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New gravity maps of the Eastern Alps and significance for the crustal structures

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Abstract

The deep seismic profile TRANSALP crosses, from north to south, Germany, Austria and Italy. The gravity measurements for each country were made by national agencies with different reference systems and data reduction methods. Within the frame of the TRANSALP-project a comprehensive database of the Eastern Alps was compiled covering an area of 3.5° by 4° in longitude and latitude (275 by 445 km), respectively. To increase the data coverage in the south Alpine area two gravity surveys were carried out, resulting in 469 areally distributed new stations, of which 215 have been measured with the intent to improve the geoid in the area of the planned Brenner Basistunnel (BBT). The resulting gravity database is the best in terms of resolution and data quality presently available for the Eastern Alps. Here the free air, Bouguer and isostatic gravity fields are critically discussed. The spatial density of existing gravity stations in the three countries is discussed. On the Italian side of the Alps the spatial density is rather sparse compared to the Austrian side. The Bouguer-gravity field varies between $-190*10^{-5}$ m/s^2 and $+25*10^{-5}$ m/s^2, with the minimum located along the Alpine high topographic chain, but with a small offset (a few tens of km) to the greatest topographic elevation, showing that the Airy-type local isostatic equilibrium does not fully apply here. The maximum of the Bouguer anomaly has an elongated shape of 100 by 50 km located between the towns of Verona and Vicenza and covers the Venetian Tertiary Volcanic Province (VTVP), a feature not directly related to the plate collision in the Eastern Alps. The gravity high is only partly explainable by high-density magmatic rocks and requires also a deeper source, like a shallowing of the Moho. The isostatic residual anomalies (Airy model) are in the range $\pm 50*10^{-5}$ m/s^2, with the greatest positive anomaly corresponding to the location of the

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VTVP, indicating here under-compensation of masses. At last a discussion of a 2D density model based on reflection seismic data and receiver functions is made.

Keywords: TRANSALP; Eastern Alps; Free air; Bouguer; Isostatic anomaly

1. Introduction

During recent decades, quantitative interpretation of the gravity field of the Eastern Alps has been conducted only with respect to regional aspects. Due to sparse reflection and refraction seismic data in the Eastern Alps and because gravity data sets have been only available with a maximum spacing of 10 km, no detailed analysis of crustal structures was possible. Mainly 2-dimensional (2D) modelling along gravity profiles, crossing the Eastern Alps was performed by Makris (1971), Behle et al. (1972), Ehrismann et al. (1973, 1976), Schöler (1976) and Götze et al. (1976, 1978, 1979). Important 3D modelling results of the entire central part of the Eastern Alps were first published by Götze (1984), who re-interpreted former 2D models using powerful interactive 3D modelling tools (Götze and Lahmeyer, 1988). A detailed interpretation of the nappe structure adjoining the Tauern Window in SE was published by Ruess (1980). Delleske (1993) has investigated the Northern Calcareous Alps in Tyrol in more detail.

The aim of the TRANSALP project was to gain a better insight into the complex structure of the Eastern Alps, especially the transition from the basins in the north and south to the mountain chain and the contact zone of the European and Adria tectonic plates. The gravity field analysis is an important tool to evaluate the seismic interpretation and to extend the seismic reconstruction of the crustal structures laterally for 3D and isostatic modelling along the TRANSALP transect.

As the larger percentage of the presently available gravity data are acquired and kept by the national agencies of the three involved countries (Germany, Austria and Italy), a major effort was necessary to build a comprehensive gravity data set that would cover the entire profile on a swath about 250 km wide. This data set provided the basis for the most recent 3D density modelling of the lithospheric structure in the Eastern Alps and for investigating the isostatic conditions (Ebbing et al., 2001; Braitenberg et al., 2002; Ebbing, 2004; Ebbing et al., 2005—this volume). In the present paper we give a description of the data compilation combining existing and new gravity stations, and we present the free air, Bouguer and isostatic gravity fields and discuss their main properties.

2. The TRANSALP gravity database

In the following an account of the origin of the different data sets produced by the agencies of the three countries is given. The position of the gravity stations building up the TRANSALP gravity database is shown in Fig. 1.

2.1. Existing gravity stations

The gravity data of the German part were furnished by GGA, the Leibniz Institute for Applied Geosciences (Hannover), and amount to roughly 6400 stations. The distribution density is one station every 5 km^2 close to the Austrian borders, decreasing to one every 20 km^2 farther to the north. The terrain correction was calculated to a maximum radius of 23.5 km (Plaumann, 1990; Schleusener, 1953), but the radius used was different for the different gravity surveys. Because the stations' elevations do not exhibit marked variations, the terrain correction has not been extended to a radius of 167 km.

The German data were acquired during the past 7 decades (Plaumann, 1995) and are documented in many unpublished reports. The first regional gravity measurements were part of the geophysical survey of the former German Empire starting in 1934. They were performed by the SEISMOS Company (Hannover) using Thyssen and Askania gravimeters. The distribution of gravity stations varies regionally; at least 6 to 12 gravity stations were occupied in an area of about 120 km^2. From 1945 onwards, the Amt für Bodenforschung, and then the Geowissenschaftliche Gemeinschaftsaufgaben (Department of the geological survey of Lower Saxony), in co-operation with the geological surveys of Bavaria and Baden-Württemberg, carried out additional surveys. Depending on the aim of the survey at least 20 to 25 gravity stations were established in an area of about 120 km^2; in some parts the coverage is significantly higher. Askania, Worden, Canadian-Scintrex and LaCoste and Romberg gravimeters were used. The geophysical institutes of the universities of Clausthal-Zellerfeld, Kiel,

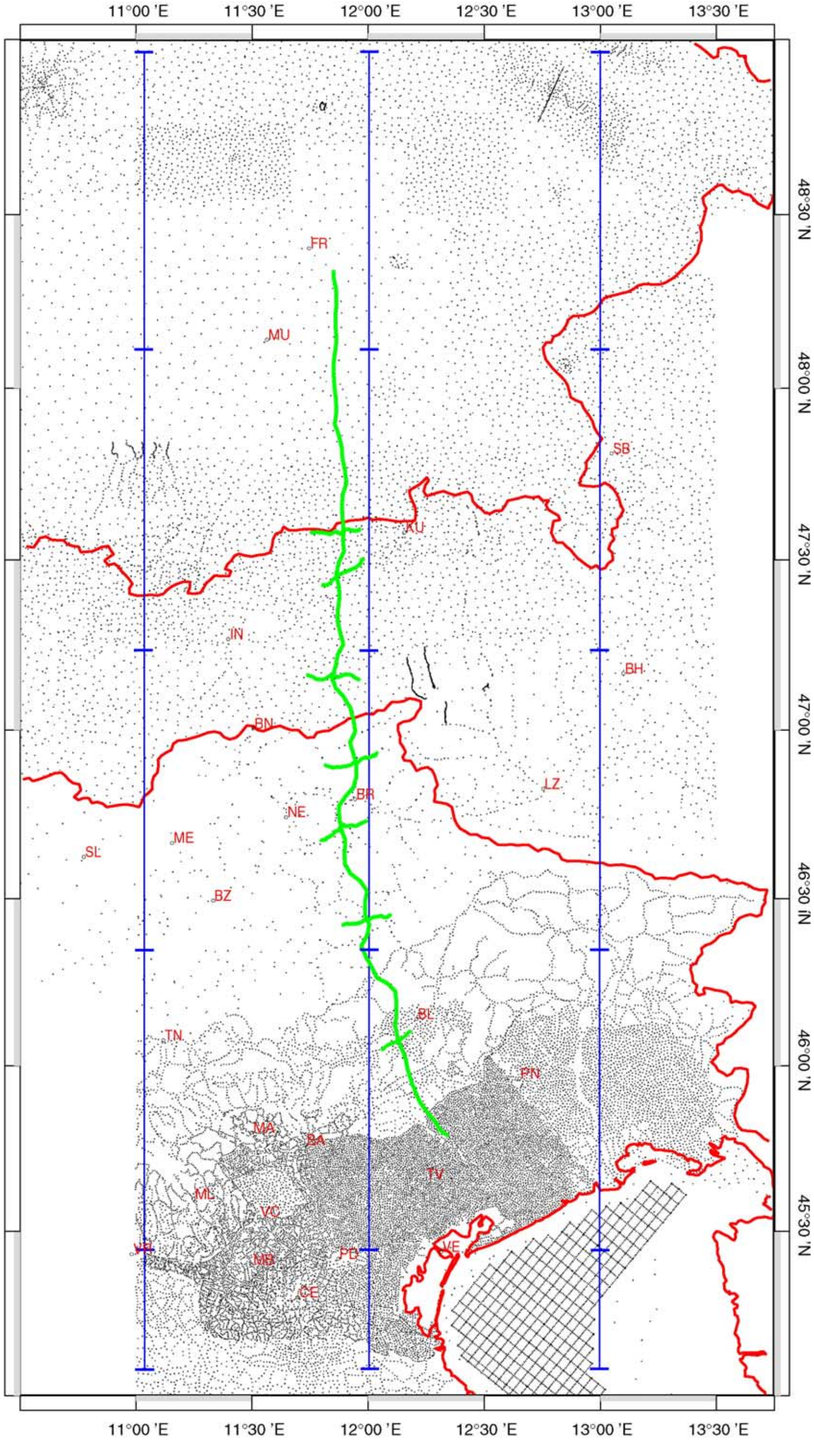

Fig. 1. Gravity stations contributing to the TRANSALP gravity database. The position of three profiles used in Fig. 7 is also shown. For abbreviations see Fig. 2.

and Mainz performed detailed gravity surveys in the vicinity of the Nördlinger Ries (Jung et al., 1965; Jung and Schaaf, 1967). All surveys were tied to local gravity networks, which were later connected to the German Gravity Network of 1962 (DGSN 62) by additional and repeated measurements. Conversion to the IGSN71 was achieved by applying a formula published by Doergé et al. (1977).

The University of Vienna made available the gravity data of Austria (roughly 4700 points). The data were acquired during the past 40 years. Initially gravity stations were installed mainly along levelling lines due to limited accessibility and the lack of stations in rugged mountainous terrain. Senftl (1963, 1965) published the first Bouguer gravity map of Austria based on this information in 1965. However, stations in the accessible parts are often situated within regions of very local anomalies, for example due to the gravity effect of sedimentary valley fillings. To achieve more detailed information about the structure of the Alpine crust a few cross sections were surveyed during the late 1960s and 1970s along NS trending profiles (Ehrismann et al., 1969, 1973, 1976; Götze et al., 1978). As interpolated gravity values do not correctly reproduce important features of the Bouguer gravity, the resulting station pattern permitted 3D interpretation only to a limited extent. Variation of up to $\pm 10 * 10^{-5}$ m/s^2 can occur in the Bouguer anomaly pattern when stations are arranged along profiles only (e.g. Steinhauser et al., 1990). Therefore, gravity stations should be distributed evenly, especially over mountain flanks and tops. This has only become possible due to remarkable changes in measuring techniques and reduction procedures. The first areal investigations were carried out during the 1970s along the Gravimetric Alpine Traverse (Meurers et al., 1987) and by the gravimetric research group of the Technical University of Clausthal (Germany) in the adjoining central part of the Eastern Alps (e.g. Götze et al., 1979; Schmidt, 1985). The Mining University of Leoben (Posch and Walach, 1989) investigated the western-most part of Austria. The Calcareous Alps are mainly covered by industrial data (Zych, 1988). A selection of this data set has been contributed for scientific purposes by OMV (Österreichische Mineralölverwaltung). Nevertheless, some gaps still remained especially along the crest of the Eastern Alps. Therefore additional gravity investigations in the Alpine area of Tyrol were made since 1990 in cooperation of the Institute of Meteorology and Geophysics (University of Vienna), the Central Institute for Meteorology and Geodynamics (Vienna) and the Department of Physical Geodesy of TU Graz. GPS techniques and helicopter transportation in otherwise inaccessible mountainous regions were applied in the course of these supplementary measurements. Presently in most areas the maximum station interval is about 3 km or less, resulting in an average station density of 1 station every 9 km^2 or higher, as for the area of special interest for interpreting the gravity field along the corridor centred on the TRANSALP transect.

The data set available along the TRANSALP transect in Austria is quite inhomogeneous, because it consists of contributions from different institutions and agencies acquired in the past four decades. Therefore reprocessing was required to obtain high quality gravity maps. Reprocessing involved especially the basic equations and the geodetic reference system used for calculating the Bouguer gravity, as well as the mass correction procedures. The Bouguer anomaly was re-calculated using the following common assumptions (Meurers, 1992):

- Geodetic Reference System 1980 (Moritz, 1984).
- Absolute gravity datum (Ruess and Gold, 1996).
- Closed expression for the gravity of the normal ellipsoid.
- Height correction by a Taylor series expansion of normal gravity up to 2nd order in geometric flattening and height (Wenzel, 1985).
- Atmospheric correction (Wenzel, 1985).
- Spherical mass correction up to 167 km radius (Hayford zone O_2) assuming a constant density of 2670 kg/m^3. This value is close to the mean density of the surface rocks in the investigated area.
- All calculations are based on an orthometric height system referred to the Adriatic Sea level.

A new digital terrain model developed at the Federal Office of Surveying of Austria (BEV) covers the entire Austrian territory with a resolution of 50 m even in areas of rugged topography. It enables the introduction of more exact and more economic procedures for calculating high precision mass corrections (Meurers et al., 2001). Flat-topped rectangular prisms represent the topographic mass in the distant zones (>1 km), while in the station vicinity the topography is approximated by arbitrary polyhedral surfaces that define the upper boundary of homogeneous prisms extending down to the reference level. The corresponding gravity effect at the stations is calculated analytically (Götze and Lahmeyer, 1988).

For the Italian part of the database ENI-E&P Division provided the TRANSALP Project with 22,300 points, each were furnished with a terrain correction up to 21 km radius. The distribution density of the stations in the foreland area was 2 stations per one km^2. It decreases to one station every 4 km^2 in the mountain belt bordering the plain, and in the high mountains area is as low as one station every 40–50 km^2. Most of the latter data where measured (NATO surveys of the late seventies) with a Worden gravity meter, with coordinates and elevations read directly from topographic maps. The Italian data have been partly published previously as Bouguer anomaly maps in Ballarin et al. (1972), Cassano and Maino (1989), and Carrozzo et al. (1991). A problem with respect to the remainder Bouguer gravity data is that the reduction density for the calculation of the Bouguer correction had been 2400 kg/m^3, therefore a complete recalculation of the topographic correction had to be made (see below).

Due to the inadequate distribution of gravity stations along the TRANSALP transect on the Italian side of the Alps, the TRANSALP Steering and Technical Committees decided to execute a gravity survey along the TRANSALP traverse and in the neighbouring valleys in the mountain area from the Austrian border to the town of Agordo. A complementary gravity survey was assigned also by the BBT within the framework of geodetic, geological and geophysical feasibility studies for a proposed 56 km long railway tunnel connecting Italy and Austria, between Franzensfeste and Innsbruck. An agreement, signed between TRANSALP and BBT, permitted the exchange of the gravity data. Thus 469 new stations were gained in the Italian mountain area.

2.2. Gravity surveys

BBT assigned the Federal Office of Surveying of Austria (BEV) to establish a set of seven absolute gravity sites in the Trentino-Alto Adige Region. The measurements were carried out with a free fall absolute gravity meter JILAG-6 (e.g. Ruess and Gold, 1996) and the results of the absolute gravity measurements are listed in Table 1.

A second assignment was made to the Istituto Nazionale di Oceanografia e di Geofisica Sperimentale (OGS, Trieste, Italy) to carry out a gravity survey for the computation of geoid undulations in the tunnel region. OGS measured 215 stations during September–October 2001. The data were collected mainly along the valleys and the distance between the gravity stations were 1.5 to 3 km according to the BBT requirements. The BBT station points, part of the Bolzano Province GPS network, had previously been geodetically measured and the staff of the geodetic team of the Bolzano Province had placed monuments. The topographic relief was completely flat between 0 and 2 m for each station, and an inner terrain correction, from 2 to 20 m has been computed according to a conic prism model with a uniform slope (Olivier and Simard, 1981).

For another survey commissioned to OGS by the TRANSALP Project 254 gravity stations were occupied in the period form November to December 2001, using the same field procedures as adopted in the BBT survey (gravimeters LaCoste and Romberg mod. G and D, DGPS positioning). The station interval was between 1 and 2 km.

In the Trentino-Alto Adige area the gravity loops started at the absolute sites of Bruneck or Neustift (Table. 1) and were closed at another absolute site or at a station belonging to the BBT gravity survey. In the Veneto area the loops started and terminated at previously occupied stations ("Veneto Net": Palmieri and Zambrano, 1992, personal communication), which were connected to the absolute gravity station of Mt. Venda (Padova). In order to avoid any bias between the reference points (BBT Net and Veneto Net), a few gravity stations have been separately tied to the two different reference points. The average gravity difference was $\pm 0.01-0.02\ 10^{-5}$ m/s^2.

The positions of the gravity stations were determined in close cooperation with the "Geodetic Team" of the Bolzano Province, with two Leica (dual frequency) and two Novatel DGPS receivers. Reference receivers have been mounted on stations with known coordinates, connected to the Italian GPS Net IGM95. The distance between GPS master and GPS rover, located at the gravity station, never exceeded 20 km, and the recording session, according to the common satellite visibility, never was less than 30 min with 10 s time sampling. The average RMS errors of the GPS adjustment are less

Table 1
Absolute gravity stations used in the area of interest: location, station code, benchmark code (if existing), geographical coordinates (WGS84), elevation, gravity values, confidence level of gravity (in 10^{-8} m/s^2), gradient and year of observation

Location	Station	Benchmark	Latitude (WGS84)	Longitude	Height [m]	Gravity 10^{-8} ms^{-2}	σ	Gradient 10^{-8} s^{-2}	Observed year
Brenner	0-148-00	P 40746A	47,0073	11,5068	1367	980.353.062	3	176	2001
Bolzano, Styler Mission	0I-BOZEN		46,4858	11,3510	285	980.556.147	4	197	2001
Bruneck, FFW	0I-BRUNE		46,7976	11,9458	835	980.482.414	3	262	2001
Meran, FFW	0I-MERAN		46,6678	11,1567	304	980.533.959	5	243	2001
Neustift bei Brixen	0I-NEUST		46,7438	11,6482	627	980.515.894	5	241	2001
Schlanders, FFW	0I-SCHLA		46,6263	10,7771	721	980.423.773	3	211	2001
Trento	0I-TRENT		46,0736	11,1319	194	980.593.522	11	212	2001
Innsbruck, Schloss Ambras	0-118-00	S0-118-00	47,2564	11,4348	637	980.546.564	3	210	1987

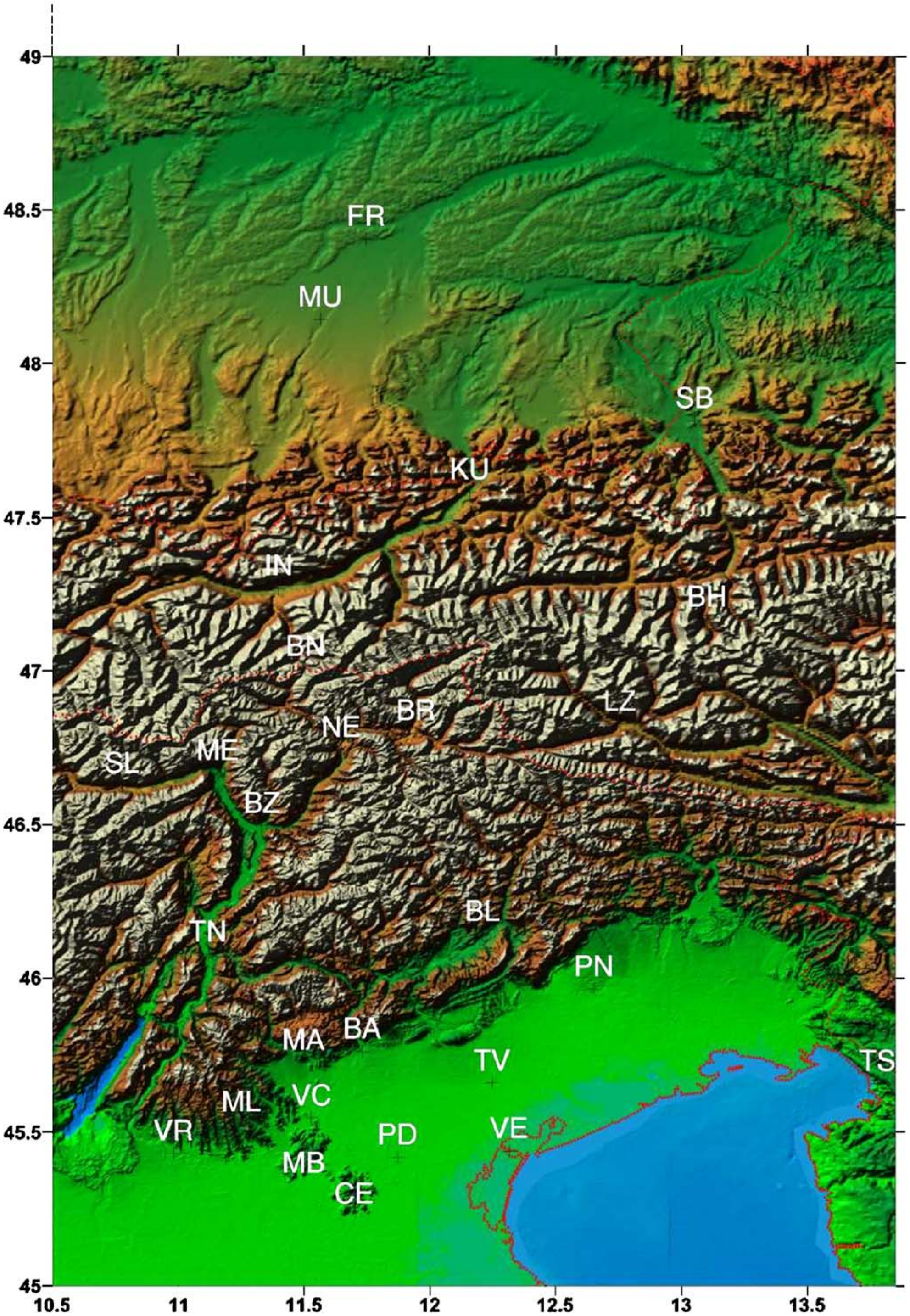

Fig. 2. Topographic map along the TRANSALP profile. Some towns and geographical indications are added, with abbreviations: BA (Bassano del Grappa), BH (Bad Hofgastein), BL (Belluno), BN (Brenner), BR (Bruneck), BZ (Bolzano), CE (Colli Euganei), FR (Freising), IN (Innsbruck), KU (Kufstein), LZ (Lienz), MA (Marosticano), MB (Monti Berici), ME (Meran), ML (Monti Lessini), MU (München), NE (Neustift), PD (Padova), PN (Pordenone), SB (Salzburg), SL (Schlanders), TN (Trento), TS (Trieste), TV (Treviso), VE (Venezia), VC (Vicenza), VR (Verona).

than 0.01 m for horizontal coordinates and between 0.01 and 0.02 m for vertical coordinates. Coordinates and elevations have been then referred to the ITRF94 system.

To homogenize the new data with the AGIP gravity data set that is referred to the Potsdam system, roughly 10 stations of the first order net of the AGIP survey have been connected to different points of the "Veneto Net". The average difference between AGIP gravity values and the newly re-measured points in IGSN-71 reference datum was determined in $-14.54 \pm 0.02 * 10^{-5}$ m/s^2. Therefore, the value of $14.54 * 10^{-5}$ m/s^2 was subtracted to all the old AGIP gravity stations to reduce them into IGSN-71 datum.

The data acquired on the Italian side have been processed according to the following steps:

a) Terrain correction in the range 20–250 m, based on the Digital Terrain Model (DTM) of Trento and Bolzano Provinces and of the Veneto Region with cell sizes of 10, 20 and 25 m, respectively.
b) Terrain correction between 0.250–167 km, computed using a DTM which was built by integrating the resampled DTM of Trento and Bolzano Provinces, the Veneto Region, the Radar Space Shuttle topographic (SRTM) data, integrated also with the Austrian DTM. The cell spacing of the final DTM used for the 0.250–167 km correction is DF = 7.5″ and Dl = 10.0″. A shaded relief map (illumination from north–west) of the topography is shown in Fig. 2.

Rectangular prisms defined in a geographically aligned system were used to model the topography. Their contribution was calculated applying the Banerjee–Das Gupta formula (Banerjee and Das Gupta, 1977). The reduction density was 2670 kg/m^3 for the landmasses and 1030 kg/m^3 for the water. Up to 20 km, the earth's curvature was taken into account. In order to convert the geometry of the Bouguer infinite slab to a spherical cap the Bullard B correction (La Fehr, 1991a,b) was applied. The Bouguer anomaly was calculated using a density of 2670 kg/m^3 for the Bouguer slab, as used for calculating the terrain correction.

The orthometric elevations were calculated by subtracting a geoid model from the ellipsoidal height (WGS84). The NIMA/NASA Geoid Height (consisting of a 0.25 degree grid of point values in the tide-free system, using the EGM96 Geopotential Model to degree and order 360) was used to perform this computation (Lemoine et al., 1998). Step b of the topographic correction (above) was then applied to all the gravity data of the Italian sector.

3. Gravity maps

The gravity data were interpolated on a regular grid of 500 by 500 m cell size. Below we will discuss the free-air gravity map (Fig. 3), the Bouguer anomaly map (Fig. 4), the isostatic anomaly map (Fig. 5) and the isostatic residual map (Fig. 6) in detail.

Fig. 3 shows the free-air gravity map. The free-air anomaly varies between -100 and $+190 * 10^{-5}$ m/s^2. Some anomaly patterns correlate with topographic features, e.g. as the linear elongated minima along the Inn- and Enns-valley, and the Vinschgau and Etsch valley. Gravity maxima are found in correspondence to the Verwall- and Lechtal Alps just north of the Italian–Austrian border and further south in the VTVP (De Vecchi and Sedea, 1995). Geographically the VTVP extends from the Lake Garda (west VR) to the Schio–Vicenza fault system (to the east, VC) and includes the area covering the Monti Lessini (ML), the Marosticano (MA), the Monti Berici (MB) and the Colli Euganei (CE), near the towns of Verona (VR) and Vicenza (VC). Geologically it is known also as the Lessinian homocline, which can be considered as the uplifted structural continuation to the north of the buried, nearly tabular, pede-Alpine homocline of Pieri and Groppi (1981). This sector is dominated by the Paleogene basaltic volcanism and by its differentiates.

A broad extended minimum is found in the Venetian plane, delimited by the Adriatic coast to the south and by the pede-mountain Alpine area to the north. Generally, topographic features dominate the free-air anomaly, while the interpretation of the Bouguer anomaly allows estimates on lithospheric structures.

The Bouguer anomaly is shown in Fig. 4. Compared to the free-air gravity map, the dominating features exhibit a much longer wavelength, indicating a deep source location. The largest negative anomaly values approximately follow the main chain of the Alpine orogen, with the minima shifted a few kilometres north of the highest elevations. The anomaly low shows clear lateral changes along the Alpine axis. To illustrate the regional changes along the axis of the Eastern Alps we present three NS-striking profiles (location shown in Fig. 1) showing the correlation between topography and the different gravity fields in Fig. 7. The central of the three profiles is located close to the TRANSALP traverse (Fig. 7b); the other two are positioned one degree to the W and E.

The Bouguer gravity map and the profiles show that the Bouguer anomaly low west of the N-Giudicarie fault system (a domain assigned to the Central Alps), has a north–south width of about 100 km and features values down to $-190*10^{-5}$ m/s^2, while in the east, the minimum is narrower than 50 km (NS extension) and shows values down to only $-160*10^{-5}$ m/s^2. Comparison with the surface geology shows that the minimum of the Bouguer anomaly correlates with the Helvetic and Austroalpine nappe structures and the Penninic windows (e.g. Tauern Window), the typical structures for the central part of the Eastern Alps. The

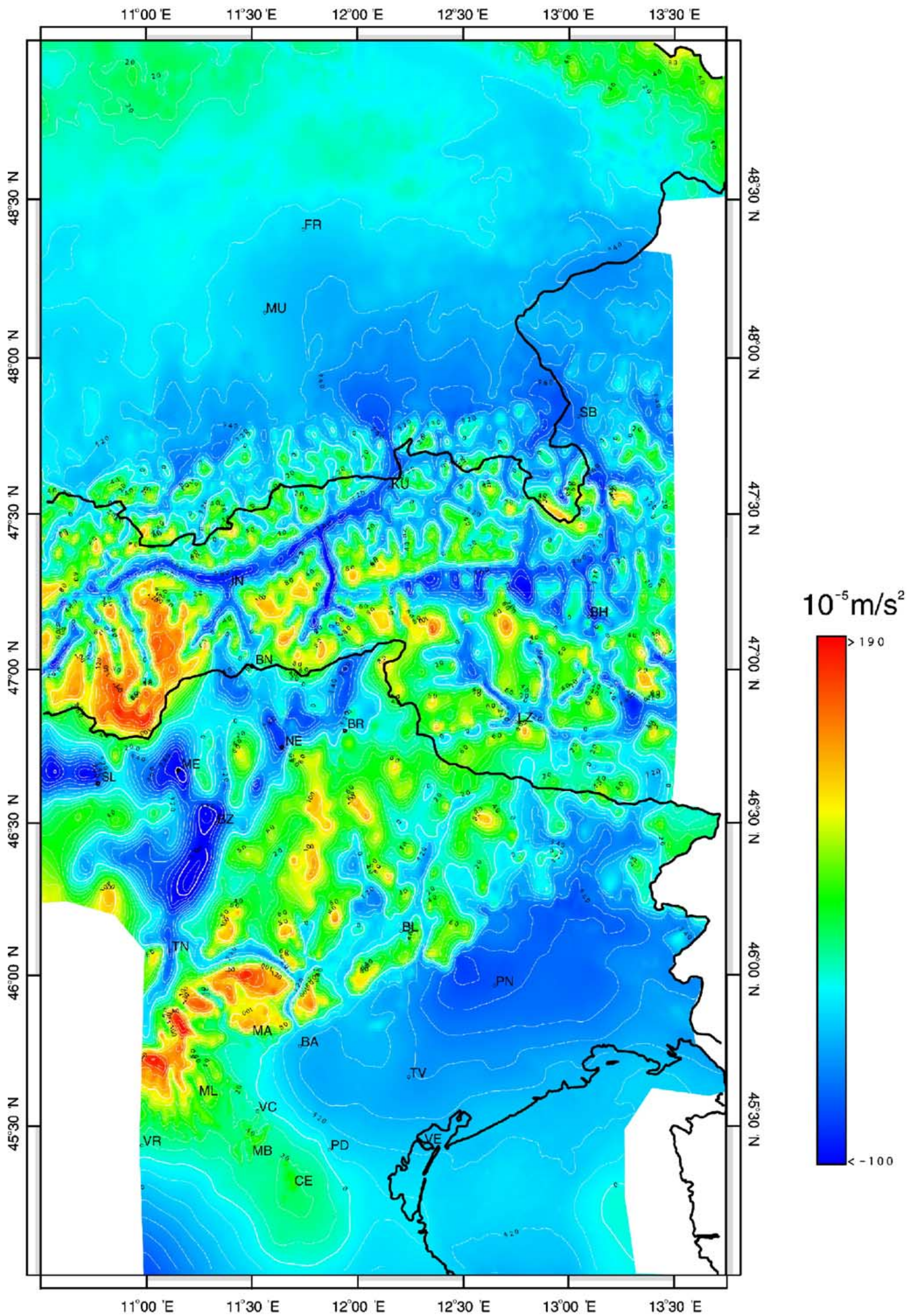

Fig. 3. Free-air gravity anomaly map. TRANSALP gravity database. For abbreviations see Fig. 2.

low-density rocks of the Tauern Window (Granser et al., 1989) are probably a source of the short-wavelength features visible in the regional Bouguer gravity low (Ebbing et al., 2001). Wide-angle seismic data show a low velocity zone at intermediate crustal levels north of Periadriatic lineament (Bleibinhaus and Gebrande, 2005—this volume), which could indicate an additional cause of the gravity minimum.

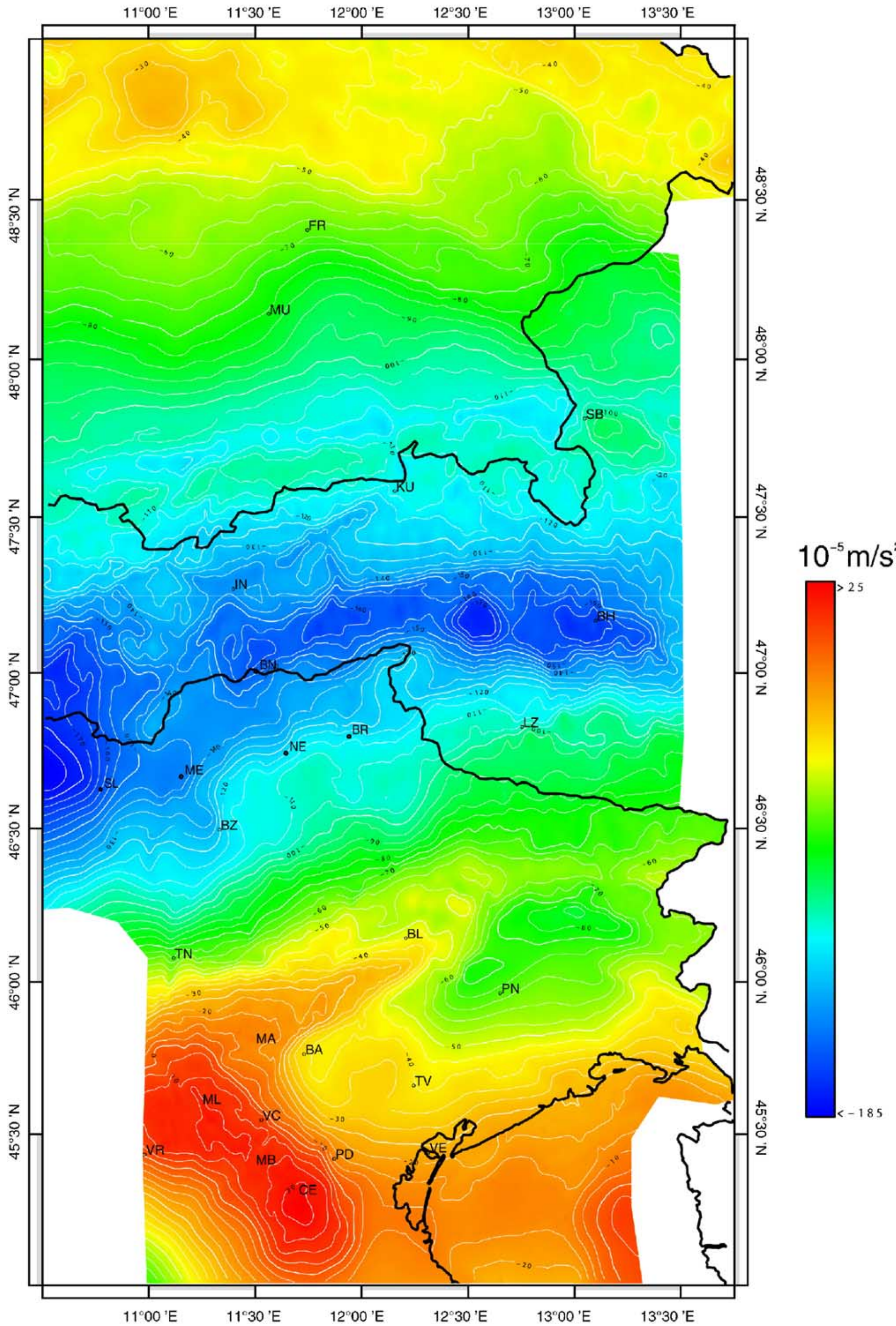

Fig. 4. Bouguer gravity anomaly map. TRANSALP gravity database. For abbreviations see Fig. 2.

To the north, the Bouguer anomaly increases smoothly and gently to a level of $-60*10^{-5}$ m/s^2 in the area of the Bavaria Molasse basin. To the south, in the South Alpine thrust belt and foreland, the increase in the Bouguer anomaly is not as smooth, but features a prominent broad elliptically shaped maximum striking in NW–SE direction known as the Verona–Vicenza gravity high. Here the Bouguer

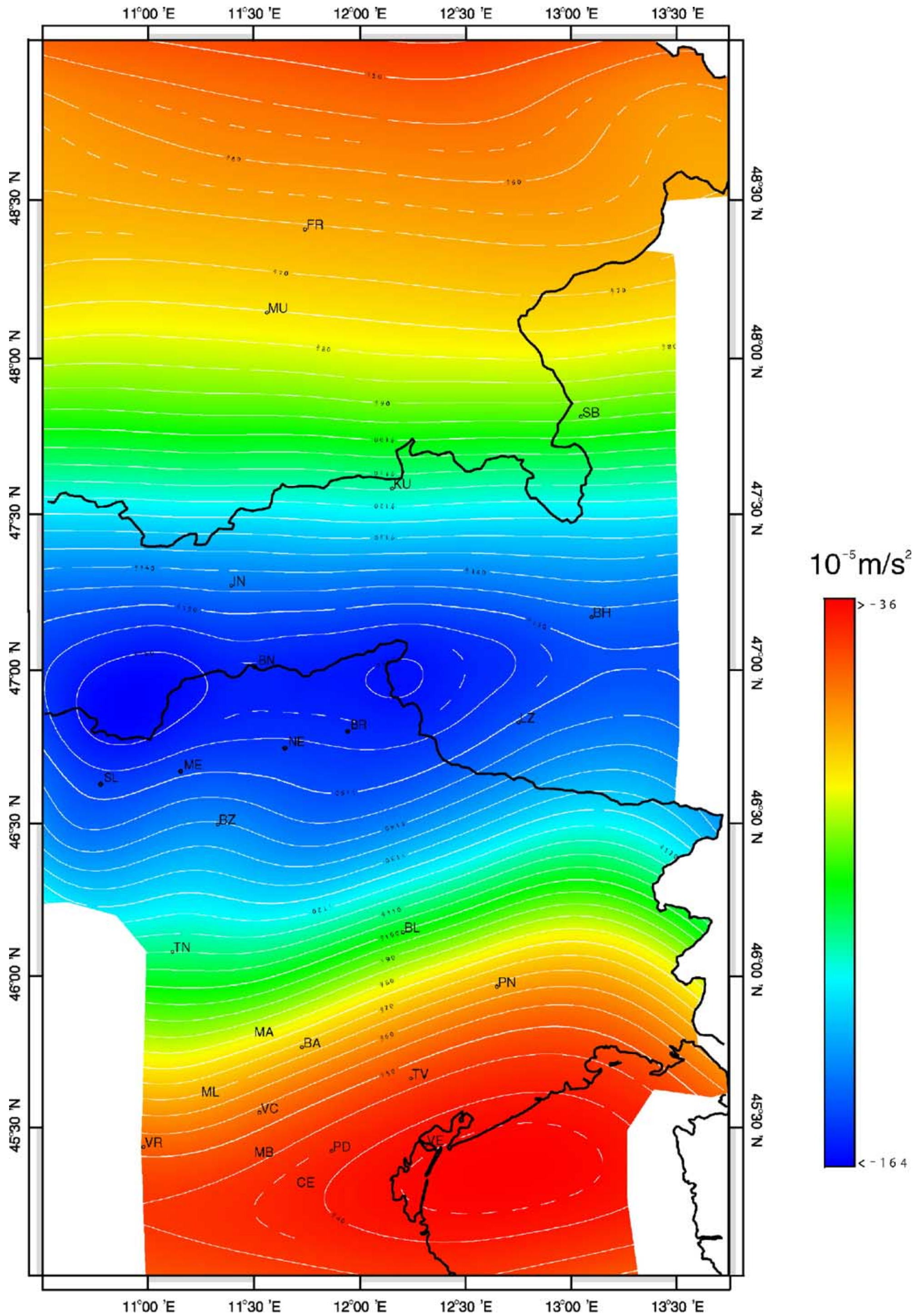

Fig. 5. Gravity field of the Airy isostatic root. Isostatic parameters given in text. For abbreviations see Fig. 2.

anomaly has its maximum with up to $+25*10^{-5}$ m/s^2. From the northern part of this elliptical shaped feature an east-oriented triangular shaped maximum emerges, termed the "Belluno nose". The area of relatively high values in the Bouguer anomaly covers the previously mentioned VTVP. The source of the broad gravity high is presumed to correlate with crustal thinning.

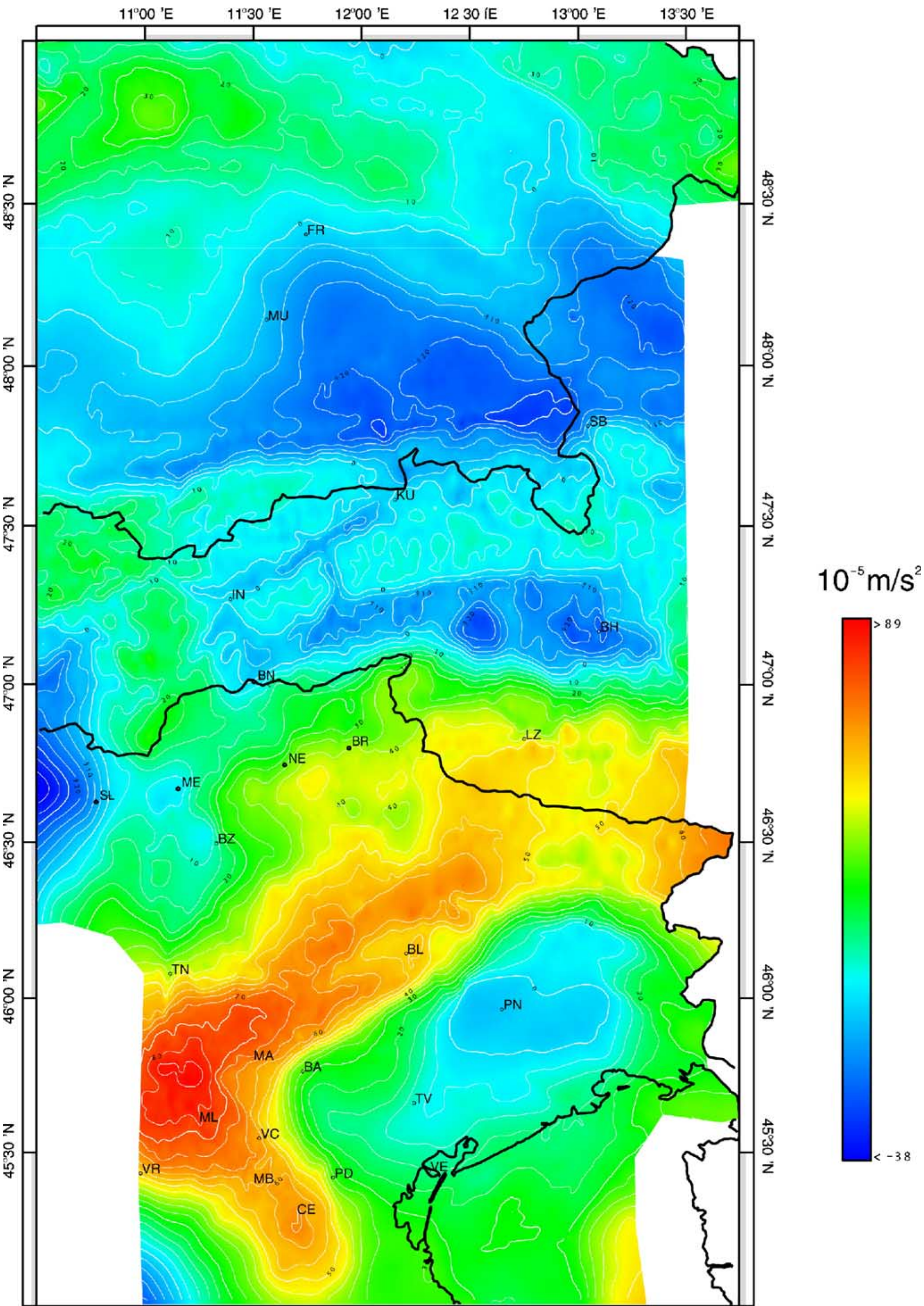

Fig. 6. Airy isostatic residual anomaly map; isostatic parameters as in Fig. 5. For abbreviations see Fig. 2.

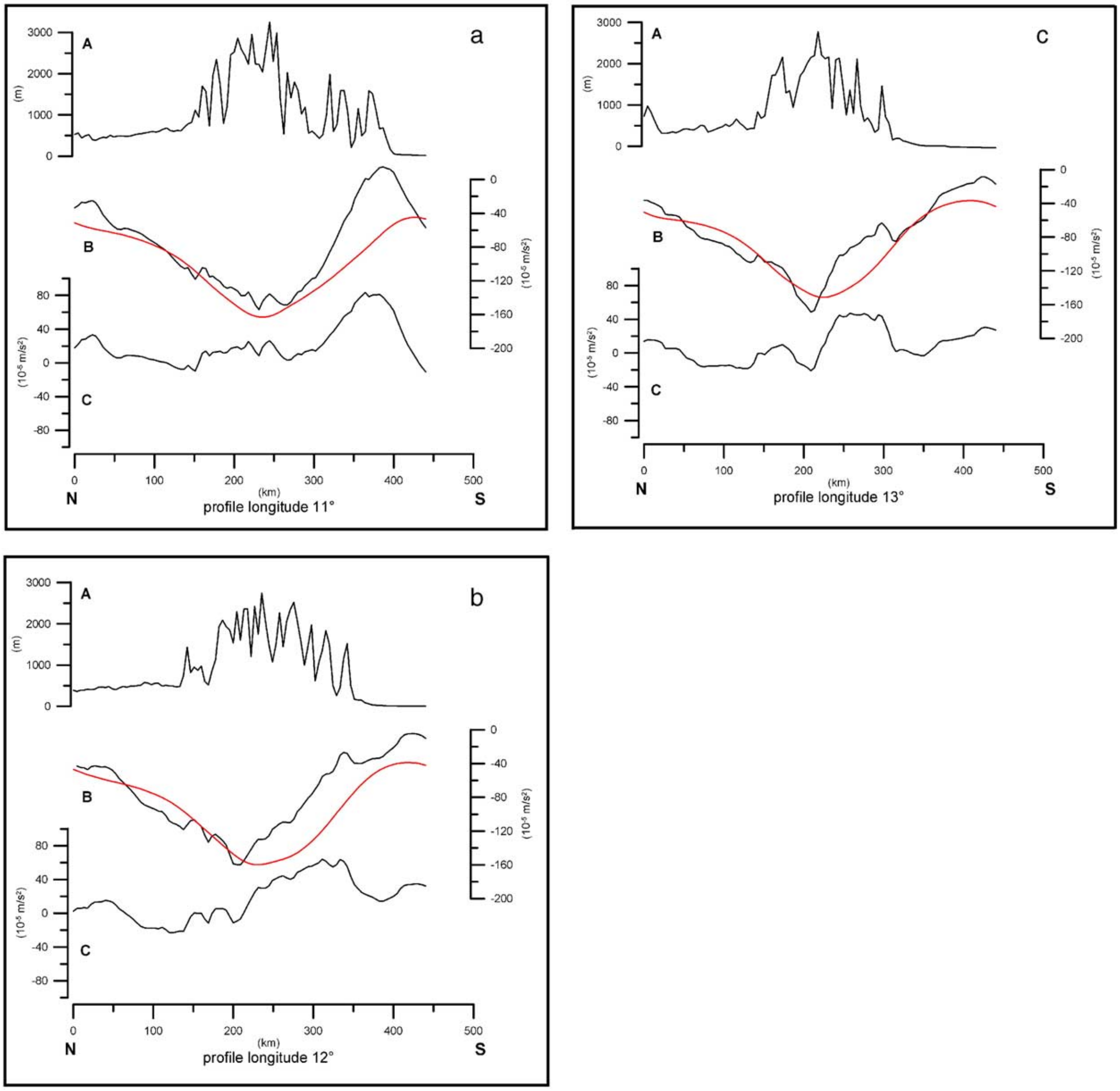

Fig. 7. Three NS oriented profiles across the SE Alps (see the positions in Fig. 1). The free-air anomaly, the Bouguer anomaly, the Airy isostatic gravity field and anomaly are shown. a) NS profile along longitude 11°, b) NS profile along longitude 12°, close to the location of the TRANSALP profile, c) NS profile along longitude 13°. A: Topography; B: Bouguer gravity anomaly (black) and gravity field of isostatic root (red); C: Airy isostatic residual anomaly. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The relatively high free-air gravity values north of the Italian–Austrian border do not have a counterpart in the Bouguer values, and thus are of superficial origin.

We calculate the isostatic anomaly according to the model of local isostatic compensation. First, the Airy crustal root, t_i, is calculated for the known topography using the formula:

$$t_i(x,y) = -T_0 - \frac{\rho_c}{\Delta\rho_{root}} h_i(x,y)$$

where T_0 is the normal crustal thickness, ρ_c the density of topography, $\Delta\rho_{root}$ the density contrast between the lower crust and the mantle, and h_i the topographic heights. For these parameters a topographic density of 2670 kg/m^3, a density contrast at the base of the Airy root of 400 kg/m^3 and a normal crustal thickness of 30 km were used. These values are consistent with previous isostatic investigations in the Eastern Alps (e.g. Wagini et al., 1988; Götze et al., 1991; Ebbing et al., 2001) and in the Western Alps (Klingele and Kissling, 1982). The gravitational attraction from the crustal root was then calculated by applying the Parker algorithm (Parker, 1972).

The resulting Airy isostatic regional anomaly (Fig. 5) shows a broad minimum along the main chain, more pronounced in the western-central parts of the study area ($-160*10^{-5}$ m/s^2), with a smooth increase to the north and south. In general, the isostatic gravity field has a smoother shape than the Bouguer gravity field and can only account for about 70% of its value. This indicates that the Eastern Alps are not compensated in the Airy-type isostatic sense. Previous studies dealing with the Airy-type isostasy of the Eastern Alps have already pointed out that the Eastern Alps are not in local isostatic equilibrium relative to the topographic loads (e.g. Wagini et al., 1988, Götze et al., 1991; Meurers, 1996). Good evidence for this is that the greatest elevations occur to the south of the observed Bouguer gravity minimum value across the Alpine range, which indicates also the presence of buried loads (Braitenberg et al., 1997; Lillie et al., 1994).

The profiles in Fig. 7 show also that the gravity field of the isostatic root reproduces the main long-wavelength features of the Bouguer anomaly, although significant discrepancies are present due to crustal heterogeneous densities. One example is the southern part of the western profile in Fig. 7a (between km 300 and 450), which crosses the Vicenza–Verona gravity high (see Fig. 4, extending between Vicenza (VC) and Verona (VR) and *Monti Lessini* (ML) and *Colli Euganei* (CE)). The isostatic residual (curve c in Fig. 7a) presents a considerable localized maximum.

The Airy isostatic residual anomaly (Fig. 6) shows the differences between the measured Bouguer anomaly

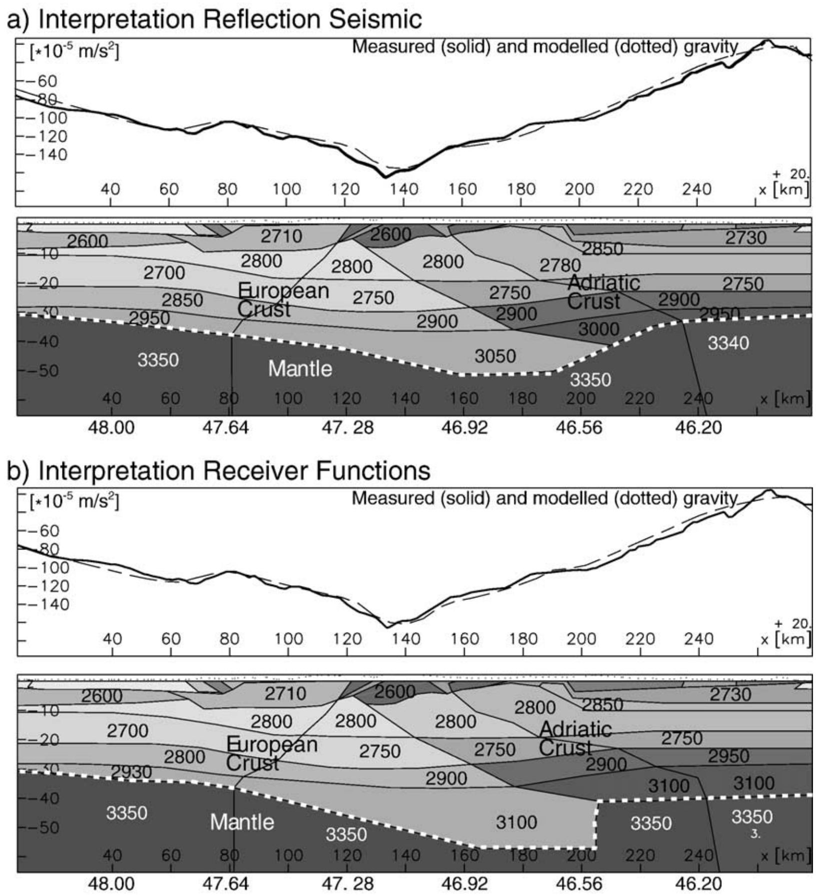

Fig. 8. 2D density models along the TRANSALP traverse: (a) more according to the results of the reflection seismics (Lüschen et al. 2005—this volume), and (b) more to the receiver functions studies (Kummerow et al., 2004). The 2D sections are N–S oriented along the geographical longitude 12E, which is close to the location of the TRANSALP traverse. The dotted line is indicating the crust–mantle boundary (Moho). Details on the upper crustal structure of the model and the isostatic implications utilizing a 3D lithospheric model are presented in Ebbing et al. (2001, 2005—this volume) and Ebbing (2004).

and the isostatic gravity field. The largest residual anomalies have maximum amplitudes between +50 and $-50*10^{-5}$ m/s^2. Only in the outermost south-western corner of the study area is the residual larger, but this feature is probably not related to Alpine tectonics. The isostatic residual anomaly correlates strongly with geological formations visible at the surface, for example the area of the Tauern Window with negative residuals ($-30*10^{-5}$ m/s^2), and the surrounding nappe structures (Northern Calcareous Alps, the Dolomites and the Southalpine thrust belt) with positive residuals (0–20$*10^{-5}$ m/s^2). For a detailed discussion of the isostatic processes, the mass distribution within the crust must be considered, which can be estimated by 3D density modelling (Granser et al., 1989; Braitenberg et al., 2002; Ebbing, 2004).

The correlation between residual anomalies and geological formations points to the uppermost crust as the origin of additional masses that cause the deviations from isostatic equilibrium and possibly initiate subsidence and uplift processes. For example, in the area of the Tauern Window, the negative values suggest uplift, which is in agreement with results from repeated geometric levelling measurements (Senftl and Exner, 1973; Steinhauser and Gutdeutsch, 1976; Höggerl, 2001).

Another well-exposed feature of the residual field is the high residual (+100$*10^{-5}$ m/s^2) in the area of the VTVP. This represents the greatest residual anomaly in the study area, and is also very prominent in the Bouguer map, but has no topographic expression. The magmatic activity took place during Paleogene and is characterized by mafic products with their differentiates (De Vecchi and Sedea, 1995). The density has been estimated to be 2800 kg/m^3 (Granser et al., 1989; Berthelsen et al., 1992). According to Castellarin and Cantelli (2000) the VTVP corresponds to a tabular or homoclinal sector, which was only weakly deformed by the Neogene Southalpine compressions due to the presence of more stiff materials in its upper crust. These materials would be the above mentioned Paleogene basalts and the Middle Triassic magmatic occurrences.

4. The crustal structure along the TRANSALP traverse

One of the aims of the new gravimetric survey was to gain insight into the transitional zone between the European and Adriatic plates. This topic is related to the thickness of the crust and the geometries within the crustal layers and of the transition.

The results of the reflection seismic (Lüschen et al., 2005—this volume) and the receiver functions experiments (Kummerow et al., 2004) give indications for different interpretations, especially in the area of the deep crustal root.

The 2D density models in Fig. 8 illustrate the different interpretations: (a) more oriented on the results of the reflection seismic, and (b) on the receiver functions studies. The modelling was done using the interactive software IGMAS (Schmidt and Götze, 1998) and is shown here for a N–S oriented stripe along the geographical longitude 12E.

The main difference between the two models is the geometry of the crustal root and the thickness and density of the Adriatic lower crust. A detailed description of the upper crustal model and the 3D structures is presented in Ebbing et al. (2001) and Ebbing (2004).

The interpretation with a 40 km thick crust requires at least higher densities for the lower crust (3100 kg/m^3) to be able to adjust the model to the Bouguer gravity anomaly (Fig. 8b), compared to the interpretation with a 30 km thick Adriatic crust. Here the densities of the lower crust are in the order of 3000 kg/m^3, slightly higher than in the lower European crust (2950 kg/m^3). The seismic results point to a higher seismic velocity in the lower 20 km of the Adriatic crust (Lüschen et al., 2005—this volume; Bleibinhaus and Gebrande, 2005—this volume), which is in agreement with our observations.

The reflection patterns of the lower crust are twice as thick within the Adriatic plate than within the European plate, which can also indicate crustal doubling. The interpretation of lower crustal stacking following tectonic erosion during the subduction process could have caused this pattern (Lüschen et al., 2005—this volume). Even if this observation can be correlated with the density models, the resolution of the densities of the deep-seated features allows no unambiguous interpretation. As for example a slight increase of the lower crustal density (+50 kg/m^3) can be adjusted by a slight decrease of mantle densities (-15 kg/m^3) to produce the same gravity signal.

However, the isostatic implications of a 40 km thick Adriatic crust are far-reaching. Either the Adriatic plate must have a high flexural rigidity or crustal doubling must cause the increase in thickness in the transition zone. A more thorough discussion on the isostatic implications and a 3D interpretation of the different crustal geometries is presented in Ebbing (2004) and a discussion of the lithospheric density structure of the Eastern Alps in Ebbing et al. (2005—this volume).

5. Conclusions

The presented gravity and topography database is the best available today along the 300 km broad swath centred on the TRANSALP profile. The database comprises German, Austrian and Italian gravity data. For the Italian data the topographic correction up to the radius of 167 km was newly calculated and a homogeneous database of Italian, Austrian and German measurements has been produced. Most prominent features of the Bouguer map are the strongly negative values aligned at the axis of the Alpine chain (up to $-190*10^{-5}$ m/s^2) and the positive values (up to $+25*10^{-5}$ m/s^2) of the VTVP. 3D forward and inverse modelling considering seismic studies have shown that the main cause of the negative Bouguer anomaly along the axis of the Alpine orogen is crustal thickening. The maximum crustal thickness has been positioned on the basis of DSS data (Giese et al., 1982) approximately 50 km south of Periadriatic line. The TRANSALP seismic images (Lüschen et al., 2005—this volume) confirmed these results of a south-dipping European Moho and of a lower crust thinning to the south. To give detailed insights into the geometry of the transition between the European and Adriatic plates is beyond the possibilities of gravity analysis. Especially, for the deep-seated sources the superposition of the gravity effect of different sources complicates the unambiguous interpretation.

The Verona–Vicenza gravity high to the south of the Eastern Alps can partly be explained by high-density magmatic rocks and intrusions, but requires also a deeper source, which could correspond to a locally shallow Moho (Braitenberg et al., 1997; Ebbing et al., 2001).

Seismic results (Italian Explosion Seismology Group, 1981) indicate that the Moho is at a depth of approximately 25 km in the area of Verona, while a lower crustal doubling is proposed very close to that region, dipping with the Moho and thinning towards west (Deichmann et al., 1986), or towards north (Panizza et al., 1981). Cassinis (2005—this volume), Kummerow et al. (2004) and Lüschen et al. (2005–this volume) presented a lower crustal doubling also in correspondence of the “Belluno nose”.

The isostatic residual anomalies (Airy local compensation model) are in the range $\pm 50*10^{-5}$ m/s^2. Some of the negative anomalies point to the presence of shallow density deficits, as the low density rocks in the Tauern Window, the sediments of the Venetian plane, and the sediments at the opening of the Inn- and Enns-valley. For the latter there could also be an effect due to the correction density used for the Bouguer calculations (2670 kg/m^3), which is too low for the Calcareous Alps. The greatest positive isostatic anomaly corresponds to the location of the VTVP and indicates an under-compensation of crustal masses. Evidently the Eastern Alps are not in isostatic equilibrium in sense of a simple Airy isostasy. The subsurface mass distribution/loading is a factor, which has to be considered in detailed isostatic analysis.

Investigations on the isostatic state of the Eastern Alps in terms of the lithospheric flexure model under consideration of the subsurface loading have been performed in the frame of the TRANSALP project (Braitenberg et al., 2002; Ebbing, 2004; Ebbing et al., 2005—this volume). These studies show that the lithosphere in the Eastern Alps is rather elastic, but has a small flexural rigidity, which contributes to the isostatic processes. The VTVP area is also characterized in the flexure models by the greatest residual isostatic anomalies. That points to processes which cannot be accounted for by isostatic concepts and a detailed study of this phenomenon is a future goal.

The newly compiled database provides a tool to carry out detailed analysis of the gravity field of the Eastern Alps on a regional as well as on a local scale.

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References

Ballarin, S., Palla, B., Trombetti, C., 1972. The construction of the gravimetric map of Italy. Pubbl. Comm. Geo. Ital. Ser. 3, 19.

Banerjee, B., Das Gupta, S.P., 1977. Gravitational attraction of a rectangular parallelepiped. Geophysics 42 (5), 1053–1055.

Behle, A., Ehrismann, W., Makris, J., Menzel, H., Morelli, C., Rosenbach, O., 1972. Gravimetrische Untersuchungen in den Ostalpen I (Messgebiet Mittenwald-Innsbruck-Verona). Z. Geophys. 38, 45–74.

Berthelsen, A., Burrolet, P., Dal Piaz, G.V., Franke, W., Trümpy, R., 1992. Tectonics. In: Blundell, D., Freeman, R., Mueller, St. (Eds.), A Continent Revealed: The European Geotraverse. Cambridge University Press.

Bleibinhaus, F., Gebrande, H., 2005. Crustal structure of the Eastern Alps along the TRANSALP profile from wide-angle seismic tomography. Tectonophysics. 414, 51–69 (this volume).

Braitenberg, C., Pettenati, F., Zadro, M., 1997. Spectral and classical methods in the evaluation of Moho undulations from gravity data: the NE-Italian Alps and isostasy. J. Geodyn. 23, 5–22.

Braitenberg, C., Ebbing, J., Götze, H.-J., 2002. Inverse modelling of elastic thickness by convolution method—the Eastern Alps as a case example. Earth Planet. Sci. Lett. 202, 387–404.

Carrozzo, M.T., Luzio, D., Margiotta, C., Quarta, T., 1991. C.N.R.-P.F. Geodinamica—Gravity Map of Italy, Scale 1:500.000, Sheet 1, SELCA (Firenze).

Cassano E., Maino A. (Eds), 1989. Carta gravimetrica d'Italia. Scale 1:1.000.000. Servizio Geologico d'Italia.

Cassinis, R., 2005. Reviewing pre-TRANSALP DSS models. Tectonophysics. 414, 79–86 (this volume).

Castellarin, A., Cantelli, L., 2000. Neo-Alpine evolution of the Southern Eastern Alps. J. Geodyn. 30, 251–274.

Deichmann, N., Ansorge, J., Müller, S., 1986. Crustal structure of the Southern Alps beneath the intersection with the European geotraverse. Tectonophysics 126, 57–83.

Delleske, M., 1993. Zur Schwerefeldseparation mittels 3D-Modellrechnungen im Hochgebirge. Berl. Geowiss. Abh. (B) 19 (74 pp.).

De Vecchi, G., Sedea, R., 1995. The paleogene basalts of the Veneto region (NE Italy). Mem. Sci. Geol. 47, 253–274.

Doergé, W., Reinhart, E., Boedecker, G., 1977. Das International Gravity Standardization Net 1971 (IGSN 71)" in der Bundesrepublik Deutschland. - Dt. geodät. Komm., B225; München.

Ebbing, J., 2004. The crustal structure of the Eastern Alps from a combination of 3D gravity modelling and isostatic investigations. Tectonophysics 380, 89–104.

Ebbing, J., Braitenberg, C., Götze, H.-J., 2001. Forward and inverse modelling of gravity revealing insight into crustal structures of the Eastern Alps. Tectonophysics 337/3-4, 191–208.

Ebbing, J., Braitenberg, C., Götze, H.-J., 2005. The lithospheric density structure of the Eastern Alps. Tectonophysics. 414, 145–155 (this volume).

Ehrismann, W., Rosenbach, O., Steinhauser, P., 1969. Vertikalgradient und Gesteinsdichte im Schlegeisgrund (Zillertaler Alpen) auf Grund von Stollenmessungen. Sitzungsber. - Osterr. Akad. Wiss., Math.-Nat.Wiss. Kl., Abt. I 178, 9–10.

Ehrismann, W., Leppich, W., Lettau, O., Rosenbach, O., Steinhauser, P., 1973. Gravimetrische Detail-Untersuchungen in den westlichen Hohen Tauern. Z. Geophys. 39, 115–130.

Ehrismann, W., Götze, H.-J., Leppich, W., Lettau, O., Rosenbach, O., Schöler, W., Steinhauser, P., 1976. Gravimetrische Feldmessungen und Modellberechnungen im Gebiet des Krimmler Ache Tales und Obersulzbachtales (Großvenediger Gebiet/Österreich). Geol. Rudsch. 65 (2), 767–778.

Giese, P., Reutter, K., Jacobshagen, V., Nicolich, R., 1982. Explosion seismic crustal studies in the Alpine-Mediterranean region and their implications to tectonic processes. In: Berckhemer, H., Hsü, K. (Eds.), Alpine-Mediterranean Geodynamics, Geodyn. Ser., Am. Geophys. Union, vol. 7, pp. 39–73.

Götze, H.-J., 1984. Über den Einsatz interaktiver Computergraphik im Rahmen 3-dimensionaler Interpretationstechniken in Gravimetrie und Magnetik. Habilitation thesis, TU Clausthal.

Götze, H.-J., Lahmeyer, B., 1988. Application of three-dimensional interactive modeling in gravity and magnetics. Geophysics 53, 1096–1108.

Götze, H.-J., Leppich, W., Lettau, O., Rosenbach, O., Schöler, W., Steinhauser, P., 1976. Gravimetrische Feldmessungen und Modellberechnungen im Felbertauerngebiet (Mittl. Hohe Tauern). Geol. Rudsch. 65 (2), 779–790.

Götze, H.-J., Rosenbach, O., Schöler, W., 1978. Gravimetric measurements on three N–S profiles through the Eastern Alps-observational results and preliminary modeling. Alps, Apennines, Hellenides, Inter-Union Comm. on Geodynamics, Scient. Rep., vol. 38. Stuttgart, pp. 44–49.

Götze, H.-J., Rosenbach, O., Schöler, W., 1979. Gravimetrische Untersuchungen in den östlichen Zentralalpen. Geol. Rundsch. 68 (1), 61–82.

Götze, H.-J., Meurers, B., Schmidt, S., Steinhauser, P., 1991. On the isostatic state of the Eastern Alps and the Central Andes—a statistical comparison. In: Harmon, R.S., Rapela, C.W. (Eds.), GSA Special Paper 265 on "Andean Magmatism and its Tectonic Setting", pp. 279–290.

Granser, H., Meurers, B., Steinhauser, P., 1989. Apparent density mapping and 3D gravity inversion in the Eastern Alps. Geophys. Prospect. 37, 279–292.

Höggerl, N., 2001. Bestimmung von rezenten Höhenänderungen durch wiederholte geodätische Messungen. Die Zentralanstalt für Meteorologie und Geodynamik 1851–2001, 150 Jahre Meteorologie und Geophysik in Österreich, ff. 630 – 644, Leykam, Graz 2001, ISBN 3-7011-7437-7.

Italian Explosion Seismology Group, 1981. Crust and upper mantle structures in the Southern Alps from deep seismic sounding profiles (1977–1978) and surface wave dispersion analysis. Boll. Geofis. Teor. Appl. 23 (9), 297–330.

Jung, K., Menzel, H., Rosenbach, O., 1965. Gravimetermessungen im Nördlinger Ries. Z. Geophys. 31, 7–26.

Jung, K., Schaaf, H., 1967. Gravimetermessungen im Nördlinger Ries und seiner Umgebung, Abschätzung der gesamten Defizitmasse (mit Faltkarte). Z. Geophys. 33, 319–345.

Klingele, E., Kissling, E., 1982. Schwere-Anomalien und isostatische Modelle in der Schweiz. Geodätisch-geophysikalische Arbeiten in der Schweiz. Bd., vol. 35. Schweizerische Geodätische Kommission.

Kummerow, J., Kind, R., Oncken, O., Giese, P., Ryberg, T., Wylegalla, K., TRANSALP Working Group, 2004. A natural and controlled source seismic profile through the Eastern Alps: TRANSALP. Earth Planet. Sci. Lett. 225, 115–129.

La Fehr, T., 1991a. An exact solution for the gravity curvature Bullard B correction. Geophysics 56, 1179–1184.

La Fehr, T., 1991b. Standardization in gravity reduction. Geophysics 56, 1170–1178.

Lemoine, F. G., Kenyon, S.C., Factor, J. K., Trimmer, R.G., Pavlis, N. K., Chinn, D. S., Cox, C.M., Klosko, S.M., Luthcke, S. B., Torrence, M. H., Wang, Y. M., Williamson, R.G., Pavlis, E.C., Rapp, R. H., Olson, T. R., 1998. The Development of the Joint NASA GSFC and NIMA Geopotential Model EGM96. Internal. Report NASA/TP-1998-206861, NASA Goddard Space Flight Center, Greenbelt, Maryland, 20771 USA.

Lillie, R.J., Bielik, M., Babuŝka, V., Plomerová, J., 1994. Gravity modelling of the lithosphere in the Eastern Alpine–Western Carpathian–Pannonian Basin Region. Tectonophysics 231, 215–235.

Lüschen, E., Borrini, D., Gebrande, H., Lammerer, B., Millahn, K., Neubauer, F., Nicolich, R., TRANSALP Working Group, 2005. TRANSALP-deep seismic Vibroseis and explosive seismic profiling in the eastern Alps, Tectonophysics. 414, 9–38 (this volume).

Makris, J., 1971. Aufbau der Kruste in den Ostalpen aus Schweremessungen und Ergebnissen der Refraktionsseismik. Hamburger Geophys. Einzelschriften, vol. 15. Hamburg.

Meurers, B., 1992. Untersuchungen zur Bestimmung und Analyse des Schwerefeldes im Hochgebirge am Beispiel der Ostalpen. Österr. Beitr. Meteorol. Geophys. 6 (146 pp.).

Meurers, B., 1996. Investigation of the isostatic anomaly of the Eastern Alps. Acta Geod. Geophys. Hung. 31 (3–4), 389–403.

Meurers, B., Ruess, D., Steinhauser, P., 1987. The gravimetric Alpine traverse. In: Flügel, H.W., Faupl, P. (Eds.), Geodynamics of the Eastern Alps. Wien, Verlag Deuticke, pp. 334–344.

Meurers, B., Ruess, D., Graf, J., 2001. A program system for high precise Bouguer gravity determination. Proc. 8th Int. Meeting on Alpine Gravimetry, Leoben 2000. Österr. Beitr. Meteorol. Geophys. 26, 217–226.

Moritz, H., 1984. Geodetic reference system 1980. Bull. Geod. 54 (3), 395–405.

Olivier, R.J., Simard, R.G., 1981. Improvement of the conic prism model for terrain correction in rugged topography. Geophysics 46, 1054–1056.

Panizza, M., Slejko, D., Bartolomei, G., Carton, A., Castaldini, D., Demartin, M., Nicolich, R., Sauro, U., Semenza, E., Sorbini, L., 1981. Modello sismotettonico dell'area fra il Lago di Garda e il Monte Grappa. Rend. Soc. Geol. Ital. 4, 587–603.

Parker, R.L., 1972. The rapid calculation of potential anomalies. Geophys. J. R. Astron. Soc. 31, 447–455.

Pieri, M., Groppi, G., 1981. Subsurface geological structures of the Po Plain. C.N.R.-P.F. Geodinamica, Sottoprog. Modello Strutturale contr. 414. AGIP Publisher, Milano, 13 pp.

Plaumann, S., 1990. Ein Verfahren zur Berechnung von Gelände-Fernkorrekturen in der Gravimetrie unter Verwendung von mittleren Höhen von TK 25-Feldern, Unpublished report 107 543, Niedersächsisches Landesamt für Bodenforschung-Geowissenschaftliche Gemeinschaftsaufgaben, 24 pp. Hannover.

Plaumann, S., 1995. Die Schwerekarte 1 : 500 000 der Bundesrepublik Deutschland (Bouguer-Anomalien), Blatt Süd., Geol. Jb. E 53; Hannover.

Posch, E., Walach, G., 1989. Das Bouguerschwerefeld in Vorarlberg und im Bereich der Übergangszone zwischen West-und Ostalpen. 5. Int. Alpengrav. Koll., Graz 1989. Österr. Beitr. Meteorol. Geophys. 2, 147–151.

Ruess, D., 1980. Gravimetrische Untersuchung am Ostrand des Tauernfensters. Unpublished Ph.D. thesis, Univ. Vienna.

Ruess, D., Gold, W., 1996. The Austrian Gravity Base Net 1995. VGI 3/96, 275–283, Wien.

Schleusener, A., 1953. Der größte Ring bei der Geländeverbesserung der Gravimetrie in der Lagerstättengeophysik. Z. f. Geophys. Sonderband, Braunschweig, pp. 33–36.

Schmidt, S., 1985. Untersuchungen zum regionalen Verlauf des Vertikalgradienten der Schwere im Hochgebirge. Ph.D. thesis, TU Clausthal.

Schmidt, S., Götze, H.-J., 1998. Interactive visualization and modification of 3D models using GIS functions. Phys. Chem. Earth 23 (3), 289–296.

Schöler, W., 1976. Die Krustenstruktur der Ostalpen nach Ergebnissen gravimetrischer Untersuchungen unter besonderer Berücksichtigung des Vertikalgradienten. Unpublished Ph.D. thesis, TU Clausthal.

Senftl, E., 1963. Cartes Mondiales des Anomalies de Bouguer 1 : 1.000.000, Feulles de Vienne. BGI Bull. d'Inf., 6.

Senftl, E., 1965: Schwerekarte von Österreich, Bouguer- Isoanomalen 1 : 1.000.000. Auflage 1965, BEV-Wien.

Senftl, E., Exner, C., 1973. Rezente Hebung der Hohen Tauern und geologische interpretation. Verh. Geol. B.-A. 2, 209–234.

Steinhauser, P., Gutdeutsch, R., 1976. Rezente Krustenbewegung und Isostasie in den Hohen Tauern. Arch. Meteorol. Geophys. Bioklimatol., A 25, 141–149.

Steinhauser, P., Meurers, B., Ruess, D., 1990. Gravity investigations in mountainous areas. Explor. Geophys. 21, 161–168.

Wagini, A., Steinhauser, P., Meurers, B., 1988. Isostatic residual gravity map of Austria, U.S. Geol. Surv. Open-File Rep, 87–402.

Wenzel, F., 1985. Hochauflösende Kugelfunktionsmodelle für das Gravitationspotential der Erde. Wiss. Arb. Fachricht. Vermess.wes. Univ. Hann. Nr. 137.

Zych, D., 1988. 30 Jahre Gravimetermessungen der ÖMV Aktiengesellschaft in Österreich und ihre geologisch-geophysikalische interpretation. Arch. Lagerstattenforsch. Geol. B.-A. 9, 155–175.