Possible causes of arc development in the Apennines, central Italy

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ABSTRACT

In central Italy, geometry, kinematics, and tectonic evolution of the late Neogene Umbrian Arc, which is one of the main thrusts of the northern Apennines, have long been studied. Documented evidence for orogenic curvature includes vertical-axis rotations along both limbs of the arc and a positive orocline test along the entire arc. The curvature's cause is, however, still unexplained. In this work, we focused our attention on the southern portion of the Umbrian Arc, the so-called Olevano-Antrodoco thrust. We analyze, in particular, gravity and seismic reflection data and consider available paleomagnetic, stratigraphic, structural, and topographic evidence from the central Apennines to infer spatial extent, attitude, and surface effects of a mid-crustal anticlinorium imaged in the CROP-11 deep seismic profile. The anticlinorium has horizontal dimensions of about 50 by 30 km and is located right beneath the Olevano-Antrodoco thrust. Stratigraphic, structural, and topographic evidence suggests that the anticlinorium produced a surface uplift during its growth in early Pliocene times. We propose an evolutionary model in which, during late Neogene time, the Olevano-Antrodoco thrust developed in an out-of-sequence fashion and underwent about 16° of clockwise rotation when the thrust ran into and was then raised and folded by the growing anticlinorium (late Messinian-early Pliocene time). This new model suggests a causal link between mid-crustal folding and surficial orogenic curvature that is consistent with several available data sets from the northern-central Apennines; more evidence is, however, needed to fully test our hypothesis. Additionally, due to the occurrence of mid-crustal basement-involved thrusts in other orogens, this model may be a viable mechanism for arc formation elsewhere.

KEYWORDS: oroclines, Apennines, fold and thrust belts, gravity anomalies, and seismic reflection profiles.

INTRODUCTION

Arcuate belts are among the most ubiquitous but also enigmatic and debated structures within orogenic settings (e.g., Marshak, 2004; Sussman and Weil, 2004). In a recent classification of curved orogens, Weil and Sussman (2004) recognize primary arcs, progressive arcs, and oroclines. Primary arcs, which are non-rotational curves, adopt their curvature during the initial phase of deformation and experience no appreciable tightening and vertical-axis rotations during subsequent deformation. In contrast, both oroclines and progressive arcs are rotational curves (e.g., Weil, 2006). Progressive arcs either acquire their curvature progressively throughout their deformation history (i.e., thrust rotations accommodate continuous along-strike variations in shortening; Sussman et al., 2004) or acquire a portion of their curvature during a subsequent deformation phase. Oroclines acquire their curvature in a two step process consisting first of the formation of a linear orogen and subsequently of the bending of that orogen to form an arc.

Distinguishing between oroclines, progressive arcs, and primary arcs is relatively simple when the appropriate methods of surface investigation can be used (e.g., paleomagnetic, structural, and stratigraphic analyses to understand the temporal relationship between thrusting and vertical-axis rotations; Weil and Sussman, 2004). In contrast, understanding the curvature's causes is usually difficult, among other reasons, because of the paucity of subsurface data.

In this paper, we address the problem of the curvature's cause for the case of the southern portion of the Umbrian Arc (i.e., the so-called Olevano-Antrodoco thrust) in the Apennine fold-thrust belt, Italy (Fig. 1). This belt includes two main orogenic arcs, namely the northern and southern arcs (Fig. 1). These arcs are different in size, shape, shortening, and involved rocks, and include a set of major and minor curved thrusts (Royden et al., 1987; Ghisetti and Vezzani, 1997; Macedo and Marshak, 1999). It is widely accepted that the development of the greater external arcs (i.e., presently buried beneath the Adriatic and Ionian seas; Fig. 1) is mostly the result of non-cylindrical rollback of a subducting segmented lithosphere (Royden et al., 1987; Faccenna et al.,

2004; Rosenbaum and Lister, 2004). In contrast, the origin of several curved thrusts within the greater northern and southern arcs is still unexplained.

Paleomagnetic studies of the Umbrian Arc provide conflicting interpretations on the development of mountain belt curvature, namely (1) oroclinal bending of an originally linear orogen (Channel et al., 1978; Eldredge et al., 1985; Muttoni et al., 1998), and (2) an arc with fold axes trends that have no relationship to vertical-axis rotations recorded by paleomagnetic declinations (Hirt and Lowrie, 1988). Recent paleomagnetic data from the Umbrian Arc (Fig. 1C) conclusively demonstrate secondary orogenic curvature (Speranza et al., 1997; Mattei et al., 1998). In particular, evidence was provided for a positive orocline test along the entire Umbrian Arc, whose curvature was acquired by simultaneous, and opposite-sense, vertical-axis rotations of the arc's limbs mostly after Messinian time (Mattei et al., 1995, 1998; Speranza et al., 1997; Muttoni et al., 1998). The cause for such rotations is, however, still unclear. In addition, the Olevano-Antrodoco thrust shows an even more evident curvature. Most authors (Eldredge et al., 1985; Calamita and Deiana, 1988; Ghisetti and Vezzani, 1997) have hypothesized that the main cause for orogenic curvature of the southern limb of the Umbrian Arc is connected with a contrasting mechanical competence of the involved rocks (i.e., Latium and Sabina carbonates; Fig. 1B). According to this model, stiff carbonate rocks in the central Apennines (i.e., Latium platform carbonates) restrained the advancement of the arc's southern limb, thus causing a displacement gradient along the northern Apennine thrusts and their subsequent curvature.

The Umbrian Arc intersects with the southern arc thrusts in the central Apennines, where the CROP-11 deep seismic profile highlighted the presence of a thick mid-crustal anticlinorium (Billi et al., 2006). This structure is located beneath the Olevano-Antrodoco thrust, which is the southern limb of the Umbrian Arc (Fig. 1C). Our hypothesis is that the anticlinorium and the associated crustal thickening may have caused a significant surface uplift, possibly constituting an obstacle to the migration of the Olevano-Antrodoco thrust. We used gravimetric and seismic reflection data to determine attitude and spatial extent of the anticlinorium and its geometric relationship with the

Olevano-Antrodoco thrust. We then combined our results with available paleomagnetic, stratigraphic, structural, and topographic evidence to understand the influence of the anticlinorium on the development of the southern limb of the Umbrian Arc. Based on this evidence, we argue that our hypothesis of a causal relationship between mid-crustal folding and orogenic curvature in the central Apennines is viable; more evidence is, however, needed to fully test our hypothesis. Additionally, due to the occurrence of mid-crustal basement-involved thrusts in other orogens, this model may be a viable mechanism for arc formation elsewhere.

GEOLOGICAL SETTING

Regional Setting

Within the framework of Alpine-Himalayan orogenesis, the Apennine fold-thrust belt developed mostly during Neogene time as a consequence of tectonic convergence between the European and African (i.e., Nubia) plates (Fig. 1). The parallel migration of the trench and orogenic wedge toward the east and southeast occurred concurrently with westward and northwestward subduction of oceanic lithosphere beneath the European plate and with the progressive involvement of the Adriatic (African affinity) continental margin with contractional deformation (Malinverno and Ryan, 1986; Royden et al., 1987; Dewey et al., 1989; Faccenna et al., 2004; Rosenbaum and Lister, 2004).

The Apennines are characterized by major NW-striking thrust sheets generally dipping toward the southwest with gentle angles and verging toward the northeast (Fig. 1). Thrust imbrication occurred mostly in a forelandward piggyback sequence (Fig. 2) with some out-of-sequence or backward thrusting episodes (e.g., Ghisetti and Vezzani, 1997; Cavinato and DeCelles, 1999; Patacca et al., 2008). The thrusting style of the Apennine belt has been for years the subject of contrasting interpretations including, in particular, thin-skinned and thick-skinned styles (e.g., Ghisetti et al., 1993; Mazzoli et al., 2000). Because of the paucity of subsurface data, in most

sectors of the Apennine chain, it is still unclear if thin-skinned or thick-skinned thrusting is the most appropriate model for structural style (e.g., Mazzoli et al., 2008; Steckler et al., 2008).

Normal faults and associated extensional basins of Miocene-Pleistocene age are widespread in the Tyrrhenian side of the Apennines and also in the axial sector of the fold-thrust belt (Fig. 1B) (Malinverno and Ryan, 1986; Barchi et al., 1998; Jolivet et al., 1998; Cavinato et al., 2002). Through time, the locus of extension has progressively migrated toward the east (Fig. 2), parallel but west of the eastward-migrating locus of contractional deformation (Malinverno and Ryan, 1986; Patacca et al., 1992). The lag time between the onset of thrusting and initial extension at any given locality in the central Apennines is about 2-4 m.y. (Fig. 2) (Cavinato and DeCelles, 1999).

Seismic data across the Apennines show that the crust thickness increases from a minimum of about 22 km in the Tyrrhenian side of the belt, to a maximum of almost 50 km in the axial sector (Barchi et al., 1998; Cassinis et al., 2003; Billi et al., 2006; Mele et al., 2006; Di Luzio et al., 2008).

Central Apennines

Major thrust sheets in the central Apennines (i.e., Volsci, Simbruini, Marsica, Morrone, Gran Sasso, and Maiella thrust sheets; Fig. 1C) are mostly NW-striking, NE-verging structures (Parotto and Praturlon, 1975; Vezzani and Ghisetti, 1993). Dimensions of the exposed portion of these thrust sheets are between about 40 and 120 km along-strike and about 20-30 km across-strike. Most of these structures are thrust systems consisting of several imbricate major and minor thrusts. For instance, the Marsica thrust system includes several thrusts, of which the westernmost Vallelonga thrust is a NW-striking NE-verging structure located to the west of the Fucino basin (Fig. 1C). The subsurface prolongation of this structure is considered in our analysis of the CROP-11 profile (Fig. 3) to infer the age of mid-crustal deformation.

Toward the west, the Olevano-Antrodoco thrust is the N-trending southern limb of the Umbrian Arc (Fig. 1B). Geometries, kinematic indicators, and stratigraphic relationships along and over this fault show its contractional nature and reverse displacements (Salvini and Vittori, 1982; Cosentino

and Parotto, 1992; Corrado, 1995; Ghisetti and Vezzani, 1997). In addition to reverse displacements, however, some kinematic indicators on the Olevano-Antrodoco thrust zone and stratigraphic evidence show that this structure accommodated younger right-lateral strike-slip displacements during late Neogene time, possibly during early Pliocene time (Castellarin et al., 1978; Salvini and Vittori, 1982).

The Olevano-Antrodoco thrust marks an important surface lithologic transition. In the hangingwall, Mesozoic pelagian carbonates and marls are the dominant lithology (Sabina transitional carbonates in Fig. 1B) with some exceptions such as the Rocca di Cave shelf (Accordi and Carbone, 1986). In contrast, the footwall mostly consists of Mesozoic platform carbonates (Latium platform carbonates in Fig. 1B; Parotto and Praturlon, 1975; Accordi and Carbone, 1986). The thickness of the Sabina and Latium carbonates is about 3 and 5 km, respectively (Parotto and Praturlon, 1975; Accordi and Carbone, 1986). The contrasting thickness and rigidity of the soft marly rocks (Sabina carbonates) to the west of the Olevano-Antrodoco thrust, and hard platform carbonates (Latium carbonates) to the east has been considered the main cause for the formation of the Umbrian Arc (e.g., Calamita and Deiana, 1988; Ghisetti and Vezzani, 1997). It should be considered, however, that the Sabina carbonates include, at the succession bottom, the thick and rigid Calcare Massiccio Formation (i.e., Jurassic platform carbonates), which controls the deformation pattern of the entire succession (Coward et al., 1999). From exploratory well data, it is known that the Calcare Massiccio Formation is about 0.8 km thick (Anelli et al., 1994).

Thrust Timing and Vertical-Axis Rotations

In the central Apennines, detailed stratigraphic analyses on sedimentary rocks and, specifically, on syntectonic sedimentary bodies filling temporally- and spatially-successive foredeeps and thrust-top basins (Patacca et al., 1992; Cipollari and Cosentino, 1995; Patacca and Scandone, 2001) constrain the thrust evolution (e.g., Cavinato and DeCelles, 1999; Cosentino et al., 2003). The cessation of thrusting in each locality is marked by the onset of continental sedimentation driven by

188 the post-orogenic extensional tectonics. Fig. 2 presents a synoptic diagram of results from previous
189 studies showing that the central Apennines mostly grew by in-sequence thrusting between late
190 Tortonian (Volsci thrust) and early Pliocene (Gran Sasso and Maiella thrusts) times. In places,
191 adjacent synchronous thrusting occurred (e.g., Marsica and Morrone thrusts). Out-of-sequence
192 thrusting is documented for the Gran Sasso and Olevano-Antrodoco thrusts (Cipollari et al., 1993;
193 Ghisetti and Vezzani, 1997; Satolli et al., 2005). In particular, during late Messinian-early Pliocene
194 time, the Olevano-Antrodoco thrust was emplaced over late Messinian, siliciclastic, foredeep
195 deposits (i.e., flysch) exposed to the north of the Simbruini thrust (Cipollari et al., 1993; Cipollari,
196 1995). The age of thrusting (Fig. 2) along with the truncation relationship with earlier adjacent
197 thrusts, and with temporally- and spatially-successive foredeeps and thrust-top basins (Fig. 1C),
198 indicates that the late Messinian-early Pliocene activity of the Olevano-Antrodoco thrust was out-
199 of-sequence (Cipollari and Cosentino, 1995; Mattei et al., 1995). Some authors infer also additional
200 activity of the Olevano-Antrodoco thrust during early-middle Messinian time (Cipollari and
201 Cosentino, 1992; Cipollari et al., 1993; Cavinato and DeCelles, 1999). In contrast, based on the age
202 of foredeep deposits presently exposed to the east and west of the Olevano-Antrodoco thrust, Mattei
203 et al. (1995) argue that the Olevano-Antrodoco thrust did not develop earlier than late Messinian
204 time.

205 In the southern sector of the Umbrian Arc, and in the adjacent areas (Fig. 1C), three main
206 paleomagnetic domains are recognized (Mattei et al., 1995, 1998): (1) the Sabina region (i.e., the
207 Olevano-Antrodoco thrust sheet), which rotated clockwise by about 16° (95% confidence half-
208 angle, α_{95} = 11.5°) after early-middle Miocene time (Mattei et al., 1995) with no significant
209 rotations since middle Pliocene time (Sagnotti et al., 1994); (2) the Roveto Valley, which rotated
210 counterclockwise by about 28° (α_{95} = 10.5°) during post-Messinian times; and (3) the Tuscan-
211 Latium (i.e., Tyrrhenian side of the Apennines) neoautochthonous basins (Neogene-Quaternary),
212 which have been affected by non-rotational deformation (Sagnotti et al., 1994; Mattei et al., 1996).
213

THE CROP-11 SEISMIC REFLECTION PROFILE

The CROP-11 deep seismic reflection profile was planned and acquired across the central Apennines (Fig. 1C) to image the crustal-scale tectonic architecture of the junction between the northern (i.e.,, Umbrian Arc) and southern orogenic arcs (Parotto et al., 2003). Parameters of acquisition and processing of the CROP-11 profile are provided in a previous paper (Billi et al., 2006). Time-to-depth conversion of the CROP-11 seismic profile was not attempted because detailed velocities of P-waves in the study area were not appropriately known at the time of data processing (now available in Di Luzio et al., 2008 and Patacca et al., 2008 for the eastern portion of the seismic line).

The central segment of the CROP-11 profile (Fig. 3) shows the core of the orogenic wedge, where strong reflections occur between about 5 and 8-9 s two ways travel time (TWTT). These reflections outline a wide and thick anticlinorium that is interpreted as being developed above a middle-lower crust shear zone occurring between about 7 and 9 s TWTT with variable dip angles. From seismic refraction data (Cassinis et al., 2003), it is inferred that the shear zone is as deep as about 20-22 km (i.e., corresponding to about 9 s TWTT). The anticlinorium is characterized by two hinge zones imaged by two sets of upward-convex reflections (Fig. 3B). The vertical component of displacement on the basal shear zone, as estimated on the CROP-11 profile, is about 2 s TWTT corresponding to about 4-5 km.

In the CROP-11 profile, the near-surface portion of the Olevano-Antrodoco thrust is imaged as a low-angle, shallow structure dipping toward the west and resting above the crest and backlimb of the mid-crustal anticlinorium (Figs. 3B and 3C). The geometric relationship between the Olevano-Antrodoco thrust and the underlying anticlinorium are not straightforward in the seismic image. The weak, ramp-flat geometry (consisting of near-horizontal flats and low-angle ramps) of the Olevano-Antrodoco thrust seems only partially parallel to the geometry of the underlying anticlinorium. In particular, the hinge between the crest and the backlimb of the anticlinorium is not coincident with the hinge between the ramp and flat segments of the Olevano-Antrodoco thrust. Moreover, the

interlimb angle of the anticlinorium is smaller than the angle between the flat and ramp segments of the Olevano-Antrodoco thrust. These geometric relationships suggest that the Olevano-Antrodoco thrust postdates the anticlinorium; however, some parallelism between the anticlinorium crest and the Olevano-Antrodoco thrust main flat may represent evidence that the Olevano-Antrodoco thrust was affected by some folding connected with anticlinorium growth.

To the west of and beneath the Fucino basin, some shallow reflections (shallower than 2 s TWTT) located to the east of the mid-crustal anticlinorium are parallel to its forelimb (Fig. 3B). Such a geometric relationship suggests that these shallow reflections were involved in the anticlinorium-related folding and, therefore, that the anticlinorium postdated the shallow thrust sheets located immediately to the east. The location of the E-dipping shallow reflections suggests that they represent the eastward subsurface prolongation of the Marsica thrust sheet (i.e., the bedding panels forming the Vallelonga thrust sheet; Fig. 3B), whose age is late Messinian-very early Pliocene (Figs. 1C and 2). The overall E-dipping attitude (i.e., by about 20°) of the exposed portion of the Vallelonga thrust sheet (Servizio Geologico d'Italia, 1968; Vezzani and Ghisetti, 1993) supports the hypothesis of a linkage between the exposed Vallelonga thrust sheet and the E-dipping shallow reflections imaged in Fig. 3(B) to the west of and beneath the Fucino basin (see also Patacca et al., 2008).

ANALYSIS OF GRAVITY DATA

We analyzed the regional gravity data of the central Apennines (Fig. 4) to determine the gravity signature of the mid-crustal anticlinorium (Fig. 3B) and to infer its areal (i.e., map-view) extent. The gravity dataset was obtained through a stripping-off procedure (sensu Hammer, 1963), which consisted of removing the effect of all geological bodies located in the upper crust from the Bouguer anomaly data (Carrozzo et al., 1991; Fig. 4A). The stripping-off procedure applied to obtain the map shown in Fig. 4(B) is thoroughly explained in Tiberti et al. (2005). The geometry and density of the shallow bodies, whose gravity effect was removed during the stripping-off

266 procedure, are known from about 60 logs of hydrocarbon wells drilled in the central Apennines, and
267 from several previously published studies on the subsurface geology of this region (e.g., Bally et al.,
268 1988; Anelli et al., 1994; Butler et al., 2004). In particular, density data used in this paper are
269 mainly after Mostardini and Merlini (1986). These data were integrated with other published
270 information (Table DR1).

271 The Tyrrhenian and Adriatic domains are characterized by gravity highs, whereas a relative
272 gravity low occurs in the axial sector of the Apennine fold-thrust belt (Fig. 4B). The gravity low is
273 ascribed to the regional deepening of both the Moho and the top of the crystalline basement (Tiberti
274 and Orlando, 2006).

275 In the Olevano-Antrodoco and Simbruini thrust areas (Fig. 1C), a second-order gravity low
276 affects the Bouguer and regional gravity anomalies (Figs. 3D, 4A, and 4B). This second-order
277 gravity low consists of a negative variation of about 10 mGal (Fig. 3D) and suggests the presence of
278 a relatively low density body in the middle crust. Provided that the effects of all the shallower
279 bodies have been properly removed, the 40 km wavelength of the 10-mGal-gravity-low is consistent
280 with a source depth between about 10 and 20 km since, at greater depth, density contrast of about ±
281 100 kg/m^3 would affect an area broader than 40 km.

282 To define the areal extent of the 10-mGal-gravity low in the Olevano-Antrodoco and Simbruini
283 thrusts area, the tips (i.e., the lateral closures) of the second-order gravity low were searched in 70
284 gravity cross-sections arranged on a grid covering the study area, including the Olevano-Antrodoco
285 and the Simbruini thrust sheets (Fig. 1C). One of these cross-sections (i.e., the one coincident with
286 the CROP-11 profile) is shown in Fig. 3(D). The obtained tips were then plotted on the map of Fig.
287 5 and joined with a closed line (i.e., the dashed line encompassing the shaded area in Fig. 5). The
288 resulting area is roughly elliptical and N-S-elongated, being about 50 km long by 30 km wide. Its
289 N-S-trending long axis approximately coincides with the surface trace of the Olevano-Antrodoco
290 thrust.

Assuming that the second-order gravity low imaged in the gravity cross-section (Fig. 3D) and in the maps of the Bouguer and regional gravity anomalies (Figs. 4A and 4B) is related to the anticlinorium (Fig. 3B), we applied again the stripping-off procedure, which consisted, this time, of calculating and removing from the Bouguer anomaly map (Fig. 4A) the effect of a geological body with the same geometric and geologic characteristics (i.e., location, depth, and shape) of the anticlinorium. The areal extent of the structure was approximately as inferred from the seismic section (Fig. 3B) and from the anomalous shape of the gravity isolines (see inset in Fig. 4B), the maximum overall thickness of the whole structure was fixed at about 8 km from the seismic profile (Fig. 3B), dropping progressively toward the lateral closures of the structure as drawn in Fig. 3(B). By a trial-and-error procedure, we found that the second-order gravity low could be best compensated by assigning a density of 2570 kg/m^3 to the rocks forming the anticlinorium. Such a density, for rocks lying at the depth of the mid-crustal anticlinorium, is consistent, for instance, with low grade metamorphic rocks such as argillites or some kinds of phyllites. The occurrence of fluids within these rocks may have reduced their density and increased their seismic reflectivity. The reliability of the data used to model the anticlinorium is shown by the result of the stripping-off procedure displayed in Fig. 4(C), where the second-order gravity low is almost completely absent (i.e., compare insets in Figs. 4A, 4B, and 4C) and the main gravity anomalies become approximately linear and aligned with the NW-SE regional structural trend.

DISCUSSION

The rotational origin of the Olevano-Antrodoco thrust is demonstrated by a positive orocline test and by paleomagnetic data (Fig. 1B), which show a clockwise rotation of about 16° between early-middle Miocene and middle Pliocene times (Sagnotti et al., 1994; Mattei et al., 1995, 1998; Speranza et al., 1997). Paleomagnetic measurements are from seven sites on the Prenestini Mts, which form the hangingwall of the Olevano-Antrodoco thrust. We think that more paleomagnetic

data are necessary to better constrain the rotation of the Olevano-Antrodoco thrust sheet and reduce the error connected with past measurements (Mattei et al., 1995).

The analysis of the CROP-11 seismic image (Fig. 3A) shows the presence of a thick dome-structure related to folding in the middle crust (i.e., the mid-crustal anticlinorium) right beneath the Olevano-Antrodoco thrust (Fig. 3B). For the part visible in the CROP-11 profile, the Olevano-Antrodoco thrust is imaged as a shallow thin-skinned thrust sheet, whose basal thrust emerges above the crest region of the anticlinorium (Figs. 3C and 5). Due to the lack of appropriate subsurface data, the subsurface geometry of the Olevano-Antrodoco thrust was mostly unknown before the acquisition of the CROP-11 profile. We were able to compensate for the gravity anomalies observed in both cross-section (Fig. 3D) and map (Fig. 4) views with a geological body similar to that observed in the CROP-11 profile at the mid-crustal level and characterized by a horizontal dimensions of about 50 by 30 km. The long axis of this structure is approximately N-S-trending (Fig. 5). By combining these results with the seismic reflection image, we interpret the near-elliptical geological body detected by the gravity analysis as a N-trending anticlinorium related to contractional displacement on an basal shear zone lying at a middle-lower crust level (Figs. 3 and 5).

The timing of the anticlinorium development can be inferred, at least in part, by analyzing the geometric relationship between the anticlinorium and the exposed or shallow thrusts, whose age is known from previous studies (Fig. 2). In particular, in the CROP-11 image (Fig. 3B), the Vallelonga thrust sheet is parallel to the forelimb of the underlying anticlinorium. This relationship suggests that the Vallelonga thrust, whose age is late Messinian-very early Pliocene (i.e., see the age of the Marsica thrust in Fig. 2), was involved in the growth of the anticlinorium. It follows that the age of the anticlinorium should be early Pliocene (Fig. 2). In middle Pliocene time, contractional deformation was mostly inactive across the presently-exposed portion of the central Apennines, and normal faulting was already active at least in the inner and axial sectors of the belt (Fig. 2). Furthermore, the geometric relationship between the Olevano-Antrodoco thrust and the

anticlinorium (Fig. 3B) is consistent with the inferred age of anticlinorium growth (i.e., early Pliocene time). The Olevano-Antrodoco thrust, in fact, whose age is late Messinian-early Pliocene (Fig. 2), seems partly involved in the mid-crustal folding. The hypothesized tectonic interaction between the Olevano-Antrodoco thrust and the underlying anticlinorium likely took place during the latest phase of thrust activity (i.e., during early Pliocene time).

To verify whether the Olevano-Antrodoco thrust is folded, we analyzed the elevation pattern of the emerging thrust (A-B and C-D cross-sections in Fig. 6B). The longitudinal topographic profile of the Olevano-Antrodoco thrust has a gentle antiformal shape with elevation varying between about 700 m and 1600 m above sea level. The minimum elevation of the Olevano-Antrodoco thrust is not known because, toward the south, this structure is covered by recent volcanic deposits (Fig. 6A). The antiformal longitudinal profile of the Olevano-Antrodoco thrust (Fig. 6B) suggests that the thrust is folded. This inference is true, however, only if the profile (Fig. 6B) actually tracks the same structural depth along the thrust surface; otherwise, the antiformal shape may be connected with a variation of structural depth along the thrust. The amplitude of the antiformal shape (Fig. 6B) suggests, however, that such geometry is more an expression of a regional folding than an apparent structure due to the intersection between the profile and the thrust. If this inference is true, then the longitudinal folding of the Olevano-Antrodoco thrust is consistent with the hypothesis that the mid-crustal anticlinorium produced a surface uplift.

Further evidence indicating possible surface uplift in the study area may come from sedimentologic studies. On top of the Simbruini Mountains (Fig. 6A), several conglomeratic deposits are exposed at different altitudes (Accordi and Carbone, 1986). Most of these deposits are still to be studied, mapped, and dated in detail. In some of these conglomerates, clasts deriving from lower Cretaceous platform carbonates have been found (M. Parotto, personal communication). This observation may imply the erosion of at least 1000 m of a Cretaceous-Paleogene carbonate succession (Accordi and Carbone, 1986); however, the occurrence of hiatuses in the Mesozoic-Paleogene carbonate succession of central Italy makes this evidence not sufficient to demonstrate

the erosion during Pliocene time. Moreover, in the Simbruini-Roveto area, the Puddinghe di Canistro e Broccostella Formation (indicated as main Pliocene conglomerates in Fig. 6A) consists of lower Pliocene conglomerates including rounded, exotic, sedimentary clasts, which are probably derived from hinterland areas located toward the west and northwest (Cipollari and Cosentino, 2002). These conglomerates unconformably rest on Mesozoic carbonates or synorogenic flysch deposits (Accordi and Carbone, 1986). The presence of lower Pliocene conglomeratic deposits in the Simbruini-Roveto area (Fig. 6A) suggests the occurrence of significant erosion in the area located to the west and northwest of these deposits (Fig. 5), such erosion being possibly connected with the hypothesized surface uplift generated by anticlinorium growth during early Pliocene time.

Based on the above evidence and inferences, we propose the following model for orogenic curvature of the southern portion of the Umbrian Arc (Fig. 7). The Olevano-Antrodoco thrust developed and propagated during late Messinian-early Pliocene time with an eastward vergence. The thrust underwent an orogenic clockwise curvature when it ran into the surface uplift induced by the growing mid-crustal anticlinorium, which then raised and folded the Olevano-Antrodoco thrust. This process halted the eastward advancement of the Olevano-Antrodoco thrust. The interaction between the Olevano-Antrodoco thrust and the anticlinorium-related surface uplift caused nonplane-strain deformation recorded by vertical-axis rotations detected in the hangingwall of the Olevano-Antrodoco thrust, and by right-lateral displacements detected on the thrust surface (Castellarin et al., 1978; Salvini and Vittori, 1982; Mattei et al., 1995). According to this model, the southern portion of the Umbrian Arc can be classified as a progressive arc (Weil and Sussman, 2004), where the orogenic curvature was progressively acquired during the propagation of the thrust in late Messinian-early Pliocene time. The three-dimensional architecture of the anticlinorium and its relationships with the adjacent structures are mostly inferred from two-dimensional evidence (Fig. 3). Uncertainty and error inherent with modeling a three-dimensional structure from two-dimensional evidence compel a revision of this model in the future when new subsurface data will be available.

The model proposed in this paper for the curvature of the southern sector of the Umbrian Arc agrees with several previous models in that the main cause of curvature is a geologic obstacle that obstructed thrust migration (e.g., Eldredge et al., 1985; Calamita and Deiana, 1988). In previous studies, the impingement of the Olevano-Antrodoco thrust was mostly ascribed to the stiff carbonate succession forming the Adriatic-Apulian foreland and the thrust sheets of the central Apennines (Ghisetti and Vezzani, 1997). In contrast, we propose that the impingement of the Olevano-Antrodoco thrust was caused by a mid-crustal anticlinorium, which was first imaged in the CROP-11 profile (Billi et al., 2006). For some aspects, this latter model refines the one proposed by Lavecchia et al. (1988), who hypothesized the role of deep-crust structures on the formation of the Umbrian Arc, but could not ascertain the occurrence of these structures because of the lack of proper subsurface data.

For several geometric and kinematic characteristics, the mid-crustal anticlinorium imaged in the CROP-11 profile (Fig. 3B) is similar to some mid-crustal basement thrusts depicted in the Andean backthrust belt, Bolivia, by McQuarrie and DeCelles (2001) and in other fold-thrust belts (e.g., Alps, Appalachians, Caledonides, Himalaya, and Sevier belt; see Hatcher and Hooper, 1992; Yonkee, 1992; DeCelles et al., 1995; Kley, 1996; McBride and England 1999; Wobus et al., 2005). The frequency, in fold-thrust belts, of curved thrusts and mid-crustal thick folds such as that depicted in this paper suggests that mid-crustal contractional structures may be revealed as one of the important factors controlling local or regional curvature in orogens. The mature and final evolutionary phases of fold-thrust belts, in fact, are often characterized by both deep folds, and inner shallow out-of-sequence thrusts (e.g., Wobus et al., 2005), which both contribute to re-establishing orogenic taper subcriticality. As such, deep folds may be at the origin of topographic obstacles that obstruct the propagation of inner shallow thrusts such as the Olevano-Antrodoco thrust in the central Apennines.

CONCLUSIONS

(1) Results from the analysis of geological and geophysical data from the central Apennines are consistent with a causal link between clockwise rotation of the southern limb of the Umbrian Arc during late Neogene time and the penecontemporaneous growth of a thick mid-crustal anticlinorium. More evidence is required to fully support our hypothesis. In particular, more subsurface data are necessary to define the three-dimensional structure of the anticlinorium, and additional paleomagnetic evidence is necessary to better constrain the rotation of the southern limb of the Umbrian Arc.

(2) The tectonic process invoked to explain rotation of the southern limb of the Umbrian Arc (i.e., by developing a mid-crustal anticlinorium whose surface effects obstructed the advancement of an inner out-of-sequence shallow thrust) is a novel explanation for the origin of orogenic arcs around the world (e.g., Macedo and Marshak, 1999; Schellart and Lister, 2004; Sussman and Weil, 2004); however, because both out-of-sequence shallow thrusts and mid-crustal thick folds are common in curved fold-thrust belts, mid-crustal contractional structures may be the cause of thrust curvatures at the local or regional scale in other orogenic systems.

(3) Results from this study show that the solution of complex geological issues, such as the comprehension of orogenic arcs, requires the contribution of appropriate subsurface data and their integration into a multidisciplinary research including, for instance, geomorphologic, geophysical, stratigraphic, and tectonic analyses. In this study, results from subsurface prospecting by seismic and gravity methods and their integration in a multidisciplinary research compelled the revision of previous models of arc development and thrust evolution in the central Apennines, the past models being based mainly on surface data.

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623

FIGURE CAPTIONS

Figure 1. (A) Digital elevation model of Italy and surrounding areas. Main Cenozoic fold-thrust belts are shown. The northern and southern arcs of the Apennine fold-thrust belt are indicated. The main curved structure of the northern arc is the Umbrian Arc (Eldredge et al., 1985). The study area is located in the central Apennines and includes the N-S-trending southern limb of the Umbrian Arc, also known as the Olevano-Antrodoco thrust. **(B)** Geological map of the northern Apennines. The Cervarola flysch mainly consists of sandstones and shales. Epi-Ligurian units are mainly sandstones and marls derived from a pristine, continent-ocean margin. Ligurian units are ophiolites and sedimentary and low-grade metamorphic rocks derived from a pristine, oceanic basin. The Sabina carbonaceous sequence include transitional carbonates originally located between the Latium platform carbonates (central Italy) and the Umbrian pelagian carbonates (northern Apennines). The Sabina sequence includes also a thick sequence of platform limestones (Calcare Massiccio Formation) at the base of the succession. The Latium carbonates are mostly platform limestones and dolostones. The Tuscan succession consists of a pile of carbonates, marls, shales, evaporites, and sandstones deposited in different environments succeeded through Mesozoic-Paleogene times. **(C)** Geological map of the central Apennines. "th." stands for thrust sheet. Arrows are tilt corrected paleomagnetic declinations (Mattei et al., 1998).The CROP-11 seismic profile ("W-E") cuts across the southern limb (i.e., the Olevano-Antrodoco thrust) of the Umbrian Arc.

Figure 2. Time-distance diagram including thrusting, out-of-sequence thrusting, and post-orogenic basin sedimentation in the central Apennines (modified after Cavinato and DeCelles, 1999). The diagram refers to a SW-NE transect across the central Apennines including all main thrusts and extensional basins. The diagram shows that the central Apennines mainly evolved by in-sequence thrusting. Some late out-of-sequence thrusts also occurred. In each locality, the onset of extensional basin sedimentation is the temporal upper limit for contractional tectonics. The inferred age for the mid-crustal anticlinorium (Fig. 3B) is also shown.

Figure 3. (A) Central segment of the CROP-11 seismic reflection profile. See the related track ("W-E") in Fig. 1(C). TWTT is two ways travel time. The entire CROP-11 profile from the Tyrrhenian Sea to the Adriatic Sea and the related acquisition and processing parameters are available in Billi et al. (2006). **(B)** Line drawing and interpretation of the CROP-11 profile displayed in (A). The mid-crustal anticlinorium (i.e., indicated as "hangingwall") involves

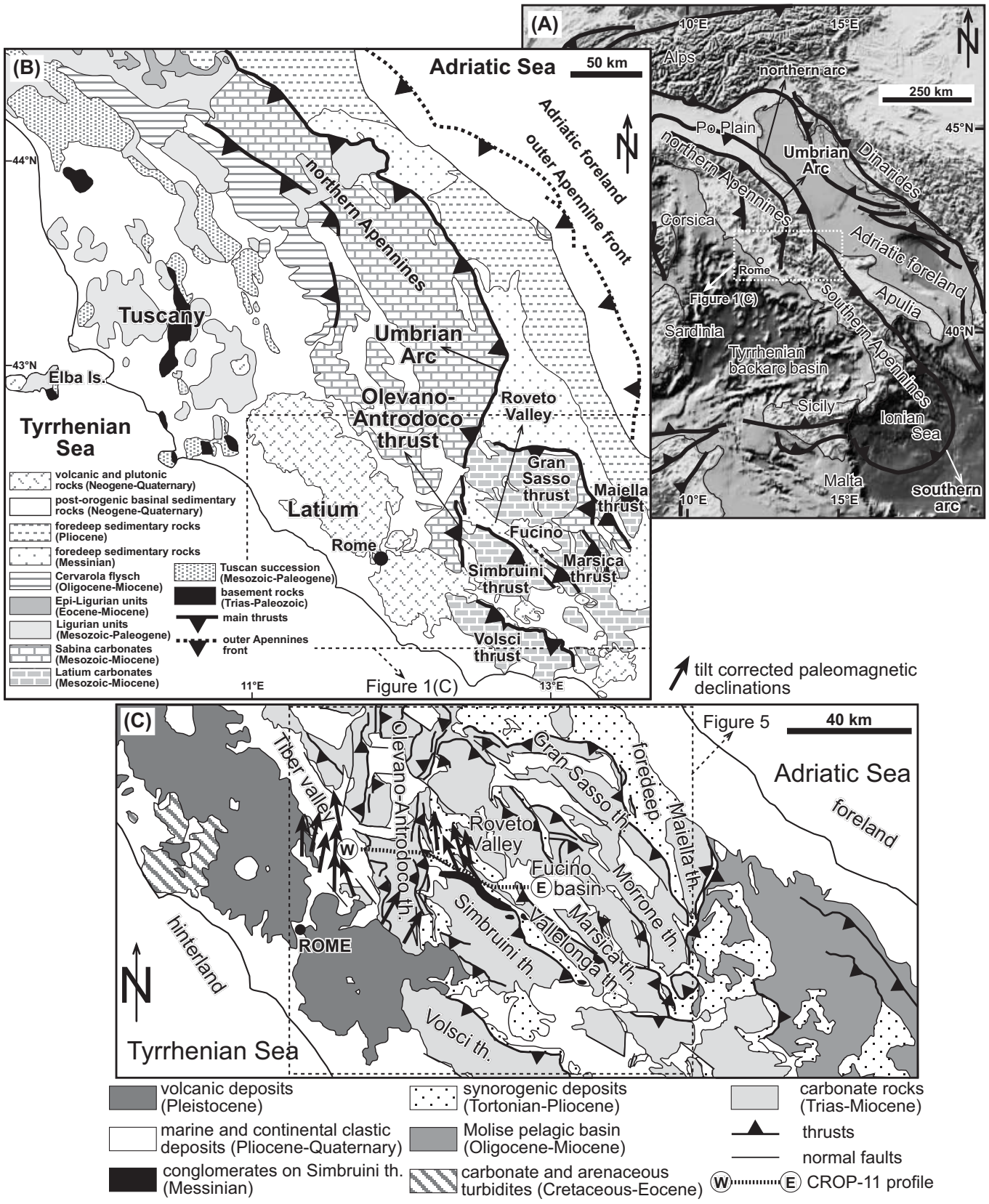
reflections between about 7-9 (i.e., the mid-crustal shear zone) and the topographic surface in the footwall of the Olevano-Antrodoco thrust. **(C)** Enlargement (left) and related interpretation (right) of the sector of the CROP-11 profile including the near-surface portion of the Olevano-Antrodoco thrust, which is interpreted as a shallow, low-angle, reverse structure. **(D)** Gravity cross-section along the segment of the CROP-11 profile shown in (A). The shaded area is the effect (i.e., negative) induced by the tectonic duplication (i.e., the anticlinorium) shown in the CROP-11 profile. Without this structure, the gravity cross-section would run along the upper (dotted) line.

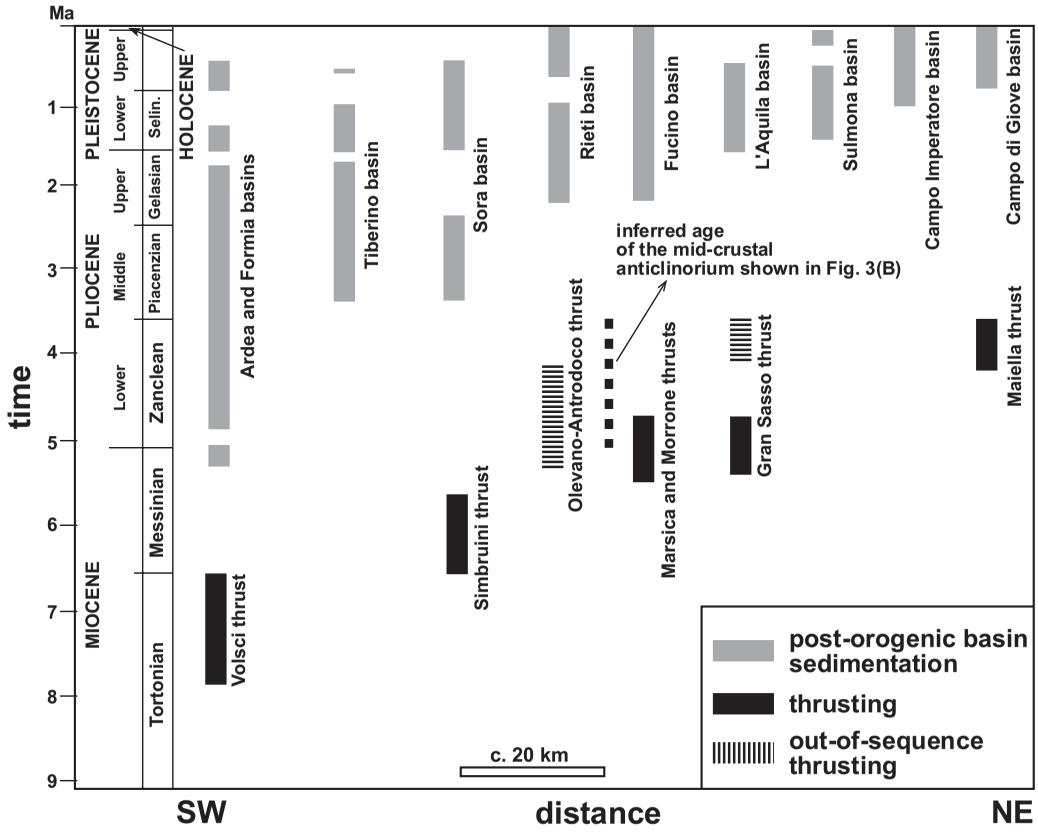
Figure 4. Gravity maps of central Italy. **(A)** Bouguer anomaly map. **(B)** Regional gravity map. **(C)** Regional gravity map after the removal (stripping-off procedure) of the effect of the mid-crustal anticlinorium shown in Fig. 3(B).

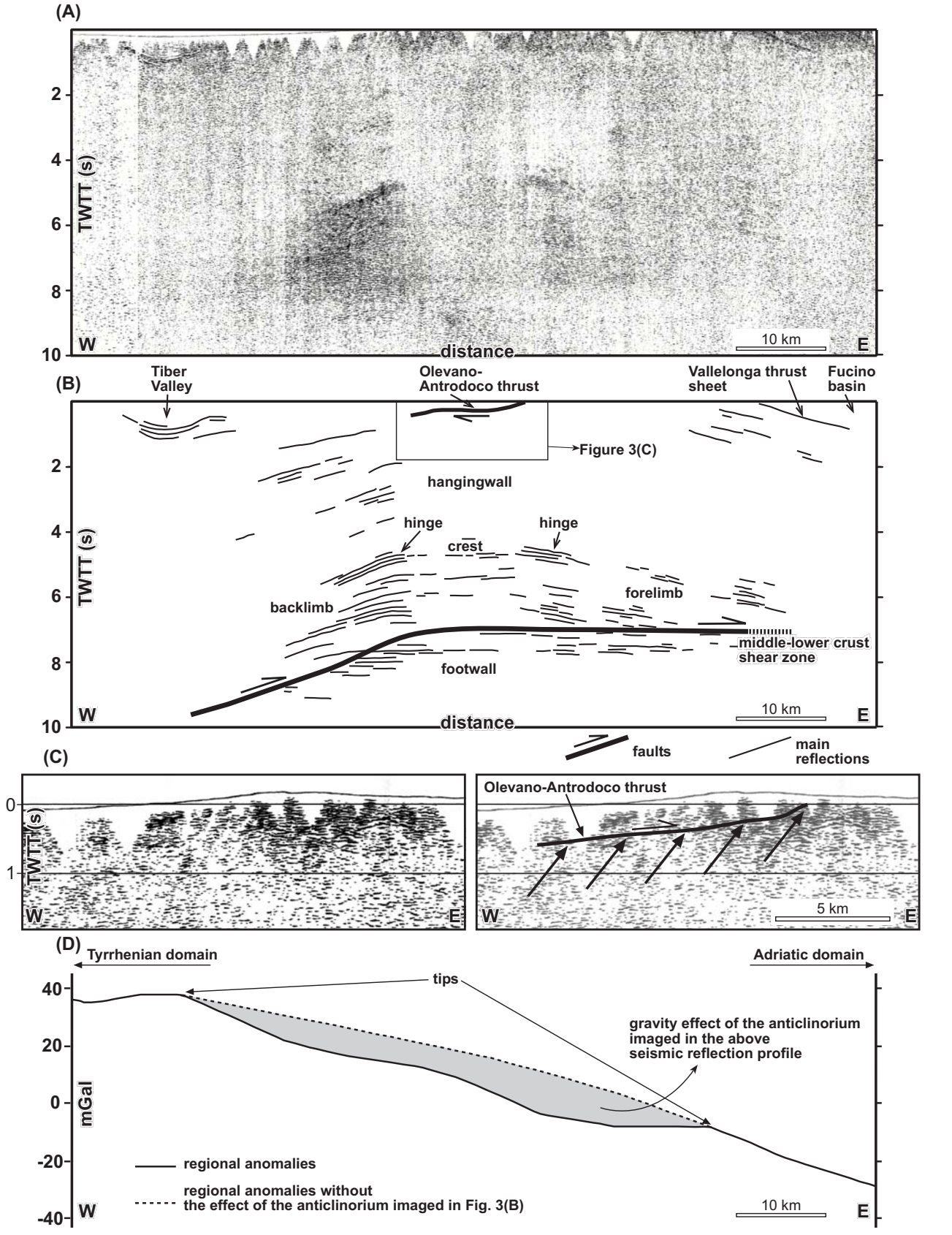
Figure 5. Schematic tectonic map of central Italy (location of this figure is indicated in Fig. 1C). The shaded area represents the gravity anomaly induced by tectonic duplication associated with the anticlinorium imaged in the CROP-11 profile (Fig. 3B). This area is interpreted to represent a N-trending mid-crustal anticlinorium related to displacement on a basal shear zone lying at the middle-lower crust level (Fig. 3B). The shaded area is drawn by joining the points representing the projection on the map of the lateral tips of the gravity anomaly connected with the anticlinorium and observed on 70 gravity cross-sections (see one of these cross-sections in Fig. 3D). As such, this area represents the approximate areal extent (i.e., where the gravity signature induced by the tectonic duplication is sufficiently marked to be detected) of the mid-crustal anticlinorium. The paleomagnetic data are from Sagnotti et al. (1994) and Mattei et al. (1995).

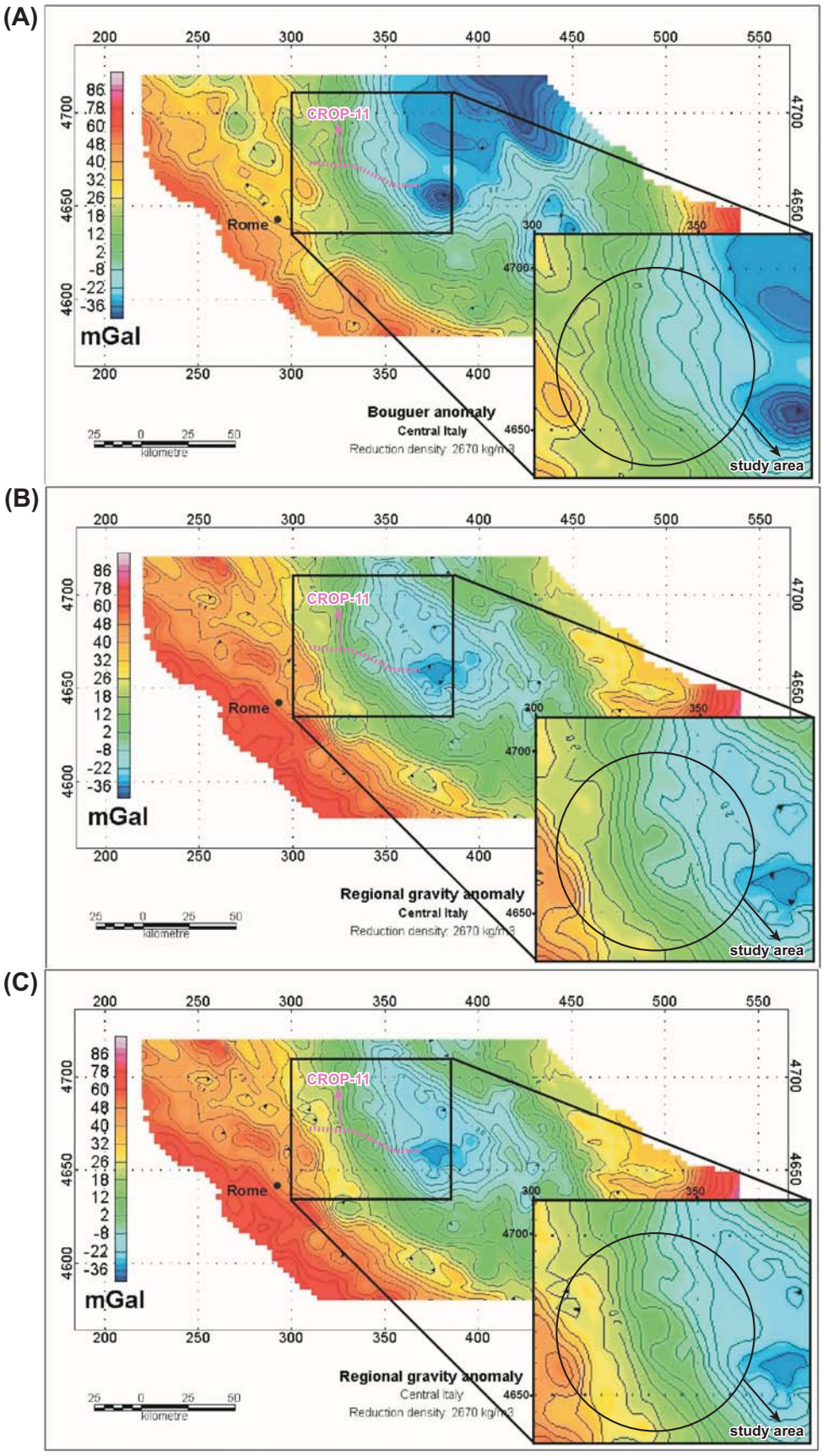
Figure 6. (A) Geological map of central Apennines. The tracks of topographic cross-sections shown in (B) are displayed. The flysch deposits (i.e., mainly sandstones with shale intercalations) are undifferentiated and indicated as Tortonian-Pliocene in age. Because of the northeastward progression of the fold-thrust belt, flysch deposits are younger toward the northeast. In the Roveto Valley, flysch deposits are Messinian in age and are overlain by the Olevano-Antrodoco thrust, whose latest age is, therefore, post-Messinian (i.e., early Pliocene) (Cipollari and Cosentino, 2002). **(B)** Projection of the altitude of the emergence of the Olevano-Antrodoco thrust on the A-B and C-D tracks. The vertical scale is greatly exaggerated.

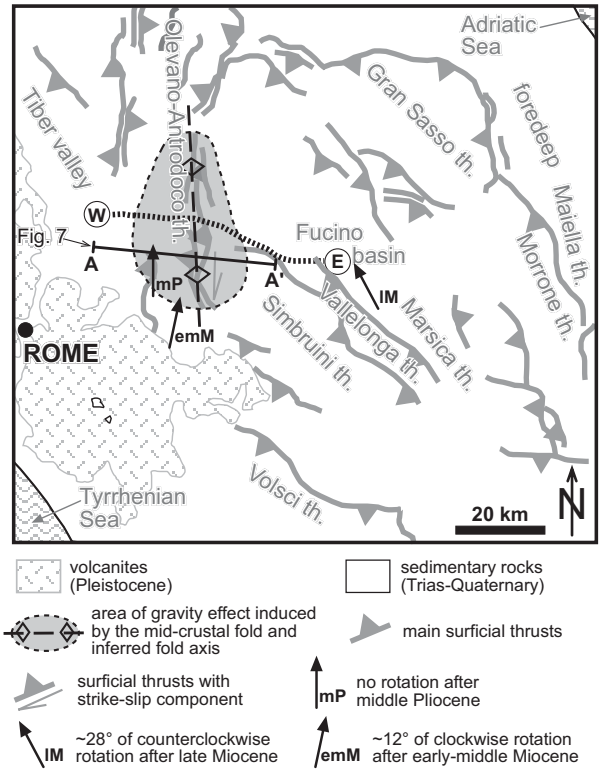
Figure 7. Schematic cross-sectional cartoon (see the approximate AA' track in Fig. 5) showing the interaction between the development of the Olevano-Antrodoco thrust and that of the mid-crustal anticlinorium during early Pliocene time. During this time, the Olevano-Antrodoco thrust developed and migrated toward the east as a shallow out-of-sequence structure. In the mean time, a mid-crustal thick anticlinorium developed ahead (east) of the Olevano-Antrodoco thrust by folding a thick section of the middle-upper crust and by generating a surface uplift. As the Olevano-Antrodoco thrust run into the anticlinorium, the thrust was raised and folded by the growing anticlinorium and the thrust propagation was eventually halted. The northern prolongation of the Olevano-Antrodoco thrust kept advancing toward the east, thus ultimately forming the Umbrian Arc thanks to the impingement of the Olevano-Antrodoco thrust against the mid-crustal anticlinorium. The fold is modified after Davis and Reynolds (1996).

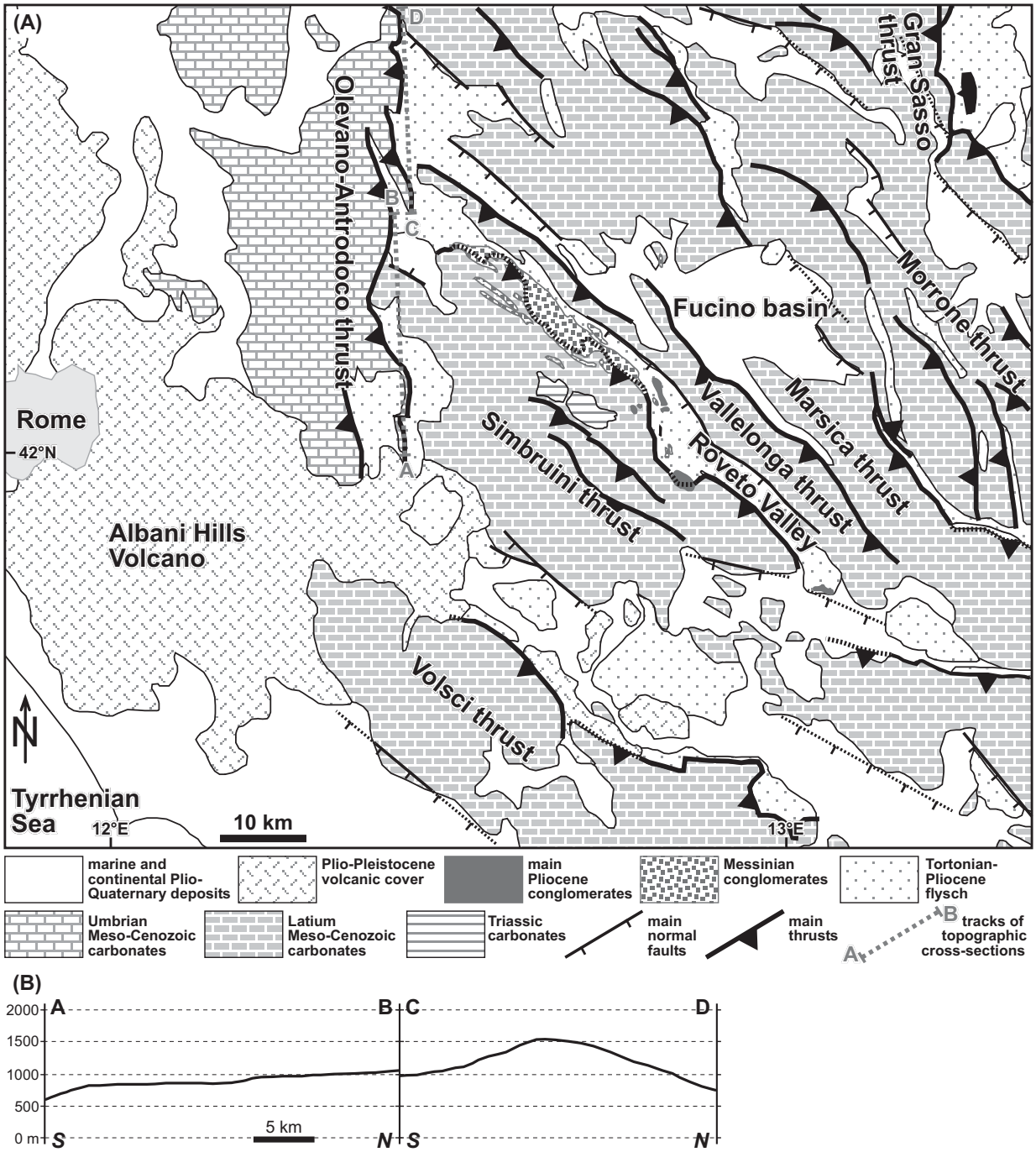

(A)
10°E
15°E
Alps
northern arc
250 km
Po Plain
45°N
Umbrian Arc
Dinarides
northern Apennines
Corsica
Adriatic foreland
Rome
Figure 1(C)
Apulia
Southern Apennines
Sardinia
40°N
Tyrrhenian backarc basin
Sicily
Ionian Sea
Malta
10°E
15°E
southern arc
(B)
Adriatic Sea
50 km
Adriatic foreland
outer Apennine front
northern Apennines
44°N
Tuscany
Umbrian Arc
43°N
Elba Is.
Olevano-Antrodoco thrust
Roveto Valley
Tyrrhenian Sea
Gran Sasso thrust
Maiella thrust
Latium
Fucino
Rome
Marsica thrust
Simbruini thrust
Volsci thrust
11°E
13°E
Figure 1(C)
volcanic and plutonic rocks (Neogene-Quaternary)
post-orogenic basinal sedimentary rocks (Neogene-Quaternary)
foredeep sedimentary rocks (Pliocene)
foredeep sedimentary rocks (Messinian)
Cervarola flysch (Oligocene-Miocene)
Epi-Ligurian units (Eocene-Miocene)
Ligurian units (Mesozoic-Paleogene)
Sabina carbonates (Mesozoic-Miocene)
Latium carbonates (Mesozoic-Miocene)
Tuscan succession (Mesozoic-Paleogene)
basement rocks (Trias-Paleozoic)
main thrusts
outer Apennines front
tilt corrected paleomagnetic declinations
(C)
Figure 5
40 km
Adriatic Sea
foreland
foredeep
Tiber valley
Olevano-Antrodoco th.
Gran Sasso th.
Maiella th.
Roveto Valley
W
Fucino basin
E
Morrone th.
Simbruini th.
Marsica th.
Vallelonga th.
ROME
hinterland
Volsci th.
Tyrrhenian Sea
volcanic deposits (Pleistocene)
marine and continental clastic deposits (Pliocene-Quaternary)
conglomerates on Simbruini th. (Messinian)
synorogenic deposits (Tortonian-Pliocene)
Molise pelagic basin (Oligocene-Miocene)
carbonate and arenaceous turbidites (Cretaceous-Eocene)
carbonate rocks (Trias-Miocene)
thrusts
normal faults
W E CROP-11 profile

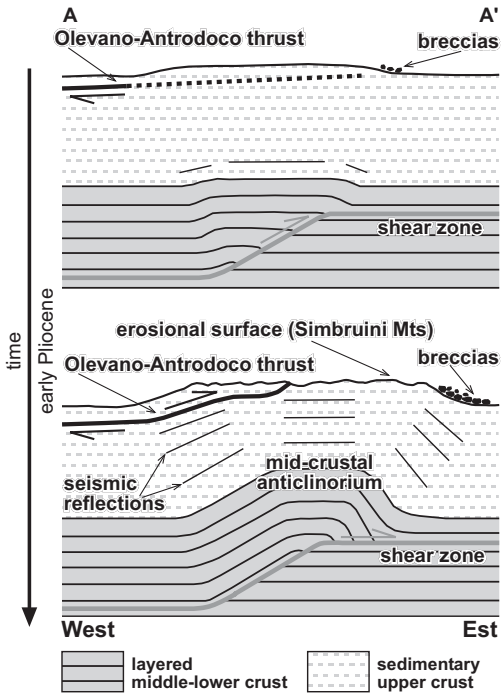

Ma
time
1
2
3
4
5
6
7
8
9
PLEISTOCENE
PLIOCENE
MIOCENE
Upper
Lower
Upper
Middle
Lower
Selin.
Gelasian
Piacenzian
Zanclean
Messinian
Tortonian
HOLOCENE
Ardea and Formia basins
Volsci thrust
Tiberino basin
Sora basin
Simbruini thrust
Olevano-Antrodoco thrust
Rieti basin
inferred age
of the mid-crustal
anticlinorium shown in Fig. 3(B)
Marsica and Morrone thrusts
Fucino basin
Gran Sasso thrust
L'Aquila basin
Sulmona basin
Campo Imperatore basin
Maiella thrust
Campo di Giove basin
c. 20 km
post-orogenic basin sedimentation
thrusting
out-of-sequence thrusting
SW
distance
NE


(A)
TWTT (s)
2
4
6
8
10
W
distance
10 km
E
(B)
Tiber Valley
Olevano-Antrodoco thrust
Vallelonga thrust sheet
Fucino basin
Figure 3(C)
hangingwall
hinge
hinge
crest
backlimb
forelimb
middle-lower crust shear zone
footwall
TWTT (s)
2
4
6
8
10
W
distance
10 km
E
faults
main reflections
(C)
0
1
TWTT (s)
W
E
Olevano-Antrodoco thrust
W
5 km
E
(D)
Tyrrhenian domain
Adriatic domain
tips
gravity effect of the anticlinorium imaged in the above seismic reflection profile
40
20
0
-20
-40
mGal
regional anomalies
regional anomalies without the effect of the anticlinorium imaged in Fig. 3(B)
W
10 km
E


(A)
CROP-11
Rome
mGal
86
78
60
48
40
32
26
18
12
2
-8
-22
-36
Bouguer anomaly
Central Italy
Reduction density: 2670 kg/m^3
kilometre
study area
(B)
CROP-11
Rome
mGal
Regional gravity anomaly
Central Italy
Reduction density: 2670 kg/m^3
kilometre
study area
(C)
CROP-11
Rome
mGal
Regional gravity anomaly
Central Italy
Reduction density: 2670 kg/m^3
kilometre
study area


Adriatic Sea
Olevano-Antrodoco th.
Tiber valley
Gran Sasso th.
foredeep
Maiella th.
Morrone th.
W
Fig. 7
A
A'
Fucino basin
E
mP
IM
emM
Simbruini th.
Vallelonga th.
Marsica th.
ROME
Volsci th.
Tyrrhenian Sea
20 km
N
volcanites (Pleistocene)
sedimentary rocks (Trias-Quaternary)
area of gravity effect induced by the mid-crustal fold and inferred fold axis
main surficial thrusts
surficial thrusts with strike-slip component
mP no rotation after middle Pliocene
IM ~28° of counterclockwise rotation after late Miocene
emM ~12° of clockwise rotation after early-middle Miocene


(A)
D
B
C
A
Olevano-Antrodoco thrust
Gran Sasso thrust
Morrone thrust
Fucino basin
Vallelonga thrust
Marsica thrust
Roveto Valley
Simbruini thrust
Rome
42°N
Albani Hills Volcano
Volsci thrust
Tyrrhenian Sea
12°E
10 km
13°E
marine and continental Plio-Quaternary deposits
Plio-Pleistocene volcanic cover
main Pliocene conglomerates
Messinian conglomerates
Tortonian-Pliocene flysch
Umbrian Meso-Cenozoic carbonates
Latium Meso-Cenozoic carbonates
Triassic carbonates
main normal faults
main thrusts
tracks of topographic cross-sections
(B)
2000
1500
1000
500
0 m
A
B
C
D
S
N
5 km
S
N


A
A'
Olevano-Antrodoco thrust
breccias
shear zone
time
early Pliocene
erosional surface (Simbruini Mts)
Olevano-Antrodoco thrust
breccias
mid-crustal
anticlinorium
seismic
reflections
shear zone
West
Est
layered
middle-lower crust
sedimentary
upper crust