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Seismic interpretation of the Laga basin; constraints on the structural setting and kinematics of the Central Apennines

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Abstract: The Messinian Laga basin is the largest foreland basin within the Central Apennines fold and thrust belt (Italy). This area, actively investigated in the 1980s and 1990s for hydrocarbon resources, is considered a valuable analogue for clastic reservoirs developed in confined structural settings. Furthermore, it represents a key area for understanding the evolution of the Apennines, as it links the internal, structurally uplifted Early Miocene fold and thrust belt of the western Central Apennines with the more external and recent belt to the east. Despite several papers published on this area, the only reconstruction of the substratum structure is an internal and classified industry report. During the present study, we had access to a seismic database comprising 200 km of seismic profiles that were collected between 1983 and 1990. These data allowed us to reconstruct the structural setting of the Laga basin substratum, define the lateral continuity of the main compressional structures within the basin, construct a balanced cross-section, and define the shortening values.

The Laga basin, the largest Messinian foreland basin within the Apennine fold and thrust belt of central Italy, was an area of active hydrocarbon exploration during the 1980s and 1990s. Excellent exposure continuity and the limited tectonic omission of stratigraphic successions allow for reconstruction of the geometry and distribution of the sedimentary units. From this point of view, the Laga basin represents a type locality of a buried reservoir consisting of confined turbiditic sandstone bodies, where sediment deposition and distribution was controlled by tectonic activity (Milli *et al*. 2007). The Laga basin has recently been the subject of renewed scientific interest, with studies being performed to better understand the architecture of clastic reservoirs that consist of foreland basin sandstones in convergent tectonic settings (Artoni 2003; Milli *et al*. 2006, 2007; Bigi *et al*. 2008). A further reason to study this area is the fact that the Laga basin is a key area for reconstructing the evolution of the Central Apennines (Patacca & Scandone 1989), as it forms the footwall of two main regional outcropping thrusts: the Mt. Sibillini thrust to the west and the Gran Sasso thrust to the south (Ghisetti & Vezzani 1991; Mazzoli *et al*. 2005). The Laga basin is also the hanging wall of a buried, north–south-trending regional thrust known as the Teramo thrust (Bigi *et al*. 1999; Figs 1 and 2). The evolution of this basin records the migration of the foredeep depocentres, from the early Miocene foredeep domain of the Marnoso Arenacea Formation to the west (Ricci Lucchi 1986; Roveri & Manzi 2006) to the equivalent Pliocene domain to the east (Periadriatic basin; Ori *et al*. 1991; Centamore *et al*. 1992*a*,*b*; Bigi *et al*. 1997*b*; Patacca *et al*. 2008, and references therein; Fig. 1).

Recently, the nationally funded Vi.D.E.P.I. project ('Visibility of petroleum exploration data in Italy') has been offering free access to public technical reports of petroleum exploration in Italy from 1957 to 2007 (UNMIG–Società Geologica Italiana–AssoMineraria 2009). Most of the 2D seismic lines used in this study originated from this source, and an additional four 2D seismic lines were supplied by ENI–AGIP Exploration and Production Division. Based on this 2D seismic database it was possible to reconstruct the geometry of the Laga basin substratum, using the Marne con Fucoidi Formation (Aptian–Albian) as the key level. These data also allowed us to reconstruct the deep geometry of the Gorzano normal fault, which was one of the faults that was partially reactivated during the 6 April 2009 earthquake sequence (main shock magnitude M_w 6.3) that struck the city of L'Aquila and caused more than 300 deaths (Chiarabba *et al*. 2009). A geological cross-section was reconstructed in two-way travel time, converted to depth, and balanced using 2D Move (version 2009.1, Midland Valley) to obtain the initial geometry of the Laga basin. The total shortening value and the main deformation rate were also determined.

Stratigraphy

The stratigraphy of the study area includes sedimentary sequences belonging to the Mesozoic–Tertiary Adriatic continental margin; most of the carbonate substratum of the Laga basin consists of the Umbria Marche basinal succession (Centamore *et al*. 1992*a*,*b*; Santantonio 1994; Bigi *et al*. 1999), whereas the Latium–Abruzzi carbonate platform sequences are exposed in the hanging wall of the Gran Sasso thrust in the southern part of the study area (Fig. 2). These passive margin sequences are all capped by Tortonian–Messinian siliciclastic turbidites of the Laga Formation (Centamore *et al*. 1992*a*,*b*).

The Jurassic portion of the Umbria–Marche succession records the rifting phase and the development of the passive continental margin (Santantonio 1994), followed by the Late Jurassic to Oligocene calcareous and marly sedimentation of the Maiolica Formation, the Marne a Fucoidi Formation and the Scaglia Group (Scaglia bianca, Scaglia rossa, Scaglia rosata and Scaglia cinerea Formations, of Late Cretaceous–Oligocene age). The Miocene interval consists of hemipelagic and carbonate turbidites of the Cerrogna Marls and Orbulina Marls Formations (Centamore *et al*. 1992*a*,*b*; Bigi *et al*. 1999).

Mesozoic dolomites, limestones and dolomitic limestones form the Latium–Abruzzi carbonate platform succession, which is unconformably overlain by the detrital limestones of the

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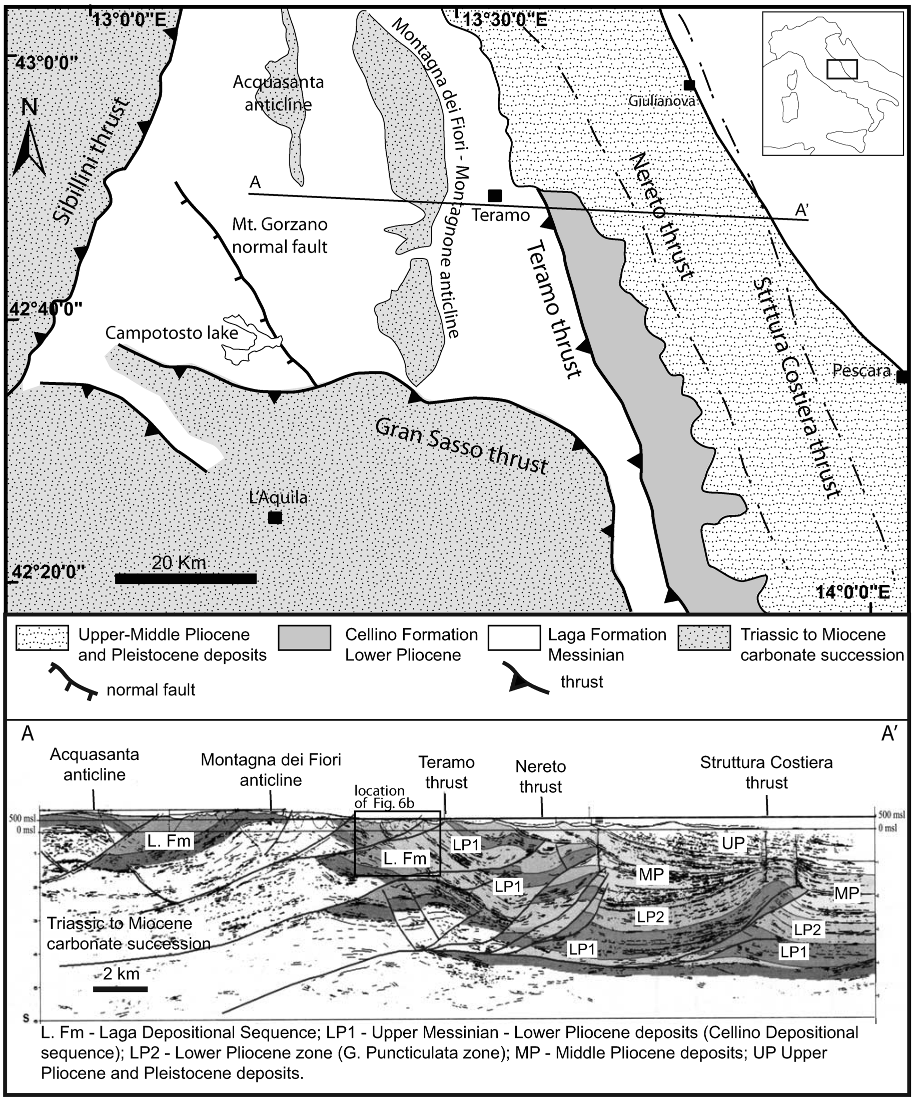

L. Fm - Laga Depositional Sequence; LP1 - Upper Messinian - Lower Pliocene deposits (Cellino Depositional sequence); LP2 - Lower Pliocene zone (G. Puncticulata zone); MP - Middle Pliocene deposits; UP Upper Pliocene and Pleistocene deposits.

Fig. 1. (**a**) Geological map of the Central Apennines. (**b**) Line drawing of a seismic line and interpretation of a regional cross-section from Acquasanta to the Adriatic Sea (from Albouy *et al.* 2003, modified).

Calcari a briozoi e litotamni Formation (Langhian–Tortonian) and Tortonian–Messinian hemipelagic and siliciclastic turbidites (Salto and Aterno Valleys turbidites; Milli & Moscatelli 2000; Milli *et al.* 2006).

The Laga Formation, coeval with the Messinian-aged Salto Valley and Aterno Valley turbidites, fills the Laga basin and overlies the Orbulina Marls Formation (Centamore *et al.* 1992*a*,*b*; Milli *et al.* 2006, 2007; Bigi *et al.* 2009, and references therein). The Laga Formation represents an Early Messinian depositional system, subdivided into two main units (Units 1 and 2), that is characterized by a general fining upward trend until the occurrence of a gypsum–arenite horizon. A third unit, overlying these first two and located in the eastern sector of the basin, is considered to be the beginning of a different, younger depositional system (Milli *et al.* 2007; Bigi *et al.* 2009).

Units 1 and 2 represent the fill and overfill of the basin, respectively. During the filling stage, the sedimentological and stratigraphical characteristics of the Unit 1 deposits suggest that the main basin was localized westward of Mt. Gorzano (Figs 2 and 3a). During Unit 2 deposition, the basin was deformed by a forward thrust propagation and by a progressive uplift, as documented by multi-sourced confined turbidite depositional systems with a fining upward trend (Milli *et al.* 2007; Bigi *et al.* 2009). The turbidite geometries and facies distribution indicate the occurrence of growing anticlines within the basin, which controlled the location of depocentres (maximum vertical thickness of siliciclastic deposits) and of the source areas. The sedimentological and stratigraphical architecture of Unit 2 suggests that thrust activity occurred widely during sedimentation and that the entire basin underwent a general uplift (Milli *et al.* 2006; Fig. 3b). During the Late Messinian, the new regional internal slope of the basin migrated eastward, and was located to the east of the Montagna dei Fiori–Montagnone thrust, bordering the internal and uplifted source areas. The Cellino depositional sequence was deposited in this new, easternmost basin; it was composed of the Late Messinian sandstone and marls of Unit 3 of the Laga Formation and the Early Pliocene turbidite siliciclastic deposits of the Cellino Formation (Milli *et al.* 2007; Bigi *et al.* 2009; Fig. 3c).

Seismic dataset

The Laga basin area has been analysed using a dataset of seismic lines, tied by well log data (Fig. 4). The 2D seismic dataset

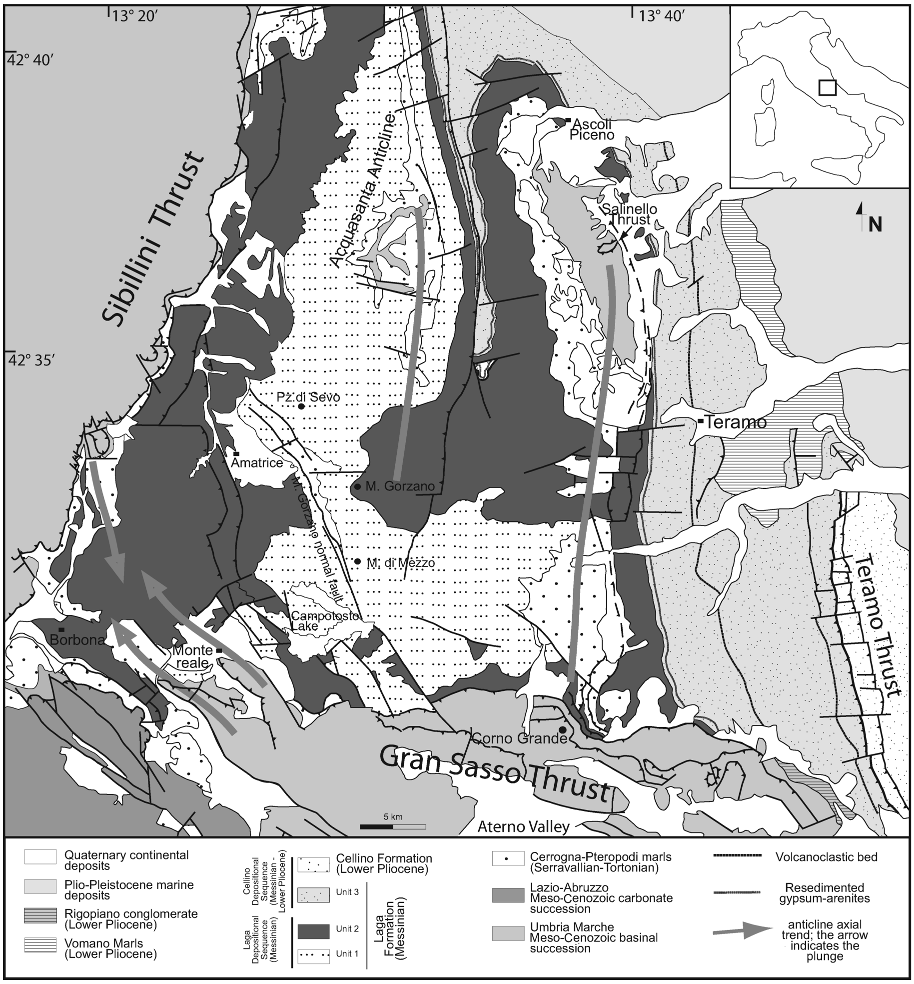

Fig. 2. Geological map of the Laga basin.

includes profiles that are part of surveys carried out from 1983 to 1990, with a total length of about 200 km (Casero & Bigi, 2006). In the study area, the carbonate substratum comprises the Umbria–Marche Meso-Cenozoic sequences, as recognized from boreholes in this area (Campotosto 1, Varoni 1 and Villadegna 1 wells, Figs 4 and 5).

The velocity logs of the Campotosto 1 and Varoni 1 wells (Albouy *et al*. 2003) were used to calibrate the seismic lines, adopting the time interval scheme of Table 1. Seismic data have been interpreted with the recognition of several seismic markers corresponding to (from top to bottom): the top of the Cerrogna Marls Formation (corresponding to the base of Laga Formation); the top of the Scaglia Rossa Formation (corresponding to a high reflection coefficient owing to the transition from carbonate to marls in the stratigraphic succession); the top of the Marne con Fucoidi Formation, which is one of the best defined seismic reflectors because of the widespread regional occurrence of this laterally continuous marl formation (50–100 m thick); the top of the Calcare Massiccio Formation; the top of the Burano Anhydrites Formation (Fig. 5a). The location of the top of the basement *sensu lato* is one of the most debated topics in this area and throughout the Apennines (Coward *et al*. 1999; Mazzoli *et al*. 2006; Patacca *et al*. 2008, among many others). Unfortunately, the low quality of the seismic lines does not clearly distinguish the base of the sedimentary sequences. Nevertheless, based on the minimum thickness of the Burano anhydrites and dolostone crossed by well logs in the area (Varoni 1 well, Villadegna 1 well; Fig. 5), and the geometry of the thrust belt obtained by our seismic interpretation, the bottom can be placed at about 3000 m below the top of the Burano Anhydrites Formation. This implies a limited involvement of the crystalline basement in the thrust belt, at least in correspondence to the areas of major structural elevation (core of the main hanging-wall anticlines) (Coward *et al*. 1999; Speranza & Chiappini 2002; Mazzoli *et al*. 2006; Patacca *et al*. 2008).

The seismic reflector corresponding to the Marne a Fucoidi Formation is one of the best defined reflectors in the subsurface dataset. This is due to its widespread regional occurrence and its position in the stratigraphic sequence; this thin and laterally continuous level of marls is interposed between the Scaglia Group (Cretaceous to Oligocene) and the Maiolica Formation (Upper Cretaceous) and is characterized by a high reflection coefficient owing to the seismic interval velocities of 4000–4400 and 5700–6000 $m\,s^{-1}$, respectively (Mazzoli *et al*. 2005). The top of the Calcare Massiccio Formation also represents a good marker within the Laga basin. It is characterized by a constant thickness of about 800 ms TWT (two-way travel time) of a transparent seismic facies, which is clearly recognizable in most of the analysed seismic sections. Under the Calcare Massiccio Formation, two reflectors, at a constant distance of about 300 ms TWT, have been recognized in most of the analysed seismic lines, and are correlated with the 400 m thick dolostone interval intersected by the Varoni 1 well (Figs 5 and 6).

In the western sector of the basin, seismic quality does not

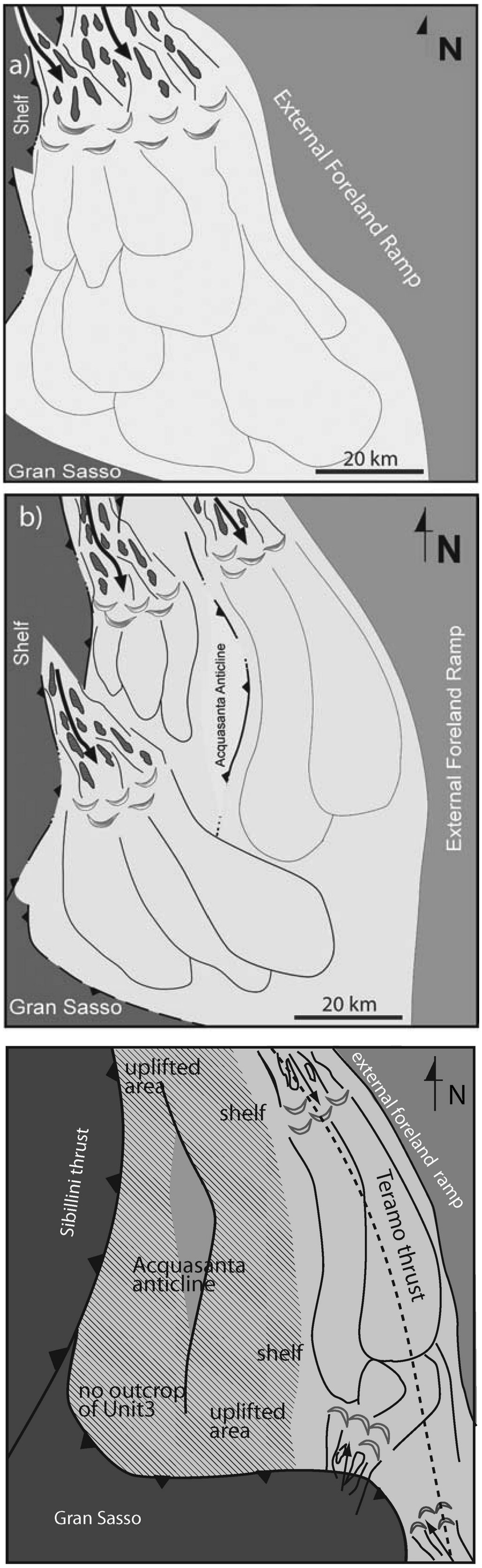

Fig. 3. Depositional setting of the Laga basin during sedimentation of Unit 1 (**a**), Unit 2 (**b**) and Unit 3 (**c**) of the Laga Formation (modified from Milli *et al*. 2006).

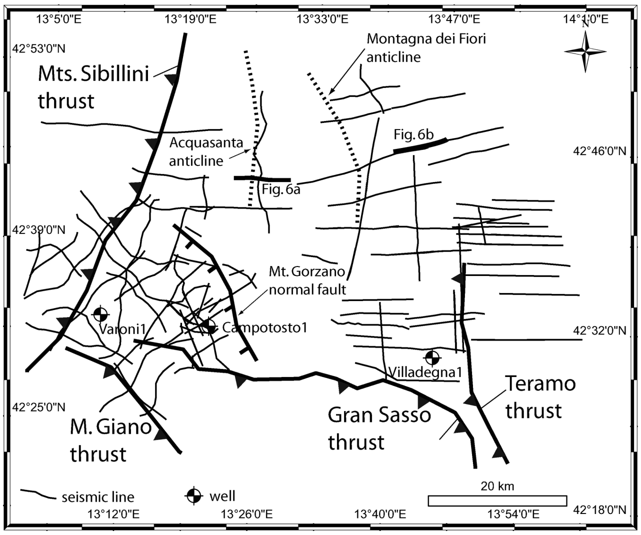

Fig. 4. Basemap of 2D seismic database and well logs in the Laga basin area. Location of Figure 6a and b is shown.

allow for determination of the geometric relationship between the Messinian turbidites and the Meso-Cenozoic substratum, as can be observed in the field. Generally, the onlapping geometries reconstructed in the field are not visible in the interpreted seismic lines. These include the onlap geometries exposed around the Acquasanta anticline (Milli *et al*. 2006) and the progressive eastward onlap of the Messinian turbidites on top of the Meso-Cenozoic sequences in the eastern sector. The same observation applies to the occurrence of syndepositional normal faults that have been identified and widely documented at the outcrop scale within the Laga basin (Mazzoli *et al*. 2002, and references therein). Nevertheless, seismic line interpretation allows for the reconstruction of the structural trends of the main thrusts (related to anticlines within the Laga basin) and the main normal faults cropping out in the area. The isochron map shown in Figure 7 is the reconstruction of the Laga basin substratum defined using the key horizon of the Marne con Fucoidi Formation.

Surface and subsurface structural setting

The structural style of the Laga basin is characterized by thrust-related, north–south-trending anticlines with high-angle thrust planes (40–45°) and small displacement along each thrust. Generally, displacements are of the order of a few kilometres and progressively decrease from north to south.

The main structure, the Teramo thrust (Figs 1, 2, 6b, 7 and 8), shows 10 km displacement, passively transported a syncline of Upper Messinian–Lower Pliocene deposits in the hanging wall, and placed the Messinian Laga basin domain onto the siliciclastic turbidites of Cellino Formation (Lower Pliocene) (Bigi *et al*. 1997*a*, 1999, 2009; Albouy *et al*. 2003). This thrust is regionally well developed and has been recognized in seismic sections by several researchers, although its total geometry is dissimilar in some cases (Bigi *et al*. 1997*a*, 1999; Mazzoli *et al*. 2002; Albouy *et al*. 2003; Casero 2004). At the regional scale, the Teramo thrust has a north–south trend and can be followed in outcrop for about 100 km from the north (Teramo area) to the south (Caramanico Valley) (Bigi *et al*. 1999; Mazzoli *et al*. 2002; Albouy *et al*. 2003; Fig. 1). The hanging-wall anticline of the

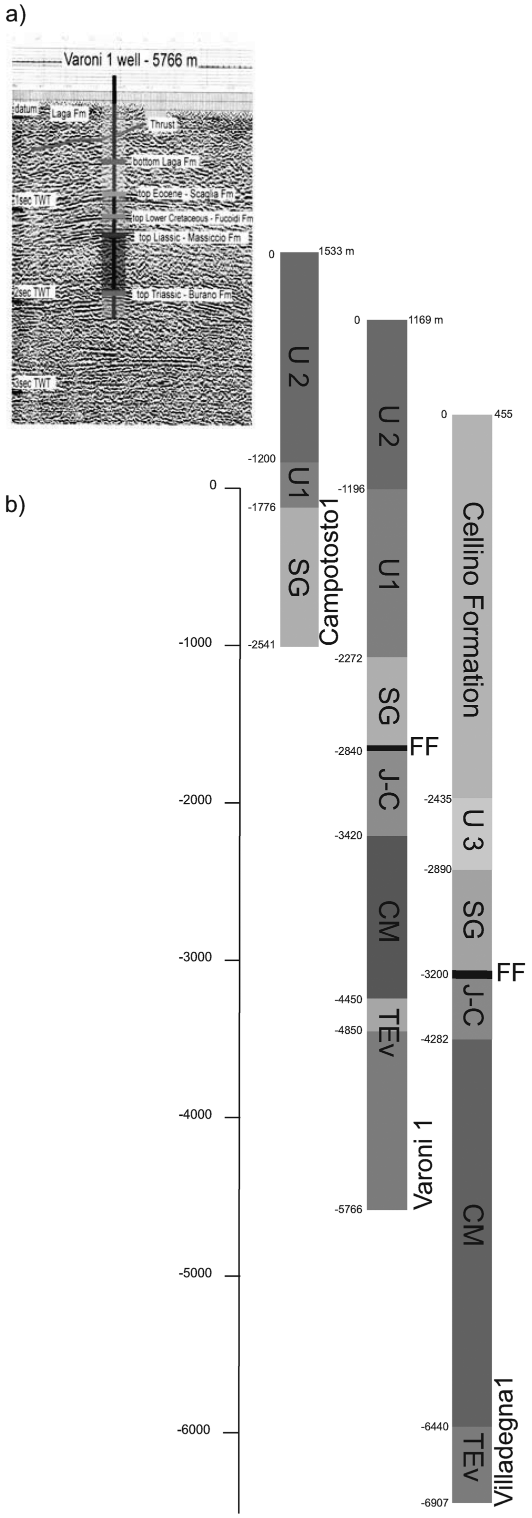

Fig. 5. (**a**) Calibration of the seismic line using the Varoni 1 well logs. (Note the double reflectors located at the top of the Burano Anhydrites Formation.) (**b**) Available well logs in the study area. U1, U2 and U3, Units 1, 2 and 3 of the Laga Formation; SG, Scaglia Group (Upper Cretaceous–Oligocene); J-C, Jurassic–Cretaceous basinal sequences (Corniola, Rosso Ammonitico, Diaspri and Maiolica Formations); CM, Calcare Massiccio Formation; TEv, Triassic evaporites and dolostones.

Table 1. *Time interval scheme used for depth conversion of the cross-section of Figure 8*

Lithological interval	Velocity (m s^{-1})
Laga depositional sequence	3600
Top Scaglia Fm–top Cerrogna Fm	4500
Top Fucoidi Fm–top Scaglia Fm	5800
Top Massiccio Fm–Top Fucoidi Fm	6100
Top Burano Fm–Top Massiccio Fm	6400
Burano Fm	6040

Teramo thrust is complicated by the occurrence of the Montagna dei Fiori–Montagnone thrust plane, which crops out in the Salinello Valley in the core of the anticline (Calamita *et al*. 1998; Di Francesco *et al*. 2010; Fig. 2). It cuts the unconformity surface folded by the Teramo thrust, where Unit 1 of the Laga Formation progressively onlaps (Fig. 8). According to this geometrical relationship, the development of the Montagna dei Fiori thrust is the last contractional event in the Laga basin. The western limb of the related hanging-wall anticline is folded by several blind back-thrusts, whereas at the surface it is offset by a normal fault that dips westward (Figs 2 and 7). The crosscutting relationship between these structures is not clear in the seismic images, where only the back-thrust planes are evident, and can be reconstructed even in the southwestern area. This suggests that the outcropping normal fault can be considered a pre-thrusting normal fault, as already described by several workers (Calamita *et al*. 1998; Mazzoli *et al*. 2002; Di Francesco *et al*. 2010), that has been completely obliterated by the subsequent thrusting deformation visible in our seismic dataset.

The north–south Mt. Gorzano–Acquasanta anticline and related thrust occur in the western sector of the basin (Figs 1, 2 and 6a). At the surface this anticline is surrounded by an unconformity surface, which corresponds to the top of Orbulina Marls Formation where Units 1 and 2 of the Laga Formation progressively onlap; this suggests major growth activity during the deposition of Unit 2 (Bigi *et al*. 2009) (Fig. 3). The Mt. Gorzano–Acquasanta thrust is associated with a ramp anticline with a strong axial culmination to the north. Following this axial trend, the displacement rapidly decreases along strike, and the thrust plane passes laterally to a simple anticline in the southern sector, where it is cut by the subsequent Mt. Gorzano normal fault (Figs 7 and 8). This normal fault, which has a strike of N 140°, placed the upper part of Unit 2 in the hanging wall onto the basal portion of Unit 1 of the Laga Formation, resulting in a total offset of about 1000 m. The seismic lines reveal a clear listric geometry, with a high-angle dip close to the surface that progressively turns to horizontal at depth. At about 3 s TWT, corresponding to a depth of about 4000 m, it joins the Mt. Gorzano–Acquasanta thrust (Fig. 8).

The Gran Sasso thrust

The reconstruction of the trend of the Gran Sasso thrust in the western sector of the basin and the definition of its relationship with the Messinian turbidites is one of the contributions of this study. The Gran Sasso thrust is a complex structure, essentially composed of two stacked tectonic units. Its hanging-wall geometry, which has been debated over the last decade (Ghisetti & Vezzani 1991; Ghisetti *et al*. 1993; Bigi *et al*. 1997*a*; Scisciani *et al*. 2002), is beyond the scope of this work; it is generally reported to be strongly controlled by the Mesozoic palaeomargin architecture and by the occurrence of pre-thrusting normal faults

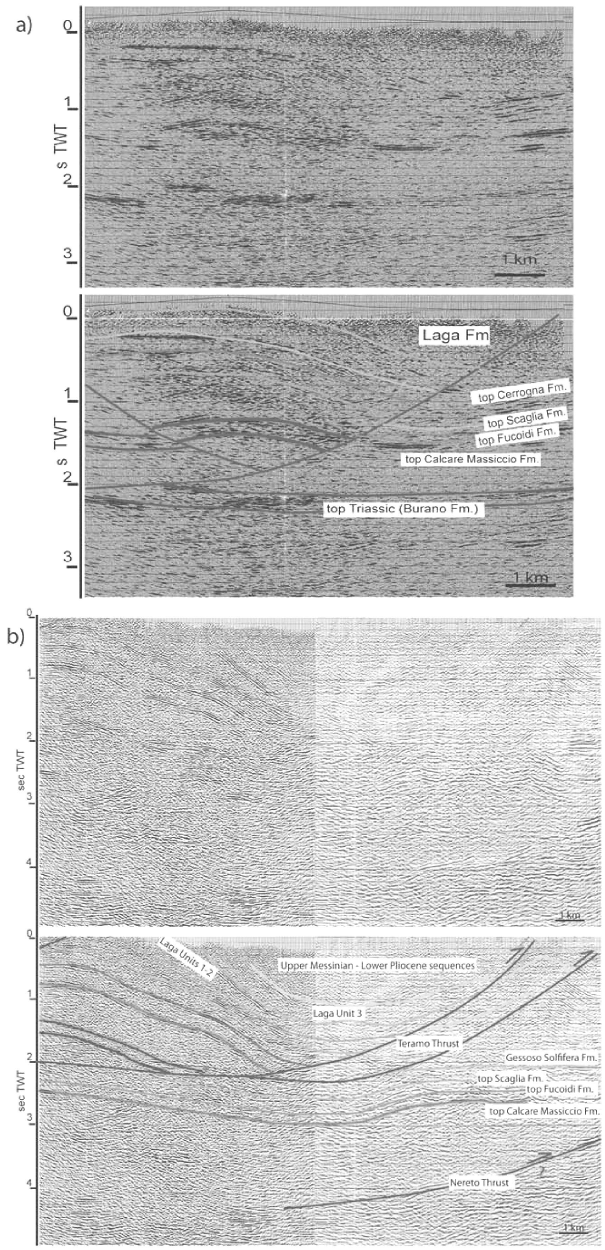

Fig. 6. (**a**) Seismic profile across the Acquasanta anticline and its interpretation; the location is shown in Figure 4. (Note the low seismic resolution corresponding to the top of the Cerrogna Formation. This surface corresponds to the outcropping onlap surface of the Laga Formation.) (**b**) Seismic profile across the Teramo thrust and its interpretation (location shown in Figs 1 and 4). (Note the forelimb dipping eastward and the rapid decrease of the thickness of Units 1 and 2 of the Laga Formation.)

connected to the flexure process (Scisciani *et al*. 2000; Calamita *et al*. 2002). The truncation, folding, and partial reverse reactivation of the pre-existing normal faults are extremely common throughout the Apennine fold and thrust belt. As a consequence, the compressive structures emphasize the pre-existing variations in elevation, such that the platform or intra-basinal plateau areas remain high whereas the basin remains as a structural low (Scisciani *et al*. 1999, 2002; Tavarnelli 1999; Bigi & Costa Pisani 2002, 2005; Tavarnelli & Peacock 2003). The Gran Sasso structure roughly reflects the trend of the pre-existing normal faults affected by the subsequent compressional deformation. The occurrence of rotated Miocene normal faults, trending east–west, is documented along the northern sector of the Gran Sasso structure, and the palaeogeography of the area is characterized by structural highs developed during the Jurassic (Scisciani *et al*. 2000, 2002; Calamita *et al*. 2002). This explains the occurrence of two contrasting features in the Gran Sasso structure: the highest structural elevation of the Apennines and the small offset (a few hundred metres) measured along the outcropping thrust.

The Gran Sasso thrust front is composed of two roughly orthogonal segments, one oriented east–west and the other north–south, separated by a narrow apex of the Corno Grande structure (Fig. 2). Along the east–west front the amount of shortening decreases westward at the surface, passing from the central stack of the Corno Grande to the N 100–130° thrust-related folds of the Montereale and Borbona, which plunge northwestward (Fig. 2). Palaeomagnetic data indicate a homogeneous counter-clockwise rotation in the central part of the east–west front and an absence of rotation in the eastern sector (Speranza *et al*. 2003). The absence of rotation and the plunge of the anticlines could indicate a lateral closure of the Gran Sasso thrust in the Borbona area, as suggested by several workers (Ghisetti & Vezzani 1991; Dela Pierre *et al*. 1992; Speranza *et al*. 2003). In a previous hypothesis, based on the occurrence of outcropping reverse faults involving the Laga Formation, the Borbona area was proposed to be the hanging wall of the Gran Sasso thrust, which extends to the Amatrice plain to the north (Bigi *et al*. 1999).

In agreement with this latter hypothesis, our interpretation of seismic lines crossing the area of Borbona and the western sector of the Laga basin defines the Gran Sasso thrust plane in this area, as mapped in Figure 7. The hanging wall is composed of an array of outcropping anticlines and synclines involving the upper part of the Meso-Cenozoic carbonates and the Messinian turbidites of the Laga Formation. They have a N 100–140° axial trend and are associated with back-thrust planes on their back limb. The Montereale and Borbona anticlines plunge northward whereas the anticlines to the north strongly plunge southward, thereby creating a complicated interconnection of fold axes. At the surface these opposing plunges create a SW–NE structurally depressed area in the central part of the study area, corresponding to the anticline crossed at depth by the Varoni 1 well in the footwall of the Gran Sasso thrust (Figs 2 and 7).

Our seismic dataset lacks information towards the east, in the footwall of the east–west Gran Sasso thrust (Fig. 4). In this area, the Gran Sasso thrust was reconstructed from surface data. Its hanging wall, composed of an overturned anticline that can be correlated with the Borbona and Montereale anticlines to the west, involves the Meso-Cenozoic carbonate basinal succession and the Laga Formation. This relationship indicates that the uplift and deformation of the Gran Sasso unit started during the earlier phase of Laga basin filling, and that this area was the southern part of the Laga basin during the Early Messinian. This result is an important constraint for reconstruction of the basin evolution; it allows the correlation of turbidites across the Gran Sasso thrust, considering that they can be interpreted as deposits of different turbiditic facies (proximal and distal) belonging to the same depositional system (Milli & Moscatelli 2000).

Geological cross-section restoration and timing of deformation

As can be observed in the geological cross-section of Figure 8, this sector of the chain is characterized by two structural levels.

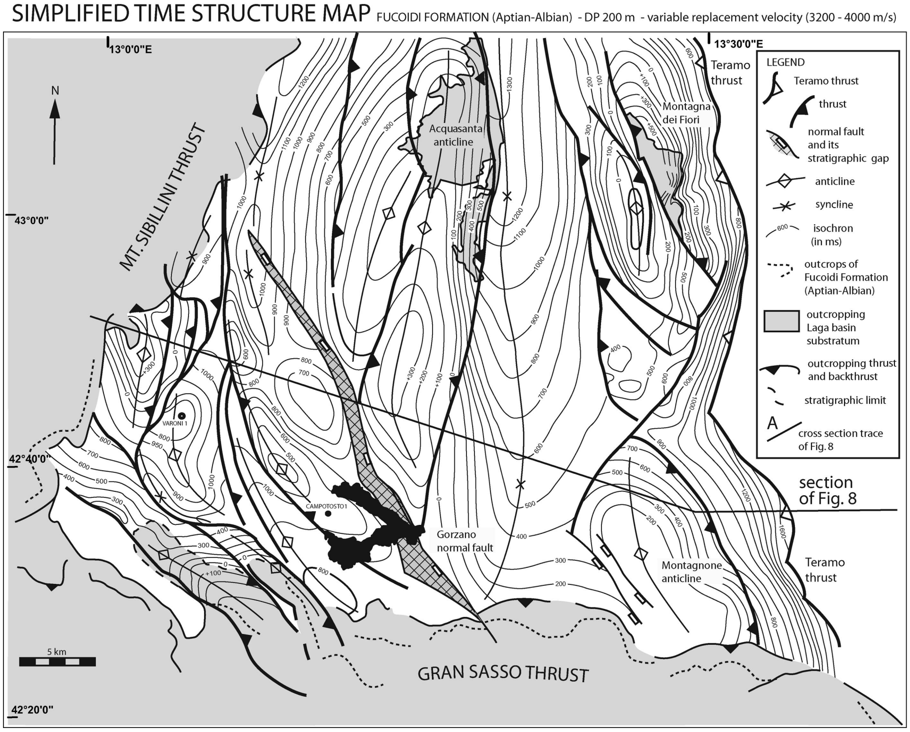

Fig. 7. Simplified time–structure map of the Laga basin substratum reconstructed at the horizon of the Marne a Fucoidi Formation.

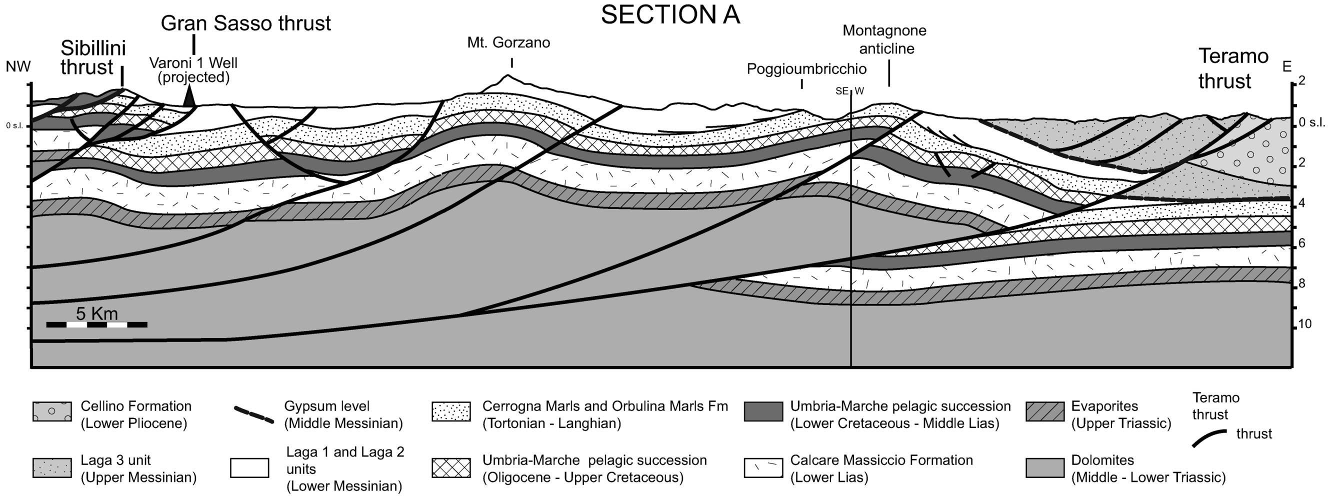

Fig. 8. Geological cross-section across the Laga basin; the location is shown in Figure 7.

The lower one, between depths of 7 and 10 km, is the site of the main tectonic transport and detachment levels, essentially represented by the Teramo thrust. The thrusts in the upper level generally have a small offset, of the order of hundreds of metres (Bigi *et al*. 2004; Tozer *et al*. 2006). To explain the observed distribution of displacement along these thrust planes, several workers have proposed that the displacement was transferred from a lower and more internal thrust to upper and external flats by several ramps. According to this theory, the displacement along each shallow thrust was progressively reduced as soon as a more external structure developed from the same upper flat, or a new deeper thrust developed from the deeper level (Bigi *et al*. 2004; Tozer *et al*. 2005). This explanation requires that thrust propagation was necessarily younger than sedimentation of the foredeep Messinian–Pliocene deposits. This is not the case for the Teramo thrust, which was active mainly during the Late Messinian, in agreement with the proposed interpretation of the filling of the Messinian–Early Pliocene basins (Milli *et al*. 2007; Bigi *et al*. 2009).

The cross-section presented in Figure 8 was first constructed in time and then converted to depth using the velocity values in Table 1 and surface data. The obtained geological section has been restored using 2DMove software (version 2009.1, Midland Valley) by performing the following procedure: (1) remove fault displacement; (2) remove folding related to flexural slip (Fig. 9). This procedure was adopted for each thrust in the section. Folds were restored using a flexural slip algorithm using pins located along zones of no inter-bed slip. Flexural slips in the area were

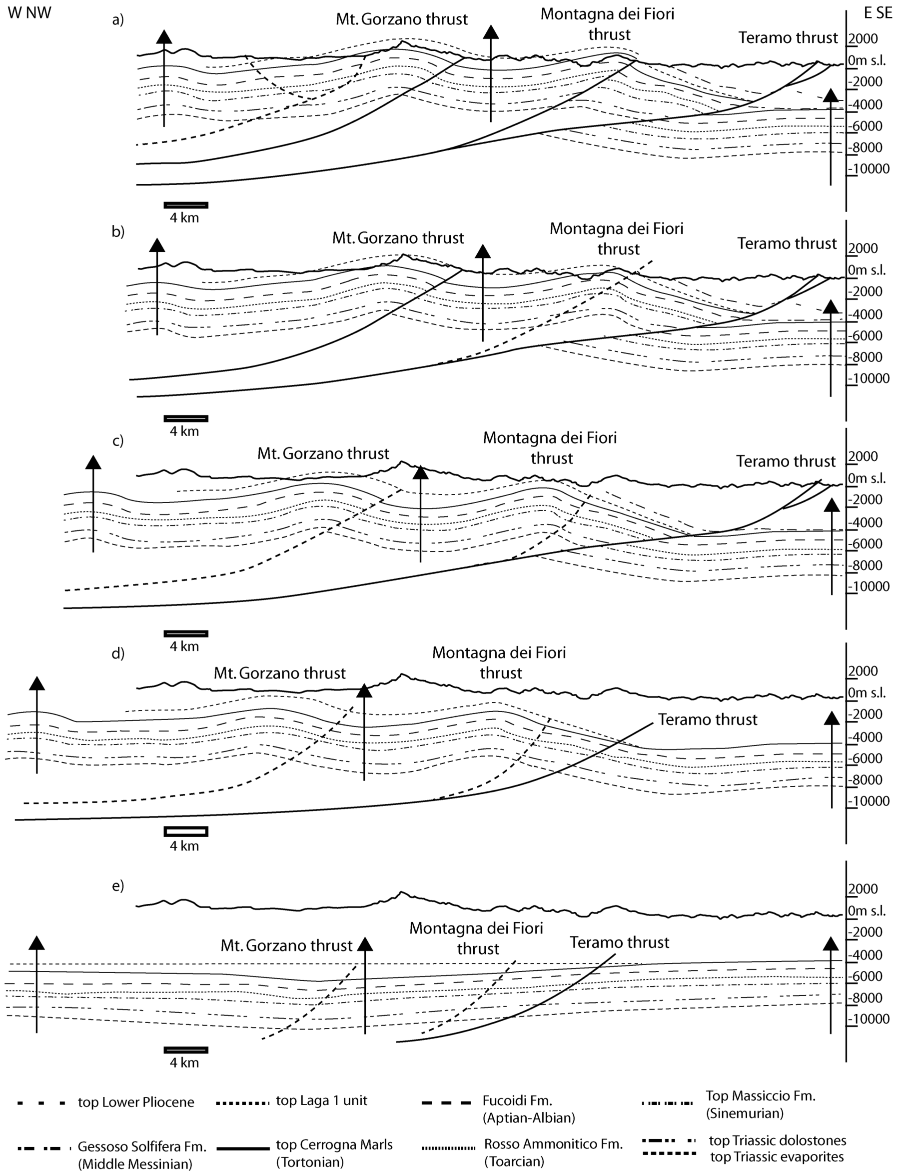

Fig. 9. Restoration of the geological section of Figure 8. Each stage represents the restoration of one of the main events of basin evolution.

identified as the dominant deformation mechanism, as indicated by the occurrence of ubiquitous shear fibres on bedding planes and roughly perpendicular to the fold axes. Two-dimensional restorations commonly assume that there is no movement of material into or out of the section plane. To determine the correct orientation for such plane strain sections, it is necessary to analyse the tectonic transport direction from minor structures in the field (S–C fabrics, slickensides and duplexes). The transport direction in this study area has been previously examined; the dominant kinematics varies from top-to-the-NE to top-to-the-east, moving along strike from north to south (Koopman 1983; Bally *et al*. 1986; Ghisetti *et al*. 1993; Bigi *et al*. 1997*a*; among many others). The direction of the chosen section was a compromise between the direction of the available seismic lines and the main tectonic transport directions (Fig. 7).

The sequence of restoration follows the main deformation episodes of the basin, based on the geometrical and kinematic relationships between single thrust planes and between synorogenic turbidites and thrust planes (Acquasanta–Mt. Gorzano thrust, Montagna dei Fiori–Montagnone thrust, Teramo thrust). The main activity of the Sibillini thrust was coeval with the deposition of Units 1 and 2 of the Laga Formation, when the uplifted hanging wall corresponded to the western shelf of the basin in the northern sector. During the same period, the slope of the basin was generated by the Gran Sasso thrust activity to the south, as documented by the relationship to the Messinian turbidites (Fig. 3).

Tectonic activity within the Laga basin started from the deposition of Unit 2, which recorded a general uplift of the more western part of the basin (Fig. 9d). This uplift is associated with the activity of the Teramo thrust, which propagated through the lower part of the Meso-Cenozoic portion of the succession (Fig. 9c). Immediately after, the Acquasanta–Mt. Gorzano thrust propagated in the hanging wall block of the Teramo thrust, leading to the generation of accommodation space to the east. The tectonic activity of the Teramo thrust continued until the Early Pliocene (Lower Pliocene deposits were involved in the footwall, and passively transported in the hanging wall) (Fig. 9b) and coeval with the propagation of the Montagna dei Fiori thrust (Fig. 9a).

Restoration allowed for the calculation of the shortening along the section, which was 19% ($L_0 = 73$ km and $L_1 = 61$ km). This value is lower than or consistent with previous reports, as is the mean slip rate of 12 mm a^{-1}, calculated for a time interval of about 1 Ma (Messinian–Early Pliocene; Mazzoli *et al*. 2002; Tozer *et al*. 2005).

Discussion

Seismic interpretation tied with well log data allowed us to construct a time map of the Laga basin substratum and constrain geological cross-sections that illustrate its structural setting (Figs 7 and 8). In this sector of the chain, the compressional deformation involves the siliciclastic turbidites (Messinian–Lower Pliocene) and the carbonate substratum (Triassic–Miocene); the involvement of the underlying basement is less clear, but it was probably deformed in the areas of higher structural elevation (Tavarnelli 1995, 1999; Scisciani *et al*. 1999, 2002; Mazzoli *et al*. 2002; Bigi & Costa Pisani 2005).

The time-to-depth conversion of the geological cross-section identified a single thrust at a depth of about 9 km that divides two sectors: the hanging wall of the Teramo thrust, essentially consisting of the uplifted Laga basin, and the footwall of the Teramo thrust, where the foredeep deposits are represented by the more external and younger Cellino depositional sequence (Upper Messinian–Lower Pliocene sequence, Bigi *et al*. 2009; Figs. 1b and 8). In the more external and younger sector of the chain, thrusts and related folds involving the Lower Pliocene–Pleistocene sequence are connected to the deeper ramp in the carbonate substratum by a shallow detachment level (at depths from 4 to 7 km below sea level; Fig. 1). The hanging wall of the Teramo thrust is characterized by thrust-related anticlines and synclines, with a north–south trend and a kilometre-scale wavelength. Within the Laga basin, the well-preserved syntectonic turbidites recorded the uplift and deformation that occurred in the basin during the Messinian. Detailed biostratigraphy and stratigraphy of the basin infill provide useful information to constrain the ages of the thrust activity and to define the sequence of thrust propagation (Centamore *et al*. 1992*a*,*b*; Milli *et al*. 2006, 2007; Bigi *et al*. 2009; Fig. 3). The Teramo thrust acted during the deposition of the Lower Messinian turbidites (Units 1 and 2 of the Laga Formation). Subsequent compressional deformation was concentrated within the hanging wall of the Teramo thrust, where the propagation of the Mt Gorzano–Acquasanta and Montagna dei Fiori–Montagnone thrusts occurred.

This area was further uplifted by thrust activity during the overfilling phase (mainly Unit 2), whereas new subsidence areas were formed in the footwall of the Teramo thrust (Fig. 9c). This area was progressively filled by the Cellino depositional sequence, which recorded the last activity of the Teramo thrust during the Early Pliocene (Fig. 9 and ba).

This evidence suggests that, after a localized episode of subsidence most probably controlled by palaeogeography and active thrusts (i.e. the Sibillini and Gran Sasso thrusts), the Teramo thrust propagated forward and caused the slow uplift in the hanging wall of the Laga basin. This was followed by the nucleation and propagation of new thrusts in the hanging wall (i.e. the Mt. Gorzano–Acquasanta thrust and Montagna dei Fiori–Montagnone thrust planes), as recorded by the geometries described above and by the distribution of sedimentary bodies within the Laga basin (Milli *et al*. 2007; Bigi *et al*. 2009).

The described deformation sequence can be defined as a ‘break-back sequence’, where, after the propagation of a main thrust front, deformation was concentrated in its hanging wall for a period of time before propagating forward again. This can be explained by the critical wedge theory, where break-back sequences are described in episodes of subcritical wedge conditions (Davis *et al*. 1983; Storti & McClay 1995). In the Laga basin, activation and reactivation of new and previous inner thrusts trigger the wedge to continuously reach the critical dip value of the upper slope, previously reduced by Laga deposits sedimentation and Teramo thrust propagation. This mechanism has been described by numerical models as a result of the balance of work against gravity, work of fault propagation, frictional strength acting on thrust planes, and frictional strength acting on basal detachment, so as to minimize the total work of the fault system (Hardy *et al*. 1998; Del Castello & Cooke 2007). Also, the location of the ramp of the Teramo thrust, far to the east of the Sibillini thrust front, can be explained by interaction between sedimentation and thrust propagation. In some cases, it has been shown that a pronounced distance between thrust branch lines can be connected to an important episode of sedimentation that loads the basal décollement and transfers the ramp location eastward (Bigi *et al*. 2010, and references therein). During the Late Messinian the Laga basin was further uplifted, causing the migration of sedimentation towards the east in the new depressed area at the front of the Teramo thrust. This new area was the site for deposition of the Cellino depositional sequence (Milli *et al*. 2007; Bigi *et al*. 2010; Figs. 3 and 9).

This episode marks a change in the structural style of the chain, which remains more depressed and buried under syn- and post-sedimentary sequences from the Late Pliocene to the Quaternary (Patacca & Scandone 1989; Ori *et al*. 1991; Bigi *et al*. 1997*b*). In the Periadriatic sector, to the east, the compressive deformation affected mainly the Pliocene–Pleistocene siliciclastic cover (Fig. 1). Thrusts and related folds propagating across the Meso-Cenozoic sequences are connected to a shallow detachment level at the top of the carbonate substratum (located at depth ranging from 4 to 7 km below sea level). The lower and upper thrusts acted simultaneously and the compressive deformation migrated towards the ENE. The orogenic contraction was transferred from the inner and deeper levels toward the shallower detachment levels in the foreland; along these latter levels, the shortening was partitioned in a multiple array of thrust ramps (Bigi *et al*. 2004; Tozer *et al*. 2005).

Conclusions

A 2D seismic database containing all the available seismic lines and well log data within the Laga basin area was used to reconstruct the geological setting of the substratum of this Messinian basin based on the key horizon of the Marne con Fucoidi Formation (Aptian–Albian) (Fig. 7). From this analysis it has been possible to define the continuity between the Acquasanta and the Mt. Gorzano structures; these two anticlines constitute the hanging wall of the same thrust, from the northern to the southern sector of the Laga basin. In the western sector, between the Sibillini and Gran Sasso thrusts, the buried geometry of the Gran Sasso hanging-wall and footwall thrust were reconstructed (Fig. 7). This corresponds to a shallow thrust plane that extends to the Amatrice plain to the north and comprises the Borbona area in its hanging wall. This latter, composed of an array of anticlines and synclines, overlies the anticline crossed by the Varoni 1 well in the footwall of the Gran Sasso thrust at depth. In the same area we defined the geometry of the Gorzano normal fault, which has a common detachment level with the Mt. Gorzano–Acquasanta thrust (Figs 7 and 8).

A geological cross-section, located in the southern sector of the basin, was reconstructed in two-way travel time, converted to depth (Fig. 8). The geometric relationship between the hanging wall of the Teramo thrust and the Montagna dei Fiori thrust indicates this latter as the last compressional event within the Laga basin, whereas the main activity of the Teramo thrust is coeval with the deposition of Unit 2 of the Laga depositional system, which is controlled by the growth of the Mt. Gorzano thrust development (Figs 8 and 9). This deformational sequence, defined as a break-back sequence, is considered peculiar for a fold–thrust belt, where thrust propagation is accompanied by sedimentation, which controls the value of the upper slope. The converted cross-section of Figure 8 was then restored using 2D Move software (Midland Valley), based on the interpreted deformation sequence. This restoration provided the geometry of the Laga basin after the deposition of Units 1 and 2 and yielded a shortening value of about 19% (Fig. 9).

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