Trabajos de Geología, Universidad de Oviedo, 29 : 223-233 (2009)

Oviedo (Spain) 1-3 July 2008 International Meeting of Young Researchers in Structural Geology and Tectonics YORSGET

Forward modelling of the Montagna dei Fiori fault-related fold (Central Apennines, Italy), using combined kinematic models

L. Di Francesco[1*], S. Fabbi[1], M. Santantonio[1], J. Poblet[2] and S. Bigi[1]

[1]*Dipartimento Scienze della Terra, Università "La Sapienza" , P.le A. Moro, 5, 00185-Roma, Italy.*

[2]*Departamento de Geología, Universidad de Oviedo, C/Jesús Arias de Velasco s/n, 33005 Oviedo, Spain.*

[*]*e-mail: geologo22@msn.com*

Abstract: The Montagna dei Fiori has received attention by geologists through the past decades because of both its Jurassic stratigraphy and its complex present-day structure. The latter is the result of multiple phases of deformation, from the Early Jurassic, during the rift phase, which led to the opening of the Tethyan Ocean, to compression in Neogene, linked with the evolution of the Apennines fold and thrust belt. In this paper, we present a new stratigraphic interpretation of the Jurassic palaeogeography, based on a new geological mapping project in the area. Using this new stratigraphy, we constructed two forward models of the Montagna dei Fiori fault-related fold, using a combination of different kinematic models. We followed two different approaches: the first model was constructed manually starting from the construction of a balanced cross section and its restoration, followed by a definition of the main steps for the forward model; the second was constructed using 2DMove (Midland Valley), starting from a simplified version of the same stratigraphy and using the same main steps imposed in the other section.

Keywords: kinematic model, fault-related fold, balanced cross-section, Apennines.

The Montagna dei Fiori structure is located on the eastern side of the Central Apennines of Italy. It is part of the Neogene fold and thrust belt developed during the Messinian-Early Pliocene (Bigi *et al.*, 1999; Mazzoli *et al.*, 2002), and represents a key area in the study of the orogenic evolution of the external part of the Central Apennines (Fig. 1). It consists of an asymmetric, E-verging anticline related to a folded thrust. The forelimb is offset by the thrust and there are overturned beds in the forelimb in the eastern part of the hanging wall (Fig. 2). This fault-related fold involves a Triassic to Miocene basin-fill, mostly carbonate succession, which is similar to the well-known Umbria-Marche succession (Centamore *et al.*, 1971; Santantonio, 1993, 1994 and references therein). Earlier interpretations on the palaeogeography of the area envisaged instead the Lower Liassic carbonates seen at the core of the anticline as representing a Jurassic structural high (Mattei, 1987; Calamita *et al.*, 1998; Scisciani *et al.*, 2002).

In this paper, we present a novel interpretation of the Jurassic palaeogeography, based on a new geological map of the area, on a reinterpretation of the sedimentology of its Early Jurassic core, and on a new biostratigraphic dataset based on ammonite assemblages. Through an integration of this new stratigraphy with our geophysical and structural data, we constructed two forward models of the Montagna dei Fiori fault-related fold, using a combination of different kinemat-

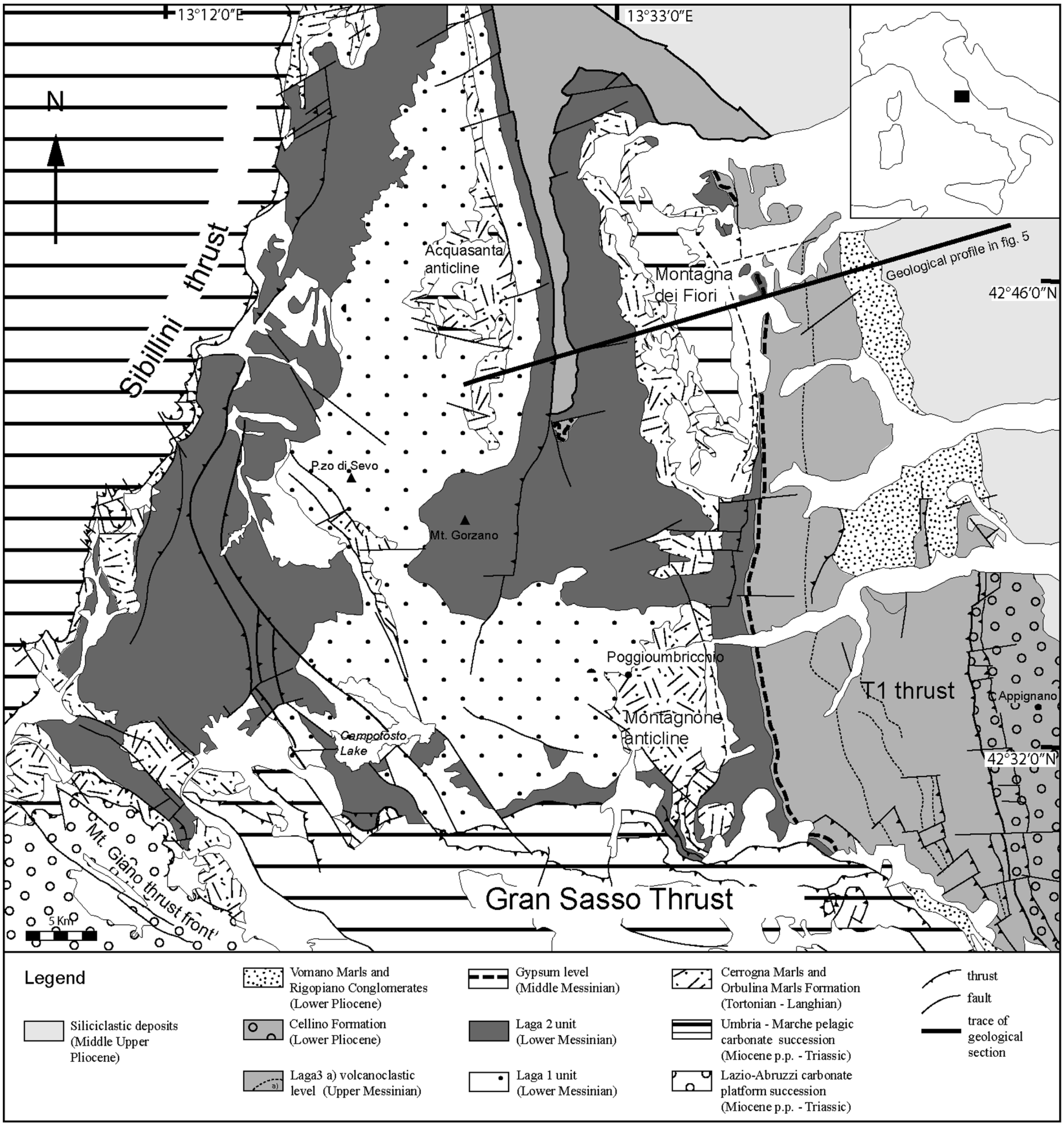

Figure 1. Simplified geological map of the Montagna dei Fiori and Laga Basin areas.

ic models, in order to describe its complex geometry. The two models overall produced a comparably similar description of the kinematic evolution of this structure, providing support for a new interpretation based on the mechanical control exerted by the stratigraphy.

Stratigraphy

Detailed field mapping of the Montagna dei Fiori structure makes use of the facies models and methods described in Santantonio (1993), Santantonio *et al.* (1996) and in Galluzzo and Santantonio (2002). The local stratigraphic succession is essentially the one known regionally as the Umbria-Marche succession, which crops out extensively across the Northern Apennines to the west of the study area (Centamore *et al.*, 1971; Galluzzo and Santantonio, 2002, and references therein) (Figs. 1 and 2). The bottom of the Jurassic Umbria-Marche succession is made of platform carbonates of the Calcare Massiccio Fm

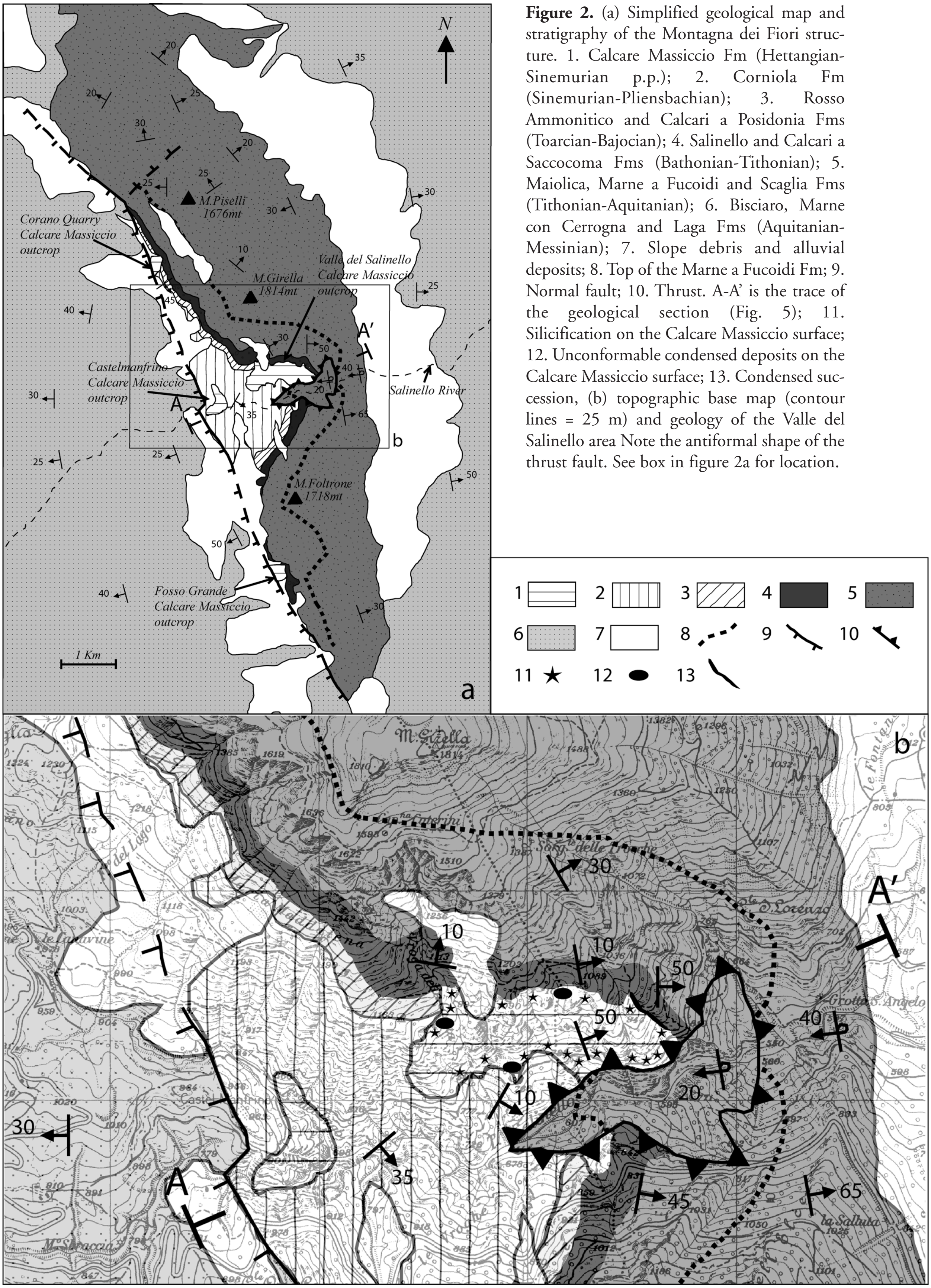

Figure 2. (a) Simplified geological map and stratigraphy of the Montagna dei Fiori structure. 1. Calcare Massiccio Fm (Hettangian-Sinemurian p.p.); 2. Corniola Fm (Sinemurian-Pliensbachian); 3. Rosso Ammonitico and Calcari a Posidonia Fms (Toarcian-Bajocian); 4. Salinello and Calcari a Saccocoma Fms (Bathonian-Tithonian); 5. Maiolica, Marne a Fucoidi and Scaglia Fms (Tithonian-Aquitanian); 6. Bisciaro, Marne con Cerrogna and Laga Fms (Aquitanian-Messinian); 7. Slope debris and alluvial deposits; 8. Top of the Marne a Fucoidi Fm; 9. Normal fault; 10. Thrust. A-A' is the trace of the geological section (Fig. 5); 11. Silicification on the Calcare Massiccio surface; 12. Unconformable condensed deposits on the Calcare Massiccio surface; 13. Condensed succession, (b) topographic base map (contour lines = 25 m) and geology of the Valle del Salinello area Note the antiformal shape of the thrust fault. See box in figure 2a for location.

(Hettangian-Sinemurian p.p.). Tethyan rifting then dismembered the peritidal platform into fault blocks with a different structural and stratigraphic evolution: i) a deep water pelagic and turbiditic succession, comprising the Corniola, Rosso Ammonitico, Posidonia Marls, Calcari Diasprigni and Calcari ad Aptici e Saccocoma Fms; and ii) a condensed pelagic succession, developed on structural highs, which became pelagic carbonate platforms (PCP) following drowning of the Calcare Massiccio platform (Fig. 3). From the latest Jurassic to the Middle Miocene the pelagic basin recorded the deposition of fine-grained limestones and marls (Maiolica, Fucoidi Marls, Scaglia Rosata, Scaglia Cinerea, Bisciaro and Cerrogna Marls Fms). Siliciclastic turbidite deposits, progressively younger eastward, of the Marnoso Arenacea and Laga Fms followed in the Late Miocene (Bigi *et al.*, 1999) (Fig. 1).

The Montagna dei Fiori Jurassic succession differs from the typical Umbria-Marche succession in that it displays huge volumes of resedimented sands shed from a coeval productive carbonate platform (the Latium-Abruzzi Platform; Fig. 1), as well as lensoid breccias made of lithoclasts of older formations, in analogy with the Sabina region lying west of the same platform (Galluzzo and Santantonio, 2002, and references therein). This resulted, in the local lithostratigraphy, in the introduction of the heavily clastic Salinello Fm (Crescenti *et al.*, 1969) as a substitute for the Calcari Diasprigni. One puzzling aspect, which becomes apparent when one goes through the published articles and maps on the area, is the absence of a condensed pelagic succession capping the inferred structural highs (Calcare Massiccio Fm outcrops of Corano, Castel Manfrino, Salinello Valley and Fosso Grande, figures 2 and 3) (Mattei, 1987). These are

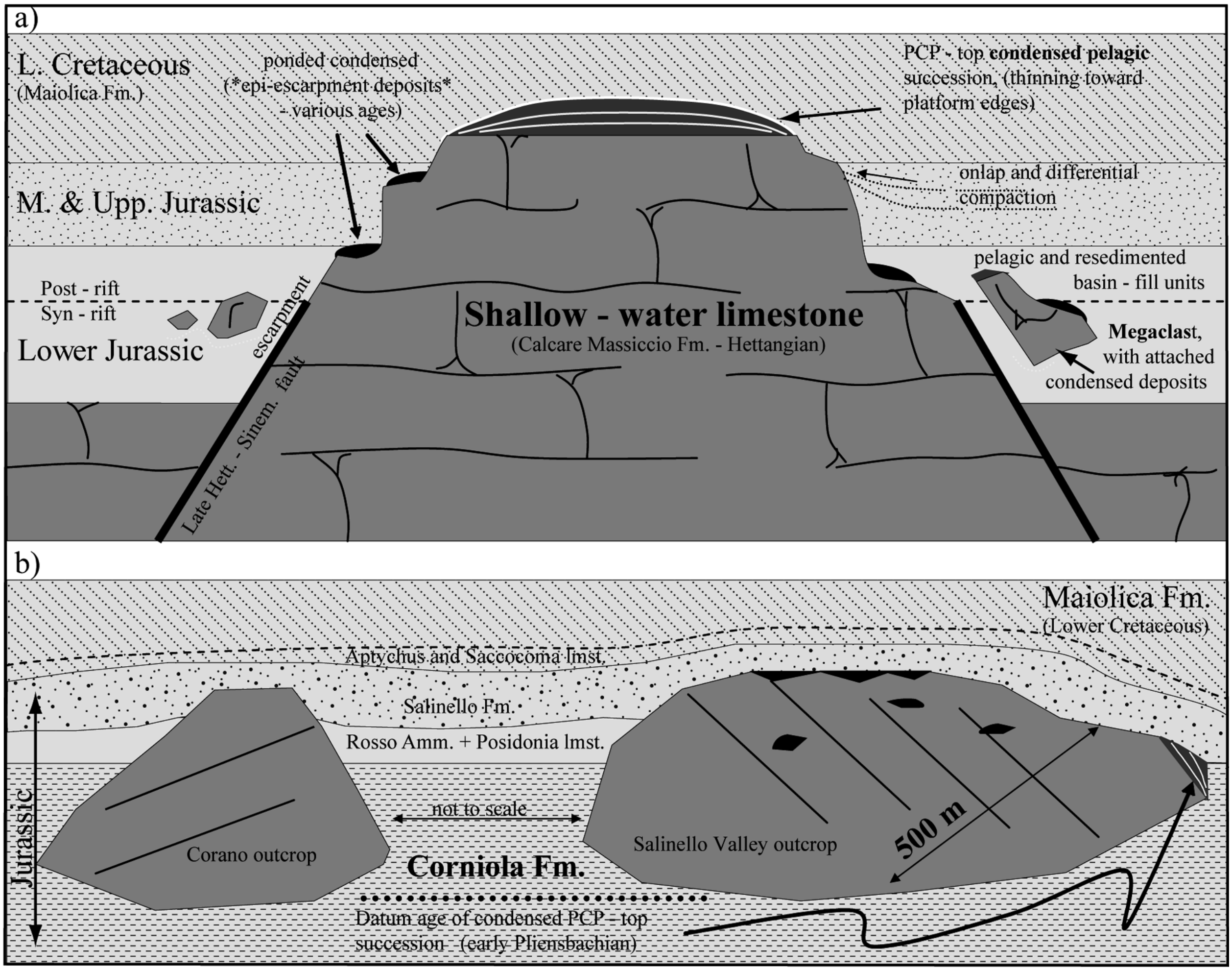

Figure 3. (a) A typical Umbria-Marche pelagic carbonate platform, surrounded and eventually buried by deep water pelagic deposits. Note the distribution of condensed pelagites on its top, at its marginal escarpments, and on the olistoliths, (b) Present-day bedding relationships between the Calcare Massiccio and the basin-fill units across an ideal Corano-Salinello transect. Note the patchy distribution of condensed deposits unconformable on the Calcare Massiccio.

buried, instead, beneath an angular unconformity, by resedimented clastic beds (carbonate breccias and turbidites) of the Salinello Fm (Upper Bajocian-Oxfordian) (Figs. 2 and 4). The basin-fill succession (Corniola, Rosso Ammonitico, Calcari e marne a Posidonia Fms) onlaps the Calcare Massiccio beds along surfaces which are thoroughly silicified at the contact. The occurrence of chert nodules and crusts in the Calcare Massiccio is a well-known diagenetic feature at unconformable contacts with siliceous basinal units (Santantonio *et al.*, 1996; Galluzzo and Santantonio, 2002).

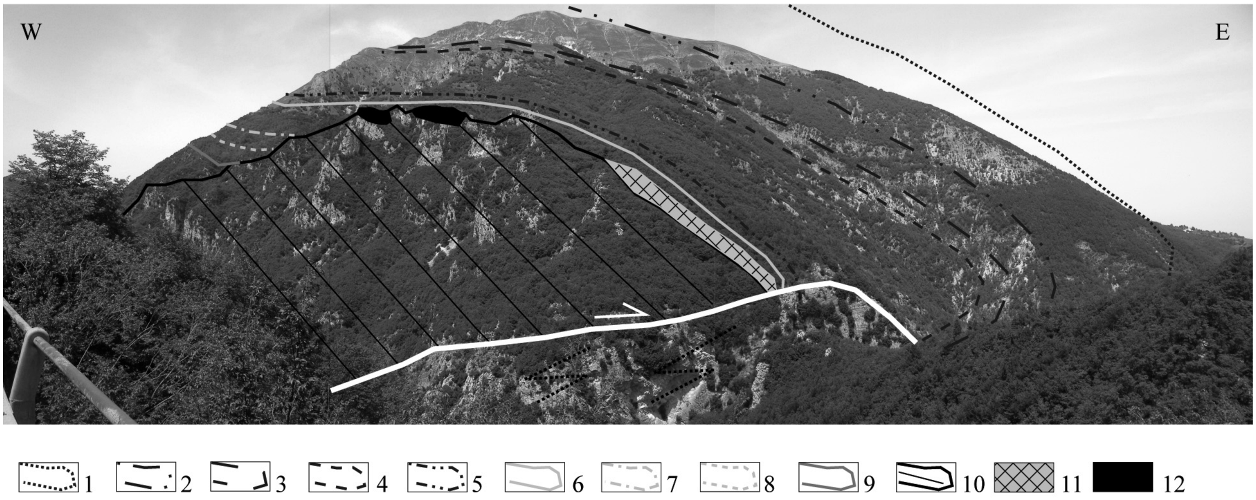

Figure 4. View of the Salinello Valley from the south. In the hanging wall of the Salinello thrust, the olistolith with the condensed deposits crops out. Eastward, the thrust plane dips to the east together with the Cretaceous-Paleogene part of the pelagic succession. The lines correspond to the top of the following formations: 1. Scaglia Cinerea Fm; 2. Scaglia Bianca Fm; 3. Marne a Fucoidi Fm; 4.Maiolica Fm; 5. Calcari a Saccocoma Fm; 6. Salinello Fm; 7. Rosso Ammonitico Fm; 8. Calcari a Posidonia Fm; 9. Corniola Fm; 10. Calcare Massiccio; 11. PCP-top condensed succession; 12. Epi-olistolith deposits unconformable on the Calcare Massiccio.

Previous Authors (Mattei, 1987; Calamita *et al.*, 1998; Scisciani *et al.*, 2002) have interpreted these contacts as traces of Liassic normal faults. However, the boundaries of the Calcare Massiccio Fm in outcrop show evidence of having a stratigraphic, rather than (paleo-)tectonic, nature, as we mentioned. Besides, our field data indicate that the outcrops of Calcare Massiccio in the Salinello Valley do not represent Jurassic horst blocks. Their 3D shape, dimensions, bed attitude of internal stratification with respect to that of surrounding formations, and lack of any condensed pelagic cap, strongly suggest they instead represent giant exotic blocks (olistoliths) embedded in the largely resedimented basin-fill succession, and rooted in the Lower-Middle Liassic Corniola Fm. This is evident with the Corano, Castelmanfrino, and Fosso Grande Calcare Massiccio outcrops (Figs. 3 and 4).

Although the main Salinello Valley outcrop has been described in earlier papers as being stratigraphically overlain by a condensed succession, field observations reveal that condensed pelagic deposits only occur here as thin discontinuous veneers resting in angular unconformity above the Calcare Massiccio. As such, they do not represent the platform top. They rather represent occasional sediment ponding and preservation on an irregular submarine escarpment (epi-escarpment deposits) (Figs. 3 and 4). A genuine, very thin condensed succession, resting conformably on the east-dipping stratigraphic top of the Calcare Massiccio, and bearing Early Pliensbachian ammonites (F. Venturi, personal communication), is found only at the easternmost termination of the Salinello outcrop, and is unconformably overlain by breccias of the Salinello Fm (Figs. 2, 3 and 4). In our interpretation, we are dealing with a tilted megablock representing the former marginal escarpment and edge of a drowned (pelagic) carbonate platform, which collapsed due to retreat of the margin.

Structural setting

The Montagna dei Fiori ridge is a regional anticline, N-S-trending, located on the eastern border of the Laga Basin, a wide area characterized by siliciclastic turbidite sedimentation in the Messinian (Laga Fm, Centamore *et al.*, 1991). To the west, the arc-shaped

Mt. Sibillini thrust has the Umbria-Marche pelagic basin overriding the Laga Fm. To the south, along the E-W-trending thrust front of the Gran Sasso unit, the Latium-Abruzzi carbonate platform palaeodomain overrides the N-S-trending structures of the Laga Basin (Bigi *et al.*, 1999; Mazzoli *et al.*, 2002) (Fig. 1).

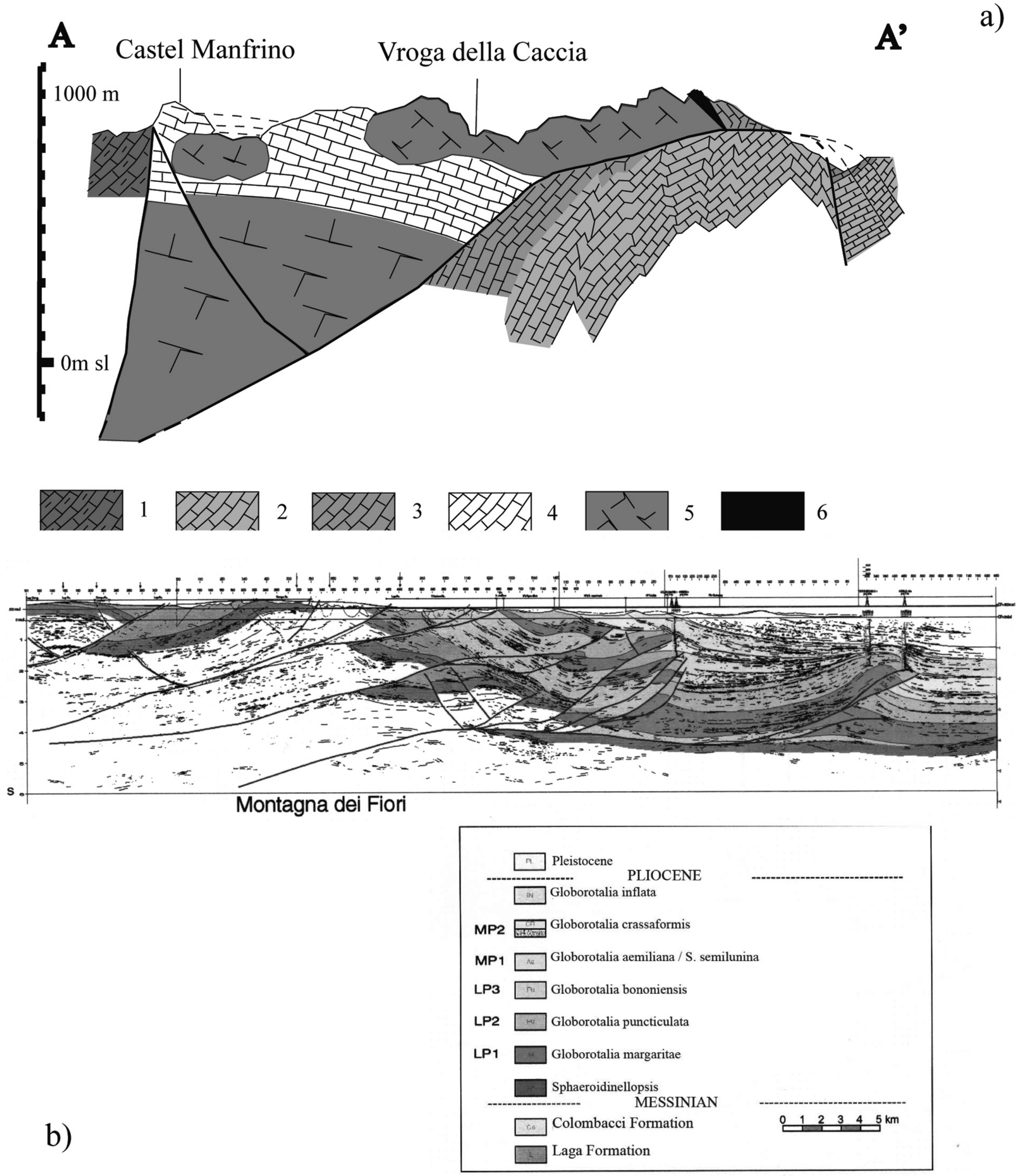

Figure 5. (a) Geological section across the Salinello Valley (trace in Fig. 2). 1. Cerrogna Marls Fm.; 2. Scaglia Fm.; 3. Marne a Fucoidi Fm.; 4. Corniola Fm.; 5. Calcare Massiccio Fm.; 6. PCP top condensed deposits. (b) Regional cross section across the Montagna dei Fiori and Laga basin, where the trajectory of T1 thrust is shown (From Casero *et al.*, 2001).

With respect to the other N-S-trending anticlines involving the carbonate substratum in the Laga Basin, the Montagna dei Fiori structure has a greater structural elevation, corresponding to an area of maximum topographic elevation. It consists of an asymmetrical anticline, with an overturned forelimb. It plunges in both directions along its axis; to the south, an equivalent structure is the Montagnone anticline, which displays a similar asymmetric geometry (Fig. 1). This N-S-trending ridge owes its structural elevation to the presence of a deeper main thrust, described by several authors and well recognizable in the 2D seismic lines that run along this area (Figs. 1 and 5) (Centamore *et al.*, 1991; Bigi *et al.*, 1999; Casero, 2004; Tozer *et al.*, 2006). Although a reconstruction of the regional setting of the Laga Basin is beyond the scope of this paper, the depth and the evolution of T1 thrust are critical to our understanding of the Montagna dei Fiori structure.

This main T1 thrust is associated with the buried E-dipping forelimb, with the Oligocene-Messinian succession being thrust over the Lower Pliocene deposits, to the east of our study area (T1 thrust, figures 1 and 5). The internal and structurally higher Montagna dei Fiori-Montagnone thrust branches from the T1 thrust. From the analysis of the 2D seismic lines crossing the structure (non available data) and according to several authors, the hangingwall anticline generated by the T1 thrust, involving deposits as young as the Messinian Laga formation, is cut by the Montagna dei Fiori-Montagnone thrust (Figs. 1 and 5); this geometric relationship is an evidence that the activity of the Montagna dei Fiori-Montagnone thrust postdates the main propagation phase of the T1 thrust (Mazzoli *et al.*, 2002; Casero, 2004).

Within the core of the Montagna dei Fiori anticline, along the Salinello Valley, the Salinello thrust is exposed (Calamita *et al.*, 1998 and references therein) (Figs. 2 and 4). The Salinello thrust has an antiformal geometry, with its E-dipping hanging wall overlying an overturned succession consisting of the Marne a Fucoidi, Scaglia Bianca and Scaglia Rossa Fms (Fig. 4).

The displacement along the Salinello thrust is about 750 m, a figure provided by the separation between the hanging wall and footwall cut off of the Fucoidi Marls. In the hanging wall, both the strata of the Corniola and Calcare Massiccio Fms form a 20° to 40° angle to the thrust plane. In the footwall, the overturned bedding of the Scaglia Rossa Fm forms an angle of about 60° with the thrust plane. To the east, although the Salinello thrust keeps an "up section" relationship with the strata, it dips eastward –into the subsurface– creating a small tectonic window in the Salinello Valley (Figs. 2 and 5). The footwall strata are involved in this fold, producing an antiformal anticline in the eastern sector of the tectonic window, which changes the footwall cut-off angle (Figs. 2 and 5).

A southwestward dipping normal fault offsets the back limb of the hanging wall anticline. The normal fault has a maximum displacement of 1400 m (Centamore *et al.*, 1991); it was active before Neogene compressional deformation (Calamita *et al.*, 1998; Mazzoli *et al.*, 2002; Scisciani *et al.*, 2002).

Kinematic models, of the Montagna dei Fiori structure

Many two-dimensional geometric and kinematic models have the aim to describe asymmetrical, recumbent folds associated with thrust development (Jamison, 1987; Chester and Chester, 1990; Mitra, 1990; Storti and Poblet, 1994; Salvini and Storti, 1996, among many others). Each model uses balancing constraints to derive relationships between geometrical variables such as fold interlimb angle, limb dip, shortening and detachment depth. The resulting geometries are often a good approximation of the natural structures. Most of the kinematic models applied currently are based on the fault-propagation folding model of Suppe and Medwedeff (1984, 1990). However the last decade has seen growing interest on the so-called trishear model (Erslev, 1991; Hardy and Ford, 1997; Zehnder and Allmendinger, 2002, amongst others).

All the previous kinematic models applied to the Montagna dei Fiori fault-related fold take into account a complex original palaeogeography, characterized by the occurrence of a Jurassic normal fault, implying an inherited structural elevation for the core of the anticline (Calamita *et al.*, 1998 and references therein; Tozer *et al.*, 2006). Instead, our stratigraphic interpretation implies that the top of the Calcare Massiccio of the Salinello Valley outcrop had no structural elevation during the Jurassic, being part of the basin fill succession. Its existence as a positive topographic feature came to an end in the Oxfordian, when it became completely buried by the Salinello Fm (Fig. 3). In this view, the strong structural elevation observed in the Montagna dei Fiori fault-related-fold should be linked with the Miocene normal fault cutting the back limb of the anticline, and with tec-

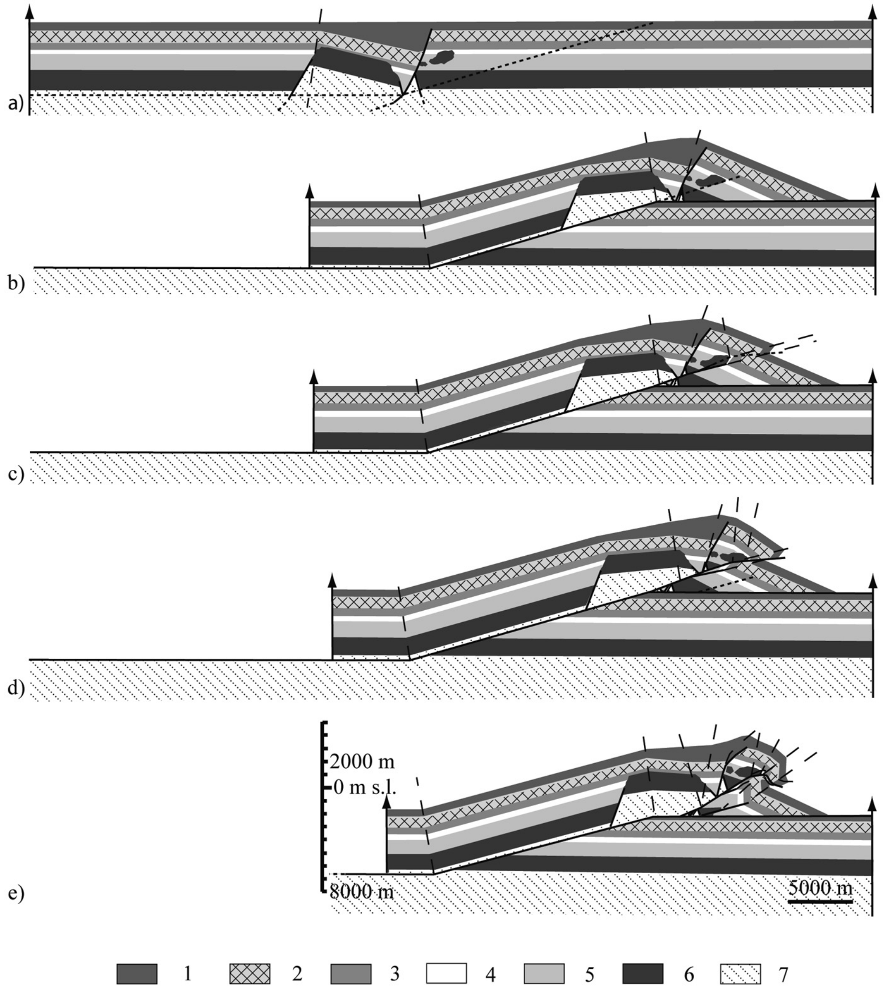

Figure 6. Forward model of the Montagna dei Fiori structure. See text for explanation. 1. Cerrogna Marls and Bisciaro Fm (Lower-Middle Miocene); 2. Scaglia, Marne a Fucoidi and Maiolica Fms (Tithonian-Aquitanian); 3. Salinello and Calcari a Saccocoma Fms (Bathonian-Tithonian); 4. Rosso Ammonitico and Calcari a Posidonia Fms (Toarcian-Bajocian); 5. Corniola Fm (Sinemurian-Pliensbachian); 6. Calcare Massiccio Fm (Hettangian-Sinemurian p.p.); 7. Dolostone (Upper Triassic).

tonic transport along the main deeper thrust (T1 thrust, figures 1 and 5), as already proposed by Calamita *et al.* (1998).

The first forward model was constructed by hand (Fig. 6) and the second one was constructed using directly the software 2DMove (Midland Valley), starting from a simplified version of the stratigraphic template (Fig. 7) and following the same main steps imposed in the previous restoration.

Construction of the models was based on a large number of constraints provided by our new data and by previous works:

1) The Jurassic stratigraphy is characterized by the occurrence of large rigid bodies (olistoliths) within a layer-cake geometry represented by the pelagic succession (Fig. 3). No Jurassic normal faults can be mapped in the Salinello Valley, so they did not control the anticline geometry. The contrast of competence at the core of the anticline is due to the lateral onlap contact between the huge blocks of Calcare Massiccio Fm and the well bedded Corniola and Rosso Ammonitico Fms;

2) the pre-contractional stratigraphic setting includes a Miocene normal fault, which offsets the pre-Miocene pelagic succession and generates the strong thickness variation in the Miocene deposits (Cerrogna Marls; Calamita *et al.*, 1998) (Figs. 5 and 6);

3) the main thrust front in the area is the one linked with the T1 thrust, which is buried to the east of the outcropping anticline, as evidenced by seismic images (Bigi *et al.*, 1999; Casero, 2004; Tozer *et al.*, 2006) (Figs. 1 and 5). This thrust, responsible for the structural elevation of the Montagna dei Fiori anticline, displays a hanging wall fold geometry which fits a fault-bend fold model (Fig. 5);

4) the Salinello thrust propagated from the main thrust T1; it cuts through the core and the forelimb of the hanging wall anticline of the T1 thrust, which suggests that it is younger than the T1 thrust (Fig. 5);

5) the small offset produced by the Salinello thrust, with respect to the high elevation of the fold, suggests a very variable value of fault propagation rate vs. slip ratio (P/S) (Williams and Chapman, 1983) during the hanging wall anticline development;

6) the folded geometry of the Salinello thrust can be explained by a subsequent development of a thrust in its footwall (see below).

The discrete steps of our forward model are illustrated in figure 6. The initial stratigraphic template includes the occurrence of the Miocene normal fault, whose phase of main activity controlled deposition of the Cerrogna Marls (Calamita *et al.*, 1998). The inferred position for the Jurassic structural high, sourced the olistoliths, is shown to the west of the main structure (Fig. 6a). The first phase of deformation explains the observed structural elevation and the geometries associated with the T1 thrust. We used a simple fault-bend fold (Suppe, 1983) to represent thrust T1 at depth, taking into account the offset predicted by several authors (Bigi *et al.*, 1999; Tozer *et al.*, 2006) (Fig. 6b). The second thrust plane (corresponding to the Salinello thrust) branches from the T1 thrust and cuts through its hanging wall anticline (Fig. 6c). We adopted the fault-propagation model (Suppe and Medwedeff, 1990) to construct the new thrust plane in the hanging wall ramp of the previous

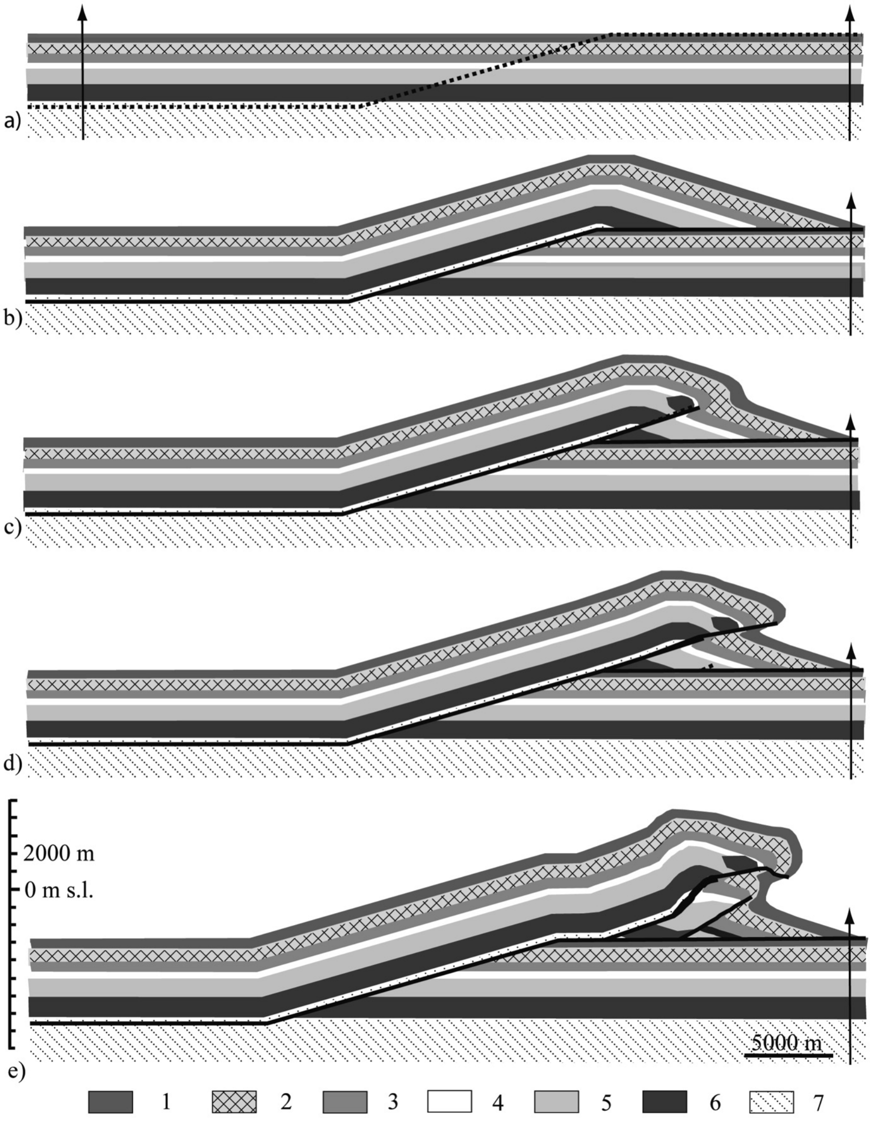

Figure 7. Forward model of the Montagna dei Fiori structure constructed using 2D Move (Midland Valley). In this case, the trishear model was used instead of the fault-propagation fold model in steps c, d and e. 1. Cerrogna Marls and Bisciaro Fm (Lower-Middle Miocene); 2. Scaglia, Marne a Fucoidi and Maiolica Fms (Tithonian-Aquitanian); 3. Salinello and Calcari a Saccocoma Fms (Bathonian-Tithonian); 4. Rosso Ammonitico and Calcari a Posidonia Fms (Toarcian-Bajocian); 5. Corniola Fm (Sinemurian-Pliensbachian); 6. Calcare Massiccio Fm (Hettangian-Sinemurian p.p.); 7. Dolostone (Upper Triassic).

thrust. It propagates upward generating the overturned forelimb in the hanging wall (Fig. 6d), and it is followed by the propagation of the same plane across the fold with a lower dip angle, using the anticline breakthrough model, as constrained by the measured cut-off angles and offset values along the Salinello Valley (Fig. 6d). In this step we consider that the occurrence of the huge olistolith in the core of the anticline triggered a deviation of the thrust trajectory, or a repeated branch process. A third thrust propagation is required in order to obtain the folded geometry of the Salinello thrust and the overturned setting of the forelimb of the Montagna dei Fiori anticline. Development of this younger thrust plane, located in the footwall of the previous one (being the hanging wall ramp of the T1 thrust), would account for this geometry, according to a fault-propagation fold model (Fig. 6e).

In the forward model of figure 7, we used 2DMove software (Midland Valley) in order to simulate the same steps and validate the obtained results. In this case, we started from a simplified stratigraphic template, where the Miocene normal fault and the Jurassic olistoliths were omitted, as well as the inferred position of the Jurassic structural high. Moreover, instead of the fault-propagation fold model, we used the algorithm for the trishear model (Hardy and Ford, 1997; Zehnder and Allmendinger, 2002). This allowed us to vary the propagation/slip rate and the apex angle that controls the dip angle of the thrust plane, obtaining comparable geometries (Fig. 7).

Conclusions

The Montagna dei Fiori is a regional scale recumbent fold associated with a folded thrust, named the Salinello thrust, which branches from a deeper thrust T1 (Fig. 1). A new field mapping resulted in a novel interpretation of the Jurassic stratigraphy of the area: the outcrops of Calcare Massiccio Fm (Hettangian-Early Sinemurian) are interpreted as olistoliths produced by retreat of the margin of a pelagic carbonate platform, which took place shortly after its drowning (Early Pliensbachian). These slid into a basin where abundant resedimented material was shed by a coeval productive carbonate platform, eventually burying it in the Oxfordian. No genuine Jurassic normal faults can be traced in the core of the main anticline (Figs. 2, 3 and 4).

Two forward models, based on a combination of different kinematic models and following the same main steps were constructed to account for the geometry and kinematics of the Montagna dei Fiori structure.

The first step of deformation is propagation of the T1 thrust, producing a large offset, followed by localized fault propagation in its hanging wall, and development of the recumbent anticline related to the Salinello thrust. During this second phase, several steps are recognized: the propagation of the Salinello thrust, the variation of the propagation/slip ratio, the variation of dip direction, and the propagation of another thrust in its relative footwall (Figs. 6 and 7). This strong localization of deformation in the hanging wall of the T1 thrust could be controlled by the peculiar stratigraphy of this area, where a horizontal mechanical contrast of competence was due to the occurrence of large rigid bodies within the layer cake geometry of the pelagic succession.

Acknowledgements

We acknowledge financial support by projects CGL2005-02233/BTE, CGL2008-03786/BTE, CGL2006-12415-C03-02/BTE and CSD2006-0041 (Topo-Iberia) under Consolider-Ingenio 2010 Program funded by the Spanish Ministry for Education and Science, CGL2008-00463-E/BTE funded by the Spanish Ministry for Science and Innovation, and CNG08-15 funded by the Asturian Ministry for Science and Education. We would like to thank the editors of this special issue.

References

BIGI, S., CALAMITA, F., CELLO, G., CENTAMORE, E., DEIANA, G., PALTRINIERI, W., PIERANTONI, P. P. and RIDOLFI, M. (1999): Tectonics and sedimentation within a Messinian foredeep in the Central Apennines, Italy. *J. Petrol. Geol.*, 22: 5-18.

CALAMITA, F., PIZZI, A., RIDOLFI, M., RUSCIADELLI, M. and SCISCIANI, V. (1998): Il buttressing delle faglie normali sinsedimentarie pre-thrusting sulla strutturazione neogenica della catena appenninica: l'esempio della M.gna dei Fiori (Appennino Centrale esterno). *B. Soc. Geol. It.*, 117: 725-745.

CASERO, P., ALBOUY, E. and ESCHARD, R. (2001): *Tectonique, sedimentation et systemes petroliers dans les bassins sedimetaires associes aux chaines plisses.* Project FSH, Final report. IFP-RB10 – TOTAL-FINA-ELF.

CASERO, P. (2004): Structural setting of petroleum exploration plays in Italy. 32nd International Geological Congress, *Geol. Italy*, 189-199.

CENTAMORE, E., CHIOCCHINI, M., DEIANA, G., MICARELLI, A. and PIERUCCINI, U. (1971): Contributo alla conoscenza del Giurassico dell'Appennino umbro-marchigiano. *Studi Geologici Camerti*, 1: 7-89.

CENTAMORE, E., ADAMOLI, L., CANTALAMESSA, G., BERTI, D., BIGI, G., BIGI, S., CASNEDI, R., FUMANTI, F., MORELLI, C., RIDOLFI, M. and SALVUCCI, R. (1991): *Carta geologica dei bacini della Laga e del Cellino e dei rilievi carbonatici circostanti. SELCA Firenze, scale 1:100 000*; 1 sheet.

CRESCENTI, U., CROSTELLA, A., DONZELLI, G. and RAFFI, G. (1969): Stratigrafia della serie calcarea dal Lias al Miocene nella regione marchigiano-abruzzese (Parte II – Litostratigrafia, biostratigrafia e Paleogeografia). *Mem. Soc. Geol. It.*, 85: 343-420.

CHESTER, J. S. and CHESTER, F. M. (1990): Fault-propagation folds above thrusts with constant dip. *J. Struct. Geol.*, 12: 903-910.

ERSLEV, E. A. (1991): Trishear fault-propagation folding. *Geology*, 19: 617-620.

GALLUZZO, F. and SANTANTONIO, M. (2002): The Sabina Plateau: a new element in the Mesozoic palaeogeography of Central Apennines. *B. Soc. Geol. It. Spec. Vol.*, 1: 561-588.

HARDY, S. and FORD, M. (1997): Numerical modeling of trishear fault propagation folding. *Tectonics*, 16: 841-854.

JAMISON, W. R. (1987): Geometric analysis of fold development in overthrust terranes. *J. Struct. Geol.*, 9: 207-219.

MATTEI, M. (1987): Analisi geologico-strutturale della Montagna dei Fiori (Ascoli Piceno, Italia Centrale). *Geol. Rom.*, 26: 327-347.

MAZZOLI, S., DEIANA, G., GALDENZI, S. and CELLO, G. (2002): Miocene fault controlled sedimentation and thrust propagation in the previously faulted external zones of the Umbria-Marche Apennines, Italy. *E.G.S., Stephan Mueller Spec. Publ.*, 1: 301-324.

MITRA, S. (1990): Fault-propagation folds: geometry, kinematic evolution, and hydrocarbon traps. *AAPG Bull.*, 74: 921-945.

SALVINI, F. and STORTI, F. (1996): Progressive rollover fault-propagation folding: a possible kinematic mechanism to generate regional scale recumbent folds in shallow foreland belts. *AAPG Bull.*, 80: 174-193.

SANTANTONIO, M. (1993): Facies associations and evolution of pelagic carbonate platform/basin systems: examples from the Italian Jurassic. *Sedimentology*, 40: 1039-1067.

SANTANTONIO, M. (1994): Pelagic Carbonate Platforms in the Geologic Record: Their Classification, and Sedimentary and Paleotectonic Evolution. *AAPG Bull.*, 78: 122-141.

SANTANTONIO, M., GALLUZZO, F. and GILL, G. (1996): Anatomy and paleobathymetry of a Jurassic pelagic carbonate platform/basin system, Rossa Mts, Central Apennines (Italy). Geological Implications. *Palaeopelagos*, 6: 123-169.

SCISCIANI, V., TAVARNELLI, E., CALAMITA, F. and PALTRINIERI, W. (2002): Pre-thrusting normal faults within sun-orogenic basins of the outer Central Apennines, Italy: implication for Apennine tectonics. *B. Soc. Geol. It., Spec. Vol.*, 1: 295-304.

STORTI, F. and POBLET, J. (1994): The role of growth strata to infer the kinematics of shallow foreland thrust tip fold (abs): Fault Dynamics workshop. *Royal Holloway University of London Abstr.*, 42.

SUPPE, J. (1983): Geometry and kinematics of fault-bend folding. *Am. J. Sci.*, 283: 684-721.

SUPPE, J. and MEDWEDEFF, D. A. (1984): Fault-propagation folding. *Geol. Soc. Am. Bull.*, Abstracts with Programs, 16: 670.

SUPPE, J. and MEDWEDEFF, D. A. (1990): Geometry and kinematics of fault-propagation folding. *Eclogae Geol. Helv.*, 83: 409-454.

TOZER, R. S. J., BUTLER, R. W. H., CHIAPPINI, M., CORRADO, S., MAZZOLI, S. and SPERANZA, F. (2006): Testing thrust tectonic models at mountain fronts: where has the displacement gone? *J. Geol. Soc. London*, 162: 1-15.

WILLIAMS, G. D. and CHAPMAN, T. J. (1983): Strains developed in the hanging walls of thrust due to their slip/propagation rate: a dislocation model. *J. Struct. Geol.*, 6: 563-571.

ZEHNDER, A. T. and ALLMENDINGER, R. W. (2002): Velocity field for the trishear model. *J. Struct. Geol.*, 22: 1009-1014.