Zeitschrift: Eclogae Geologicae Helvetiae

Herausgeber: Schweizerische Geologische Gesellschaft

Band: 83 (1990)

Heft: 2

Artikel: The Quaternary sedimentary fill of some Alpine valleys by gravity modelling

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DOI: https://doi.org/10.5169/seals-166589

Eclogae geol. Helv. 83/2: 311–321 (1990)

0012-9402/90/020311-11 $ 1.50 + 0.20/0
Birkhäuser Verlag, Basel

The Quaternary sedimentary fill of some Alpine valleys by gravity modelling[1])

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Key words: Gravity modelling, Alpine valleys.

ABSTRACT

Gravity profiles across Alpine valleys, placed according to the surface geology and the local gravity field, provide fast, cheap, and precise means to determine the depth of the Quaternary sedimentary fill.

ZUSAMMENFASSUNG

Mit Schwereprofilen, welche unter Berücksichtigung des lokalen Schwerefeldes und der Geologie plaziert werden, können rasch und mit geringen Kosten relativ genaue Aussagen über die Tiefe des Felsuntergrundes unter den Quartärsedimenten in den Alpentälern gemacht werden.

Introduction

The bedrock below most large Alpine valleys is covered by thick, mostly Quaternary sediments. For some geotechnical projects this imposes great problems, for example, when planning a tunnel beneath an Alpine valley with such Quaternary fill. On the other hand, many Swiss benefit from these sedimentary fills as they provide excellent and easily accessible aquifers. While the tunnel engineer likes to avoid the sedimentary fill, the ground water technician searches for the best place to sink a well within the sediments. One common question in such circumstances is: how deep is the bedrock in this valley?

The answer to such questions is also of geologic interest. For example, the two most prominent valleys of the central Alps, the Rhine and the Rhone valleys, follow major tectonic structures that are often undetectable beneath the sedimentary fills. Other important geological results are the maximum depth of the bedrock and the dominant type of erosion that formed the valley, information that is derived from the form of the valley base.

In some cases the internal structure of the sedimentary fill or of the bedrock beneath it demands high-resolution seismic methods to meet the required accuracy. Seismic field surveys, however, are of considerable costs compared to a relatively

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cheap and quick gravity study. In addition, preceding gravity modelling can help to choose the optimum location for the seismic lines and later it may provide density information essential for the interpretation of seismic velocities.

Method

The proposed gravity modelling technique is based on three-dimensional (3D) model calculations for data points along one or several gravity profiles across a valley and up the flanks of the bordering mountains. The profiles are placed according to the target area, the known geologic units of the bedrock and the sediments, the regional gravity field (Fig. 1), and the accessibility of field measurements.

A trial 3D-model (with known surface geometry and with minimum and maximum density contrasts) will help define the necessary amount and the best locations of data points to be measured. Usually the data of a known section across a valley of similar geometry provide an excellent initial 3D-model. Where the form of the valley base (and not only the maximum depth) is of interest, many points are required at either side of the valley and along the flanks of the mountains. Another important piece of

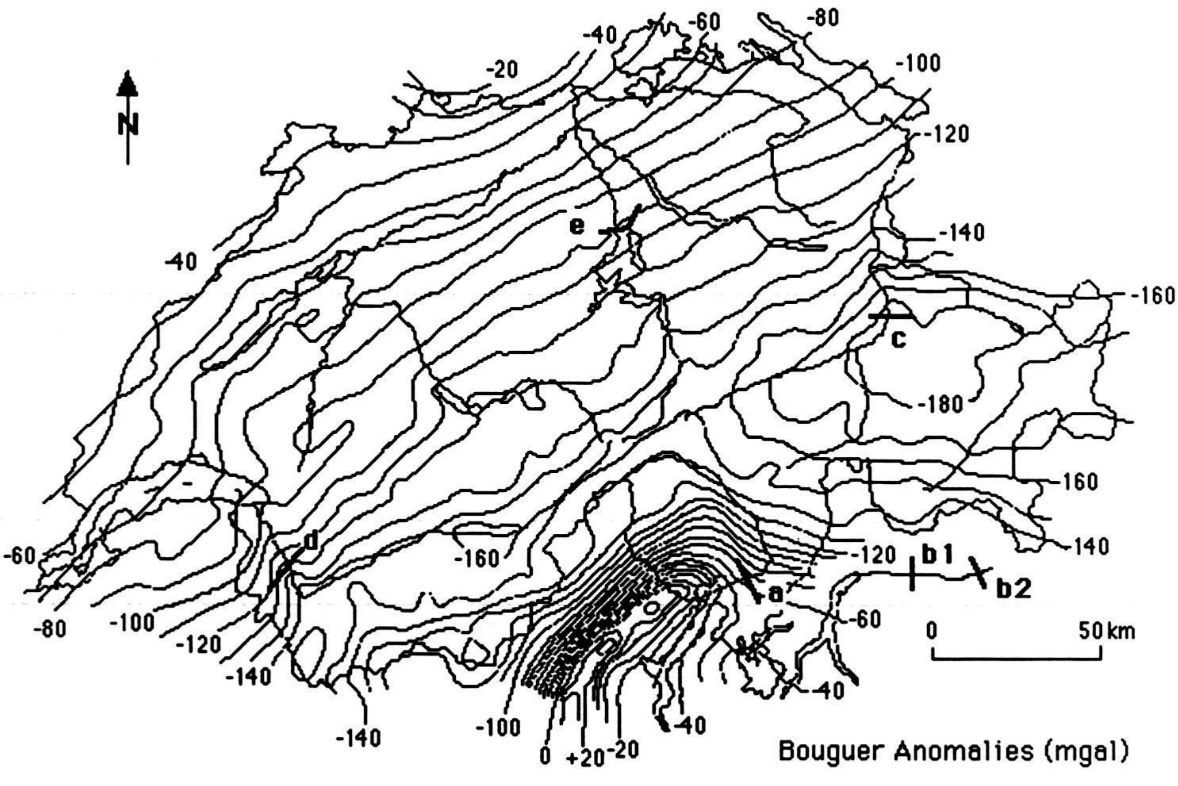


Fig. 1. Bouguer gravity map of Switzerland (Klingelé & Olivier 1980; Kissling 1980; Schwendener 1984). Values are given in (mgal), where 1 mgal = 10^{-5} ms^{-2}. The locations of the Alpine valleys discussed in the text are marked with:

(a): Magadino Plain of the Ticino Valley
(b): Valtellina profiles: b1 = Berbenno; b2 = Sondrio
(c): Rhine Valley at Zizers
(d): Rhone Valley at Aigle
(e): Reuss Valley below Luzern (Rifferswil-Sins)

information that can be derived from such pre-measurement modelling is the minimum horizontal distance from the valley to the point where the local gravity effect is smaller than the accuracy of the measurements. The profile will have to be of at least such length.

The data sampled by the gravity survey are reduced to Bouguer anomalies by standard gravity reduction procedures (see, for example, KLINGELÉ 1972 or SCHWENDENER 1984). In cases such as the Magadino Plain (Fig. 1) the Bouguer gravity anomaly contains several local anomalies of different wave length that need to be separated before analysis (Fig. 2).

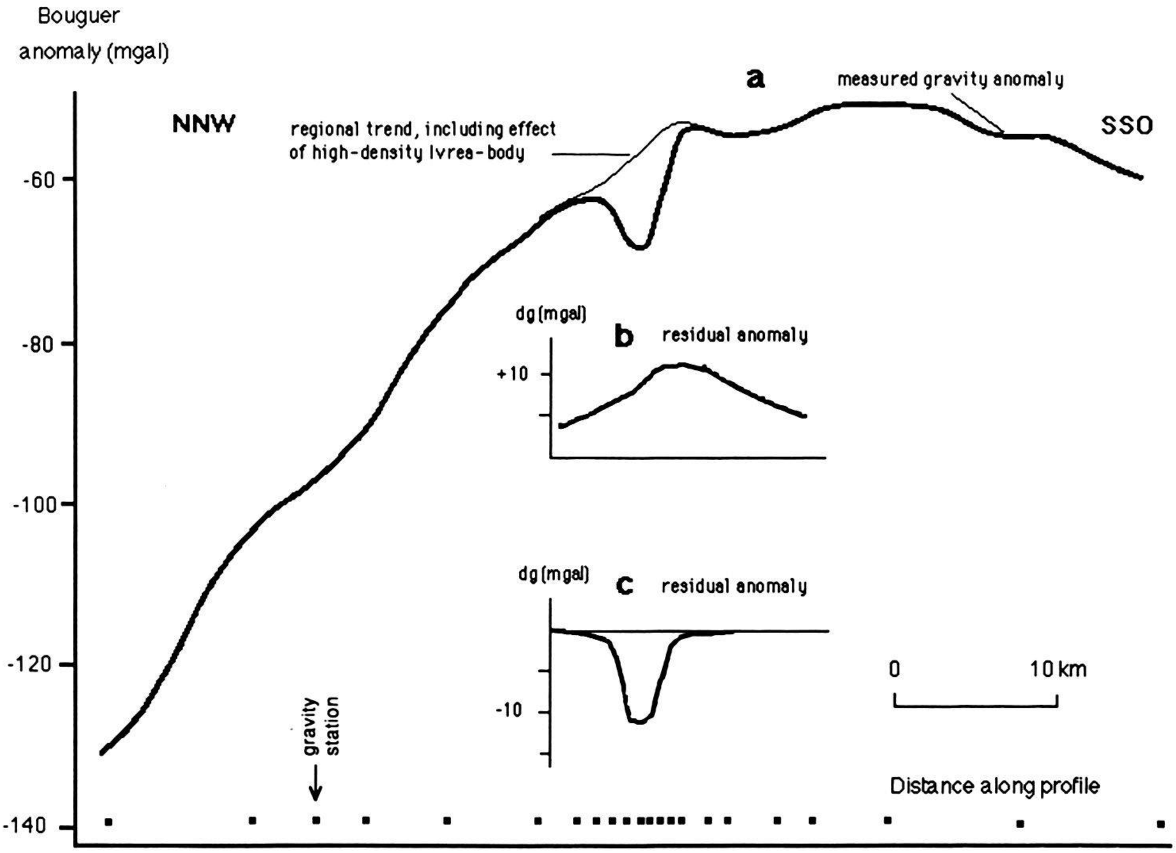


Fig. 2. Bouguer anomaly (a) along a profile across the Magadino plain in southern Switzerland (KISSLING 1980). The different wavelengths allow the separation of the regional gravity anomaly (mainly caused by the thickened crust beneath the Alps) from the local anomalies. The side-effect of the intracrustal high density body of the Ivrea-Verbano zone (b) can be separated from the anomaly of the valley sediments (c) by 3D-gravity modelling (KISSLING 1984).

Prism Method:

The applied method (see below) is a modification of the standard forward modelling technique using analytical solutions for gravitating prismatic bodies (JUNG 1961). The local gravity anomaly that is attributed to the valley sediments of the Magadino Plain has a maximum value of -12 mgal (1 mgal $= 10^{-3}$ cm s^{-2}) and a wave length of about 5 km. The amplitude of the anomaly allows a first-order estimate of the

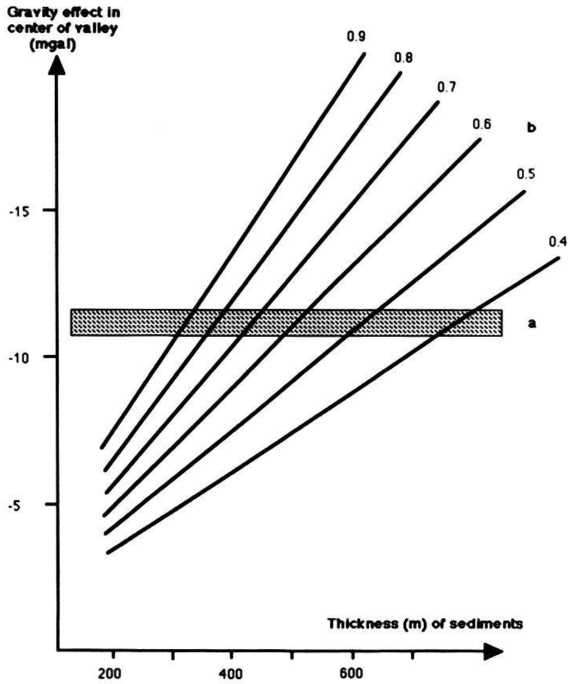


Fig. 3. Gravity effect of prismatic bodies of various thickness and density for the sedimentary fill of the Magadino Plain (see text). The average elevation of the Magadino Plain is 200 m above sea level.
(a): maximum amplitude (in mgal) of observed local gravity anomaly.
(b): density values in g cm^{-3}.

maximum thickness of the sediments using the formula by JUNG (1961) for a gravitating prism of the length of the Magadino Plain perpendicular to the profile (about 12 km) and the width of the valley along the profile (about 3 km). These two dimensions of the prism are held fixed. The depth extent of the prism and its density contrast are varied within reasonable bounds. The calculated corresponding gravity effects for a station in the middle of the valley are shown in Fig. 3. As an example, using the amplitude of −12 mgal and assuming an average density contrast of 0.6 g cm^{-3} between the bedrock (density of 2.6 g cm^{-3}) and the sedimentary fill (density of 2.0 g cm^{-3}) we would derive a thickness of the sediments of about 500 m for the Magadino Plain.

Thickness of sedimentary fill of Alpine Valleys

Magadino Plain

Obviously, such an estimate depends primarily on the assumed density contrast. In general the precise in situ-bulk densities[3]) of gravitating bodies to be modelled are rather poorly known and account for a large part of the modelling error. Fortunately, in the case of the Quaternary sediments in Alpine valleys it is possible to calculate an excellent density-depth relationship by means of an "inverse" Nettleton profile. The

[3]) in situ bulk density = overall density of studied volume, including cracks, pore fluids, and inhomogeneities of the rock.

depth of the bedrock beneath the Magadino Plain has been mapped in detail by seismic surveys (Geologischer Atlas der Schweiz. Map 1313 Bellinzona, 1974). Using this topography of the bedrock and our gravity data as a Nettleton profile (Fig. 4), we calculate the average density contrast between the bedrock and the sedimentary fill as 0.6 g cm^{-3}. By 3D-modelling of the known geometry we may also derive the density-depth curve for the Quaternary sediments that best fits our data (Fig. 5). The calculation of the gravitational effect of the 3D-body that comprises the sediments has been performed by a routine (KISSLING 1980) which follows the method of TALWANI & EWING (1960) that approximates a body of arbitrary shape by polygonal slices of equal depth. The density-depth function (Fig. 5) derived for the Quaternary sediments in the Magadino Plain can be used as an estimate of the average density of sediments in other Alpine valleys.

The simple prism method (Fig. 3) yields a thickness of about 500 m for the sediments in the Magadino Plain. The same value is obtained by 3D-gravity modelling

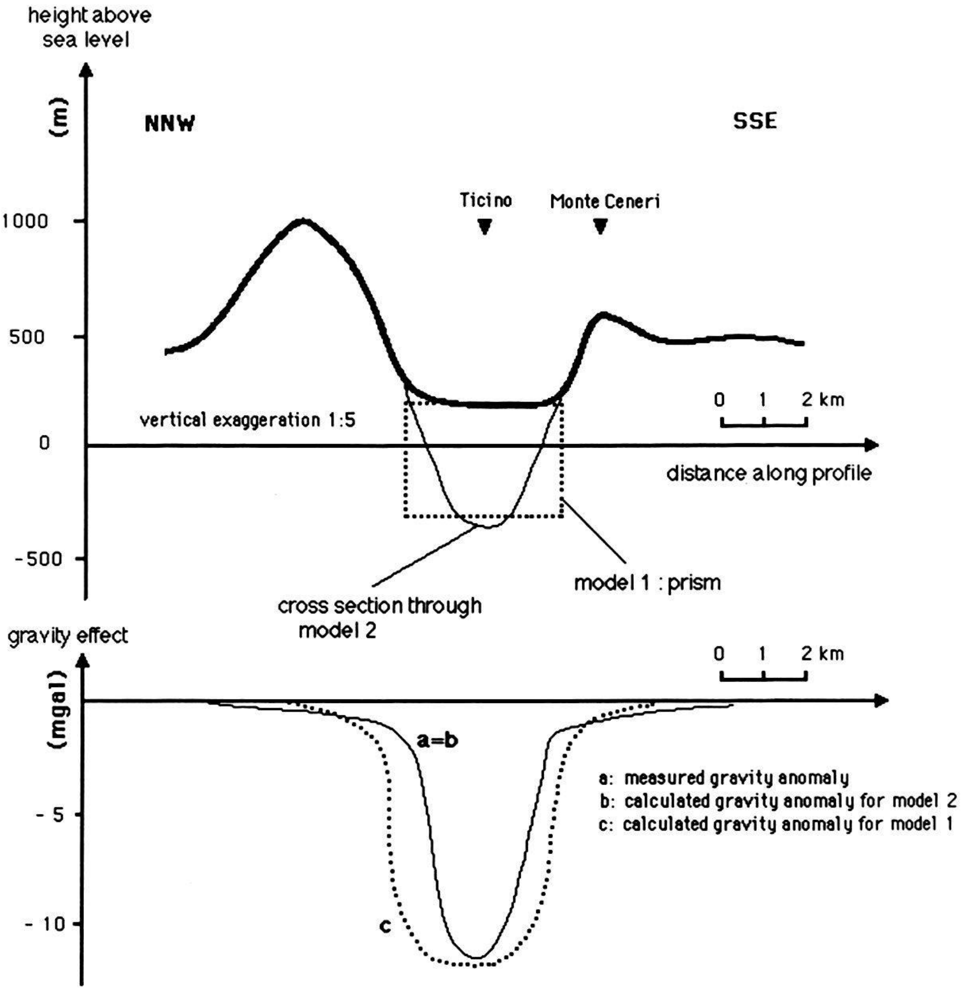


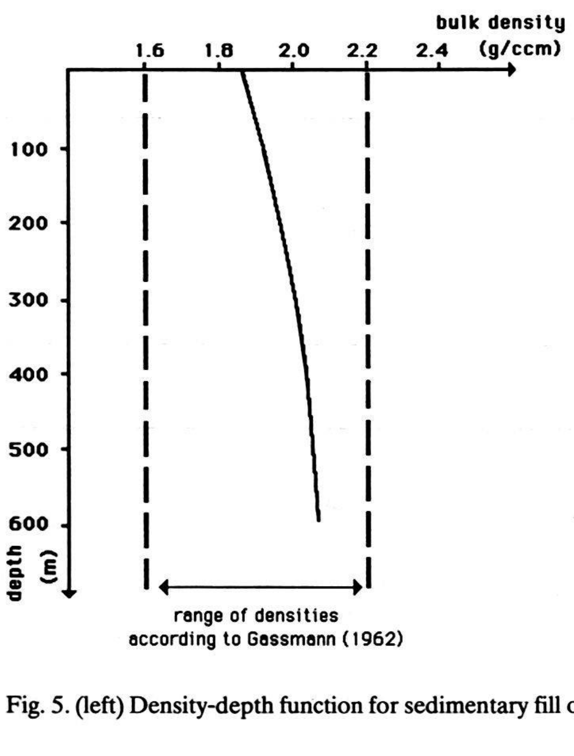
Fig. 4. Magadino Plain. Comparison between a prismatic model and a cross section through the 3D-model 2 based on seismic results (see text). While both model anomalies (b and c) are of equal amplitude (12 mgal) only the calculated anomaly (b) that belongs to the 3D-model fits the observed residual gravity anomaly (a). Model 2 has been used to calculate the density-depth function shown in Fig. 5.

(Kissling 1980). This is in good agreement with the 530 m derived by seismic sounding (Geologischer Atlas der Schweiz. Map 1313 Bellinzona, 1974).

Valtellina Valley

The Valtellina (see Fig. 1 for location of profiles) is a prominent Alpine valley that follows the EW-striking suture of the Insubric Line which separates the Southern Alps from the Central Alps. Because of its proximity to higher mountains the Valtellina is characterized by several large alluvial fans that need to be accounted for by 3D-modelling (Schwendener 1984) when calculating the form of the valley floor.

The maximum thickness of the sedimentary fill, however, may be obtained by the prism-method described above provided the surface topography (alluvial fans!) has been accounted for by 3D-modelling. Schwendener (1984) measured several gravity profiles across the Valtellina. The amplitudes of the local anomalies for two of his profiles are 9 mgal (profile b1, Fig. 1) and 8 mgal (profile b2, Fig. 1). Using an average density contrast between the bedrock and the sedimentary fill of 0.6 g cm^{-3} we obtain



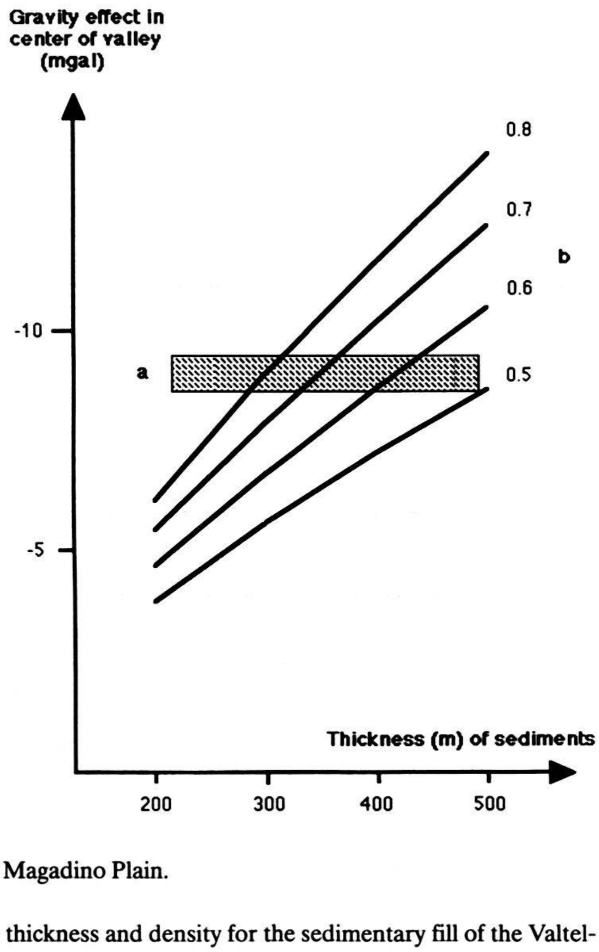


Fig. 5. (left) Density-depth function for sedimentary fill of Magadino Plain.

Fig. 6. (right) Gravity effect of prismatic bodies of various thickness and density for the sedimentary fill of the Valtellina at Berbenno (profile b1). The elevation of the Adda river is 271 m above sea level.
(a): maximum amplitude (in mgal) of observed local gravity anomaly.
(b): density values in g cm^{-3}.

values for the thickness of the sediments in Valtellina of 400 m for profile b1 (Fig. 6, Berbenno) and of 380 m for profile b2 (Fig. 7, Sondrio).

Rhone Valley

The model of the upper Rhone Valley is the last example of an Alpine valley that belongs to the Mediterranean drainage system. Here no new gravity profile was measured. Rather, a value of some 19 mgal for the amplitude of the local gravity anomaly associated with the sedimentary fill at Aigle (see Fig. 1 for location of profile) was derived from the Bouguer map of Switzerland (KLINGELÉ & OLIVIER 1980) and from a local gravity study by GONET (1965). Calculations with prismatic models for this profile (Fig. 8) give an estimate of at least 700 m thickness for the valley fill, a value compatible with the results of FINGER & WEIDMANN (1987) and PUGIN (1988) for other cross sections of the Rhone valley. This indicates that the surface of the bedrock in the Rhone valley and in the Magadino Plain are a few hundred meters below the present sea level compared to about 100 m in the case of the Valtellina valley.

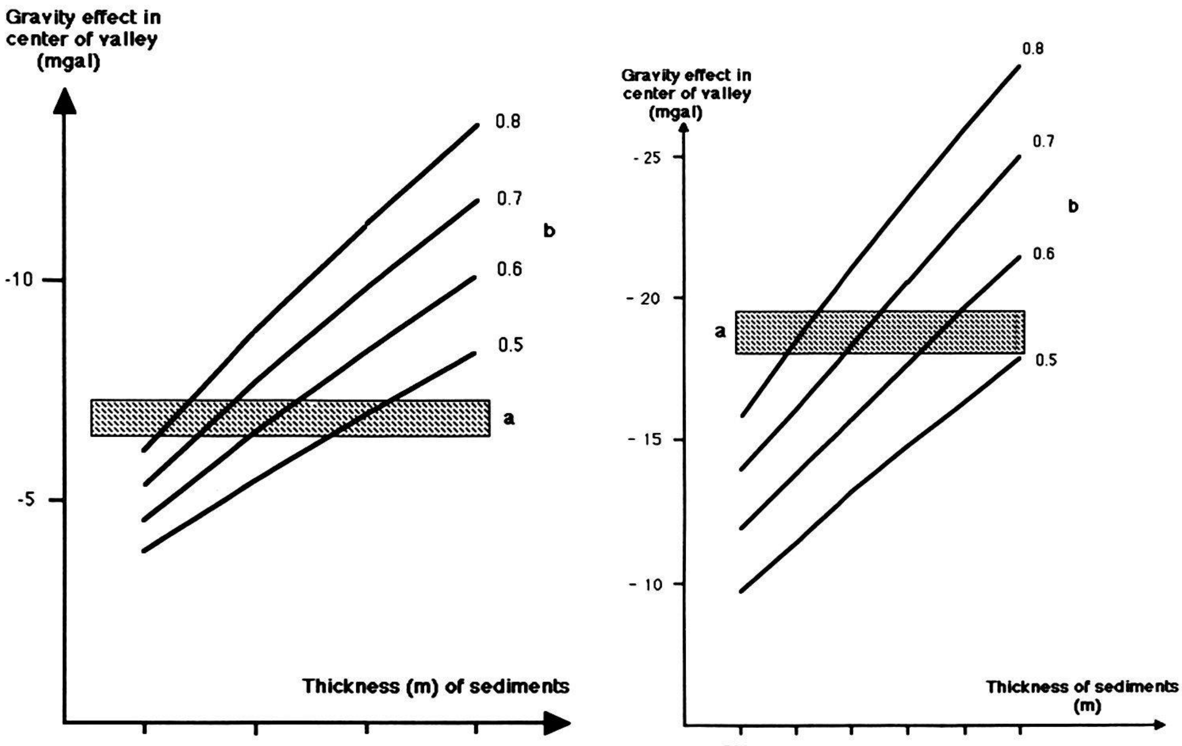


Fig. 7. (left) Gravity effect of prismatic bodies of various thickness and density for the sedimentary fill of the Valtellina at Sondrio (profile b2). The elevation of the Adda river is 288 m above sea level.
(a): maximum amplitude (in mgal) of observed local gravity anomaly.
(b): density values in g cm^{-3}.

Fig. 8. (right) Gravity effect of prismatic bodies of various thickness and density for the sedimentary fill of the Rhone valley at Aigle (Fig. 1, profile d). The elevation of the Rhone river is 380 m above sea level. The lowest point in the Lake of Geneva is +62 m.
(a): maximum amplitude (in mgal) of observed local gravity anomaly.
(b): density values in g cm^{-3}.

Rhine Valley

Several local gravity profiles have been measured across the upper Rhine Valley by Schwendener (1984). As an example, the profile close to the village of Zizers (see Fig. 1 for location of profile c) shall be used for modelling. The error estimate of 1 mgal for the amplitude of the observed local anomaly (Fig. 9) is due to the uncertainty in the regional gravity field. Unlike profiles a, b1 and b2, the gravity effects in the profile at Zizers of the locally varying surface rocks are poorly constrained. This EW-trending profile lies within the realm of the eastern limit of the Aar massif, which descends beneath the Helvetic and Eastern Alpine nappes. The estimated thickness of the sediments in the Rhine Valley at Zizers is 500 m +/−30 m, thus putting the top of the bedrock just above the present sea level. This estimate is in good agreement with the results of a gravity study by Gassmann & Müller (1961) for the Rhine Valley upstream lake of Konstanz. Other Alpine valleys that belong to the Rhine drainage system like the Reuss Valley or the Aare Valley (Cagienard et al. 1984) have given similar results of a minimum bedrock surface slightly above sea level (see Wildi 1984 for a map of the depth of bedrock for northeastern Switzerland).

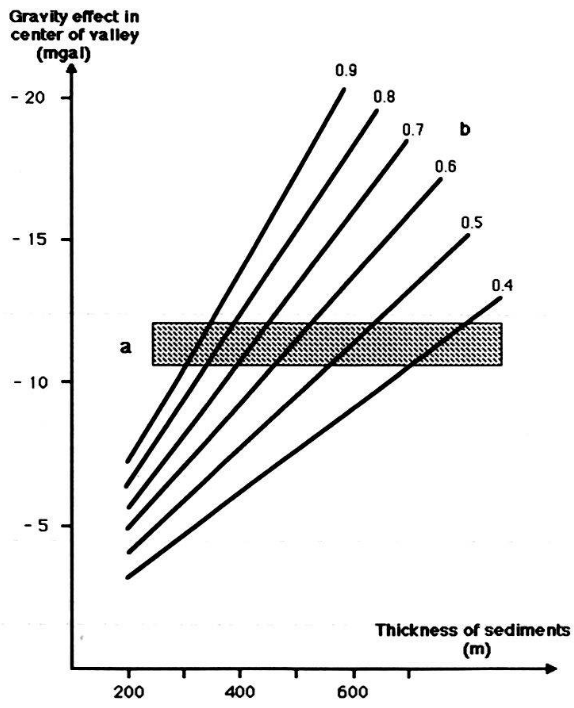


Fig. 9. Gravity effect of prismatic bodies of various thickness and density for the sedimentary fill of the Rhine valley at Zizers (Fig. 1, profile c). The elevation of the Rhine river is 530 m above sea level.
(a): maximum amplitude (in mgal) of observed local gravity anomaly.
(b): density values in g cm^{-3}.

Lower Reuss Valley

Another problem in the context of valley sediments often encountered in Switzerland outside the main mountain chains is the problem to locate the deep narrow

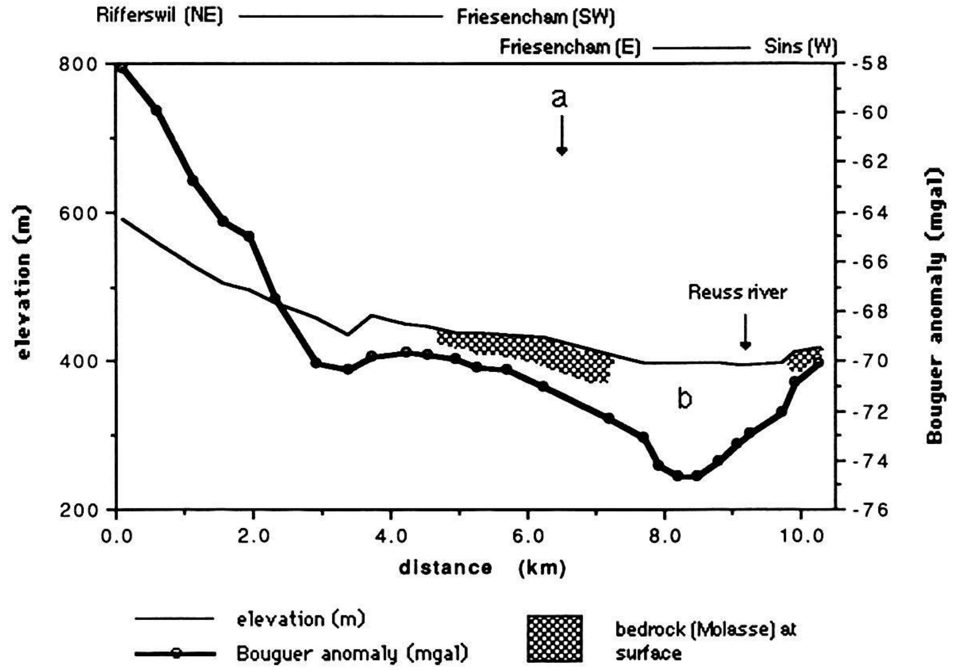


Fig. 10. Gravity profile across the lower Reuss Valley at Rifferswil.
(a): bend in profile (Fig. 1, profile e).
(b): location of deep erosional channel in bedrock.

canyons in the bedrock that were eroded during the last glaciation. These canyons are primary targets to sink wells for drinking water. An example is the Reuss valley below Luzern. Nowadays the river meanders in a 2 km wide valley of very little topography. Some 30 km downstream Sins (Fig. 1), after a short canyon, the Reuss joins the Aare river at a point roughly 150 m below the valley floor at Rifferswil. From borehole and surface geology information (Läuppi 1983) we know of the existence of a narrow deep canyon cut into the bedrock by the ancient Reuss river. The location of this canyon, now covered by alluvial sediments, can easily be obtained by gravity profiling across the valley (Fig. 10). The usual ambiguity, intrinsic to most gravity studies, is insignificant in such a case as there is no need for model calculations. With a series of profiles across the valley the buried canyon can be traced and thus the water well be placed.

Discussion

We believe that gravity profiling is a simple but usefull tool to obtain information about the near surface structure provided the necessary geometric contraints are given and the structure in question gives rise to a local gravity anomaly of sufficient amplitude. To obtain the dip of the valley flanks a large number of gravity stations in topographically rough areas are necessary. While the prism method in gravity modelling might be applied to any other area, we like to emphazise the importance to determine the densities of the sediments and of the bedrock in each individual case as it was done in this study for the Magadino plain.

As the example of the Reuss Valley has shown, gravity profiling can be used to explore the groundwater potential in the wide valleys of the Molasse Basin. For the problem of the proposed Alpine tunnels beneath deep reaching valleys, the method of gravity modelling might not be precise enough for all cases. However, given a local gravity map of high station density and some seismic control, we believe the 3D-gravity modelling to have a precision better than 10% for the maximal depth to the bedrock. In the case of the Magadino Plain independent 3D-gravity and seismic modelling yielded results that differed by only 30 m.

An interesting result of the gravity profiling in Alpine valleys is the general difference in the depth of the bedrock between the valleys that belong to the southern and those that belong to the northern drainage system. All large Alpine valleys that belong to rivers draining into the Mediterranean sea for most of their length show a depth of bedrock a few hundred meters below the present sea level, while none of the rivers that drain into the Rhine flow in valleys with the bedrock deeper than the present sea level. Possibly, the Rhine valley shortly upstream lake of Konstanz is an exception (Wildi 1984). However, this is a local depression and not representativ for the main stream channel since the bedrock upstream (this paper) and downstream is again some hundred meters above present sea level (Wildi 1984).

These findings suggest stream erosion to be the controlling factor for the depth of the Alpine valleys. We can find no reason why the north-trending glaciers should generally have had less erosional effects than the glaciers descending to the south. According to Hsü et al. (1973) during Messinian time the Mediterranean sea was being desiccated thus lowering the base level of erosion for this drainage system by more than 2000 meters below the present sea level. Finckh (1978) studied the geometry of two southern Alpine lakes by means of seismic reflection and refraction profiles and found a pronounced slope of the bedrock to the south. His conclusion was: "The downstream gradient of the valley favors the assumption of stream erosion during a time with lowered base level (Finckh 1978, p. 300)."

The discussion about the dominant erosional forces that formed the U-shaped valleys partially filled with sediments that are typical for young mountain ranges started over a century ago at a time when geophysical mapping of the subsurface bedrock topography was not yet possible. Later, in one of the earlier experiments of controlled source seismology Gutenberg et al. (1956) outlined the bedrock floor beneath Yosemite valley (California) and attributed most of the excavation of the valley to glacial erosion. Much like some other valleys and many fjords the bedrock beneath Yosemite valley forms one or more closed depressions (troughs, as opposed to river valleys) that could only be formed by either glacial scour or by tectonic subsidence.

The exact form of the Alpine valleys below their sedimentary cover is but approximately known for most cases. Closed depressions in the bedrock, however, seem not to be a dominant feature of the larger Alpine valleys within the main mountain range. The form of the gravity anomalies (see, f.e., Fig. 4 and Schwendener 1984) suggest a more U-shaped than a V-shaped bedrock geometry for all large Alpine valleys. This supports the idea of primary downcutting by fluvial erosion alternating in time with glacial erosion. Glacial erosion primarily enlarges the valleys with less effect on their maximum depth.

Acknowledgments

We thank our colleagues J. Ansorge, R. Freeman, K. Holliger, and U. Kradolfer for their suggestions and for critically reviewing the manuscript.

REFERENCES

FINCKH, P.G. 1978: Are southern Alpine lakes former Messinian canyons? Geophysical evidence for preglacial erosion in the southern Alpine lakes. Marine Geol. 27, 289–302.

FINGER, W. & WEIDMANN, M. 1987: Quelques données géologiques nouvelles sur la vallée du Rhône entre Sierre et le Léman. Bull. Murithienne 105, 27–40.

GASSMANN, F. & MÜLLER, P. 1961: Gravimetrische Bestimmung der Gesteinsdichte und der Lotkrümmungen für den Punkt St. Anton des Basis-Vergrösserungsnetzes Heerbrugg. Schweiz. Z. Verm. Kulturtechn. Photogr. 9, 1–20.

Geologischer Atlas der Schweiz, Map 1313 Bellinzona (1974). Schweizerische Geologische Kommission, Basel, Switzerland.

GONET, O. 1965: Etude gravimétrique de la plaine du Rhône. Beitr. Geol. Schweiz, Ser. Geophys. 6.

GUTENBERG, B., BUWALDA, J.P. & SHARP, R.P. 1956: Seismic explorations on the floor of Yosemite valley, California. Bull. Seism. Soc. Am. 67, 1051–1078.

HSÜ, K.J., CITA, M.B. & RYAN, W.B.F. 1973: The origin of the Mediterranean evaporites. In: Initial Reports of the Deep Sea Drilling Project (Ed. by W.B.F. RYAN, et. al.), 13, U.S. Gov. Printing Office, Washington, D.C., 1203–1231.

JUNG, K. 1961: Schwerkraftverfahren in der Angewandten Geophysik. Geophys. Monograph 2, Akademische Verlagsgesellschaft Geest und Portig, Leipzig.

KISSLING, E. 1980: Krustenaufbau und Isostasie in der Schweiz. Ph.D. thesis, ETH Zürich, Switzerland.

— 1984: Three-dimensional gravity model of the northern Ivrea-Verbano zone. Beitr. Geol. Schweiz, Geophysik 21, 53–61.

KLINGELÉ, E. 1972: Contribution à l étude gravimétrique de la Suisse romande et des régions avoisinantes. Ph.D. thesis, Univ. Genève, Switzerland.

KLINGELÉ, E. & OLIVIER, R. 1980: La nouvelle carte gravimétrique de la Suisse (Die neue Schwerekarte der Schweiz). Beitr. Geol. Schweiz, Geophysik 20.

LÄUPPI, U. 1983: Geomorphologie im mittelländischen Reussgletschergebiet. Ph.D. thesis, Univ. Zürich, Switzerland.

PUGIN, A. 1988: Carte des isohypses de la base des sédiments du Quaternaire en Suisse occidentale, avec quelques commentaires. Rapp. géol. Serv. Hydrol. Géol. natl. 3.

SCHWENDENER, H. 1984: Ein gravimetrisches Krusten-Mantel-Modell für ein Profil vom nördlichen Alpenvorland bis an die Ligurische Küste. Geodät. geophys. Arbeiten in der Schweiz 36, Schweiz. Geodät. Komm., ETH Zürich, Switzerland.

TALWANI, M. & EWING, M. 1960: Rapid computation of gravitational attraction of three-dimensional bodies of arbitrary shape. Geophysics 25/1, 203–225.

WILDI, W. 1984: Isohypsenkarte der quartären Felstäler in der Nord-und Ostschweiz mit kurzen Erläuterungen. Eclogae geol. Helv. 77/3, 541–551.

Manuscript received 7 February 1990
Revision accepted 30 March 1990