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Flexural response of the Venetian foreland to the Southalpine tectonics along the TRANSALP profile

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ABSTRACT

The Venetian Basin was affected by flexure related to the Southalpine shortening phase during the Middle Miocene – Early Pliocene. This downbending is quantified here using a two-dimensional flexural model. A recently improved data set on basin geometry based on the bottom of the Serravallian–Tortonian clastic wedge, on palaeobathymetry and gravity anomalies is used to constrain the components of flexure and to test the importance of the initial bathymetry in evaluating the contribution of surface loads to deflection. A good fit is obtained assuming a northward broken plate configuration of the downbent Adriatic plate with an effective elastic thickness of 20 km. Results highlight that, in the studied region, flexure related to the Eastern Southern Alps is totally due to surface loads (topographic load partly replacing initial bathymetry) and that no hidden loads are required. Furthermore, the palaeobathymetry contributes up to 50% to the total flexure in the studied region.

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Introduction

The present work aims to quantify the driving mechanisms for subsidence in the Venetian foredeep recorded during the main tectonic phases of the Eastern Southern Alps (middle Miocene to early Pliocene) along a NS-trending section. To this end, geophysical and geological data recently collected by the TRANSALP project have been used together with the interpretation and depth conversion of a well-calibrated industrial seismic line (Fig. 1). Further information is provided by revised micropalaeontological associations in three wells (Barbieri *et al.*, 2002) showing that palaeobathymetric changes occurred during middle–late Miocene times as an effect of flexure.

From a lithospheric point of view, this new seismic profile (Fig. 1: TRANSALP Working Group, 2001, 2002) extending from Munich (European foreland, Germany) to Treviso (Adriatic foreland, Italy) has added further detail to the crustal geometries already recognized (Fantoni *et al.*, 1992; Scarascia and Cassinis, 1997, and references therein). According to the lithospheric models proposed by Castellarin *et al.* (2002) and Lammerer and TRANSALP Working Group, 2002) the European crust deepens to the south down to about 55–60 km depth beneath the Alps where it is overlain by Adriatic crust.

Gravity anomalies on the southern side of the analysed section show a short-wavelength positive variation, which is referred to as 'Belluno nose'. Recent studies, related to the TRANSALP project (2002), interpreted this anomaly as due to the occurrence of high-density bodies located between the upper and the lower Adriatic crust or even deeper. Further positive anomalies exist south of this zone and are possibly due to a three-dimensional (3D) influence of either Eocene – late Oligocene volcanics occurring westward (e.g. De Vecchi and Sedea, 1995) or a relatively shallow Moho, related to an Apenninic forebulge in the Istrian area (Kruse and Royden, 1994).

In general, modelling studies have revealed that the flexural response to the load of mountain belts strongly controls the evolution of the adjacent foreland systems (Miall, 1995, and references therein; DeCelles and Giles, 1996). Initial water depth, sedimentary infill and overthrusting of a deep-water continental margin are further surface loads able to affect the flexure of the lower plate (Stockmal *et al.*, 1986). However, models show that these components are not always sufficient to account for the total subsidence occurring in the foredeep basin. For this reason, subsurface loads, geologically related to the effect of slab pull, high-density bodies or asthenosphere mantle flows, have been assumed to solve the difference between observed and calculated flexure (Royden and Karner, 1984; Royden, 1988; Doglioni, 1993; Catuneanu *et al.*, 1997; Buiter *et al.*, 1998).

Several models have been proposed for the flexural response of the western edge of the Adria plate to the Northern Apennines belt load (Royden, 1988; Kruse and Royden, 1994; Buiter *et al.*, 1998; Carminati *et al.*, 1999; Kroon, 2002). Besides lateral variations in flexural parameters and determination of lithospheric characteristics such as effective elastic thickness (T_e), all interpretations have shown that subsidence in the Apenninic foredeep basins is strongly affected by hidden loads that change along strike.

By contrast, only one model has been proposed (Royden, 1993) for the response of the northernmost sector of the Adria plate, corresponding to the Venetian foredeep (NE Italy), to the Eastern Southern Alps load. At that time, relatively few data were available on the subsurface of the Po–Venetian Basin, on palaeowater depths before and during crustal flexure and on the deep structure of the Southern Alps. Therefore, the

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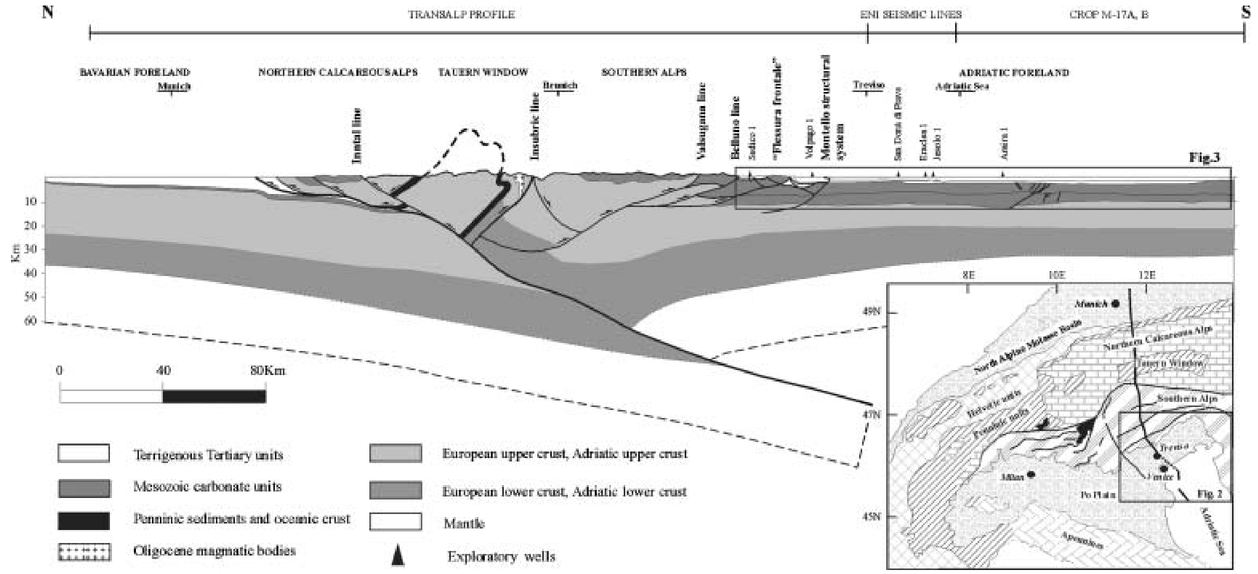

Fig. 1 Geological cross-section interpretation along the southernmost part of the TRANSALP profile (modified after TRANSALP Working Group, 2002) extended, to the south, by ENI seismic lines and CROP M-17A and B, interpreted and depth-converted in this work. The part of the geological section corresponding to the retro-foreland associated with the Southern Alps in the Venetian sector has been highlighted by a black square both in the inset map and along the section, and this is enlarged in Figs 2 and 3, respectively. In the inset map, the trace corresponding to the TRANSALP section is indicated by a continuous line, whereas dotted and dashed lines show ENI and CROP sections, respectively.

resulting model was quite poorly constrained and we now conclude that the topographic load due to the Southern Alps is the main driving mechanism for subsidence, and no subsurface loads have to be applied to explain the observed northward bending of the Adria plate.

Geological setting

During Tertiary time, three partly overlapping foreland basins, different

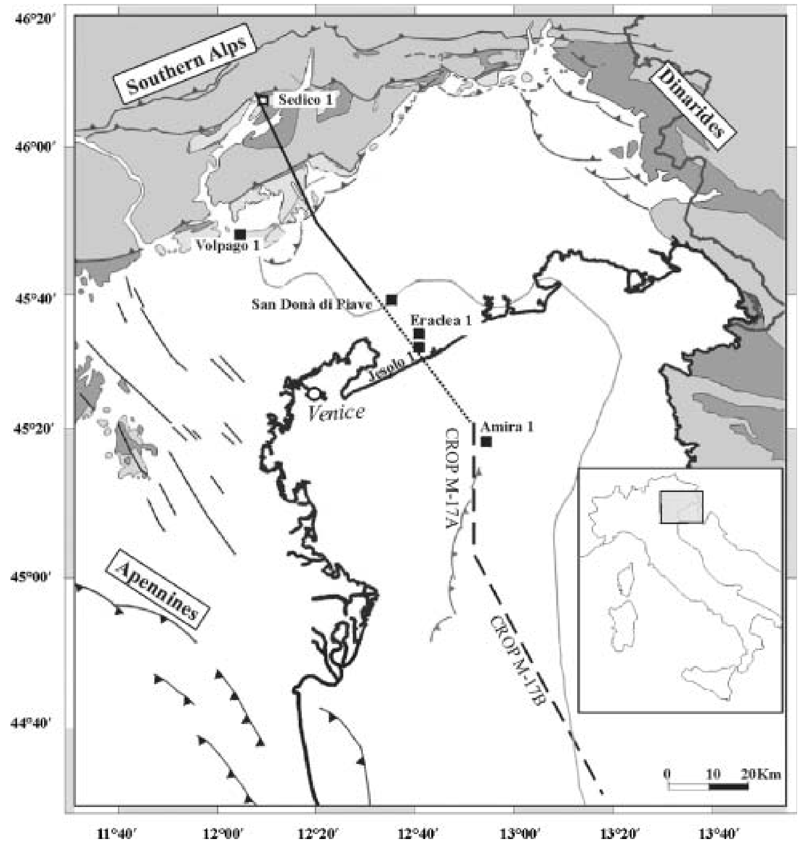

Fig. 2 Simplified tectonic map of the Venetian foredeep basin (NE Italy). The black solid line represents the southernmost part of the TRANSALP, the dotted line has been used for the ENI seismic lines and a dashed line for the trace of CROP-M17A and B, as reported by Finetti *et al.* (2001). The location of the seismic lines and wells used for calibration and depth conversion are reported; bathymetric analyses have been performed on Volpago 1, San Donà di Piave and Eraclea 1. The study area inherited a complex topography from Mesozoic time. The solid grey line represents the edge of the Mesozoic platform (to the east) and the adjacent basin progressively filled during the Palaeogene.

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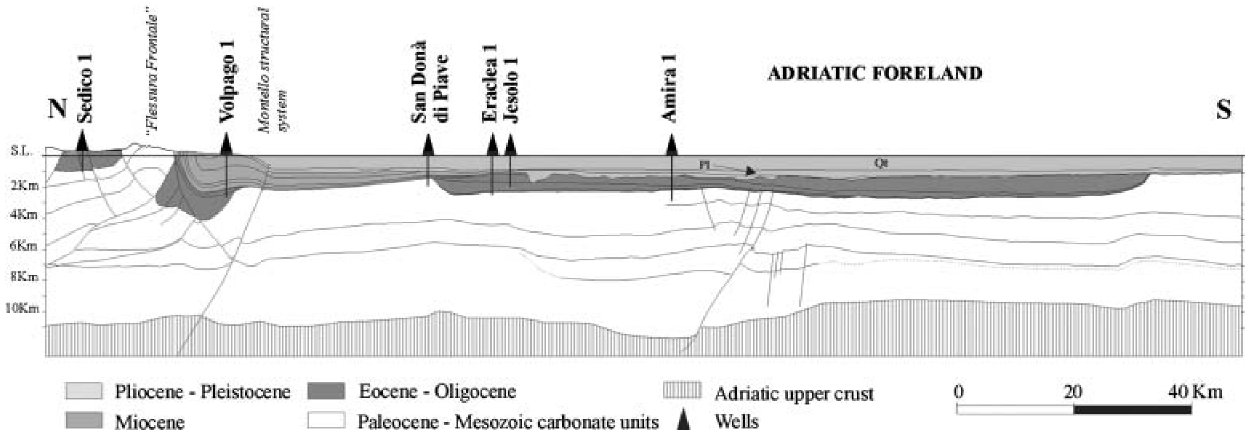

Fig. 3 Section consisting of the southernmost 66 km of the TRANSALP profile (Fig. 1) extended, to the south, by several industrial seismic transects (courtesy of ENI), for a total length of 210 km. The vertical scale is twice the horizontal scale. Eocene–Oligocene sediments represent the passive infill of the space inherited from Cretaceous time. During Serravallian–Tortonian time a northward-thickening wedge develops in front of the Southern Alps and rapidly thins southward, bending the top of the lower Miocene unit. The progressive infill of this wedge-shaped basin led to the deposition of Serravallian sediments limited to the area north of San Dona di Piave 1 well, whereas Tortonian deposits occur all along the section. The southern part of the section was strongly eroded during the Messinian sea-level fall. Pliocene (Pl) deposits thicken slightly to the north and fill the Messinian erosion to the south. Quaternary (Qt) sediments have a more or less constant thickness along section.

in both age and polarity, developed in the Venetian plain, as a consequence of the main orogenic phases of the Dinaric belt to the east, the Eastern Southern Alps to the north and the Apennines to the south-west (Fig. 2; e.g. Doglioni and Carminati, 2002). The Dinaric foredeep formed in the east during the Palaeocene – middle Eocene (Massari, 1990; Tunis and Venturini, 1992) as a result of flexure of a Mesozoic platform beneath the Dinaric thrusts, whereas the westernmost sector, crossed by the studied section, was characterized by the progressive infilling of a basin inherited from Cretaceous bordering the Mesozoic platform (Fantoni *et al.*, 2002a; Fig. 3).

The Southern Alps shortening had its maximum development during the middle – late Miocene (Castellarin and Cantelli, 2000) when a Southalpine foredeep formed, characterized by a northward-thickening wedge (Fig. 3). The accommodation space, recorded close to the mountain front during Serravallian time (Mellere *et al.*, 2000; Fig. 3), is filled mainly by the first massive appearance of extrabasinal carbonate grains produced by the erosion of the Southern Alps (Stefani, 1987). The Serravallian to Messinian sedimentary infill is characterized by a shallowing- and thickening-upward trend ending with continental conglomerates. Studies performed on these units (Massari *et al.*, 1993) revealed the occurrence of a still active tectonic setting responsible for frequent angular unconformities and a vertical change in composition that reflects the progressive unroofing of the chain.

The Southalpine foredeep did not grow significantly during Pliocene time, although a period of Southalpine deformation is recorded along the front of the Southern Alps (Bertelli *et al.*, 2002). By contrast, a Plio-Quaternary SW-merging foredeep developed, according to Fantoni *et al.* (2002a,b), in the south-westernmost part of the Venetian Basin due to the Apenninic main orogenic phases, although it has been recognized to extend further to the

Table 1 Values used for the best fit. The main density values have been considered for the foredeep sedimentary infill and the units constituting the mountain belt (Ebbing *et al.*, 2001, and references therein). The initial water depth values (in metres) have been inferred for the base of the Serravallian–Tortonian clastic wedge. A deepening trend, related to flexure, can be observed upsection. The northern edge of the basin (zero water depth conditions) is considered to correspond to the Valsugana line, which constitutes the more active line during the Serravallian–Tortonian. A progressive shallowing trend toward a forebulge structure is thought to occur south of the analysed zone

Input values in the best fit model	
Plate end boundary	164 km
Effective elastic thickness	20 km
Poisson's ratio	0.25
Young's modulus	7×10^{10} N m^{-2}
Water density	1000 kg m^{-3}
Sedimentary load	2450 kg m^{-3}
Sediments involved in the mountain range	2720 kg m^{-3}
Crust density	2800 kg m^{-3}
Mantle density	3300 kg m^{-3}
Vertical shear force	0 N m^{-1}
Bending moment	0 N
Wells used for bathymetric reconstruction	
N Volpago 1	400 ± 200 m
San Donà di Piave	400 ± 200 m
S Eraclea 1	200 ± 100 m

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Table 2 Velocities used for depth conversion of the studied seismic section. Values have been estimated from three wells located along section (Sedico 1, San Donà di Piave and Jesolo 1; for locations see Fig. 1) and from calibration of the intersection points with surrounding seismic transects. Well control suggests that depths are accurate to about 10 m at 1200 m depth and about 20 m at 2450 m

Interval	Velocity (m s^{-1})
Pleistocene	2000–2100
Lower Pliocene	2100–2300
Tortonian/Serravallian	2450
Burdigalian/Langhian	2450
Eocene/Palaeocene	3000
Mesozoic Units	5800–5900

north (e.g. Merlini *et al.*, 2002; Carminati *et al.*, 2003).

Method and model constraints

A 2D forward flexural model is applied here to study subsidence of the Venetian foredeep as related to the main tectonic phases of the Southern Alps and to quantify the mechanisms involved in the flexure. The applied numerical method is discussed in Zoetemeijer *et al.* (1990).

The reasons for choosing the studied NNW–SSE-trending section are two-fold. First, its orientation roughly parallel to the Apennines thrust front allows the geometries related to the Southalpine flexure to be highlighted and, vice versa, the control on flexural geometry by Plio-cene–Pleistocene Northern Apennines load to be disregarded, as it can be considered homogeneous along section and probably to be very minor (cf. Doglioni and Carminati, 2002; Doglioni, 2003). Secondly, numerous good quality data are available along this section both on the belt region (TRANSALP Project) and on the Venetian foreland basin (seismic data provided by ENI).

The input data required to calculate flexure concern the present mountain load, the initial water depth and the densities of the bodies involved in the system. Other parameters such as T_e, subsurface loads and plate end location are eventually entered and varied to improve the fit.

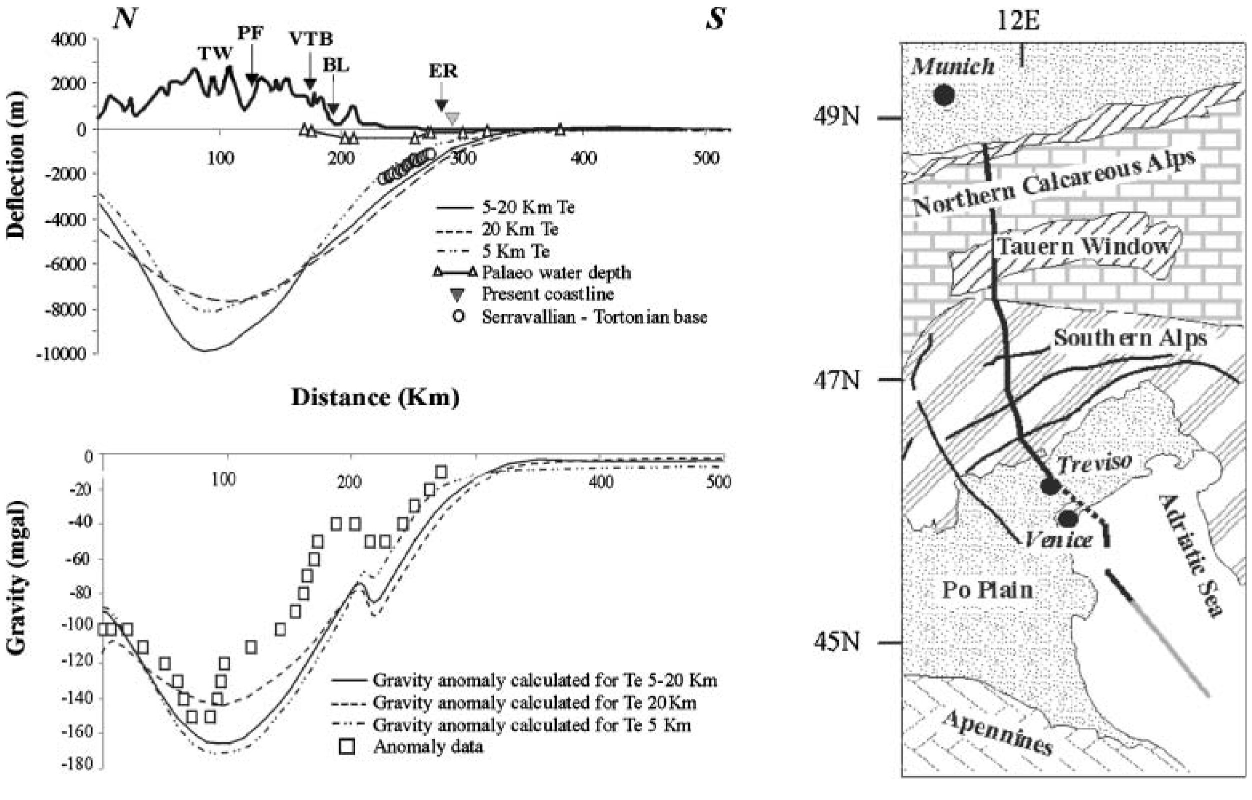

Fig. 4 Results of the modelling for a continuous plate condition. Two tests with a homogeneous T_e value corresponding to 5 and 20 km, respectively, have been carried out. The former corresponds to the value proposed by Braitenberg *et al.* (2002) for the T_e in the central part of the Alps, on the basis of gravimetric analyses. The latter is the value generally found for the best fit on the Adriatic plate (Royden, 1993; Buiter *et al.*, 1998; Kroon, 2002). In the third case, both values are considered, the former used in the northernmost part, and the latter to the south, the change occurring beneath the Dolomites. TWG, Tauern Window; PF, Periadriatic Fault; VTB, Valsugana Thrust belt; BL, Belluno Line; ER, Eraclea 1. The trace of the model (inset map) consists of the TRANSALP, of the interpreted and depth-converted seismic lines and of a further prolongation (about 100 km) to the south, in order to avoid errors due to boundary effects in the study area.

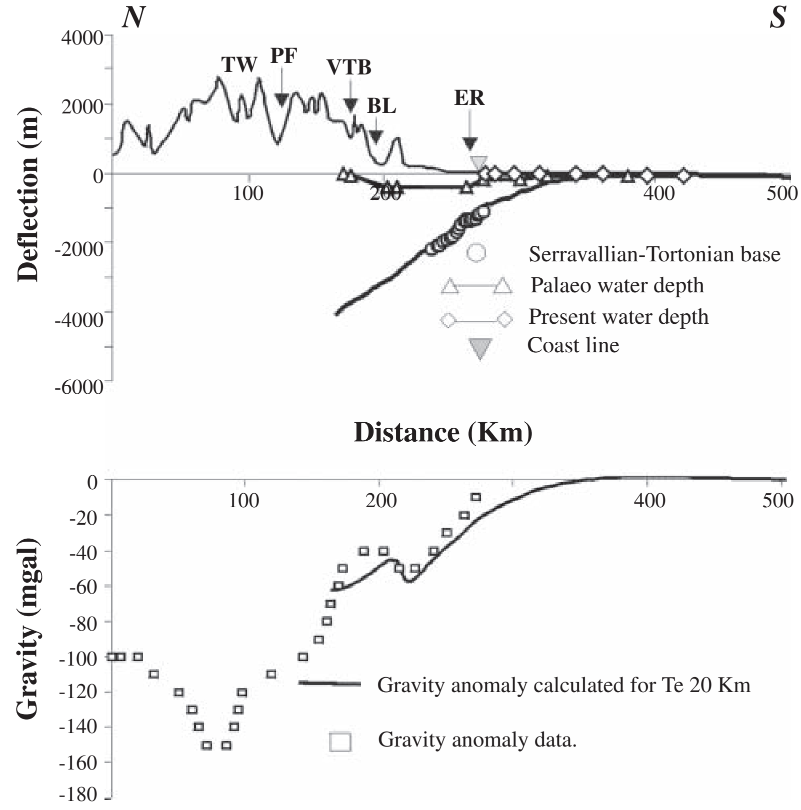

Fig. 5 Results for a broken plate condition. Flexural and gravimetric curves fitted to the geological data for a plate boundary located at 164 km, representing the position where the overthrusting plate is assumed no longer to load the underthrusting plate vertically. Such isostatic uncoupling does not exclude a physical continuation of the plate and a horizontal coupling. The trace of the model is shown in Fig. 4.

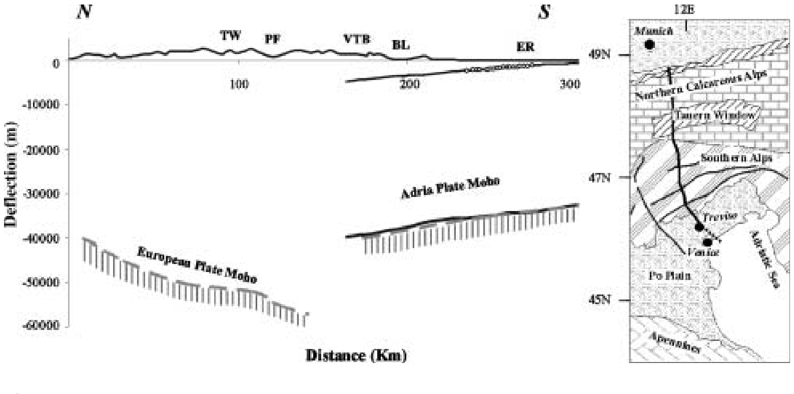

Fig. 6 Enlargement of the northern 300 km of the calculated best fit model (Fig. 5), showing the position of the Moho according to Scarascia and Cassinis (1997) and the Moho beneath the model calculated for the 164 km plate end (dashed and solid grey line, respectively). The location of this model is shown in the inset map. TWG, Tauern Window; PF, Periadriatic Fault; VTB, Valsugana Thrust belt; BL, Belluno Line; ER, Eraclea 1.

Bathymetric analyses, based on a study of the foraminifera content, have been carried out on cuttings recovered from three wells located along section (Volpago1, San Donà di Piave and Eraclea1, Figs 1 and 3), according to the method proposed by Mancin and Pirini (2002). Besides wedge geometries, bathymetric results provide good evidence of the beginning of the flexure due to the Southern Alps load because the Langhian overall neritic environment was abruptly replaced, during Serravallian–Tortonian time, by bathyal conditions in the northernmost area close to the belt front, whereas neritic conditions persisted further south (Table 1).

The calculated flexure is compared to the observed depth of the foredeep base, obtained by interpretation and depth conversion (Table 2) of a detailed 210-km-long seismic section provided by ENI (Fig. 3). This surface, Serravallian–Tortonian in age, has been identified to deepen northward with an angle of about 2° (Fig. 3), consistent with the value obtained by Mariotti and Doglioni (2000).

Unlike the late Miocene succession, the Pliocene–Quaternary sediments do not constitute a Southern Alps related wedge-shaped infill. In spite of this, the model is performed for the present, the contribution of the Plio-Quaternary infill is considered and the estimation of the mountain load is based on the present topography of the Alpine chain. This choice allows us to avoid speculations regarding belt topography at the end of the Pliocene, which is difficult to constrain and is not part of the aims of the present study.

This numerical method also allows us to calculate the gravity anomaly curve induced by the geometry of the crust–lithospheric mantle boundary. In the present work, the Moho depth has been traced taking into account the interpretation of Deep Seismic Soundings (DSS) data given by Scarascia and Cassinis (1997).

The calculated Bouguer gravity anomalies represent an independent control to test the validity of the flexural model; with this aim in mind, they are compared with those obtained by the gravity anomaly map of Scarascia and Cassinis (1997).

The first step in the simulations is focused on the choice between continuous or broken plate conditions to model the complex transition between the European and the Adriatic plate beneath the Dolomites. In lithosphere analyses, the broken plate assumption is related to the isostatic decoupling concept, which

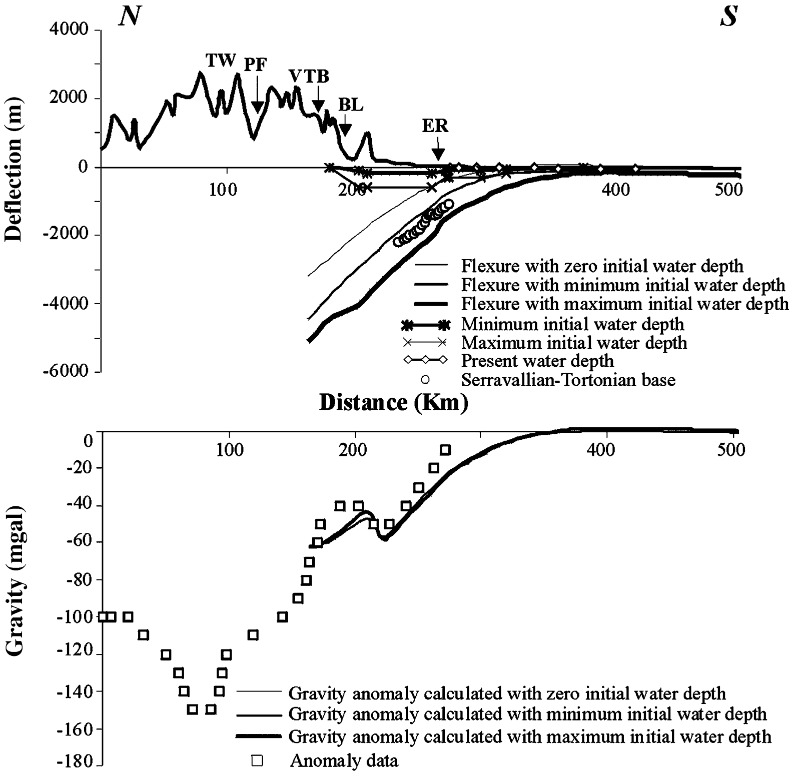

Fig. 7 Influence of the initial water depth component in the total flexure. Results show that the bathymetry contributes to about 50% of the total flexure. TWG, Tauern Window; PF, Periadriatic Fault; VTB, Valsugana Thrust belt; BL, Belluno Line; ER, Eraclea 1.

does not imply a real break between plates, because a strong decrease in T_e, from the foredeep to the innermost part of an orogen, can give similar results. Therefore, a broken plate condition should suggest a mechanical decoupling between the European and the Adriatic plate, although their physical continuation should not be excluded (Zoetemeijer *et al.*, 1999). In fact, horizontal (de)coupling is still possible, but horizontal forces are not modelled in the present work. Because good bathymetric data are available for the beginning of the flexure, further information on the influence of this parameter is tested to quantify its contribution as surface load. This constitutes an important point of the present work because this parameter has not been well constrained in most previous models (Kruse and Royden, 1994; Kroon, 2002). A further test on the sensitivity of T_e will be performed.

Best fit conditions and model sensitivity

Following the assumption of a continuous plate condition (Fig. 4) two tests have been carried out with homogeneous T_e values of 20 and 5 km, respectively, while a heterogeneous T_e, corresponding to 5 km beneath the alpine belt and 20 km in the adjacent foredeep, has been used for a third test. Flexural curves obtained for 5 and 5–20 km T_e values provide the best results even if they remain shallower and deeper than the observed surface, respectively, and, in addition, both models are not supported by a gravimetric fit. Therefore, the continuous plate configuration has been discarded and a broken plate condition has been tested (Fig. 5).

Assuming mechanical decoupling between the European and the Adria plate, a good fit can be observed for a fixed T_e value of 20 km and a plate boundary at 164 km (Fig. 5). This model is consistent with the TRANSALP working group (2002) results and the data of Scarascia and Cassinis (1997) and Lueschen *et al.* (2002), who locate the Adria plate end beneath the Dolomites, just north of the Valsugana thrust, which is the most important tectonic line of the Southern Alps (Fig. 6).

The calculated gravity curve fits the overall trend of Bouguer anomaly data, but short-wavelength local anomalies, such as the 'Belluno nose', are not reproduced.

Although a good fit occurs close to the mountain front, a forebulge located close to sea-level is predicted, to the south, from the model but this is not observed in the present Adriatic Sea. To the best of our knowledge, this structure could have existed during the Miocene, but the Pliocene westward flexure of the Adria plate, possibly due to the Apenninic load (e.g. Carminati *et al.*, 2003), should have allowed subsidence to flatten this gentle relief. As the influence of the Southern Alps load is here analysed in 2D, the 3D effect probably related to the Apenninic load cannot be analysed as well as the misfit occurring in the southernmost part of the gravimetric anomaly curve.

Tests on the sensitivity of the model to initial water depth have shown that the initial bathymetry is, together with the mountain load, the most important parameter determining subsidence in the adjacent foredeep (Fig. 7). Tests performed on the T_e value suggest that the acceptable range for this parameter is quite narrow (Fig. 8), as expected because of the strong constraints used in the present work.

Conclusions

The very good fit of the 2D crustal flexural model, together with the results of detailed interpretation and depth conversion of a 210-km-long seismic line and the observed gravimetric field, give new insight into the mechanical behaviour of the Southern Alps – Adriatic plate geodynamic system, on its tectonic evolution and, more generally, on the influence of some variables on the fit of models to reality.

The first point to be highlighted is that the flexural response of the

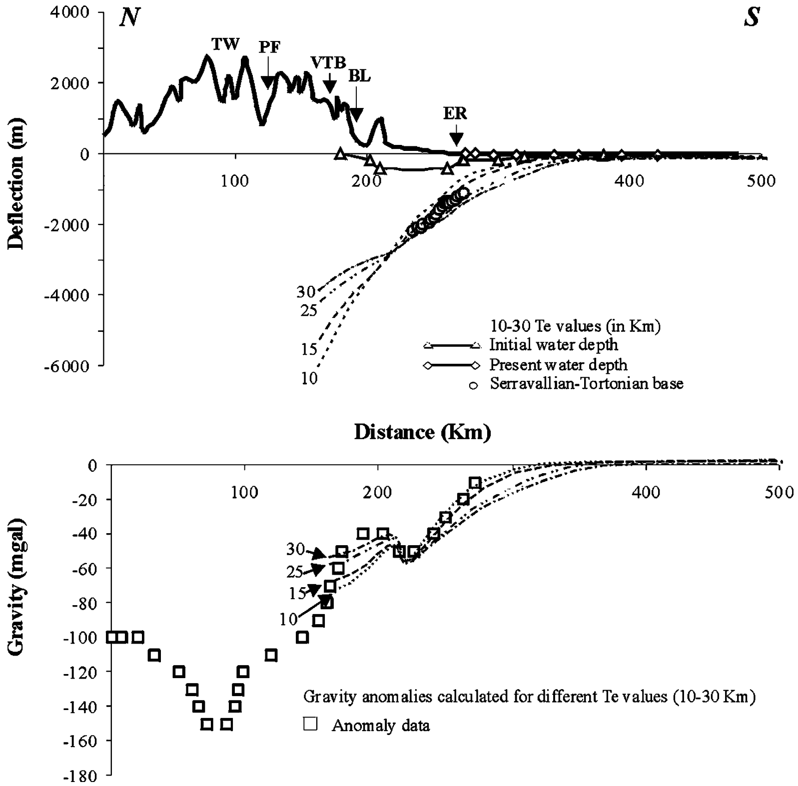

Fig. 8 Estimation of the influence of the T_e value. Values ranging from 10 to 30 km have been used to test the sensitivity of the model to T_e variations. Fit can be provided by a quite narrow range of T_e values (18–22 km) on both flexural and gravimetric anomaly curves. TWG, Tauern Window; PF, Periadriatic Fault; VTB, Valsugana Thrust belt; BL, Belluno Line; ER, Eraclea 1.

Adriatic crust to the Southern Alps load definitely reflects broken plate behaviour, as no satisfactory fit resulted with a continuous plate model. This means that, according to its flexural response, the Adriatic crust must be considered mechanically decoupled from the Southern Alps crust. Our results apparently contrast with the conclusions recently reported by Braitenberg *et al.* (2002) according to gravimetric data, even if the extremely small T_e of the crust predicted by them below the Southern Alps clearly approximate a broken plate configuration from a mechanical point of view.

The second point to be stressed is that the model requires a termination of the Adriatic plate located below the Dolomites. This conclusion fits well with recent results of deep seismics from the TRANSALP Project, which pointed to a clear Moho dislocation in the same region.

The last noteworthy point is that no subsurface loads can be assumed to explain the flexural response of the Adriatic crust to the Southern Alps topographic load, as a very good fit is obtained if the palaeowater depth of the reference stratigraphic unit is taken into account in addition to the topographic load. This is particularly relevant as the model used here proved to be extremely sensitive to the palaeobathymetric constraint, which conversely is quite poorly considered in many crustal models of collisional belt – foreland basin systems.

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