



Geophysical Investigation and 3D Modeling of Bedrock Morphology in an Urban Sediment-Filled Basin: The Case of Bolzano (Northern Italy)

SGATTONI GIULIA,^{1,2} MORELLI CORRADO,³ LATTANZI GIOVANNI,² CASTELLARO SILVIA,² CUCATO MAURIZIO,³
CHWATAL WERNER,⁴ and MAIR VOLKMAR³

Abstract—Bedrock mapping is essential for understanding seismic amplification, particularly in sediment-filled valleys or basins. However, this can be hard in urban environments. We conducted a geophysical investigation of the sediment-filled Bolzano basin in Northern Italy, where three valleys converge. This study uses low-impact, single-station geophysical methods suitable for urban areas to address the challenges of mapping in such environments. A dataset of 574 microtremor and gravity measurements, along with three seismic reflection lines, allows for the inference of the basin's deep bedrock morphology, even without direct stratigraphic data. The dataset facilitates a detailed analysis of the spatial patterns of resonance frequencies and amplitudes, revealing 1D and 2D characteristics of the resonances. Notably, 2D resonances predominate along the Adige valley, i.e., the deepest part of the basin with depths up to 900 m. These 2D resonances, which cannot be interpreted through simple 1D frequency-depth relationships, are better understood by integrating gravity data to develop a depth model. The study identifies resonance frequencies ranging from 0.27 to over 3 Hz in Bolzano, affecting different building types during earthquakes. Maximum resonance amplitudes occur at lower frequencies, specifically at 2D resonance sites, therefore primarily impacting high structures. The 2D resonances are directional, with the most significant amplification occurring longitudinally along the valley axes. The resulting 3D bedrock model aids in seismic site response modeling, hydrogeological studies, and geothermal exploration and provides insights into the geological history of the basin, highlighting the role of the Adige Valley as a major drainage pathway.

Keywords: Sedimentary basin, bedrock mapping, 1D resonances, 2D resonances, HVSR, gravimetry.

1. Introduction

Imaging the shallow subsurface is of primary importance in populated areas for several applications, e.g., for seismological engineering problems, seismic wave propagation modelling, geotechnical modelling, hydrological modelling. Urbanized areas are often built on soft sediment covers and bedrock mapping is the first task required for example to assess seismic site amplification. This is even more important in narrow valleys where large amplification of earthquake shaking occurs due to 2D/3D resonance phenomena and edge effects caused by trapping of seismic waves in the sediment fill (e.g., Bard & Bouchon, 1980a, 1980b).

A common approach for bedrock reconstruction is to combine direct geological and indirect geophysical data. Geological data in the form of boreholes reaching the sediment-bedrock interface are often limitedly available, especially in deep valleys/basins. Geophysical surveys are therefore the main method used for subsoil stratigraphic mapping, as they allow refining spatial resolution when sparse or no boreholes are available. However, not all geophysical techniques are easily applicable in urban environments, especially when the target surface is several 100 m deep or more. A classical approach is the use of seismic reflection methods, usually by means of 2D surveys (e.g. Cavinato et al., 2002; de Franco et al., 2004; Patruno & Scisciani, 2021), however, this cannot be used extensively in urban areas.

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¹ Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Bologna, viale Berti Pichat 6/2, 40127 Bologna, Italy. E-mail: giulia.sgattoni@ingv.it

² Dipartimento di Fisica e Astronomia, Alma Mater Studiorum - Università di Bologna, viale Carlo Berti Pichat 8, 40127 Bologna, Italy.

³ Ufficio Geologia e Prove Materiali, Provincia Autonoma di Bolzano, Cardano, Italy.

⁴ AFRY Austria GmbH, Vienna, Austria.

Therefore, single-station geophysical techniques, such as H/V (Horizontal over Vertical spectral ratios; Nakamura, 1989) and gravity methods, are more easily applicable. They allow stratigraphic mapping over wide and challenging areas with minimal effort and cost.

The stratigraphic application of the H/V technique relies on the correlation of observed resonance frequencies (detected as peaks on the H/V curves) to sediment thickness and S wave velocity (V_s) of the resonating layer, while the gravity method allows identifying negative gravity anomalies due to sediment-filled valleys or basins. The two methods have been applied for stratigraphic reconstruction at different scales both individually (e.g. H/V, Ibs-Von Seht & Wohlenberg, 1999; Mantovani et al., 2018; Rohmer et al., 2020; gravity: McPhee et al., 2007; Perrouy et al., 2015; Chakravarthi et al., 2017; Mancinelli et al., 2021) and combined (Sgattoni & Castellaro, 2021). The effectiveness of the H/V and gravity single-station methods depends on several factors; (1) the influence of 2D/3D effects on the H/V curves that prevents straightforward correlation of resonance frequencies with bedrock depth (le Roux et al., 2012; Roten et al., 2006; Sgattoni & Castellaro, 2020); (2) the influence of anthropic structures and disturbances on microtremor recordings in urban areas; (3) the possibility to separate the gravity anomaly depending on the geologic source of interest (e.g. Johnson & Klinken, 1979); (4) the availability of constraints to effectively model resonance frequencies and gravity anomalies. In addition, the use of single-station techniques for detailed 3D mapping requires dense spatial sampling within the investigated area (e.g. Sgattoni et al., 2023).

The Bolzano alluvial-sedimentary basin (northern Italy) is a rather narrow (4–5 km wide) and deep (>600 m) basin, that was formed by the junction of three valleys (the Adige, Isarco and Sarentino valleys). The city of Bolzano, one of the most populated cities in the Alps, is located at about 250 m above sea level and occupies the northeastern part of the basin. Borehole data down to the base of the sediment fill are not available, however the depth of the Adige valley is constrained to about 700 m a few tens of km north-west of Bolzano (Felber et al., 2000; Rosselli et al., 1998). Relatively unknown is the depth of the

bedrock below the city of Bolzano and its morphology at the junction of the Adige and Isarco valleys.

Although the historical and recent seismicity of the area is rather low (Guidoboni et al., 2018, 2019; Rovida et al., 2020, 2022), a few seismogenic sources capable of producing large earthquakes are known in the region (DISS Working Group, 2021), e.g. the Western Periadriatic and Brenner seismogenic sources located about 40 km north of Bolzano. Because of the potential of sedimentary basins to amplify ground motion, it is therefore crucial to map the sediment thickness in a densely populated basin. However, the investigation of its buried bedrock morphology poses an interesting challenge for conventional geophysical investigation methods by means of 2D seismic surveys.

Recently, a few geophysical studies were conducted in the area, based on single-station geophysical methods. Sgattoni and Castellaro (2020) and Sgattoni et al. (2023) found strong experimental evidence of 2D resonances on single-station microtremor measurements and identified features in the data that allow distinguishing 1D- and 2D-type ground resonances. They also described the spatial features and directionality of 2D resonances within the basin. Sgattoni and Castellaro (2021) exploited a dataset of single-station microtremor (180 sites) and gravity (49 sites) measurements to test a methodology to combine ground resonances and residual gravity anomalies for bedrock mapping in urbanized areas. In the present paper, we further expand the investigation of the Bolzano basin by complementing the dataset with 270 new microtremor measurements, 75 new gravity measurements (for a total of 574 points distributed within the basin) and 3 seismic reflection profiles. The rich geophysical dataset allows us to present a high-resolution 3D model of the bedrock morphology and to discuss and describe the challenges encountered. We show how we interpret 1D and 2D ground resonances and how gravity data help for the bedrock interpretation where 2D resonance dominates, how we make use of the seismic lines to constrain the model in depth and how we combine all the geophysical data to reconstruct the 3D bedrock geometry. We also provide a comprehensive analysis of 1D and 2D ground resonances across the basin, by investigating the directivity, frequency and amplitude

spatial patterns. The resulting model provides insight into the geologic evolution of the basin and is useful for applications such as microzonation studies, hydrological modeling, and ground motion modeling.

2. Geological Overview

The Bolzano intramountain basin lies at the junction of the Adige Valley to the west, the Isarco Valley to the east, and the Sarentino Valley to the north. The surrounding elevations rise up to 1660 m and generally have very steep slopes with abrupt connections to the valley floor. The deepest part of the basin runs on the western side along the course of the Adige River, the northeastern part is occupied by the broad coalescent alluvial fans of the Talvera and Isarco rivers with slopes between 2 and 0.6% respectively, pushing the Isarco and Adige rivers towards the opposite slope (Fig. 1).

The basin of Bolzano is cut into the Permian volcanic rocks of the Athesian Volcanic Group (Avanzini et al., 2007; Morelli et al., 2007) (Fig. 1). The dominant lithologies are rhyolitic ignimbrites well exposed in the elevations immediately north and east of Bolzano. To the west, above the volcanic rocks, the basal sequence of the Dolomites is also present. The Quaternary infill of the Adige Valley is only known in its upper part, and consists of alluvial and marsh deposits following the last glacial maximum (LGM). Till of the LGM are diffusely present on the slopes adjacent to the main valley. Upper Pleistocene alluvial deposits are exposed below the LGM deposits in the Oltradige, a North–South elongated trough located to the SW of Bolzano and separated from the main valley by a rocky ridge (Avanzini et al., 2007; Castiglioni & Trevisan, 1973).

2.1. Available Stratigraphic Information of the Basin Infill

Direct information on the subsurface of the Bolzano basin is derived from the stratigraphy of boreholes and surveys, the largest part of which goes down to less than 50 m, while there are few data down to 100 m. The alluvial fan of the Isarco River consists of coarse sediments, with subordinate sand

levels and lenses. In the distal southern part there are also sandy siltstones and siltstones sometimes organic, linked to the floods of the Adige River.

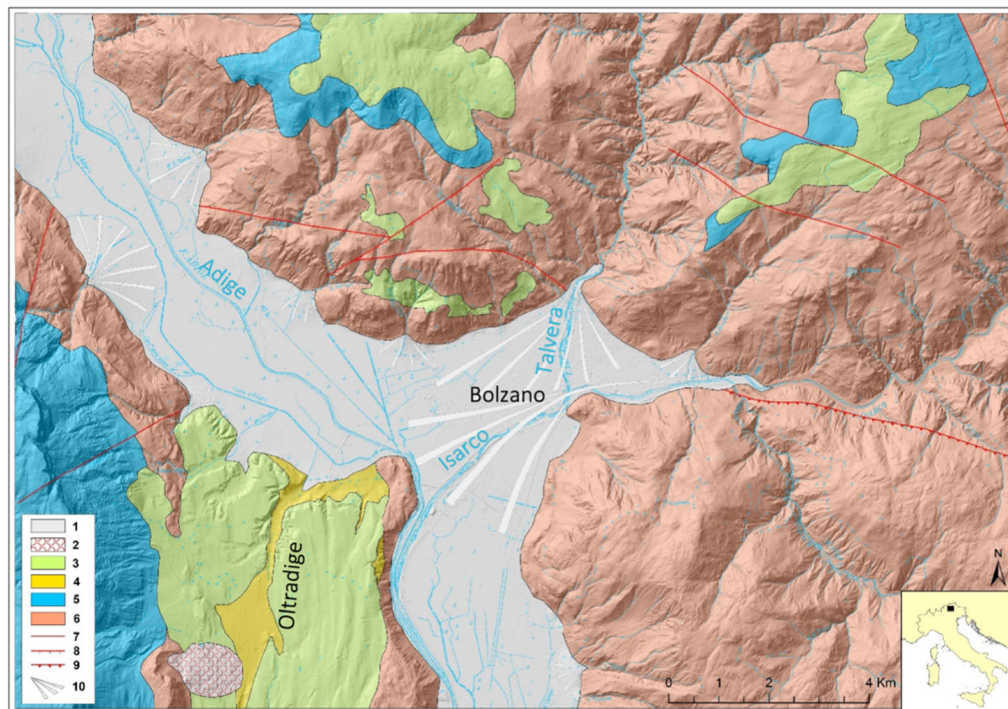
The Talvera alluvial fan is also predominantly made up of coarse sediments (gravel and sandy gravel) with subordinate levels or lenses of sand and silt, up to decameter thick. In the western area (St. Mauritius Hospital area) the coarse sediments of the Talvera are known up to a depth of 25 m, while deeper down to 40–50 m, sands, silty sands and silt sometimes organic prevail. Further to the SW (Neufeld), fine sediments (silt and fine sand) predominate, with minor interlayers of gravel and sand that increase in thickness towards the south (Ponte Adige). These sediments are attributable to the Adige River locally replaced by organic silts and peats of marshy environment.

Overall, the fill of the first 50–80 m of the Bolzano basin consists of sediments of fluvial origin, related to medium–high energy torrential transport or flooding processes.

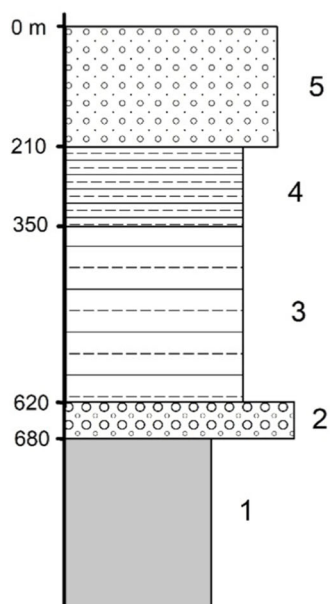
Boreholes deeper than 100 m are only available in a few locations in the valley segment between Bolzano and Merano. At Nalles about 8 km NW of Bolzano, a borehole reached a depth of 209 m, encountering up to 150 m predominantly sand, sand and gravel, with subordinate interbedded levels of silts and clayey silts with peat, the latter predominating at greater depths (Autorità di Bacino Nazionale dell'Adige, 1998).

A thermal water well located along the Adige valley near the town of Sinigo about 20 km northwest of Bolzano, combined with a reflection seismic line (Bargossi et al., 2010) constrains the maximum depth of the valley at 670 m. A well velocity survey was also conducted at the same site (Ufficio Geologia e Prove Materiali, 2001), detecting average P-wave velocities of the sediment fill of about 1950 m/s. The first 260 m consist mainly of coarse sediments (gravels and sands) from a fluvial environment, followed by well-stratified fine sediments, referable to a lacustrine environment, up to approximately 400 m from the surface. These, at greater depth (between 400 and 600 m), become less organized, locally associated with sandy-gravel sediments. The environment is still lacustrine, but with flow discharges and the possible presence of glacial

a)



b)



c)



◀Figure 1

a Geological map of the Bolzano basin: (1) Recent alluvial deposits, (2) landslide, (3) glacial deposits of the Last Glacial Maximum (LGM), (4) alluvial deposits pre-LGM, (5) permiantriacic sedimentary rocks, (6) permian volcanic rocks, (7) fault, (8) normal fault, (9) thrust, (10) alluvial fan. **b** Log stratigraphy of the Sinigo well. (1) Bedrock, (2) Alluvial conglomerates, (3) Fine lacustrine sediments with debris-flow intercalations, (4) Fine lacustrine sediments, (5) Alluvial sediments (gravel and sand). Redrawn after data from Cucato and Felber (2002). **c** well location on a Google Earth satellite image

deposits. In the deepest part, between 600 m and the bedrock at 670 m, there are poorly cemented conglomerates of an alluvial or torrential environment (Fig. 1).

This succession is similar to that described for the subsurface near Trento (~50 km south of Bolzano) from seismic, gravimetric and borehole data by Felber et al. (2000) and Rosselli et al. (1998). They showed that in the deep valley infill there are important fluvial, as well as lacustrine, sequences, while glacial deposits have only been identified locally with great uncertainty. The authors constrained the depth of the Adige valley near the town of Trento to more than 600 m.

3. Geophysical Data

We describe in this section all the geophysical data used to infer the bedrock geometry in the study area. These include 450 single-station microtremor measurements, 124 gravity measurements and three seismic reflection lines (Fig. 2). The distribution of measurement sites was designed according to the following criteria: (1) to obtain a regular and dense sampling of resonance frequencies across the basin, given the time and hardware available; (2) to complement microtremor measurements with gravity measurements along lines crossing the basin and valleys from edge to edge, in order to identify sediment resonances and provide additional constraints on bedrock modeling; and (3) to calibrate the model along lines where seismic reflection profiles are available. Part of these data were already described in Sgattoni and Castellaro (2020, 2021) and Sgattoni

et al. (2023) where the interpretation of 1D and 2D resonances is discussed and a method to combine single-station gravity and microtremor data is presented.

3.1. Single-Station Microtremor Measurements

We acquired 450 single-station microtremor measurements within the Bolzano alluvial-sedimentary basin and along part of the Adige valley to the west and south of Bolzano (Fig. 2a). The data were acquired within 2 years between 2018 and 2020 with Tromino seismometers (MoHo srl) at 128 Hz sampling rate and lasted 16 min. A few longer duration acquisitions were compared with shorter ones to ensure the stability and significance of the short-duration measurements. Instruments were always oriented with the y and x components parallel to the geographical NS and EW directions. The duration of the acquired signals was chosen to optimize acquisition times while being able to resolve spectral frequencies down to 0.2 Hz. This is crucial as our analysis requires covering the basin with as many measurements as possible and, in general, investigating a large number of sites is useful, if not necessary, to interpret the observed patterns. The reader is referred to Sgattoni et al. (2023) for further discussion on the acquisition strategy.

Since most of the area is urbanized, the instrument positioning was sometimes difficult. We tried to position the instrument, as more as possible, in natural open fields. However, this was not possible in the city of Bolzano, where most of the times the instrument was placed on paved ground. We observed, however, that the quality of recordings acquired on paved roads was usually better than those acquired on small green spaces, e.g. small flowerbeds.

The recordings were processed using the Grilla software. Each waveform was split into non-overlapping 30 s long windows, detrended, tapered, padded, FFT-transformed and smoothed with triangular function with width equal to 5% of the central frequency to obtain individual spectral components. The H/V function was then calculated by averaging H/V ratios of each window, H being computed as $\sqrt{x^2 + y^2}$.

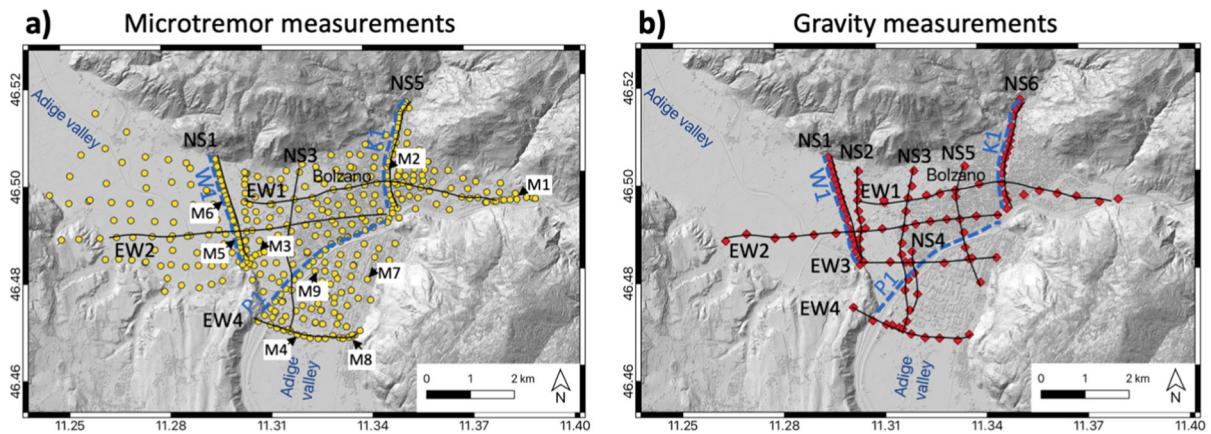


Figure 2

Location of microtremor and gravity measurements acquired within the Bolzano alluvial-sedimentary basin. The blue dashed lines identify the three seismic lines shown in Fig. 3. The black solid lines in **a** identify the H/V profiles shown in Fig. 5 and the black lines in **b** identify the gravity profiles shown in Figs. 6 and 10

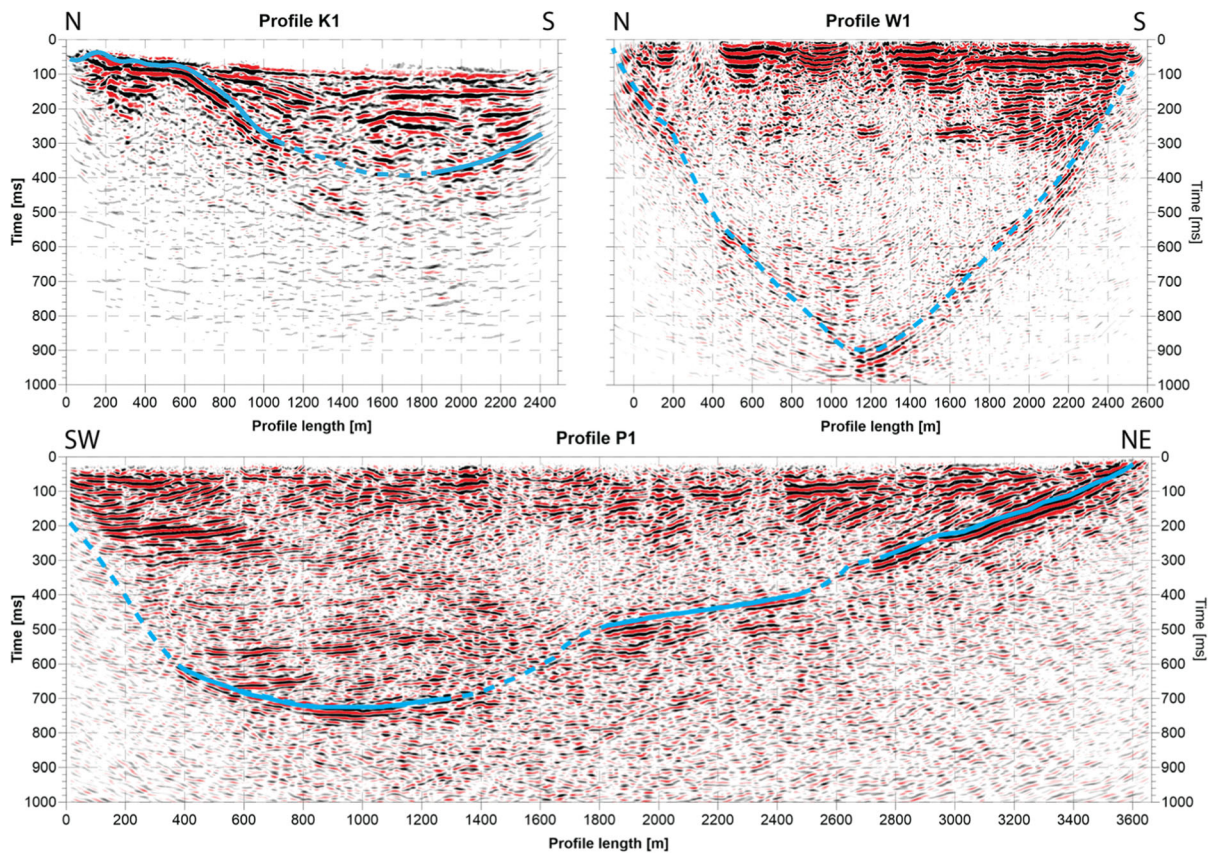


Figure 3

Seismic reflection profiles acquired along the lines shown in Fig. 2. The light blue lines highlight the possible bedrock reflection surface. Dashed lines denote uncertain interpretation. The zero time is referenced to elevation 310 m for Profile K1, 235 m for Profile W1 and 250 m for Profile P1

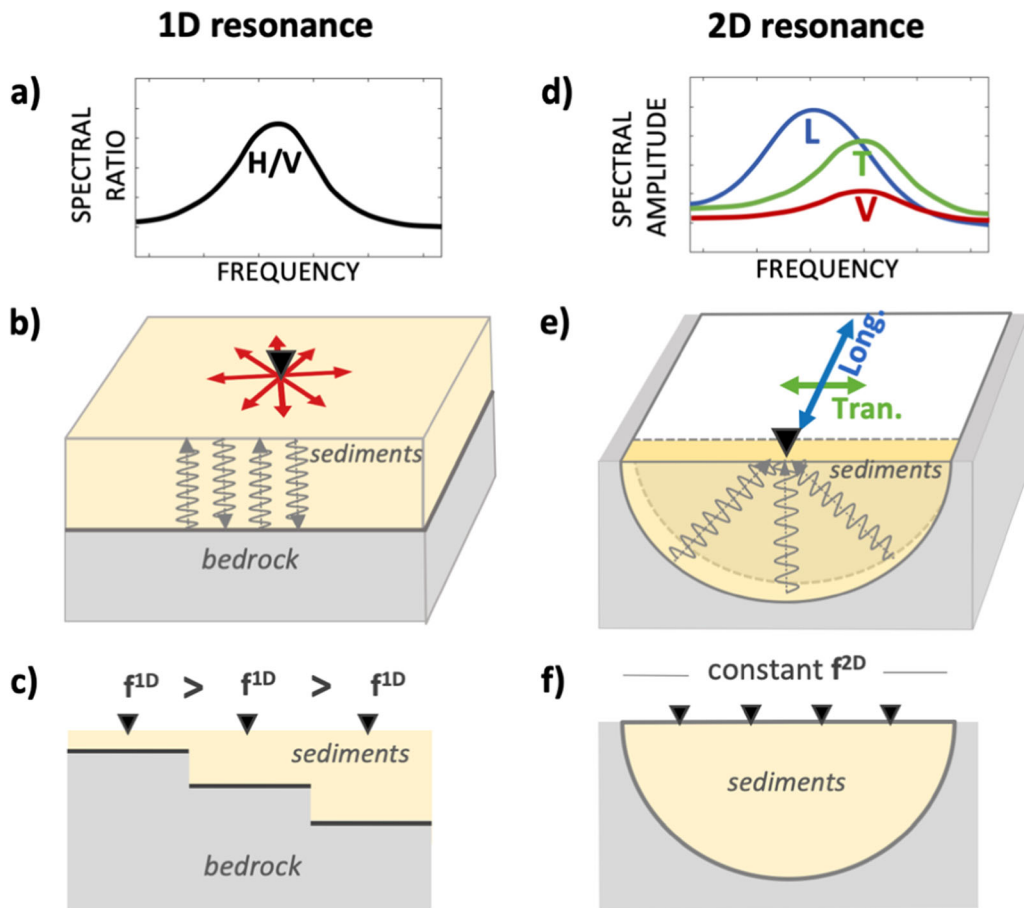


Figure 4

Schematic representation of 1D and 2D resonances and how they are identified through single-station microtremor recordings. In the plane-parallel 1D case, resonances are detected as peaks on H/V curves (a) as their dynamic behavior does not change along any horizontal directions (b) and lateral bedrock depth changes lead to frequency variations (c). In narrow valleys, directional 2D resonance modes arise, identifiable as distinct peaks on individual spectral components of motion (d) along the longitudinal and transverse direction of the valley (e; modified from Sgattoni et al., 2023). 2D resonances develop within valley cross-sections (yellow volume in e) and do not correlate with local bedrock depth but depend on the whole cross-section geometry and sediment mechanical properties (f)

3.2. Gravity Measurements

Nine gravity lines were acquired within the basin, for a total of 124 measurement sites (Fig. 2b). The data were collected between 2018 and 2020 with a Lacoste-Romberg gravity meter model D. We followed the looping technique in order to correct for the instrumental drift. We kept each loop no longer than 2 h so that the drift can be treated as a linear function of time and each line was acquired within 1 day. Most of the gravity stations are located at flat sites within the basin. As for the seismic measurements, the densely urbanized area makes the use of

any geophysical technique more challenging. Gravity measurements are influenced, e.g., by the presence of buildings and big infrastructures. Therefore, care was taken in choosing measurement sites as far as possible from buildings, by choosing all open squares and gardens. Furthermore, the sites have been chosen as far away as possible from busy roads and sources of vibration in order to obtain stable measurements.

We treated each gravity line independently and did not convert them to absolute values as this is not required for our scope. We analyzed each profile by calculating relative gravity anomalies to the beginning of each line. To derive the residual Bouguer

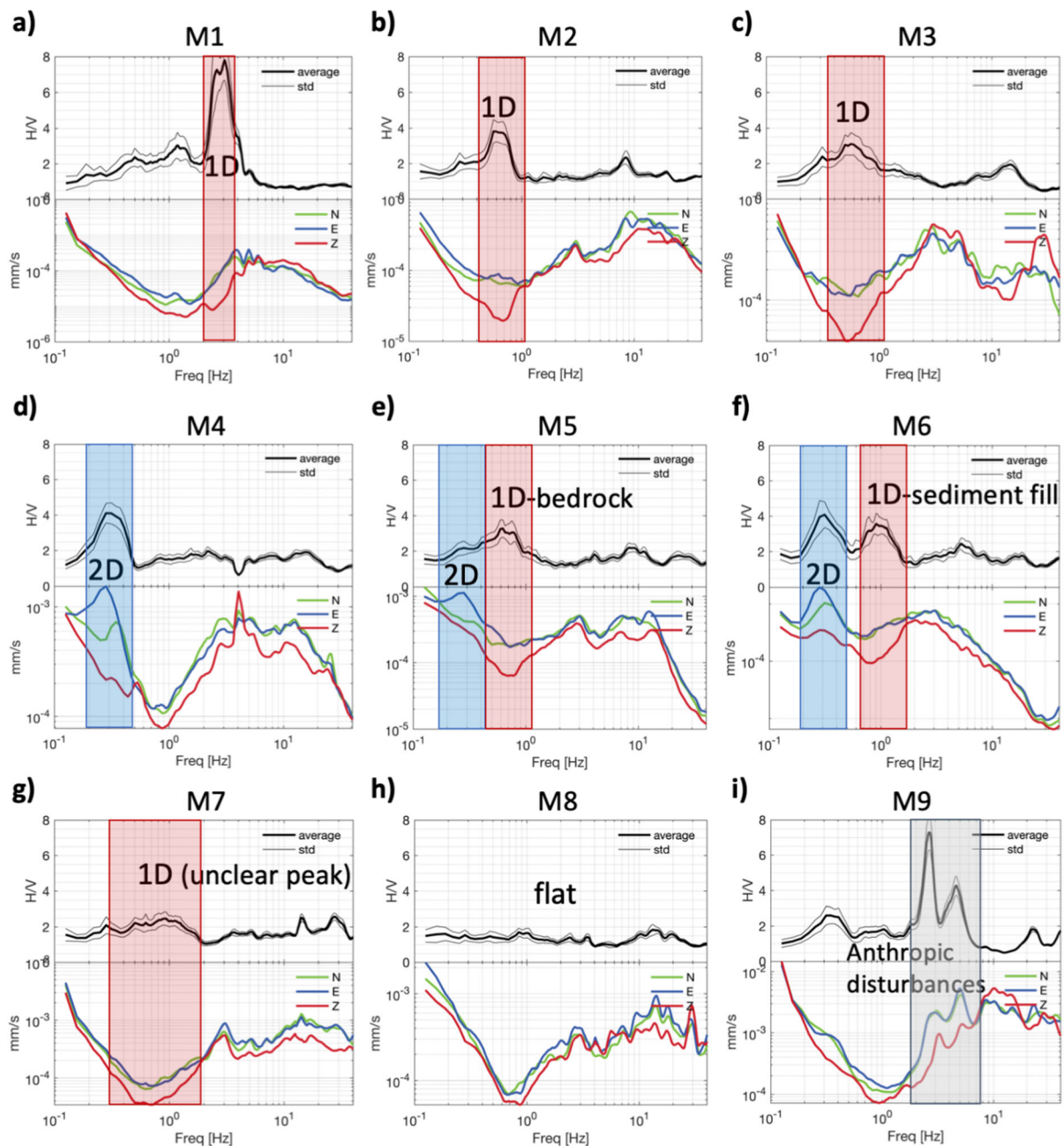


Figure 5

Examples of H/V curves and corresponding individual spectral components at different measurement sites (top and bottom of each panel). The location of the measurement sites is shown in the maps of Fig. 2. **a–c** Examples of 1D resonance peaks characterized by different widths and amplitudes. **d** Measurement with 2D resonance only, characterized by individual peaks on the horizontal spectral components of motion. **e** Measurement located near the valley edge, with H/V peak corresponding to 1D resonance associated to the sediment-bedrock interface and relics of 2D resonance peaks on the individual spectral components. **f** Measurement located in the center on the Adige valley, with marked 2D resonance at low-frequency and a secondary 1D resonance peak at higher frequency associated to a shallower interface within the sediment fill. **g** Unclear resonance peak on the H/V curve with 1D features. **h** Flat H/V curve. **i** Example of anthropic disturbances at a site located in the city center

gravity anomaly we applied corrections for the instrumental drift, latitude, free-air, Bouguer slab, terrain and regional gradient.

The bedrock density utilized for computing the Bouguer slab and terrain corrections was set at 2600 kg/m^3 , an average value derived from known rock densities measured within the basin.

For the elevation corrections required in the free-air and Bouguer corrections, a LiDAR-derived digital terrain model (DTM) was employed, with horizontal resolution of 0.5 m and a declared relative elevation precision of 15 cm. To calculate elevation and terrain corrections, gravity values at each point of interest were computed by summing the contributions of segmented hollow cylinders centered at observation points. These cylinders varied in density, radius, and vertical distances, with the gravitational attraction of each segment being calculated and summed to obtain the overall correction.

The regional gradient was derived using regional gravity data from ISPRA, ENI, OGS (2009), by fitting a 3rd-order polynomial surface within a rectangular area extending up to 20 km from the study area. The resulting surface, mostly affecting the east–west direction, was subtracted from each gravity line to obtain the residual gravity field related to the sedimentary basin.

During the processing, we tracked uncertainties and propagated them through the additional operation of the gravity correction process. Elevation correction uncertainties range from 0.04 to 0.2 mGal, accounting for elevation uncertainties of 0.2–1.0 m. Terrain correction uncertainty was estimated by simulating ± 1 m elevation variations in flat areas and ± 3 m in mountainous regions, resulting in errors ranging from ± 0.03 to ± 0.1 mGal. Regional trend uncertainties were estimated using different polynomial surfaces and ranged from ± 0.1 to ± 0.5 mGal, with maximum values along east–west profiles. Combining all uncertainties in the gravity correction process yielded errors between 0.05 and 0.8 mGal, with the largest uncertainties near mountainous areas and along EW profiles that are more affected by the regional gradient.

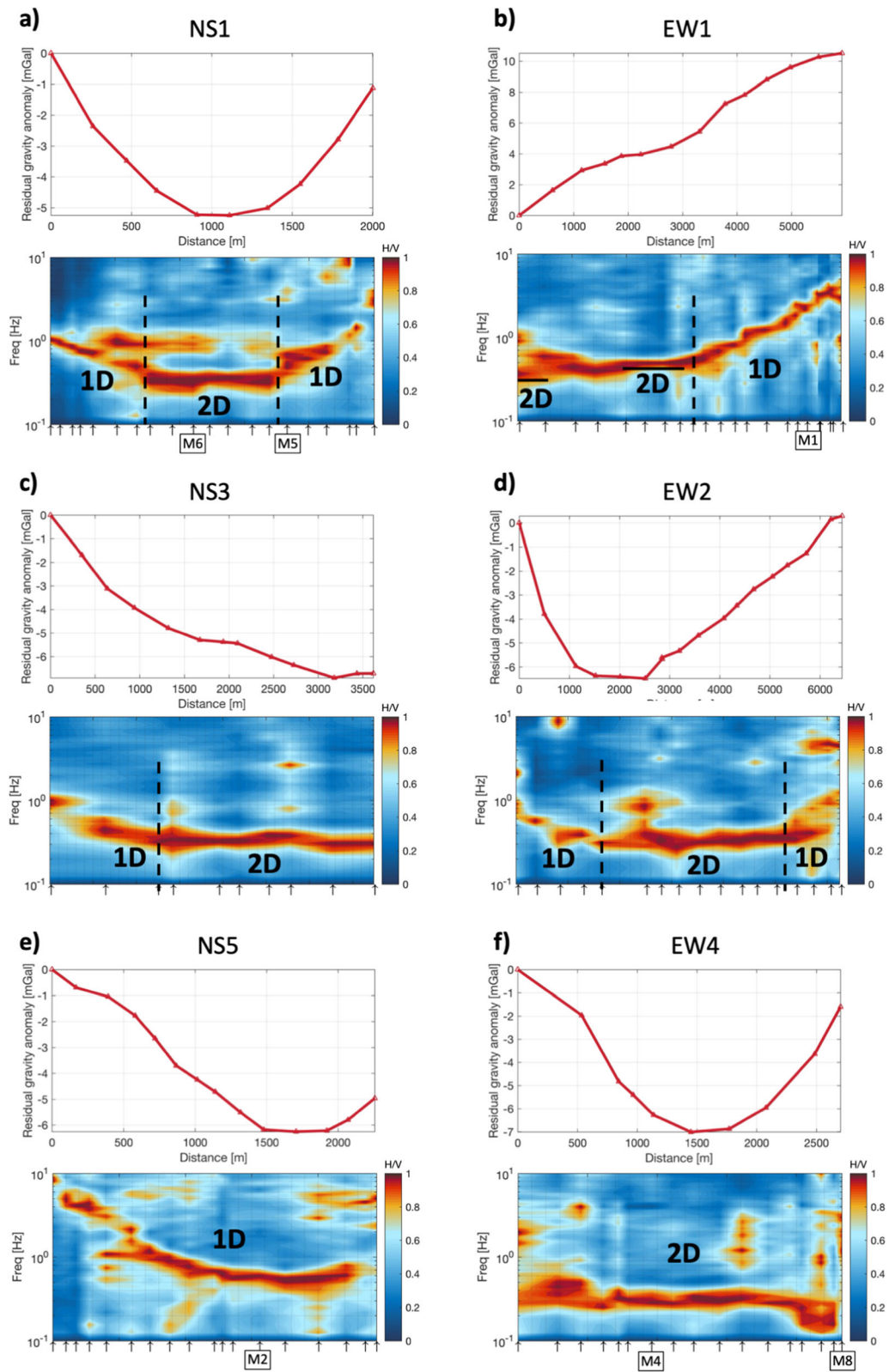
The details of the processing techniques are discussed in Sgattoni and Castellaro (2021), where a part of the same data is presented.

3.3. Seismic Reflection Lines

Because the area is densely populated, the acquisition and processing of long seismic lines is challenging due to the high background noise level, space limitations, use of low-impact sources. We collected the results of three 2D seismic reflection lines that were acquired, processed and interpreted in 2016, 2017 by Pöyry Infra GmbH and 2021 by Afry Austria GmbH (Pöyry, 2017, 2021). The three lines cross the valleys to the west (W1), south (P1) and east (K1) of the Bolzano basin and are 2.6, 2.6 and 3.7 km long, respectively. To get good quality data the seismic waves were generated by a drop weight (EWG-III). The obtained seismic data was processed with ProMAX[®] (Landmark Graphics Corp.) including processing steps, as Automatic Gain Control (AGC), spiking deconvolution, bandpass filter, velocity analysis, Dip Move Out (DMO)-correction, CDP-stacking, and depth migration for the reflection seismics. The N-S oriented line K1 and the E-W oriented line P1 were running along the Talvera and Isarco river respectively. Their location is nearby the center of the city of Bolzano and because of the strong traffic noise, the lines were measured during the night. This greatly improved the quality of the seismic data, but more in the case of P1. West of Bolzano, the W1 line traverses the Adige valley and, despite the greater distance from the city of Bolzano, the data quality was inferior compared to the two other profiles. The reason was the presence of clay and peat layers with low velocities near the surface which attenuated the seismic wave amplitudes. Results of the three lines are shown in Fig. 3, where light blue lines denote possible interpretations of the sediment-bedrock surface. Since certain depth or velocity calibrations were lacking, we present the profiles in the time domain as unmigrated stacks. These lines will serve as independent information to calibrate the model obtained from the joint analysis of gravity and microtremor data.

4. Single-Station Geophysical Data Analysis

In this section, we describe how we analyzed single-station geophysical data to extract the



◀Figure 6

Comparison between residual gravity anomalies and H/V profiles along 6 lines located as shown in Fig. 2. The arrows in the bottom of the H/V contour plots mark the location of each H/V measurement. Each H/V curve is normalized so that the color scale ranges from 0 (blue) to 1 (dark red). Along the H/V profiles NS1, EW1, NS2 and EW2 in panels a–d, 1D and 2D resonances are observed along the profiles, while profile NS5 in e is dominated by 1D resonance and profile EW4 in f is dominated by 2D resonance.

See text for further discussion

parameters needed for bedrock depth modeling. We first identified 1D and 2D ground resonances by inspecting H/V curves and the corresponding individual spectral components of motion. Then, we compared microtremor and gravity data along common profiles crossing the basin in different portions to identify the resonance peaks associated with the sediment-bedrock interface. Once we completed the identification of ground resonances, we conducted a directional analysis of 2D resonances and mapped resonance frequencies and peak amplitudes to analyze their spatial distribution across the basin.

4.1. 1D/2D Resonance Identification

When interpreting single-station microtremor measurements acquired within valleys, it is crucial to distinguish between 1D- and 2D-type resonances. This can be done based on the features described in Sgattoni and Castellaro (2020) and Sgattoni et al. (2023) also shown in the scheme of Fig. 4. In the case of a 1D geometric configuration, i.e., when plane-parallel stratigraphy occurs at least locally, the dynamic behavior does not change along any horizontal directions (Fig. 4a, b), and 1D resonance of a sediment layer over a rigid bedrock is identified as a peak on the H/V curve (Fig. 4a). In this case a spatial variation of resonance frequencies can be related to a lateral stratigraphic variation (Fig. 4c). In the case of 2D structures, such as deep valleys, the dynamic behavior differs along the longitudinal and transverse direction to the elongation axis (Fig. 4d, e). 2D resonances are therefore identified as peaks with different frequency in the horizontal spectral components of motion recorded along the longitudinal and transverse direction of the resonating body. These

peaks correspond to the 2D longitudinal (L) and transverse (T) resonance modes developing within a valley cross-section (Fig. 4d, e) and they cannot be linked to the local stratigraphy below the measurements site, but depend on the whole valley geometry and mechanical properties (Fig. 4f). The fundamental L mode occurs at lower frequency with respect to the T mode. The latter is also associated with a vertical component V (Fig. 4d; Bard & Bouchon, 1985; Ermert et al., 2014; Roten et al., 2006).

We show in Fig. 5 some examples of representative H/V curves and their corresponding spectral components denoting 1D- and 2D-type resonances. We report also examples of an unclear, broad H/V peak, of a flat H/V curve and of H/V peaks associated to anthropic disturbances (that appear as narrow spikes in all the spectral components; Castellaro, 2016) that are discarded from the analysis. The locations of all the sites characterized by unclear flat H/V curves are shown as black dots in the maps of Figs. 7 and 8. Typically, 1D resonances are identified as peaks on the H/V curves and are usually associated to local minima in the vertical spectral component (Fig. 5a–c). 2D resonances, instead, are identified on the individual spectral components as distinct peaks with different frequency and amplitude along the horizontal directions (Fig. 5d–f). In some cases, the vertical component of the T mode is visible as a peak on the Z spectrum along the transverse direction to the valley axis (Fig. 5d, f).

At a same site both 1D and 2D resonances can be observed. While 2D resonances are always related to the sediment-bedrock interface, 1D resonances may be associated either to the bedrock or to the sediment fill layering. In order to interpret these features, we analyze the spatial correlation of resonance frequencies along lines as described in the next section.

4.2. Analysis of Ground Resonances and Residual Gravity Anomalies Along Profiles

In Fig. 6 we show H/V contour plots and residual gravity anomalies along a few example lines. When 1D resonance is observed, such as along profile NS5 (Fig. 6e), the correlation between the spatial variation of H/V peaks (red shades in the H/V contour plots) and the shape of the residual gravity anomaly is

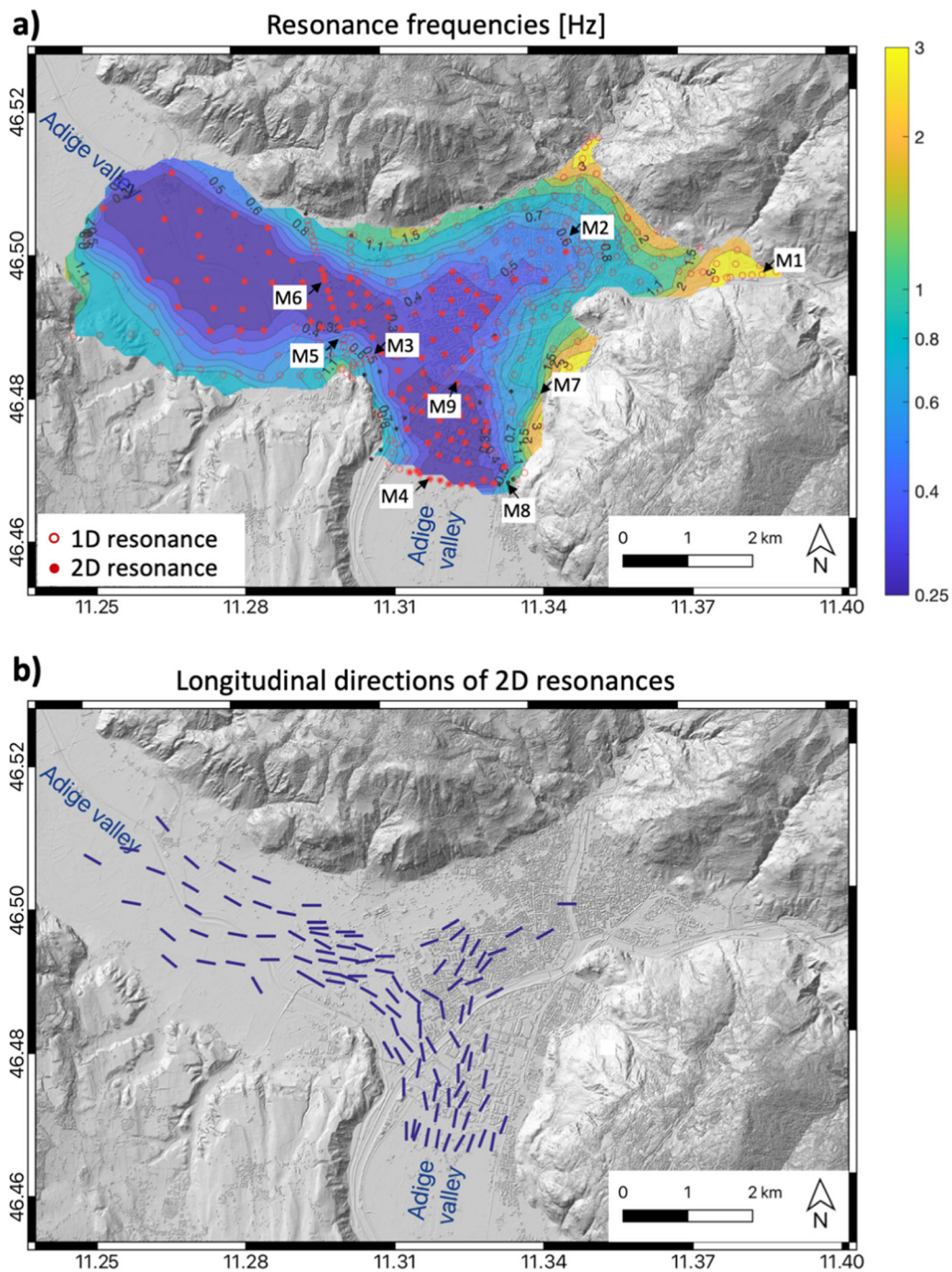


Figure 7

1D and 2D resonance frequencies associated to the base of the sediment fill of the alluvial-sedimentary basin of Bolzano. **a** Contour plot of resonance frequencies within the bases, corresponding to the H/V peak frequencies for 1D resonances and to the fundamental longitudinal frequencies for 2D resonances. The red circles denote 1D resonances and red full dots 2D resonances. **b** Orientation of the longitudinal directions at each site characterized by 2D resonance

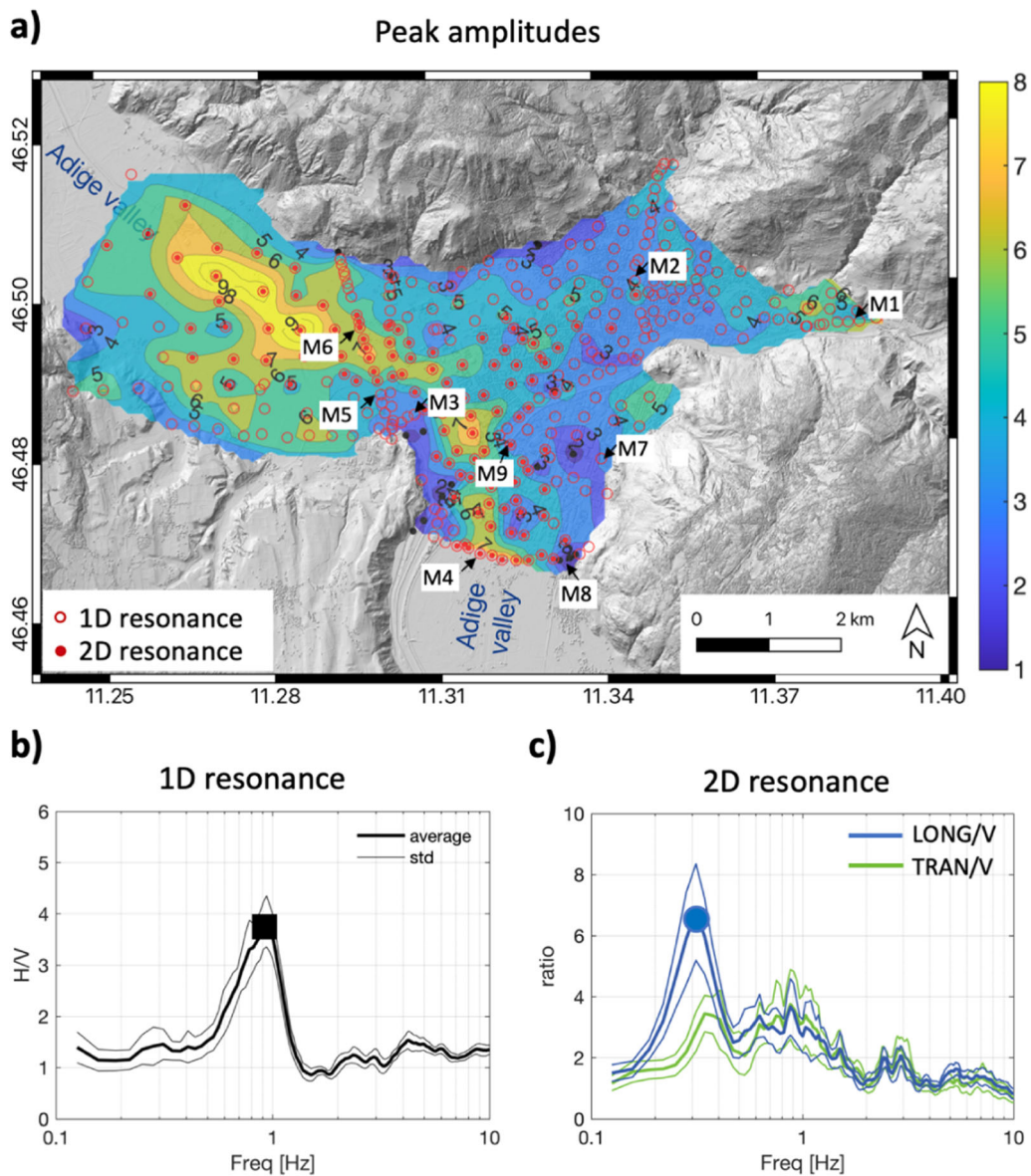


Figure 8

Resonance peak amplitudes within the Bolzano basin. **a** Contour plot of peak amplitudes at the resonance frequencies shown in Fig. 6. The red circles denote 1D resonances and red full dots 2D resonances. The peak values are taken as H/V peak amplitudes for 1D resonances (**b**) and LONG/V peak amplitudes for 2D resonances (**c**)

evident. These also correlate with the inferred bedrock geometry along the seismic reflection profile K1 (Fig. 3). On the contrary, when 2D resonance dominates, as along profile EW4 (Fig. 6f), the constant resonance frequencies observed along the valley cross-section do not correlate with the shape of

the corresponding gravity anomaly that denotes a U-shaped valley.

Along different lines crossing the basin, both 1D and 2D resonances are observed. Typically, flat patterns in the H/V contour plots correspond to 2D resonances, as confirmed by inspection of the spectral components of motion of the individual

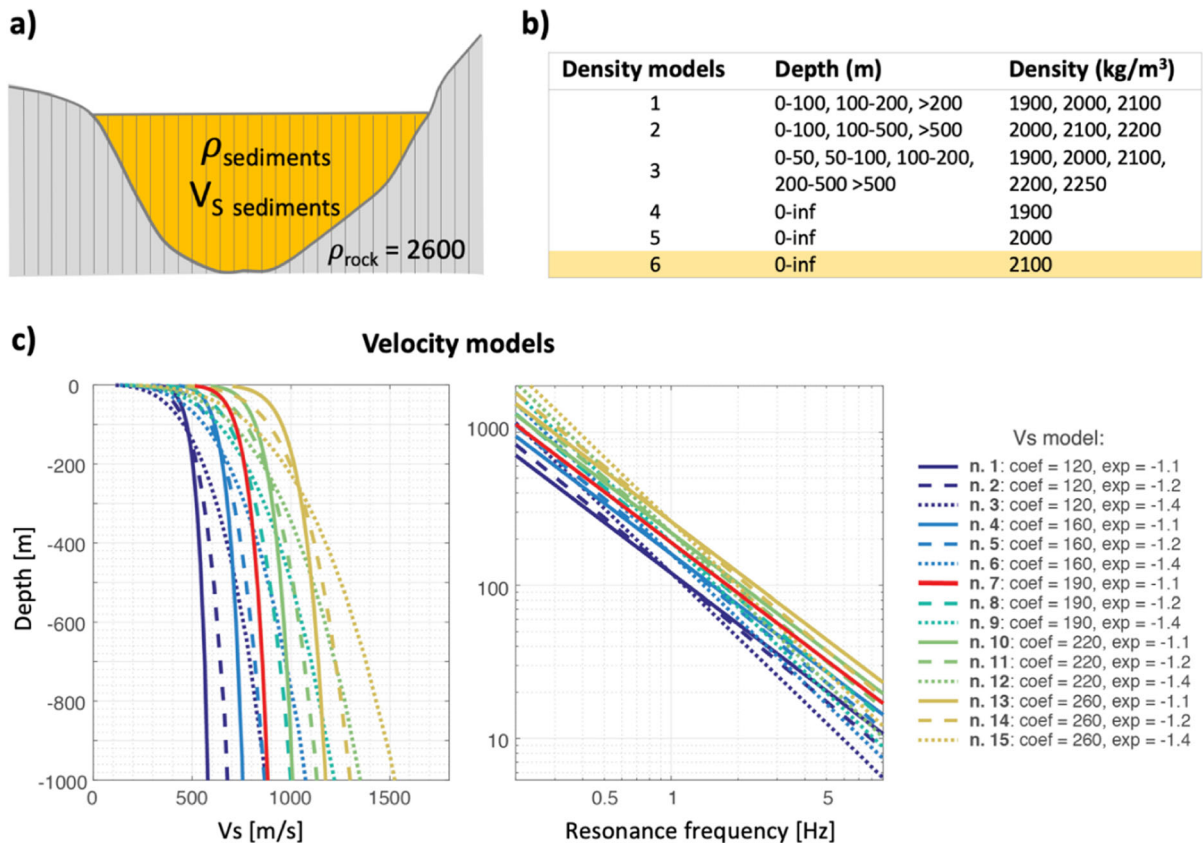


Figure 9

Parameters used for the forward gravity modelling. **a** Sketch of the discretization used: the 3D volume is discretized into vertical columns with vertically varying density according to the fixed rock density shown in **a** and 6 different sediment density models listed in **b**. The line highlighted in yellow identifies the selected density model. **c** Vs models used to convert resonance frequencies to bedrock depth. The red line corresponds to the preferred model. Modified from Sgattoni and Castellaro (2021)

measurements, e.g. at sites M4 (Fig. 5d) and M6 (Fig. 5f) along lines EW4 (Fig. 6f) and NS1 (Fig. 6a).

In some cases, both 1D and 2D resonance is observed at the same measurement site. This is the case of, e.g., site M5 (Fig. 5e) which is located near the edge of profile NS1 across the Adige valley (Fig. 2a): here the relics of the 2D resonance modes are seen on the horizontal spectral components, whereas 1D resonance associated to the sediment-bedrock interface is observed at higher frequency as a peak on the H/V function. At site M6 (Fig. 5f), located near the center of profile NS1, clear 2D resonance peaks appear in the horizontal spectral components (and are reflected in a peak in the H/V curve as well) and another H/V peak occurs at higher

frequency, denoting a secondary resonance interface within the sediment fill. This can be correlated laterally along the line as a flat feature at a frequency of about 1 Hz (Fig. 6a).

4.3. Directional Analysis and Spatial Patterns of Resonance Frequencies

After identifying the nature (1D vs. 2D) of ground resonances at all sites, we extract their frequency and amplitude information to create a map of their distribution across the basin (Figs. 7, 8). In the case of 1D-type resonances, no directional effect is observed, and frequency and amplitude values are estimated from the H/V peaks (Fig. 8b). Conversely, 2D resonances exhibit varying shaking amplitudes

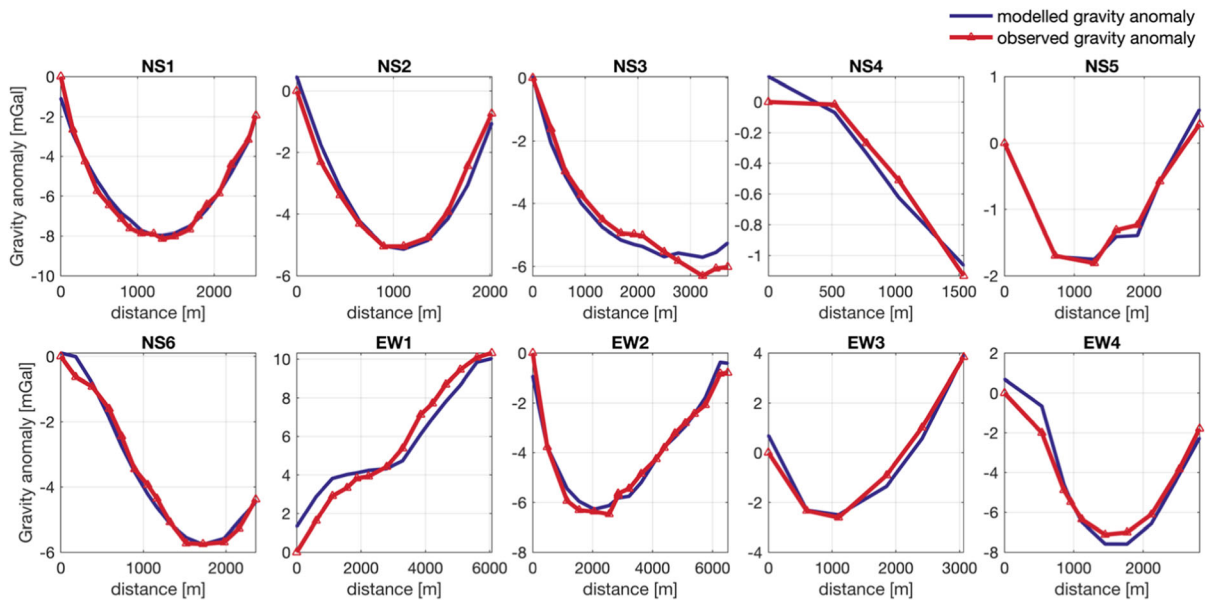


Figure 10

Comparison between modelled and observed gravity anomalies along all the lines investigated. The location of the lines is mapped in Fig. 2b

along the horizontal directions, with the highest amplitudes occurring along the longitudinal direction of the valley. Identifying the principal vibration axes for 2D longitudinal and transverse modes requires a directional analysis at each measurement site. To achieve this, we utilize the signal rotation procedure described in Sgattoni et al. (2023) on all measurements exhibiting 2D resonance characteristics. This procedure involves rotating the horizontal spectra of the signals and aims to determine the principal directions of motion for the 2D resonance modes. The obtained directions correspond to the local longitudinal (L) and transverse axes of the valley at each measurement site (Fig. 7b). Considering that the fundamental L mode exhibits greater amplitude compared to the transverse mode in Bolzano, we opt to focus on mapping the longitudinal frequencies and amplitudes at all 2D sites. The L frequency is estimated as the peak frequency on the absolute longitudinal spectral component of motion (LONG) while the amplitude is extracted from the LONG/V curve (Fig. 8c), in order to clear source effects. This is acceptable because longitudinal modes do not have a vertical component (e.g. Bard & Bouchon, 1985).

The maps of Figs. 7 and 8 show that 2D resonance dominates along the Adige valley and partly in the central portion of the basin. Here the lowest frequencies are observed, with fairly constant values between 0.27 and 0.4 Hz. Towards the edges of the Adige valley and in the eastern portion of the basin, 1D resonance is observed, with values up to >3 Hz increasing outward, as expected in the case of shallower bedrock near the edges of the basin. Also, higher 1D frequencies are observed in the southern portion of the Adige valley west of Bolzano, where the Adige valley meets the Oltradige one.

The maximum amplitudes are observed towards the center of the Adige valley, where 2D resonances dominate. We recall that these amplitudes are measured along the longitudinal directions shown in Fig. 7b, since 2D resonances have a directional behavior that, in the Bolzano basin, strongly dominates along the longitudinal direction to the valley axes. 1D resonance, instead, does not have a directional dependence and in Bolzano has, in general, lower amplitude than the 2D longitudinal mode. This is an important observation for the evaluation of the amplification potential of the basin.

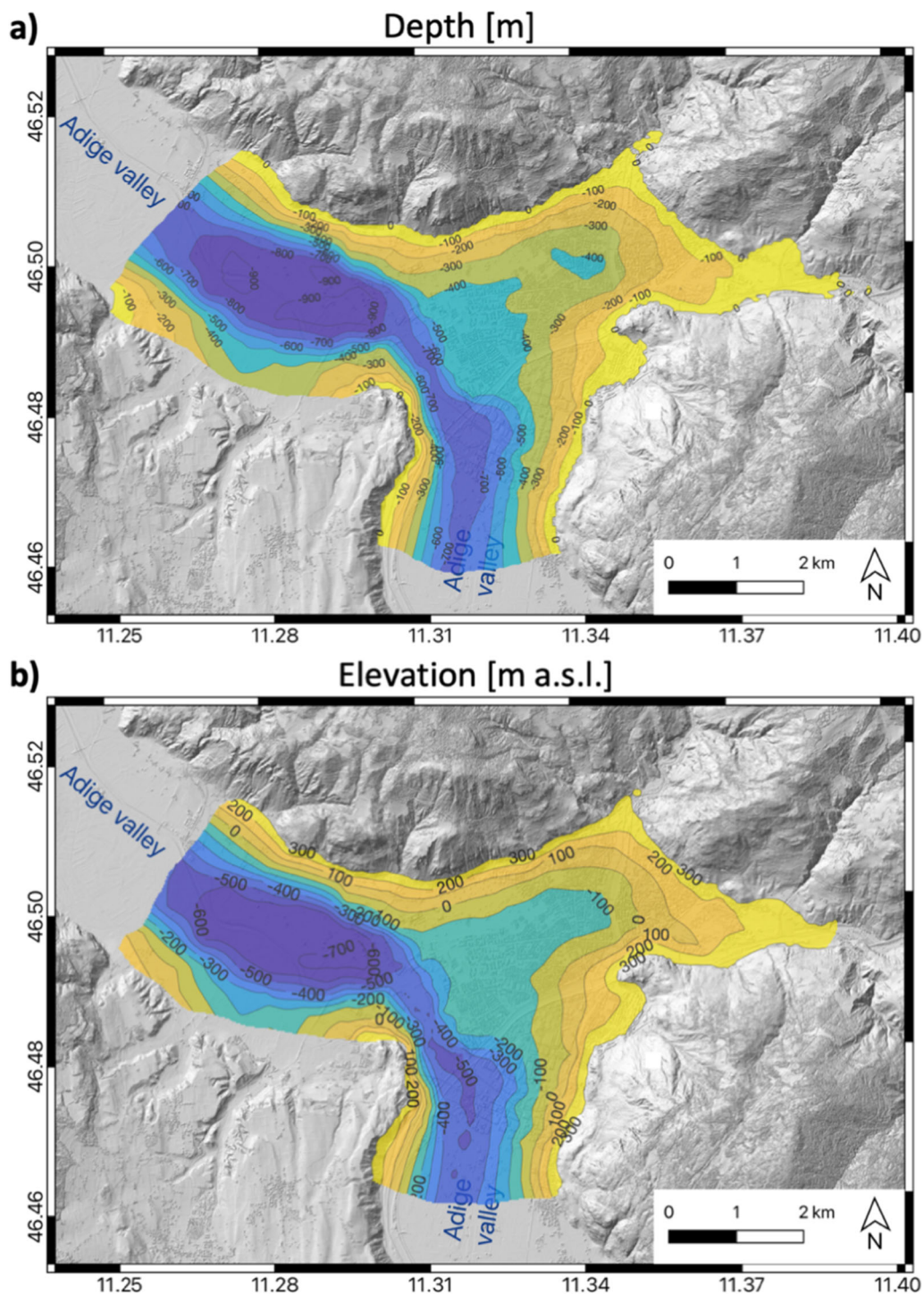


Figure 11

3D bedrock model of the Bolzano alluvial-sedimentary basin. **a** Contour plot of the bedrock depth from ground surface. **b** Contour plot of the bedrock elevation above sea level

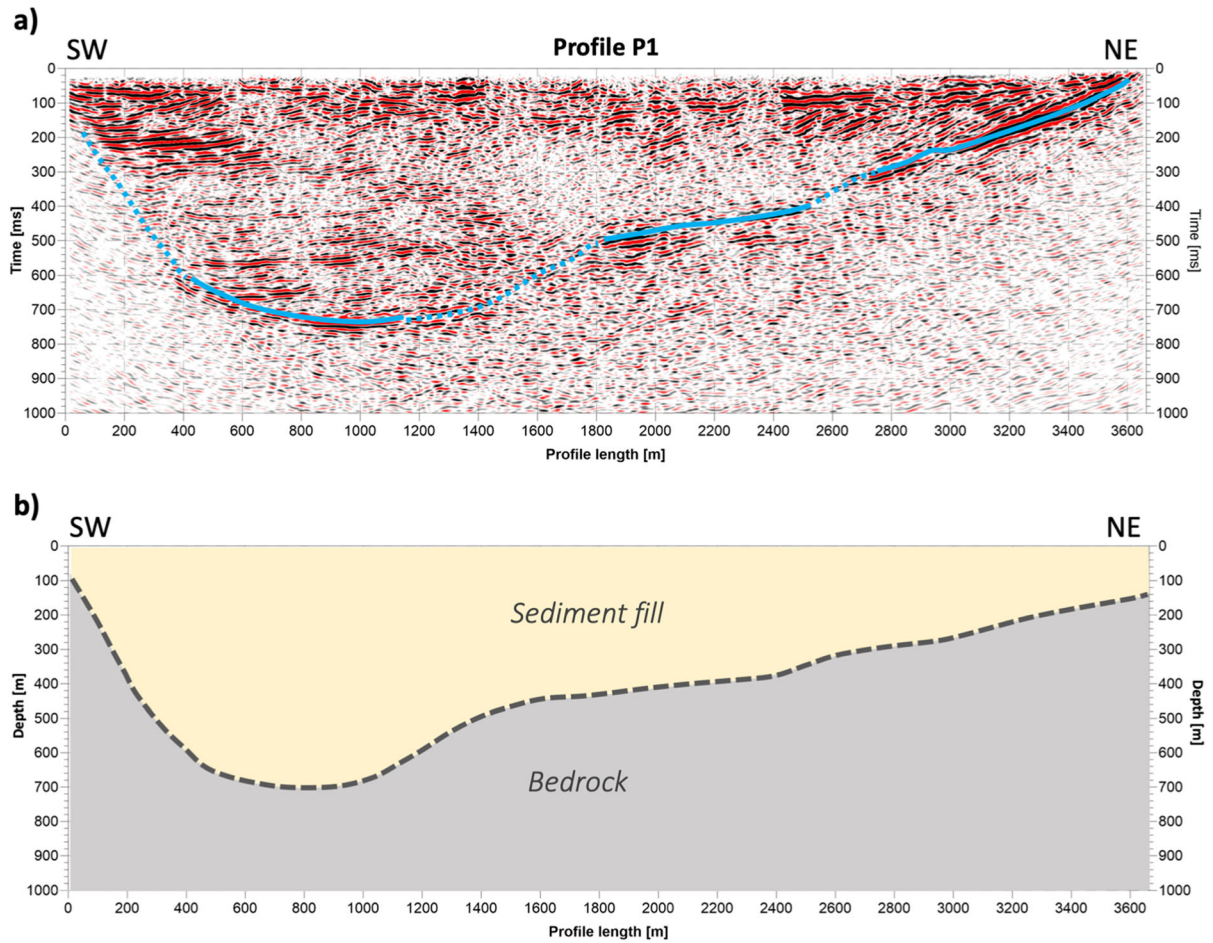


Figure 12

Interpretation of seismic line P1 (a) and corresponding bedrock morphology according to the geophysical model proposed in this study (b). In b, the light blue line highlights the proposed interpretation of the bedrock surface, with dashed line used for uncertain segments

5. Joint-Model of Seismic and Gravity Data

We use the method described in Sgattoni and Castellaro (2021) to combine single-station micro-tremor and gravity data into a joint bedrock model. We do this by first using the map of resonance frequencies associated to the sediment-bedrock interface and converting frequencies to depths using the relation between the fundamental ground resonance (f_0) and the thickness of the resonating layer (h , Eq. 1):

$$f_0 = \frac{V_s}{4h} \quad (1)$$

To apply this equation, we assume a power-law relation for the increasing V_s with depth (Ibs-Von

Seht & Wohlenberg, 1999). Once an initial depth model is available, we define a density model for rock and sediments and carry out a 3D gravity forward modelling of the basin. We perturb both V_s and density models and repeat the gravity modelling in order to find the parameters better fitting the observed gravity anomalies. The reader is referred to Sgattoni and Castellaro (2021) for further details on the method. A sketch of the modelling technique and the V_s and density models tested are shown in Fig. 9. The best fit is achieved with density model 6 and V_s model 7.

As discussed in Sect. 4, 2D resonances are not directly linked to the bedrock depth below the measurement site. This is apparent from the frequency

map of Fig. 7, where the areas of constant frequency would be interpreted as flat surfaces by means of Eq. 1. For this reason, where 2D resonance dominates, the bedrock model is adjusted to fit the gravity anomalies in order to infer the bedrock geometry. This is done with a trial and error procedure, assuming that the shapes of the measured gravity anomalies correlate with the shape of the bedrock surface. Observed and modelled gravity anomalies are shown in Fig. 10 and the corresponding best-fit bedrock model is shown in Fig. 11. We provide the 3D model data points as a.csv file in Online Resource 1.

Concerning uncertainties, we note that there is a trade-off between the main parameters involved in the bedrock modelling. The use of different V_s models to translate frequency into depth values is partly compensated by a change in density model of the basin, i.e. the same fit can be achieved by increasing/decreasing the sediment V_s (therefore increasing/decreasing the basin depth) while decreasing/increasing the sediment-bedrock density contrast. This is the reason while model parameters were varied within predefined reasonable limits. We also note that what counts in gravity modelling of relative gravity measurements is the density contrast, therefore absolute density uncertainties do not play a role in our model fit.

5.1. Calibration with Seismic Reflection Profiles

The three seismic reflection lines described in Sect. 3.3 are used to constrain the bedrock model. We note that when direct depth or velocity constraints are missing and when the deviation from a 2D approximation (i.e. when geometry/structural changes along the valley axis are not negligible) is relevant, the interpretation of 2D seismic lines can be problematic (e.g. Brückl et al., 2010; Hutchinson, 2016). However, they are useful to constrain the general shape of the bedrock interface and the two-way time values at the deepest point of the inferred bedrock surface can be used to estimate the relative depth between the three profiles. By assuming an average P-wave velocity equal to 1950 m/s from the Sinigo well, we can estimate maximum depths along the three profiles corresponding to about 400 m, 850 m and 700 m.

This is consistent with the results obtained with independent modelling of gravity and seismic data described earlier, for which the estimated depths along the three valleys are about 400, 900 and 700 m (Fig. 11a). The general shape of the three seismic lines also matches the 3D bedrock model, as consistent with the observation that H/V profiles correlate with the sediment-bedrock surface identified on reflection profiles. However, a quantitative comparison or even a direct constrain of the 3D model with the seismic lines is made difficult by the unknown P wave velocity.

In Fig. 12 we compare the highest quality reflection line (P1) with the corresponding cross-section of the 3D bedrock model obtained. The general shape of the sediment-bedrock interface exhibits a close match between the two. Notably, both profiles show evidence of a sharp elevation change in the bedrock, estimated to be 200 m in our 3D model. However, there is a slight discrepancy in the lateral positioning of this steep section along the profiles. According to the suggested interpretation of the seismic reflection profile the steep bedrock portion is situated between 1200 and 1800 m from the southwest edge of the line, while in the cross-section of the 3D model, it is found to be situated between 1000 and 1600 m.

6. Subsurface Geometry of the Bolzano Basin

The resulting 3D bedrock geometry exhibits distinct features. Along the Adige valley, a deep excavated channel dominates, reaching depths of approximately 700 m, with a deeper section (~ 900 m) in its north-western portion (Fig. 11). In the central area of the basin, a relatively flat and shallower surface is observed, with a steep cliff delineating its southwest boundary, running alongside the Adige channel. Throughout this area, the bedrock slowly slopes down from near the surface (Cardano area) to a depth of about 450 m at the western edge of the city of Bozen (Ponte Resia—Hospital area). From here, it joins the deep furrow via a steep cliff up to 300 m.

Compared to the model presented in Sgattoni and Castellaro (2021), which was based on approximately one third of the measurement points, the current study

incorporates new data that enabled the identification of the steep cliff separating the basin's center and the Adige channel in the southwest.

6.1. *Geologic Implications*

The bedrock trend below the Bolzano Basin (Fig. 11) clearly indicates the presence of a main deep trough along the axis of the present-day Adige Valley while such deepening is missing in the central-eastern sector below the path of the Isarco river.

The deep morphology of the basin suggests the following:

- during the earliest Quaternary, the Adige Valley served as the main drainage route;
- The course of the Adige River has remained relatively unchanged over time;
- Despite having a catchment area that is a quarter larger than that of the Adige, the Isarco river played a secondary role during the formation of the deep valley;
- The bedrock morphology beneath the city is substantially conditioned by erosion along the Isarco axis with the Talvera creek having a marginal impact.

Additionally, the model depicted in Fig. 11 clearly indicates a steep ascent of the bedrock towards the Oltradige. Preliminary data collected by us (Infriccioli, 2020) confirm that the Oltradige exhibits much shallower depths compared to the Adige Valley. This evidence contradicts the hypothesis put forward by Castiglioni and Trevisan (1973), suggesting that the Oltradige represented the ancient drainage of the Adige river.

The maximum depths of the valley, despite some uncertainties, align with the findings from deep wells in Sinigo and Trento (Bargossi et al., 2010; Felber et al., 2000). The significant depth of the valley, extending for at least 80 km from Merano to Trento (−450 m asl in Merano, −500/600 m in Bolzano, and approximately −430 m in Trento), suggests a pre-Quaternary origin of the deep erosion. This origin is likely situated in the Messinian period when the Mediterranean experienced a salinity crisis and the base level was considerably lower than today. Similar

deep valleys in the Alps have demonstrated this phenomenon (Bini et al., 1978; Cita & Corselli, 1990; Corselli et al., 1985; Felber & Bini, 1997; Felber et al., 1991; Finckh, 1978; Cazzini et al., 2020; Rizzini & Dondi, 1978).

On the other hand, the available data suggest a nonlinear trend in the longitudinal bedrock profile due to the presence of deeper zones. This observation holds true at both the model scale, where a zone of approximately 3 km exhibits depths up to −700 m asl, and at a larger scale. Existing literature indicates that the Bolzano area displays greater depth than the Trento area (up to approximately 250 m). This contrasts with the notion of a strictly fluvial origin for the deep furrow, which would require a continuously descending slope. This discrepancy suggests a role played by glaciers in the profound shaping of the Adige Valley, analogous to certain valleys on the northern side of the Alps (Preusser et al., 2010). This viewpoint is also supported by Winterberg et al. (2020), who argue, based on uplift and erosion rates in the Alps, that the current level of buried bedrock is inconsistent with a Messinian surface and propose a more recent glacial origin.

However, the presence of a stepwise longitudinal profile in the bedrock trend may be attributed to tectonic processes leading to differential post-Messinian uplifts. Some evidence for this is provided by reports of active Quaternary faults near Egna (Galadini & Galli, 1999; Galli & Galadini, 2001), near Merano (Bargossi et al., 2010), and on the orographic right side of the Adige valley between Bolzano and Trento (Cavallin et al., 1988). Additionally, the current distribution of strain in the Alpine region, as observed through geodetic measurements (Sanchez et al., 2018), further supports this hypothesis.

7. *Discussion and Conclusions*

Accurate bedrock mapping in urban areas is of primary importance for seismic amplification studies, especially in sediment-filled valleys or basins, where seismic waves are trapped causing an increase in the amplitude and duration of seismic motion. In addition, amplification within basins can be influenced by complex 2D/3D focusing and diffraction phenomena.

The 1D, 2D or 3D nature of ground resonance determines distinct amplification characteristics of ground motion and also a different stratigraphic interpretation of resonance frequencies. Consideration of these factors is essential when utilizing the H/V technique for stratigraphic mapping and seismic response analysis.

To model the basin response to seismic shaking, a realistic and detailed 3D model is needed. This has shown to significantly improve the waveform fit in ground-motion modelling when comparing recorded and synthetic data (e.g. Molinari et al., 2015). This is also important for other types of studies, e.g., for hydrological/geotechnical modelling and for geological studies. However, the task is challenging in deep and urbanized basin, where direct stratigraphic information down to bedrock are missing and where conventional methods such as reflection profiles are problematic.

We combined a large dataset of microtremor and gravity measurements, and three seismic lines to infer the 3D deep bedrock morphology of the sediment-bedrock interface of the Bolzano alluvial-sedimentary basin. We identified 1D/2D resonances on the individual spectral components of motion and on H/V curves computed on noise recordings. 2D resonances dominate along the deepest portion of the basin, i.e. along the Adige valley that appears as a deep excavated channel, down to maximum depth of 900 m from the surface. We also described the 1D/2D resonance behavior by comparing the spatial characteristics of H/V profiles and gravity anomalies, observing a poor correlation along profiles dominated by 2D resonance. The combination of the two techniques helps inferring the bedrock morphology when spatially constant 2D resonances would be interpreted as a flat surface with the common 1D approach.

The absence of direct stratigraphic information down to bedrock was partially compensated by three seismic reflection lines located on the western, eastern and southern parts of the basin. Although their acquisition and interpretation were complicated by the urban environment and complex bedrock geometry (which is locally very far from a 2D geometry assumed in the interpretation of a 2D seismic line), we used them to calibrate the maximum depth of the three valley branches and to qualitatively compare

the inferred bedrock geometry obtained with the other geophysical data. The final 3D bedrock model was obtained by joint modelling of microtremor and gravity single-station data, assuming an exponentially increasing V_s with depth for the sediment fill. Both techniques are low-cost and low-impact and therefore suitable for urban geophysical prospecting. A dense distribution of measurement sites is crucial for accurately interpreting ground resonances and gravity anomalies, as well as improving the resolution of modeled bedrock morphology.

The resulting morphology confirms that the bedrock surface lies well below sea level and provides insights into the drainage evolution of the basin, suggesting that the deep erosion of the Adige Valley predates the Quaternary period, likely occurring during the Messinian period. The Adige River served as the primary drainage route during the early Quaternary period, and its course has largely remained unchanged over time. The bedrock beneath the city is situated at shallower depths ranging from 100 to 450 m, exhibiting a westward sloping morphology primarily shaped by erosion along the Isarco Valley.

Some considerations can be drawn also concerning the expected seismic response of the basin. Although the quantification of seismic amplification requires specific ground-motion modelling, the spatial distributions of resonance frequencies and peak amplitudes from H/V and LONG/V ratios allow us to observe that: (1) the city of Bolzano lies in area where resonance frequencies range between 0.27 and >3 Hz, indicating that a wide range of building types may be affected by local amplification in case of seismic shaking; (2) however, maximum peak amplitudes are observed at 2D resonance sites, with frequencies ranging between 0.27 and 0.4 Hz, which would mainly affect high-rise buildings; (3) a marked directionality characterizes 2D resonances, with larger amplification expected along the longitudinal direction to the valley axis at each site.

The final bedrock depth model is provided in the Supplementary Material. This can be useful for further ground-motion modelling, seismic site response analysis, hydrogeological, geological, geothermal studies.

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Author Contributions The study conception and design were performed by G.S., C.M. and S.C. Single-station geophysical measurements were acquired, analyzed and curated by G.S. and G.L., while seismic reflection lines were analyzed by W.C. Geological data were analyzed by M.C. and W.C. S.C. wrote the codes for single-station microtremor measurement analysis. G.S. wrote the codes for the analysis of gravimetric data and for 3D bedrock modelling. G.S. prepared all figures, with contributions of M.C. and C.M. to Fig. 1 and W.C. to Fig. 3. The first draft of the manuscript was written by G.S. and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data availability

The bedrock depth model presented in this study is provided in the Supplementary Material while the seismic and gravimetric datasets are available from the corresponding author on reasonable request.

Declarations

Conflict of Interest The authors declare no competing interests.

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