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Inversion of vertical deflection data by the program GREMMO

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Abstract. Geology is the limiting factor for a precise geoid but also for geophysical inversion. To increase geoid accuracy to ±1-3 cm a special GIS for gravity field inversion by interactive crustal modelling was developed. It combines data from geodesy, geophysics, geology and petrography. As a basis for density models and a new Austrian geoid, it promotes future geotechnical cooperation. The main modules are data input, subsurface models, geological gravity computing, visualisation. This paper presents examples from the Vienna Basin and the Flysch Alps.

1. Introduction

Geoid and inversion projects can benefit very much from the data of neighbouring geosciences, especially geology. To combine and interpret interdisciplinary data lies within the domain of GIS (geoinformation systems), which are not usually suitable for 3D models, like structures of the Earth' crust however. Consequently, a special GIS has been developed for 3D modelling of geological layers and for the computation of their attraction. Other relevant aspects were:
- graphic-numerical support for difficult 3D modelling and geologic intersections;
- growing number of relevant geoscientific data (Gerstbach et al., 1990b);
- future tools for interdisciplinary co-operation;
- improvement of the Austrian geoid by 3D density data of rocks and sediments;
- priority to vertical deflections (VD) rather than to the gravity anomalies.

Concerning the last two aspects, the author could show that for alpine geoid projects astrogeodesy is more effective than gravimetry (Gerstbach, 1997). The analysis was based on the geoid projects of Austria, Germany and Switzerland (e.g. dissertation/diploma works 1996; Kühtreiber 1999, Denker et al., 1995-96; Marti et al., 1995). Accuracies or 1-2 cm require point spacings of 5 km (astro) and 1-2 km (gravimetry). Thus, the large number of gravity points

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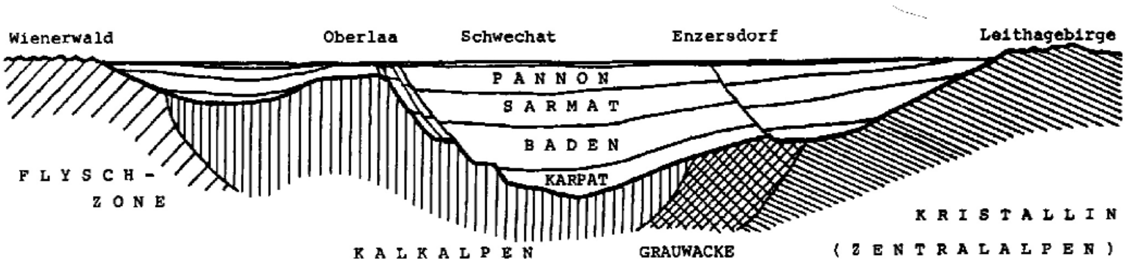

Fig. 1 - Vienna Basin, tertiary sediments and pretertiary subfloor (cross-section WNW-ESE, 50×8 km).

compensates by far, the longer astro-observation time. The reason is varying rock density, especially valley sediments which cause systematic gravity errors (<20 mGal) but smaller and quasi random effects in VD (±1-3"). This fact stimulates *automatic* vertical deflection measurements by *Charge Coupled Devices* (CCD) combined with GPS (Bretterbauer 1997; Gerstbach, 1999).

The program GREMMO (geological reduction and multi-layer models) handles the subsurface as two or more geological layers of different density. Inversion is done by interactive changing of depth and/or density (resolution 60-80% of point spacing). So far the program has been applied mainly to the Vienna Basin (Fig. 1) and to Upper Austria (Flysch-Limestone Alps, Chapter 4) where the geoid (±5 cm) was improved to ±2 cm. Similar applications in the Pannonian Basin (Papp/Kalmár 1995) are planned.

2. Main functions of GREMMO

The original programme of GREMMO is written in TurboPascal (Tengler 1993). Extensions were made in 1994 (Gerstbach/Tengler 1993) and are planned for 1999. GREMMO works on PC 486 (>8 and 200 MB); important functions are:

1. data input (from files or manually): position, height and description of data points, vertical deflection (VD) or gravity anomaly (next version), geologic/tectonic units, subsurface layers, seismic or drilled depths, interpolations, editing and data control, graphic tools;
2. subsurface density modelling: rock densities and compaction, density areas (2D, 3D), manipulation of surface and subsurface densities, density trends; semi-automatic modelling (next version);
3. depth and gravity modelling: changing of geologic/tectonic depths at points, within profiles, triangles and areas. Combining different depth and density formulas, computation of geological gravity effects (at present only VD). Adjustment of trend functions (order 2-4), VD residuals;
4. graphics for interactive modelling of depth, density and gravity field: block graphics, groundplans, profiles, gravity reduction (topography and/or geology), VD residual maps, comparison of different versions...

The subsurface structures are gridded in a regular raster of vertical prisms (usually 0.8×0.8

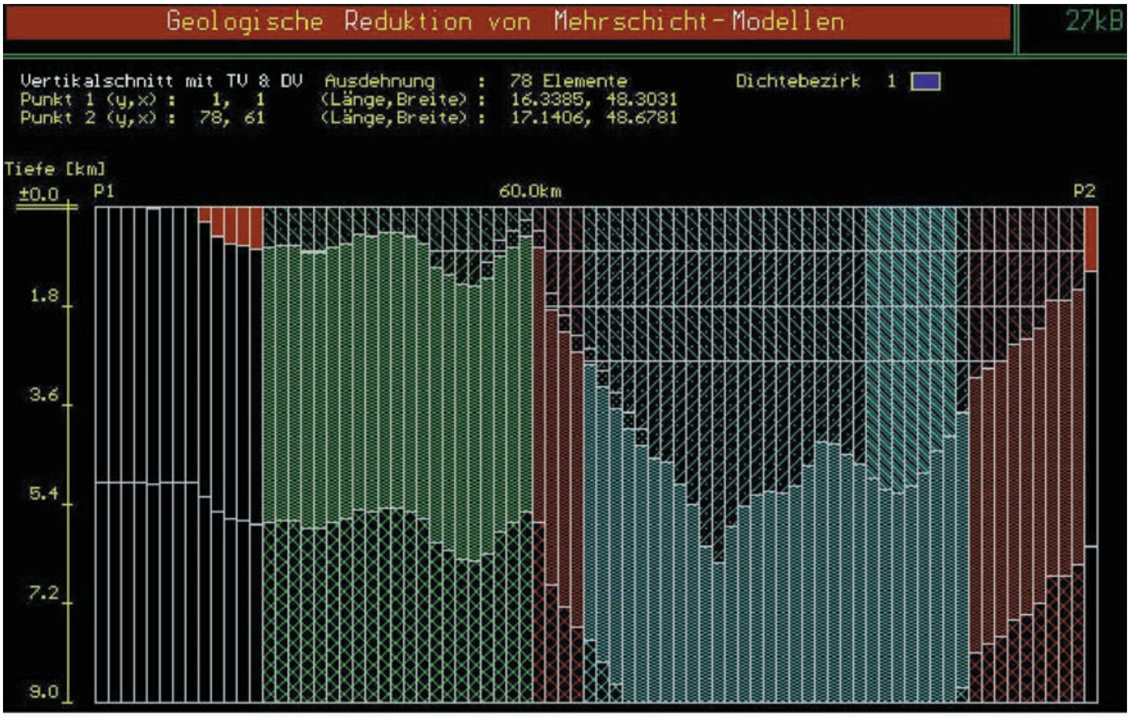

Fig. 2 - Vienna Basin modelled by GREMMO, section SW-NE. Density areas defined by the basement: DA 8 (left basin edge), 2 Flysch, 3 fracture, 4 Limestone a, 6 Limestone b. Density changes by basement layer (DA 2-4) and column (DA 4, right). A ground-plan is shown in Fig. 3.

km). Rock and sediment densities are defined by layering (Fig. 2) within “density areas” (rock types and sequence of densities). Sediment basins or alpine valleys are defined by rock type and density of the basement (Vienna basin: Flysch, Limestone, Crystalline...) and sediment compaction within the layers (e.g. Vienna Tegel: 2.0 g/cm^3+0.1 per km depth). The geological gravity effects are computed by usual formulas of vertical rectangular prisms.

The inversion is done by interactive change of densities (b) or depths (c), supported by graphics of VD residuals. These graphics (see Fig. 3) show the VD difference against a best fitting regional trend. If VD graphs of different models are overlaid (Fig. 5), the appropriate model change can be found going step by step.

The density or depth changes are defined by the maximum changes at 1 or 2 points. Within two radii the change increases from zero to maximum using linear or other functions. By using a combination of such patterns, triangular or quadrangular variation areas can be established.

3. Application to the Vienna Basin

Subsurface modelling by GREMMO can also be used for better interpolation of the gravity field and hence, for the improvement of the geoid. In Lower and Upper Austria, the geoid was improved by 40-70% (Gerstbach, 1997). Special analyses are currently being conducted in the

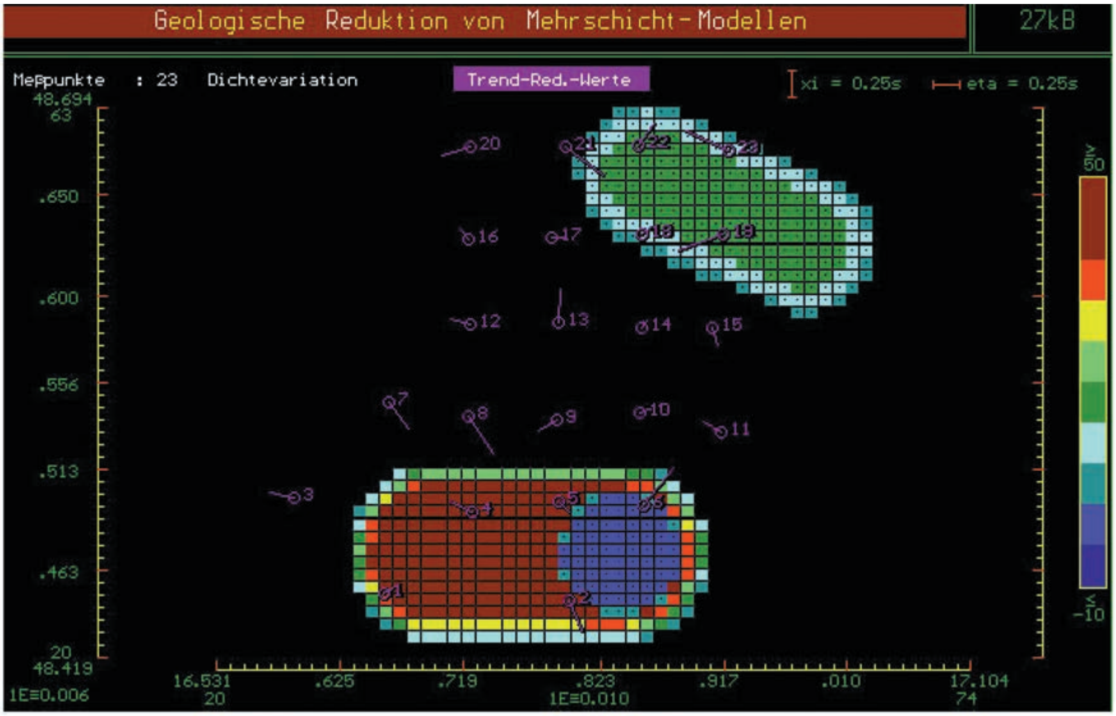

Fig. 3 - Density changes (see Fig. 2) and resulting VD residuals. South=basement layer <0.5 g/cm^3, Northeast=column <0.1 g/cm^3. The vertical deflection residual vectors (differences against a regional trend) at 23 astropoints (accuracy ±0.2“) are quasi-random (0.1-0.4").

Vienna Basin (50×200 km), located between the Alps and the Carpathes. The basin has been sinking for 20 million years and is now filled with marine and fluviatic sediments (present depth to the bedrock is 1-6 km, Figs. 1 and 2). The mean density difference with respect to the basement (Flysch, Limestone, Graywacke and Crystalline, 2.6-2.8 g/cm^3) is 0.5 g/cm^3 and varies from 0.4 to 0.7.

Therefore, 8 density areas (DA 1-8, see Fig. 2) were defined, based on seismo-geological maps (depth accuracy ~500 m) and three deep drillings. Every DA contains basement density (e.g. Granite 2.67) and 1 km sediment layers (typical compaction 2.0+0.13/km) suggested by geologists (ÖMV 1980) and improved by (Gerstbach and Tengler, 1993). Several basin models were established:

- correction of seismic depths and interpolation of oil drillings (accuracy 600 m=>300 m);
- improvement of rock densities and compaction from ±0.2 to ±0.1 g/cm^3 (ÖMV 1980);
- density determination at difficult tectonic structures up to ±0.03 g/cm^3, which may be useful for oil/gas exploration (see Fig. 5);
- improvement of the geoid from ±2 cm (dense gravity field data) to ±5-10 mm.

In the Northeast (30 × 35 km) the 3D model was varied in detail (Table 1), using 23 astropoints (46 vector components of vertical deflection: 23 ξ, 23 η).

Table 1 shows several effects:

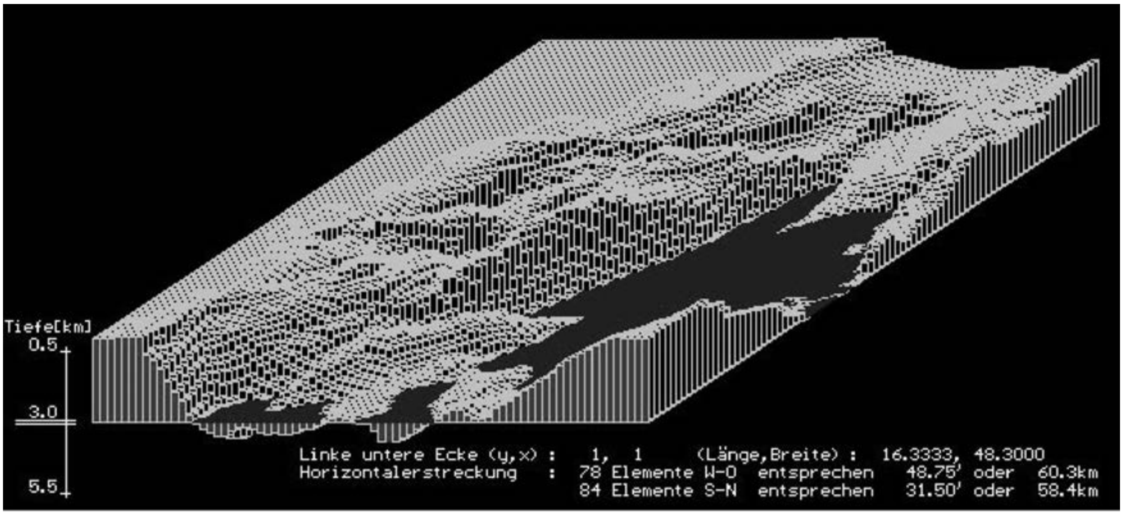

Fig. 4 - Pretertiary basement of northern Vienna Basin (60×58 km, grid 0.8×0.8 km), seismic depths (ÖMV-AG). Slope of central "Steinberg" fault 40-50°. Basin parts deeper than 3 km darkly printed.

- terrain correction improves vertical deflections from ±2-3" (original) to ±1.8";
- existing *geological* models reduce mean errors from ±2" to ±0.6", 3D *density* to ±0.4". Hence the VD integration and the geoid will improve by at least 50%, according to prior experiences (Gerstbach, 1990a/1997, Meurers, 1992);
- values <0.2" (observation accuracy) are possible, but indicate unrealistic models. The number of parameters should not greatly exceed the number of points (⇨ redundancy 30-50%).

In an area of uncertain sediment density a special analysis based on 8 astro-points has been performed. Two density changes of 0.1 g/cm^3, each starting from zero at the surface, resulted in the VD residuals of Fig. 5. As can be seen by the decreasing vectors, the resulting density accuracy is ±0.04 g/cm^3.

3.1. Geoid Improvement by 3D modeling

Table 1 - Varitions of a 3D model applied to the northeastern Vienna basin.

Model details	Var. depth / density		Var. Points	residual vectors	remarks
DTM terrain reduced	-	-	-	±1.6" ±2.1"	RMS of original
ÖMV starting model	-	-	-	±0.57 ±0.70"	VD: ±2.5"
Mod. 5, Tengler 1993	-	linear	3	±0.40 ±0.50	
Mod. 20, Tengler 1993	1	2	10	±0.36 ±0.38	
ZIM 7, Gerstbach	5	-	8	±0.30 ±0.34"	
ZIM 15, overparametr.	8	1	12	±0.14 ±0.17	observation
ZIG 24, 30 parameters	5	3	10	±0.19 ±0.21	accuracy ±0.2"

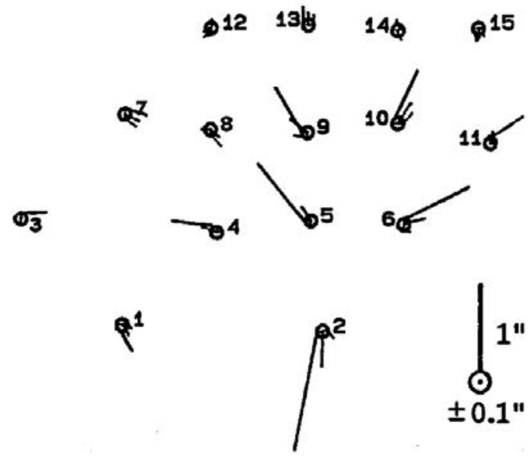

Fig. 5 - Sediment density derived by vertical deflections of 3 models. Equidistant density variations in the subfloor of 8 astropoints.

The usual way to make a better geoid is a densification of data points (VD or gravity). The improvement is about 50% if the point number and the costs increase by a factor of 4 (Gerstbach, 1990a). GREMMO has the same effect, but with very low expenses:

A more accurate integration of geoid differences is equivalent to a better VD interpolation between the astro-points. This can be done by fictive points which are reduced using a geological model based on GREMMO and the original VDs. Even an imperfect model yields a better interpolation. To test the possible geoid improvement realistically, central parts of the Vienna Basin were chosen (flat areas and Flysch Alps). Half of the points (spacing 7 km) were used for *some* subfloor variations. The other points were interpolated and agreed with their real VD data to 0.3-0.4", improving the geoid from ±2 cm to <1 cm.

4. Application to the Middle Alps

In the Alps similar effects are expected, e.g. for the sediment filling of broad valleys. Using standard density (2.67 g/cm^3), systematic reduction anomalies <20 Gal occur (Meurers, 1992). On the other hand, the vertical deflection effects are only 1-3" (for symmetry reasons) and quasi-random (Gerstbach 1997). Smaller error sources are different rock densities at the valley slopes, or subduction in the alpine foreland.

Such situations are found in central and western Austria (Molasse, Flysh- and Limestone Alps) and many alpine mountain ridges. In Upper Austria (Fig. 6) density contrasts between Crystalline/Limestone and Molasse sediments are $\Delta\rho$ 0.2-0.7 g/cm^3 which affect the gravity field by 0.5-2" (VD) or <10 mGal (gravity).

The effects were computed by a rough "inclination formula" (Gerstbach, 1993) because no 3D model exists, only outline maps of the Molasse basement (2 1/2 D). The VD reduction $\Delta\varepsilon$ depends on $\Delta\rho$ and Δz (depth difference beneath astro-points with mean spacing s). The depth z

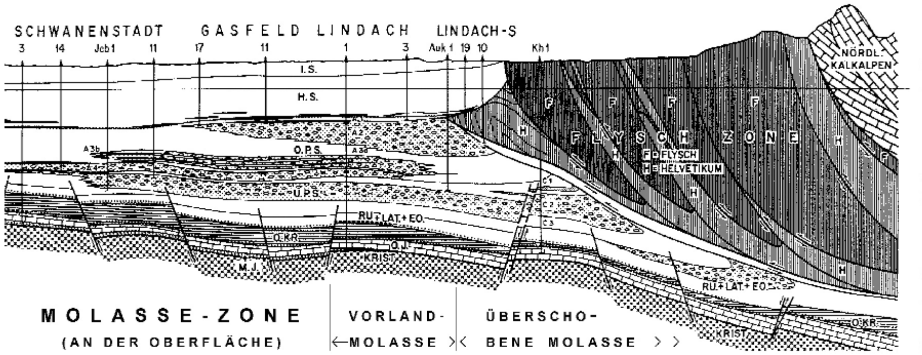

Fig. 6 - Geologic N-S profile from southern Molasse Zone to Limestone Alps (Traunstein, 1700 m). Sediments (tertiary, Kreide, Jura) subducted by Flysh and Limestone to depths 1-5 km (ÖMV 1980).

causes an esponential factor:

$$\Delta\varepsilon \approx 3.1'' \;\; \Delta\rho \;\; \Delta z^{km} \exp\,(-2z\,/\,s).$$

The 36 points within a 6800 km^2 rectangle (Salzburg, Linz, Liezen) show VD variances of ±4.5" (orig.) and ±3" (terrain reduced). Surface density (2D) yields ±1.7", 2 1/2 D ±1.4". The figures are smaller if VD is compared to a regional trend of order 4 (chapter 2): ±3", ±1.0", ±0.7" and ±0.5". Therefore, geology improves the geoid by 50% even with a very rough model.

5. Conclusion

The program GREMMO is a tool for considering geological subfloor effects in geophysical inversion and geoid projects. Gravity field interpolation is improved by > 50%, rock densities of known layers can be determined to better than 0.1 g/cm^3. The inversion by *interactive* crustal modelling requires $^1/_2$-1 hour per measured point; this may be done automatically in the next program version. Interested co-operators or dissertant(s) are welcome.

Common geoid studies using 3D models of Lower Austria / Burgenland (topography 120-2000 m) and western Hungary (100-700 m) are planned for 1999/2000 (Gerstbach, 1999; Papp and Kalmár, 1995). A dissertant will combine VD and gravimetric data to improve the geoid from ± 3-10 cm to 1-5 cm (see section 3.1).

The growing number of geoscientific data demands automatic modelling and mutual interdisciplinary understanding. Literature on geoid determination contains almost *no* GIS methods or geodetic-geological subsurface modelling (e.g. WWW, 1999). GREMMO was developed to fill this gap, but also to promote common projects of different geosciences - partly to be carried out with neighbouring countries (Gerstbach et al., 1990b; Hexagonale, 1991/92). The forthcoming interdisciplinary conference GeoLIS-4 (1999/2000) will include such topics. Future steps of GIS visualisation may further improve GREMMO.

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