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Mesozoic extension controlling the Southern Alps thrust front geometry under the Po Plain, Italy: Insights from sandbox models

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Abstract

In the Southern Alps fold and thrust belt, east-west Mesozoic rifting controlled the development of extensional faults, the deposition of the sedimentary sequences and the thickness and distribution of the main detachment levels. Vertical and lateral heterogeneities strongly influenced the structural style of the subsequent north-south contractional phase, as revealed by surface mapping and by subsurface maps derived from seismic data. Along the strike of the chain, lateral terminations of thrust faults occur at syn-rift extensional faults, trending normal with respect to the contractional structures, From west to east, the thrust sheet number decreases and the order of structures and their wavelength changes.

On a regional scale the effects produced by pre-existing heterogeneities on the development of contractional Alpine tectonic structures in the external area of the Southern Alps were evaluated by means of scaled sandbox analogue models. Modelled lateral heterogeneities produced different wavelength thrust sheets, salients and recesses, whereas vertical heterogeneities facilitated the development of structures of different orders. First-order structures detached at the base of the model and second-order structures detached at the intermediate relatively weak layers. Comparison of analogue model results with nature showed good geometrical similarities.
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1. Introduction

The Alps show several examples of structural geometries controlled by inverted extensional basins and, in general, by inherited Mesozoic or even Hercynian structural settings (Von Raumer and Neubauer, 1993). This is particularly evident in the Southern Alps fold and thrust belt where: i) the Southern Alps deformed the Adria plate margin, which had spectacularly recorded the extensional rifting phase of the Tethyan ocean (Bertotti et al., 1993; Sarti et al., 1993, and references therein); and ii) during the following contractional phases the chain remained at shallow structural levels and did not experience metamorphism, so preserving the previous tectonic history.

In the Southern Alps fold and thrust belt, syn-rift structures influenced the geological setting in terms of the mechanical behaviour of sedimentary sequences, the tectonic wedge detachment depth and the thickness and distribution of main detachment levels (Laubscher, 1985; Schönborn, 1992; Castellarin et al., 1992; Fantoni et al., 2004). The effect of these variables can be seen at different scales, from the reactivation of a single fault to the different development of entire sectors of the chain. A good example of differential variation on a regional scale is the external sector of the chain. This is buried under the Po Plain sediments in Lombardy (Fig. 1) where thrust fronts are strongly variable along strike and are interrupted laterally by a transverse zone. From west to east, thrust sheet number, fold wavelength (i.e. distance between the axial plane traces of two adjacent anticlines) and

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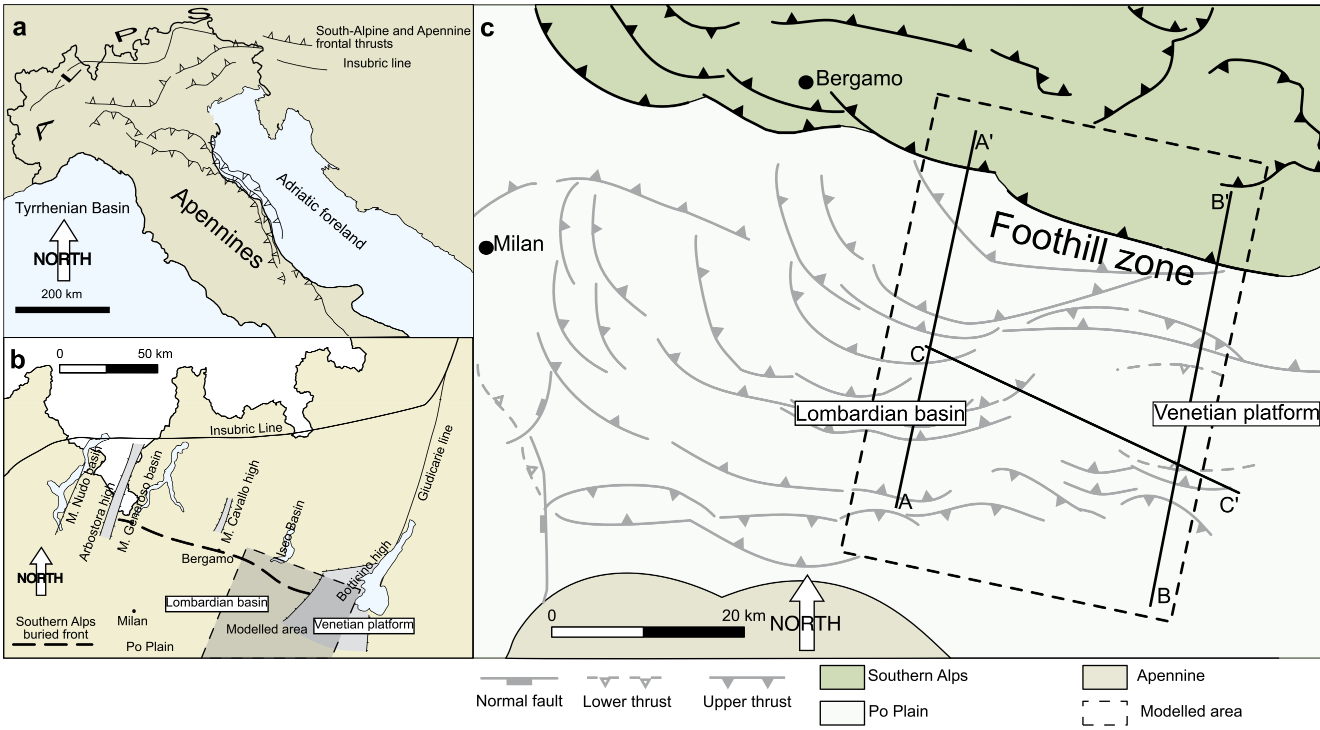

Fig. 1. a) Location map with the main regional tectonic structures. b) Structural map showing the position of the more important structural highs and basins in the Lombardian Southern Alps – Po Plain sector. c) Schematic structural map of the Southern Alps – Po Plain system showing main outcropping (black) and buried (grey) thrust fronts. The sector corresponding to the sand box modelled area is also displayed, together with traces of the cross sections.

detachment depth change significantly. This is revealed by the interpretation of two seismic sections through an inverted Mesozoic basin section AA′) and across a structural high (section BB′). At the same time, the stratigraphic setting shows vertical and horizontal heterogeneities regarding thickness and rock layer competence (Fig. 2). In this paper we use sandbox analogue models to provide insights into the structural setting of the area and the potential causes of its evolution.

2. Geological setting

2.1. The Southern Alps

The Southern Alps fold and thrust belt represents the non-metamorphic retrobelt of the double-vergent Alpine chain. It displays a southern vergence toward Africa and is in contact, along the Insubric Line, with the north verging Alpine chain (toward Europe). The belt contains an abrupt bend in strike and it is bounded to the east by the Giudicarie line, a NNE-SSW-trending fan of sinistral transpressive faults (Fig. 1b).

To the east of the Giudicarie line the Southern Alps are formed by nearly linear WSW-ESE striking south verging thrusts (Doglioni, 1987; Castellarin and Cantelli, 2000; Bertelli et al., 2003). To the west of the Giudicarie line, in the Lombardian sector, the Southern Alps strike WNW-ESE, partly outcropping in the Foothill Zone and partly buried under the thick Plio-Quaternary deposits of the Po Plain siliciclastic successions to the south (Laubscher, 1985, 1990, 1992; Castellarin et al., 1992; Fantoni et al., 2004).

From the north to the south across strike, from the hinterland to the foreland, the Lombardian Southern Alps are characterised by: i) Variscan basement unconformably covered by a volcano-sedimentary Permian successions; ii) a thick carbonatic sequence of Triassic and Jurassic units; and iii) a terrigenous Cretaceous succession. In the external sector of the chain, these units deepen and continue, buried, below the foredeep Po Plain sediments. A good interpretation of the subsurface structures can be made by means of seismic and well data (Pieri and Groppi, 1981; Cassano et al., 1986; Fantoni et al., 1999, 2004). The buried toe of the belt is characterised by a non-cylindrical fan of imbricate slices affecting both the carbonatic and the siliciclastic successions.

2.2. Type and timing of deformation

The Southern Alps belong to the northern border of the Adria plate and preserve a record of passive margin growth. During the Mesozoic, the Adria margin was affected by the Triassic rifting (Jadoul et al., 1992), followed by Late Triassic-Jurassic rifting leading to the opening of the Tethys Ocean (Bosellini, 1973; Bernoulli et al., 1979; Bertotti et al., 1993). Extension was mainly accommodated by normal fault systems delineating grabens filled by syn-rift sediments and controlling the carbonate platform distribution.

Starting from Middle Jurassic to Early Cretaceous, a drifting phase is recorded in the Adria margin by coeval sedimentary deposits that record an abrupt depth increase. Mesozoic extension resulted in the N-S horsts (M. Nudo, M. Generoso) and

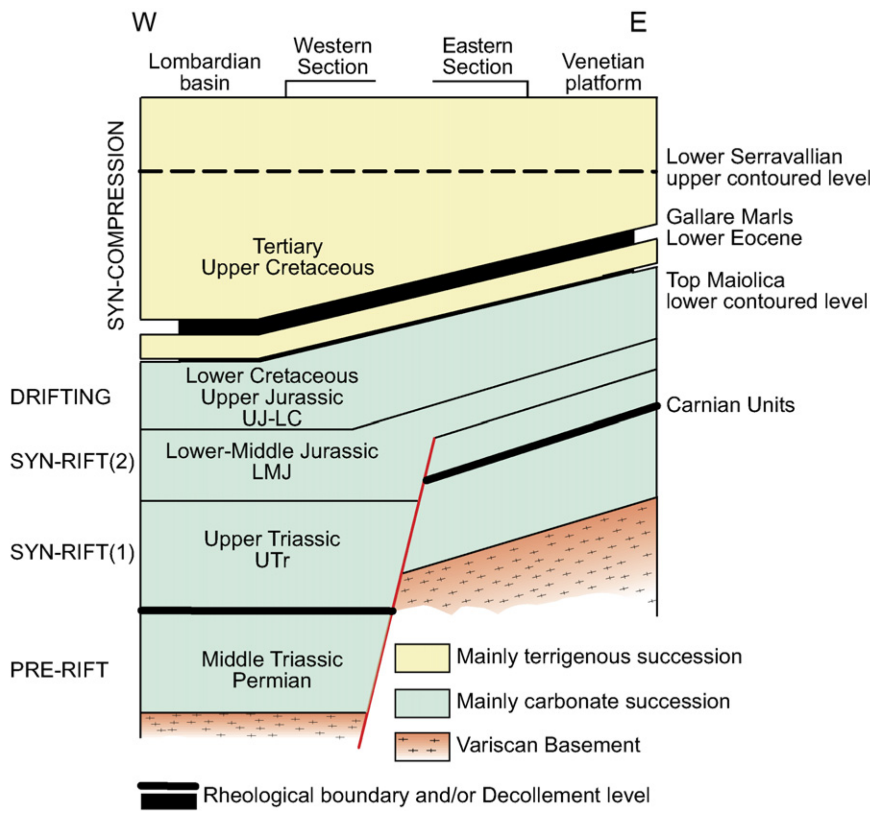

Fig. 2. Along strike simplified rheological sequence of the Po Plain basin. The approximate position of the dip sections is indicated. The main tectonic phases are indicated on the left, décollement levels and rheological boundaries are in black.

grabens (Iseo Basin) bounded by E and W-dipping master normal faults (Fig. 1). The tectonic activity began during the Norian. After a pause during Late Triassic a new extensional phase took place during the Liassic. Then extension shifted westward until the Late Jurassic. From this time to the Early Cretaceous the Southern Alps underwent post-rift thermal subsidence (Bertotti et al., 1993; Sarti et al., 1993, and references therein; Fantoni and Scotti, 2003).

At the end of the Early Cretaceous, the convergence between Adria and Europe started, as part of the contractional history of the Alps (Dal Piaz et al., 2004 and references therein; Schmid et al., 2004). The subsequent orogeny has been interpreted in terms of three main steps: the pre-collisional (eo-Alpine) event, the Paleocene-Eocene continental margin collision (meso-Alpine) event and the Oligo-Miocene post-collision deformation (neo-Alpine) event (Trumpy, 1973).

2.3. Buried Southern Alps thrusts front and Po Plain foreland in the Lombardian sector

In the Lombardian sector of the Southern Alps (Fig. 1) the buried belt is characterized by a stack of units imbricated over a regional décollement located at the top of Late Eocene Gallare Marls Late Eocene and carrying a thick clastic Tertiary wedge. Below the décollement, Mesozoic carbonatic units are affected by thick-skinned tectonics (Fig. 3a). In this sector the chain reaches the maximum southern extent and its edge is very close to the Northern Apennines buried thrust front (Fig. 1). Actually, during Late Messinian-Early Pliocene, the South Alpine thrust front was cut by the Apennine north-verging thrusts (Bello and Fantoni, 2002) and, as a consequence, the Po Plain foreland was completely entrapped by the two facing belts. During the Plio-Pleistocene the southernmost South Alpine structures were cut or re-folded after wedging of wide north-verging thrusts (Fantoni et al., 2004).

Moving along strike towards the east, the thrust front structural style abruptly changes (Fig. 3b). In less than 10 km: i) the closely spaced thrust system that in the western area affects the Tertiary clastic wedge shows an abrupt lateral termination; ii) thrusts length increase; and iii) the shortening is mostly accommodated by a sole thrust below the Mesozoic carbonates. The youngest part of the resulting fold and thrust belt, the buried South Alpine thrust system toe, has not been activate since Messinian time (Fantoni et al., 2004).

2.4. Tectono-stratigraphy and mechanical significance of the Lombardian Southern Alps successions

In Lombardy the Southern Alps thrust system incorporated levels from the Variscan Basement in the hinterland, to the Oligo-Miocene in the foreland and was buried by the Plio-Quaternary succession of the Po Plain. The stratigraphy (Fig. 2) will be described here trying only to highlight the main cycles. According to Bersezio et al. (2001) and Fantoni

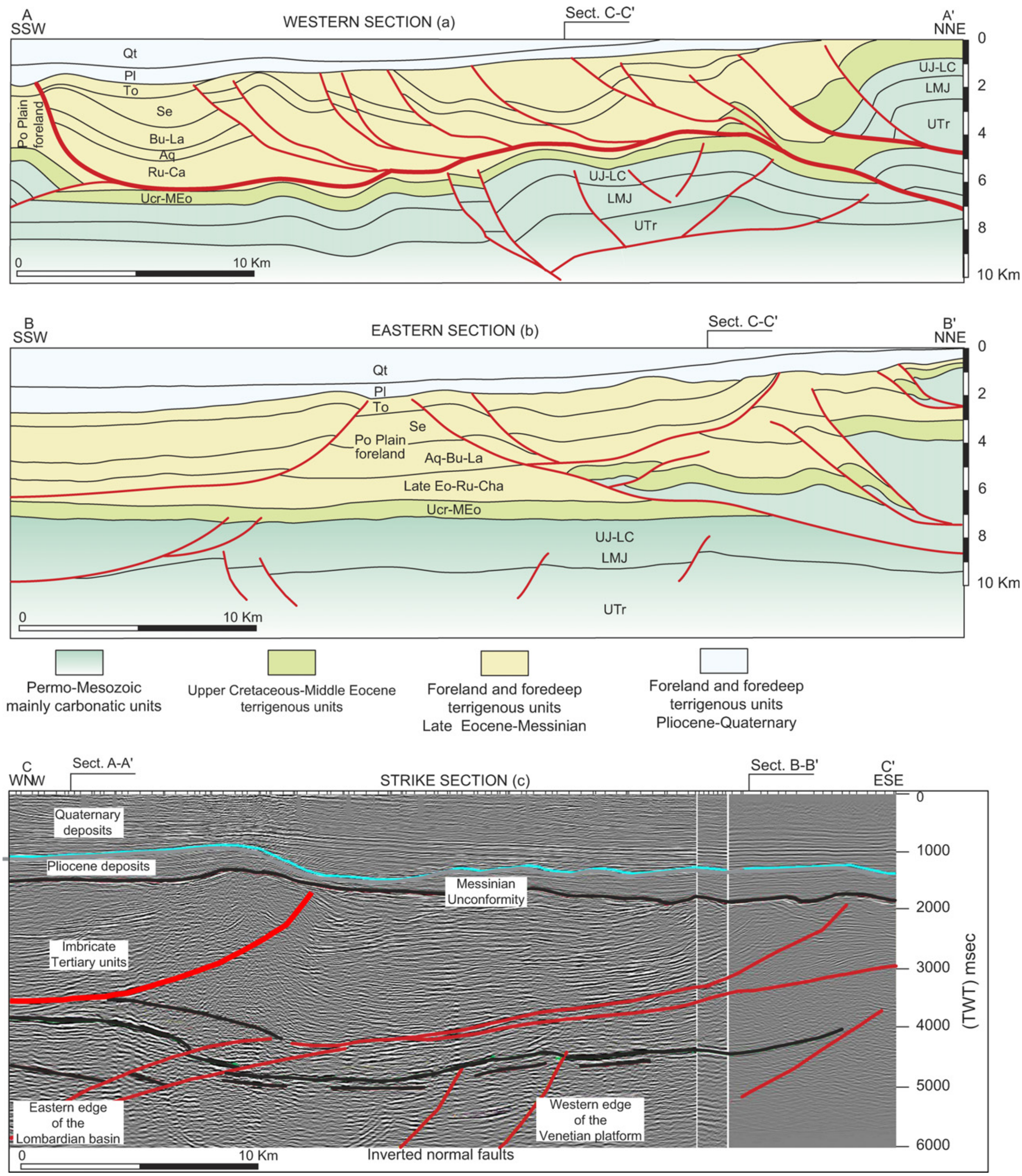

Fig. 3. Western (a) and eastern (b) geological cross sections derived from seismic interpretation and depth conversion. Strike seismic section (c), used to constrain the interpretation of the dip sections and also to check the thickness variation of the stratigraphic sequence, has not been depth converted. Section position is shown in Fig. 1. The carbonate unit ages are indicated (UTr = Upper Triassic; LMJ = Lower-Middle Jurassic; UJ-LC = Upper Jurassic-Lower Cretaceous). In the Tertiary imbricate terrigenous units and in the upper stratigraphic levels (Ucr = Upper Cretaceous; MEo = Middle Eocene; Late Eo = Late Eocene; Ru = Rupelian; Cha = Chattian; Aq = Aquitanian; Bu = Burdigalian; La = Langhian; Se = Serravallian; To = Tortonian; Pl = Pliocene; Qt = Quaternary). Thicker lines highlight fault planes directly related to dècollement levels described in the text (the deepest of these two is never visible in the sections).

et al. (2004), we can differentiate three major tectono-stratigraphic and mechanical successions: pre-rift, syn-rift and post-rift. The pre-rift succession is composed of the Variscan Basement and the Permian to Middle Triassic carbonatic and terrigenous units. The syn-rift succession is divided into two phases. The first includes Upper Triassic dolomitic and terrigenous units and the second all the mainly carbonate formations of the Lower and Middle Jurassic. The post-rift succession ranges from Upper Jurassic to Lower Cretaceous and is mainly composed of carbonatic units.

The syn-contractional succession commences with a relatively weak horizon, the Mid-Cretaceous pelites in the South-Alpine border, and is internally separated by a younger incompetent formation, the Gallare Marls (Upper Eocene – Lower Oligocene) in the Po Plain foreland.

The Plio-Quaternary sediments can be distinguished from the lower series by a regional erosion surface, the Messinian unconformity, which sealed all the brittle tectonic events involving the Tertiary Units.

3. Data

Three regional seismic profiles have been considered in this research (Figs. 1 and 3). Two NNE-SSW depth-converted dip sections survey the Southern Alps buried fronts and also the Apennine thrust front (B-B′ cross section, Fig. 3b). The dip sections, A-A′ in the western part of the study area and B-B′ to the east, are 40 and 46 km long respectively. They are parallel and separated by a distance of about 30 km (Fig. 1). The strike section links the Lombardian basin to the west and the Venetian platform to the east.

3.1. Section A-A′

The section (Fig. 3a) is located along the Iseo basin, a Mesozoic extensional depocentre and is in a sector strongly deformed and flexured during the neo-Alpine contractional phase. It is located in the western sector of the area and highlights two main décollement levels in Late Eocene Gallare marls and Carnian Units. Compressive structures with different wavelengths originate from these levels. The lower of these two, not completely shown in the geological cross section, is probably located in Carnian Units close to the base of the syn-rift succession. The section shows deep-seated compressive structures involving the whole Permo-Mesozoic succession. These structures are mainly related to the reactivation of pre-existing extensional faults that, after the inversion of the tectonic regime, acted as ramps for the following newborn thrusts.

An upper décollement level is located at the top of Gallare Marls (Late Eocene), below the syn-contraction terrigenous succession. This relatively weak horizon allowed the formation of a second-order imbricate fan and closely spaced compressive structures. The upper parts of faults and thrust-related anticlines are everywhere partially eroded by the Messinian unconformity at the end of this tectonic phase. In this section no post-Messinian brittle structures seem to be present, and the Plio-Quaternary horizons are continuous even if locally gently folded.

3.2. Section B-B′

The structural style of the B-B′ section (Fig. 3b) shows a smaller number of structures and the presence of an important backthrust. The section is located in eastern Lombardy and is characterised by the large Botticino structural high of Mesozoic age which was scarcely affected by the contractional neo-Alpine tectonic phases. The central part of the section, a segment of less than 5 km in length where horizons are poorly deformed, represents the foreland of the Northern Apennine and South Alpine chains. Two décollement levels can be detected. The first is the rheological boundary at the base of the carbonate units, the second is located above the terrigenous/carbonate units. These two levels are responsible for the presence of both first-order structures detached at depth and second-order structures detached on the upper level.

In both sections, the number of décollement levels is the same but their effects on the structural style are clearly different. The shortening amount is also different, at least in the sectors surveyed by the seismic sections. In the western section (A-A′) the lower, inverted-related thrusts are always sealed at the upper décollement level. On the contrary, in the eastern section the main first-order contractional structure involves the whole sedimentary succession. Moreover, the upper décollement level is not associated with a large number of second-order structures, probably because of the different thickness of the overlying sequence. While the western section is characterized by imbricate fans and a large number of "shallow detached" structures, this section shows just one thrust fault, a backthrust, detached above the upper décollement level.

3.3. Section C-C′

The C-C′ seismic section (Fig. 3c) illustrates the main contractional structures along strike. This seismic line has not been depth converted; it was only used as an indication of the change in structure and décollement depth along strike and the location of the previous two sections. It is evident how structures within the Tertiary sequence units are localized only below the Messinian unconformity. Pliocene deposits above the Messinian unconformity are locally folded but never involved in brittle deformation. The double décollement level of A-A′ and B-B′ sections is shown here by the presence of upper faults displacing the Tertiary units and deeper structures which show evidence of inversion. Tertiary imbricate units are affected by two faults. The western fault is the strike view of one of the second order thrusts of section A-A′, detached at the base of the Tertiary units. The eastern fault is related to the first-order structure of section B-B′, a deep-seated thrust displacing both carbonate and terrigenous successions. The westward dipping faults in the deep carbonate units are related to the syn-rift tectonics. The seismic reflector evident at the base of the Tertiary units highlights the general rise of the stratigraphic successions toward the eastern structural highs.

4. Analogue modelling

The structural style in the area is characterised by at least two orders of thrust, different thrust sheet wavelength, curved thrust fronts, transfer zones, and backthrusting. In this paper, we investigate which parameters can be considered as the main factors influencing the three-dimensional setting of the region. Bearing in mind previous modelling results on generic studies worldwide, we can recognise the following:

i) Syn-rift faults. Such faults would represent surfaces of possible reactivation if they were favourably oriented and properly positioned with respect to the compressional stresses (Sassi et al., 1993).
ii) Mechanical stratigraphy. Extensional fault systems produce horst and graben topography of passive margins. Basins are filled with syn- and post- extension sediments with different thickness and lithology, reflecting different basin depth. As a result, such faults can represent a boundary between domains with different rock rheology. Sandbox models have provided many insights regarding the influence of mechanically heterogeneous layering, both in two (Verschuren et al., 1996; Teixell and Koyi, 2003; Massoli et al., 2006) and three-dimensions (Corrado et al., 1998; Turrini et al., 2001; Ravaglia et al., 2004). Mechanical stratigraphy determines the development of several orders of thrust-related folds, staircase trajectories of fault planes and the development of transfer zones.
iii) Shape of the indenter and of the sedimentary basin (Marshak and Wilkerson, 1992; Marshak et al., 1992; Calassou et al., 1993; Boyer, 1995; Macedo and Marshak, 1999; Lickorish et al., 2002; Soto et al., 2002, 2003; Gomes et al., 2003), which may influence the shape of thrust fronts, the development of transfer zones and thrust sheets wavelength.
iv) Syn-contractional sedimentation influences structures at regional and local scale (Storti and McClay, 1995; Nalpas et al., 1999; Nieuwland et al., 2000; Barrier et al., 2002; Nalpas et al., 2003).

It is apparent that: vertical mechanical stratigraphy represents a prerequisite for the development of more orders of structures and wavelength of thrust sheets mainly depends on frictional resistance of the basal detachment, thickness of the succession and obstacles in the foreland. Curved thrusts fronts can arise from lateral mechanical heterogeneities, lateral thickness variations, shape of the indenter or different basal detachment depth and different lateral distribution of syn-contractional sediments. Given the results of published experiments and the interpreted subsurface geometry, we consider the vertical and lateral position of décollement layer as the primary controlling factor and the syn-tectonic sedimentation geometry as a secondary factor.

4.1. Models set-up and stratigraphy

We simulated a simplified stratigraphic sequence representing the buried thrust front of the Southern Alps beneath the Po floodplain. We did not reproduce the extensional structures but only their effect on the thickness and position of the main detachments, so the experiment started with the contractional phase. Only the external sector of the models have been analysed and described here.

Two synthetic stratigraphies imitate the natural conditions we believed were responsible for the structural style in the area (Fig. 4a). The scaling length ratio was around 1:200,000. We used two types of granular materials with different physical parameters, sand and glass microbeads. They are widely used in sandbox experiments, allowing scalable dynamic similarities between the model and nature (Schreurs et al., 2006). The sand has an angle of internal friction (φ) of 33°, a grain size of 100–300 μm and simulates relatively competent natural rocks such as sandstones and carbonates. The glass microbeads have $\varphi = 24°$, due to their high sphericity and rounding (Schellart, 2000), a grain size of 300–400 μm and simulate relatively incompetent rocks such as clay and shales, allowing low-friction décollement, (Sassi et al., 1993) and inter-strata slips (Turrini et al., 2001) to occur. The basal detachment has a friction angle (φ) of 30° in the east and 14° in the west. A rigid mobile backstop pushes the sand at a velocity less than 1 cm/minute. Both models were 40 cm long, 30 cm wide and the foreland of the sandbox was confined by a fixed wall (Fig. 4d).

An initial pre-contractional stratigraphy (corresponding to the pre-, syn- and post-rift sequences) 1.6 cm high was constructed (Fig. 4b,c). To the west, a 2 mm thick layer of glass microbeads rested on the basal plastic surface of the box and a pile of 14 mm of sand layers overlaid it. To the east, a simple 2 mm thick glass microbead layer was at a higher elevation, at 8 mm from the base.

The two models differ with regard the syn-contractional sedimentation stratigraphy and the final shortening. Model 1 has been built with a single syn-contractional glass microbead layer but in model 2 we simulate more precisely the stratigraphy of the area. Two sedimentation events were simulated. In model 1 (Fig. 4b), after 4 cm of shortening (10%) a 2 mm thick layer of glass microbeads was laid down followed by 6 mm of sand. After 10 cm of shortening (25%), 8 mm of sand layers were added. The final total shortening was 17 cm (42.5%).

In model 2 (Fig. 4c) the first syn-contraction sedimentation event was simulated after 7 cm of shortening (17.5%) and was made up of 10 mm of material, with a 2 mm thick glass microbead layer at the base of the sequence and 1 mm thick microbead layer in the middle. The second event was simulated after 10 cm of shortening (25%) and was made up of 9 mm of sand. The final total shortening was 19 cm (47.5%).

The final models were analysed by 14 to 16 serial cross sections (Figs. 5 and 6). The interpreted structures were then contoured at two different levels. The lower corresponds to the end of the extensional activity in the area at the top of the carbonate sequence (Maiolica Fm carbonates, Lower Cretaceous) and the shallower roughly matched the Lower Serravallian sequence of silicoclastic sediments (Fig. 7).

4.2. Model 1 results

The interpreted final structures show a long wavelength thrust sheet to the west (9, Fig. 5a–e) and a short wavelength thrust to the east (7, Fig. 5h), connected in the central domain,

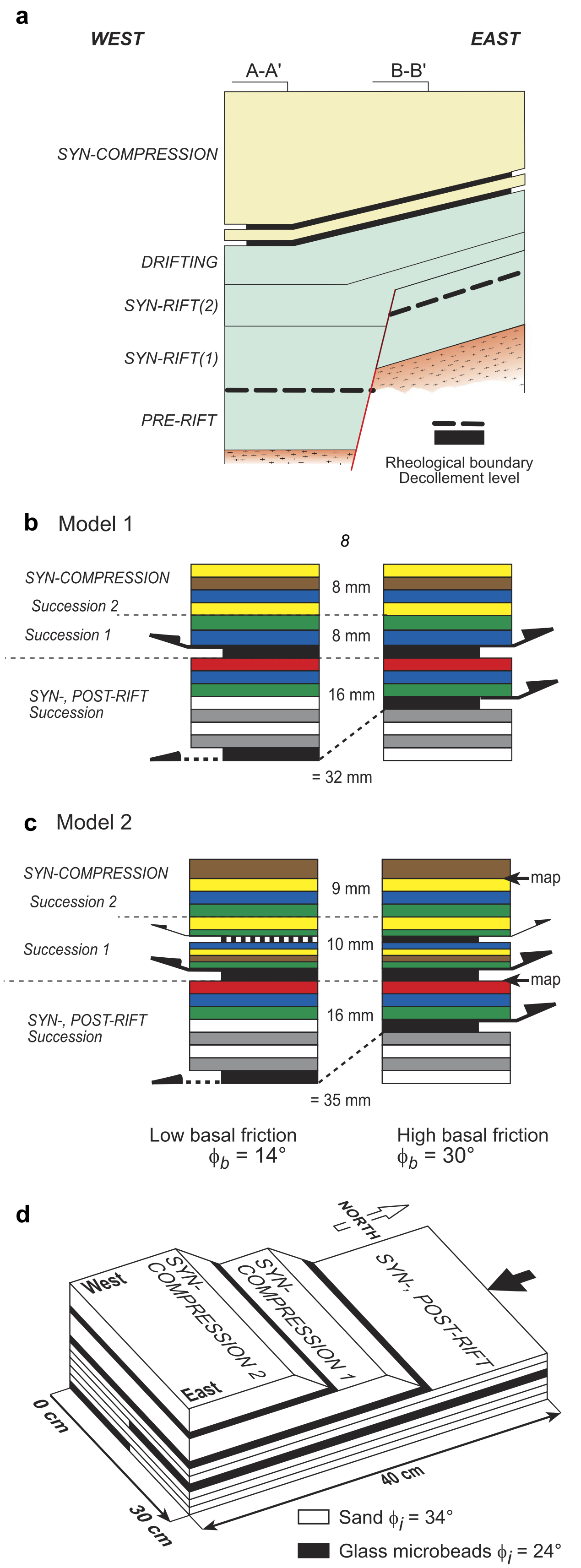

Fig. 4. Model set-up. (a) Sketch of the natural mechanical stratigraphy. (b) Synthetic mechanical stratigraphy of model 1 and (c) model 2. Inter-strata detachments and mapped levels are indicated. Syn-contraction succession 1 simulates the clastic succession from Upper Cretaceous to Lower Oligocene; succession 2 simulates the clastic succession from Lower Oligocene to Olocene. (d) Block diagram of the model 2 (not to scale).

the transfer zone, through an array of small faults with opposite vergence. The décollement style only occurs in the central transfer zone where the main culmination takes place (Fig. 5e–g). The partition of deformation in the transfer zone is particularly interesting, where two backthrusts (b1 and b2) have been replaced along strike by forethrusts 7 and 8 from the west to the east (Fig. 5). The second-order fault 7 (Fig. 5f–g) along strike deepens to root at the basal detachment of the model (Fig. 5h) in the sector with high basal friction.

4.3. Model 2 results

In the western sector (Fig. 6a,b), sections are characterized by two orders of thrusted fold. First-order thrusts (4 and 7) detached at the base of the model and second-order thrusts (5, 5a and 6) rooted in the middle and upper detachment layers. At depth, the pre-contractional sequence is affected by small backthrusts and forethrusts, favoured by the low frictional basal detachment. Toward the east (Fig. 6b–g), second-order forethrusts (5 and 6) are replaced by backthrusts. Two counter regional second-order thrusts (b3 and b4) affect the footwall of fault 7 along the central sector of the model (Fig. 6c–e). The cross cutting relationship shows that they had developed earlier that fault 7, then they were cut by it. Another second-order fault (5b) occurs in the footwall of fault 4 in the central zone. The eastern area is characterised by first-order thrusts 4 and 7, and a lack of detached structures (Fig. 6f,g). Thrust sheet 7 wavelength is shorter here than in the western sector, especially at depth, due to the high friction basal detachment. Fault 7 shows slip variations along dip; the slip increases up-section, particularly in the eastern sector. This can be explained if the upper part of the thrust was partially detached above the intermediate décollement.

The upper structure contour (Fig. 7a) reveals the curved geometry of all thrust fronts in the western area (5, 6 and 7), their periclinal shape and the continuity along strike of first-order thrusts 4 and 7. Thrust 7 at the front of the modelled belt, has a sinusoidal shape, forming a salient to the west, a recess in the central domain and a less developed salient to the east. In the central area, a narrow pericline dominates, revealing the greatest culmination on the frontal thrust. The lower structure contour (Fig. 7b) displays a single thrusted anticline, having two separates culminations, to the west and in the centre of the model, and a wavelength changing from 4.5 to 7 cm. Comparison between the maps shows a greater variation between structural levels in the western than in the eastern area. Whilst the geometry of thrusts 4 and 7 are similar across the whole model, second-order thrusts and backthrusts are confined within the upper syntectonic sequence. Moreover, the deep structural contours have a smoother surface (elevations range over 0.35 cm) than the shallower contours (0.9 cm).

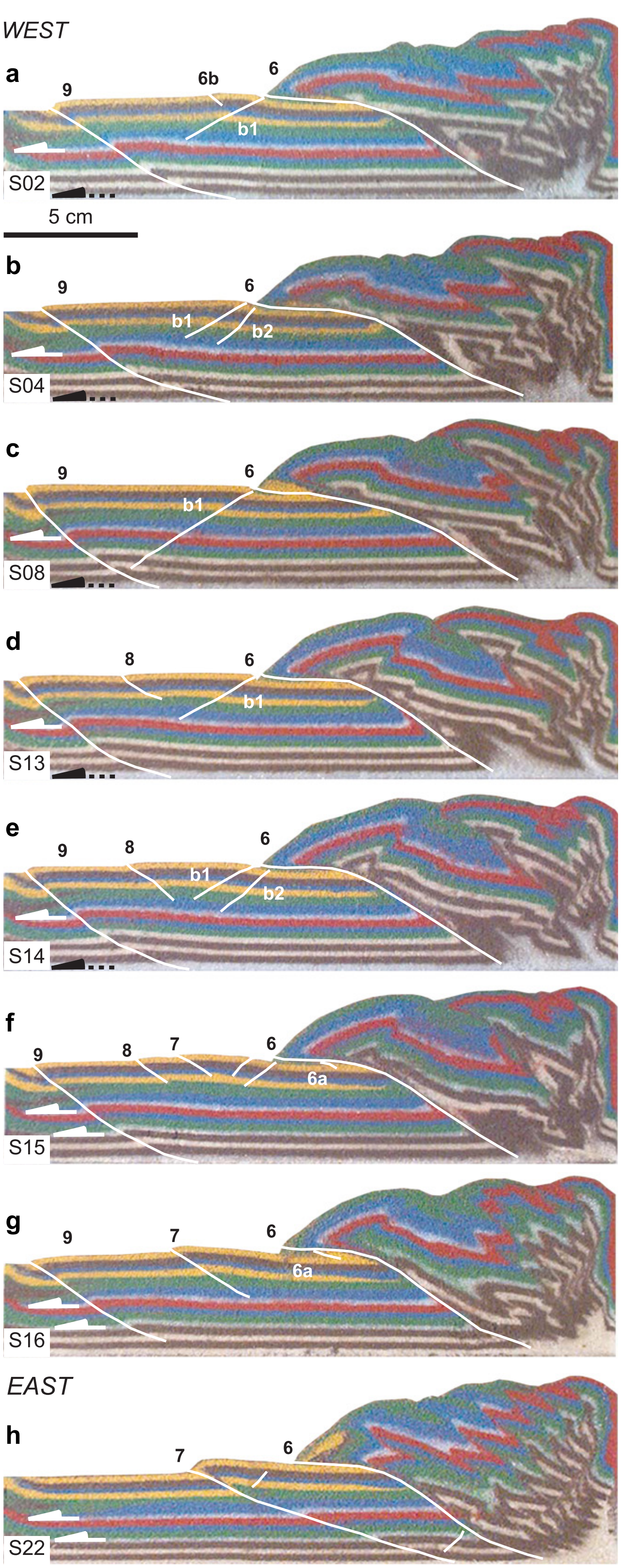

Fig. 5. Cross sections of model 1. S = cross section position from the western side of the box, in centimetres. Glass microbeads layers are lightest grey and are indicated with arrows.

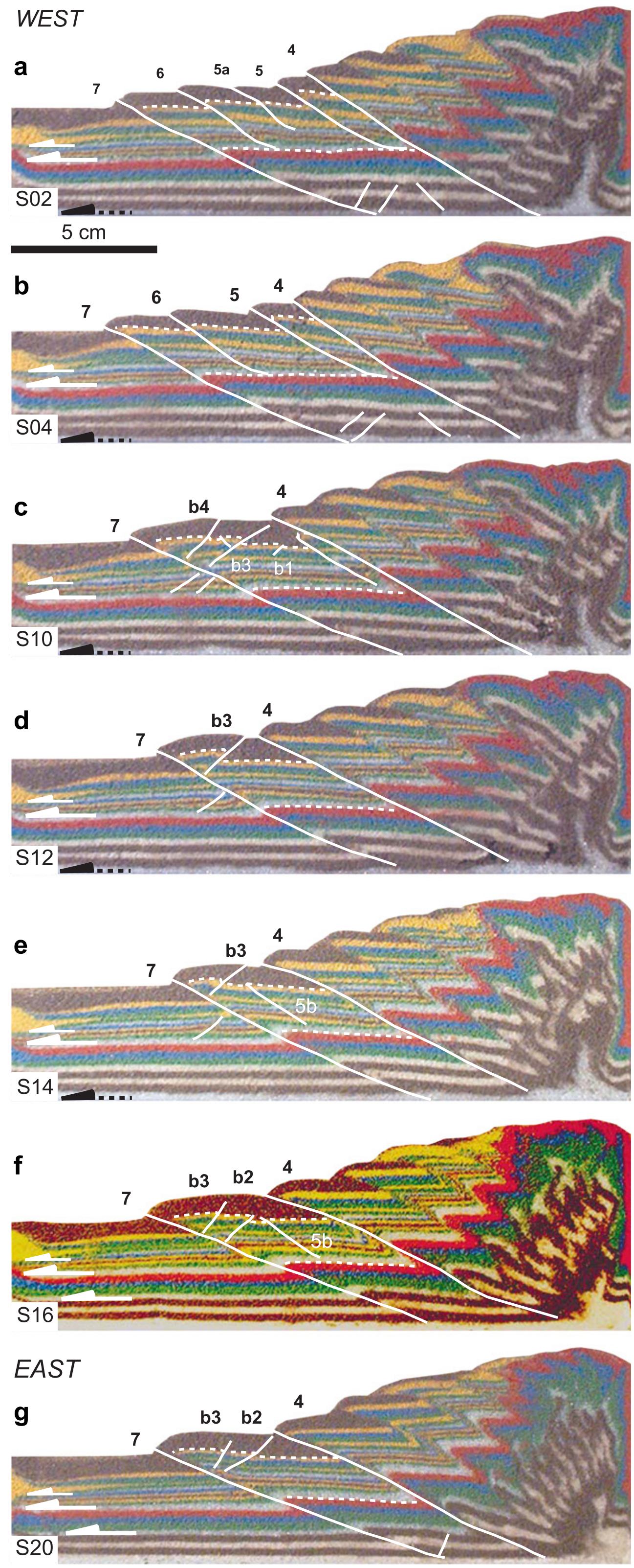

Fig. 6. Cross sections of model 2. Broken lines represent two horizons used for the contour maps. S = cross-section position from the western side of the box, in centimetres. Glass microbeads layers are lightest grey and are indicated with arrows of different size reflecting different décollement layer thicknesses.

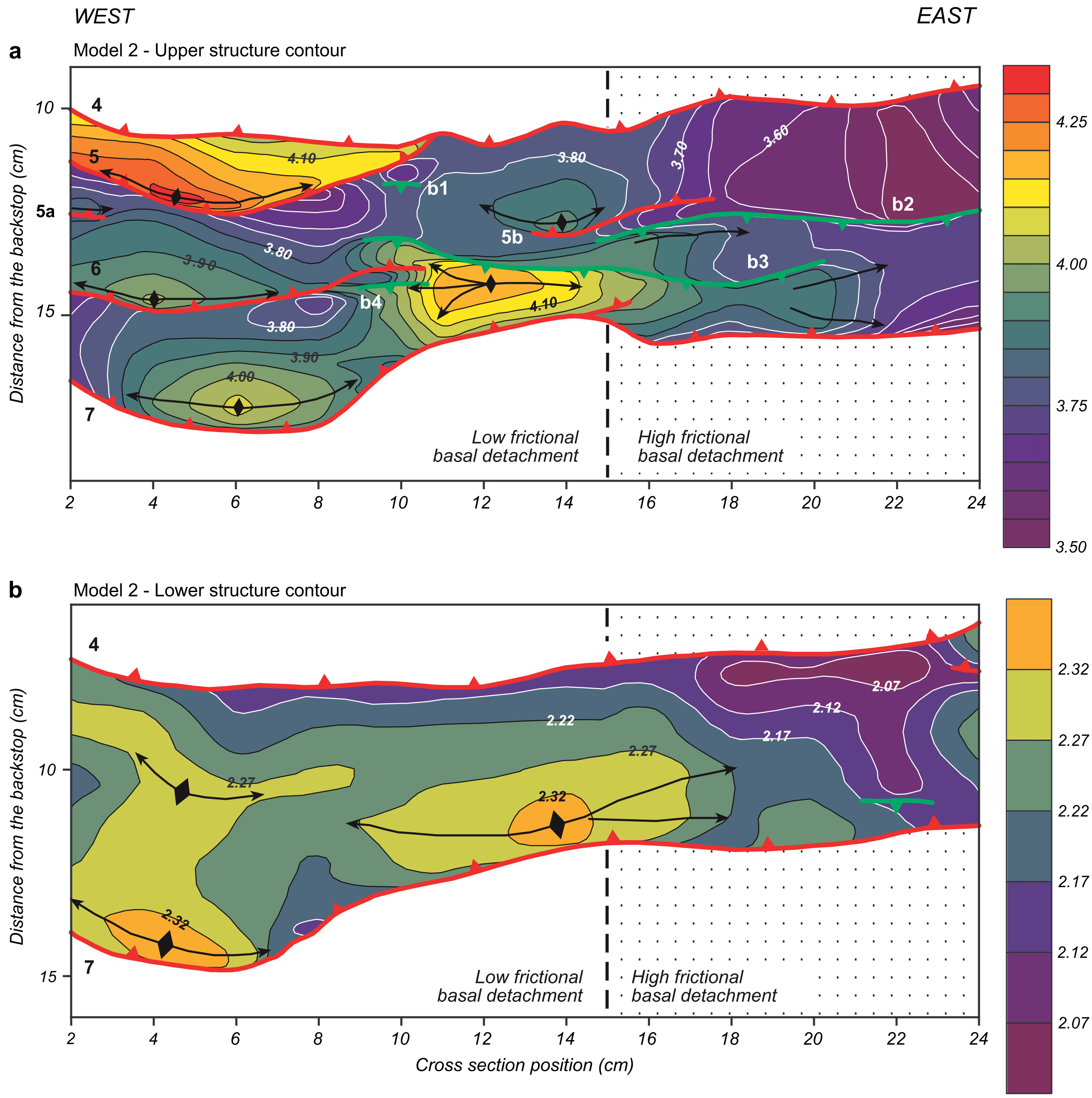

Fig. 7. Contour maps of the model 2, at (a) shallow structural level and at (b) deep structural level (corresponding to the hatched lines in Fig. 6). Elevations are in cm from the base of the model. Separation between western and eastern stratigraphic domains has been highlighted.

The general trend of the contoured surfaces defines a regional slope to the east, at both structural levels, although it is much more evident at higher levels.

4.4. Limitations of the models

The two analogue materials used are an oversimplification of the natural rocks because they do not replicate the variety of materials we have in nature. Besides, only Coulomb materials we used and we did not replicate rocks with viscous behaviour that could be important in determining structural style.

Instead of producing artificial cuts in the sand that simulate the pre-existing extensional faulting (Sassi et al., 1993) or using rigid footwalls (Gomes et al., 2003), we preferred to reproduce the effect the horst and graben palaeogeography had induced on sediment dispersal and the resulting facies distribution. In our view this results in a better "natural" simulation.

The syn-contractional sedimentation events we reproduced were mainly performed to simulate the stratigraphy of the area, so they were carried out in two or three phases. In the external area of the models that we consider the syn-tectonic sedimentation events were basically pre-tectonic and the presented sections do not show growth strata.

Finally, although the oil industry has been exploring the area since the middle of the 20th century, large uncertainties regarding the geology of the Po Plain subsurface still remain, due to the confidentiality of data.

5. Discussion

5.1. Pre-existing heterogeneities

As stated above, we did not introduce a pre-existing cut reproducing a fault in our models (cf. Sassi et al., 1993) but the lateral variable mechanical stratigraphy can be roughly considered to model a pre-existing heterogeneity. Hence we did not simulate the fault itself but only its effect. Such an abrupt lateral rheological change simulated by different basal friction and different elevation of the glass microbeads layers influenced the structural style in each domain (eastern and western) and also determined a third domain linking them; a transfer zone domain. In both models, the basal friction controlled the wavelength of the first-order thrusts. In fact, in the western sectors the low frictional basal detachment layer produced longer thrusts. This was particularly evident in model 1 (thrust 9, Fig. 5a–g; thrust 7, Fig. 6a–d). In the eastern and high frictional basal detachment areas, short wavelength thrusts formed (thrust 7, Fig. 5h; thrust 7, Fig. 6f–g). The microbead layer placed in the syn-rift tectonic sequence in this sector has probably worked as a décollement, as revealed by the greater slip measured in the upper layers with respect to the lower ones (faults 7, Figs. 5g–h and 6f–g). The deposition of two microbead layer in model 2 seems to favour decoupling in the western area of the synthetic chain where second-order structures are well developed, both along dip and strike (thrusts 5 and 6, Figs. 6a,b and 7a).

5.2. Syn-contractional sedimentation

In our models, two main syn-contractional sedimentary events were reproduced, simulating the regional-scale depositional phases. Both events influenced kinematics of the tectonic wedge, extending the activity of the internal fault that, in our models, represents the border between the outcropping and the buried chain (thrust 6, Fig. 5; thrust 4, Fig. 6) (Storti and McClay, 1995; Turrini et al., 2001). At the time of deposition, the area considered as Po Plain analogue was not yet affected by deformation so the sedimentation phase there is pre-kinematic. This means that the structures developed in the modelled Po Plain were not influenced by these sedimentary events.

5.3. Models versus nature

Model 2 seems to better fit the main characteristics of the buried Southern Alps external domain beneath the Po Plain sediments. Nature and the model maps display similar characteristics (Fig. 8a,b) particularly with respect the arcuate shape of thrust fronts in the west and the lateral termination of second-order structures in the transfer zone. The lack of access to seismic data in the transfer zone does not permit us to understand whether the external deep thrust would continue along strike. In the model the external thrust front 7 does persist along strike without interruption. In the eastern area, both maps show the occurrence of a single first-order and long wavelength thrust and the absence of detached structures, together with the development of conjugate backthrusting.

In cross section, the decoupled structural style of the modelled structures is similar to that of the interpreted thrusts from the western seismic line (Fig. 8c,d). Finally, common features include the development of two orders of structures, the short wavelength of imbricates formed in the syn-contractional sequence, the greater amount of faults and the absence of backthrusts in the syn-contractional sequence. At depth, the pre-tectonic sequence shows a greater spacing between the adjacent faults (4 and 7) in the west (Fig. 8c,d) with respect to the east (Fig. 8e,f). In the seismic sections the depth to the detachment is not interpretable as it is out of the image.

In general, only small blind faults occurred, developed normally as conjugate backthrusts especially in the deep succession (Fig. 6a,b,g). In other examples they terminate against other faults (Fig. 6c,d,e) and they are former counter-regional second-order faults cross-cut by a later foreland-vergent fault. In nature, folding mechanism seems to be a more important component than in the sandbox models. The difficulty is that natural structures cannot be reliably modelled with brittle analogue materials only. For example, in the eastern natural domain the interpreted structures possess a similar wavelength to the model but a more complex structural style. Nevertheless the comparison highlights that the present geological setting can be mainly explained factoring terms of the presence of inherited structures that produced differences in the mechanical stratigraphy.

5.4. Comparison with previous work

Even though the simultaneous use of different variables at the same time prevents the deep comprehension of the influence exerted by every single factor, it allows a better reproduction of the natural structural styles.

Curved thrust fronts similar to ours have been reproduced by others using lateral variable frictional (Colletta et al., 1991; Nieuwland et al., 2000) or Newtonian (Cotton and Koyi, 2000; Bahroudi and Koyi, 2003; Luján et al., 2003) detachments at the base of the model. The use of Newtonian material enhances the development of counter-regional thrusting with respect our frictional detachments. In all these cases, the structures formed are always detached at the base of the models. The use of Newtonian materials to produce laterally variable basal detachments also allows the development of tear faults (e.g. Cotton and Koyi, 2000; Bahroudi and Koyi, 2003).

Curved and braided thrust fronts along with detached or second order structures have been developed by Corrado et al. (1998) by means of introducing a Newtonian silicon gum inside the stratigraphy. The detached structures above the silicon gum layer do not seem to have a preferential vergence, and both foreland and counter-regional thrusts simultaneously occur. In our model, and in the Po Plain subsurface, the second order thrusts are foreland vergent.

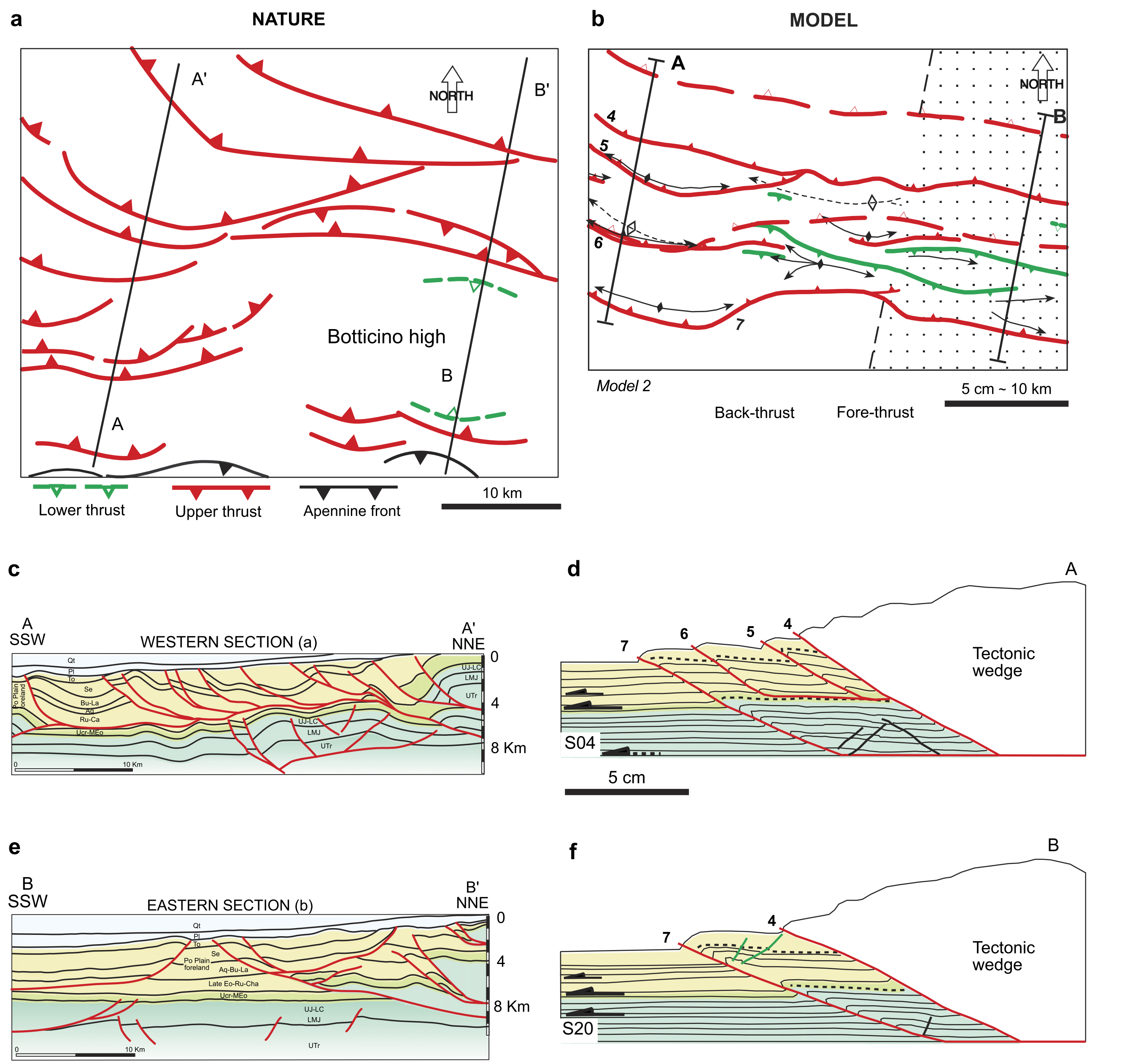

Fig. 8. Nature versus model 2 comparison. (a) Sketch map of the area and (b) cut off map of the model 2 of Fig. 7. Map 8b has been rotated 11° clockwise, similar to the regional shortening direction in the buried Southern Alps. Filled lines are shallow cut offs, hatched lines are deep cut offs. (c) Interpreted seismic section AA′ and (d) the analogue section S04 chosen for the comparison; (e) interpreted seismic section BB′ and (f) the analogue section S20 chosen for the comparison.

6. Conclusions

Pre-existing north-south-trending heterogeneities related to the Mesozoic extensional phases controlled the vertical and lateral distribution of competent and incompetent sediments and their thicknesses across the passive margin of the Adria plate. The resultant mechanical stratigraphy played a first order role in the three dimensional structural style of the following Alpine contractional phases.

Scaled sandbox analogue models have been built reflecting the effect of the syn-rift structures on the lateral and vertical distribution and thickness of the incompetent and competent analogue materials. Syn-contractional sedimentation has been reproduced as well, simulating the thick siliciclastic Tertiary sequences of the Po Plain. Lateral heterogeneities produced different wavelength thrust sheets, salients and recesses, whereas vertical heterogeneities allowed the development of structures of different orders. First-order structures detached at the base of the model and second-order structures detached at the intermediate relatively weak layers.

The comparison between the modelled structures and the natural geometries interpreted from seismic data was close demonstrating that:

i) thrust fronts are more advanced where thicker syn-rift successions occur;
ii) fault kinematics partitioning occurred in the transfer zone, where major pre-existing extensional faults exist;
iii) backthrusting took place in the eastern area characterized by thinner syn-rift successions.

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