3 GRAVITY DATABASE

For the purposes of the forward modelling, the offshore Free Air anomaly (FAA) and onshore Bouguer anomaly (BA) were used. The onshore data were reprocessed as part of this work, and both offshore and onshore data will be discussed in this chapter.

3.1 Offshore

The Free Air anomaly image made for the area off South Chile (Figure 3.1) is based on stations measured from the R/V Sonne each 20 s along more than 4000 km of the ship-track. These offshore gravity data were collected between October to December, 2001, between 32° and 42°S under the framework of the SO 161 SPOC cruise (SPOC - Subduction Processes Off Chile). The SPOC data were measured along profiles (black lines in Figure 3.1) and merged with 3 different offshore datasets to fill areas not measured by the R/V Sonne (Smith & Sandwell, 1997; KMS Andersen & Knudsen, 2001; Wang, 2000). Based on the observed differences in the FAA values, as indicated by the size of the circles (Figure 3.1), the KMS data were selected to be merged with the SPOC ship-borne gravity data (Götze et al.,2002; Schreckenberger et al., 2002). The resulting dataset, including KMS data where there is no SPOC data, was used for the forward density model.

Data processing & errors

The ship-borne gravity data were tied to the international gravity datum IGSN71 by establishing a link between an absolute gravity point in Santiago and a point in the harbour in Valparaiso where the R/V Sonne was moored. The data processing included a time shift due to the overcritical damping of the sensor, conversion of the output reading units, corrections for the instrumental drift and the Eötvös effect, and the subtraction of the normal gravity field. The resulting Free Air anomaly values have an accuracy of $\leq 1\times10^{-5}$m/s^2 (Schreckenberger et al., 2002).

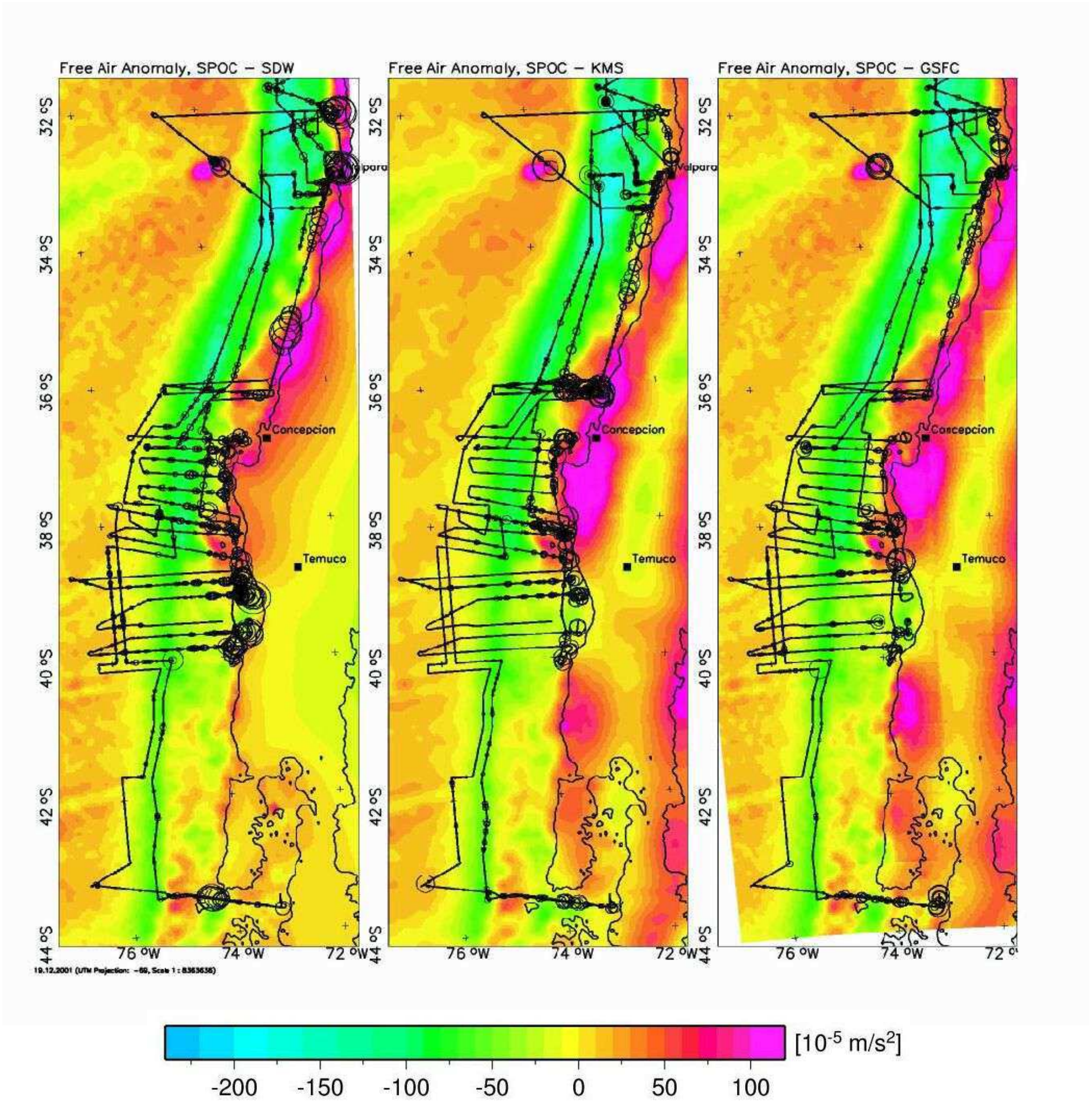


Figure 3.1
SPOC Free Air anomaly merged with three different satellite datasets, from left to right: SDW, KMS, and GSFC. Differences between the SPOC data and the satellite data are indicated by size of circles along the ship-track. Tha largest misfits are observed close to the coastline and particularly between the SPOC and SDW data. The best fit is found to be with the KMS gravity data, which also seems to be smoother than the other two datasets (Götze et al. 2002).

3.2 Onshore gravity database

The onshore Bouguer anomaly map for the study area is based on approximately 54000 land data. This dataset comprises stations from several different sources measured over the past 30 years (Table 3.1).

During the third working period of the SFB 267, gravity observations were made on land in the Northern Patagonia region of Argentina by the international MIGRA group (Mediciones Internationales de Gravedad en los Andes). Around 2000 stations were occupied between September and November 2000 along the South American Lithosphere Transect (SALT) from the Pacific to the Atlantic coastlines.

Gravity data (~40000 stations) in Argentina were also released by Repsol-YPF (Yacimientos Petroliferos Fiscales, Argentinean National Oil Company). These data, under the research contract, were reprocessed, homogenized and merged with the above-mentioned MIGRA 2000 dataset (Wienecke, 2002).

The remaining 12000 stations covering the Chilean forearc/arc region extend as far as the Main Cordillera region, until just beyond the Chilean/Argentinean border (Figure 3.2). These data were provided under an agreement with ENAP (Empressa Nacional del Petroleo) and also collected as part of a Volkswagen Stiftung Project (I/70 337, in 1995-1997) (VW) awarded to Dr. M. Araneda, M.S. Avendaño, and Prof.Dr. H.-J. Götze, together with the University of Chile, Santiago (Araneda et al. 1999a, 1999b). All of these data were reprocessed within the framework of this PhD thesis.

GRAVITY DATABASE of the Southern Andes at 36°S-42°S		
SOURCE	**LOCATION**	**NUMBER**
SFB 267	Argentina	2000
	Chile	220
YPF	Argentina	~40000
ENAP	Chile	5900
VW Project (Dr. ARANEDA)	Chile/Argentina	6400
	TOTAL:	**~54520**

Table 3.1

The number of gravity stations and their original (responsible) institution

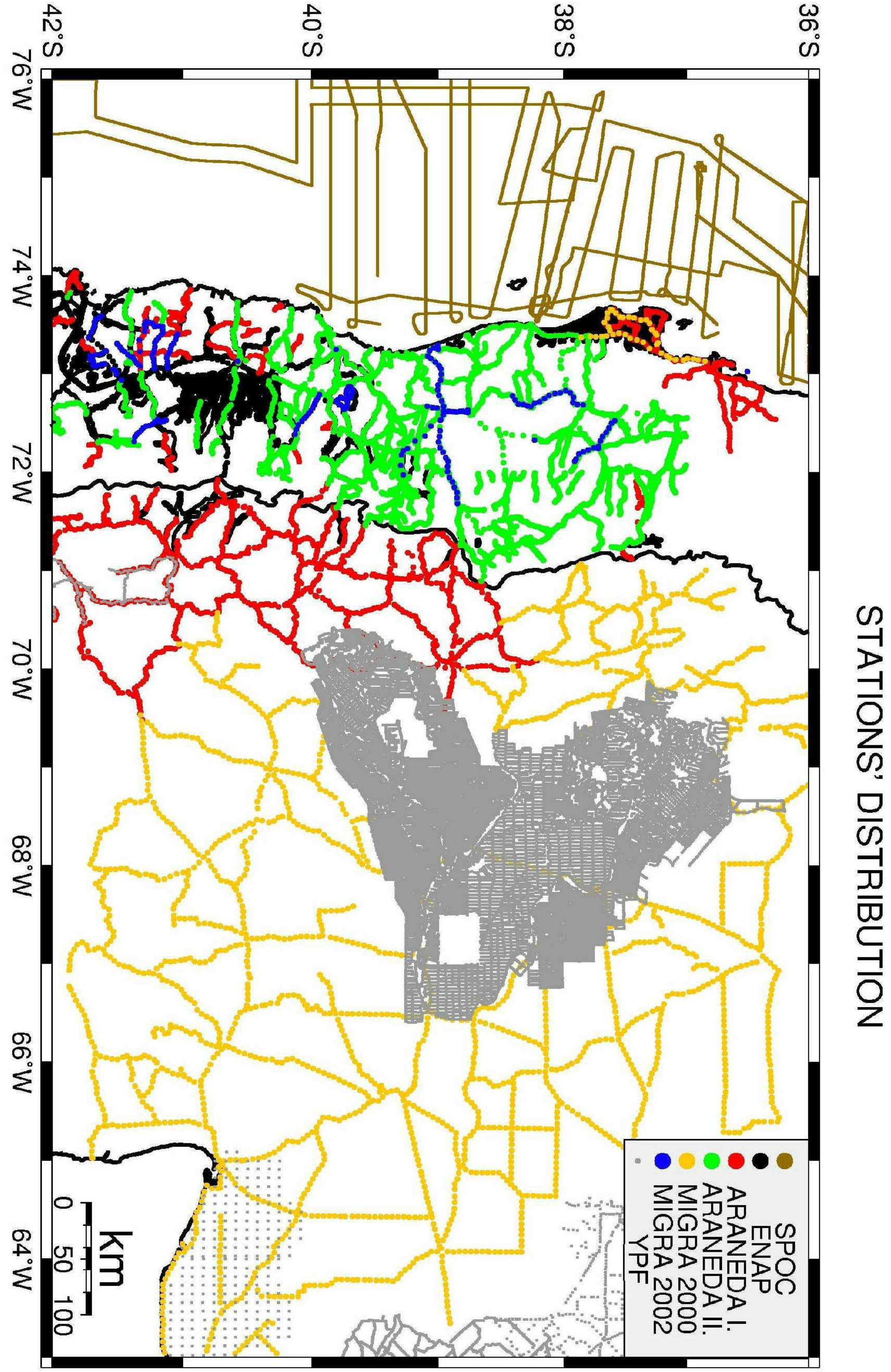
The different techniques, instrumentation and data processing methods used to acquire each dataset resulted in some severe problems within and inconsistencies between the different data files. Based on her analysis of the gravity field, Wienecke (2002) found certain discrepancies between the various Chilean datasets. All stations were again carefully reanalysed before modelling work began.

This analysis was conducted using the DbGrav software, a Java-based in-house program (Schmidt, pers.comm., 2002). Within the Chilean part of the database, three subdivisions of data were identified: the ENAP dataset with 5900 measured points and two groups from the VW Project data with 6400 stations.

All gravity stations are usually measured along the main roads, with an average spacing of 3–5 km. In Argentina, the 40000 YPF stations are mostly situated in a rather small area covering the Neuquén Basin and also the easternmost edges near the Atlantic Ocean. The remaining 2000 stations of the MIGRA 2000 campaign cover region in Argentina, larger than 500 km and broader than 900 km.

Figure 3.2 (opposite)

Gravity data used in this study. The green and red points in Chile and Argentina are stations in the ARANEDA I and II datasets; black points in southern Chile and the Arauco Peninsula are ENAP data; the gray dense network in Argentina show the YPF data; the yellow points are the stations of the MIGRA 2000 dataset, and the MIGRA 2002 data are shown in blue. The brown lines offshore denote the ship-borne gravity data profiles from the R/V Sonne.


STATIONS' DISTRIBUTION
36°S
38°S
40°S
42°S
76°W
74°W
72°W
70°W
68°W
66°W
64°W
● SPOC
● ENAP
● ARANEDA I.
● ARANEDA II.
● MIGRA 2000
● MIGRA 2002
· YPF
km
0
50
100

3.3 Analysis of the gravity database

In an attempt to identify the cause of problems within the Chilean part of the database, it was separated into three different datasets representing the different data sources (Araneda I, Araneda II and ENAP). The absolute gravity values, heights and Bouguer anomaly from three different datasets were then compared along profiles where stations overlap or are located within a given radius (~2 km; Figure 3.3). Misfits were found in all quantities.

A.

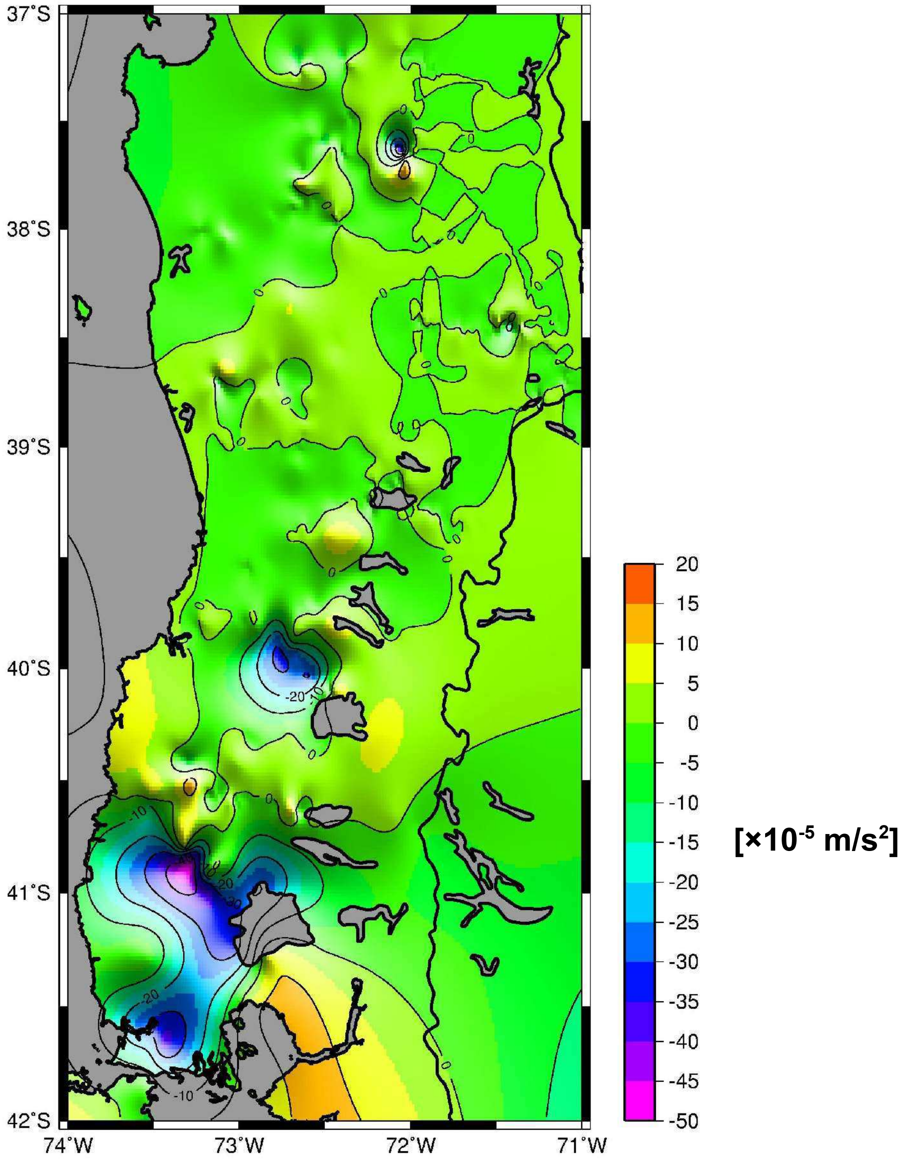


Figure 3.3

The Chilean dataset divided into three parts. The comparisons are made for the absolute gravity values where differences reach -30×10^{-5} m/s^2 (A), heights with differences reaching a maximum of ~90m (B) and Bouguer anomaly values with differences of up to -35×10^{-5} m/s^2 (C).

B.

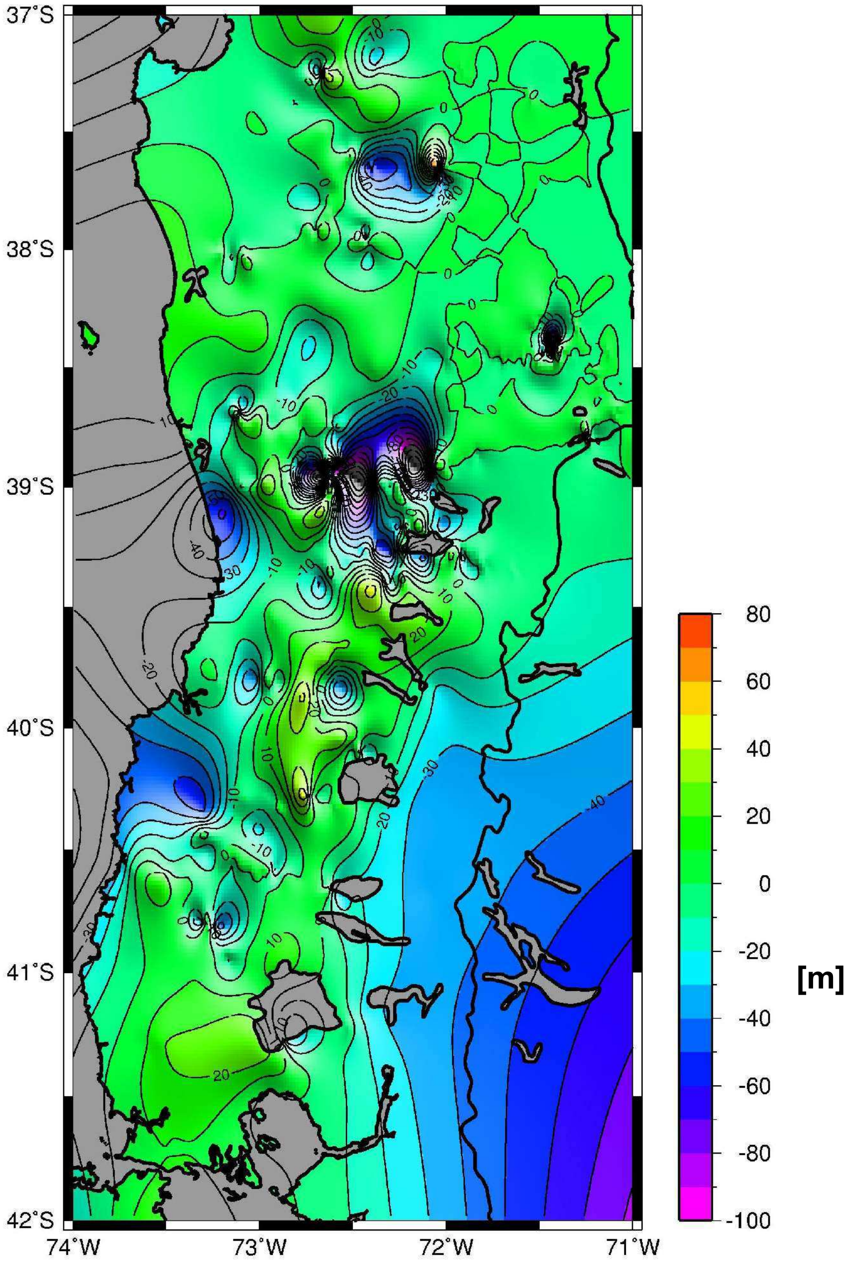


Figure 3.3 (continued)

c.

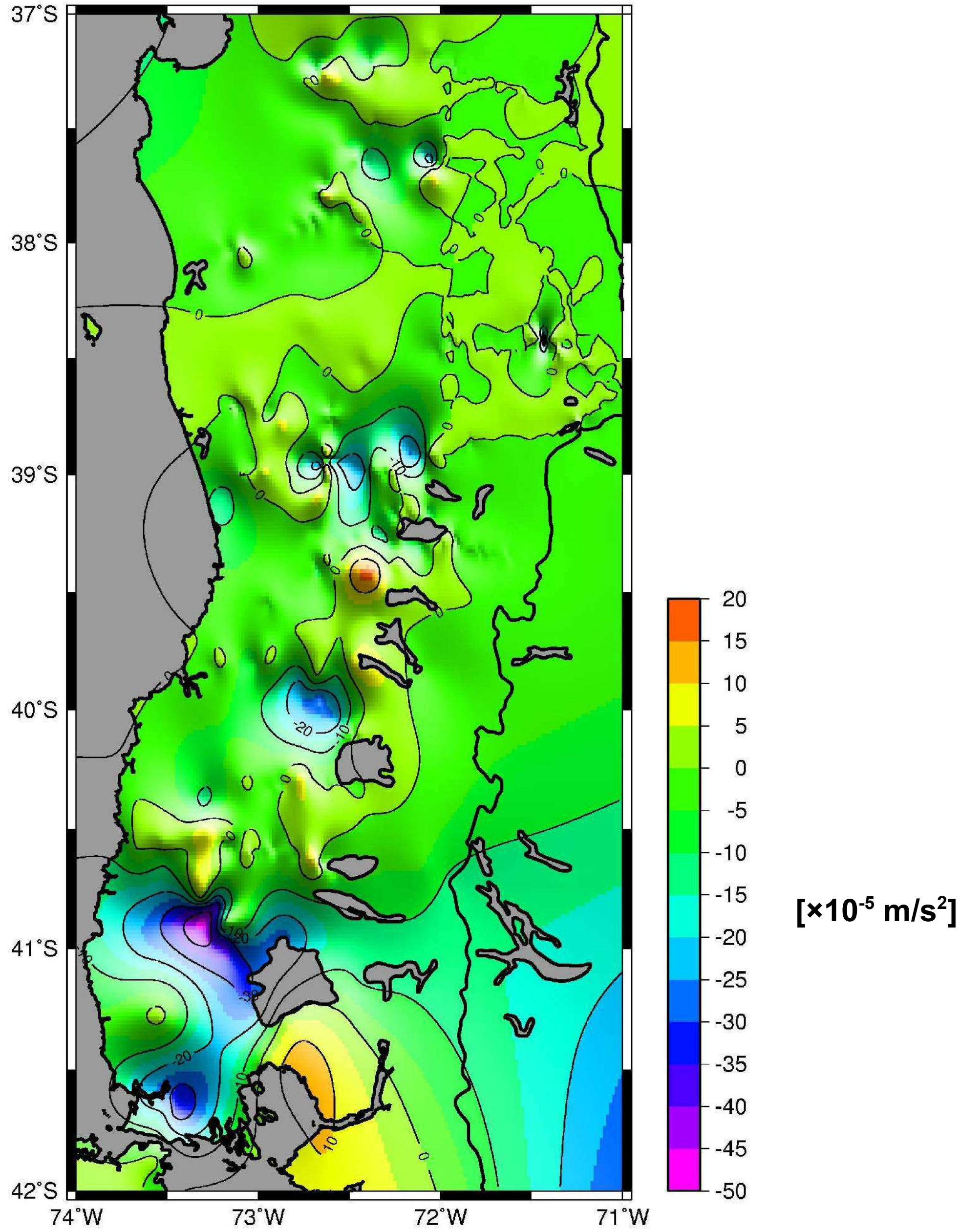


Figure 3.3 (continued)

The results of this comparison clearly reveal that the cause of the differences is not simply a shift resulting from the use of different gravity datums (e.g. the difference between absolute gravity values tied to the IGSN 71 datum and those tied to the old Potsdam gravity datum is ~14×10^{-5} m/s^2). The largest misfits occur in the southern part of the forearc region where the Bouguer anomaly values reach a maximum of ~60×10^{-5} m/s^2 (south of 40°S). The area of the gravity maximum in the study area is located at the continent-ocean transition and in the forearc region of the continental plate and is crucial for the modelling. All additional geophysical data is concentrated in this area, but only between 36° and 39°S. The density model extends to 42°S and should bring new insights into the structures causing the observed gravity field. Therefore, misfits of ~20×10^{-5} m/s^2, sporadically even 30–35×10^{-5} m/s^2 in the Bouguer anomaly (Figure 3.3 C.), are significant.

Further analysis focused on comparison only along profiles common to different datasets. Even after checking the overlapping profiles, none of the three datasets that make up the Chilean part of the database could be identified as the cause of errors. Discrepancies were found in all three tested quantities (absolute gravity values, station elevation and the Bouguer anomaly) meaning that all three parts of the dataset had problems in all three values, not only constantly in one of them. The examples from the DbGrav data processing program illustrate the possible situations (Figures 3.4 and 3.5). The figures show that sometimes the ENAP data fit well with the ARANEDA I dataset, but on different profiles there is a misfit in elevation. On other profiles, only differences in BA are observed, indicating that no topographic correction was applied to compute the station's complete Bouguer anomaly.

A.

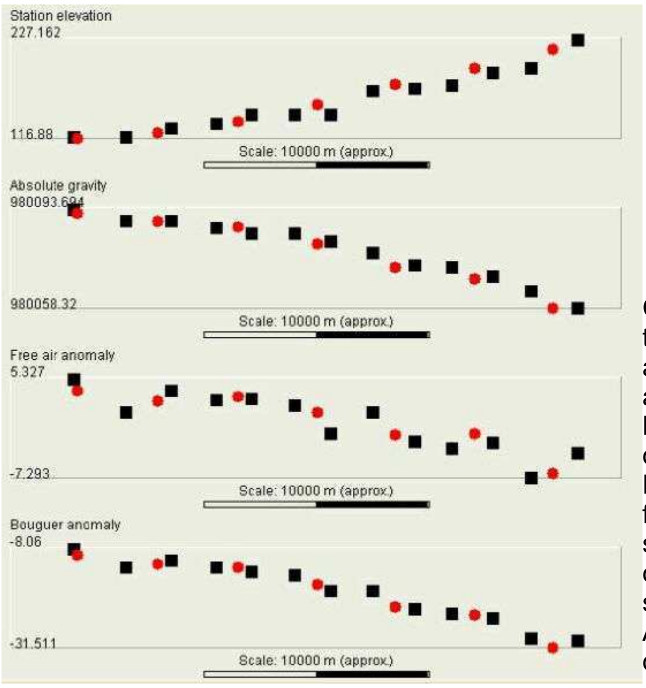


Figure 3.4
Comparison between the ARANEDA I and the ENAP datasets. The quantities shown are, from top to bottom: station elevation, absolute gravity value, Free Air anomaly and Bouguer anomaly. The colour represents different datasets: black points belong to the ENAP dataset and red points are stations from Araneda I dataset. The example in (A) shows a good fit in all four compared quantities, whereas examples (B) and (C) show misfits in the values of elevation, Free Air anomaly and the Bouguer anomaly on two different profiles.

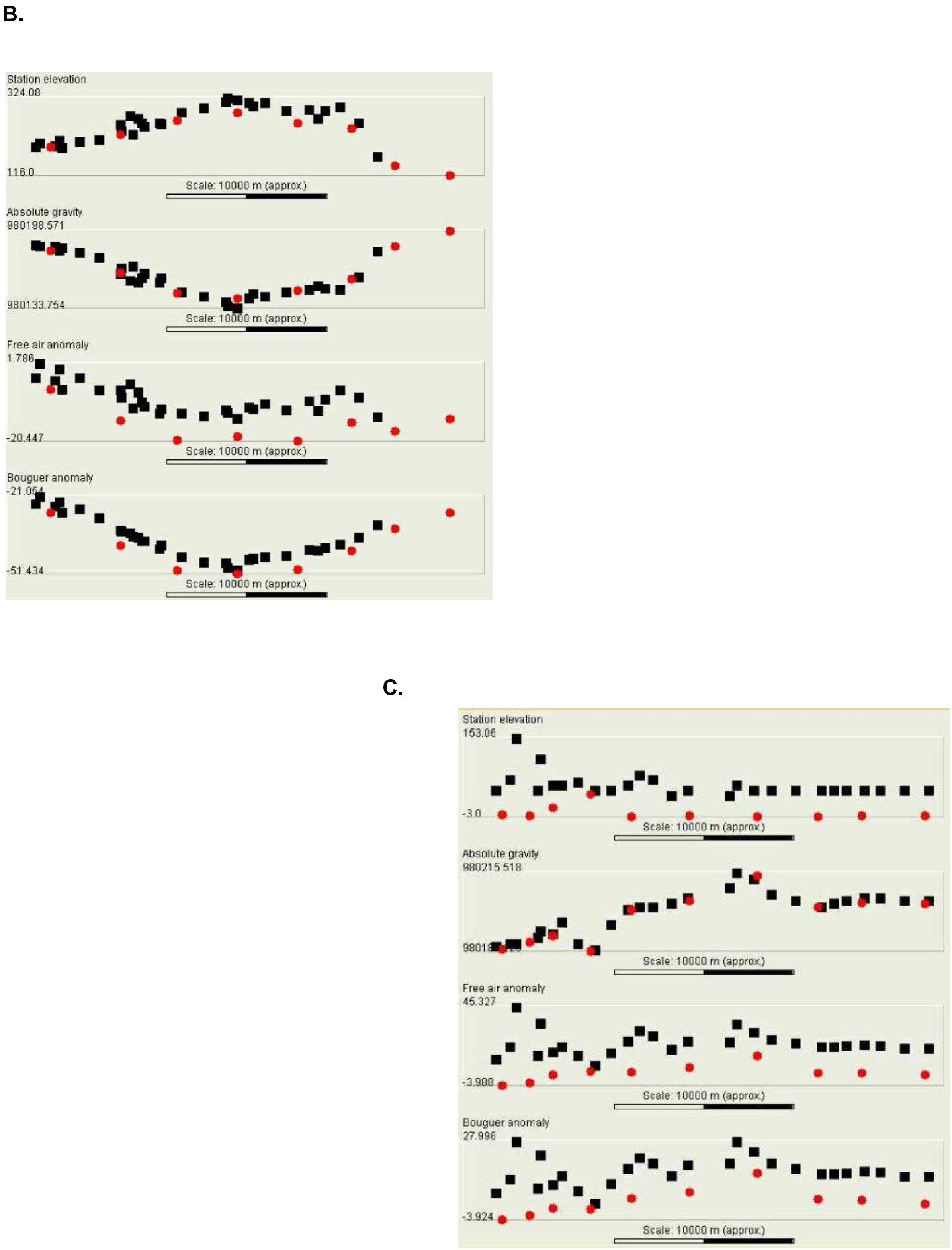


Figure 3.4. (continued)

A.

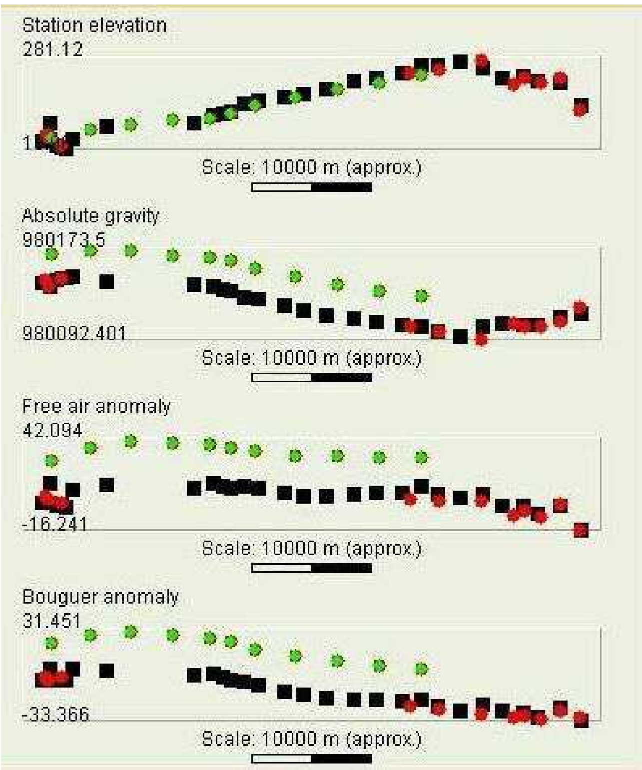
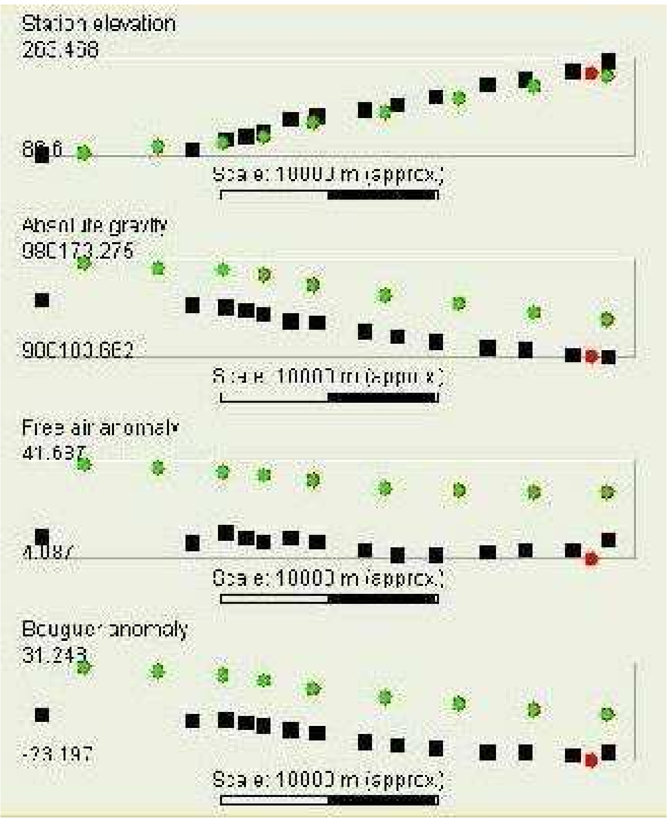


Figure 3.5

Profiles in (A) and (B) show that the stations of the ARANEDA II dataset (green) are shifted in absolute gravity by about 15-25×10^{-5} m/s^2, examples where they overlap with the ENAP (black) and ARANEDA I (red) datasets. On some other profiles, the different datasets fit well (C). The example is taken from the southern forearc region (~41° S) of the positive Bouguer anomalies where no other geophysical data are available.

B.



C.

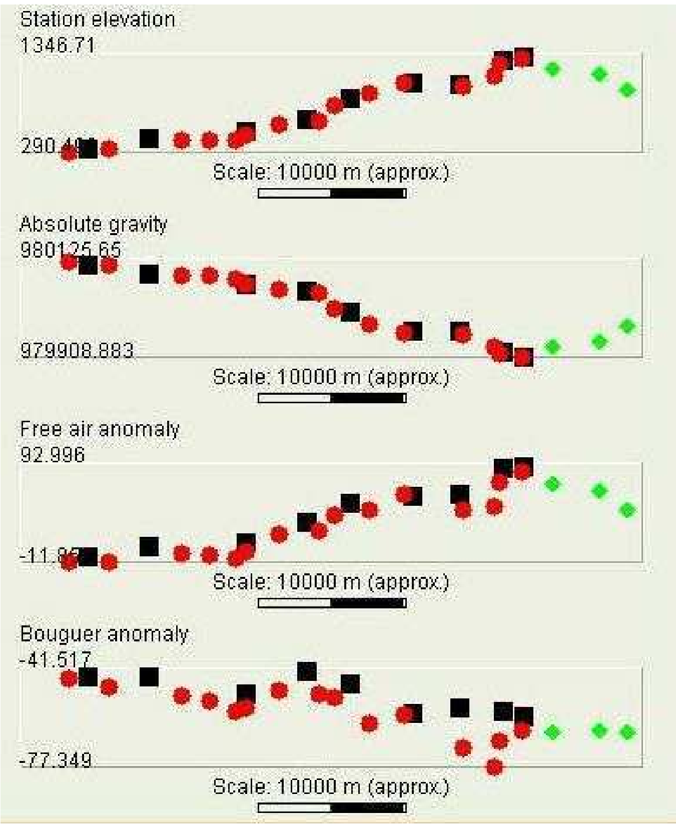


Figure 3.5 (continued)

This problem within the database led to the decision to remeasure some of the critical profiles. We conducted our own control measurements in Chile during the MIGRA 2002 field campaign. During this campaign, 220 stations on 15 selected profiles were remeasured (blue points, Figure 3.6).

The following examples show the results.

One profile of the ARANEDA II dataset in the southern part of the working area was correct (Figure 3.6 C.), the other common profiles were shifted in the absolute gravity values, on average by 25×10^{-5}m/s^2 (Figure 3.6 A., B.). Differences between the new Bouguer anomaly data and the ENAP data exist because the ENAP stations did not include topographic corrections (Figure 3.6 D.). Differences in elevations were also observed, causing differences in the Bouguer anomaly from the different different datasets (Figures 2 and 3 in the App.).

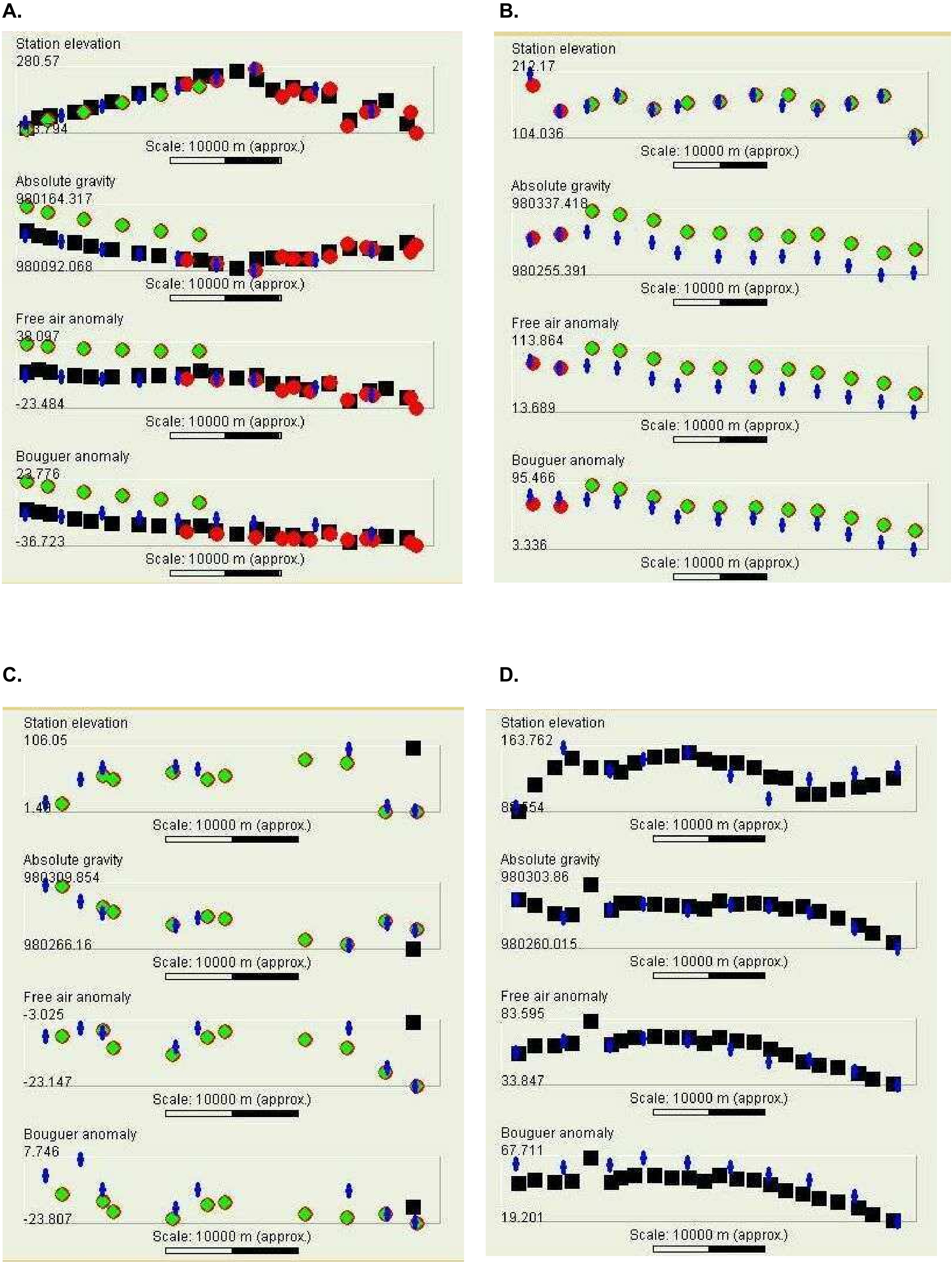


Figure 3.6

The newly measured gravity points (blue) compared with the ENAP (black), ARANEDA I (red), and ARANEDA II (green) parts of the original database. The results whow that errors dominantly occur in the ARANEDA II dataset.

After the remeasurements and additional analysis of the database, ~500 of the 12000 stations (Figure 3.7) with obvious errors were removed. The aim was to eliminate all the obvious mistakes that could be identified, and also to remove stations whose Bouguer anomaly was ≥5×10^{-5}m/s^2 different from nearby stations. Therefore, some of the newly measured MIGRA 2002 data (blue, Figures 3.2 and 3.6) completely replaced the original data (for example, in the ARANEDA II dataset, where the difference sometimes reached ~ 25×10^{-5}m/s^2). The rest of the initial data on the overlapping/neighboring profiles were left in the database together with the new measurements, since the exact same locations could not always be found and resurveyed.

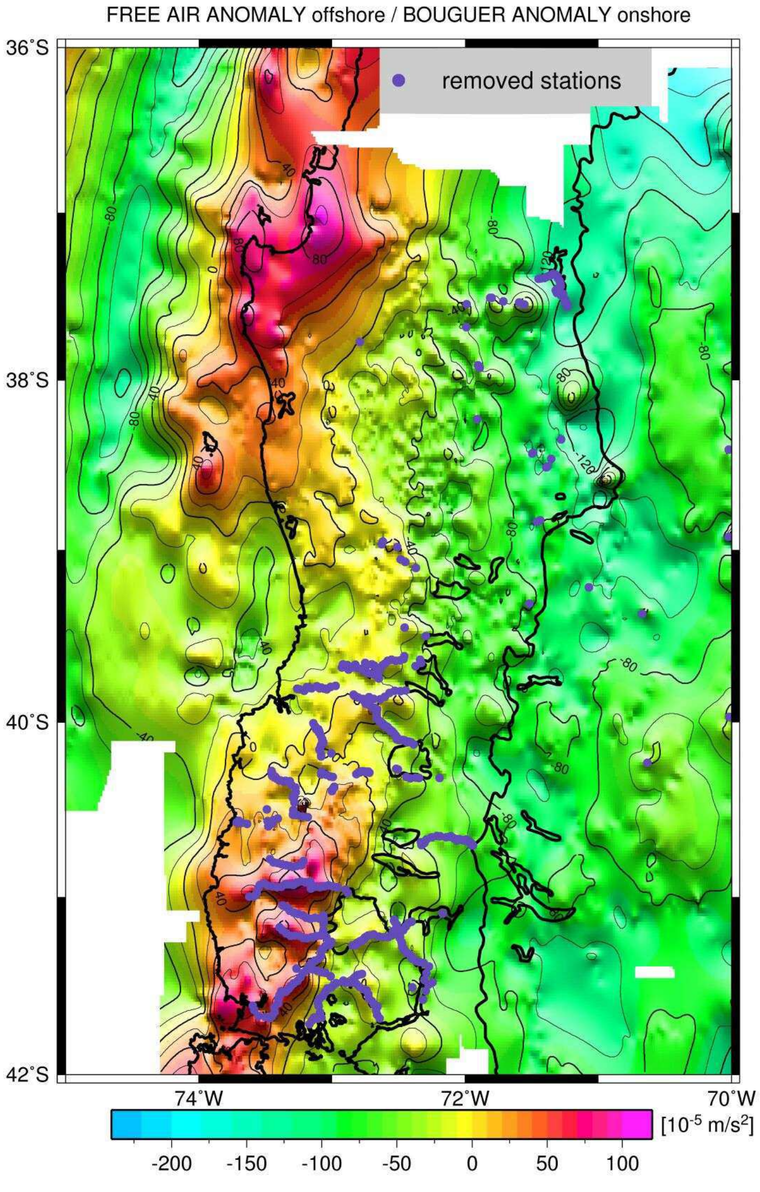


Figure 3.7

Bouguer anomaly map, based on the initial data (including the problematic stations) showing the 500 erroneous stations that were removed from the database.

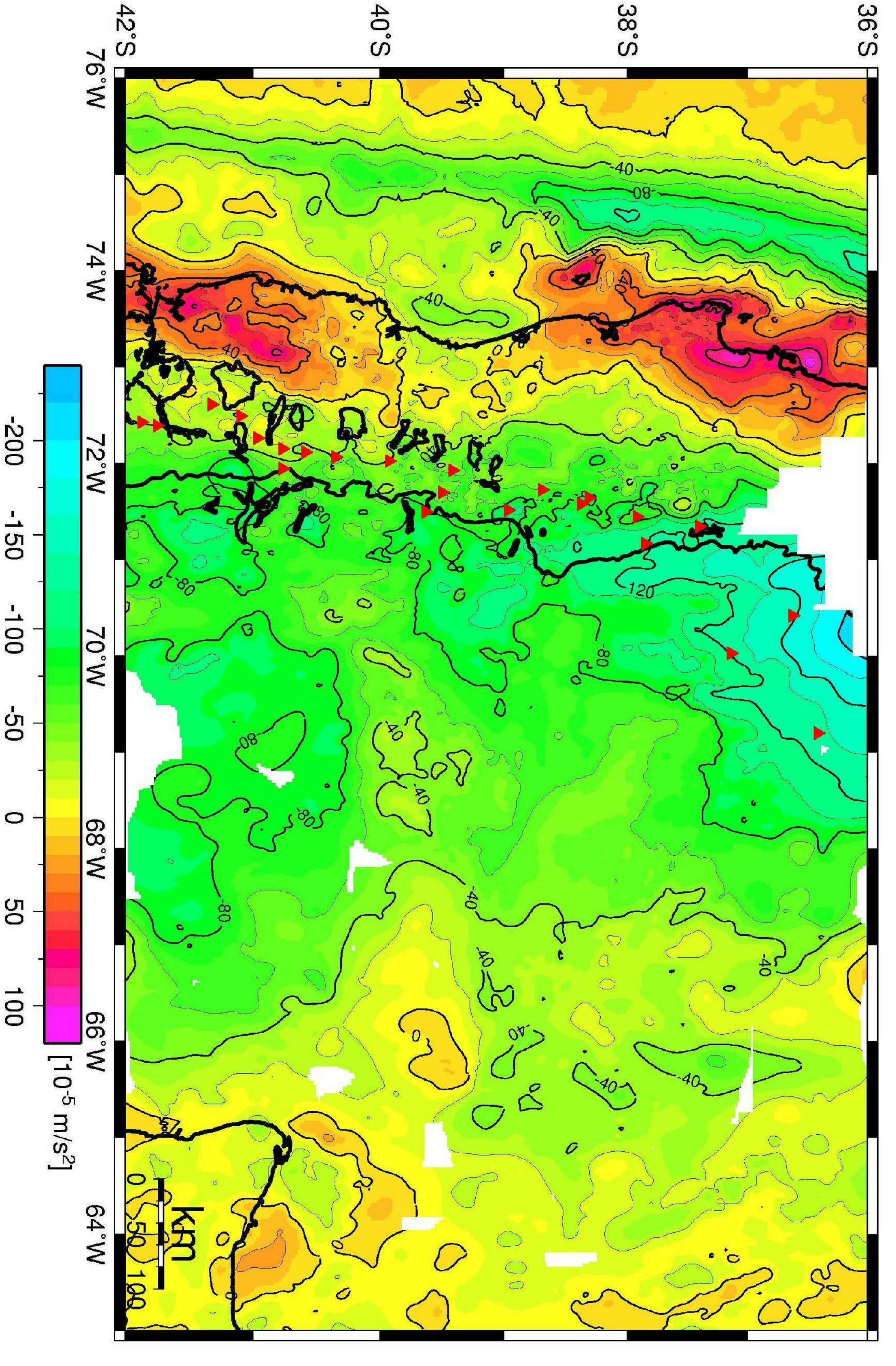
The updated Chilean dataset was then merged with the 42000 Argentinean stations. All of the onshore data were then reprocessed using the DbGrav program.

For the computation of each station's complete Bouguer anomalies, using a spherical Bouguer cap with a radius of 166.7 km, correction densities of 2.67 Mg/m^3 and 1.64 Mg/m^3 for onshore and offshore areas, respectively, were used. The normal gravity formula of 1967 was applied and all the stations were tied to the IGSN71 gravity datum. Onshore, the GLOBE (The Global Land One-km Base Elevation) DEM (Digital Elevation Model) (GLOBE Task Team and others, 1999) with spatial resolution of 1 x 1 km (30-arc-second) was used; and offshore the ETOPO 5 DEM (NOAA) combined with the Zapata grid file (Zapata, 2001) (also 1 x 1 km) were used to derive the topographic corrections. The corrections were derived using a method approximating topography by triangular facets (Götze & Lahmeyer, 1988; Müller, 1999). The Bouguer anomaly values reach a maximum of around 80×10^{-5}m/s^2 along the coastal areas of Chile, where topography is rather low, reaching only a few hundred meters (although locally around the Arauco peninsula region elevations reach 1500 m). Above the main volcanic arc along the Chilean/Argentinean border, where topography reaches ~4000 m, Bouguer anomalies decrease to -180 ×10^{-5}m/s^2.

The gravity stations in the area of interest have an irregular distribution. Altogether, there are more than 12000 stations covering the area between the coastline and the main volcanic arc. More than 2000 points out of these 12000 constitute a very dense network on the Arauco Peninsula. The rest are scattered between latitudes 36° and 41.7°S, and longitudes 73 and 62°W.

Figure 3.8

The figure shows the Bouguer anomaly onshore and the Free Air anomaly offshore. The two pronounced maxima reach values of ~ 80×10^{-5}m/s^2 and ~60×10^{-5}m/s^2 in the northern and southern parts (resp.) of the forearc region; the negative Bouguer anomaly characterizes the entire arc and backarc regions, with a minimum of ~ -180×10^{-5}m/s^2 in the northern part of the arc. A negative Free Air anomaly of -100×10^{-5}m/s^2 is observed at the trench in the northern part of the study area, which increases southwards to ~ -50×10^{-5}m/s^2. The parts of the offshore not measured by the R/V Sonne are filled with KMS data. The red triangles mark the active volcanic arc.



FREE AIR ANOMALY offshore / BOUGUER ANOMALY onshore

3.4 Accuracy of the gravity database

To estimate the accuracy of the Bouguer anomaly values, all quantities used for its computation must be analysed. This analysis only used a simplified formula (3.4.1), with an infinite horizontal plate for the Bouguer correction and an approximate Free Air correction gradient. This formula is:

$$\Delta g_B(P) = g(P) - \left[\gamma(Q) - \delta g_F(P) + \delta g_B(P) - \delta g_t(P)\right] \quad (3.4.1)$$

where:

$g(P)$ - is the measured gravity at a point P on the Earth's surface,

$\gamma(Q)$ - is the normal gravity related to the point Q on the reference ellipsoid that generates the normal gravity field,

$\delta g_F(P)$ - is the Free Air correction,

$\delta g_B(P)$ - is the Bouguer correction,

$\delta g_t(P)$ - is the topographic correction,

The Free Air correction is, in simplified form, defined as:

$$\delta g_F(P) = \left(\frac{\partial \gamma(Q)}{\partial h}\right) H(P) = -0.3086 H(P) \quad [\times 10^{-5} \mathrm{m/s^2}] \qquad (3.4.2)$$

while the vertical gradient of gravity $\partial g(P)/\partial H$ is approximated by the vertical gradient of normal gravity $\partial \gamma(Q)/\partial h$.

The simplified Bouguer correction is defined as:

$$\delta g_B(P) = 2\pi G \rho H(P) = 0.0419 \rho H(P) \qquad (3.4.3)$$

where:

G - Newton‘s gravitational constant (sometimes also denoted κ or k)

$G = 6.67 \times 10^{-11}\ \mathrm{m^3kg^{-1}s^{-2}}$

ρ – is the correction density in $\mathrm{Mg/m^3}$

H(P) - is the height in meters (ellipsoidal or orthometric)

with $\rho = 2.67 Mg/m^3$, then

$$\delta g_B(P) = 0.1119 H(P) \quad [\times 10^{-5} \mathrm{m/s^2}] \qquad (3.4.4)$$

By means of the Free Air correction, the normal gravity at the reference level is corrected to the point P. This correction accounts for the separation between the two levels.

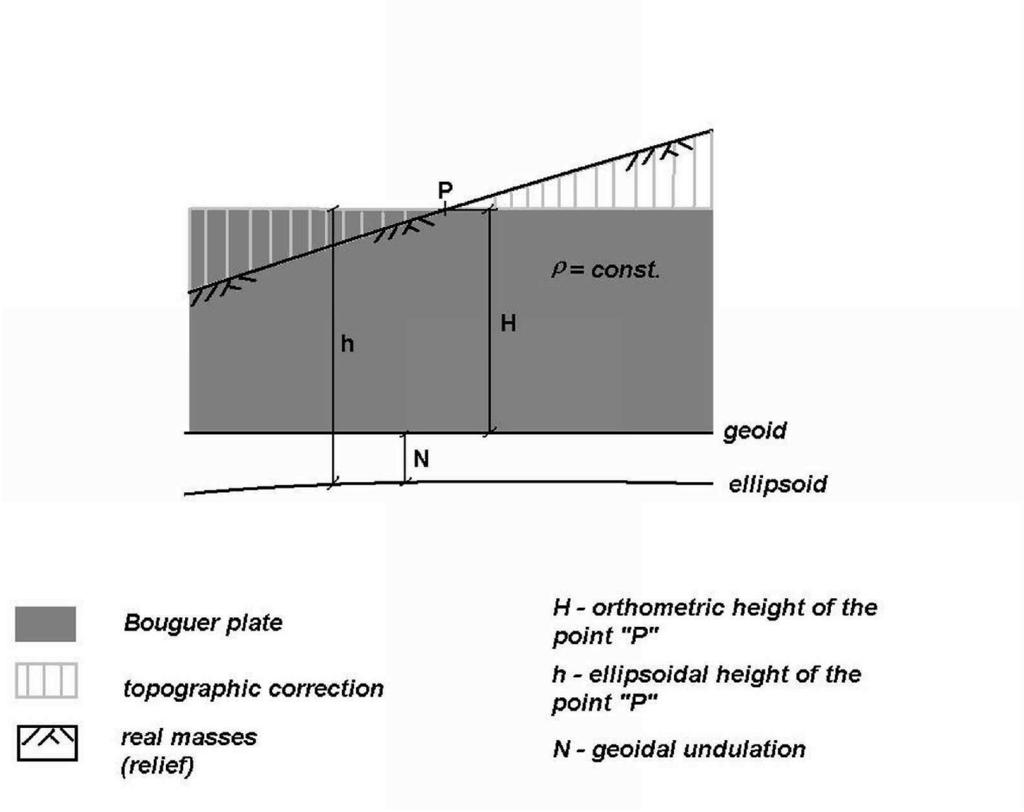


Figure 3.9
A simplified description of how the Bouguer anomaly is computed. The Bouguer plate of constant density is represented by the dark gray rectangle. The topographic correction involves the masses represented by the striped triangular bodies in the vicinity of the point P. Together, they constitute the topography (real masses) around the measurement point P.

The Bouguer correction approximately accounts for the effect of the real topographic masses, which are between the Earth's surface and the reference level (ellipsoid or geoid). The Bouguer plate, or Bouguer cap because the Earth is curved, is a plate/cap of constant density, normally 2.67 Mg/m^3, and thickness that corresponds to the height above the reference level.

In order to obtain a station's complete Bouguer anomaly, topographic correction must be applied. The topographic correction, δg_t mathematically computes the effect of the added/missing masses that are included/excluded by the Bouguer plate/cap (Figure 3.9). This correction is applied to an area of radius some tens of kilometers (e.g. 50, 100, 166.7 – the later is called also the Hayford zone O_2) around the gravity station.

The most accurate quantities in the Bouguer anomaly estimation are the measured gravity g and the normal gravity γ. The gravity measurement by the LaCoste & Romberg gravimeters achieve accuracy of $0.01\times10^{-5}m/s^2$ and the reference value of the normal gravity can be determined with an accuracy ~ $0.1\times10^{-5}m/s^2$, using older and simpler formulas (e.g. the 1967 or 1930 formulas) (Torge, 1989).

The input value that is of greatest importance concerning the precision of the Bouguer anomaly calculation is the station elevation. This quantity appears in both corrections, Free Air and Bouguer, and produces differences of ~ $2\times10^{-5}m/s^2$ /10m.

An estimate for gravity anomaly accuracy can be precisely determined only for the data remeasured during the field campaign in Chile in 2002, as well as for the MIGRA 2000 data measured in Argentina. The information concerning the data acquisition and processing is namely available only from these two campaigns. For the remaining 52000 stations in Chile and Argentina, due to the lack of information, an estimate can be only assumed.

For the MIGRA 2000 campaign, the accuracy of measured data is of the order of $0.05\times10^{-5}m/s^2$ (Wienecke, 2002). The station elevations were measured by differential GPS (DGPS) and achieve cm precision. One centimeter deviation in the height measurements mean $0.02\times10^{-5}m/s^2$ difference for the Bouguer gravity anomaly. Therefore, it can be concluded that the accuracy of the gravity anomaly values of the MIGRA 2000 dataset, without the topographic correction, is ~ ± $0.1\times10^{-5}m/s^2$.

For the MIGRA 2002 data, the accuracy of gravity measurements is of order of $0.05\times10^{-5}m/s^2$. The accuracy of the height estimates, however, is worse than for the MIGRA 2000 dataset, because the elevation was measured using absolute GPS with a standard deviation of up to several meters in the vertical direction. Assuming 20 m uncertainty in station elevation, the precision of the Bouguer anomaly is of the order of $4\times10^{-5}m/s^2$ (assuming that the density value in the Bouguer correction component, formulas 3.4.3 and 3.4.4, is correct).

For the rest of the database, we can assume the accuracy of the gravity measurements from the comparison of the data on the overlapping profiles to be of the order of 0.1×10^{-5}m/s^2. Before reprocessing, differences between MIGRA 2002 data and the other datasets, in the absolute gravity value, were found only rarely. More often, differences in elevations were found, sometimes reaching ~20-50 m, but on average only a couple of meters.

Based on 212 gravity stations, it is difficult to make an estimate for the remaining 12000 stations that were not remeasured. The remeasured profiles are concentrated in the area south of 39°S on the flat Chilean forearc land. On one of the profiles with higher elevations (~1000 m), the difference in the elevation measurements reach 90 m. It has to be assumed that elevations in a large part of the database were measured using altimeters. Without drift corrections and depending on temperature and pressure, the accuracy of altimeter measurements is no better than 10s of meters.

The overall quality of the original data was not improved by means of error elimination and new processing. The differences between the original data and the remeasured points after reprocessing on some of the overlapping/neighboring profiles are on average $1–3\times10^{-5}$m/s^2 (maximum 5×10^{-5}m/s^2) in the Bouguer value, with maximum differences in elevation reaching ~10–20 m. Such differences are also observed between the initial datasets. Also, within the same part of the database on one profile there are certain deviations of some points relative to the rest of the profile. These local deviations can be observed within the Bouguer anomaly map (Figure 3.8) and later in the cross sections of the 3D density model. Due to a lack of information dealing with the initial data and their accuracy, it is not possible to make further improvements. Therefore, data remote from the controlling measurements, were left in their original form. No other techniques to smooth the data were used, so that the real (measured) values were preserved as much as possible. These data do however contain some errors, but for the purposes of regional-scale density modelling, the database is sufficiently precise.

Taking into account all the above mentioned factors, the accuracy of the computed Bouguer anomaly values for the entire database after reprocessing is in the range of $\pm 5–10\times10^{-5}$m/s^2.

The accuracy of the heights in the digital elevation model (DEM) used for the calculation of the topographic correction are also important. As mentioned above, during the reprocessing of the data, the calculation of the topographic correction for the station complete Bouguer anomaly used the GLOBE DEM (GLOBE Task Team et al., 1999). This DEM is partly based on digitized topographic maps that were combined with other digital terrain elevation data (DTED) (GLOBE Task Team et al., 1999). Therefore, its accuracy was expected to be better than the accuracy of the GTOPO30 (global DEM with a horizontal grid spacing of 30 arc seconds, USGS EROS Data Center) that was used for the BA calculation before the remeasurements. GTOPO30 is based mainly only on DTED. Figure 3.10 shows a comparison of the BA values computed with the two above named DEMs. Maximum differences reach ~10–15×10^{-5}m/s^2.

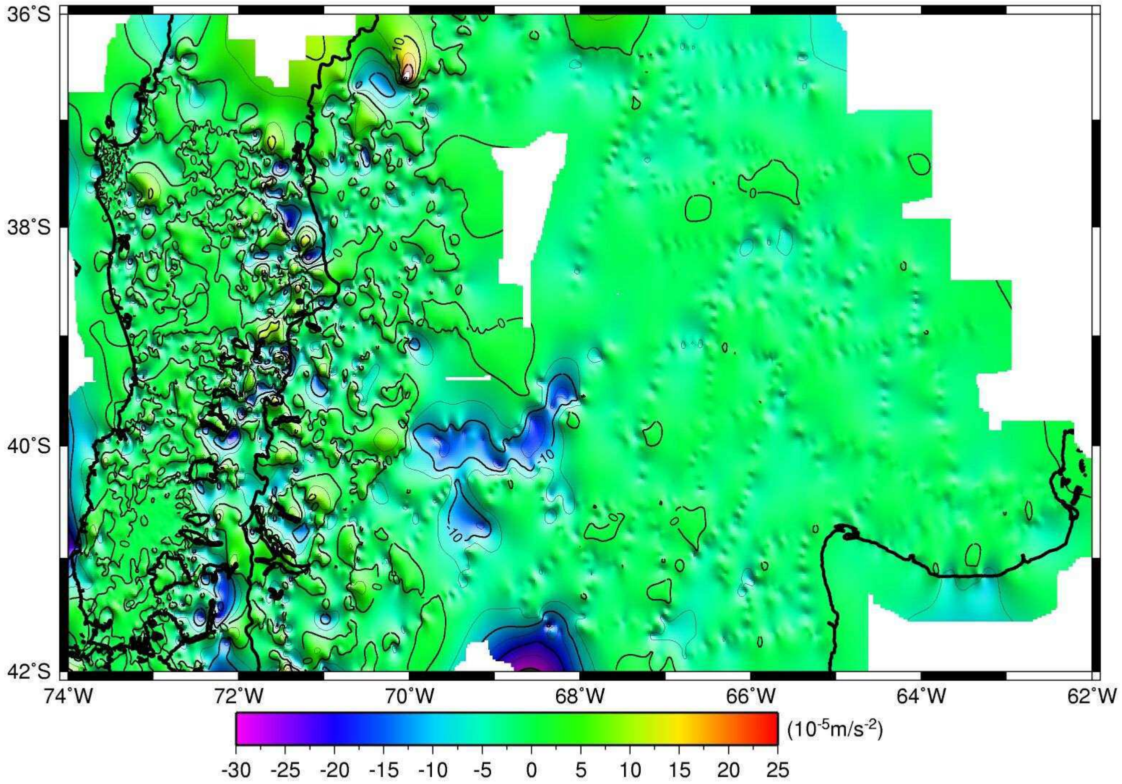


Figure 3.10

The difference in the Bouguer anomaly values [×10^{-5}m/s^2] computed by using the GTOPO30 and the GLOBE DEMs. The maximum differences reach ~ ±20 .10^{-5}m/s^2.

However, as shown in Table 3.1 (Müller-Wrana, pers. comm., 2004), in spite of the fact that there are differences between the two elevation models, their accuracy is similar. This table shows a comparison between accurate elevation measurements of gravity stations in a different study area in south Argentina and heights of these stations extrapolated from both DEMs (GTOPO30 and GLOBE).

DEM	Average value of differences	Minimum difference	Maximum difference	Standard deviation
GTOPO30	-2,64 m	-436 m	365 m	85,32 m
GLOBE	-21,16 m	-429 m	361m	90,10m

Table 3.1

Comparison of the two DEMs with accurate elevation data. This comparison was done on a limited area, therefore it cannot be generalized for the whole South American continent, covered by thse DEMs and for the study area of this thesis. However, although performed in a small area, it implies the accuracy of both elevation models.

The station complete Bouguer anomaly values (including the topographic corrections) were used also for the forward modelling, although the GLOBE DEM used seemed not to be very accurate. The maximum differences in elevation cause large differences in the calculated BA values, which is crucial for the modelling. Nevertheless, on average the topographic corrections computed using the GLOBE DEM are smaller. Only ~7.3% of the values are greater than 5×10^{-5} m/s^2 (Figure 3.11). Thus, the simple Bouguer anomaly (not including the topographic correction) was also tested during modelling. The differences in the model (its structure, density values and geometry) were insignificant. Therefore, station complete Bouguer anomalies computed with the GLOBE DEM were used while constructing the 3D density model.

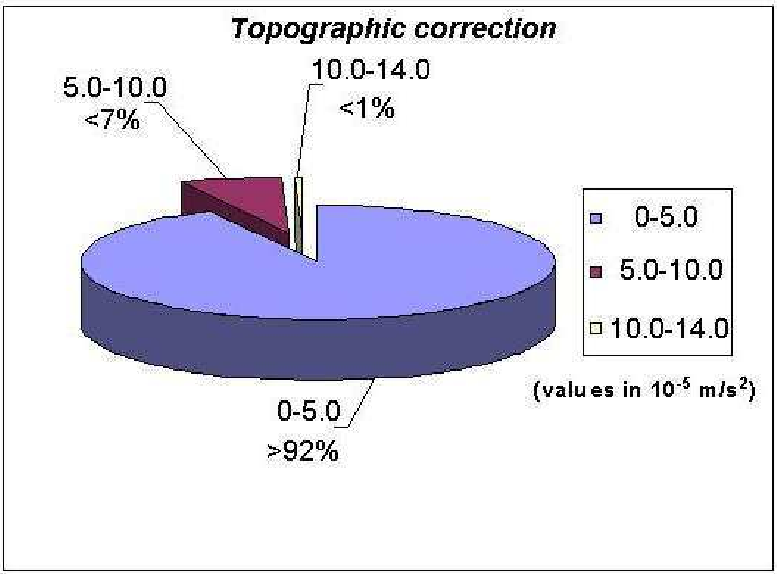


Figure 3.11

The range of the topographic correction values in %, calculated using the GLOBE DEM.

The last quantity to be analysed is the reference density used for the Bouguer plate. This value is normally 2.67 Mg/m^3. It is considered to be an average density of granite and is a standard parameter that has been used in geophysics for more than 100 years as a density that represents surface rocks (Hinze, 2003). It is often asked weather this value is correct, and how it effects the resulting Bouguer anomaly.

If another value for the reference density is used in formula 3.4.3, for instance 2.77 Mg/m^3, the Bouguer correction will then be defined as:

$$\delta g_B(P) = 0.1160 H(P) \quad [\times 10^{-5}\mathrm{m/s^2}] \qquad (3.4.5)$$

This results in a difference in the Bouguer anomaly of 4×10^{-5}m/s^2 per 1000 m elevation. In a very precise gravity dataset, and for areas with high elevation where the composition of the upper crust is well known (regionally), also this quantity should be constrained. For the Central Andean area, where the elevation exceeds 4000 m, a constant density difference of 0.1 Mg/m^3 would cause differences of 16×10^{-5}m/s^2 in the Bouguer anomaly. Taking into account probable density variations within depths, the differences in derived Bouguer anomaly would be even larger. Therefore, if possible, a study area should be precisely analysed in terms of a composition of surface rocks.

In the study area, between 36–42°S, a density difference of 0.01 Mg/m^3 is equivalent to gravity difference of 6×10^{-5}m/s^2 within the area of the Main Arc (Figure 3.12).

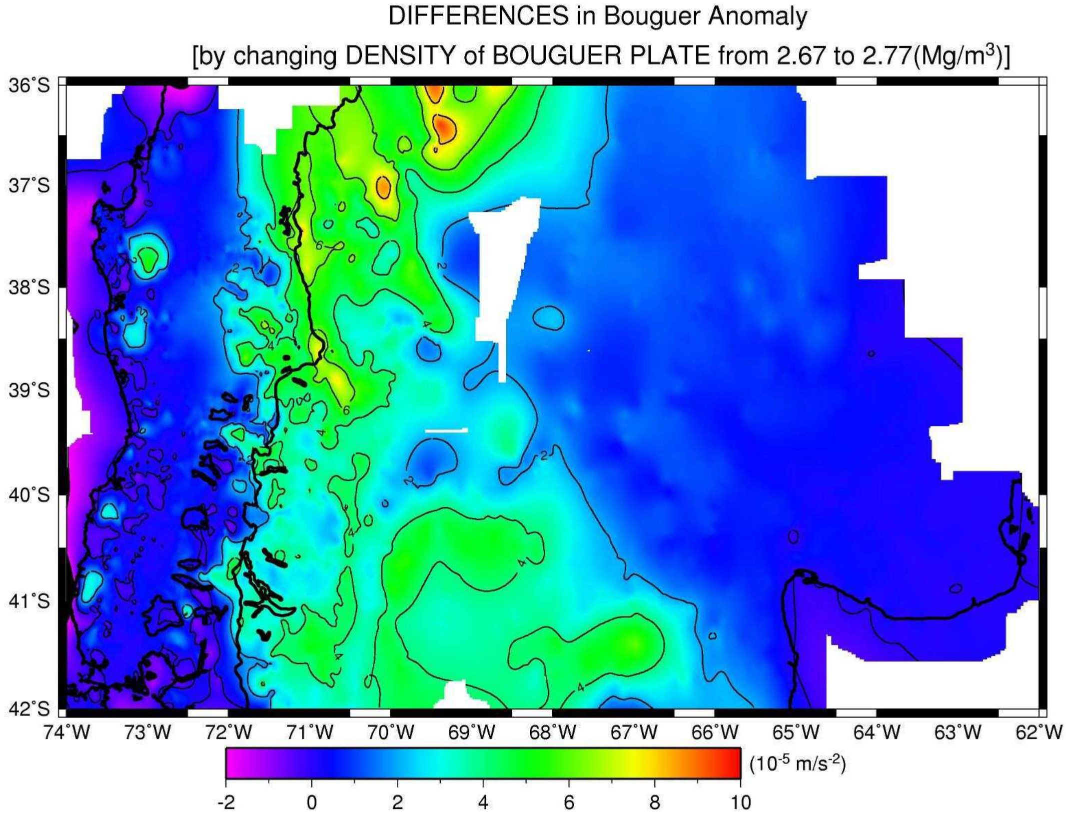


Figure 3.12

The difference in the Bouguer anomaly [$\times 10^{-5}$m/s^2] computed using two different reference densities of the Bouguer plate. The density variation of only 0.01 Mg/m^3 causes differences of 6–9$\times 10^{-5}$m/s^2 in the area of the highest topography at 36°–37°S and 69°–71°W.

The topography is not included in the density model because the effect of topographic masses is assumed to be accounted for by the Bouguer correction. Nevertheless, this correction does not consider density inhomogeneities between the reference level and the Earth's surface, thus it can cause some errors. However, the density values used in the model for the upper crust in areas with high topography (where a density difference has the strongest effect) are ~2.68–2.7 Mg/m^3 (see Chapter 5), so the Bouguer plate/cap density of 2.67 Mg/m^3 is reasonable.