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Geological and geophysical exploration of alpine and peri-alpine glacial valleys

Reply to the paper of C. Meyer de Stadelhofen: "Un exemple du mauvais usage de la géophysique"

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Key words: Alpine glacial valleys, geophysical exploration

ABSTRACT

The sedimentary architecture and bedrock topography of alpine and peri-alpine valleys result principally from processes active in former glacial and peri-glacial environments. Along ancient margins of the glaciers, lateral and vertical changes of sedimentary facies are relatively abrupt, but in the centers of the valleys and basins the lithofacies are rather continuous. In applied and fundamental research related to glacial deposit geology, details at a variety of scales are required. Interpretations of gravity data constrained by geological and other geophysical information are generally most appropriate for resolving large-scale problems. Pugin's (1988) depth-to-bedrock map for the western Swiss Plateau was drawn on the basis of compilations of geological and geophysical data, including pseudo-2 D density models derived from the residual Bouguer gravity maps of Olivier (1983). At any one location the reliability of the isopach contours on Pugin's (1988) map depends mainly on the density and quality of the original gravity data, on the suitability of the regional-residual Bouguer anomaly separation, on the availability of relevant rock property information and on the presence or absence of compacted sediments older than the last glacial cycle. The revised depth-to-bedrock estimates for the Aubonne valley, based on new gravity measurements, Bouguer anomaly calculations, regional-residual separations and borehole information (Meyer de Stadelhofen, this issue), merely highlights the ambiguity of interpretations of gravity data noted by Pugin (1988).

RESUME

Le relief de l'interface entre rocher et dépôts quaternaires et l'architecture des sédiments des vallées alpines et périalpines sont essentiellement dus aux processus glaciaires et périglaciaires. En bordure des anciens stades glaciaires, les changements latéraux et verticaux des faciès sédimentaires sont rapides, alors que les formations sont plutôt continues au centre des bassins. En recherche fondamentale et appliquée concernant des problèmes liés à la géologie glaciaire, les méthodes géologiques et géophysiques d'investigation doivent répondre aux besoins de ces deux échelles. La gravimétrie offre essentiellement des possibilités intéressantes concernant l'exploration de morphologies et de formations de grande extension. La précision des résultats dépend cependant dans une large mesure des possibilités de calibrage par forage, par sismique réflexion, logging et d'autres méthodes d'investigation. La fiabilité de la carte des isohypses du toit de la Molasse dans les vallées périalpines de Suisse occidentale établie par Pugin (1988) par compilation de données géologiques et géophysiques, ainsi que par modélisation gravimétrique à partir des cartes publiées par Olivier (1983), est fonction de la présence (reconnue ou non) de sédiments compactés, antérieurs au dernier cycle glaciaire, de la densité et qualité des

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données disponibles, ainsi que des possibilités de calibrage. La vallée de l'Aubonne, qui a fait l'objet de nombreux levés gravimétriques récents, de nouveaux calculs ou corrections de l'anomalie de Bouguers (?) et d'un sondage de calibrage (Meyer de Stadelhofen, ce volume) illustre parfaitement ce principe déjà formulé par Pugin (1988).

1 Introduction

The Quaternary sediment fill of alpine and peri-alpine valleys provides reservoir rocks for drinking water, and the associated fluvial terraces support the essential roads, railways and building sites of alpine countries. Unfortunately, these sediments are also exploited extensively for such raw materials as gravel and sand, and are affected in many locations by contamination from waste disposal sites. In this stressed urbanised environment there is a pressing need to better understand the architecture of glacial deposits for the purpose of resource protection and management.

The geometry and structures of Quaternary sedimentary deposits are complex, being highly changeable over short distances. Research on these deposits is difficult, so that appropriate investigation procedures are a continuous source of discussion amongst earth scientists. The geophysical methodology adopted by Pugin (1988) for regionally mapping the interface between the Quaternary fill and basement of the Swiss alpine and peri-alpine valleys is contested in the commentary of Meyer de Stadelhofen (this issue). A misunderstanding on his part of the adopted approach and objectives of the work may have resulted from a lack of precision in the original description. We hope that this misunderstanding will be corrected here.

As a case study and a partial response to Meyer de Stadelhofen (op. cit.), the use of gravimetric methods for the mapping of depth-to-bedrock will be evaluated briefly. After recalculating bulk densities for this region we demonstrate through additional gravity modelling the level of error introduced by using a pseudo-2 D interpretation technique versus a more conventional 2 D approach. We will then describe one geological model of a glacial valley and review the different geological and geophysical methods for investigating the geometry and character of valleys.

2 Gravity methods and their calibration for determining bedrock depth

For many years applied geologists have attempted to map the depth-to-bedrock beneath the sedimentary fill of valleys. Provisional depth-to-bedrock maps for the northern alpine valleys based on various geological and geophysical data have been published by Wildi (1984; eastern and central Switzerland) and by Pugin (1988; western Switzerland). Interpolations and extrapolations based on a variety of data were used to determine first-order approximate estimates of depth-to-bedrock (Fig. 1). In the introduction of Pugin (1988, p. 7) it was stated clearly that improved geological and geophysical data coverage would undoubtedly improve the estimates of the dimensions and morphology of the Quaternary sedimentary basins: "Cette recherche a été effectuée en un temps très limité; une amélioration de la carte des isohypses (planche hors texte) est de ce fait toujours possible. Dans beaucoup de secteurs, de nouveaux sondages géologiques et des mesures géophysiques préciseront certainement les dimensions et la morphologie des bassins sédimentaires quaternaires."

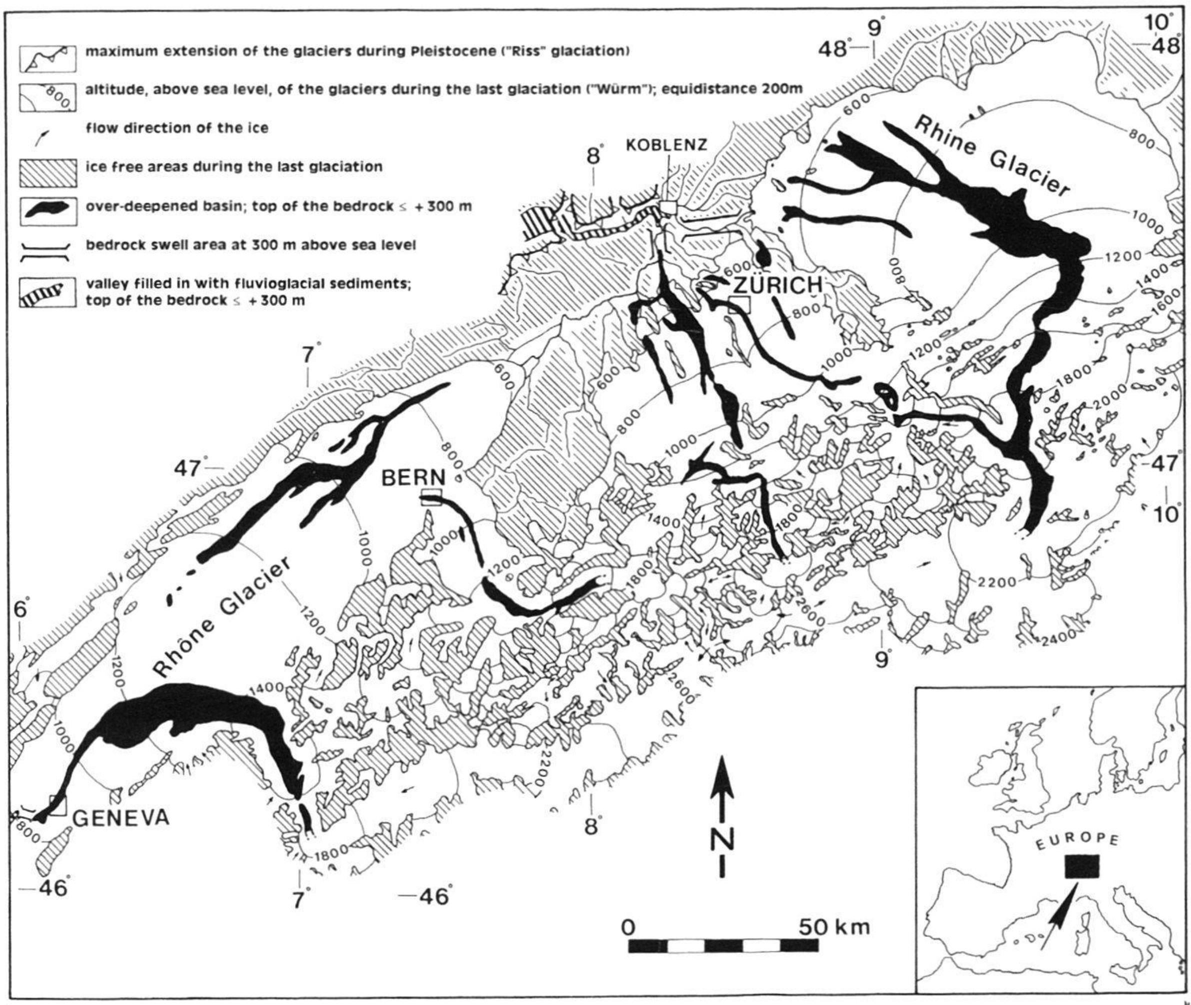


Fig. 1. Overdeepened alpine and peri-alpine valleys north of the Alps. Map shows areas (in black) where bedrock is deeper than 300 m above sea level (mainly after Pugin 1988 and Wildi 1984). Other areas in the map region are also deeper than 300 m above sea level, but the evidence is not yet published.

Examples given in Meyer de Stadelhofen (this issue) illustrate well the above quoted assertion. His figure 1 shows a residual Bouguer anomaly map based on existing and recently collected gravity data in the Aubonne area. Residual Bouguer anomaly values in parts of this new map are double those on the residual Bouguer anomaly map of Olivier (1983) (see also Fig. 2). Furthermore, the presence of a deep elongated valley has been established on the basis of recent borehole data (op. cit., unpublished log). The reason for the major differences between the residual Bouguer anomaly maps of Olivier (1983) and Meyer de Stadelhofen (this issue) is not explained by the latter, but probably result from different approaches for separating the regional and residual Bouguer gravity fields (see below). A two hundred percent difference between the bedrock depth estimate of Pugin (1988, data from Olivier 1983) and that based on the new data is therefore not surprising.

It is emphasized that Pugin (1988) tempted to account for the possibility that the Aubonne basin may contain older compacted Quaternary fill, but at that time no con-

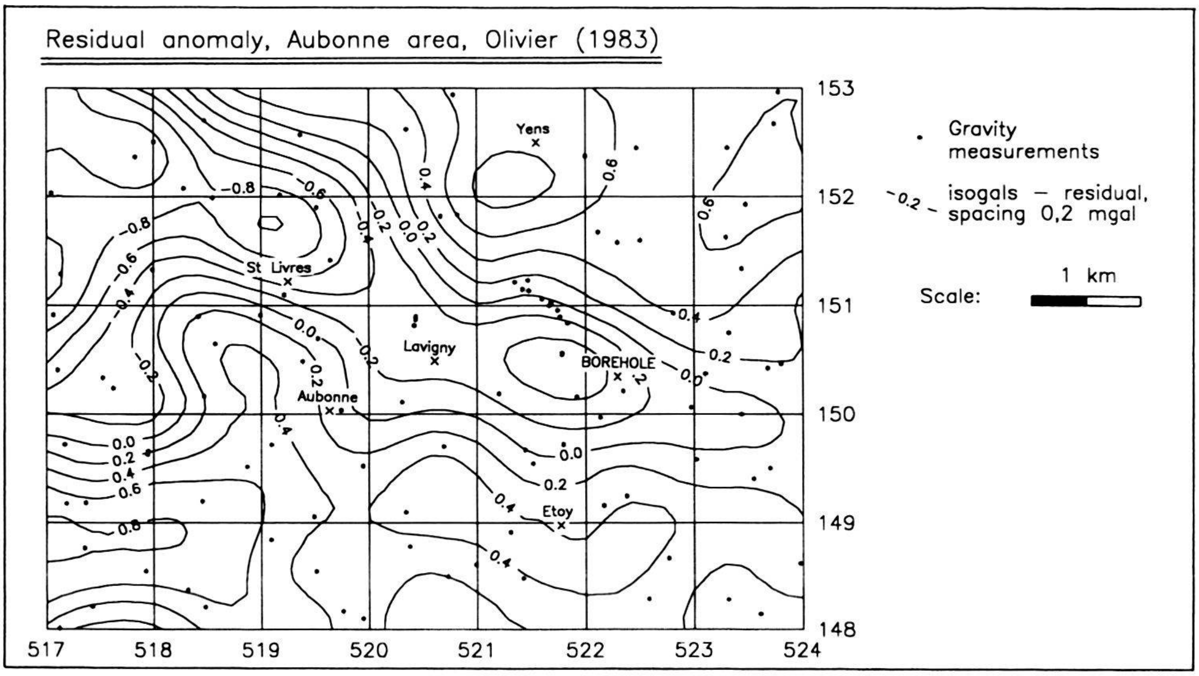


Fig. 2. Residual Bouguer anomaly map of the Aubonne area extracted from Olivier, 1983.

straints from deep boreholes were available. For this reason, three question marks were drawn on the depth-to-bedrock map in this region; the intention being to warn the user of the map about the problematic quality of the data and interpretation there. Such warnings are usually sufficient to alert the vigilant earth scientist. Meyer de Stadelhofen's comment demonstrates that the following caution by Pugin (1988, p. 8) was appropriate: "En appliquant cette méthode, nous avons pu quelquefois sousestimer une profondeur, faute de connaître des sédiments compactés tels que silts argileux ou moraines anciennes."

To understand better the reliability of the gravity method used for contouring the bedrock surface, three error domains are considered: regional-residual Bouguer anomaly separation, density variations and modelling.

2.1 Regional-residual Bouguer anomaly separation

Defining the gravity anomalies associated with the features of interest is an important step in the modelling of gravity data. To determine the depth-to-bedrock beneath sediment-filled valleys it is necessary to separate the generally shorter wavelength anomalies (residual field) associated with the valley fill and the topography of the basin from the usually longer wavelength anomalies (regional field) due to density variations in the basement (crust). For meaningful depth-to-bedrock determinations the separation of residual anomalies from the regional anomaly field may be critical.

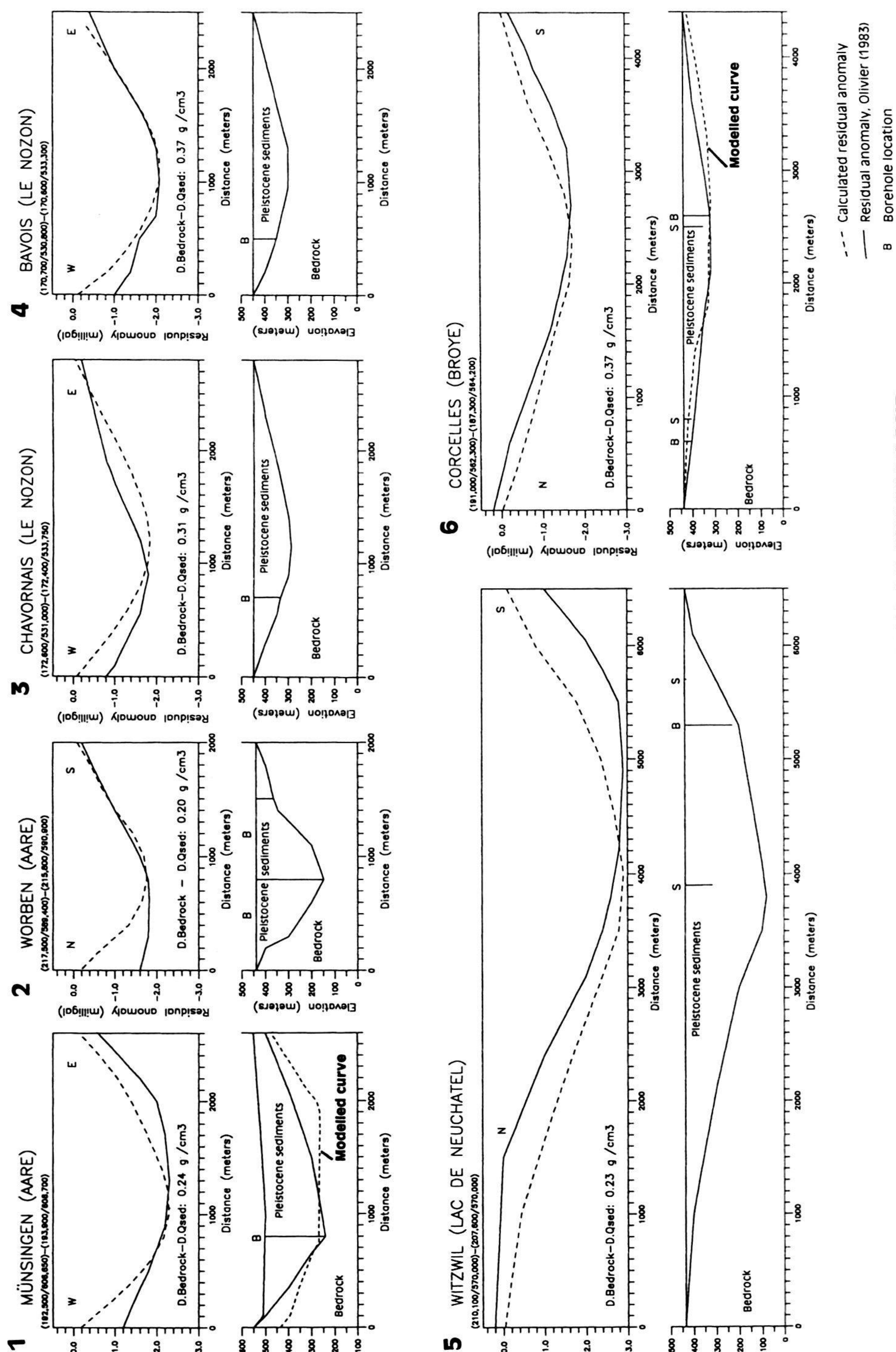
It is our understanding that the residual Bouguer anomaly maps of Olivier (1983) were intended to represent, in a broad-scale sense, the effects of the valley fill and basement topography – these residual anomaly maps were never intended to represent in detail local features associated with individual segments of the valleys. For example, parts of the residual Bouguer anomaly data shown for the Münsingen region along profile 1 of figure 3 may be in "error" by as much as 1 mGal along the borders of the valley, because the regional Bouguer anomaly map of Olivier (1983) for this region did not account for all bedrock outcrops. Similar problems exist for other Bouguer anomaly profiles shown in Figure 3 that pass close to bedrock outcrops along the margins of the valleys. On modelling such residual Bouguer anomaly profiles it is found that the depth-to-basement estimates near the sides of the valleys are in substantial error. However, we contend that although the detailed shape of the residual Bouguer anomaly profiles may be inaccurate near the edges of the valleys, with few exceptions (e.g. the Aubonne valley) the maximum amplitudes of the residual anomaly profiles, which mostly coincide with the valley axes, are generally reliable. Appropriate recalculation of regional anomaly maps in any region would undoubtedly improve the residual gravity anomaly representation of the valley fill and basement topography.

2.2 Density variations

The models represented by the solid curves in the lower of the pairs of diagrams shown in figure 3 were derived by the same pseudo-2 D "plateau correction" approach as used by Pugin (1988). They are based on the residual Bouguer anomaly map of Olivier (1983) and are constrained by borehole information; the residual Bouguer anomaly profiles extracted from Olivier (1983) are shown by the solid lines in the upper diagrams of figure 3. The dashed lines in these upper diagrams represent the residual Bouguer anomalies due to the models represented by the solid lines in the lower diagrams, as calculated by a conventional 2 D density modelling computer program (a modification of that described by Talwani et al. 1959). The difference between the residual Bouguer anomaly values extracted from Olivier (1983) and the calculated values is a measure of the error introduced by the pseudo-2 D "plateau correction" method used by Pugin (1988).

Calculated mean density differences between the valley sediments (often of Quaternary age) and the Molasse bedrock range from 0.2 to 0.35 g/cm^3. The lower density contrasts correspond in many places to the presence of compacted layers of Pleistocene sediments that predate the last phase of Würm glaciation, as for example in the Seeland valley (Kellerhals & Tröhler 1981; see the Worben profile in Fig. 3) and in the Aaretal valley from Thun to Bern (Schlüchter 1976, 1979; see the Münsingen profile in Fig. 3). New borehole data have also revealed the presence of compacted sediments beneath the Gürbetal, suggesting that earlier depth-to-bedrock estimates were too low. In more proximal areas, such as the Orbe and Broye valleys, where older sediments were eroded completely during the last ice age, the density difference is close to 0.35 g/cm^3; this is the value used by Läuppi (1983). Pugin (1988) generally used the same value, but employed other density contrasts in areas where calibrations were available.

The most common Molasse rock densities observed at the Nagra (Nationale Genossenschaft für die Lagerung radioaktiver Abfälle) test site of Burgdorf vary between 2.3 g/cm^3 and 2.5 g/cm^3 (Ammann et al. 1993). Quaternary sediment densities of 1.3, 2.0, 2.2 and 2.3 g/cm^3 were obtained by Finckh & Klingelé (1991) on converting seismic velocities to densities in the Vouvry area of the Rhone valley. In this region the bedrock comprises. Alpine rocks rather than Molasse sedimentary rocks. The density/geology model of these authors (op. cit.) is in close agreement with the results obtained by Finger &



MODELING OF BOUGUER RESIDUAL ANOMALY IN SOME VALLEYS OF SWITZERLAND

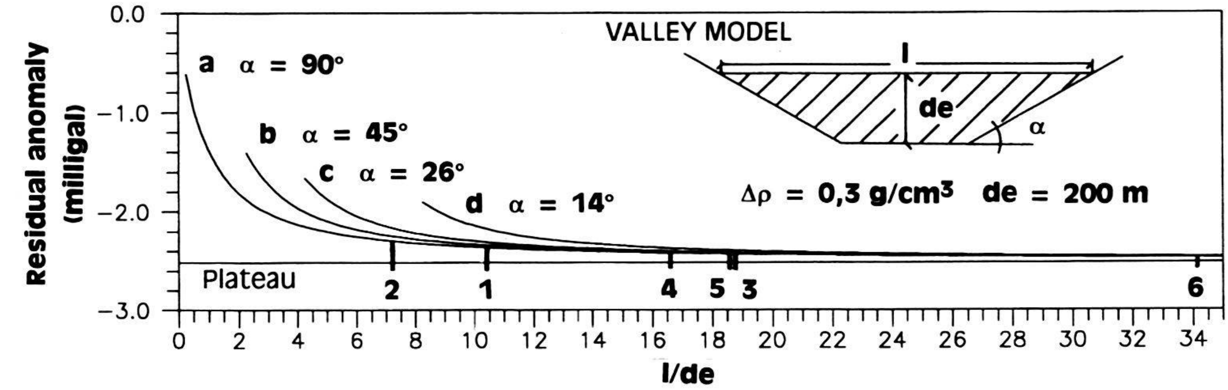


Fig. 4. Computed Bouguer residual anomaly for U-shape valleys with varying slope of valley walls ($\alpha = 14°$, 26°, 45° and 90°) and varying width/depth (**l/de**) ratios using a conventional 2 D modelling algorithm (curved lines) and the pseudo-2 D "plateau correction" method. Points 1 to 6 on the graph correspond to the profiles represented in Figure 3. See discussion in the text. Parameters: **l** width of the valley, **de** depth of the valley, α slope of the valley wall.

Weidmann (1987) and Pugin (1988). However, at this location, as well as at those studied by Kissling & Schwendener (1990), who used the "prism modelling method" of Jung (1961), density contrasts are notably higher than in areas with Molasse bedrock.

2.3 Modelling

The pseudo-2 D "plateau correction" method used by Pugin (1988) is considered unsuitable by Meyer de Stadelhofen (this issue) for calculating the maximum depth-to-bedrock. We have modelled two of the residual Bouguer profiles shown in figure 3 using a conventional 2 D density modelling program (a modification of that described by Talwani et al. 1959). The resultant models, which are shown by the dashed lines in the lower diagrams for profiles 1 and 6 in figure 3, match the respective residual Bouguer anomaly values extracted from Olivier (1983). The differences between the solid and dashed models in these diagrams illustrate again the error introduced by the pseudo-2 D "plateau correction" method. It is clear from Figure 3 that maximum depth-to-bedrock values are reasonably well determined by the pseudo 2 D "plateau correction" method, but that the general shapes of the valleys may not be represented accurately, particularly near the valley walls – remember, it is in these regions of many profiles where Olivier's (1983) residual Bouguer anomaly values may not be representative of the valley fill and bedrock topography!

Figure 4 shows differences between the maximum residual Bouguer anomaly amplitudes calculated with the conventional 2 D and the pseudo-2 D "plateau correction" methods for U-shape glacial valleys; many of the valleys inestigated by Pugin (1988) have

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Fig. 3. Gravity models of bedrock morphology (Molasse) for some valleys of western Switzerland based on Bouguer residual anomalies given by Olivier (1983). The thicknesses of the valley fill are calibrated in all sections by information from at least one borehole.

such geometries. Note, that the differences (errors) for V-shape valleys would be higher by a factor of approximately two. The horizontal straight line at –2.5 mGals represents values determined by the pseudo-2 D "plateau correction" method and the curved lines were calculated with the conventional 2 D technique. Numbers 1 to 6 in figure 4 correspond approximately to the respective locations of residual Bouguer profiles 1 to 6 in figure 3. The differences between the residual anomaly curves calculated by the pseudo 2 D "plateau correction" method and the conventional 2 D technique (i.e. the errors) are quite large for the modelled Münsingen and Worben profiles (Fig. 3). Along the Münsingen profile (site 1 in Fig. 4), where the valley wall slopes at approximately 22°, the error is about 0.15 milligal. Such an error in residual Bouguer anomaly corresponds to a 12 m mis-calculation for bedrock at 260 m depth. The Worben profile, site 2 in figure 4, is uncommonly narrow and deep and in addition needs to be considered as a three-dimensional problem. For all other profiles, sites 3 to 6, the differences (errors) are in the range 0.05 to 0.08 mGal. These differences are small compared to errors introduced by inappropriate regional-residual separations (values as high as 1 mGal) and uncertainties associated with the lack of detailed information concerning lateral and depth variations of densities.

It is suggested here that residual Bouguer anomaly maps computed for broad regions (e.g. Olivier 1983) are valuable for obtaining first-order approximate estimates of maximum depth-to-bedrock along the Swiss valley system. To determine reliably the geometry of the valleys requires more site-specific calculations of the regional Bouguer anomalies. However, we contend that the pseudo-2 D "plateau correction" approach to modelling the Olivier (1983) residual Bouguer anomaly map is sufficient for constructing a generalized 1 : 250,000 compilation map of depth-to-bedrock.

3 Alternative approaches for estimating depth-to-bedrock and sedimentary infill

The key to reliable interpretations of potential field data is appropriate constraints from geological and other geophysical information. In modelling gravity data from the alpine and peri-alpine valleys the density contrast between the Quaternary sediments and bedrock and the geometry of the sediment-bedrock contact are the principal parameters to be determined. The following geophysical methods offer independent information on these parameters and provide constraints that may limit the range of possible density models that fit a particular gravity data set (see résumé in Tab. 1):

Borehole data

Formation depths and sedimentary facies may be determined from logging of borehole cores. The correlation of lithologies with densities should be established by geophysical methods (i.e. studies of core densities or geophysical logging).

Electric resistivity sounding

Geoelectric sounding is often able to distinguish between lithologies of significantly different permeability, but it is a potential field method and is therefore often treated as a semi-quantitative or qualitative technique. Calibration of gravity data with geoelectric

Tab. 1. Advantages and disadvantages of various methods for investigating basins glacial.

METHOD OF INVESTIGATION	PHYSICAL PARAMETERS & DIMENSION	ADVANTAGES	DISADVANTAGES
Surface mapping and outcrop study	– 1D, 2D, 3D	with some relief, vision in 3D; sediment genesis, and paleogeographical reconstruction are possible; inexpensive.	lack of deep information; land may be covered and altered by the biosphere and landslides.
Borehole	– 1D	recognition of the grain size and thicknesses of lithologies; possibilities for hydrogeological, geotechnical and geophysical tests (logging); calibration of indirekt geophysical methods.	no information on the sedimentary features and their geometry expensive.
Geoelectric	electrical conductivity usually 1D sometime 2D	good differentiation of varying porosities; surface mapping of clay and gravel below the biosphere; relatively inexpensive.	poor vertical and horizontal resolution; limited ability to detect dipping layers.
Gravity	density 2D, 3D	quick method to detect large sedimentary bodies and determine their gross geometry; relatively inexpensive.	calibration with a borehole or a seismic data is usually needed; limited information on the geometry of small sedimentary bodies.
Ground Penetrating Radar	dielectric constant 2D, 3D	very high-resolution in the first ten meters; good penetration in porous dry sediments; relatively inexpensive.	low penetration in fine, conductive sediments.
Seismic refraction	velocity, density 2D, 3D	near-surface high-resolution for near-surface low-velocity layers.	interpretation is based on modelling; using conventional methods each lower layer must have a higher velocity.
Seismic reflection	velocity, density 2D, 3D	high spatial resolution possibility for 3D acquisition and processing; yields an image of the sedimentary structures; compared to the amount of information, the method is inexpensive.	data quality is highly variable, being a function of subsurface conditions; calibration is sometimes needed; experience in acquisition and processing is required.

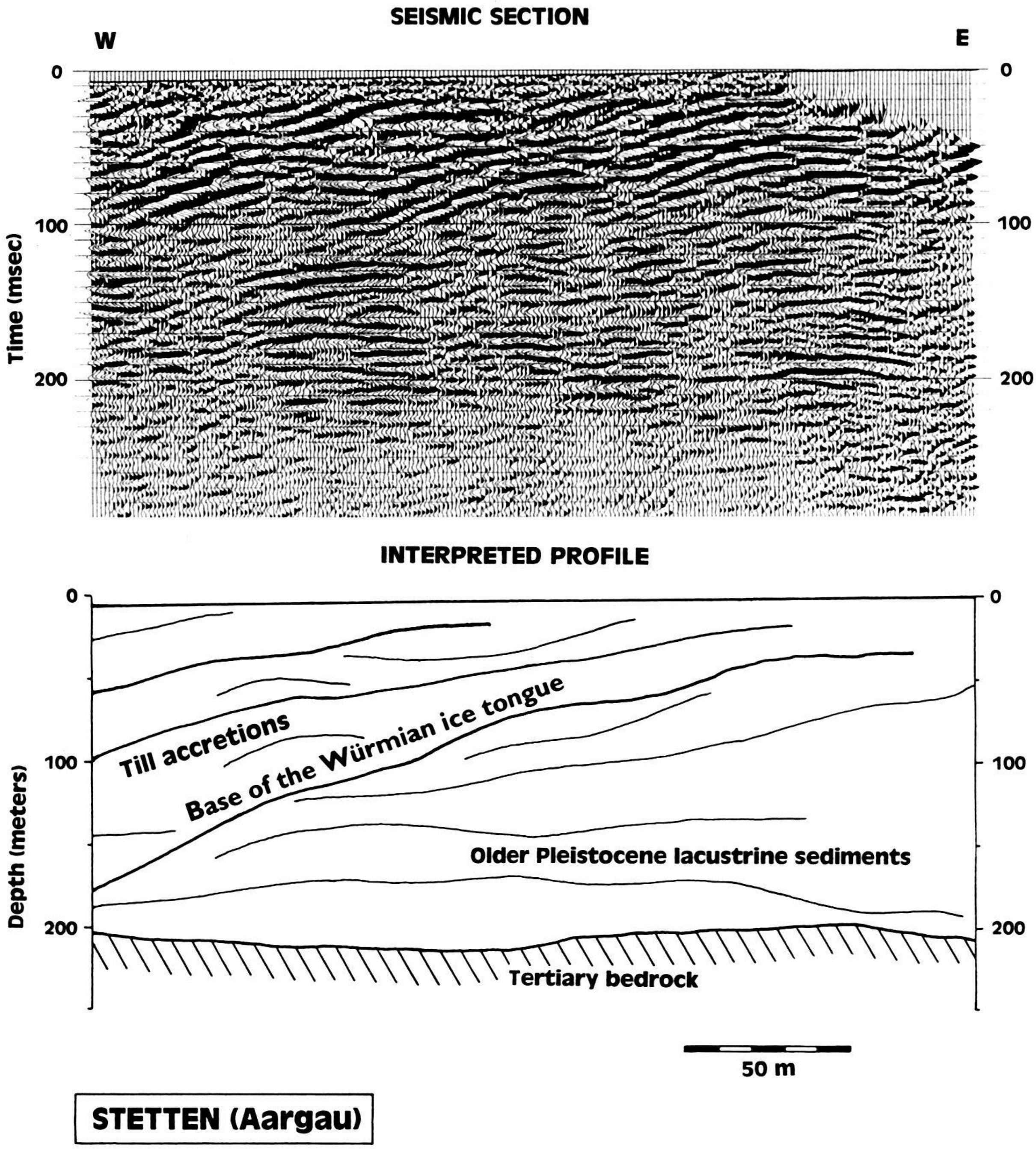

Fig. 5. Interpreted high-resolution seismic reflection section recorded at the border of a former glacial valley, showing the complicated geometry of fluvio-glacial and glacio-lacustrine sediments. The horizontal scale is twice the vertical. The section is from Stetten (Aargau, Coord 250,850/664,150). Acquisition parameters: 48 traces, receiver spacing 2.5 m, shot spacing 2.5 m, offset 2.5 m, hammer source, 5-stacks averaging. Processing sequence: gain recovery, frequency and f-k filtering, static corrections, mute, CMP sorting, NMO correction, stack. The strong west-dipping reflections were initially interpreted as the sheard base of the glacier; however, new 3 D reflection surveys have shown the presence of erratic blocs inducing strong obliquous diffractions. The flatlying reflection at approximately 200 meters is the Pleistocene sediment-bedrock interface.

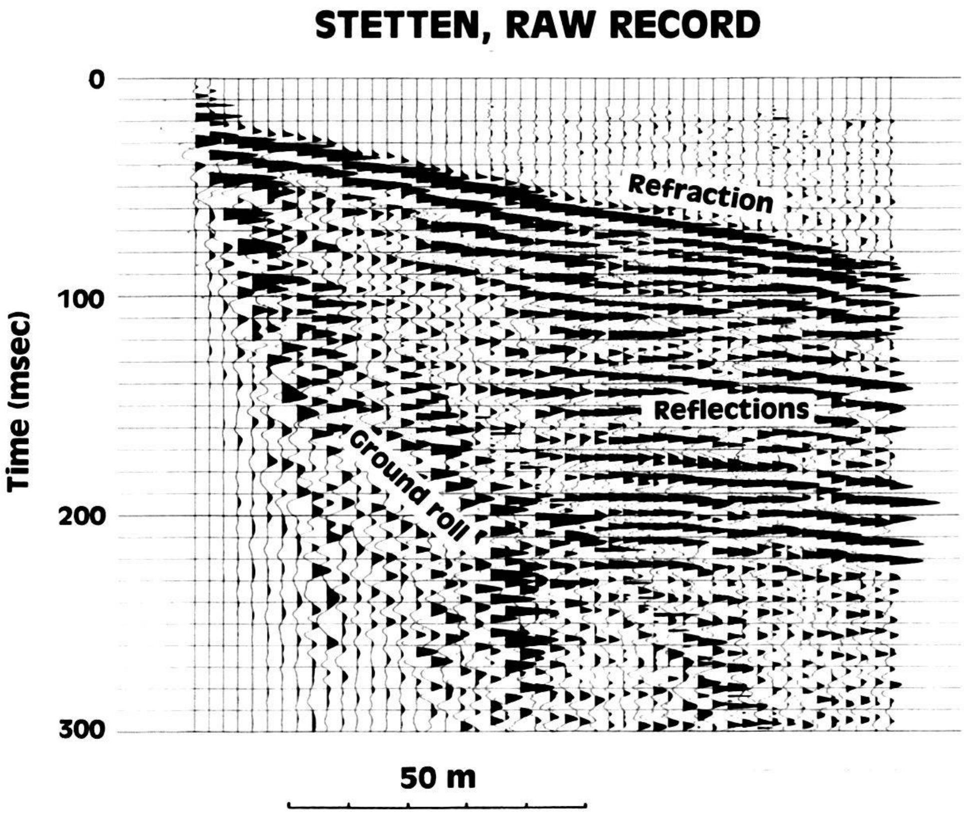

Fig. 6. Raw shot gather (traces are normalised, analog low-cut filter of 96 Hz). The reflection of the bedrock is at 220 milliseconds. Note the high quantity of informations within the quaternary infill.

sounding information may not always be suitable. For example, along the Witzwil profile in Figure 3 a small electrical resistivity contrast between the Pleistocene sediments and the Tertiary Molasse basement led to an erroneous interpretation of the gravity data by Axelrod (1978).

Ground-penetrating radar

Ground-penetrating radar is a relatively new tool for mapping the detailed geometry of structures in the upper few tens of meters of the earth. It has limited depth-penetration and may provide no useful information in the presence of highly conducting surface layers of clay.

Seismic refraction methods

Seismic refraction methods are useful for investigating layered geological structures in which the velocity mostly increases monotonously with depth.

Seismic reflection methods

The lateral continuity of formations, sediment facies and geometry, and the morphology of the bedrock are best determined by a combined geological mapping-reflection seismic approach. With its high-resolution capabilities, the reflection seismic method is the most reliable means for providing 2 D or 3 D images of the subsurface (Fig. 5, 6; Steeples & Miller 1991; Pullan & Hunter 1991; Frei 1993; Pugin & Rossetti 1992). Seismic velocities established during the processing of seismic reflection data may be useful for determining rock densities (e.g. Heim & Finckh 1984; Finckh & Klingelé 1991).

From the above discussion and information contained in table 1 it can be concluded that an integrated multi-disciplinary approach is necessary for determining the lithofacies of the valley fill and for defining the geometry of the various sedimentary units and sediment-basement contact.

4 The geology of glacial valleys and their exploration

Valleys are formed by tectonic, fluvial and glacial processes. Tectonic control of valley formation along the Rhine graben is a well-accepted phenomenon (Laubscher 1982; Wildi 1984). Late Tertiary fluvial erosion as a controlling factor has been proposed for some northern Alpine valleys by Hantke (1978) and Kissling & Schwendener (1990), and for valleys of the southern Alps by Finckh (1978) following Hsü et al. (1973). However, most erosion of the alpine and peri-alpine valleys and their subsequent filling are linked to glacial processes (Wildi 1984; Pugin 1988). Clearly, a better understanding of the architecture of the sedimentary fill and the morphology of the underlying bedrock surface is dependant on improved knowledge of the processes of deposition and erosion that occurred during cold climatic periods. The environments, processes and products that have to be considered are as follows (Eyles 1983):

1. Sub-glacial environments experience fluvial erosion (sub-glacial canyons) and glacial abrasion and plucking (*roches moutonnées,* overdeepened V- or U-valleys morphology of drumlins); sedimentation is due mainly to sub-glacial meltout, which results in the deposition of lodgement till and to fluvial processes that build eskers in ice tunnels.
2. Intraglacial and supra-glacial environments are characterised by glacial and flow tills, aeolian loess and fluvial and lacustrine clastic sediments; these sedimentary units are generally deformed by collapse during melting of the ice.
3. Lateral and frontal glacial environments are dominated by melting and glacial growth and declines; diamictites of supra-glacial and infra-glacial origin, glacio-lacustrine sediments, kame deltas and fluvial sandur deposits accumulate rapidly and form complex sedimentary structures at different scales.
4. Peri-glacial environments are dominated by slope processes under permafrost conditions, gelifraction, aeolian loess deposition, etc.

The general geological architecture that results from the advance of a valley glacier (Fig. 7) is characterised initially by distinctive erosional bedrock morphologies, followed by sedimentary sequences that reflect the different glacial environments mentioned above. For example, in the centre of overdeepened alpine and peri-alpine valleys, sub-glacial fluvial deposits and lodgement till from the advancing ice stream may be buried by later glacio-lacustrine and fluvial sediments. The most complicated sedimentary structures and geometries are found in the former marginal and frontal areas of glaciers, where ice front

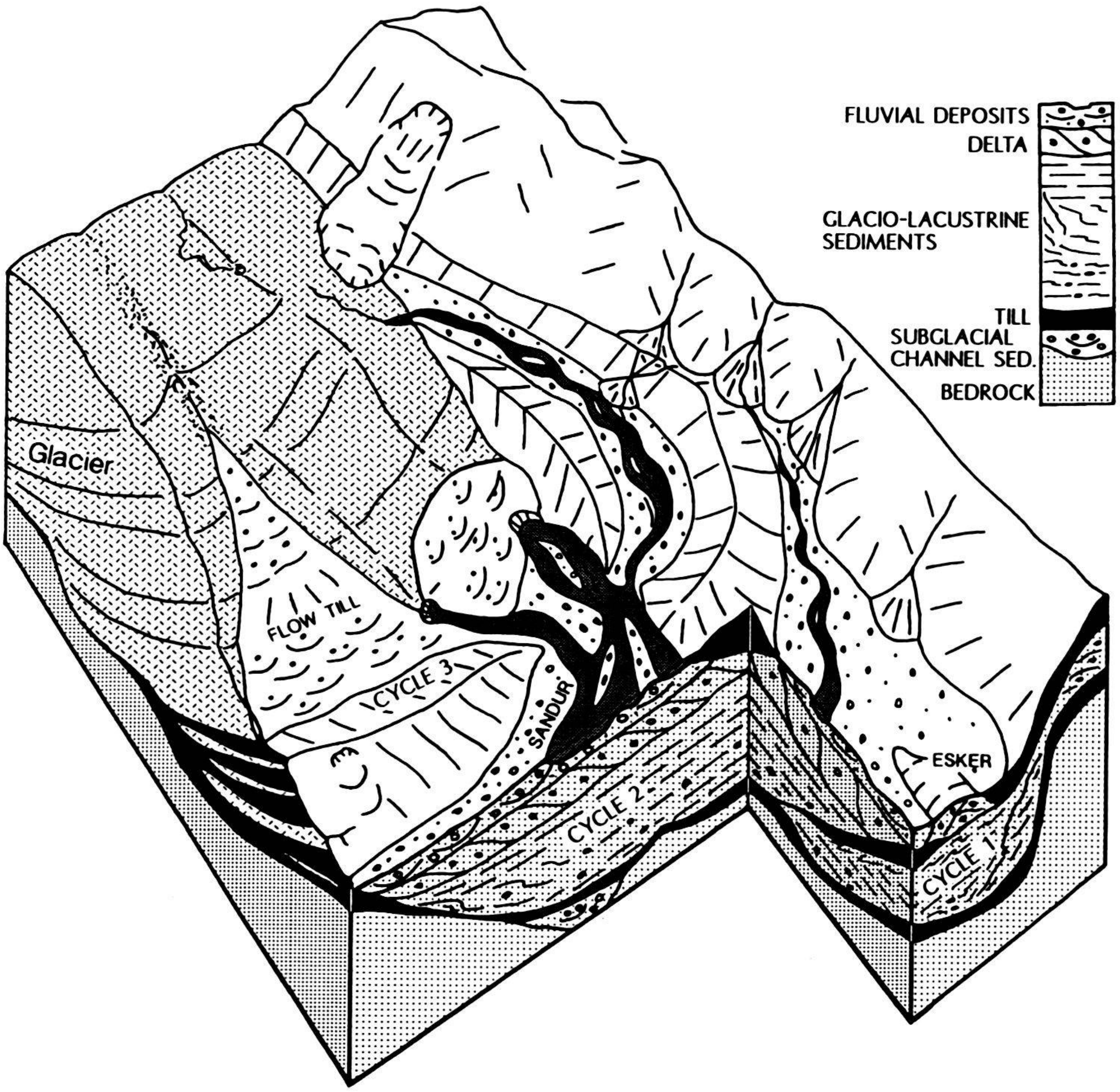

Fig. 7. Generalized geological model of an alpine glacial valley and its sediment fill. The glacier is prograding over older Pleistocene glacial deposits. Principal unconformities are underlain by glacial tills. Most of the erosion processes are related to ice shear and sub-glacial water flow.

fluctuations may produce shear structures, sediment cycles and lateral facies variations over short distances. This is well illustrated by the seismic profile acquired in the Reuss valley (Fig. 5; Stetten locality of Fig. 1). This profile was recorded perpendicular to the ice flow close to the frontal Würmian maximal advance. The inclined reflections may be interpreted as erosional features and till accretion in an ice contact environment.

By comparison, sedimentary facies, structures and geometries may be laterally quite continuous in the centre of glacial valleys and basins. In valleys containing sedimentary deposits from two or more glacial cycles most continuous reflections result from erosional surfaces.

Exploration of Quaternary sediments in this context has to take into account geological structures with very different geometries. On the one hand metre- to decametre structures, such as fluvial channel fills, sub-glacial fluvial channels, etc., need to be delineated. On the other hand larger-scale structures, such as the bedrock morphology in the main valleys and the extension of lacustrine sediments of overdeepened valleys need to be mapped.

5 Conclusions and discussion

Modelling of a selection of residual Bouguer gravity profiles from the western Swiss alpine and peri-alpine valleys using conventional 2 D algorithms demonstrates that the pseudo-2 D "plateau correction" plateau method used by Läuppi (1983) and Pugin (1988) is appropriate for first-order estimates of depth-to-basement. The utility of any gravity modelling method depends strongly on the density and quality of the original data, on the suitability of the regional-residual Bouguer anomaly separation, on the availability of relevant rock property information and on the presence or absence of compacted sediments older than the last glacial cycle. This point is confirmed by the new data and calibration by drilling in the Aubonne valley (Meyer de Stadelhofen, this volume). Borehole density and core lithology logs, and information on sedimentary geometry from seismic sounding are among the most useful constraints for limiting the range of possible density models.

In former glacial valleys the sedimentary geometry and the bedrock morphology are due mainly to tectonic, fluvial and glacial processes. Good knowledge of these processes and their products, and as a consequence, close collaboration of geologists, who describe and model the depositional environments, with geophysicists, who derive objective views of the subsurface, is needed to obtain a valid result for environmental and hydrogeological studies.

Acknowledgements

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