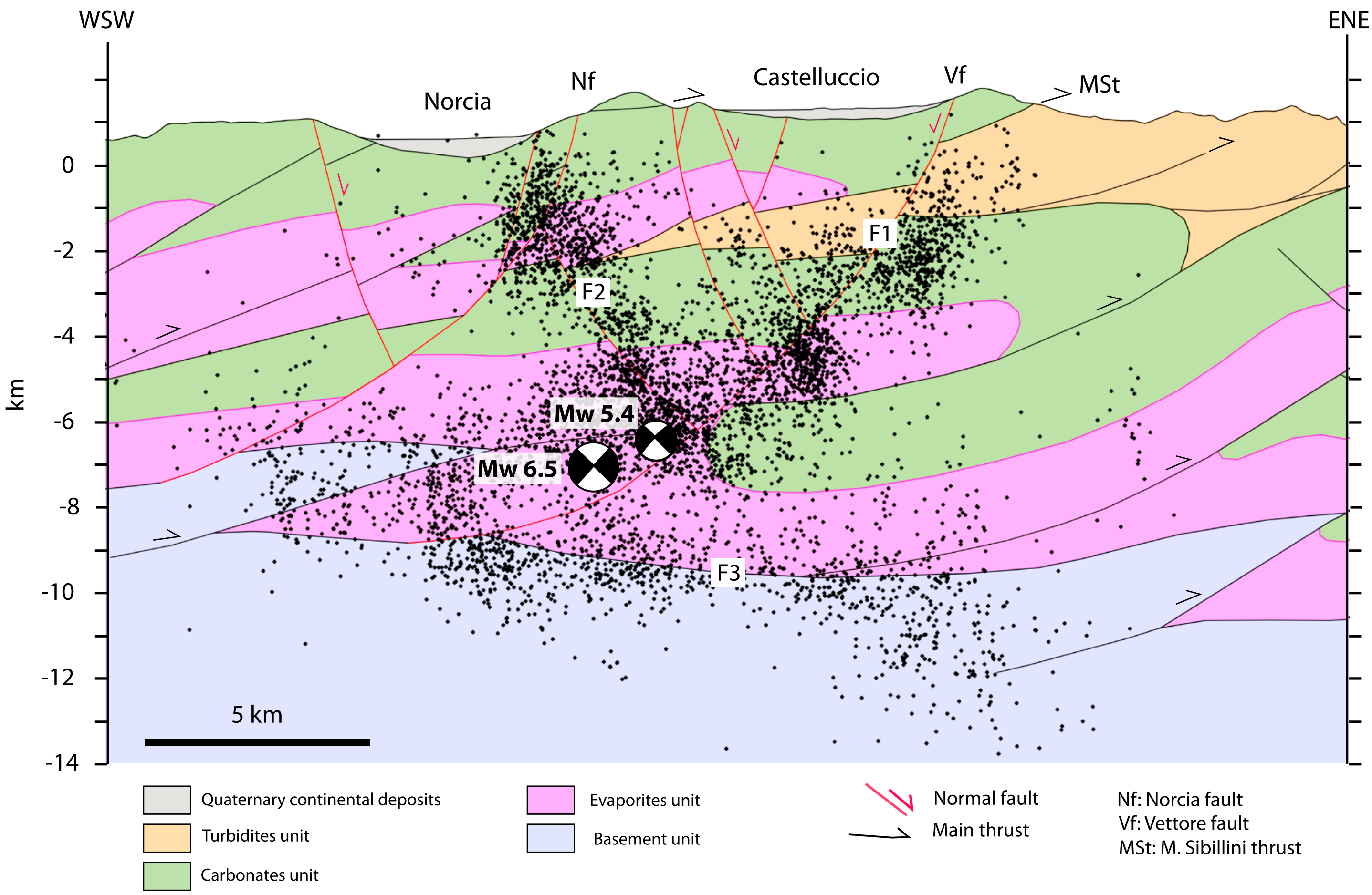

Figure 9. Geological reconstruction of the Norcia-Mount Vettore sector with the hypocenter distribution projected with respect to the section S1 (strip of 3 km). The mainshocks M_W 5.4 (24 August 2016 and M_W 6.5 (30 October 2016) are also reported with their focal mechanisms along the section.

reflection database, which may be significantly improved in the future, by integrating other seismic profiles and possibly other geophysical data.

In order to analyze the relationships between the distribution of the seismicity and the subsurface structure along our S1 section, we extracted from the "Earthquake location and catalog" by Chiaraluce, Di Stefano, et al. (2017) the hypocenters of the closest mainshocks (the M_W 5.4 of the 24 August 2016 and the M_W 6.5 of the 30 October 2016) and all the aftershocks, located in a strip of 3 km from the section trace (Figure 9). All these selected events have been projected into the S1 section along the mean strike of the activated faults, that is, along N150°. We projected about 5,760 events well constrained for their location in an interval time from 24 August to 29 November 2016 (97 days).

The distribution of the hypocenters along the S1 section (Figure 9, and also Chiaraluce, Di Stefano, et al., 2017, Figure 3, sections 6 to 8) is particularly complex, consisting of at least three groups of grossly aligned hypocenters, possibly corresponding to three major activated structures (seismological faults, sensu Barchi & Mirabella, 2009). The first structure (F1) is a WSW dipping normal fault (part of the Vf), dipping about 50°, as also indicated by the focal mechanism of the 30 October (M_W 6.5) mainshock. At the surface, F1 corresponds to the coseismic ruptures observed along the western slope of Mount Vettore producing >1 m downdip displacement in the area of the M_W 6.5 (Emergeo working group, 2016). The second structure (F2) is a major ENE dipping antithetic fault, dipping more than 60°, with no obvious geological or geomorphological expression at the surface, pointing to the base of the eastern slope of the Norcia Basin, almost in correspondence of the well-known WSW dipping Nf (Brozzetti & Lavecchia, 1994; Lavecchia et al., 1994), that controls the evolution of the Basin and its recent seismicity (e.g., 1979 Norcia earthquake). Both F1 and F2 merge at depth into a third structure (F3), a gently east dipping, 2 km thick alignment of hypocenters, located at 8–10 km of depth, and reaching a greater depth of 12 km toward east. The base of F3 grossly corresponds to the seismicity cutoff. During the 2016–2017 seismic sequence, extensional events with maximum M_w of 4.4 were registered, driving its interpretation as a complex, 2 km thick, extensional shear zone (Chiaraluce, Di Stefano, et al., 2017).

With the limits described in the previous sections 5 and 6, seismic data supported the tracing of the main west dipping normal fault (Vf), as well as of some of its major synthetic and antithetic splays. Figure 9 shows that our reconstructed faults reasonably fit the seismicity distribution (seismological faults F1 and F2). In general, the fault dips are in good agreement with the seismicity distribution, with steeper (about 60°) NE dipping faults, antithetic to a major SW dipping fault, dipping about 50°. In particular, the trajectory at depth of the WSW dipping seismogenic Vf, as reconstructed in this study, matches quite well with the main cluster of the hypocenter alignment F1, as well as the M_w 6.5 position and its focal mechanism. We were also able to recognize the trajectory of a major, blind NE dipping fault, nicely corresponding to the east dipping alignment of seismicity (F2).

The planar versus listric geometry of seismogenic faults has been largely debated in the literature, also for other structures of the central Apennines (e.g., Chiaraluce, 2012, and references therein). In general, it has been observed that the geological faults exposed at the surface are systematically steeper (>60°) than the corresponding seismological faults highlighted by focal mechanisms and aftershocks alignment (Barchi & Mirabella, 2009). This may be also the case of the west dipping Vf: at the surface, reactivated fault planes dip at high angle (60° to 70°), while at intermediate depth, both the aftershock alignment and the focal mechanism point to a shallower dip of about 50°, which needs to be reconnected at depth with the flat basal detachment, marking the seismicity cutoff. The variation of fault dip with depth is at least partly controlled by the mechanical stratigraphy of the region, that is, by the rheology of the different lithologies involved in the faulting. Based on field and laboratory data, collected in the evaporites (dolostones and anhydrites) of the same area, Collettini et al. (2009) suggest that, during the onset of faulting, the deformation is prevalently ductile and early faulting occurs at dip of around 45°. Subsequently, the upward propagation of the ruptures involves the overlying carbonates, more brittle and with higher friction coefficient, where the normal faults dip at range of 60–70°.

In our interpretation, both SW and NE dipping fault show a slightly concave upward, “listric” geometry, where the high-angle normal faults, exposed at the surface, gradually diminish at depth, eventually merging into the low-angle, gently east dipping basal shear zone (F3). However, we are conscious that the low quality of seismic data beneath the Umbria-Marche Domain, along with the uncertainties in the adopted velocity model, does not allow us to effectively constrain the along-dip trajectory of the imaged faults, at least for this stage of the research.

The most important correspondence between the seismic reflection data presented in this paper (the geological faults) and the above described seismicity distribution (the seismological faults) is the presence of a major group of reflections (Figure 7), whose depth and attitude actually follows the gently east dipping, seismically active shear zone (F3). This correspondence is particularly meaningful, since the presence of this prominent reflector indicates that the deep shear zone is also a significant mechanical discontinuity, where rocks with strongly contrasting acoustic impedance are directly superposed.

We interpret this seismic horizon as pertaining to the top basement reflector (Figures 7 and 8), as also suggested by previous experience on the seismic stratigraphy of the Umbria-Marche region (e.g., Barchi et al., 1998; Mirabella et al., 2008). However, we also note that, exactly in the same area, where the deep alignment of seismicity is observed, the amplitude of the signal is much higher than in the adjacent, lateral continuations of our composite profile. This brings to speculate that a connection may exist between the magnification of the top basement reflectors and the seismogenic activity along F3 (Figure 9). Alternatively, we can speculate that this prominent seismic horizon marks a portion of a low-angle, east dipping normal fault, separating an active hanging wall from an almost aseismic footwall block. In this hypothesis, the geometry and tectonic meaning of this detachment would be similar to the Altotiberina Fault (Chiaraluce, Barchi, et al., 2017, and references therein), recognized in northernmost sectors of the Umbria-Marche Apennines. Along the seismic profiles considered in this study, however, the limited continuity of this structure does not allow us to constrain this hypothesis. Collettini and Barchi (2002) proposed that seismicity along mechanically misoriented faults could be triggered by fluids, related to mantle degassing

(Chiodini et al., 2000), entrapped between the permeable (fractured) crystalline basement and the low-permeable phyllitic and evaporites rocks. These conditions at high depths favor the attainment of localized fluid overpressures, which lead to the nucleation of small earthquakes.

Considering the overall distribution of the aftershocks, Figure 9 shows that most of seismicity is restricted into the sedimentary cover (carbonates and evaporites) and does not affect the basement rocks, except for a few low-magnitude events, located at depths >10 km. The cutoff of the seismicity seems to be controlled by the top of the basement, comprised between 8 and 10 km, and subhorizontally distributed.

In particular, clusters of aftershocks along the section seems to mainly interest the Triassic evaporites rocks of the evaporites (mostly Anidriti di Burano Fm., i.e., alternated anhydrites and dolomites), where the mainshocks of the sequence (e.g., M_w 6.5) are also nucleated. A similar behavior has been recognized by Bonini et al. (2014) for the 2012 Emilia Romagna earthquake, Mirabella et al. (2008) for the 1997–1998 Colfiorito sequence, and Collettini et al. (2003) for the Gubbio area. The mechanical properties of these rocks and their possible role in the seismogenesis of the region have been intensely studied by combined laboratory experiments, field analyses, and numerical modeling (e.g., De Paola et al., 2008; Pauselli & Federico, 2003; Pauselli & Ranalli, 2017; Trippetta et al., 2010). Laboratory measurements conducted on both borehole and outcrop samples have highlighted that the evaporites represent a key lithology in terms of both sealing properties and earthquake triggering. In particular, the localization of slip along thin shear zones made of anhydrite and dolomite promotes the transition from velocity strengthening to velocity weakening behavior (Scuderi et al., 2013). An increase in the Vp/Vs ratio was also observed in experiments under saturated conditions for all the applied pressures, in agreement with 4-D seismic tomography that relates the increase in Vp/Vs ratio to the migration of the fluid during the 1997–1998 Colfiorito seismic sequence (Chiarabba et al., 2009).

8. Conclusions

The results of this work provide new insights on the subsurface structure of the region struck by the 2016–2017 seismic sequence, contributing to a long-lasting debate on some critical points, such as the style of deformation of the thrust belts and the relationships between the thrusts and the subsequent normal faults.

We have reconstructed the subsurface geology along a geological section (S1), crossing the area affected by the M_w 6.5 mainshock close to the Norcia town. The main features investigated in this work are the trajectory of the main thrust and normal faults, the depth of the basement, and its role in controlling the thickness of the seismogenic layer, as imaged by the seismicity distribution.

Even if the quality of the analyzed seismic data hampers a detailed reconstruction of the actual trajectory of the single thrusts, the attitude of frequent, west dipping reflections (top of Carbonates and/or Marne a Fucoidi Fm.) suggests that the carbonate ridge of the Umbria-Marche Domain consists of stacked thrust sheets of carbonates and evaporites, where the ramps dip at relatively low angle (lower than 40°). The trajectory of the main active seismogenic faults has been reconstructed by combining reflection seismic and surface data: these faults are characterized by dip angles of 60°–70°, where they crop out (and where the coseismic ruptures were observed) and become progressively less steep at depth, as indicated by the focal mechanisms of the mainshocks and by the distribution of the aftershocks. In general, therefore, our reconstruction suggests that the seismogenic normal faults are significantly steeper than preexisting thrusts. The poor relationship between these two tectonic structures is further confirmed by the attitude of the active normal fault system, which obliquely dissects the arc-shaped thrust belt, as shown in Figure 1.

Along our composite seismic profile the top basement reflectors are not continuous and are located at about 2.6 s (below Norcia) 3.2 s (below Castelluccio), and 4 s (below the ACQ Anticline): the eastward deepening of the basement is explained by its involvement in the major thrust sheets (Figures 5 and 8), corresponding to about 8–11 km of depth. In the region of the M_w 6.5 mainshock, this depth also corresponds to the seismicity cutoff. In the same area, the amplitude of the reflector is magnified, possibly driven by peculiar processes (high fluid pressure), which might be responsible for its seismic activity. The correspondence between the top basement and the thickness of the seismogenic layer was already established in adjacent areas of the Central Italy extensional seismic belt (Barchi & Mirabella, 2009).

The depth and thickness of the seismogenic layer is lithologically controlled, since the majority of seismicity is confined within the sedimentary cover and does not penetrate the underlying basement. The mainshocks are located close to the bottom of the seismogenic layer, within the Triassic evaporites. A subhorizontal cutoff of seismicity is well recognized at the top of the basement, whereas only a few and low-magnitude events are able to penetrate the substrate at depths higher than 12 km.

We are able also to recognize a triangle-shaped deformation zone below the Castelluccio Basin, corresponding to the conjugate system of seismogenic normal faults, activated during the 2016–2017 seismic sequence (Figure 7). Unfortunately, the poor definition of the seismic data does not allow us to describe in details the geometries of these faults, as well as their mutual relationships. A future reprocessing of the seismic data and the study of the entire available data set could provide new highlights for the reconstruction of the actual geometry at depth of these active and seismogenic faults, as well as their segmentation along strike.

Improving the subsurface geological model may also provide good constrains for definition of reliable velocity models that, in turn, are fundamental for a better relocalization of the earthquakes. At present, very few examples exist, where a coherent velocity model is adopted for both the localization of the hypocenters at depth and for the depth conversion of the seismic profiles (e.g., Latorre et al., 2016).

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