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Recent vertical movements from precise levelling in the vicinity of the city of Basel, Switzerland

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Abstract The southern end of the Upper Rhine Graben is one of the zones in Switzerland where recent crustal movements can be expected because of ongoing seismotectonic processes as witnessed by seismicity clusters occurring in this region. Therefore, in 1973 a control network with levelling profiles across the eastern Rhine Graben fault was installed and measured in the vicinity of the city of Basel in order to measure relative vertical movements and investigate their relationship with seismic events. As a contribution to EUCOR-URGENT, the profiles were observed a third time in the years 2002 and 2003 and connected to the Swiss national levelling network. The results of these local measurements are discussed in terms of accuracy and significance. Furthermore, they are combined and interpreted together with the extensive data set of recent vertical movements in Switzerland (Jura Mountains, Central Plateau and the Alps). In order to be able to prove height changes with precise levelling, their values should amount to at least 3–4 mm (1σ). The present investigations, however, have not shown any significant vertical movements over the past 30 years.

Keywords Geodetic measurements · Precise levelling · Recent vertical movement · Tectonic · Upper Rhine Graben flexure

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Introduction

Geodesy and recent crustal movements

The quantitative compilation of geodynamic processes, especially of crustal movements, is usually based on the determination and comparison of geometric or physical measurements at the same point at different time periods. The smaller the time intervals and the smaller the amount of movement, the more accurate the measuring method has to be in order to determine significant changes. Analyses of geophysical measurements allow comparisons dating back millions of years.

Traditional geodetic measurements with repetition cycles of a few years or even decades, however, correspond to very recent processes in geological terms. These processes are therefore called "recent crustal movements" (RCM). This disadvantage is compensated by the advantage that geodesy can provide information on ongoing processes rather than the integral of geodynamic processes over millions of years (Wiget und Gubler 1988). This aspect is even more highlighted by the introduction of modern global positioning system (GPS) permanent networks, which allow the monitoring of movements in real time.

Prerequisites for the determination of recent crustal movements using geodetic methods

A few basic principles must be considered when RCM are to be analysed with geodetic measuring methods. At least two observations at different epochs are required for determining horizontal or vertical changes. The significance of the determined movement is limited by the accuracy of the observations. Should a change actually be proven, the time interval between the measurements must be large enough so that the movement exceeds the inaccuracies of the observations. In addition, the a priori values are usually unknown.

However, the greater the time interval between observations, the more accurate and more certain is the significance of a movement.

If there are only two observations available, it is impossible to prove any variations in the sequence of the movements. The only conclusions to be drawn pertain to the total amount of a displacement in the observed time interval or to the average velocity.

A further crucial prerequisite is that the observed control points are well monumented and stable so that the measurements can be observed at exactly the same points. Owing to the active construction in urban areas, this trivial principle cannot necessarily be guaranteed and unfortunately a large number of points are lost between observations.

If control points should yield information on tectonic movements of the crust, all exogenic influences such as slips, slides and compaction of loose rock, changes due to the fluctuation of the ground water, and all other modifications caused by construction must be excluded.

Possibilities for tectonic investigations in Switzerland and the adjoining Upper Rhine Graben

Basically there are three major methods in classical and modern geodesy, which can be applied in the investigation of tectonic movements in Switzerland:

- Triangulation and trilateration (angle and distance measurements)
- Precise levelling
- Satellite positioning (GPS)

Based on earlier investigations and the known maximum magnitude of the expected movements, the classical angle and distance measurements used in national surveying to determine horizontal changes are not appropriate.

At present, GPS is the predominant geodetic method for determining three-dimensional tectonic movements. The installations in Switzerland and in the adjoining Rhine Graben are relatively new, which means the observation series and the time interval are too short to yield significant results.

Our results will therefore be limited to the investigations carried out with precise levelling. This very labour-intensive observation method, however, is restricted to the determination of vertical changes. The essential criteria mentioned in the preceding chapter are at least reasonably fulfilled, and therefore, several acknowledged investigations have been carried out in Switzerland with the available observation material.

In the City of Basel and its surroundings, the first special levelling networks were established and measured across the Rhine Graben flexure in 1973. In the scope of the project EUCOR-URGENT the main goal was the re-measurement and a regional adjustment of the precise levelling in the vicinity of Basel.

Precise levelling and recent vertical movements

The method

Precise levelling is one of the oldest, simplest and still most accurate methods for determining height differences between points. The elementary method of measuring the height difference between two levelling rods in precise levelling is the result of a particular observation sequence, extremely precise equipment and the modelling of external influences.

With this straightforward measuring method, it was possible to carry out relatively precise measurements already in the nineteenth century. The greatest loss of accuracy was mostly due to the levelling rods. The stability of the initially used wooden rods was dependent on temperature and humidity variations. After 1913, the alloy "invar", whose expansion coefficient is 10 times smaller than that of steel, was used in levelling rods. From that time on, precise levellings yielded a comparable accuracy to that obtained by today's most modern digital instruments. The analyses of first order levelling data yield a mean observation accuracy of approximately 0.8 mm/km (1σ) for precise levelling.

First and second order levelling

The Swiss Federal Office of Topography (swisstopo) observes and maintains a levelling network with a length of about 3,500 km and consisting of approximately 10,000 control points. This so-called first and second order-levelling network, initially observed between 1903 and 1945, is divided into 18 loops. It is still the basis for all height measurements in Switzerland. From 1943 until the end of the twentieth century almost all lines were observed a second time; individual sections have even been observed a third time. The average time interval between the observations reaches about 50 years. An overview of the first and second order-levelling network is shown in Fig. 1.

The model for determining vertical movements

The height differences determined by levelling always refer to the behaviour of the local equipotential surfaces of the earth's gravity field. As these are usually not parallel, the levelled height differences are dependent on the route. The total sum of the error-free height differences of a closed loop is not zero but is given by the so-called loop misclosure. This influence may be neglected for local height determinations and especially for the determination of local height changes. For the adjustment of the national height system, however, the height differences $\delta h'$ are converted into route-independent potential differences δC by means of gravity g measured along the levelling lines:

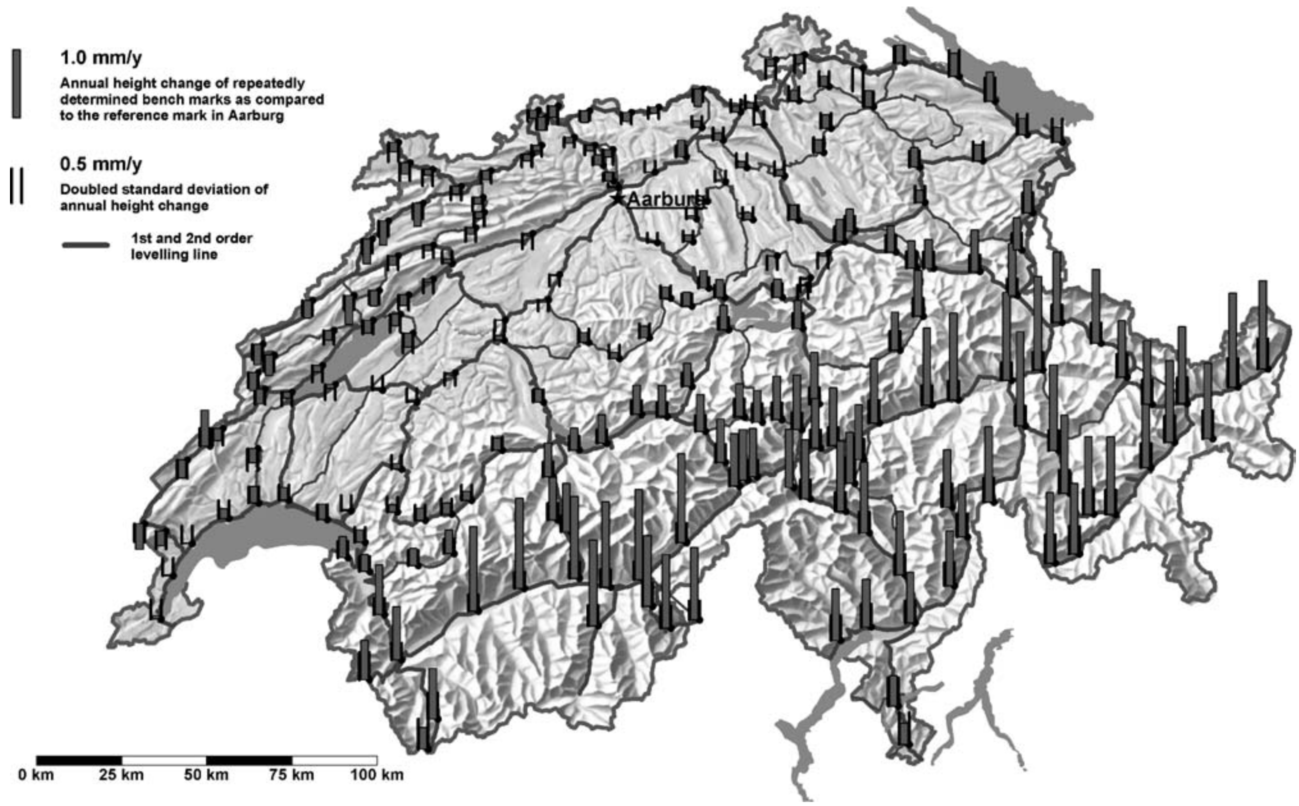

Fig. 1 Swiss first and second order-levelling network and annual height changes with respect to the reference bench mark in Aarburg

$$\delta C = \sum g \cdot \delta h' \quad (1)$$

Swisstopo developed a special program for the determination of vertical crustal movements (Gubler et al. 1984). With a least squares adjustment the geopotential values C of the control points at a certain epoch t_0 and their mean potential changes d C/d t are computed. The functional model is described as follows:

$$\Delta C_{i,j}^{k} = C_j^0 - C_i^0 + (t^k - t^0) \cdot \left(\frac{\mathrm{d}C_j}{\mathrm{d}t} - \frac{\mathrm{d}C_i}{\mathrm{d}t} \right) \quad (2)$$

whereby, $\Delta C^{k}{}_{i,j}$ is the observed potential difference between two control points i and $j$at epoch k.

By introducing the mean normal gravity, the potential changes of the points can be transformed into their metric velocities. The principle of levelling allows the determination of relative height changes between observed control points. The method described above requires a reference value for the absolute height as well as for the potential changes. Furthermore, the model assumes that height changes within the observation window are linear. Variations in the movements can only be ascertained if more than two observations were carried out. The functional model is satisfied when more than two observations of a point show a movement with a constant velocity. A significant deviation of the velocity from a linear pattern acts as an interference of the adjustment, and the data must be eliminated.

Recent crustal movements in Switzerland

The computation of RCM in Switzerland has a long tradition at swisstopo (Jeanrichard 1972; Gubler et al. 1981; Gubler et al. 1984; Mälzer et al. 1988; Müller et al. 2002).

With the publication of the first nationwide results, it was possible to detect a continuing uplift of the Alpine massif with respect to the Central Plateau (Jeanrichard 1972). With the annually repeated observations of approximately 100–150 km of levelling lines, the computations according to the above method were updated and the results extended and improved. Figure 1 shows the current status of these nationwide investigations on the basis of about 250 repeatedly observed control points. Whenever possible, only points that are monumented in solid rock were selected for these investigations. For those points where more than two observations were available, the assumed constant movement was confirmed at almost all stations. Since the control points were initially established for the purpose of height measurements, repeated measurements of points on solid rock are rather rare except in the vicinity of Alpine passes. Only approximately 5% of all the points can, therefore, be included for such investigations because the rest of the points were usually monumented on buildings established on younger sedimentations.

The vertical velocities represented in Fig. 1, which show a significant uplift of a large part of the Alps with respect to the Central Plateau, correspond to a reference point in the southern Jura Mountains in Aarburg. The choice of this fundamental point is arbitrary and is not based on any geological presumptions. Should anyone disagree with this reference point, the uplift rates can be computed with respect to any other reference by means of a uniform shift. This has no influence on the relative uplift velocities.

There are probably two main reasons for the so-called "exhumation of the Alps" (Geiger et al. 1993; Labhart 1993):

- Uplift as a direct response to an orogenetic, tectonic process, mainly the penetration of the Adriatic block into the European lithosphere;
- Uplift as an isostatic process to compensate for erosion.

Some local results in accordance with geomorphological observations along the Rhine–Rhone Line also suggest that postglacial isostatic movements (rebound) might be a reason for relative uplifts (Kahle et al. 1980; Eckhardt et al. 1983).

Most of the movements in the Central Plateau and in the Jura Mountains are not significant, but they do show tendencies such as the subsidence in the Jura or the uplift in the region of Lake Constance.

No distinct patterns can be deduced from the data in the vicinity of the Upper Rhine Graben in Basel. These data, which can only show changes for the last century, do, however, suggest a possible continuation of the rift under the Jura Mountains as derived from the results showing a predominant subsidence. Indications for recent tectonic activity are the diverging movements in the area of the Lac de Joux (Vallorbe, southwest of Neuchâtel).

Precise levellings and height changes in the area of the Upper Rhine Graben in Basel

The installation of the RCM profiles Basel and the observation campaigns

Within the range of its possibilities, swisstopo is dedicated to investigate RCM in tectonically active areas. For this reason, a first control network was established in 1973 with two levelling profiles (RCM profiles) running diagonally across the Upper Rhine Graben flexure to the east of Basel (see Fig. 2, upper left). Since large sections of the profiles are parallel to the levelling lines of the Canton of Basel, the investigations were carried out in cooperation with the Cantonal Surveying Office of the city of Basel. The network was extended several times and re-measured in the years 1980 and 1991.

The most recent campaign in the years 2002 and 2003 was carried out especially for EUCOR-URGENT and was funded to a large part by the ETH Zurich. The total length of 54 km of precise levelling includes not only all

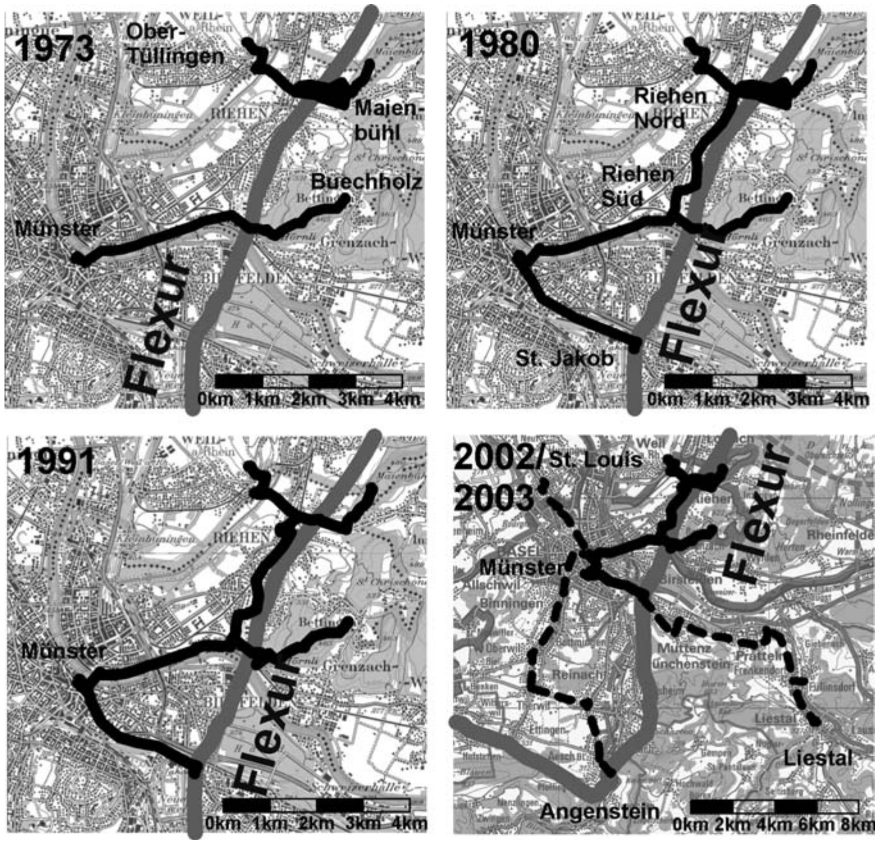

Fig. 2 Network configuration and the campaigns of the RCM profile Basel between 1973 and 2002; first order levelling network Angenstein—Basel (Münster)—St. Louis—Liestal (only *lower right*)

of the RCM profiles but also extended connections to the first order levelling in the direction of Angenstein, Liestal and St. Louis (France) (see Fig. 2, lower right). Including the measurements from 2003, there are now three epochs of observations available for these lines. Levelling campaigns of comparable quality were carried out in 1911/1917 and 1967/1972.

Geological evaluation of the control points

The levelling lines run predominantly across the dominating quarternary gravel, alluvial sedimentation or loess clay. In these regions the control points are monumented exclusively on buildings. Therefore, the height changes reflect mostly the irregular subsidence of buildings or local slips, which makes it impossible to filter out tectonic signals. Solid rock or molasse layers are accessible in only a few regions, and only a small number of points can be included in tectonic investigations based on the subterranean character or on the age of the buildings.

The particularly suitable points or groups of points that are mentioned in the following results are described briefly:

- Angenstein: at the beginning of the line in Angenstein, the control points are monumented directly on solid limestone below the castle (see Fig. 3a).
- Münster Basel: the control points around the cathedral of Basel are all monumented on historical buildings resting on approximately 14 m of sound layers of gravel (Niederterrassenschotter). Their suitability with respect to other points in Basel has been confirmed in nationwide investigations.
- Weir in Birsfelden: it is assumed that the weir is connected with the molasse layers and that the control points monumented on the weir are therefore suitable (see Fig. 3b).
- St. Jakob (“Bauschänzli”): one of the few exposed locations of the flexure was excavated in 1977 during the construction of the freeway and declared as a geological monument (Bitterli 1978). An important control point of the RCM network was placed in the steep limestone banks and measured for the first time in 1980 (see Fig. 3c, d).
- Horngraben, Buechholz and Maibühl: specifically for this investigation these three groups of points were monumented in solid limestone or in dolomite of the Trias and protected by cast iron manholes (see Fig. 3e, f).
- Ober-Tüllingen: this group of markers is monumented on buildings that are probably well-founded in the tertiary. Thereafter, the levelling line drops down a steep slope, actually a slip called “Schlipf”, and continues in the direction of Riehen.

Analysis of the observations

The following two strategies were applied to the local investigations:

1. A pure documentation of the *height changes* of the major points of the RCM network with respect to the points “Münster Basel” (Fig. 4).
2. Overall adjustment and classification into individual epochs of all observations using the model for constant *vertical movement* (Figs. 5, 6, 7).

Height changes

In contrast to movements that show the advantage of standardization in time, the first adjustment shows the actual height changes between the observations. The height changes are a result of a comparison between the raw height differences from the various campaigns and an identical reference point. This value is regarded as more concrete by geological experts. Based on the accuracy of ± 0.8 mm/km known from experience, a measure of accuracy for the displacement between two observations ($m\Delta H$) may be deduced, which is dependent on the distance (Dist) between the points:

$$m\Delta H(1-\alpha=95\%)=\sqrt{2}\cdot 0.8\,\text{mm/km}\cdot\sqrt{\text{Dist}} \qquad (3)$$

In the bar graphs in Fig. 4, this level of significance (1σ) is represented by a horizontal line.

Figure 4 illustrates the height changes and their level of significance (1σ) for the selected points of the RCM profile Basel relative to the point of origin on the cathedral. The reason that this point was chosen is that it had been included in all observation campaigns and could, therefore, be considered as the common point of connection.

Vertical movements

The main results of the second adjustment method are the mean vertical movements of the individual control markers. Besides a free, over-all adjustment of all available observations (the only fiducial point being “Münster Basel”), the individual epochs (e.g. RCM profile 1973–1980, 1980–1991, etc.) were also investigated in order to discover any changes in the pattern of movement. Owing to the relatively small time intervals between the RCM profile observations, these epoch solutions also had to be fixed with the velocities of the overall adjustment of the points ’Buechholz’, ’Ober-Tüllingen’ and ’Maienbühl’.

To obtain a better descriptive representation, the results of selected points are shown in Figs. 5, 6, 7 as cross sections along the individual profiles.

Analysis of the results

As a whole, Fig. 4 shows that the height changes between individual observation campaigns are small and from the geodetic point of view, may hardly be considered significant even at a 1σ-level. The maximum height differences between two observations relative to the reference point

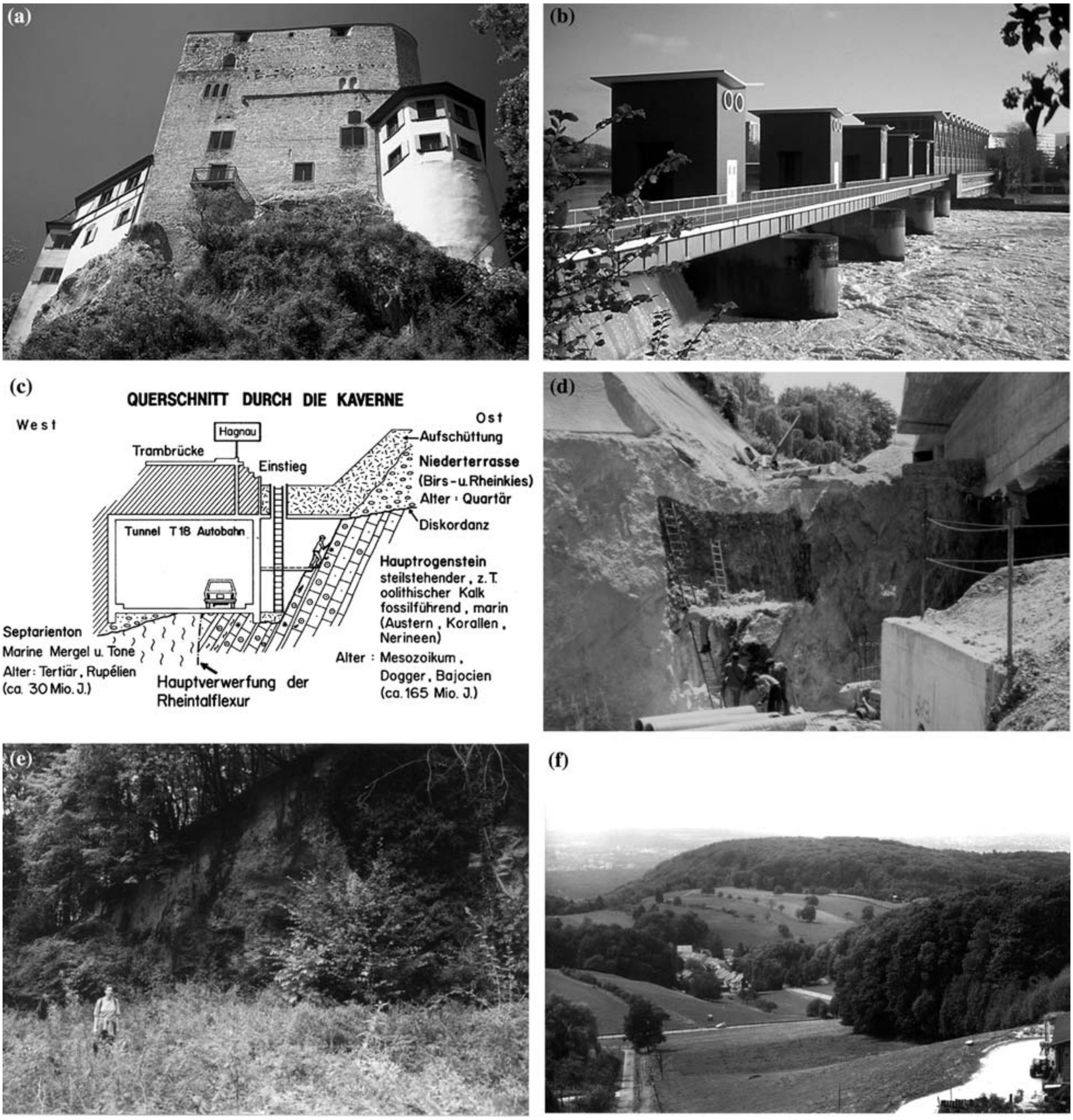

Fig. 3 **a** Angenstein castle, **b** Weir in Birsfelden, **c** cross section of the geological monument, **d** steep limestone layers of the exposed flexure during construction of the freeway, **e** rock formation in ‘‘Horngraben’’, **f** view from Chrischona on Buechholz, direction Basel (from *upper left* to *lower right*)

‘‘Münster’’ amount to approximately 3–4 mm. They correspond to the minimum critical value (1σ), which defines the limit for proving height changes with precise levellings in the RCM profiles. Three of the four suitable point groups to the east of the flexure tend to show subsidence. From the purely statistical point of view (within the accuracy of 3–4 mm), no significant relative displacements have taken place between the points to the east and to the west of the flexure in the past 30 years.

Figures 5 and 6 show the annual height changes along the national levelling lines ‘‘Angenstein - Basel’’ and ‘‘Basel - Liestal’’. With respect to the corresponding time intervals, these velocities can also be converted into height changes.

Even over the past 90 years, no striking relative changes in the movement pattern can be observed, neither in the overall adjustment (1911–2003) nor in the individual epoch solutions. There are no mean relative changes between ‘‘Münster Basel’’ and the end points ‘‘Liestal’’ (Fig. 5) and ‘‘Angenstein’’ (Fig. 6). The anomalous behaviour of epoch 1972–2003 in ‘‘Liestal’’ corresponds to a height change of 4–6 mm which, with

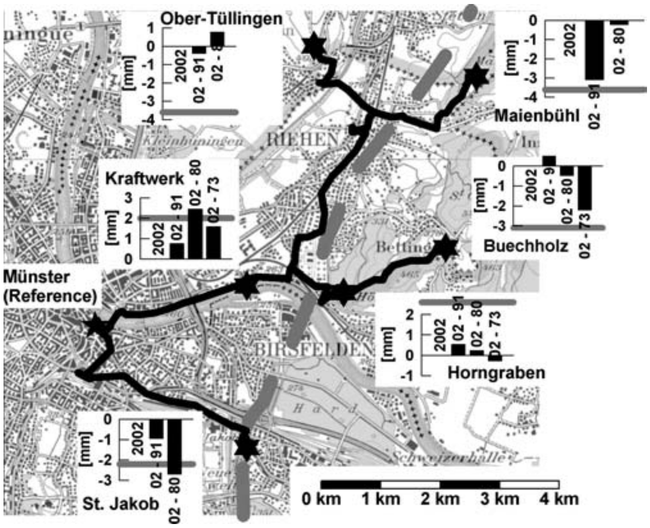

Fig. 4 Height changes and level of significance (1σ) of selected points of the RCM profile Basel relative to the control points "Münster" and the campaign 2003

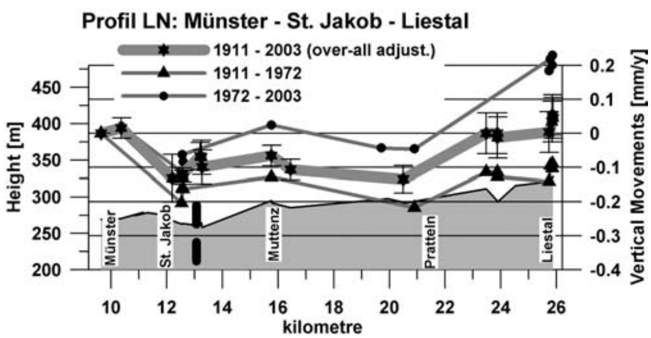

Fig. 5 Vertical movements along the first order-levelling line Basel—Liestal

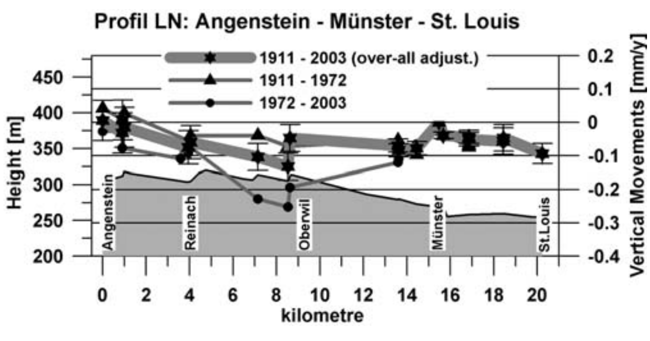

Fig. 6 Vertical movements along the first order-levelling line Angenstein—Basel—St. Louis

respect to the observation accuracy, can be considered insignificant. Subsidence tendencies are evident along both lines. Since most of the points are monumented on buildings resting on the quarternary, it is not permissible to ascribe these subsidences solely to tectonic movement.

Furthermore, the local profiles of the RCM Basel (Fig. 7) have not detected any significant movements either. The most striking tendencies, which have in part been confirmed in the individual epoch solutions, are: an "uplift arch" between the "weir Birsfelden" and "Horngraben" with respect to the points "Münster", subsidence between "Horngraben" and "Buechholz" (Fig. 7, profile 1), and also a subsidence of the geological monument to the east of "St. Jakob" (Fig. 7, profile 2).

Conclusions

The precise levellings carried out across the rift in the Rhine Graben to the east of the city of Basel do not show significant height changes during the past 30 years. They would have to exceed 3–4 mm to be considered as statistically significant (1σ). Furthermore, the annual

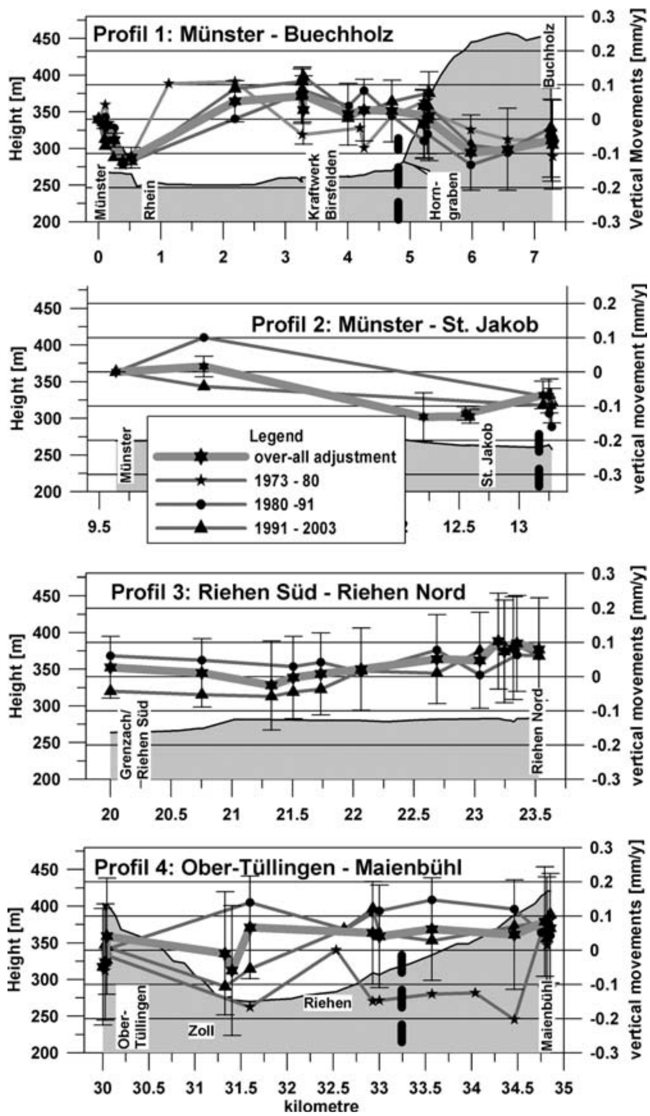

Fig. 7 Vertical movements along the individual RCM profiles (profiles 1–4)

height changes at an observation interval of approximately 90 years between "Münster Basel" and the control points in "Angenstein" and "Liestal" are extremely small and, as opposed to the Alpine uplift confirmed by national levelling, are statistically considered insignificant.

However, the conclusion that the Upper Rhine Graben is tectonically inactive may not be correct. The geodetic observations can only provide information for a geologically short time window of 30 and 90 years, respectively. A rift system would hardly show the same behaviour as a mountainous massif during an exhumation process. A lack of detectible movements in the Upper Rhine Graben, however, may be interpreted as an indication of accumulating stress along the rift.

Acknowledgements Independent of the project EUCOR-URGENT, the precision levelling observations 2002/2003 were financed by the ETH Zurich, commissioned by the Geodesy and Geodynamics Lab (GGL-ETHZ). The major part of the adjustments and documentation were financed by swisstopo as a research and development project. Special thanks go to these two organizations as well as to the Cantonal Surveying Office of the city of Basel, which was significantly involved in the previous campaigns.

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