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Geometry and mechanical crustal properties in NE Italy based on seismic and gravity data

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Abstract. A mechanical model along two sections of the crust in the South Eastern (SE) Alpine area, which includes the values of density, P-wave velocity, and elastic parameters is presented. Two published seismic refraction profiles crossing the SE-Alpine belt are the basis for a gravimetric interpretation of the Bouguer anomalies, adopting the experimental relations which correlate the P-wave velocity of a sample to its density. The elastic parameters of the model are then calculated from the seismic velocities and the densities obtained from the gravimetric modelling, assuming the Poisson hypothesis. The velocity-density model allows conclusions to be drawn regarding the crustal lithology, if laboratory measurements of rock samples are taken for granted. We find that the partition into upper, middle and lower crust is in good agreement with the results obtained in the Central Alps. Knowledge of the mechanical and geometrical characteristics of the crustal structures is of great interest in studies of the time evolution of the deformational field in seismic areas and its interpretation in terms of the acting stress field.

1. Introduction

The Alpine belt marks a convergence zone between the European and African plates; and, in its eastern part, an important role is being played by the Adriatic promontory of the African plate (or Apulian microplate) (see Anderson and Jackson, 1987). This Euro-African collision causes the complexity of the lithospheric tectonic structures in the area. Geological data suggest that in NE-Italy crustal shortening has reduced NS lengths by up to 30%. The collisional event may also be traced in the deep structures and is responsible for the lithospheric thickening (for a review see Kissling, 1993).

The Alpine orogenesis is still active, as demonstrated by the high seismic activity present in the E-Alps. Part of the complexity of the SE-Alps derives from the interference between the

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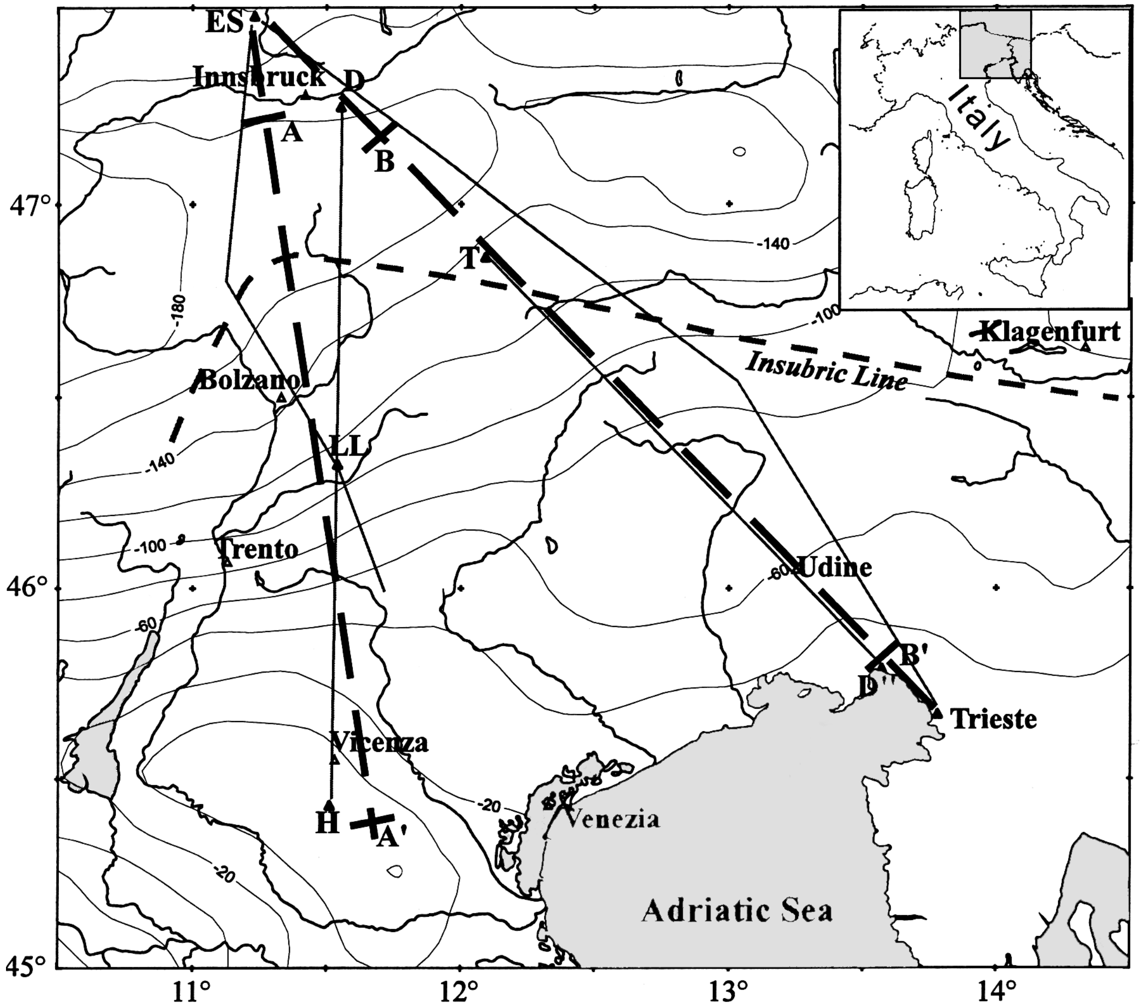

Fig. 1 - Gravimetric map of NE-Italy. Dashed lines: transverse seismic sections from Scarascia and Cassinis (1992) obtained by reprocessing of seismic profiles (solid lines) D”-T, H-D (IESG et al., 1981) and ES-TS, ES-LL (Giese and Prodehl, 1976). Sections A-A’, B-B’ are the profile traces of the gravimetric 2D modelling.

Alpine domain, with EW-oriented structures, and the Dinaric domain, oriented NW-SE (Barbano et al., 1985; Carulli et al., 1990; further references in Slejko et al., 1987). One problem in understanding the time evolution and processes which are responsible for the seismic activity, is the determination of the stress and strain field variations in the area. The Department of Earth Sciences of the Trieste University runs a tilt-strainmeter network, giving reliable data since 1977. From the analysis of the deformational records spanning the time interval of nearly two decades, interesting results regarding the directions of the deformation have emerged, revealing the superposition of a NS (Alpine compression) and a nearly EW-oriented long term deformation (Zadro and Rossi, 1991). The interpretation of the observed deformational rates in terms of the acting stress field requires knowledge of the local geometrical and mechanical crustal properties, which

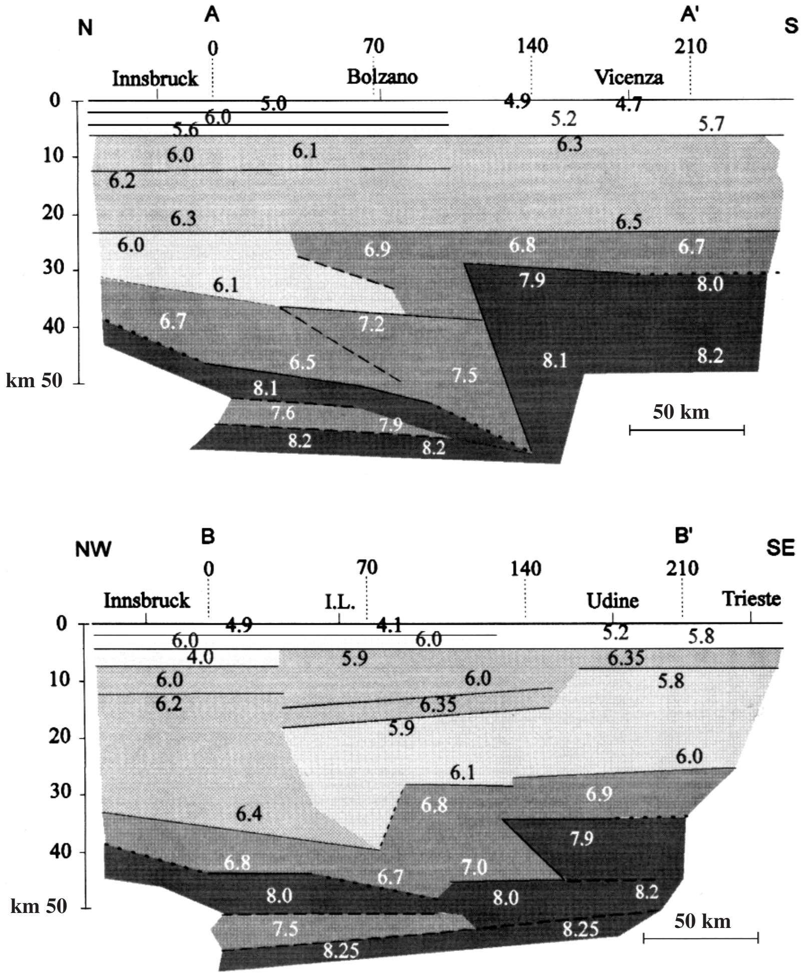

Fig. 2 - Transverse seismic sections modified after Scarascia and Cassinis (1992). A-A' and B-B' indicate extension of the gravimetric profiles of the present modelling. The *Vp* velocities are in km/s.

we obtain from the integration of seismic and gravitational data. The gravimetric modelling is accomplished along two profiles A-A' and B-B' (Fig. 1). These coincide with the two profiles presented by Scarascia and Cassinis (1992), who have reprocessed seismic sections obtained between 1960 (Giese and Prodehl, 1976) and 1978 (IESG et al., 1981) (Fig. 1). The integration of seismic and gravitational data in the SE-Alps has been approached previously, by Mueller and Talwani (1971), IESG et al. (1981) and Slejko et al. (1987).

The western N-S profile (A-A'), starts from the Austro-Italian border south of Innsbruck and reaches the Colli Euganei south of Padova, cross-cutting rocks of different ages and fabrics: Hercynian granitoids, the metamorphic basement (Hercynian and Pre-Hercynian), Permian volcanites, Jurassic and Cretaceous limestones, and Tertiary volcanites. The second profile (B-B'), running in a NW-SE direction, commences at the metamorphic basement cropping out towards the Austro-Italian border, cuts the Permo-Triassic units of the Carnic Alps and Prealps and the

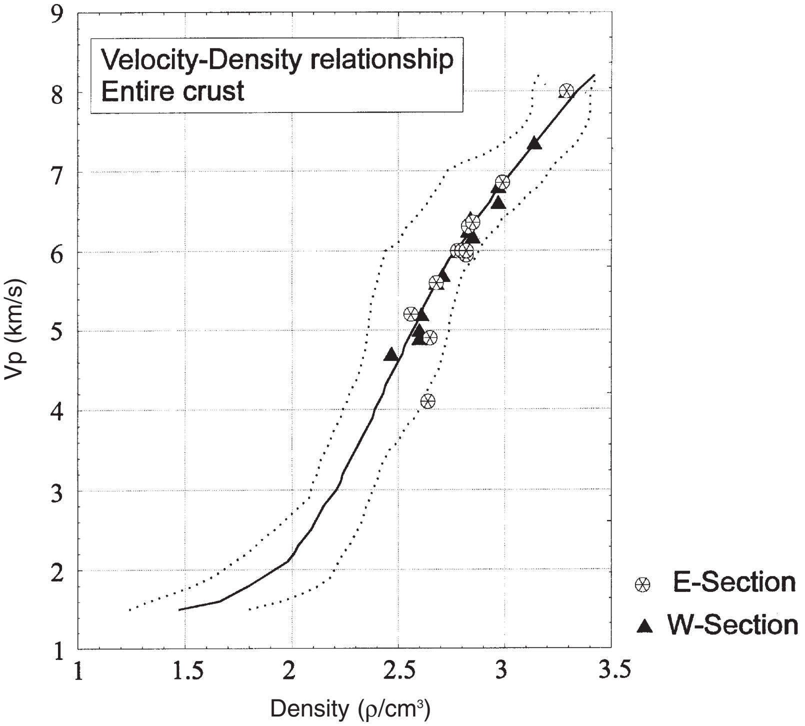

Fig. 3 - P-wave velocity (*Vp*) vs. density (ρ) diagram of the Nafe and Drake curves, compared to the values found in our model. Continuous lines show the mean (solid), maximum and minimum (dotted) Nafe and Drake curves (Barton, 1986). The single data points indicate the blocks in the western (triangles) and eastern sections (asteriscs).

sedimentary deposits of the Friuli plain, until it reaches the Jurassic-Cretaceous limestones near Trieste.

2. Methodology

The integration of the seismic and gravimetric data along the two profiles A-A' and B-B' was carried out by first considering the seismic section, to obtain constraints on the geometry of the crust, which was divided into a finite number of blocks. The two transverse seismic sections presented in Scarascia and Cassinis (1992) and crossing the Eastern Alpine belt in NS and NW-SE directions, are shown in Fig. 2. Only those parts of the seismic sections for which the Moho was well defined were used, so the gravimetric sections have shorter extension.

The seismic data furnish good constraints for the 2D gravity modelling - the seismic and the gravimetric section chosen to coincide - as they provide the depths to velocity discontinuities, which are likely to also reflect density discontinuities. The particular value of the corresponding density (ρ) may be obtained from the empirical relationships between seismic P-wave velocity (*Vp*) and density obtained from field and laboratory measurements (Ludwig et al., 1970;

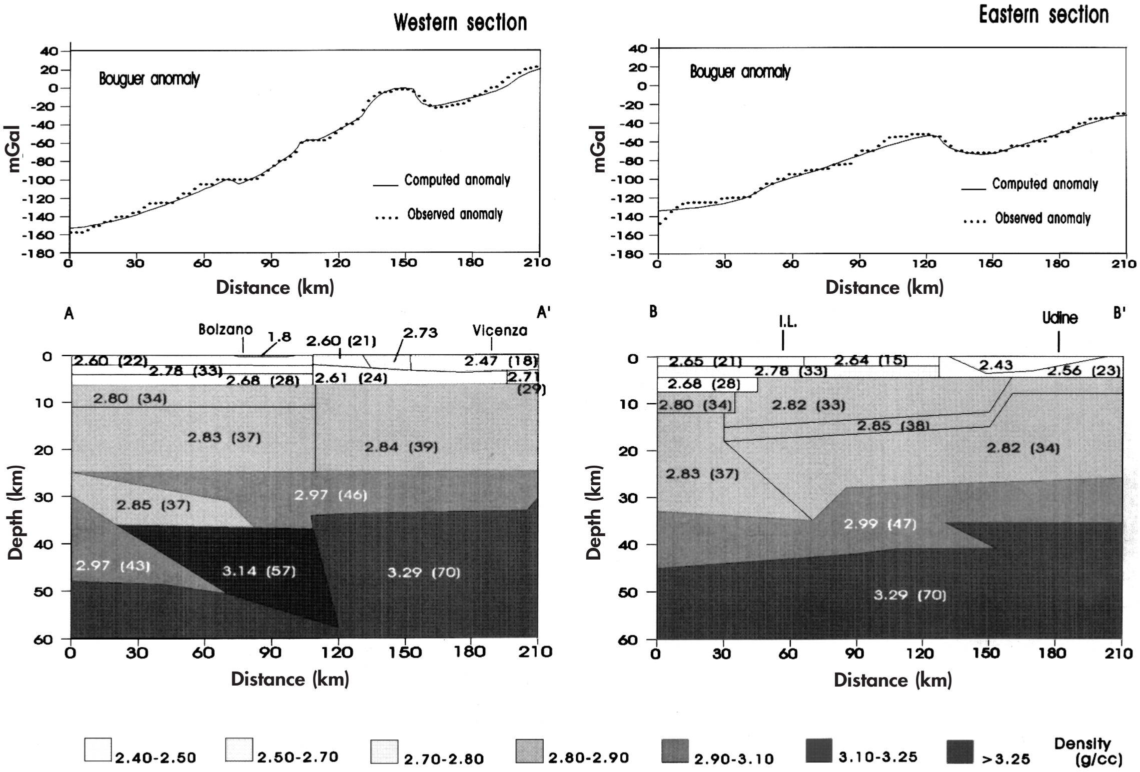

Fig. 4 - Mechanical model (density in g/cm^3, and rigidity in GPa (in parentheses)) and observed and calculated Bouguer anomalies of the western section A-A' and of the eastern section B-B'; I.L. = Insubric Line).

Woollard, 1975; Barton, 1986). Although this method has been frequently applied (e.g., Klingelé et al., 1990), its shortcomings should, however, be borne in mind (Mengel and Kern, 1992). The value of the density value for a certain P-wave velocity has error bounds of about ±0.25 g/cm^3, inherent in the above empirical relationships (Fig. 3), and must therefore be checked by gravity modelling. Furthermore, the sensitivity of density to velocity in the *Vp* range between 3 and 6 km/s is rather low, and results in values ranging between 2.2 and 2.8 g/cm^3. In our study we have used the mean values of Nafe and Drake, tabulated in Barton (1986), to obtain the starting values for the density model (2D Talwani algorithm; Talwani et al., 1959). Subsequently, an interactive optimization procedure for the model is applied, where the density values are allowed to vary in order to obtain a minimization of the gravity residual.

3. Gravity modelling of mechanical properties

A 2D gravity modelling was carried out along the above-mentioned profiles. Prior to the interpretation of the seismic sections in terms of densities, some general rules were set up pertaining to the gravimetric modelling: a) in the process of model optimization, the geometry defined by the seismic interfaces was generally not varied, except when explicitly specified, and where geological evidence made changes necessary. In cases where in the original seismic model the interface was hypothetic or dubious, the gravity data were used to ascertain the structure; b) inside a seismically identified stratum, the velocity gradient was replaced by an average velocity value; c) the lamination of the crust-mantle boundary, characterized by the alternation of slow and fast velocity channels, was replaced by a single fundamental Moho boundary. The first reason for this is that lamination, seated below 50 km depth, cannot possibly be resolved by gravimetric methods. The second is that lamination has been hypothesized, but not verified along the two profiles.

In computing the theoretical Bouguer anomalies of our crustal structure, we adopted a one-layered reference crust of density $\rho = 2.83$ g/cm^3, and thickness $d = 35$ km, which overlies the mantle of $\rho = 3.29$ g/cm^3. Except for eventual border effects, the use of a one- or multilayer reference crust in the anomaly calculations has no effect on the final anomaly values, as long as the density of the one-layer reference crust is chosen so as to produce the same constant gravity value as the multilayer crust. For instance, an equivalent three-layer reference crust would be composed of an 8 km thick upper crust of density $\rho_1 = 2.83$ g/cm^3, a 14 km thick middle crust of density $\rho_2 = 2.80$ g/cm^3, and a lower crust of 12 km thickness and density $\rho_3 = 2.95$ g/cm^3. A different assignment of the reference crustal column will create an up- or downward shift of the calculated anomaly curve. The gravity Bouguer values refer to the Italian Gravimetric Map by Carrozzo et al. (1986), which were adjusted in the north to the data of the Austrian Gravimetric Map of Senftl (1965). The elastic parameters of the crustal sections were then obtained according to the Poisson hypothesis, by setting the Lamé parameters, $\lambda = \mu = 1/3\ \rho\ Vp^2$, ρ being the density and Vp the P-wave velocity of each crustal block. Below we give a detailed description of the results obtained for the two sections.

The maximum average depth of the Moho in the western section reaches 57 km. In the southernmost part of the section we have accounted for a Moho high beneath the Colli Euganei, which has been hypothesized by various authors (e.g., Nicolich and Dal Piaz, 1990). Scarascia and Cassinis (1992) propose a fragmentation of the Moho in this area, which is not resolved by seismic sounding as it falls beneath the southern extremity of the profile. In Fig. 4 the gravitational model and the observed and calculated gravity values are graphed. The values in parentheses, shown on the gravity model, are the rigidity values (μ) of each block, obtained under the Poisson's assumption. Deviation of the calculated gravity from the observed gravity values is small overall. At the surface, the gravity modelling requires one superficial higher density body north of Vicenza, which corresponds to the presence of Tertiary volcanic rocks reported in the Structural Map of North Eastern Italy included in Slejko et al. (1987). Furthermore south of Bolzano a superficial low density body was required, which is in the vicinity of the alluvium of the Adige river.

The gravity modelling along the eastern section required other information in addition to the seismic profiles, in order to obtain an acceptable fit with the observed gravity data. In particular, the sediments of the Friuli plain (triangular superficial inlay centered at a distance of 150 km from its NW end), not resolved by deep seismic sounding but important for their gravitational effect, were inserted following the model of Cati et al. (1987). Geologically this wedge represents the maximum thickening of the Miocene-Paleogene sediments. In Fig. 4 the density model

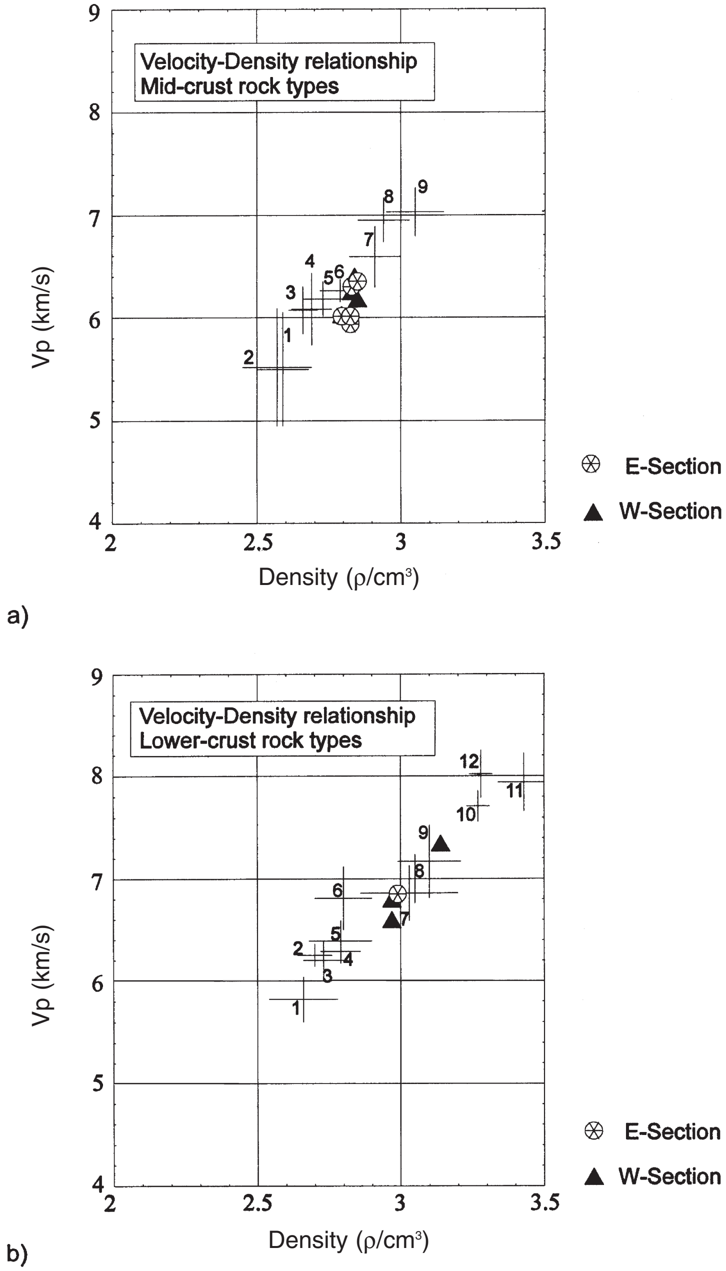

Fig. 5 - P-wave velocity vs. density from laboratory measurements (Holbrook et al., 1992) for different classes of rock-types; width of each cross equals two standard deviations. Triangles and stars refer to the W-section and E-section of our model, respectively. a) mid-crust. Class 1 - Serpentinite, 2 - Quartzite, 3 - Granite, 4 - Granodiorite, 5 - Felsic amph. facies gneiss, 6 - Quartz-mica Schist, 7 - Metagabbro (Greenschist), 8 - Gabbro, 9 - Amphibolite. b) Lower crust. Class 1 - Quartzite (Granulite), 2 - Felsic Amphib. gneiss, 3 - Felsic granulite, 4 - Quartz-mica schist, 5 - Intermediate granulite, 6 - Anorthosite, 7 - Mafic granulite, 8 - Amphibolite, 9 - Metapelite (Granulite), 10 - Pyroxenite, 11 - Eclogite, 12 - Dunite/Peridotite.

Table 1 - Densities given by Schwendener and Mueller (1990) and Holliger and Kissling (1992) for the upper, middle and lower crust and upper mantle in the Central Alps; ranges of density and rigidity obtained in the present paper for the SE-Alps.

	Schwendener and Mueller (1990) density [g/cm^3]	Holliger and Kissling (1992) density [g/cm^3]	Present paper density [g/cm^3]	Present paper rigidity [GPa]
Upper crust	2.73	2.70	2.6-2.8	15-33
Mid-crust	2.89	2.80	2.80-2.85	34-39
Lower crust	2.96	2.95	2.95-3.00	43-47
Upper mantle	3.34	3.25	3.29	70

and the observed and calculated Bouguer anomalies are drawn. The overall good agreement between the observed and calculated data is apparent. No rigidity values could be calculated for the block representing the Friuli plain sediments (Eastern section), as no P-wave velocity could be identified in the seismic sounding model.

The different blocks of the mid crust in both the eastern and western section, identified by the seismic method, are not confirmed by the gravity modelling, due to the small density difference found. In order to compare the density values used by us with the mean Nafe and Drake curve, in Fig. 3 the values of Vp are plotted against density values for each block of the model, together with the mean, maximum and minimum Nafe and Drake curves (Barton, 1986) for the western and eastern sections. The only block for which the velocity and density values differ considerably from the mean Nafe and Drake curves is a superficial block in the eastern section. The density we obtain from gravity ($\rho = 2.64$ g/cm^3) is near the value found in the northern part of the section, whereas the block has a relatively low velocity ($Vp = 4.1$ km/s) in the seismic model.

4. Discussion and conclusion

We have succeeded in modelling the mechanical properties along two 2D skew profiles cross-cutting the seismically active SE-Alps region and extending over a length of 200 km, while reaching a depth of 60 km. The model was calculated from the integrated analysis of two seismic refraction and gravity profiles. The small gravity residuals obtained in the modelling show that the two sets of geophysical data are in good overall agreement for both sections, assuming two-dimensional structures. The good agreement of the P-wave velocity vs. density values of our model with the mean Nafe and Drake curve shows the adequacy of the latter empirical curve in the SE-Alps.

The mechanical model we obtained for the crust indicates that the 3-layer crustal partitioning proposed for the Central Alps may also be appropriate for the SE-Alps. In Table I the densities used by Schwendener and Mueller (1990) and Holliger and Kissling (1992) for the upper, middle and lower crust, and upper mantle in the Central Alps are listed; also listed are the values we obtained for density and rigidity, and it can be seen that the densities calculated in the two areas compare well.

It would be of great interest to discuss our mechanical model in terms of crustal lithology, making use of the laboratory measurements of rock samples. One problem is the effects of pressure and temperature on velocity and density, which must be accounted for. This has been accomplished by the compilation of laboratory-measured physical properties (among which P-wave velocity, density and Poisson's ratio) of possible mid- and lower-crustal rock types, published by Holbrook et al. (1992). The compositions range from felsic to ultramafic and metamorphic grades up to granulite and eclogite facies. The middle crustal rock types are divided into 9 classes, and the lower crustal types into 12 classes, as may be seen in Figs. 5a and 5b, where the P-wave velocity Vp is plotted versus density for each class. We have added the field-determined Vp versus density values of the mid- and lower crustal blocks of our model: although some superposition among the rock-type classes does occur, it is possible to identify those classes which are compatible with the field values. We find that the middle crust (Fig. 5a) could consist of gneiss, schist and greenschist, whereas in the lower crust (Fig. 5b) we find magmatic and metapelitic rocks in amphibolite-granulite facies as probable constituents.

In calculating the elastic model of the crust, we have imposed Poisson's assumption, which implies that the Poisson's ratio σ is 0.25. Laboratory measurements support this assumption for the mid-crustal blocks, as for rock types 5, 6, 7 (Fig. 5a) Holbrook et al. (1992) give Poisson's ratios equal to 0.25, 0.26, and 0.27, respectively. Slightly larger ratios are expected for the lower crustal blocks, where for classes 7, 8, 9 (Fig. 5b), the laboratory measured values $\sigma = 0.31$, 0.29, and 0.27 are given, respectively. The deviation from Poisson's assumption in the lower crust would imply a correction in the rigidity values of our model, leading to a reduction of about 15-20%.

In conclusion, we emphasize that our mechanical model can provide the basis for a quantitative evaluation and modelling of deformational processes in the area. Furthermore in petrological studies concerned with the composition of the crust, knowledge of the physical parameters of density and rigidity may also set constraints on the compositional variability of the crust.

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