Invitation to a gravity-modelling challenge: an open dataset to constrain the Balmuccia peridotite body (Ivrea-Verbano Zone, Italy)

György Hetényi[1,@], Ludovic Baron[1], Matteo Scarponi[1], Shiba Subedi[1], Konstantinos Michailos[1,+], Fergus Dal[2], Anna Gerle[3], Benoît Petri[4], Jodok Zwahlen[1], Antonio Langone[5], Andrew Greenwood[6], Luca Ziberna[7], Mattia Pistone[8], Alberto Zanetti[5], Othmar Müntener[1]

[1] University of Lausanne, Switzerland (gyorgy.hetenyi@unil.ch)
[2] MSc of Geomatics, ETH Zurich, Switzerland
[3] Independent investigator
[4] University of Strasbourg, France
[5] University of Pavia & IGG CNR, Italy
[6] Montanuniversität Leoben, Austria
[7] University of Trieste, Italy
[8] University of Georgia, USA
[+] now at: University of Geneva, Switzerland
[@] Corresponding author: gyorgy.hetenyi@unil.ch

Abstract

The Balmuccia peridotite exposes relatively fresh mantle rocks at the Earth’s surface, and as such it is of interest for geologists and geophysicists. The outcrop is a kilometre-scale feature, yet its extent at depth is insufficiently imaged. Our aim is to provide new constraints on the shape of the density anomaly this body represents, through 3D gravity modelling. In an effort to avoid personal or methodology bias, we hereby launch an invitation and call for participative modelling. We openly provide all the necessary input data: pre-processed gravity data, geological map, *in situ* rock densities, and digital elevation model. The expected inversion results will be compared and jointly analysed with all participants. This approach should allow us to conclude on the shape of the Balmuccia peridotite body and the associated uncertainty. This crowd effort will contribute to the site surveys preparing a scientific borehole in the area in frame of project DIVE.

Keywords

Gravimetry; Gravity Anomaly; Modelling; Open Science; Alps; Balmuccia peridotite

1. Introduction and motivation

Modelling of geophysical data is often subject to choices made by the researcher(s) undertaking the work. The level of structural complexity in the model, the bounds on parameters imposed by *a priori* knowledge, the thoroughness and efficiency in exploring the parameter space may all lead to bias in determining what the best fitting models can be.

To avoid personal or any other bias related to prior information and methodology in constraining the subsurface shape of a given density anomaly, we hereby invite anyone interested to create their own model(s) on a targeted case study: the Balmuccia peridotite body (45.84°N, 8.16°E) in the Ivrea-Verbano Zone (IVZ), Western Alps, Italy. Here relatively fresh, least serpentinized mantle rocks (e.g., Lensch 1971) are naturally exposed at the surface, in the broader context of the IVZ, a middle- to lower crustal terrain along the Eurasia-Adria plate boundary’s eastern side. The surface exposure of the Balmuccia peridotite is ca. 4.4 km N-S by ca. 0.6 km E-W, with outcrop elevation changes exceeding 1000 m.

We here provide the same starting conditions to all participants in this crowd-modelling effort. Practically, all the necessary input data have been measured, pre-processed, and are shared in this work: (1) gravity data measured in the field at 151 new points; (2) the local geological map, including four units and structural indicators; (3) *in situ* rock density values for each of the four units; (4) the local digital elevation model (DEM) – see section 2 for a detailed description. Each participating researcher or group will be able to download the data freely and will subsequently be expected to submit their solution(s). The resulting collection of models will be compared during a dedicated workshop, based on which a joint publication can be envisaged – see section 3 for the proposed frame.

Beyond the modelling challenge, the interest in constraining the subsurface shape of the Balmuccia peridotite body is that it is a future target of the Phase 2 of the DIVE continental drilling project (Drilling the Ivrea-Verbano zonE; Pistone et al. 2017; www.dive2ivrea.org and https://www.icdp-online.org/projects/by-continent/europe/dive-italy/). Therefore, the expected results will be of practical use in planning the drilling site and geometry, and in case of drilling the model(s) can be compared with real data at depth.

2. Data description

The openly shared input data contains four parts. These are presented below in the following order: digital elevation model, geological map compilation, rock densities, and new gravity data following pre-processing. The files corresponding to each part are described in the last sub-section.

2.1 Digital elevation model

The most recent, LiDAR-based DEM for the area of study was downloaded from the Piemonte Region geoportal, under the name “RIPRESA AEREA ICE 2009-2011 - DTM 5" (https://www.geoportale.piemonte.it/geonetwork/srv/ita/catalog.search#/metadata/r_piemon:224de2ac-023e-441c-9ae0-ea493b217a8e, sheets 93 and 72, last downloaded on 02.11.2023). The downloaded data, available under the Creative Commons licence, is in UTM coordinates (zone 32 T), and elevation is (seemingly) above sea-level. According to the accompanying metadata, the base data was acquired in 2009-2011 with aerial photogrammetric survey and LiDAR measurements using Leica ASL at an altitude of 400 m. The DEM has a nominal spatial resolution of 5 m, and an elevation accuracy of ±0.30 m (±0.60 m in wooded and densely urbanised areas). This is the most recent and highest quality topographic data that we could identify.

As a way of checking the DEM quality, the peak of the peridotite body, Cima di Lavaggio (45.84651°N, 8.16325°E) was climbed in 2022, and a GPS point acquisition was performed. Following PPP processing and geoid height correction (see section 2.4.4 for details), the new determination of Cima di Lavaggio summit has been compared to the value taken from the local maxima in the DEM (Table 1).

Method	**UTM X (m)**	**UTM Y (m)**	**Elevation (m)**
GPS (PPP, geoid corr.)	435’029.8 ± 0.014	5’077’334.6 ± 0.023	1596.06 ± 0.16
DEM local summit grid pt.	435’027.5 ± 2.5	5’077’332.5 ± 2.5	1596.49 ± 0.30 (0.60)

Table 1: Location and elevation of Cima di Lavaggio, from new field observation and the selected Digital Elevation Model.

The input elevation data to this study as a subset of the selected DEM, covering 12 km in each cardinal direction from 45.84°N, 8.16°E. The selected area extends from 422’770 to 446’770 in the X and from 5’064’615 to 5’088’615 in the Y direction, with cell-centred elevation values (full matrix size: 4800*4800), ranging from 352.83 to 2797.29 m (Fig. 1). Beyond this distance, we recommend using SRTM or other elevation models of similar resolution, as even poorly resolved topography would yield negligible artefacts in the gravity signal.

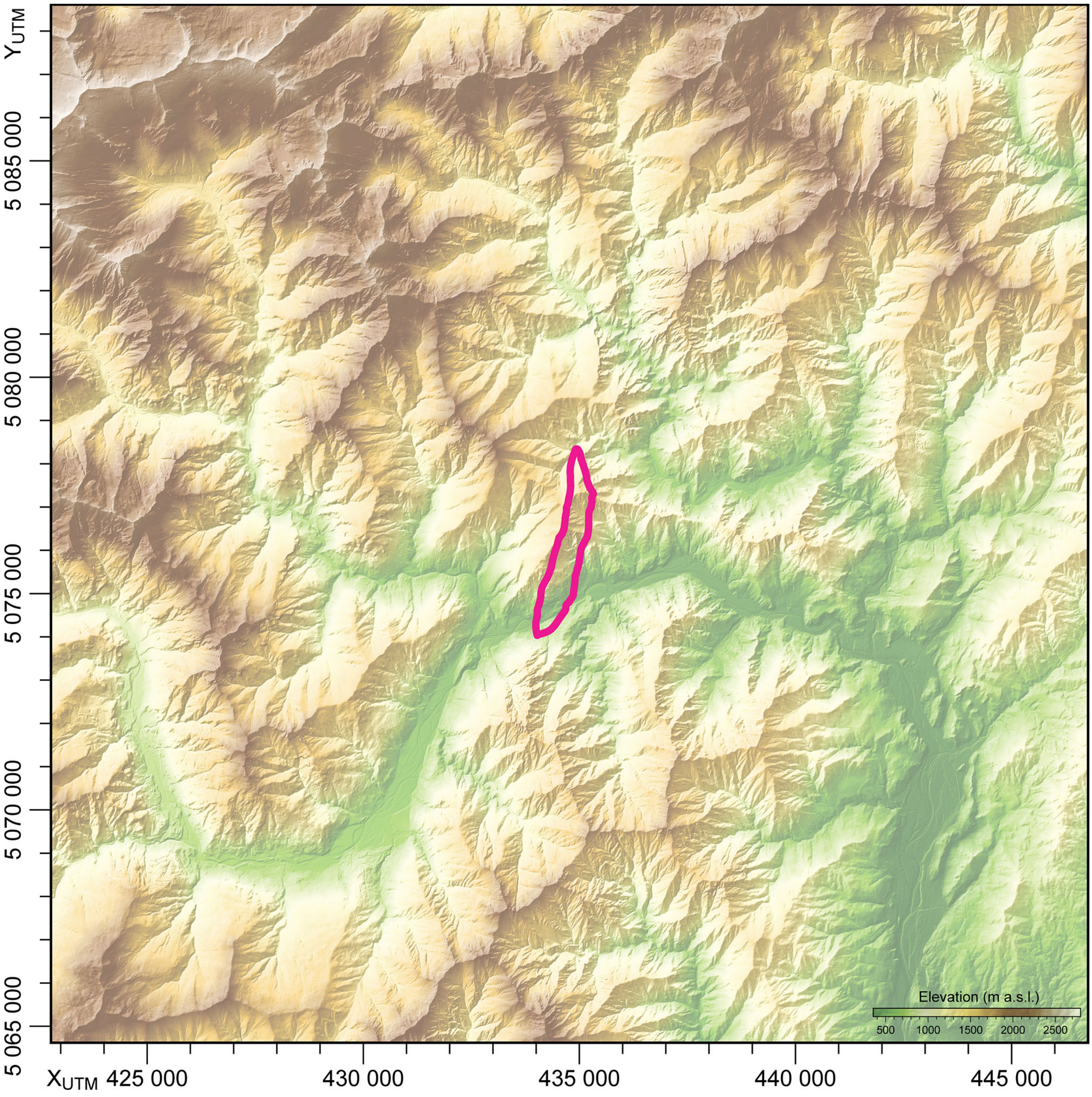

Figure 1. Topographic map of the area, with the contour of the Balmuccia Peridotite unit. Document produced by the authors, based on "RIPRESA AEREA ICE 2009-2011 - DTM 5" of the Regione Piemonte Geoportal (weblink, last download 02.11.2023).

2.2 Geological map

The aim of providing a geological map as an input to the modelling challenge is to share the upper boundary condition: the contour of the main lithologies (for which densities are described in section 2.3), and structural indicators of dip to indicate the general orientation of structures (i.e., foliation and layering) at the surface.

The Balmuccia peridotite body and surrounding areas have been the focus of several local and part of numerous regional geological maps (e.g., Rivalenti et al. 1975; Shervais 1979; Horstmann 1981; Rivalenti et al. 1981; Rivalenti et al. 1984; Shervais and Mukasa 1991; James 2001; Quick et al. 2003). These maps agree on the general contour of the peridotite body, which is central to our purpose of delineating the main lithologies, therefore we are not focusing on local and other descriptive differences between the maps. Relatively small (1-10 m) extent units are not considered because their influence on the gravity signal is negligible. The focus of the shared surface geological map is on the 0.1-1 km size units, and our compilation based on earlier maps and our own field observations comprises four main lithological units. These units, from East to West, are (Fig. 2):

- the Mafic Complex, corresponding to lower crustal rocks from the Adria side (gabbro, norite, diorite);
- the Balmuccia Peridotite, largely made of spinel lherzolite representing mantle rocks;
- the Insubric Zone: a km-wide deformation zone expressing the Adria-Europe plate boundary, with mafic mylonites and other lithologies (metadiorite, metagabbro) most of them in the greenschist facies with local and minor pseudotachylytes;
- the Sesia Zone: mainly greenschist facies orthogneiss belonging to the Austroalpine nappes on the Eurasia side.

The boundaries between the zones are part of the input data. The Balmuccia Peridotite unit’s contour has been drawn after Quick et al. (2003), and is topologically an enclave in the Mafic Complex unit – but its downward continuity is part of the modelling challenge. The Insubric Zone contours have been drawn after Horstmann (1981) and related works. In addition, a set of 20 representative dip-direction and dip-angle values of the foliation and layering from the aforementioned maps and own field measurements are included and are located in three of these units. They generally show vertical to sub-vertical, westward dipping structures at the surface (Fig. 2). The sub-vertical structures are shown to continue below the surface along the “Strada Provinciale 10” road between Balmuccia and Boccioleto for about 1 km depth (Liu et al. 2021). Further proposals on the subsurface extent of the peridotite body range from a “peridotite lens” (Quick et al. 2003) to a downward broadening “tip of the mantle-berg” geometry (Ryberg et al. 2023). We here refrain from discussing further considerations regarding sub-surface geometries to avoid bias in the participants’ model setup. The model geometry below the surface, as well as in map view beyond the depicted and digitally provided area is left to the participants.

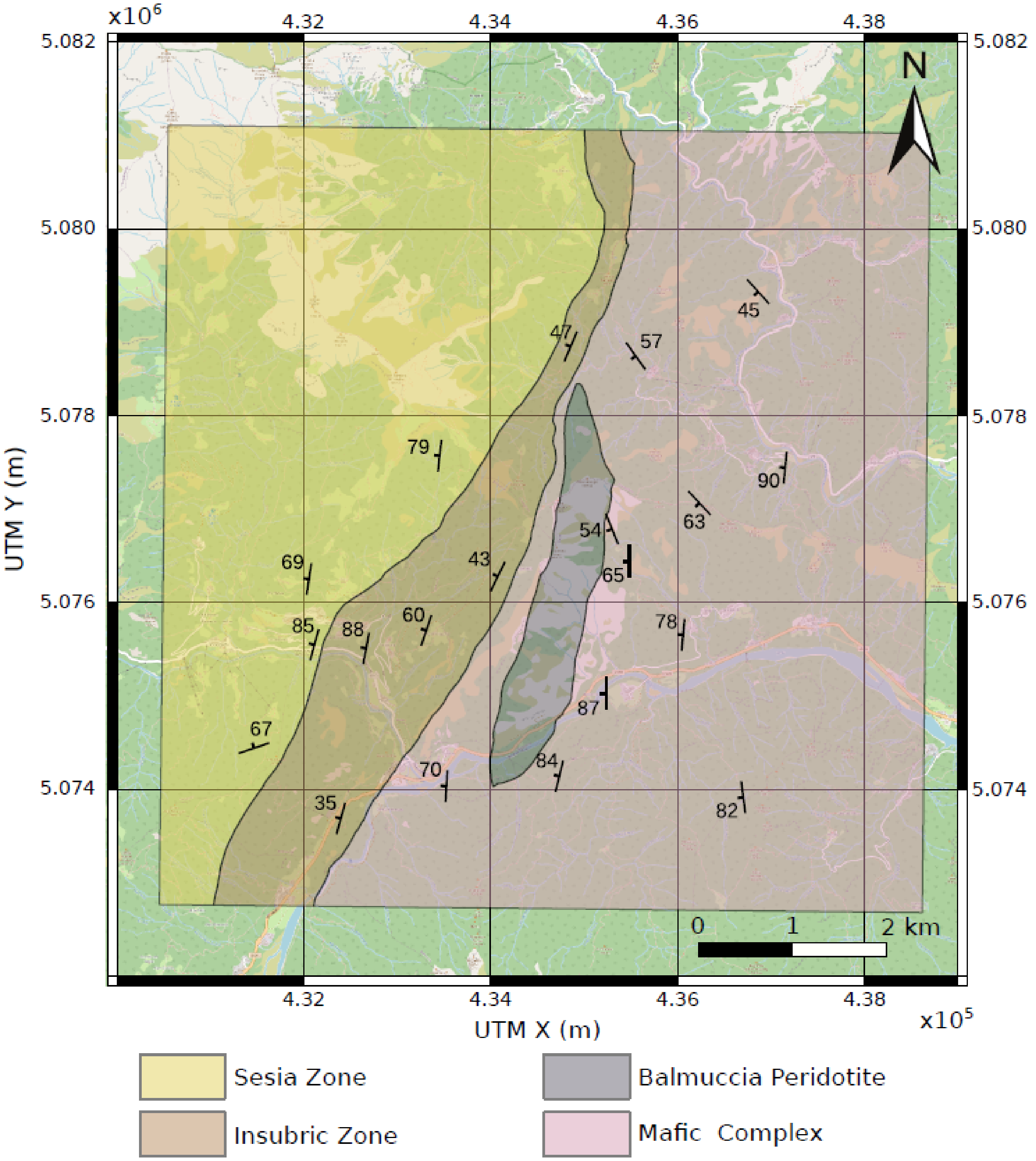

Figure 2. Contours of the four main geological units, and the 20 structural indicators.

2.3 Rock density data

2.3.1 Existing data

Several papers report single bulk rock density values for given lithologies in the Ivrea-Verbano Zone (e.g., Khazanehdari et al. 2000), but none of them has a representative compilation for all four lithological units of interest in this study. Therefore, the density data is based on a large compilation of rock physics data, called SAPHYR (Zappone and Kissling 2021), which, with an effort spanning several years, has collected the most comprehensive database in this regard. SAPHYR allowed us to trace back each sample's location and lithology, based on which we selected those that fall in the study area, in the near vicinity of the Balmuccia peridotite body. SAPHYR contained 13 values for the Mafic Complex gabbros, eight for the Balmuccia peridotite, two for the Insubric Zone, and unfortunately none for the rocks of the Sesia Zone. Further literature search has yielded four more values for the Insubric Zone from Siegesmund and Kern (1990), but none from the Sesia Zone.

2.3.2 New rock samples

To fill the gap in the rock density data, new field samples have been collected, primarily in the Sesia Zone and within the study area. Samples have been taken at 8 different places in the Sesia Zone, two new samples within the Insubric Zone, and one new sample from the Balmuccia Peridotite, at the summit of Cima di Lavaggio. This way, the number of samples for each lithology became of comparable size (Table 2). Note that in the literature the Sesia Zone is a much larger area than shown in our map, and that our samples were taken within the modelled area for this purpose.

2.3.3 Density determinations

From the samples taken at 11 new locations (Fig. 3), a total of 29 pieces were cut. All initial samples were large, their altered surfaces were cut, and fracture zones eliminated. Subsequently, 6 cm diameter cylinders of 4-10 cm height were cut (Fig. 3). Density was measured with an Archimedes type setup: (1) measurement of the dried sample on a good precision table balance; (2) measurement of the wet sample on the same table balance while it was hanging in water, with the tank sitting on a support above the balance. Dried rocks were at 300 °C for 72 hours, then at 60°C for 24 hours. Wet samples were immersed in water for 24 hours in a vacuum chamber. This way, only two measurements and a correction for water density as a function of temperature already yield a final density value. Thanks to the relatively large sample weight (200-800 g), a precise balance (0.01 g), and temperature reading at 0.2 °C uncertainty, the final measurement uncertainty is on the order of 1-5 kg $\cdot$m^{-3}. The obtained density values were first averaged for each sample collection location and then added to the database.

Figure 3. (a) Photo of the newly collected, larger rock samples before laboratory work. (b) One of the cut cylinders ready for Archimedes type density determination.

2.3.4 Range of densities by lithology

In summary, the four lithological units' rock density values are representatively characterized as shown in Table 2, including the average ± standard deviation, median, minimum, and maximum values. The field location of the samples is shown in Figure 4.

Lithological unit	**N**	ρ_{AVERAGE}	$\rho_{\text{st.DEV}}$	ρ_{MEDIAN}	ρ_{MINIMUM}	ρ_{MAXIMUM}
Mafic Complex	11	3011	±178	2942	2775	3265
Balmuccia Peridotite	14	3247	±121	3285	2957	3360
Insubric Zone	8	2877	±116	2845	2720	3050
Sesia Zone	8	2750	±40	2764	2675	2784

Table 2. Summary of bulk rock density (ρ) values in kg·m^{-3} for the four lithological units in this study. N is the number of samples representing the respective units.

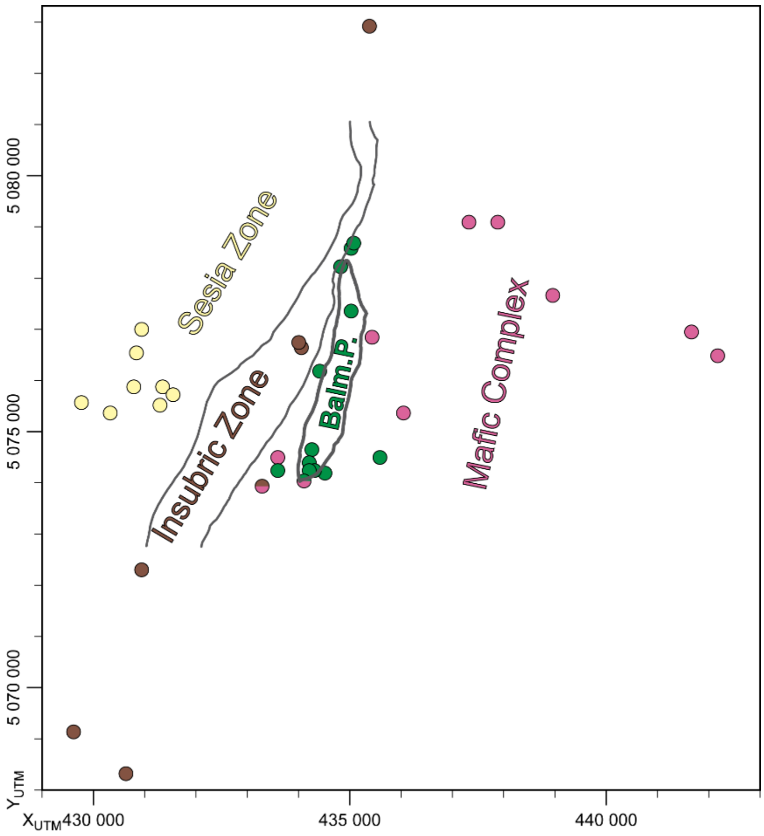

Figure 4. Location of the rock samples for bulk density values used in this study, and their association to the four main lithological units represented by the corresponding colours. See main text for details and references.

2.4 Gravity data and pre-processing

2.4.1 Overview

A total of 151 new gravity data points have been measured within a radius of ca. 3 km from the centre of the Balmuccia peridotite body. The daily loops of relative measurements are all tied to the same reference point. Elevation has been determined using differential GPS. The pre-processing includes corrections for tides, latitude, and instrumental drift, but no free-air, no Bouguer plate, and no terrain correction. This approach allows density-dependent topography to be included in the models, which should directly reproduce the pre-processed gravity values provided here.

2.4.2. Planning, logistics

At the scale of our survey, there was only one gravity data point available until Spring 2021, we have therefore planned to cover the Balmuccia peridotite area as much as possible. Given the steep and often inaccessible slopes, a thorough search of topographic maps, hiking maps, satellite pictures, and geological maps with indication of local observations (e.g., dip) hinting at past access was carried out, together with gathering information from colleagues and locals. Although we planned to survey the area at tighter spatial resolution at the edges of the peridotite body, and less tight farther away, the final geometry of gravity observations is primarily governed by accessibility.

The field surveys happened over 18 days in 2021. The planning of measurement points considered the already surveyed point geometry. Teams of usually two, sometimes three people have surveyed the area, carrying ca. 20 kg of geophysical equipment. The survey was carried out primarily on foot, along more or less accessible paths and slopes, reaching over 1000 m climb and then descent a day. Ultimately, gravity has been measured at 151 new points.

2.4.3. Gravimetric field measurements

The measurements have been carried out with a Scintrex CG-5 relative gravimeter of the University of Lausanne (S.N. 032). The majority of the daily surveys were performed in a loop, starting and ending at a physical reference point in Varallo, which we have established and tied to an absolute gravity reference station in Milan earlier (see Scarponi et al. 2020). For practical reasons, we have used one of the surveyed points as another physical reference, and have measured in a loop from that point on one day. Additionally, one survey day started in Varallo and ended at the other reference point. All these aspects have been taken into account when calculating the daily drift of the gravimeter. The gravimeter’s height above ground for each daily loop’s beginning and end was within 1 cm.

Farther away from the Balmuccia peridotite, regional gravity data is available at a few km spacing. The dataset is described in Scarponi et al. (2020), and openly available at https://zenodo.org/records/10075734.

2.4.4. Location determination of gravity points

The location of gravity data measurements has been determined using differential GPS (dGPS) technique. On each gravity campaign day, a base GNSS antenna was set up at a location where we expected visibility of the same set of satellites as at the location of the same day’s planned gravity measurements. For one day we changed the base antenna location between morning and afternoon in a coordinated manner.

The base antenna was recording GNSS data every second, for the entire duration of the daily measurement plan. The location of these daily base antenna positions was processed with the Precise Point Positioning service of National Resources Canada (https://webapp.csrs-scrs.nrcan-rncan.gc.ca/geod/tools-outils/ppp.php).

The rover antenna was also recording location data every second, for at least 10 but usually 15-20 minutes, at sites where at least 4-5 satellites but usually 6-9 satellites were in sight. The dGPS processing of each rover point with respect to its base was carried out in the MagNet software using both L1 and L2 GNSS information, except for 6 points where only L1 was used.

The obtained horizontal positions are precise for our purpose (median 3.6 cm, average 4.4 cm, minimum 2.1 cm, maximum 16.2 cm). At 17 sites, we have manually adjusted from the GPS antenna's horizontal location to the gravimeter's location using a measuring tape and a compass as this horizontal distance exceeded 2 m in the field (the largest correction distance was 20 m, the 16 others were between 2.1 and 8.5 m).

The obtained vertical position uncertainties are reasonably small (median 1.0 cm, average 2.3 cm, minimum 0.5 cm, maximum 16.4 cm; 9 values exceed 10 cm). This is less than – or comparable to – the uncertainty of the manual correction of the GNSS antenna height to the ground at the location of the gravimeter, which we estimate to be between 1 and a few cm, as measured by tape.

The obtained vertical position values represent the ellipsoidal height (with respect to WGS84), from which we subtracted the geoid height to obtain elevation data fitting the reference of the DEM. This has been done using the geoid model ITG2009 of Corchete (2010) and linear interpolation of their grid at the position of each gravity measurement point. The geoid height in the area covered by the survey varies between 51.9 and 52.6 m, and the final elevation values range between 503 and 1724 m.

To test the compatibility of the dGPS-derived elevation data at the new gravity points and the elevation data of the DEM, we have compared the two by interpolating the latter at the location of the former. The median and average (±standard deviation) differences are -1.64 m and -1.25 (±1.54) m, and the differences range between -6.48 and 4.48 m, the most frequent values are around -2 m. This is beyond the declared vertical accuracy of the DEM, ±0.3 m (in some areas ±0.6 m), although not surprising in the areas of steep topography and dense vegetation that characterize this terrain. Our suggestion to handle these differences is to locally (to few 10s of metres distance) modify the DEM to match the elevation measured at the location of the gravity points. The exact implementation will be discussed with the participants of the modelling challenge (see also the schedule in section 3).

The final gravity dataset with the 151 survey points is shown on Figure 5.

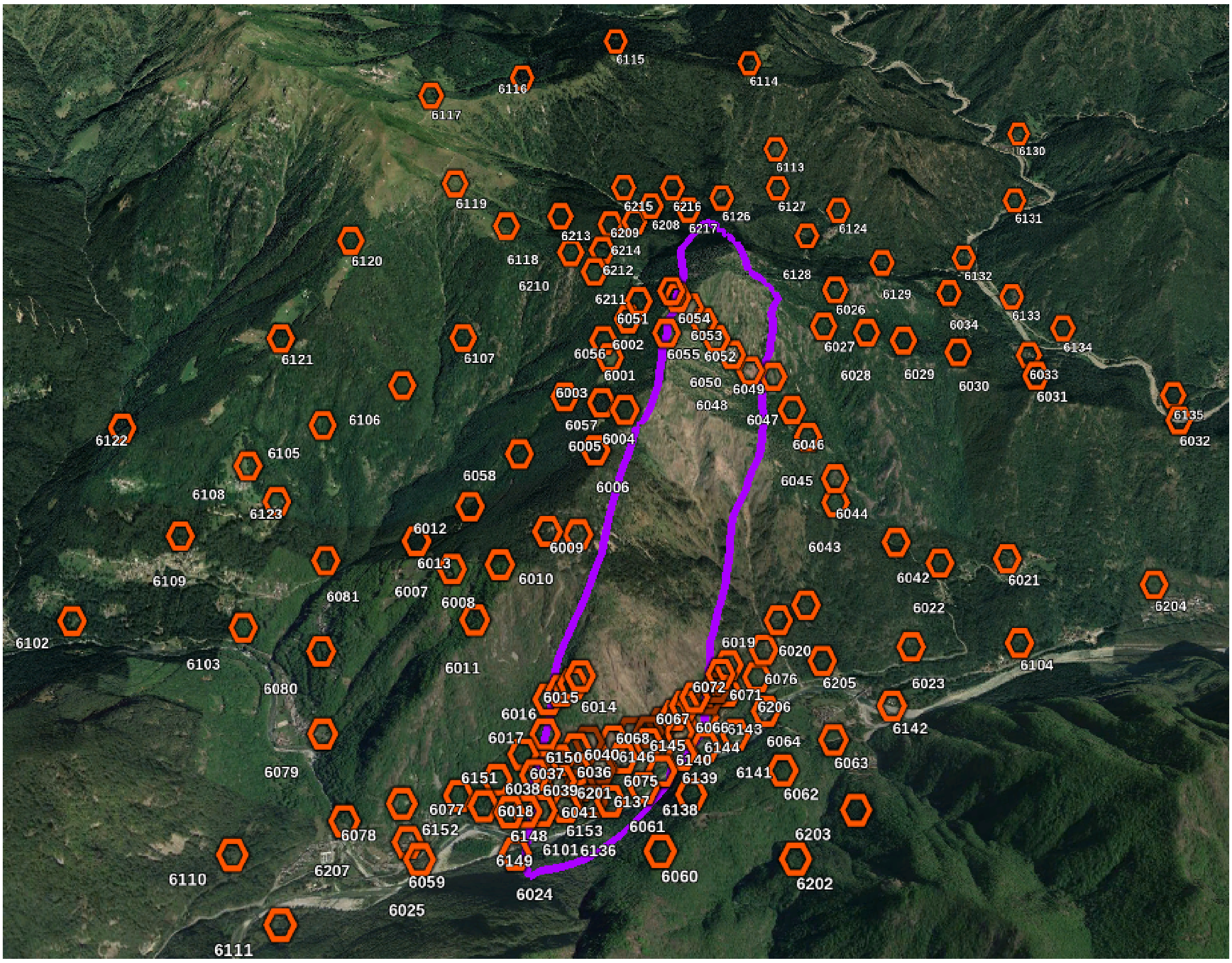

Figure 5. Perspective view on the final dataset of 151 new gravity points, covering Balmuccia Peridotite (purple contour) study area. Basemap: GoogleEarth (© 2023 Maxar Technologies).

2.4.5 Gravity pre-processing

We chose to perform a minimum set of pre-processing steps on the raw gravity data, and also chose not to perform free-air, Bouguer plate and terrain corrections. With this approach, we make it possible – and encourage participants – to compute forward model values directly at the points of observation. This way, density-dependent topography can be readily included by combining the geological map and the in situ rock density value ranges described above.

The pre-processing starts with the raw data acquired in the field, and includes the following steps:

- **Point-wise gravity data**: at each measurement point, a series of 5 to 12 measurements was performed, each of them recording the average of 60 measurements (one every second). We observed that the temporal trend of these short time series appeared exponential. Therefore, instead of averaging, we have fitted an exponential decay curve in time t using in the form $a - b \cdot e^{-c \cdot t}$, and calculated a small correction between the last measured value to the flat part of this fitted curve. The value of this correction remained small (median: 1.7 µGal, mean: 2.8 µGal, max: 23 µGal, only 12 points exceeded 10 µGal).

- **Gravimeter height**: the gravimeter's height above ground was not part of the corrections. Instead, this value was measured and is provided with the dataset for each point. The value reflects the vertical position of the CG-5 sensor's spring (as indicated in the manual) above ground level, as determined by GPS. The range of gravimeter heights was 21 to 213 cm, with 2/3 of the points at a standard 25-26 cm. We recommend using this value as part of the gravity modelling.
- **Gravimeter calibration factor**: the Scintrex CG-5 gravimeter was calibrated along the Jungfraujoch line a few months after the last campaign. The newly determined scaling factor with respect to the one set in the gravimeter during our campaigns was applied to the data: 0.999611.
- **Latitude correction**: was applied to each point according to the formula: $978032.67715 \cdot (1+0.0052790414 \cdot \sin^2\varphi+0.0000232718 \cdot \sin^4\varphi)$, where φ is the latitude.
- **Tidal corrections**: both solid Earth tide and ocean tides have been corrected, using the procedure of Cattin et al. (2015). Typical values were 50 and 4 µGal, respectively.
- **Instrumental drift**: the daily drift of the gravimeter was calculated by comparing the measurements at the point closing the loop, and then corrected at all intermediate points proportional to time. For the single day where the measurements started at a known reference point and finished at another, the difference between the expected (from the reference stations) and observed (after the above corrections) gravity values was taken as the drift. The daily drift values for loops varied between 10 µGal and 172 µGal, with a median of 76 and average of 86 µGal. The drift with the measurements between the two reference points had a drift of 170 µGal.

2.4.6 Uncertainty assessment

The uncertainties related to the gravimetric measurements add up from the following factors:

- **Standard deviation** of the 60-second measurements: on a total of 1699 averaged values at 191 individual points (including the loops), the standard deviations range are small: a median of 12 µGal, and an average of 13.4 µGal. While the individual minimum is 3 µGal, a single noisiest station has an average of 134 µGal – this is due to the positioning of the gravimeter on a locally horizontally growing tree near the ground, improvised due to the lack of hard rock, and only snowy and soft grounds available around the target location.

- **Gravimeter height** above ground level has been measured with ±0.5 cm accuracy, the equivalent uncertainty in the gravity values is ±1.5 µGal.
- **Elevation**: the uncertainty in the dGPS-determined vertical position translates to a median of 3 µGal and an average of 7 µGal (10 values exceeding 31 µGal, up to 51 µGal). We note that this is an expression of precision, and not accuracy. This latter could be up to 0.46 mGal (ca. 1.5 m) in the rare cases of a low number of satellites, based on the example of one point measured in two different campaigns.

Overall, the largest source of uncertainty remains the vertical position uncertainty of the measurement locations, which is challenging to reduce in a rough terrain such as the Balmuccia peridotite area. The sum of each average uncertainty factor listed above is 22 µGal, and while the sources of uncertainty are unrelated, in extreme cases the uncertainty may reach a few hundred µGal.

2.5 Files and formats

The files shared in the frame of the current modelling challenge, and the related information are summarized in Table 3.

Data	**Filename**	**File format**	**Comment**
DEM	Balmuccia12km_topo.zip	.csv [591.8 MB], with 1 header line, compressed into a .zip archive [121.1 MB], elevation values are **cell-centered**	Columns are: 1: UTM X (m) 2: UTM Y (m) 3: Elevation (m)
Geology map	Lithology_UTM.zip	Shapefile [9.2 kB] with 6 files: .cpg, .dbf, .prj, .qmd, .shp, .shx	Coordinates in UTM zone 32N
Structure	Structures.csv	.csv [1.5 kB], with 1 header line	9 columns (see header)
Rock density	*see Table 2 of this paper*	-	-
Gravity	Balmuccia_gravity.csv	.csv [7.4 kB], header line	Columns are: 1: Point ID 2-3: UTM X and Y (m) 4: Elevation 5: Processed Gravity (mGal) 6: Gravimeter sensor height above ground [m]

Table 3. The distributed files corresponding to the common input elements of the Balmuccia gravity modelling challenge.

3. Crowd-modelling: frame and timeline

To access the prepared input data, interested participants are requested to download the freely available dataset that accompanies this description from the repository at https://zenodo.org/records/10390437. An e-mail message notifying our group of your interest would be appreciated (but not compulsory), as this would allow us to assess the level of interest, and to simultaneously inform participants.

The solution models, inversion results should be prepared in the following frame:

- use the UTM coordinate system, and elevation as in the input dataset;
- describe considerations during the model setup, test models and/or inversion procedure;
- provide the 3D shape of the density anomaly/anomalies, and the respective density value or relative density change in $kg \cdot m^{-3}$;
- estimate uncertainties or range of possible shapes, values, if possible/available;
- it is also conceivable to submit and describe models that are ruled out, in comparison with others that are possible;
- a researcher or group is welcome to submit several solutions if the considerations or/and the methodology are different.

The proposed timeline for this crowd-modelling project is the following:

- publication of this notice and a summary: January 2024;
- interested participants start downloading the data and collect eventual questions;
- an online meeting is organized mid-April, during week 15 or 16 to discuss the DEM adjustment, other questions, and to agree on the timeline foreseen for the modelling (initial suggestion: 6-7 months, i.e., until end of October);
- the solutions are shared electronically by the end of the agreed time period;
- a one-day hybrid workshop is organized to present, compare and discuss the results in the subsequent 2 months (tentatively: November-December 2024);
- a decision is brought together whether or not to publish the comparative results, and if yes, in which format.

As much as possible we intend to keep the format flexible and remain open to suggestions; nevertheless, the model results should be in comparable format and the timeline should have a reasonable end date.

Acknowledgements

The support of the Balmuccia municipality is greatly appreciated, together with the help of local people. We thank Alba Zappone for sharing relevant point-wise data from the SAPHYR database, as well as Niccolò Menegoni for pointing at the most recent available DEM in the area. For some specific gravimetric advice, we thank Hans-Jürgen Götze, Sabine Schmidt and Urs Marti. We thank the staff of the Library of the Faculty of Geoscience and Geography at the University of Göttingen (Germany) for accessing, scanning, and digitalizing Master research theses on the geology and structures of the Insubric Zone under the supervision of Hans Ahrendt.

Author contributions

	LB	FD	AGe	AGr	GH	AL	KM	OM	BP	MP	MS	ShS	AZ	LZ	JZ
Study design	+			+	+			+		+	+		+	+	
Planning, logistics	+			+	+	+			+	+	+			+	
Fieldwork		+	+		+		+				+	+			
Samples					+										+
Data processing	+				+				+						+
Writing					+		+		+	+	+				+
Approval of release	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+

References

Cattin R, Mazzotti S, Baratin L-M (2015) GravProcess: An easy-to-use MATLAB software to process campaign gravity data and evaluate the associated uncertainties. Comp & Geosci 81:20-27. doi:10.1016/j.cageo.2015.04.005

Corchete V (2010) The high-resolution gravimetric geoid of Italy: ITG2009. J Afr Earth Sci 58:580-584. doi:10.1016/j.jafrearsci.2010.05.010

Horstmann U (1981) Petrographische, tektonische und mikrothermometrische Untersuchungen an der Insubrischen Line im Val Sermenza (Provinz Vercelli, Norditalien). Diploma thesis, University of Göttingen.

James T (2001) A study of the geological structure of the Massiccio dei Laghi (Northern Italy). Doctoral thesis, University of Manchester.

Khazanehdari J, Rutter EH, Brodie KH (2000) High-pressure-high-temperature seismic velocity structure of the midcrustal and lower crustal rocks of the Ivrea-Verbano zone and Serie dei Laghi, NW Italy. J Geophys Res 105:13843-13858. doi:10.1029/2000JB900025

Lensch G (1971) Die Ultramafitite der Zone von Ivrea. Annales Universitatis Saraviensis: Scientia 9:5-146.

Liu Y, Greenwood A, Hetényi G, Baron L, Holliger K (2021) High-resolution seismic reflection survey crossing the Insubric Line into the Ivrea-Verbano Zone: Novel approaches for interpreting the seismic response of steeply dipping structures. Tectonophys 816:229035. doi:10.1016/j.tecto.2021.229035

Pistone M, Müntener O, Ziberna L, Hetényi G, Zanetti A (2017) Report on the ICDP workshop DIVE (Drilling the Ivrea–Verbano zonE). Sci Drill 23:47-56.

Quick JE, Sinigoi S, Snoke AW, Kalakay TJ, Mayer A, Peressini G (2003) Geologic map of the southern Ivrea-Verbano Zone, northwestern Italy. US Geological Survey, Geological Investigations Series Map I-2776.

Rivalenti G, Garuti G, Rossi A (1975) The origin of the Ivrea-Verbano basic formation (western Italian Alps): Whole rock geochemistry. Boll Soc Geol Italiana 94:1149-1186.

Rivalenti G, Garuti G, Rossi A, Siena F, Sinigoi S (1981) Existence of different peridotite types and of a layered igneous complex in the Ivrea Zone of the western Alp. J Petrol 22: 127-153.

Rivalenti G, Rossi A, Siena F, Sinigoi S (1984) The layered series of the Ivrea-Verbano igneous complex, western Alps, Italy. Tschermaks Mineral Petrogr Mitt 33:77-99.

Ryberg T, Haberland C, Wawerzinek B, Stiller M, Bauer K, Zanetti A, Ziberna L, Hetényi G, Müntener O, Weber M, Krawczyk CM (2023) 3-D imaging of the Balmuccia peridotite body (Ivrea–Verbano zone, NW-Italy) using controlled source seismic data. Geophys J Int 234:1985-1998. doi:10.1093/gji/ggad182

Scarponi M, Hetényi G, Berthet T, Baron L, Manzotti P, Petri B, Pistone M, Müntener O (2020) New gravity data and 3D density model constraints on the Ivrea Geophysical Body (Western Alps). Geophys J Int 222:1977-1991. doi:10.1093/gji/ggaa263

Shervais JW (1979). Petrology and structure of the alpine lherzolite massif at Balmuccia, Italy. Doctoral dissertation, University of California, Santa Barbara.

Shervais JW, Mukasa SB (1991) The Balmuccia orogenic lherzolite massif, Italy. J Petrol 2:155-174.

Siegesmund S, Kern H (1990) Velocity anisotropy and shear-wave splitting in rocks from the mylonite belt along the Insubric Line (Ivrea Zone, Italy). Earth Planet Sci Lett 99:29-47. doi:10.1016/0012-821X(90)90068-9

Zappone A, Kissling E (2021) SAPHYR: Swiss Atlas of Physical Properties of Rocks: the continental crust in a database. Swiss J Geosci 114:13. doi:10.1186/s00015-021-00389-3