Netherlands Journal of Geosciences / Geologie en Mijnbouw 81 (2): 223-230 (2002)

Recent movement pattern of the Lower Rhine Embayment from tilt, gravity and GPS data

J. Campbell[1,5], H.-J. Kümpel[2,3], M. Fabian[2], D. Fischer[1], B. Görres[1], Ch.J. Keysers[1,2] & K. Lehmann[2,4]

[1] Geodätisches Institut der Universität Bonn, Nussallee 17, 53115 Bonn, Germany
[2] Geologisches Institut der Universität Bonn
[3] now at: Leibniz Institute for Applied Geosciences, Hannover
[4] now at: Geological Survey of Nordrhein-Westfalen, Krefeld
[5] corresponding author; e-mail: campbell@sn-geod-1.uni-bonn.de

Manuscript received: August 2000; accepted: January 2002

Abstract

As part of the activities of the Collaborative Research Centre 'SFB 350', measurements of geodetic and geodynamic changes in the area of the Lower Rhine Embayment and the Rhenish Shield are being performed at different scales in space and time. Continuous borehole tilt measurements and repeated microgravimetric surveys yield information on the local stability of the ground and changes in horizontal gravity gradients that are both dominated by seasonal fluctuations. Results of more than seven years of regular GPS campaigns are discussed in terms of vertical and horizontal point motions. The most prominent motions are man-induced effects occurring in or near the browncoal mining areas, where groundwater withdrawal produces subsidence of up to 2.2 cm/y in the area under investigation. Horizontal and vertical motions at other GPS points are smaller by one order of magnitude and in most cases are only marginally detectable. The eastward motion of two points in the Bergisches Land and the westward motion of two points in the Eifel near the Belgian border may be interpreted as a result of the ongoing extension of the Cenozoic rift system in the western part of the Eurasian plate.

Keywords: tilt measurements, gravity survey, GPS, height variations, subsidence, Lower Rhine Embayment

Introduction

Under the general theme of the Collaborative Research Centre 'SFB 350', i.e. the study and modelling of interactions between continental geosystems, one project is concerned with the tectonic and sedimentary evolution of the Lower Rhine Embayment and the Rhenish Massif. In support of the modelling efforts that are concentrated on the crustal dynamics of the rift system in the Lower Rhine Embayment in situ geodetic and geophysical measurements form a substantial part of the project.

The geodetic and geophysical data are collected over several scales in space and time that are accessible with modern observational systems. The data include continuous recordings of borehole tilt measurements at sites suited for studies of local ground movements, profiles of gravity changes by repeated precise gravity measurements and precise geometric surface data (horizontal and vertical geodetic control by precise levelling and GPS) at selected sites on the different crustal blocks and the surrounding Rhenish Massif (Fig. 1).

The tilt and microgravimetric measurements have been carried out in selected areas to provide insight into the processes at shallow depths that may have an effect on the stability of points at the surface. Tilt measurements are focussed at the immediate vicinity of a point in terms of soil inclination due to the movement of underground fluids. Gravity changes give indications on mass movements, but also contain a component of vertical change.

As for the GPS surveys, the vertical and horizontal motions due to ongoing tectonic forcing are estimat-

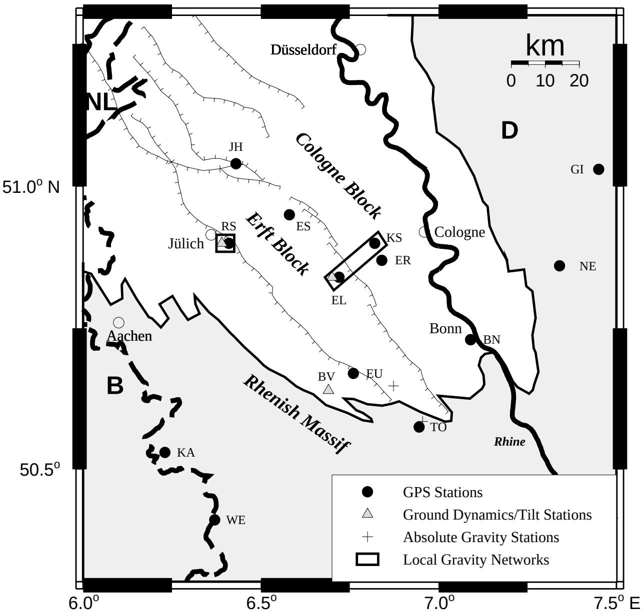

Fig. 1. Locations of measuring systems in the area of the Lower Rhine Embayment.

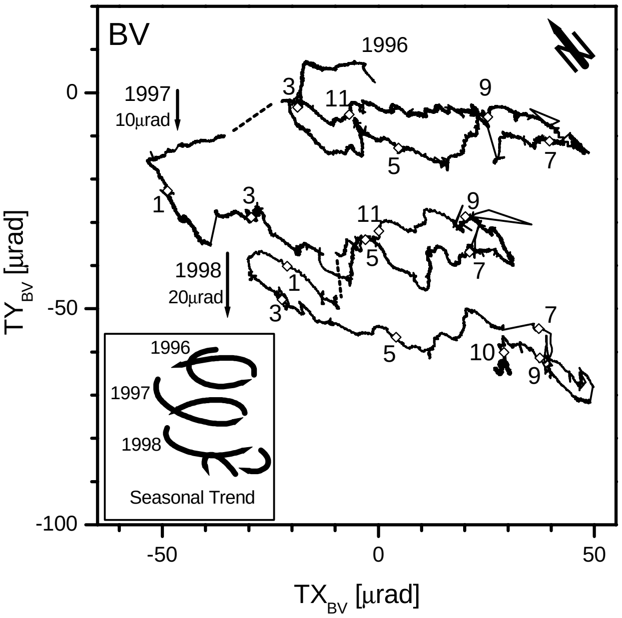

Fig. 2. Trace plot of tiltmeter records obtained at the site Bürvenich (BV), west of Euskirchen from Feb. 1996 till the end of 1998. For clarity, signals of individual years have been offset by fixed amounts as indicated. Numbers along traces denote tilt positions at the end of each respective month.

ed to be much smaller than the effects due to the open pit mining activities and will – if at all – only be detected on the solid margins of the Rhenish sedimentary basin and on the Rhenish Massif itself.

Continuous tilt measurements and repeated microgravimetric surveys

Quasi-continuous recordings with biaxial borehole tiltmeters of resolution 0.1 ìrad (0.02 arcsec) are carried out at three selected sites, i.e. west of Euskirchen (BV=Bürvenich), south of Kerpen (WS=Wissersheim) and at the site of the Research Centre Jülich (RS); see Fig. l. The purpose of these measurements is to assess the magnitude of typical ground movements on the local scale, for periods ranging from hours to years (Lehmann et al., 1998; Kümpel et al., 2001). Ground movements due to transient pore pressure gradients are of particular interest because they can reach considerable amplitudes and are often unavoidable (Kümpel et al., 1988). Therefore, the sites have been chosen to represent different types of hydrological regimes. Installation depths of the tiltmeters range from 3 m to 5 m; the length of the instruments is 0.85 m. Fluctuations in depth of the groundwater level, soil temperature, air pressure variations, and precipitation are monitored together with the tilts. Correlation analysis of these signals allows the identification of influential hydrological and meteorological quantities.

Fig. 2 shows tilt signals observed during February 1996 till end of 1998, taken at site BV. Significant types of ground movements that can be identified are due to seasonal effects (most likely thermoelastic; order of 100 ìrad), transient pore pressure gradients in shallow aquifers after rainfalls (up to 15 ìrad), occasional diurnal effects (thermoelastic and/or poroelastic deformation resulting from surface heating and/or water consumption of nearby trees; 2 ìrad), and due to the passage of seismic waves from distant earthquakes (10 ìrad). Under the assumption that similar tilt amplitudes would also be observed by tiltmeters of base lengths up to 10 m, maximum ground deformations on this very local scale should not exceed l mm.

Microgravimetric measurements with a resolution of about 5 ìGal are still a challenge, mainly due to the individual drift behaviour of spring-type gravimeters. A LaCoste-Romberg gravimeter, acquired by the University of Bonn in 1992, has been extensively tested and, after several years of ageing, now displays a high internal stability. To check whether height changes at selected parts of the Lower Rhine Embayment coincide with variations in gravity, two clusters of stations were selected for microgravimetric surveys at weekly to monthly intervals (Keysers & Kümpel, 2000; Keysers, 2001). One cluster is inside the area of the Research Centre Jülich (Fig. l), the second one follows a profile of levelling benchmarks crossing the Erft Fault (Fig. 3). The accuracy of readings taken within a time interval of 12 hrs proved to be better than 5 ìGal.

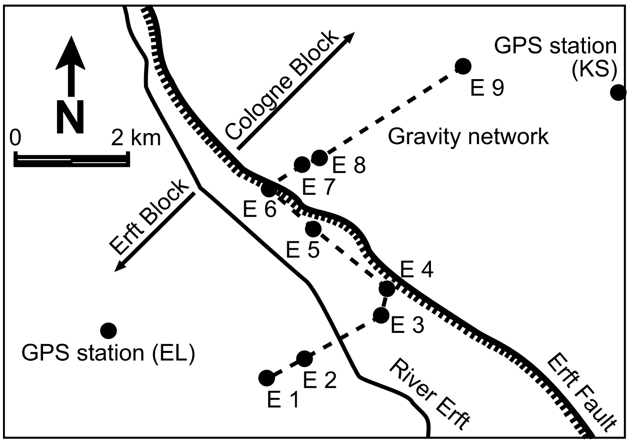

Fig. 3. Gravity network across the Erft Fault. The dashed line represents the levelling line with numbers denoting the points of the state levelling network; A1 and A61 are motorways crossing the area (thick lines); the river Erft (medium line) follows the trace of the main Erft fault (thin line).

Gravity variations in the cluster of the Research Centre Jülich (see Fig. l) were less than 10 ìGal during the period of April 1998 to March 2000. Some results of the investigations across the Erft Fault are presented in Fig. 4. These are gravity differences between (a) two benchmarks on the south-western side of the fault, (b) two benchmarks on the north-eastern side of the fault, and (c) two benchmarks on opposite sides of the fault. While the variations of gravity differences on either side of the Erft fault are small (±10 ìGal), those across the fault reach amplitudes of up to 50 ìGal. Moreover, the latter differences reveal significant temporal changes, apparently exhibiting a seasonal character. A possible explanation is that the shallow underground consists of dissimilar types of soil with a different moisture balance and/or different groundwater regimes, producing a gravity effect that correlates with the course of hydrologic seasons (Bonatz, 1967).

Results from the repeated GPS campaigns disclose rather large differences in vertical displacements across this part of the fault (see below). Yet, it is not clear whether these differences can be linked to the gradients in the gravity readings. Ongoing measurements are expected to improve the understanding of the underlying physical processes in this area.

Geodetic GPS-campaigns

Before the advent of the Global Positioning System (GPS), spirit levelling was the most commonly used method to establish precise vertical control with millimetre accuracy over distances of hundreds of kilometres (Müller, 1990; Christie, 1994). Faced with mining-induced height changes at many of the official benchmarks in the Lower Rhine Embayment, the survey institutions in cooperation with the mining com-

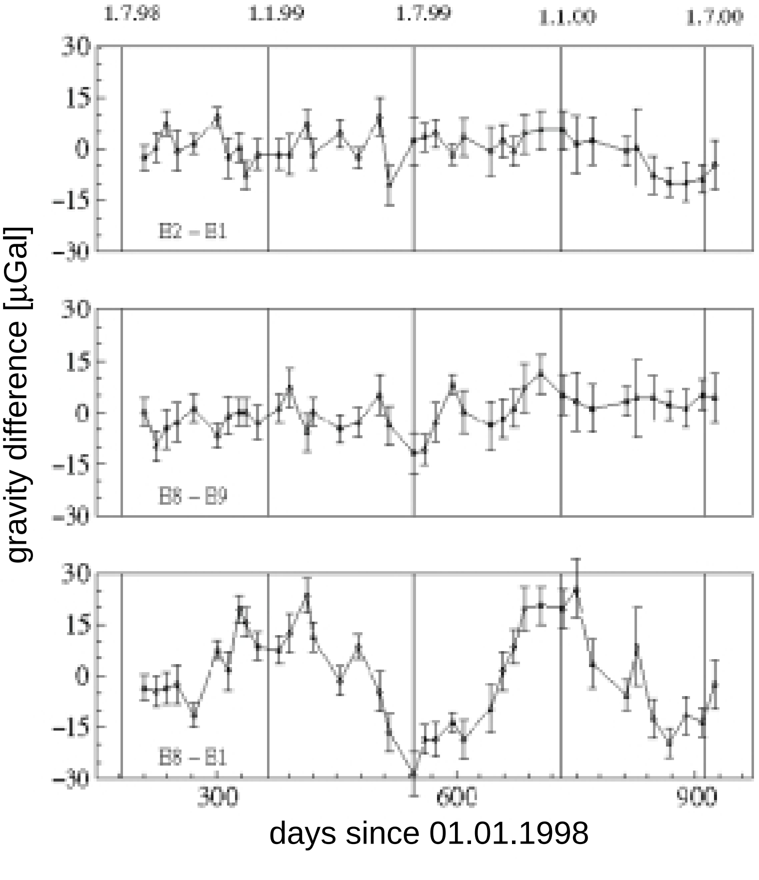

Fig. 4. Time series of differences in gravity between selected stations of the Erft Fault network (cf. Fig. 3 for station numbers); scaling is the same in all three plots.

panies were obliged to perform levellings in the entire area at regular intervals, every four years and in certain parts even every two years, to record and map the vertical changes, and to prevent the network of height control from failing in its basic function (Fröhlich & Müller, 1986). 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.

With the Global Positioning System fully deployed in the early nineties, a new possibility of faster and more cost-effective vertical control has become available (Christie, 1994; Lorenz et al., 1995). In a testing phase in 1991-1992 we have been able to demonstrate that a relative vertical positioning accuracy (in terms of repeatability) of several millimetres over a distance of 20 km is feasible if certain stringent requirements are fulfilled (see Tables 1 and 2; Görres, 1996a, b; Görres & Campbell, 1998). The most important elements of strategy are observing sessions of 24 h duration with simultaneous observations at all sites, low elevation cut-off at the sites (free horizon) and the use of precise IGS (International GPS Service) satellite orbits (Beutler et al., 1994) in the data processing.

Table 1. Strategies for GPS field measurements.

site selection	surroundings free of reflections visibility down to 10 E elevation
equipment	uniform antenna types
observations	24h duration of session total of at least 3 sessions per epoch all sites observed simultaneously
meteorological data	no field data required

Table 2. Strategies for GPS data processing.

orbits	precise IGS orbits
antenna phase centres	calibration required for all antennas
ionospheric refraction	ionosphere free linear combination
tropospheric refraction	estimation of tropospheric parameters every 6 hours
phase ambiguities	estimated and fixed to integer values
elevation cut-off	10 E

In setting up 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. Among the total of 13 sites 7 are located on buildings to permit 24h unattended operation. A collaboration with several different institutions has been arranged in order to obtain logistic support and a sufficient number of receivers for simultaneous observations on all 13 sites. In view of these constraints no more than one campaign per year has proved to be feasible.

In order to be able to assess the accuracy of the result of each epoch, three consecutive 24 h observing sessions were carried out each year and three-day averages were taken as the final result. The scatter of the results of the individual days provides a measure of the short term repeatability achieved at each epoch.

The GPS data processing was carried out with the Bernese Software Versions 4.0 and 4.2 using all of the observations (Ät=30 sec) in the ionosphere free phase combination (L3) mode (Rothacher & Mervart, 1996).

Results from GPS measurements

The representation of point motions in geodetic networks requires the adoption of a number of initial conditions in order to stabilise the underlying coordinate system. To extract the maximum information from the measurements in our regional network, we adopted a strategy of minimal constraints by fixing only one point and making use of the inherent stability of the IGS network. The IGS network consists of a large number of globally distributed and permanently observing GPS stations and provides satellite orbits in the global frame and forms a contributing part of the International Terrestrial Reference Frame (ITRF). Using IGS orbits and polar motion series in the analysis ensures that all observations are tied in fact to this frame. Therefore, rotations about a fixed point cannot exceed the residual rotations of the global network, i.e. less than 0.3 mas (1 mas = 10^{-6} seconds of arc) at both short and long time scales. At a distance of 100 km this translates into a residual point displacement (either horizontal or vertical) of less than 0.15 mm. Accordingly, the orientational accuracy of the regional network is, above all, determined by the strength of the geometrical configuration of the network.

In Figures 5a and b we present the annual motion of the GPS-sites with respect to the site of Todenfeld, which is located on the Rhenish Massif in the southern part of the network. 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. In this analysis, the results of 8 campaigns in the period from 1993 to 2000 have been used. Note that the motion vectors shown here represent relative motions with respect to one station fixed (translational constraint) and the IGS global frame (scale and orientational constraint). The accuracy of the velocities is derived from the scatter of the epoch values around the fitted straight line and ranges from ±0.5 to ±2 mm/year in the vertical and ±0.4 to±1.0 mm/year in the horizontal components.

From Fig. 5a it is obvious that the most prominent vertical motions are confined to the lignite mining areas, where groundwater withdrawal is still going on. Maximum values of subsidence of 2.2 cm/y are found on the Erft Block in the areas of Gymnich (ERFL), Jülich (JUEL), and Paffendorf (PAFF). Apart from these man-induced effects, the velocities are smaller by one order of magnitude and are barely detectable. The uplift of about 1 mm/y at two points in the southwest near the Belgian border (Kalterherberg, KALT; Weißer Stein, WEIS) appears to be consistent with the uplift of the Rhenish shield as seen in several levelling results (Quitzow & Vahlensiek, 1955; Müller, 1990). The other points outside the mining areas are either showing small downward motion (Euskirchen, EUSK; Gimborn, GIMB) or remain stable (Jackerath, JACK; Frechen, BERG and ERFR; Bonn, BNT7; Neunkirchen, NEUN), which agrees well with the tectonic situation in the area.

In general, horizontal motions are believed to be less affected by man-induced groundwater level variations. Still, we expect a significant influence in the vicinity of faults, because most of the faults dip at angles of around 70° or even less (Ahorner, 1975; Van den Berg et al., 1994). Therefore we interpret the relatively large horizontal motions of points on the Erft Block (at stations ERFL, PAFF, and JUEL) to be associated with ongoing movements along faults. In contrast to these man-induced motions, the eastward motion at stations GIMB and NEUN, and the small westward motion of KALT and WEIS can be interpreted as an extensional motion throughout the Lower Rhine Embayment.

In addition to the regional network covering the entire study area, a smaller network has been established to monitor motions in the immediate vicinity of the surface trace of the Erft Fault. A section of this fault near Gymnich (Donatus-Sprung) can easily be identified from topography and effects on buildings and roads. The area has therefore been the object of several surveying campaigns both by terrestrial and GPS techniques (Sager, 1995). The network consists of 15 survey markers belonging to the 3rd and 4th order triangulation network with distances between points of 0.5 to 2 km. In November 1992 a first GPS campaign was carried out by the State Survey of Nordrhein-Westphalen with 4 receivers in seven sessions of 1.5 hours average duration. The observing plan made sure that each point was occupied twice during the campaign. The second and third GPS-campaigns in November 1997 and March 2000 were carried out jointly by the State Survey and the Geodetic Institute of the University of Bonn. In these campaigns 8 receivers were available and the observing time was extended to 4 hours for each session. The accuracy achieved with the relatively short data sets was still quite acceptable with uncertainties of the velocities ranging from ±1.5 to ±3.5 mm/y both in the horizontal and vertical components.

In Fig. 6a and b. the vector motion results from the three epochs of GPS measurements are presented. First of all, there can be no doubt that the observed pattern of motion is a direct consequence of the ongoing groundwater withdrawal in the mining areas. The pattern of vertical and horizontal vectors shows a striking dissimilarity in the motion of groups of points on either side of the fault. The horizontal velocities are largest on the western side of the fault, but tend to decrease rapidly with increasing distance from the fault. Vertical velocities become larger with increasing distance from the fault. The scenario suggested by these measurements indicates a reluctance of the Erft Block border to follow the overall subsidence that is observed at some distance away from the fault. Instead, the part of the Erft Block bordering the fault is moving away from its counterpart, the Köln Block (Ville), with the consequence that the fault is widening at or near the surface.

Conclusions

Geodynamical and geodetic monitoring within the Lower Rhine Embayment is being performed at different scales in space and time. Continuous tilt measurements at shallow depth reveal that local ground dynamics due to seasonal meteorological/hydrological effects produce the largest signals. Yet, ground deformation associated with these signals is unlikely to exceed 1 mm. Repeated gravity surveys exhibit a 50 ìGal anomaly in a local network across the Erft fault, exhibiting a seasonal character. The GPS measurements, after seven years of regular campaigns, are producing significant results at the mm/y level, both in terms of vertical and horizontal site motions. The most prominent movements are related to man-induced subsidence and amount to a level of 2 cm/y. In addition, small tectonic motions were detected that are in good agreement with the long-term geological and geotectonic models of the area.

If the indications of the extension of the Lower Rhine Embayment in Southwest to Northeast direction are confirmed by the GPS campaigns in the coming years, this work will provide a strong argument in

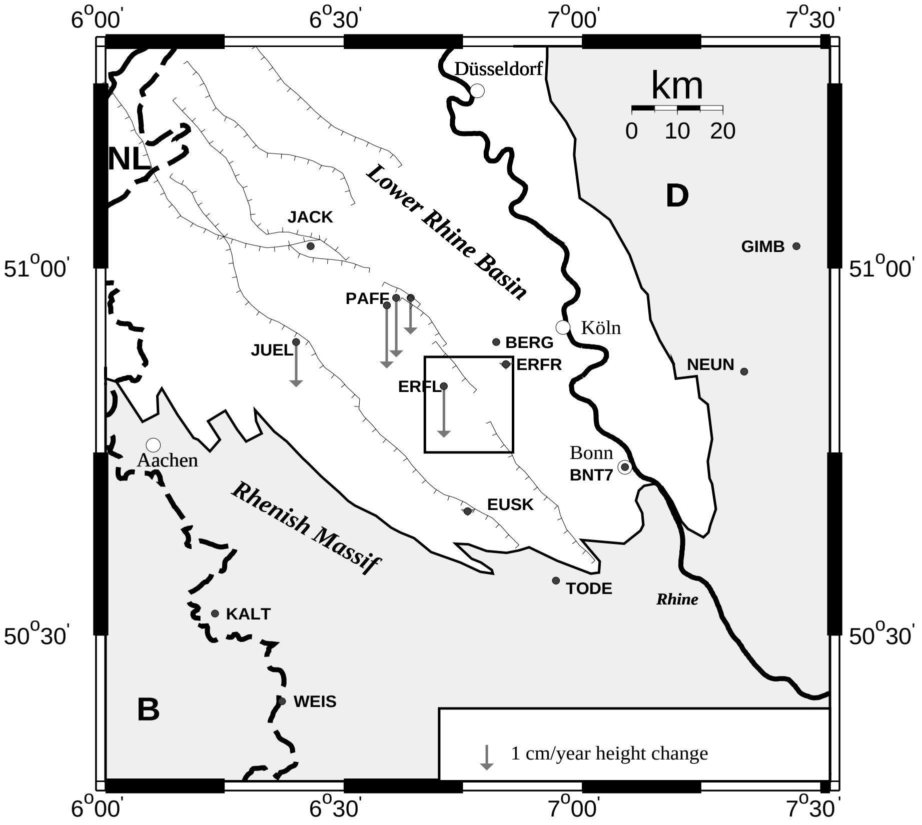

Fig. 5a. Vertical point motions in the GPS network HEIKO.

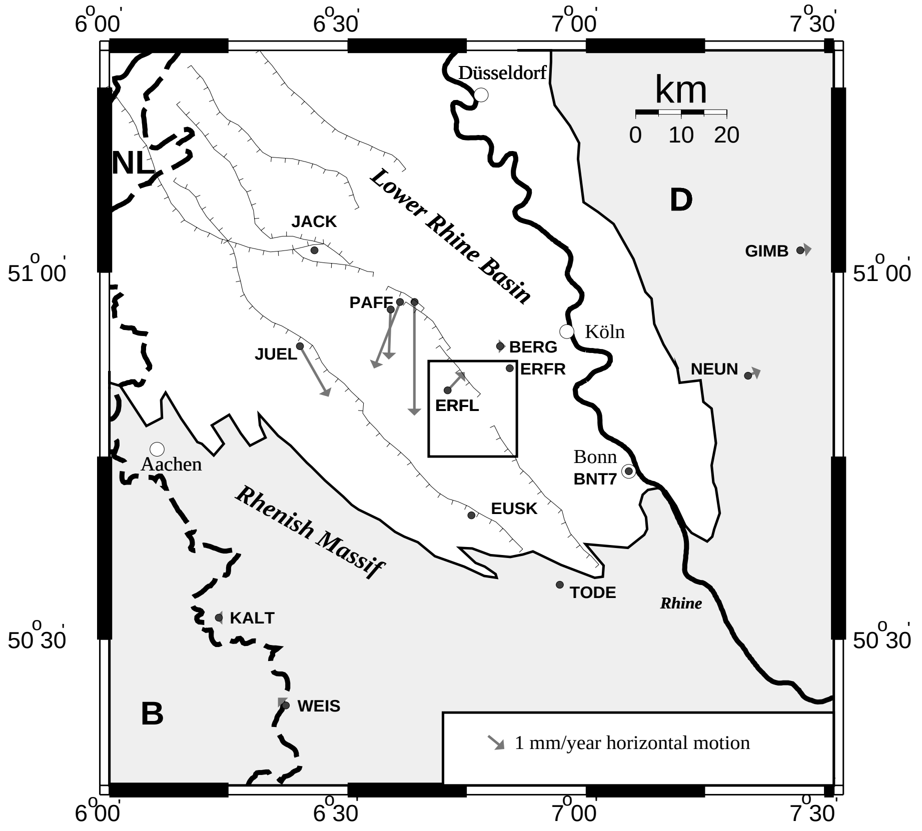

Fig. 5b. Horizontal point motions in the GPS network HEIKO.

the discussion of several of the tectonic scenarios in the West European weakness zone (see e.g. Ahorner, 1975; Illies, 1975; Chenevart & Riesen, 1985; Klostermann et al., 1998; Schreiber & Rotsch, 1998).

In view of the importance of the overall geotectonic situation of Northwest Europe for the interpretation

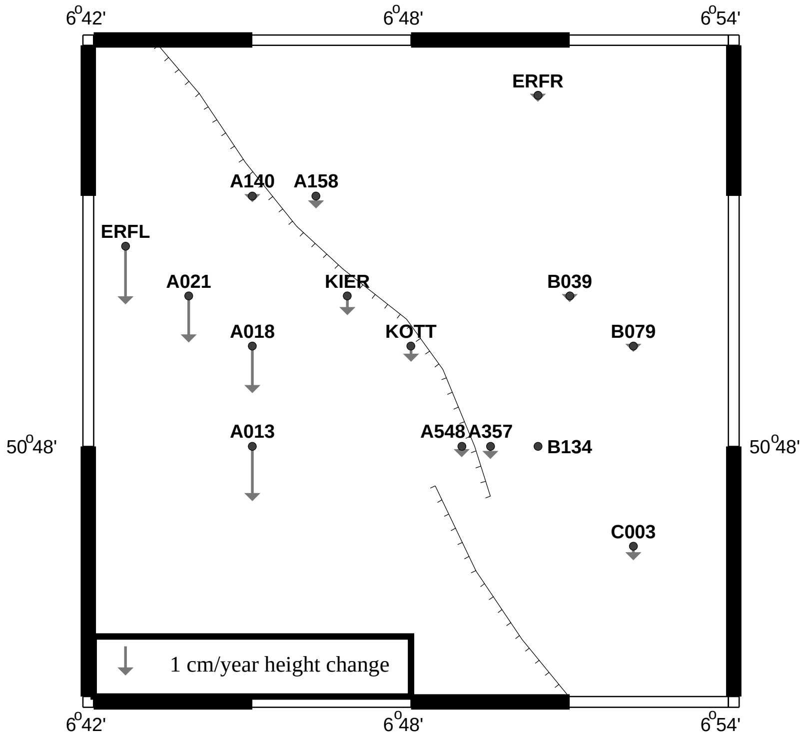

Fig. 6a. Vertical velocity vectors measured in the local area network 'Donatussprung'.

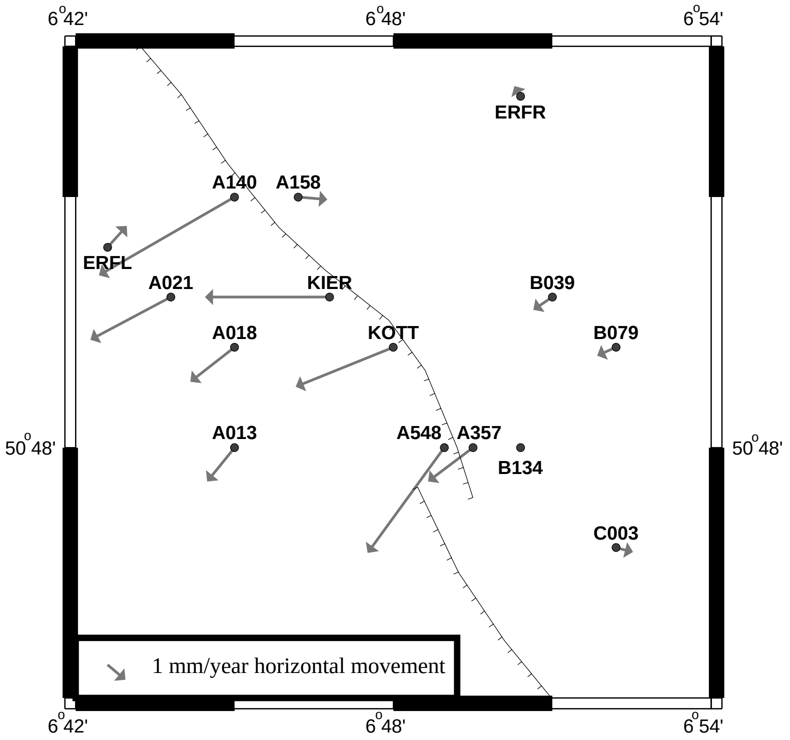

Fig. 6b. Horizontal velocity vectors measured in the local area network 'Donatussprung'.

of the crustal dynamic regime in the Rhine Embayment, it will be of strong interest to include the European VLBI measurements (Haas et al., 2000; Campbell & Nothnagel, 1996, 2000) as well as the GPS permanent observations in the European Reference Frame (Gubler & Hornik, 1999). The integration of all available geodetic data at different levels will enable the creation of a consistent picture of the ongoing geotectonical processes that influence the active regional tectonics of the Rhine Embayment.

References

Ahorner, L., 1975. Present-day Stress field and seismotectonic block movements along major fault zones in central Europe. Tectonophysics 29: 233-249.

Beutler, G., Brockmann, E., Gurtner, W., Hugentobler, U., Mervart, L., Rothacher, M. & Verdun, A., 1994. Extended orbit modelling techniques at the CODE processing centre of the International GPS Service for Geodynamics (IGS): theory and initial results. Manuscripta Geodaetica 19: 367-386.

Bonatz, M., 1967. Der Gravitationseinfluß der Bodenfeuchtigkeit. Zeitschrift für Vermessungswesen 92: 135-137.

Campbell, J. & Nothnagel, A., 1996. Bestimmung rezenter Krustenbewegungen im Europäischen VLBI-Netz. Zeitschrift für Vermessungswesen 121: 255-263.

Campbell, J. & Nothnagel, A., 2000. Results of the VLBI Analyses of the first observation period in the European Crustal Motion Network. Journal of Geodynamics 30: 321-326.

Chenevart, C.J. & Riesen, A., 1985. Possible Significance of Eurafrican wrench-fault zones: differential drift and driving mechanism. Bulletin of the Swiss Association of Petroleum Geologists and Engineers 51/121: 23-58.

Christie, R.R., 1994. A New Geodetic Heighting Strategy for Great Britain. Survey Review 32: 328-343.

Fröhlich, H. & Müller, G., 1986. Leitnivellements und regionale Deformationsanalyse in Nordrhein-Westfalen. Vermessungswesen und Raumordnung 48: 1-19.

Görres, B., 1996a. Bestimmung von Höhenänderungen in regionalen Netzen mit dem Global Positioning System. Deutsche Geodätische Kommission, Reihe C, Nr. 461 (Frankfurt).

Görres, B., 1996b. Determination of Height Changes in Regional GPS Networks. Proceedings 11th Working Meeting on European VLBI for Geodesy and Astrometry, held at Göteborg, Sweden, Aug 22-23, 1996: 143-152.

Görres, B. & Campbell, J., 1998. Bestimmung vertikaler Punktbewegungen mit GPS. Zeitschrift für Vermessungswesen 123: 222-230.

Görres, B., Campbell, J. & Kotthoff, H., 1999. Vertical Ground Movements in the Lower Rhenish Embayment. Abstract in IUGG 99, Vol. A, 59, Birmingham.

Gubler, E. & Hornik, H. (eds), 1999. IAG/EUREF Publication No. 7/I and No. 7/II, Reports on the EUREF-Symposium Bad Neuenahr, June 10-13, 1998 and on the results of the European Vertical Reference Network GPS Campaign 97 (EUVN97), Mitt. Bundesamt f. Kartographie und Geodäsie (Frankfurt/Main).

Haas, R., Gueguen, E., Scherneck, H.-G., Nothnagel, A. & Campbell, J., 2000. Crustal Motion. Results derived from observations in the European Geodetic Network. Earth Planets Space 52, 759-764.

Illies, H., 1975. Intraplate tectonics in stable Europe as related to plate tectonics in the Alpine system. Geologische Rundschau 64: 677-699.

Keysers, Ch., 2001. Erfassung von Schwereänderungen in zwei lokalen Netzen in der Niederrheinischen Bucht von 1998 bis 2000. Dissertation Universität Bonn. Shaker-Verlag Aachen: 157+XVI pp.

Keysers, Ch.J. & Kümpel, H.-J., 1999. Two local precise gravity networks in the Lower Rhine Embayment, Germany. *submitted to:* Cahiers du Centre Européen de Géodynamique et de Seismologie, Proc. Workshop on High Precision Gravity Measurements and 2nd GGP-Workshop, Munsbach castle, Luxembourg, March 24-26, 1999.

Klostermann, J., Kremers, J. & Röder, R., 1998. Rezente tektonische Bewegungen in der Niederrheinischen Bucht. Fortschritte in der Geologie von Rheinland und Westfalen 37: 557-571.

Kümpel, H.J., Peters, J.A. & Bower, D.R., 1988. Nontidal tilt and water table variations in a seismically active region in Québec, Canada. Tectonophysics 152, 3/4: 253-265.

Kümpel, H.J., Lehmann, K., Fabian, M. & Mentes, Gy., 2001. Point stability at shallow depths – experience from tilt measurements in the Lower Rhine Embayment, Germany, and implications for high resolution GPS and gravity recordings. Geophysical Journal International 146: 630-644.

Lehmann, K., Mentes, Gy., Kümpel, H.-J. & Varga, P., 1998. Approaching local ground dynamics by measurements of ground tilt. *In:* Kahmen, H., Brückl, E. & Wunderlich, Th. (eds): Geodesy for Geotechnical and Structural Engineering. Inst. f. Landesvermessung u. Ingenieurgeodäsie, TU Wien: 99-104.

Lorenz, G.K., van Beusekom, W., Groenewoud, W. & Hofman, M., 1995. Geodetic determination of land subsidence in the Netherlands. *In:* Barends, Brouwer, Schröder (eds), Land Subsidence. Bakema (Rotterdam).

Müller, G., 1990. Wiederholungsmessungen im nordrhein-westfälischen Anteil des DHHN 1980-1985 und im Netz 2. Ordnung – Erfahrungen, erste Ergebnisse, Ausblick. Vermessungstechnische Rundschau, 52: 120-130.

Quitzow, H.W. & Vahlensiek, O., 1955. Über pleistozäne Gebirgsbildung und rezente Krustenbewegungen in der Niederrheinischen Bucht. Geologische Rundschau 43: 56-67.

Rothacher, M. & Mervart, L., 1996. Bernese GPS Software V4.0, Astronomical Institute University of Berne/Switzerland.

Sager, B., 1995. Erste Deformationsanalyse des Lagenetzes Donatussprung in der Kölner Bucht. Vermessungswesen und Raumordnung 57: 311-319.

Schreiber, U. & Rotsch, S., 1998. Cenozoic block rotation according to a conjugate shear system in central Europe – indications from palaeomagnetic measurements. Tectonophysics 299: 111-142.

Van den Berg, M.W., Groenewoud, W., Lorenz, G.K., Lubbers, P.J., Brus, D.J. & Kroonenberg, S.B., 1994. Patterns and velocities of recent crustal movements in the Dutch part of the Roer Valley rift system. Geologie en Mijnbouw 73: 157-168.