DETERMINATION OF SITE MOTIONS IN THE VICINITY OF THE ERFT FAULT IN THE LOWER RHINE EMBAYMENT

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Abstract
The intensive brown coal mining activities occurring since the mid-fifties of the last century in the Lower Rhine Embayment have caused massive landscape changes in these areas. Less obvious but equally dramatic are the effects on the earth's surface such as soil movements which are mainly due to groundwater withdrawal associated with the open-pit mining activities. Larger discontinuities in the pattern of motion tend to appear at pre-existing fault lines and are causing sizable damage to buildings and roads.
Precision levelling carried out by the survey administration in regular intervals, and in recent years also GPS, are being used to measure these motions and monitor their behaviour with high precision. As a recent example, the measurements in the local area deformation network "Donatussprung", which is a part of the Erft Fault System where its surface trace can easily be identified from topography and effects on buildings and roads, have yielded displacements of up to 5 mm/yr in horizontal and 20 mm/yr in vertical direction. Vertical and horizontal motions due to recent tectonics are much smaller by at least an order of magnitude.
The highly significant pattern of vertical and horizontal vectors shows a striking dissimilarity in the motion of groups of points on either side of the fault. Velocities are largest on the western side of the fault. Furthermore horizontal velocities tend to decrease with increasing distance from the fault, whereas vertical velocities become larger with increasing distance. The scenario suggested by these measurements indicates that the Erft Block at its rim is not following the overall subsidence that is observed at some distance away from the fault. Possible interpretations are also discussed.

1. Introduction

At least one third of the ground surface of Northrhine-Westfalia is affected by ground motions, due to both recent tectonics as well as mining (see Fig. 1). The Lower Rhine Embayment as a part of the West European Rift Belt is known for its present-day seismo-tectonic activity. The rift system characterises the weak crustal zone of northwest Germany and the Netherlands. It continues in the directions of the Alps and the North Sea respectively. The active faults run from the NW to the SE. One special section of the Erft Fault System in the region located south-west of Cologne can be easily

Figure 1: Open-pit brown coal mining near Cologne

identified by topography and the effects on buildings and roads (see Fig. 3). In the immediate vicinity of the surface trace of the so-called "Donatussprung" which separates the Erft-Block from the Köln-Block (Ville), a local area GPS network has been established (Fig. 2). The vertical and horizontal motions due to ongoing tectonic forcing are estimated to be much smaller than the effects due to the open pit mining activities, since parts of the region are strongly influenced by ground water withdrawal down to some 100 m associated with the extensive brown coal mining. In or near brown coal mining areas groundwater withdrawal produces subsidence of up to 2 cm/year in the area under investigation.

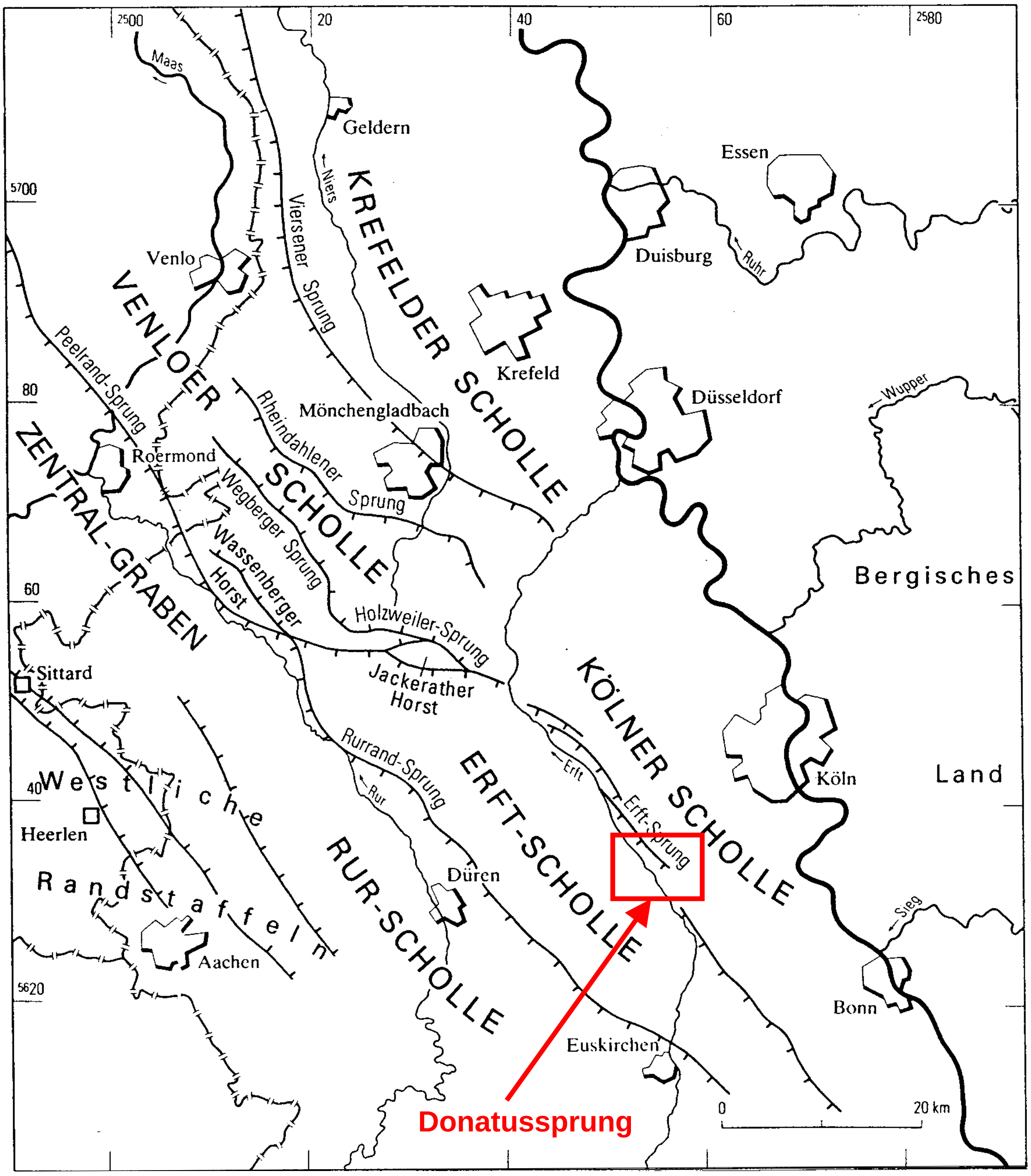

Figure 2: Geological sketch map of the Lower Rhine Embayment [4]. The red square denotes the area under investigation in the vicinity of the Donatussprung

In geological time scales tectonic subsidence of the embayment down to a maximum depth of 1000 m has been recorded in the strata. From precise re-levellings between 1920 and 1950 crossing the embayment, rates of up to 1.5 mm/year subsidence have been derived [1, 13]. Therefore, it is assumed that this tectonic process is still continuing but today is covered by the consequences of mining.

Before GPS had been fully deployed, spirit levelling was the most commonly used method to establish precise vertical control with millimeter accuracy. Faced with mining-induced height changes at many of the official benchmarks in the Lower Rhine Embayment, the survey administrations in cooperation with the mining companies were obliged to perform levellings in the entire area at regular intervals since the 1950ies, every four years and in certain parts even every two years, to record and map the vertical changes [6, 10, 14]. By this effort, subsidence of up to 3.3 m over a time span of 40 years caused by the groundwater withdrawal has been recorded in central areas of the mining activities. Today with GPS a new possibility of vertical and horizontal control has become available. The area has therefore been the subject of several surveying campaigns both by terrestrial and by GPS techniques [18].

Since only height changes are well known from regular levellings, the University of Bonn decided to set up a GPS network to study recent ground motions in all three components. While establishing the HEIKO network (Höhenänderungen in Eifel und Köln-Bonner Bucht) the selection of the sites for the GPS receivers has been accomplished with great care, taking into account the requirements for high precision measurements, e.g. long-term stability of the markers [7, 8]. The series of annual GPS campaigns covering 13 simultaneously observed points has been started in 1993. The size of the GPS network is about 100 km x 100 km. The main topic at the onset of the project was the development of strategies to improve the accuracy (repeatability) of the vertical component. Apart from taking into account tropospheric refraction it is important to extend the observation sessions to at least 24 hours and to use low elevation observations. All antennas were calibrated for phase center variations. Extensive tests show that the best repeatabilities are obtained when using an elevation cutoff of 10°.

For the purpose of monitoring motions in the immediate vicinity of the surface trace of the Erft Fault a smaller local area network “Donatussprung” (Fig. 3 and 4) has been established in addition to the regional HEIKO network covering the entire area. In the work presented here the HEIKO network is used as a reference frame for the campaigns observed in that local area network.

2. GPS local area network „Donatussprung“

The local area network has been established to monitor motions in the immediate vicinity of the surface trace of the Erft Fault to clarify the movement pattern near the main fault (Fig. 4). The network consists of 15 survey markers belonging to the 3rd and 4th order triangulation network with a total size of the network of 11 km in NE-SW direction and 8.5 km in NE-SW. The distances between points range from 0.5 to 4 km [15] with two sites of the HEIKO main network being included.

In November 1992 a first GPS campaign was carried out by the State Survey of Nordrhein-Westfalen (NRW) with 4 receivers in seven sessions of 1.5 hours duration. The observation plan made sure that every point was occupied twice. The second and third campaigns in

Figure 3: A special section of the Erft Fault, called Donatussprung, can be easily identified at the surface.

November 1997 [2] and March 2000 [5] were carried out jointly by the State Survey NRW and the Geodetic Institute of the University of Bonn. In these campaigns 8 receivers were available and the observing time was extended to four hours for each session. In order to be able to assess the accuracy of the results of each epoch, two consecutive full observing sessions were carried out

3. GPS processing

In 1992, the processing of the campaign DONA1992 was carried out in two steps with the then available program GPPS (Ashtech). The later campaigns DONA1997 and DONA2000 were processed with the Bernese GPS Software at the Geodetic Institute using the strategies developed for the HEIKO network [8].

The accuracies of the campaigns of the years 1997 and 2000 where two consecutive observation sessions were carried out are given using the formula of a standard deviation of the mean of 2 measurements (Table 1):

$$\sigma = \frac{1}{2}\sqrt{\frac{\Sigma d_i d_i}{n}}$$

with d_i = difference in the session results for marker number i, n = number of markers

	DONA1997	DONA2000
horizontal	10.0 mm	7.7 mm
vertical	8.6 mm	5.3 mm

Table 1: standard deviation of the mean of 2 measurements (campaigns)

The scatter of the results of the individual session results provides a measure of the short term repeatability achieved at each epoch. Although there are no reliable accuracy estimates for the campaign DONA1992, we may assume an accuracy level of better than 1 cm for all components in all campaigns from the results of other similar campaigns.

4. Movement pattern derived from GPS in the local area network Donatussprung

In Table 2 we present the annual motion of the GPS sites with respect to the site ERFR of the HEIKO net. It is evident that the representation of point motions requires a number of initial constraints. To extract the maximum information from the measurements in our local area network we adopted a strategy of minimal constraints by fixing the velocities of point ERFR to its velocities estimated from HEIKO and making use of the inherent stability of the orbital frame of the GPS [8]. Assuming linear point motion, straight-line fits have been applied to the coordinate time series in order to derive the mean motion in all three components. The wrms is derived from the scatter of the epoch values around the fitted straight line.

Marker name	latitude(N-S)		longitude (E-W)		height	
	drift rate [mm/Jahr]	wrms [mm]	drift rate [mm/Jahr]	wrms [mm]	drift rate [mm/Jahr]	wrms [mm]
ERFL = 1	+ 1.0 ± 0.5	2.6	+ 0.9 ± 0.3	1.7	-21.9 ± 0.6	3.3
ERFR = 107	+ 0.5 ± 0.4	2.2	- 0.3 ± 0.5	2.2	- 2.4 ± 0.6	3.4
KIER = 53	+ 0.0 ± 0.8	2.7	- 5.9 ± 1.2	3.7	- 7.3 ± 2.0	8.3
KOTT = 78	- 1.9 ± 0.3	1.0	- 4.6 ± 0.3	0.9	- 5.9 ± 2.5	10.2
3	- 0.2 ± 1.0	2.4	+ 0.8 ± 2.7	6.8	- 4,7	
13	- 1.6 ± 1.4	3.5	- 1.3 ± 0.4	1.1	-20.7 ± 3.8	9.9
18	- 1.6 ± 0.6	1.4	- 2.1 ± 0.7	1.7	-17.8 ± 1.7	4.4
21	- 2.0 ± 0.4	1.1	- 3.8 ± 1.0	2.6	-17.7 ± 3.8	10.0
39	- 0.6 ± 0.7	1.8	- 0.9 ± 0.1	0.2	- 2.3 ± 3.9	10.2
79	- 0.4 ± 1.2	3.0	- 0.9 ± 0.2	0.4	- 2.2 ± 1.9	4.9
134	+ 0.2 ± 1.3	3.1	- 0.4 ± 0.3	0.8	- 0.6 ± 0.7	1.8
140	- 3.0 ± 0.6	1.6	- 5.1 ± 1.0	2.5	- 2.4	
158	- 0.1 ± 0.6	1.5	+ 1.1 ± 2.2	5.4	- 4.7 ± 2.2	5.8
357	- 1.6		- 2.1		- 4.7	
548	- 5.0		- 3.6		- 4.1	

Table 2: Rates of motion and wrms for the net Donatussprung

The accuracy of the relatively short data sets is still quite acceptable with uncertanties of the velocities of up to 2,7 mm/year for the horizontal and up to 3.9 mm/year for the vertical components. Agreement in terms of wrms repeatability between all campaign results is at the level of 1 mm to 1 cm both in the horizontal and vertical components.

Looking at the velocity vectors for the horizontal as well as for the vertical component on the map (Fig. 4a and b) the pattern of vertical and horizontal vectors shows a striking dissimilarity in the motion of groups of points on either side of the fault. It becomes apparent that the points with the most prominent motions of several cm/year in the vertical component and several mm/year in the horizontal are located on the Erft block where the brown coal mining areas are situated. There is no doubt that the observed pattern of motion is groundwater induced, a direct consequence of the ongoing groundwater withdrawal in the mining areas.

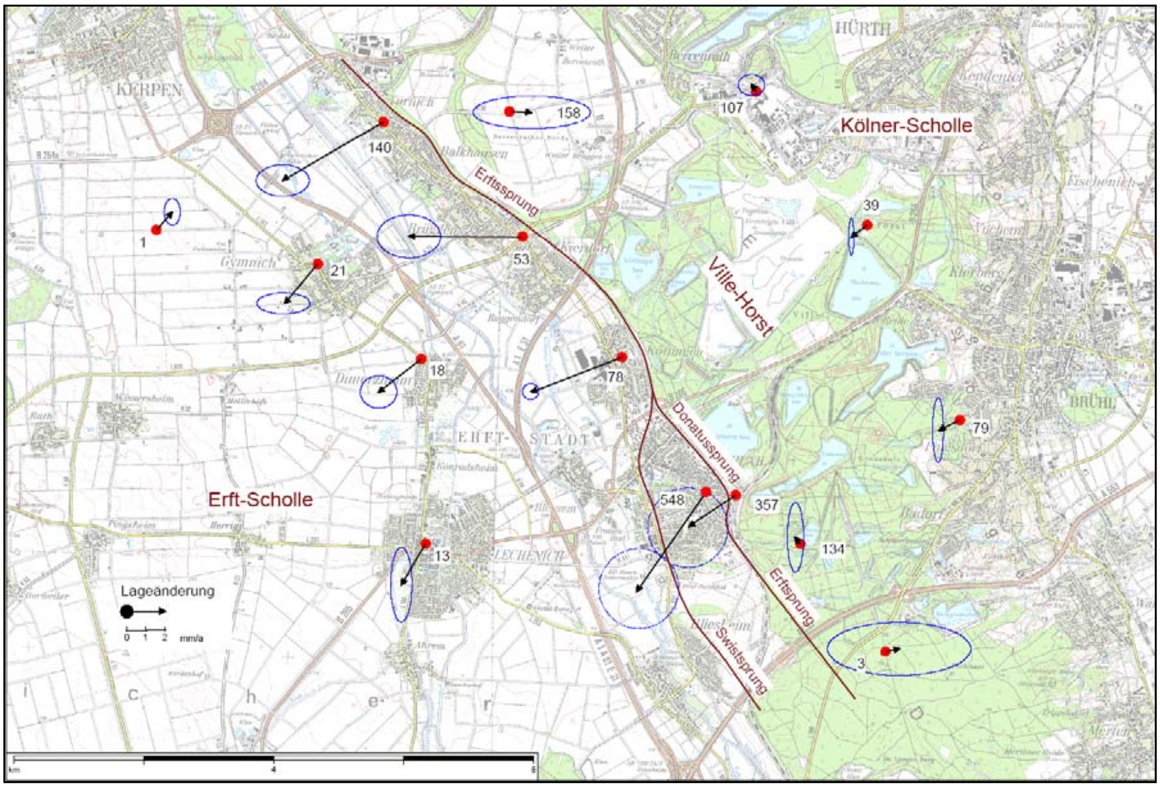

Figure 4a: Horizontal point motions measured in the local area network „Donatssprung". The red line marks the main Erft Fault and the "Donatus Fault".

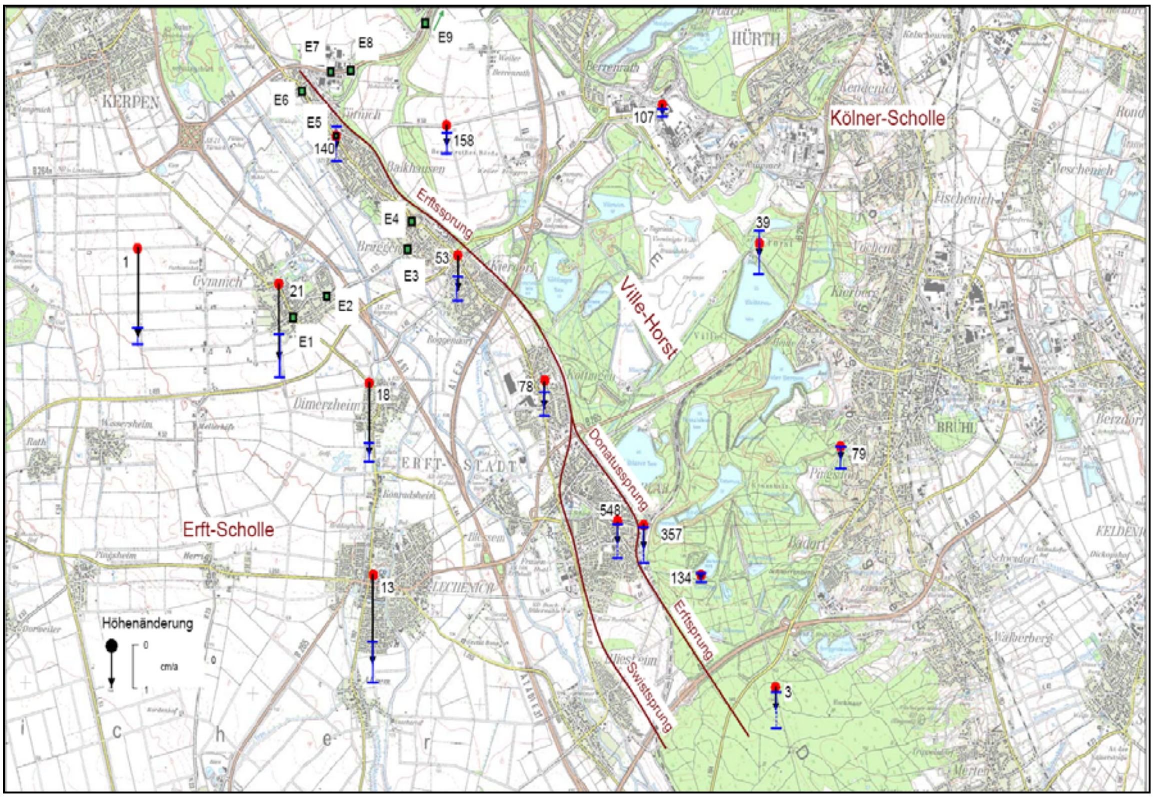

Figure 4b: Vertical point motions measured in the GPS network „Donatussprung „ The green triangles indicate the levelling benchmarks E1 bis E9

The horizontal velocities appear to be largest in the immediate vicinity on the western side of the fault with rates up to 5.9 mm/year for the horizontal components, but relatively small height changes up to maximum values of 7.3 mm/year. The horizontal motions then tend to decrease rapidly with increasing distance from the fault to 4 mm/year for the horizontal component, but the opposite seems to be the case for the vertical velocities which are growing larger with increasing distance. They reach maximum values of subsidence of 21.9 mm/year at a 4 km distance (a more detailed description can be seen in [9]).

The points on the Cologne block show either small motions or remain stable which is in good agreement with the tectonic situation and the groundwater situation.

5. Comparison with the results from terrestrial geodetic surveys

To check whether the movement pattern derived from GPS agrees with the results of the precise geometric surface data, a comparison of horizontal and vertical point movements derived from terrestrial geodetic surveys was carried out.

From the re-levellings carried out in the area by the survey administration at regular intervals a profile of 9 levelling benchmarks crossing the Erft Fault north west of Liblar was selected which has also been used for microgravimetric surveys [11, 3]. The green triangles in Fig. 4b represent the levelling line with numbers denoting the points of the state levelling networks. The levellings give an excellent reference for the estimated GPS heights and provide an impressive confirmation of the GPS results.

For comparison of the horizontal motions derived from GPS we were able to use the results from a precise traverse measured across the Donatus Fault in the upper town section of Liblar. All points of this traverse are resurveyed annually with tachymeters by the mining company RWE Power in order to study local motions in built-up areas near the fault. The horizontal motions derived from this traverse show an increasing tendency starting at a level of 3 mm/year in the first 20 meters west of the surface track of the fault and converging to a level of 4.4 mm/year further on [16] (see Fig. 5). The motions of 4 to 5 mm/year at the three GPS-points 78, 53 and 140 which are all at about 200 to 300 m west from the fault line fit nicely into this picture (for details see [9]).

Finally the integration of all available geodetic data in Fig. 5 at different distances from the Erft Fault enables the drawing of a consistent picture of the ongoing processes. No system transformations were applied, because only temporal changes are considered here. For the heights this is of course only valid if constant reference frames may be assumed, i.e. if gravity changes may be neglected.

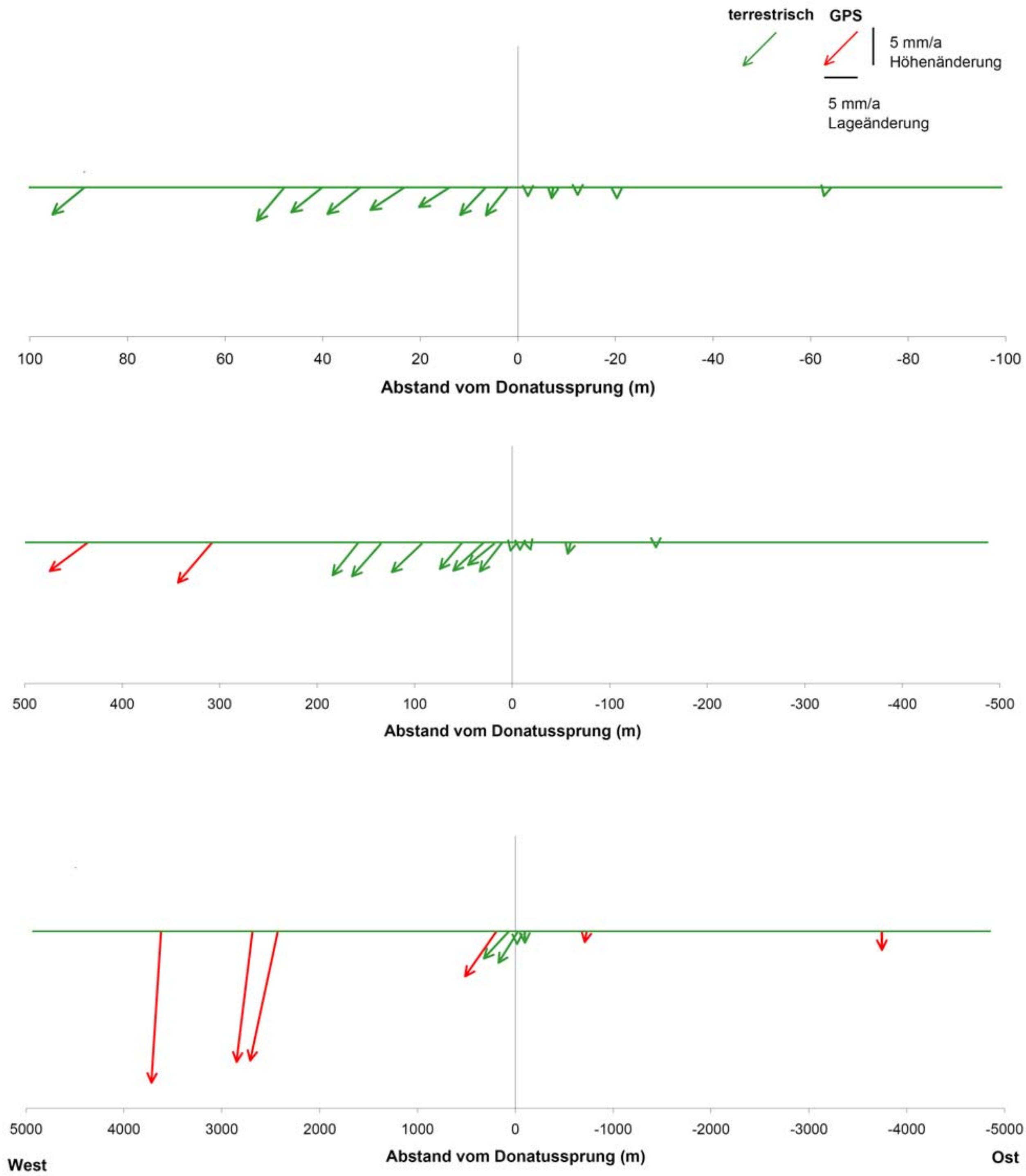

Figure 5: Velocity vectors from GPS and terrestrial geodetic surveys as a function of distance from the fault (in three distance scales)

6. Observed pattern of ground movements and possible interpretations

There remains little doubt that the observed pattern of ground motions is related to the continued groundwater withdrawal in connection with the browncoal mining activities in the wider area of the Rhenish Embayment. The present dropping of the groundwater level in the vicinity of the Donatus network still ranges around 0.5 to 3 m/year [19].

In the neighbourhood of faults with fault plane angles of about 60 to 70 degrees [1, p. 54] we also have to expect significant horizontal motions in addition to the vertical motions which tend to decrease with increasing distance from the fault. A geometric model usually applied describes the process at the fault as a near-surface layer sliding steadily downwards along the dipping fault plane (Fig.6).

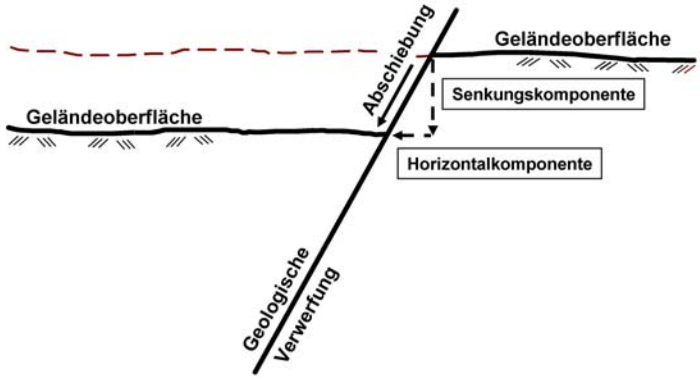

Figure 6: Generalised motion along a dipping fault plane [16].

In this model, the relation between horizontal and vertical velocities of motion is determined by the dipping angle. From fig. 6 it is obvious that there is less observed vertical motion than expected from the model.

A different approach is provided by the model of a depressional trough (Fig. 7), which is formed in a homogeneous section of the surface by the collapse of a mining gallery [e.g. 20, 12]. This model yields a horizontal velocity that starts at zero at the border of the trough, increases to a maximum and decreases again to zero at its center.

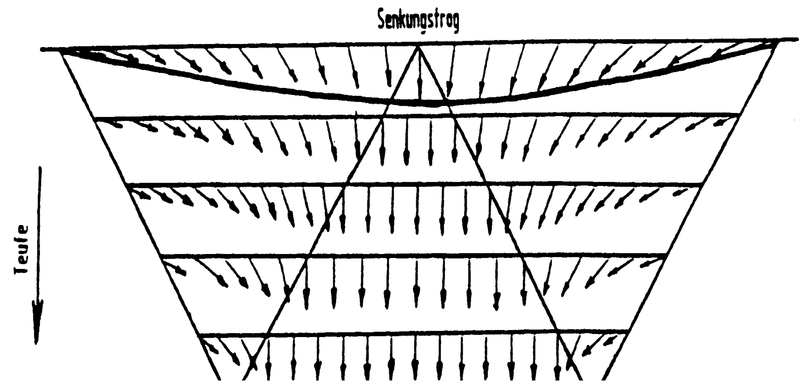

Figure 7: Deformation model of a depressional trough according to the Aachen formulas of Spettmann [19]

If we compare the pattern of observed motions (Fig. 5) with either one of these models before embarking on a detailed analysis, it becomes already clear that a correct description of the observed pattern has to combine the concepts of both models, i.e. a depressional trough supplemented with the effects of a dipping fault plane. So further studies with more data and improved models are needed. However, this is beyond the scope of this study.

7. Conclusions

After several carefully planned and executed GPS campaigns as well as precise terrestrial surveys (levelling and tachymetry) a significant pattern of vertical and horizontal motions of 3 to 20 mm/year in an area affected by browncoal mining has been determined. The results show a clear separation of the motion patterns on both sides of the Donatus (Erft)-Fault: the absence of motion or small irregular displacements on the stable Ville-Horst and a regime of highly significant motions on the Erft Block, in agreement with the ongoing depletion of the groundwater tables on the Erft Block side of the fault. Further observational efforts will be carried out in order to refine the picture of observed motions, while suitable models are to be developed to achieve a satisfactory description of the observed kinematic scenario.

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