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SPECIAL

First results from the CROP-11 deep seismic profile, central Apennines, Italy: evidence of mid-crustal folding

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The CROP-11 deep seismic profile across the central Apennines, Italy, reveals a previously unknown, mid-crustal antiform here interpreted as a fault-bend fold-like structure. The seismic facies and gravity signature suggest that this structure consists of low-grade metamorphic rocks. Geomorphological, stratigraphic and tectonic evidence in the overlying shallow thrusts suggests that this structure developed in early to mid-Messinian time and grew out of sequence in late Messinian–Pliocene time. The out-of-sequence growth may reflect a taper subcriticality stage of the Apenninic thrust wedge, which induced renewed contraction in the rear.

The Apennines (Italy) form a NW-trending, ENE-vergent, fold–thrust belt (Fig. 1), which developed within the frame of convergence between Africa and Eurasia during the Neogene (Malinverno & Ryan 1986). During this time, contractional deformations migrated eastward, mostly in a piggyback sequence towards the foreland (Cipollari & Cosentino 1995) favoured by the parallel retreat of the subduction zone toward the Adriatic foreland (Malinverno & Ryan 1986).

Whereas the deep style of thrusting across the northern and southern Apennines has been unveiled by, respectively, the CROP-03 (Pialli *et al*. 1998) and CROP-04 (Scrocca *et al*. 2005) deep seismic profiles, the deep tectonic architecture beneath the central Apennines is still unconstrained because of the lack of deep data. As a consequence, thin-skinned and thick-skinned thrusting have been proposed as alternative models for the tectonic accretion, these models leading to strongly contrasting inferences about the amount and rate of shortening, and about the tectonic evolution of the central Apennines (Ghisetti *et al*. 1993). By applying a thin-skinned criterion, for instance, Hill & Hayward (1988) computed 157 km of shortening over a section of 226 km length across the central Apennines. In contrast, by applying a thick-skinned criterion over about the same section, Tozer *et al*. (2002) obtained 37 km of shortening over a distance of 158 km.

Below we present the central segment of the CROP-11 deep seismic profile across the central Apennines (Fig. 1). These data show the most prominent structure imaged in the entire profile, i.e. a hitherto unknown mid-crustal antiform.

Results and interpretation. The CROP-11 profile runs approximately east–west from the Tyrrhenian Sea to the Adriatic Sea. The location of the CROP-11 profile is the best compromise between field accessibility and the occurrence of two structural trends, namely north–south in the NW and NW–SE in the SE (Fig. 1). The CROP-11 profile cuts across two major crustal domains (Fig. 2a): the Adriatic domain (east), where the Moho is imaged at *c*. 12 s two-way travel time (TWTT) (*c*. 32 km deep), and the Tyrrhenian domain (west), where the crust has been thinned by backarc extension (Malinverno & Ryan 1986) and the Moho is imaged at *c*. 9.5 s TWTT (*c*. 25 km deep). In the Adriatic domain, the CROP-11 profile includes flat or gently inclined reflections, which image the front of the ENE-vergent orogenic wedge lying above the regional foreland monocline. Steeper reflections occur in the central and western segments of the CROP-11 profile, where the core of the orogenic wedge is imaged. In the central segment, strong reflections occur between *c*. 5 and *c*. 8–9 s TWTT and define a wide, mid-crustal antiform (Fig. 3). Two sets of upward-convex reflections image the relative hinge zones. The antiform is associated with a ramp-flat-shaped shear zone occurring between *c*. 7 and *c*. 10 s TWTT. Flat-lying reflections are imaged in the footwall of the shear zone. Beneath the Fucino and Marsica areas (Figs 1–3), shallow reflections ($<$3 s TWTT) are inclined toward the east and are parallel to the deep reflections in the forelimb of the antiform (Fig. 3b). In and above the backlimb of the antiform, a set of parallel reflections included between the ramp-flat-shaped shear zone and the Olevano–Antrodoco thrust shows a constant westward inclination. The Olevano–Antrodoco thrust is imaged as a shallow structure and is representative of an out-of-sequence event in the central Apennines (Cipollari & Cosentino 1995).

To infer the physical attributes and lithology of the mid-crustal antiform, we analysed the regional gravity anomalies obtained through a 'stripping off' method. This method consisted in the removal of the gravity effect produced by the geological bodies shallower than 10 km from the Bouguer anomaly database (which has a grid cell size of 3 km) of the Italian Geological Survey (Tiberti *et al*. 2005). In the gravity profile (Fig. 2b), the Tyrrhenian and Adriatic domains are characterized by gravity highs, whereas a relative gravity low occurs in the central Apennines beneath the Fucino basin and the Marsica area. A second-order gravity low of *c*. 8 mGal occurs in the transitional region between the Tyrrhenian high and the Fucino low. Its location corresponds to the mid-crustal antiform imaged in the

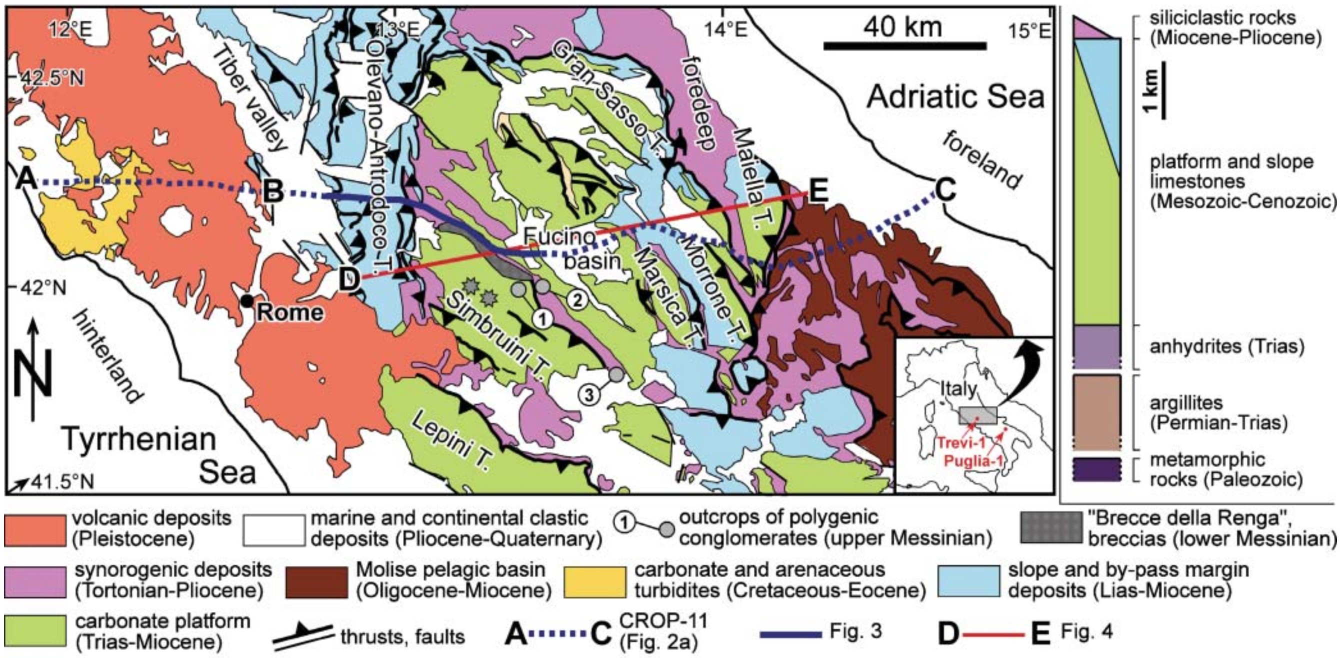

Fig. 1. Geological map of the central Apennines. T., thrust sheet. Two grey stars on top of the Simbruini Mts show the location of exposed Triassic rocks, i.e. the most elevated rocks of that age in the central Apennines. At the northeastern front of the Simbruini thrust sheet, the lower Messinian 'Brecce della Renga' formation (i.e. pre-salinity crisis) constitutes the largest wedge of breccias in the central Apennines. Younger conglomerates (upper Messinian) occur on top of and at the front of the Simbruini thrust. On the right, synthetic stratigraphy of the central Apennines compiled according to the Puglia-1 (41.05°N, 16.20°E, depth 7070 m) and Trevi-1 (41.88°N, 13.20°E; depth 3549 m) wells and surface data (Accordi & Carbone 1986).

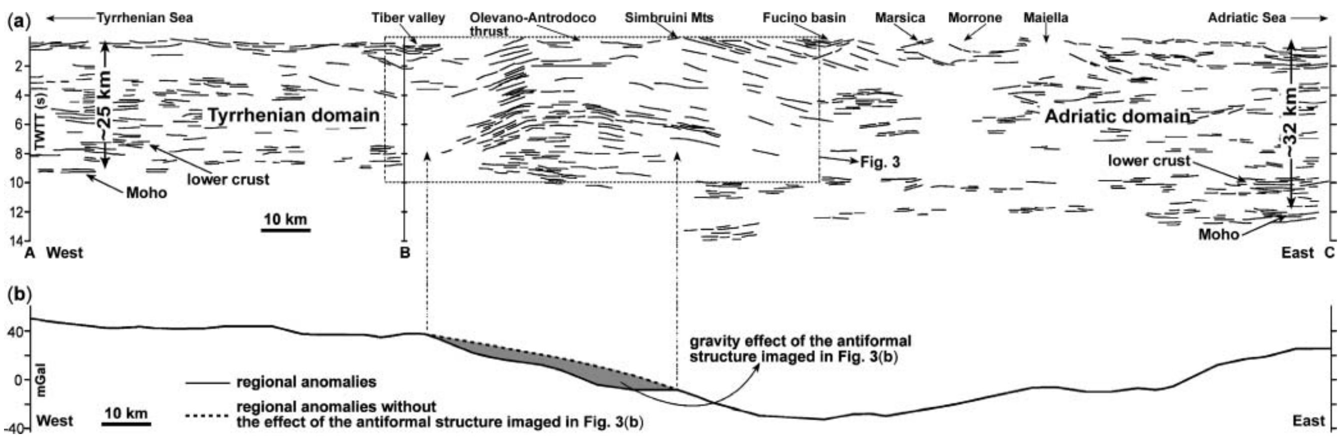

Fig. 2. (**a**) Line drawing of the CROP-11 seismic profile. The relative location is shown in Figure 1. The 0 s datum corresponds to 500 m above sea level (a.s.l.). Depths in kilometres of the Moho in the Tyrrhenian (west) and Adriatic (east) domains are known from two seismic refraction profiles (Cassinis *et al*. 2003). A high-resolution image of the CROP-11 profile, the relative parameters and the station coordinates are available online at http://www.geolsoc.org.uk/SUP18249. A hard copy can be obtained from the Society Library. (**b**) Regional gravity anomaly along the CROP-11 profile. In the central sector, the gap (shaded area) between the observed regional trend (continuous line) and the hypothesized (unaffected) regional trend (dashed line) indicates the effect of the mid-crustal antiform imaged on the CROP-11 profile. The gravity low is entirely compensated by assuming this structure is as thick as *c*. 10 km and as dense as *c*. 2570 kg m^{-3}.

seismic profile (Fig. 2a) and its wavelength indicates a source depth between 10 and 20 km, a maximum thickness of *c*. 10 km, and an average density of *c*. 2570 kg m^{-3} (for details, see Tiberti *et al*. 2005).

Discussion and conclusions. We interpret the antiform imaged in the CROP-11 profile and the associated shear zone as a mid-crustal, fault-bend fold-like structure (Suppe 1983). This interpretation provides a first-order and possibly oversimplified description of the actual tectonic architecture imaged in the CROP-11 profile. More detailed analyses on specifically processed segments of the CROP-11 profile are planned for the future.

An immediate question raised by the occurrence of a mid-

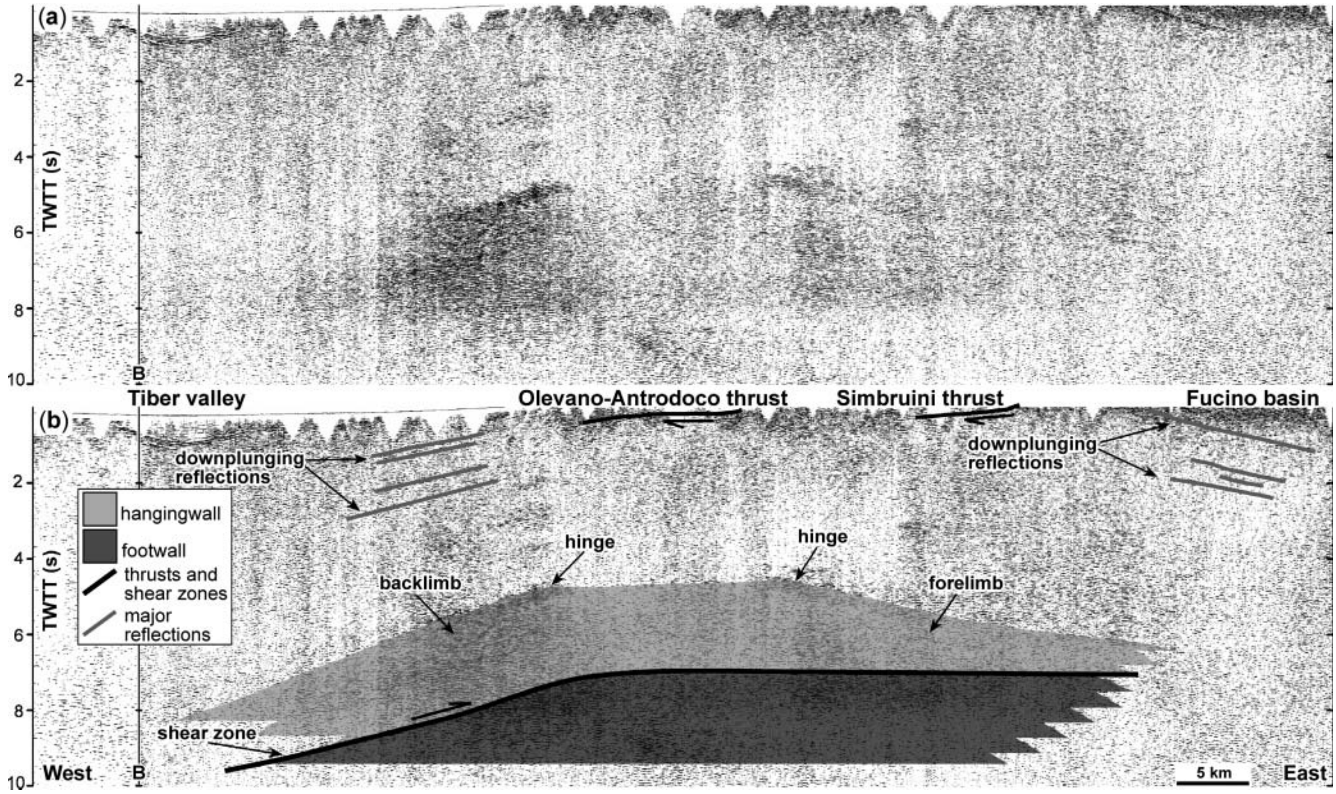

Fig. 3. (**a**) Central segment of the CROP-11 profile (i.e. between the Tiber valley and the Fucino basin; see Fig. 2a). (**b**) Interpretation of first-order tectonic structures. The upper boundary of the hanging-wall area is drawn where a major change of seismic facies occurs.

crustal antiform beneath the central Apennines concerns the nature of the material involved. The seismic facies of the hanging-wall panels and the relative gravity data suggest that the rocks involved in the antiform are probably layered, very low-grade metamorphic rocks. Of the rock types known in the central Apennines, the Permian–Triassic argillites (Fig. 1) best fit these physical properties. The sonic log from the Puglia-1 well shows that the Permian–Triassic argillites have a strong acoustic impedance contrast with the overlying carbonates. This physical attribute and the possible occurrence of pressurized fluids entrapped in the mid-crustal antiform may explain the high reflectivity of the rocks forming this structure. In the northern Apennines, seismic reflections similar to those forming the mid-crustal antiform of Figure 3 correspond to the top of a phyllitic basement underlying the Triassic argillites (Pialli *et al*. 1998).

Mid-crustal folding in the central Apennines must have significantly influenced the topographic and tectonic architectures of the thrust wedge. The evidence that the entire rock multilayer in the hanging wall is involved in the crustal antiform (Figs 2 and 3) suggests that this structure was active in an out-of-sequence fashion since late Messinian times. This age is inferred from the timing of the Marsica–Morrone thrusts (Messinian–early Pliocene, Fig. 4), which are at present tilted toward the east and are roughly parallel to the forelimb of the mid-crustal antiform. The presence on top of the hanging wall of the lower Messinian 'Brecce della Renga' breccias, which are the largest and thickest deposits of Neogene conglomerates in the central Apennines (Figs 1 and 4), suggests that the underlying mid-crustal antiform was already active during early Messinian time,

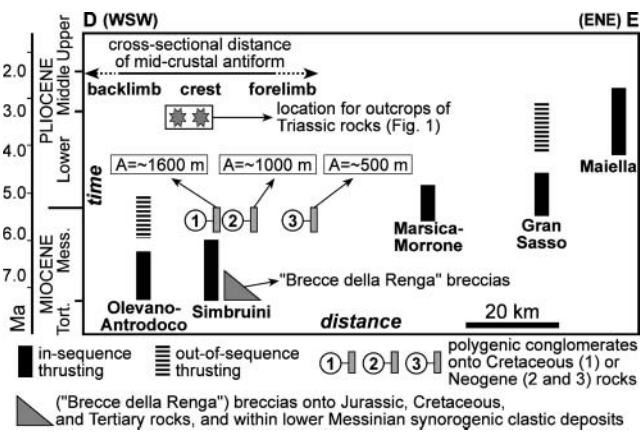

Fig. 4. Schematic diagram showing the time–space migration of thrusting and the distribution of Messinian clastic deposits. Data are plotted along the profile D–E across the central Apennines (the location is shown in Fig. 1). Columns of conglomerates correspond, by number, to outcrops shown in Figure 1. 'A' is the approximate altitude for the outcrops of upper Messinian conglomerates. The location and linear extension of the antiform shown in Figure 3b is displayed in the top left of the diagram. Two grey stars show the location (corresponding to the crest of the mid-crustal antiform) along the profile D–E of exposed Triassic rocks on top of the Simbruini thrust sheet (see Fig. 1). This diagram shows that the central Apennines consist of an imbricate fan of shallow, carbonate, thrust sheets accreted in a piggyback sequence directed towards the foreland with episodic out-of-sequence thrusting.

possibly causing localized uplift and associated subaerial erosion. Such a localized uplift is also supported by the occurrence of exposed Triassic rocks (i.e. the oldest rocks exposed in the central Apennines) only in correspondence to the crest of the mid-crustal antiform (Figs 1 and 4). Moreover, in the same area, upper Messinian polygenetic conglomerates rest unconformably on eroded Mesozoic carbonates and synorogenic Miocene deposits (Figs 1 and 4). Significant vertical separations occur between the upper Messinian conglomerates at present lying atop the crestal region of the mid-crustal antiform and those preserved atop the forelimb (Fig. 4). These deposits suggest that the mid-crustal antiform was active during late Messinian time, whereas their vertical displacements suggest a post-late Messinian growth.

In synthesis, the available geophysical and geological data suggest, for the mid-crustal antiform imaged in the CROP-11 profile, an early Messinian–Pliocene evolution. From the location of the mid-crustal antiform and the time–space migration of thrusting in the central Apennines (Fig. 4), we infer that the mid-crustal antiform grew as an out-of-sequence structure since late Messinian time. The out-of-sequence growth of this structure can be explained by assuming that the Miocene–Pliocene sequence of thrusting breaking towards the foreland (Fig. 4) caused the superficial taper of the orogenic wedge to shallow. The taper consequently became subcritical and contractional deformations were resumed at the rear of the thrust wedge, causing the out-of-sequence growth of the mid-crustal antiform. In the study area, post-orogenic normal faulting is a young process (<4–5 Ma) that has produced significant crustal extension only in the first 2 s TWTT (Cavinato *et al*. 2002), and is therefore negligible for the mid-crustal, structural architecture.

From the CROP-11 profile, the vertical and horizontal displacements on the ramp-flat-shaped shear zone at the base of the mid-crustal antiform can be estimated at *c*. 2.5 s TWTT (i.e. *c*. 5 km) and *c*. 30 km, respectively. The vertical displacement is about consistent with the thickness of the eroded sedimentary cover on top of the antiform crest, where Triassic rocks are exposed (i.e. 4–5 km of eroded Jurassic–Palaeogene limestones on top of the Simbruini Mts; Fig. 1).

The discovery of a mid-crustal antiform beneath the central Apennines compels: (1) further research into the superficial geology of this region to properly constrain the effects and chronology of the mid-crustal antiform; (2) further geophysical prospecting to constrain the 3D geometry and vergence of the mid-crustal antiform; (3) the critical revision of previously proposed tectonic models for this region, possibly abandoning the oversimplified contraposition between thin-skinned and thick-skinned end-member templates.

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