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Post-mining flooding-induced ground displacements, microseismicity, and gas anomalies: a synthesis of research on the abandoned Ruhr, Saar, and Ibbenbüren hard coal districts in Germany

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Abstract

Raw material depletion, uneconomic production, and government policies will result in the abandonment of hundreds to thousands of underground mines worldwide within the next years. Hence, mine drainage becomes operationally and economically dispensable. Consequently, the mine flooding is initiated by the mine operator. This increases the subsurface pore fluid pressure potentially inducing seismicity and ground displacements. Here, we present a synthesis on published and unpublished research on three abandoned hard coal mining districts in Germany (Ruhr, Saar, Ibbenbüren), which are currently undergoing flooding. The interdisciplinary approach (3D fault modelling and stress analysis, seismological, ground displacement, and outgassing monitoring) suggests that flooding correlates with the temporal occurrence of post-mining microseismicity (mainly $M_L < 2$) and ground displacements (centimeters-decimeters). Flooding-induced microseismicity in the Ruhr area is focused in pillar areas below the mine panels and is not correlated with the activation of large-scale fault systems. Anomalous outgassing into soil is a temporally variable process in the Ruhr area. Ground displacements from InSAR measurements show complex spatio-temporal patterns that correspond to developing mine water levels in different parts of the mines. The ground displacements analyzed vary during different phases of mine life cycle: 1. Strong subsidence during production; 2. Residual subsidence after end of production; 3. acceleration of subsidence with beginning rebound of mine water; 4. Reverse to uplift after the mine water reaches a certain impoundment depth; 5. Waning uplift after the final mine water level has been reached.

Article highlights

- Post-mining microseismicity is focused in pillar areas below the mine panels

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- Gas-monitoring with commercial and newly developed sensors shows temporally variable and anomalous outgassing into soil (Ruhr).
- InSAR data give a detailed picture of the codevelopment of mine water and surface displacements at Heinrich-Robert (Ruhr) and at Ibbenbüren (Ostfeld).

Keywords Post-mining · Mine flooding-induced seismicity · InSAR ground displacement monitoring · Soil gas geochemistry · 3D fault model · Fault geomechanics

1 Introduction

The discovery, exploration, and production of raw materials constitute the first and intermediate stages of the mine life cycle (e.g. Peters 1969). The efficient conversion of raw materials into forms of energy that can be used by humankind is the basis of prosperity and wealth (McKelvey 1959). Subsequent raw material depletion, uneconomic production, and/or government policies to mitigate climate change and to promote the energy transition, however, will result in the abandonment of hundreds to thousands of mines worldwide within the next years (Measham et al. 2024 and references therein). These mines consequently transition into the post-mining phase that constitutes the last stage of the mine life cycle (Peters 1969; Laurence 2006; Measham et al. 2024; Everingham et al. 2022; Gardiner et al. 2023; Quandt et al. 2023).

Currently, numerous European underground hard coal mines have already entered the post-mining phase (e.g. Quandt et al. 2023 and references therein). As a result, mine water pumping as performed during active mining becomes dispensable from operational and economic points of view. Consequently, mine operators adjust pumping capacities and initiate the mine water rebound. This increases the subsurface pore fluid pressure. In general, increases in pore fluid pressure may change the local effective stresses and induce (micro-)seismicity and ground displacements (e.g. Foulger et al. 2018; Keranen and Weingarten et al. 2018). Besides these environmental challenges, abandoned hard coal mines also open new possibilities such as geothermal applications, underground gas storage, and unconventional gas production (e.g. Durucan et al. 2004; Piessens and Duser 2004; Busch et al. 2009; Wirth et al. 2012; Izart et al. 2016; Menéndez et al. 2019; Privalov et al. 2020; Everingham et al. 2022).

In previous case studies, mining-induced seismicity and ground movements during active or post-mining were quantified and discussed (e.g. Bischoff et al. 2010; Fritschen 2010; Alber and Fritschen 2011; Rosner 2011; Samsonov et al. 2013; Schütz and Konietzky 2016; Declercq et al. 2023; Rische et al. 2023; Quandt et al. 2026). Some of these publications stem from FloodRisk, an interdisciplinary project with partners from KIT, Ruhr University Bochum, EIFER, DMT and Geologischer Dienst Nordrhein-Westfalen. FloodRisk jointly aimed at explaining how flooding-induced microseismicity and ground displacements observed in the Ruhr, Saar, and Ibbenbüren hard coal districts are geomechanically coupled with the geological subsurface (final report: FloodRisk 2023).

Here, we present a synthesis of FloodRisk-related multidisciplinary studies integrating 3D geological, geomechanical, petrophysical, seismological, and geochemical (soil gas) data and supplement them with unpublished geodetic post-mining ground displacement data covering the active and post-mining phase. This interdisciplinary approach allows to establish a cost and time efficient workflow to point out the major controls on induced microseismicity, outgassing into soil, and ground displacements in the study areas. Due to the adaptability of this workflow to other post-mining districts and the availability of high-quality data, the mining districts studied here may become model regions for underground mines facing flooding. In countries like Germany where mine-flooding licensing requires an assessment of induced seismicity (Alber et al. 2020), the conclusions presented here facilitate future mine water management and decision making. Therefore, this study may be of interest for the post-mining research community as well as mine operators and decision makers.

2 Study areas

2.1 Geological setting

The NW German Ruhr and Ibbenbüren as well as the SW German Saar hard coal districts constitute the largest hard coal resources in Germany (Fig. 1). Decades-long industrial mining and research activities recovered hundreds of drill cores, recorded hundreds of kilometers of seismic reflection lines, and produced large data sets, which provide a well understanding of the geological evolution of each area (e.g. Schäfer 1989; Drozdowski 1993; Maynard et al. 1997). In brief, coal formation in central Europe began with the deposition of peat in equator-near sedimentary basins under a warm-humid climate in the Late Carboniferous (Opluštil and Cleal 2007;; Cleal et al. 2009). At this time, central Europe was subject to the culminating stages of the Variscan orogeny due to the convergence of the supercontinents Gondwana and Laurussia including the Armorica and Avalonia microplates (Matte 2001). The load of the resulting Variscan orogen induced lithospheric flexure and foreland basin formation in the presentday locations of the Ruhr and Ibbenbüren hard coal districts in northwestern Germany. In these foreland basins, a few km thick siliciclastic sediment succession indicative of deltaic and fluvial environments was deposited (Opluštil and Cleal 2007). These Late Carboniferous deposits and structures of the W-E striking Variscan foreland basin are traceable in the eastern United States and Central Europe (Opluštil and Cleal 2007; Cleal et al. 2009).

Further basins formed within the Variscan orogen. In these intramontane basins such as the Saar-Nahe basin, subsidence was controlled by regional fault systems (Henk 1993; Korsch and Schäfer 1995; Opluštil and Cleal 2007). Kilometer-deep burial in the foreland and intramontane basins converted the deposits into siliciclastic rocks and hard coal with characteristic fining and coarsening upward sequences indicative of spatially and temporally varying depositional environments (e.g. Littke et al. 1994, 2000; Bruns et al. 2013; Greve et al. 2023, 2024a, b; Quandt et al. 2022a, 2024a, b, 2026).

Several episodes of tectonic activity resulted in the uplift and exposure of parts of the Upper Carboniferous rock successions. Consequently, complex fault systems indicative of changing stress regimes and basin inversion evolved in the respective study areas (Henk 1993; Korsch and Schäfer 1995; Kley and Voigt 2008). At present day, natural seismic activity in the Ruhr and Ibbenbüren study areas is considered low, whereas in the Saar study area natural seismicity has been detected (Ahorner and Murawski 1975; Grünthal 2014).

2.2 Studied mines

The study focuses predominantly on three mines: 1. Mine Heinrich-Robert is part of the Haus Aden water province in the eastern Ruhr hard coal district; 2. Ibbenbüren Ostfeld; 3. Primsmulde in the Saar hard coal district. Mining there was conducted within folded structures, including synclines and anticlines with plunging fold axes, where dip varies strongly (from sub horizontal values to very steep angles) depending on the structural position (e.g., fold limbs versus fold axes). In the Heinrich-Robert mine, two major synclines with associated anticlines are present. Similarly, the Saar hard coal district displays synclines and anticlines probably associated with hanging wall deformation of a listric detachment fault (Henk 1993; Körniger and Stollhofen 2001). Although formed in different geological settings, the surrounding rocks in each study area are similarly characterized by mostly tight (i.e. porosity < 10%, permeability < 1 md) sequences of sandstones, siltstones, and claystones (Quandt et al. 2022a, 2024a; Greve et al. 2023). Petrophysical data only available for Ibbenbüren show that grain size also controls rock wave velocities and Young's moduli (Quandt et al. 2022a). Basic mining technical data are listed in Table 1. Mining depths are given in meters above mean sea level.

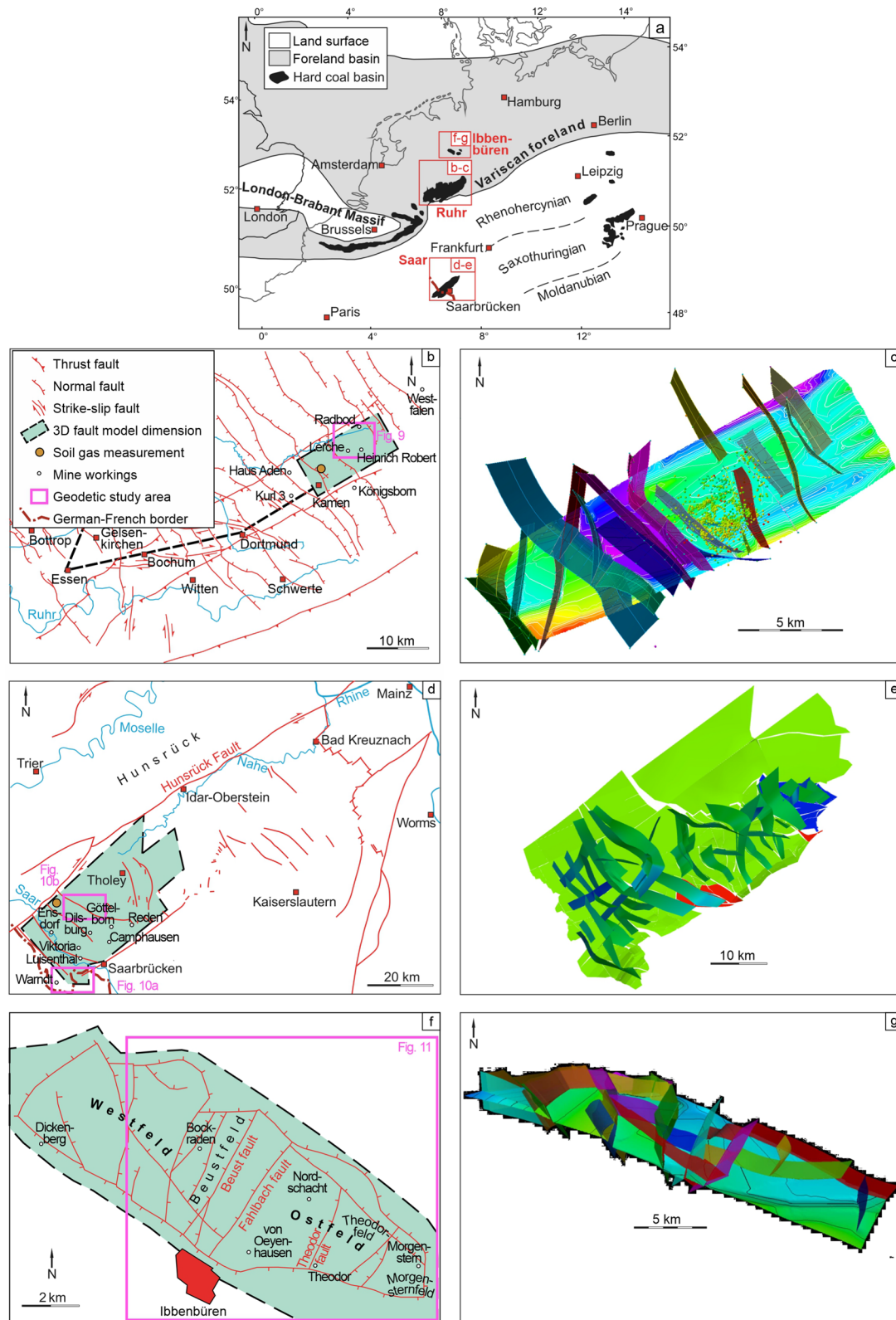


Fig. 1 **a** Simplified Late Carboniferous paleogeographic map indicating the locations of the different hard coal mining districts studied here (modified after Brix et al. 1988 and Quandt et al. 2022a). Simplified geological maps and 3D fault models of the **b** & **c** Ruhr, **d** & **e** Saar, and **f** & **g** Ibbenbüren hard coal districts (modified after Drozdowski 1985; Meschede 2018; Geologischer Dienst NRW 2020; Allgaier et al. 2024; Quandt et al. 2024a; FloodRisk 2023; Hollmann 2002). Dashed black line in **(b)** subdivides the Ruhr area into regions with low (W and SW of the line) and high outgassing potential (E and NE of the line)

Table 1 Mining technical data for the exploited deposits (provided by RAG Aktiengesellschaft)

Study area	Heinrich-Robert	Ibbenbüren Ostfeld	Primsmulde
Minimum depth among panels	– 724 m	– 363 m	255 m
Maximum depth among panels	– 1151 m	– 1402 m	– 1232 m
First documented mining depth	– 735 m (01.10.1964)	– 600 m (01.03.1967)	211 m (01.03.1966)
Last documented mining depth	– 1135 m (31.01.2010)	– 1130 m (17.08.2018)	– 709 m (25.05.2012)
Total number of mined panels	623	193	108
Average thickness of mined panels	1.92 m	1.61 m	2.26 m

2.3 Mine flooding in the study areas

In each study area, an individual flooding procedure in space and time is scheduled. Mine water levels are inferred from measuring stations in former vertical shafts that do not provide information on mine water levels within the surrounding rock mass. Flooding may be spatially heterogeneous within the study areas, i.e. different measuring stations in the same study area may show different mine water levels and varying flooding rates over time.

2.3.1 Ruhr hard coal district

The mine water rebound in the Ruhr hard coal district is controlled at six dewatering sites (Balzer and Roth 2019), which currently are in different flooding stages. In the dewatering site Walsum in the western Ruhr hard coal district, flooding was already completed when a mine water level of – 754 m NN was reached in 2016. Since then, wet-pit pumps keep the mine water level constant (Aktiengesellschaft 2025a). In contrast, in the Haus Aden water province in the eastern Ruhr hard coal district (Fig. 2a), flooding is currently ongoing. In the Haus Aden mine, hard coal production was abandoned in 2010. Between 2011 and 2013, the deepest pumps were switched off. In August 2020, the mine water level reached a depth of – 967 m NN at which the mines Lerche, Heinrich Robert, and Radbod 5 are hydraulically connected. Since then, mine water rebounds uniformly along the hydraulically connected mines. In August 2021, mine water levels at shaft Kurl 3 further in the east reached the levels of the western measuring stations shaft Lerche, shaft Heinrich, and shaft Radbod 5. The flooding concept at Haus Aden provides that at a mine water level of – 600 m, pumping will be re-initiated and mine water will rebound slowly. When the mine water level reaches a depth of – 380 m, the mine water level will be permanently maintained by wet-pit pumps (Aktiengesellschaft 2025b).

2.3.2 Saar hard coal district

The Saar hard coal district was originally hydraulically connected to the adjacent French Lorraine hard coal district (Fig. 2b). Before flooding of the Lorraine mines and a part of the Saar hard coal district (i.e. Warndt) in 2006, simultaneous flooding of the remaining Saar hard coal districts, where mining continued until 2012, was avoided by a subsurface high-pressure dam (Kessler et al. 2020, RAG Aktiengesellschaft 2025c). In the Saar hard coal district, a two-phase mine flooding process was initiated (Stemke and Wieber 2022). After a mine water rebound from – 600 to – 320 m below sea level in the first phase, the second phase provides that mine water will further rise and eventually discharge into the receiving water course (Stemke and Wieber 2022). However, due to legal issues, RAG has not yet applied for the planned mine water rebound. The hydraulic connection of the shafts Duhamel, Nordschacht (Saar mine, Primsmulde), and Dilsburg at a depth of – 384 m below sea level would result in simultaneous mine water rebound above this depth (Melchers et al. 2020). The current (September 2025) mine water level at Nordschacht is – 982 m (BID 2025).

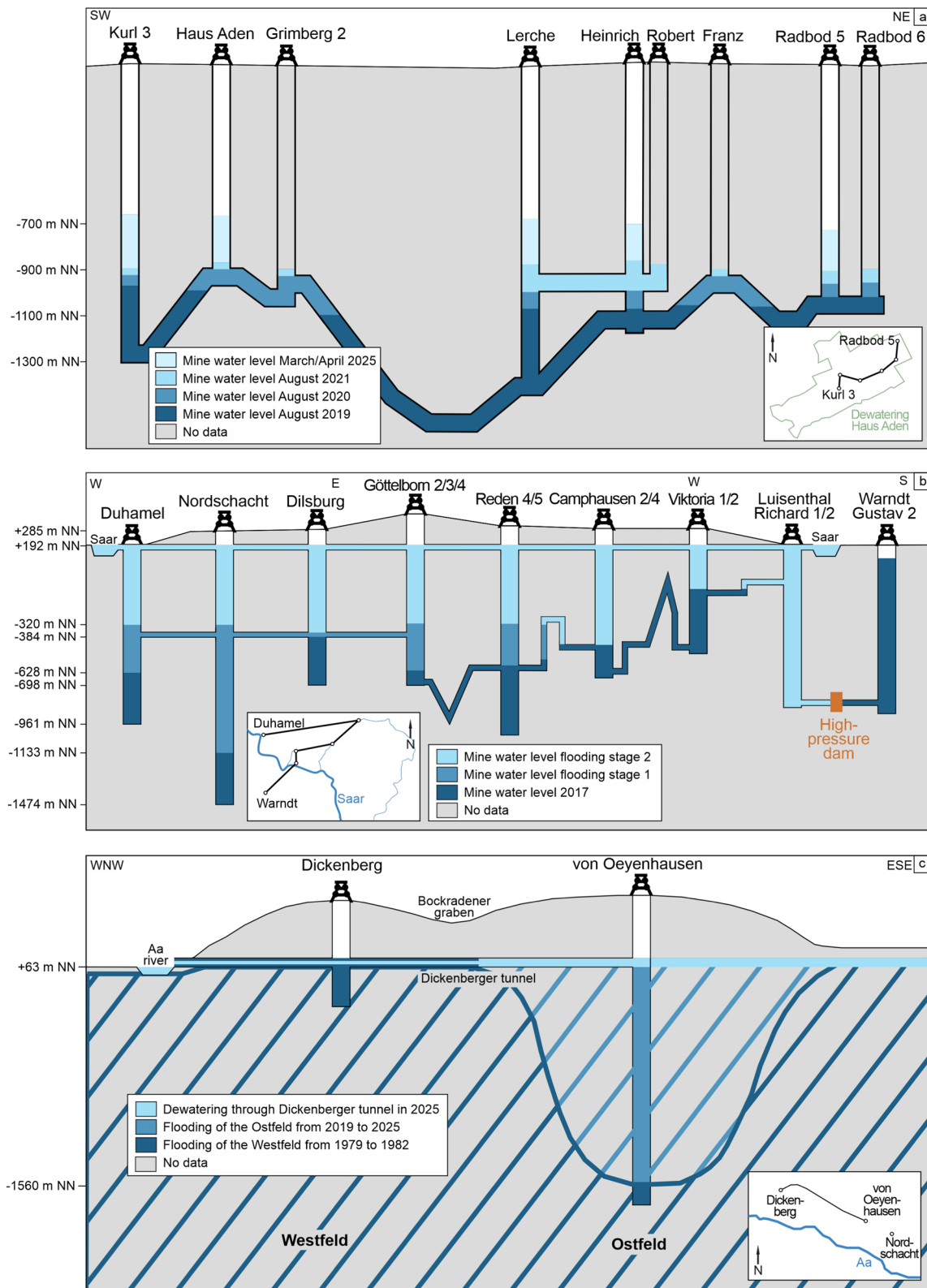


Fig. 2 Flooding concepts for the **a** Ruhr, **b** Saar, and **c** Ibbenbüren hard coal districts (modified after Melchers et al. 2020, Rische et al. 2023, RAG Stiftung 2024, RAG Aktiengesellschaft 2025a, b, c). Different time periods of flooding in a-c are chosen to highlight the temporal correlations of flooding with microseismicity and ground movements described in the discussion. Mine water levels measured in shafts give no indication of mine water level in the surrounding rock mass

2.3.3 Ibbenbüren hard coal district

Mining in the Ibbenbüren hard coal district took place in the Ostfeld and Westfeld (Fig. 2c). The Westfeld was abandoned in 1979 and 1982 mine water reached a level of + 65 m NN discharging into the Aa river through the Dickenberger tunnel (BID 2025). Mining in the Ostfeld continued until its abandonment in 2018. Subsequent mine water rebound proceeded with occasionally high rates of 1.00 m per day between December 2020 and August 2022 measured at Nordschacht (BID 2025). Besides measuring station Nordschacht, a limited number of mine water level measurements is also available for measuring station Oeyenhausen 3 (BID 2025) starting from June 2022. It is planned that the mine water in the Ostfeld will rebound to the same level as in the Westfeld. At a level of + 63 m NN pumps will be switched off and mine water from the Ostfeld and Westfeld will discharge into the Aa River through the Dickenberger tunnel (Voß 2018).

3 Data and methods

3.1 Compilation of published data

In this study, previously published geological (lithological columns, 3D fault models), geomechanical (regional stress orientations, magnitudes, derived values such as slip and dilation tendencies), petrophysical (porosity, permeability), geochemical (soil gas compositions), and seismological (seismic events during active and post-mining) data are compiled (Table 2). Detailed descriptions how these data were collected and processed are given in the respective publications (Allgaier et al. 2022, 2024; Greve et al. 2023, 2024a, b; Niederhuber et al. 2022; Quandt et al. 2022a, 2024a, b, 2026; Rische et al. 2023; Ukelis et al. 2023; FloodRisk 2023). These published data are supplemented with previously unpublished geodetic ground displacement data of all study areas generated during the project FloodRisk (Table 2). Geodetic methods are described in detail in chapter 3.2.

In brief, the subsurface geology of the different study areas was characterized on different scales from the microscopic pore space to km-scale regional fault systems in three dimensions. For this purpose, representative drill cores from each study area were logged, sampled, and analyzed for petrography (e.g. mineralogy, grain size, texture, structure), petrophysical properties (e.g. porosity, permeability, heat conductivity, wave velocities, Young's modulus, Poisson's ratio) as well as slip and dilation tendencies following standard procedures (Ferrill

Table 2 Overview of compiled data on post-mining used in this study

Study area	Data type	Publication
Ruhr	Geology	Allgaier et al. (2022), Greve et al. (2023, 2024a, b), Quandt et al. (2024b)
	Geomechanics	Niederhuber et al. (2022, 2025a, b), Allgaier et al. (2024)
	Seismology	Rische et al. (2023)
	Geodesy	Previously unpublished/this study
	Gas geochemistry	Ukelis et al. (2023), FloodRisk (2023)
Saar	Geology	Quandt et al. (2024a, b)
	Geomechanics	Quandt et al. (2026)
	Seismology	Quandt et al. (2026)
	Geodesy	Previously unpublished/this study
	Gas geochemistry	FloodRisk (2023)
Ibben-büren	Geology	Quandt et al. (2022a, b, 2024b), FloodRisk (2023)
	Geomechanics	FloodRisk (2023)
	Seismology	FloodRisk (2023)
	Geodesy	Previously unpublished/this study
	Gas geochemistry	No data available

et al. 2019; Greve et al. 2023, 2024a, b; Quandt et al. 2022a, b, 2024a, b). 3D fault models were created based on coal seam models available for each study area (Allgaier et al. 2024; Quandt et al. 2026). Considering the regional stress orientation (Niederhuber et al. 2022) and magnitude data (Stelling and Rummel 1992; Niederhuber et al. 2025a), the slip tendency of previously created 3D faults was evaluated for the Ruhr hard coal district (Allgaier et al. 2024) and estimated for the Saar and Ibbenbüren hard coal districts (FloodRisk 2023; Quandt et al. 2026) using slip and dilation tendencies calculated according to Morris et al. (1996) and Ferrill (1999), respectively.

Based on promising slip and dilation tendencies, fault exposure, soil properties, and soil gas, suitable measurement locations were identified (Ukelis et al. 2023; FloodRisk 2023). Soil gas components and concentrations were measured with commercial and newly developed low-cost in-situ gas sensors, for short-term and permanent applications, respectively (Ukelis et al. 2023; FloodRisk 2023). The development of modular gas sensor prototypes for permanent monitoring was a fundamental part of the work (FloodRisk 2023). Stable carbon isotopic compositions ($\delta^{13}\text{C-CO}_2$) of soil gases were measured with an isotope ratio mass spectrometer. Isotopic values are given relative to VPDB with $1\sigma \pm 0.3$.

Seismicity was monitored with local seismic network stations. A dense network was installed in the Ruhr area (Rische et al. 2023), which enabled detailed, precise localization in the area of the water province Haus Aden (former Bergwerk Ost). In Ibbenbüren, the existing stations of the RN-network (Ruhr University Bochum 2007) were used, which allowed good detection of the induced events, but only localization with large inaccuracies. Event distribution in the Primsmulde field of the Saar hard coal district (Alber et al. 2019, 2020) was estimated based on spatial proximity, relative travel time, and similarities using HypoDD (Waldhauser 2001). The spatial and temporal distribution of seismicity could be observed at all locations with different resolutions and correlated with other measurement parameters. Mine water levels are publicly available from (BID 2025). Other geotechnical data such as 3D mine working layouts were provided by the RAG Aktiengesellschaft.

3.2 Geodetic data processing

Ground displacements during the post-mining phase were observed with radar interferometry (InSAR). InSAR can detect gradients in the displacement field that might be associated with risks for infrastructure. It is a mature technology and an advanced InSAR-algorithm operated by an experienced expert is well capable of dealing with the displacements observed during post-mining as its spatio-temporal gradients are moderate. Nevertheless, there are general limitations of InSAR that are not specific to our study cases (Macchiarulo et al. 2022).

Sentinel-1 data from ascending and descending orbit were processed. PS and DS were jointly evaluated (for more details on the processing see Even et al. 2020). A small temporal baseline approach for unwrapping allowed us to deal with the challenge of a spatiotemporally variable displacement field. Finally, the results from both orbits were combined to obtain vertical and W-E displacements. Only vertical displacements are discussed in the following. For each of several ten thousand measurement locations, a time series of 500 values is obtained. For interpretation, we use a clustering approach based on a broken stick model. Broken stick models are continuous functions consisting of piecewise linear segments. The points in time when changes of rate occur between the linear segments are called break points. The definition of a broken stick model includes a restriction on the number of break points that is allowed. We applied a broken stick model with a maximum of 7 break points. From experience, such a model can approximate our time series quite well without introducing unnecessary degrees of freedom. For the set of break points of all measurement points, feature vectors are formed, which contain the measurement location, the break time, the change of displacement rate, and the displacement until the break time. Feature vectors with a small change of rate after the break point, small time intervals between successive break points, or small absolute value of change of displacement rate multiplied with the length of the consecutive time interval are removed. Clustering has been performed on the remaining feature vectors by Density-Based Spatial Clustering of Applications with Noise (Ester et al. 1996).

The obtained clusters correspond to changes in the vertical displacement field at a certain location at a certain time. With this approach, it was possible to describe the spatio-temporal patterns of changes in vertical displacement near mine Heinrich-Robert in the eastern Ruhr hard coal district (Haus Aden) and at the Ibbenbüren hard coal district (Ostfeld). For the mines in Saarland (Primsmulde and Warndt), a linear model suffices to describe the vertical displacements.

3.3 Interdisciplinary spatial and temporal analyses

Based on the multidisciplinary data, spatial and temporal analyses of the occurrence of seismicity and ground displacements were conducted (Fig. 3a–b). For the spatial analysis, geodetic ground displacement maps, microseismicity maps, mine maps, mine water levels, and geological maps were combined and integrated into a 3D fault model with calculated slip and dilation tendencies. As a result, any potential spatial correlation between microseismicity, ground movements, faults, and mine workings can be tested. For the temporal analysis, time series data of seismic events, ground displacements, and mine water levels were compared using the same time scale.

4 State of knowledge about the research areas

4.1 Seismicity, 3D fault model, and geomechanics

4.1.1 Eastern Ruhr hard coal district

Up to a few hundred events with magnitudes M_L between 0.7 and 3.3 per month were detected during active mining (Fig. 4) (Bischoff et al. 2010). They comprise events spatially related to the edges of longwall mining and temporally associated with the progress of longwall mining occurring on the scale of working hours and days as

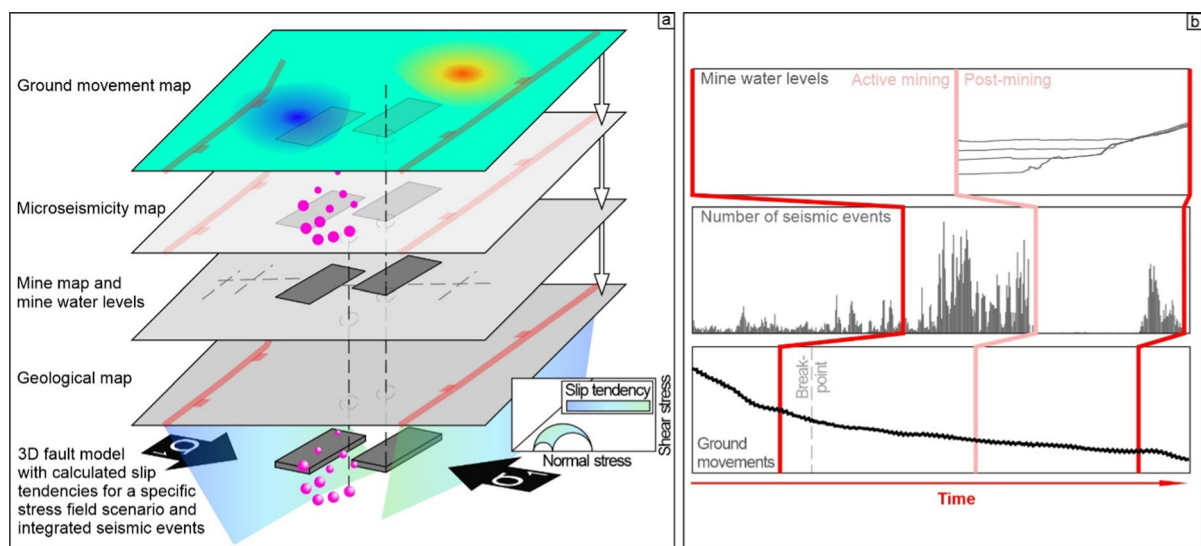


Fig. 3 General methodological approach to investigate the **a** spatial and **b** temporal distribution of mine flooding-induced microseismicity and ground movements (modified after Quandt et al. 2026). **a** Maps indicating areas of uplift (blue), subsidence (red), and microseismic events, mine maps, and geological maps are projected into each other and into the 3D fault model with calculated slip tendencies for a specific stress field scenario. **b** General methodological approach to investigate temporal distribution of mine flooding-induced microseismicity and ground movements. For this purpose, temporal correlations between time series data of microseismicity and ground movements with mine water levels are respectively tested

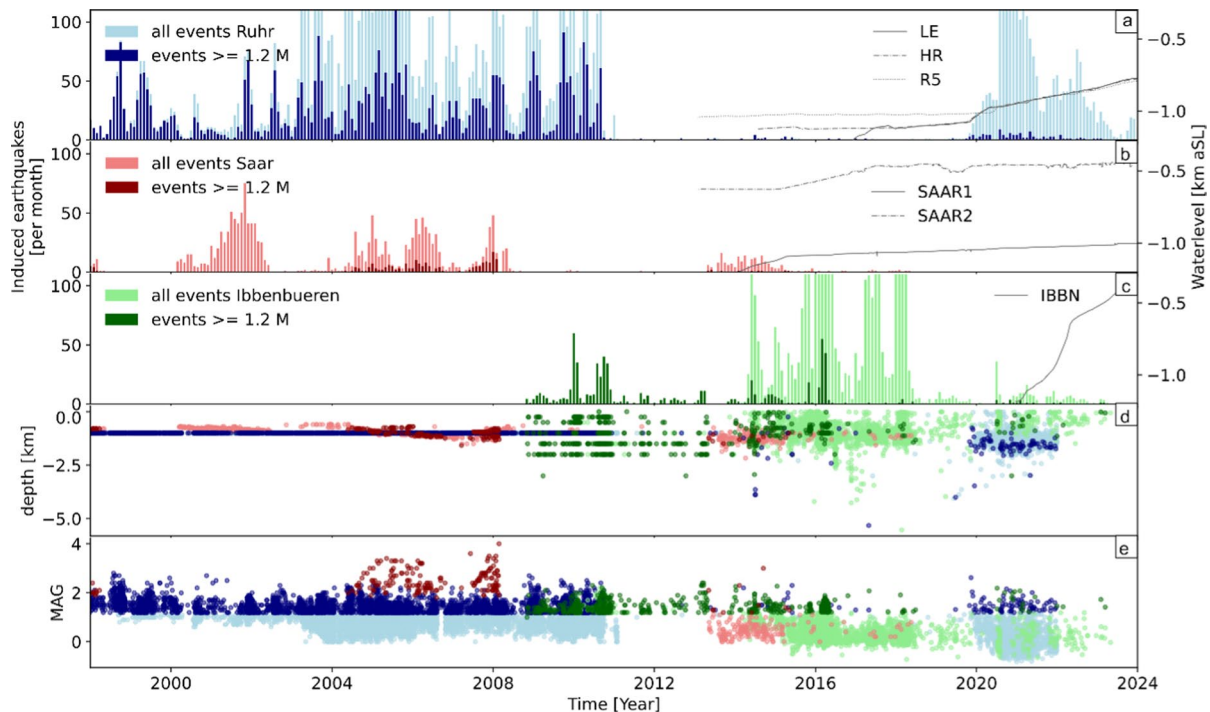


Fig. 4 Microseismic events (occurrence, depth, magnitude) over time in comparison with the mine water levels. The upper three panels **a–c** show the occurrence of seismic events in eastern Ruhr (blue), Saar (red), and Ibbenbüren (green) hard coal districts. The lower two panels **d, e** show depth and magnitude distribution of all three regions over time. For the Saar hard coal district, no seismic data are available after 2018, for Ibbenbüren recording starts 2009. During the registration period, the configuration of the networks changed, which led to different detection thresholds and, in some cases, limited depth determination. The completeness of the data sets is complete for magnitudes ≥ 1.2 M (dark colours). The mine water levels are measured at shafts Lerche (LE), Heinrich Robert (HR), Radbod 5 (R5), Nordschacht (Saar 1), Duhamel (Saar 2), and Nordschacht (IBBN)

well as events possibly caused by brittle failure on small-scale pre-existing tectonic structures (Alber et al. 2009; Bischoff et al. 2010; Wehling-Benatelli et al. 2013).

After mine abandonment in 2010, the number of induced microseismic events rapidly decreased to < 10 events per month (Rische et al. 2023). In mid-2019, the mine water rebound was initiated in the study area. Seismicity began to increase from late 2019 onwards. Increasing mine water levels in beginning of October 2019 temporally correlate with an increase in the number of events per month to > 10 . A second increase in seismicity was observed in August 2020 when the mine water levels measured at shafts Heinrich, Radbod 5, and Lerche reached a depth at which these shafts are hydraulically connected. Above this depth, mine water simultaneously rebounds in the three shafts (Rische et al. 2023; Niederhuber et al. 2025b).

The high-resolution data of the post-mining phase reveal that microseismicity was induced below the lowest mine workings where pillars are located (Rische et al. 2023; Niederhuber et al. 2025b). This spatial occurrence was explained by stress arch effects and proven by geomechanical model calculations (Niederhuber et al. 2025b). Accordingly, stress concentrates below pillars and at the edges of excavation zones. In contrast, no spatial correlation between microseismicity and large faults (i.e. faults with offsets < 10 m) was observed (Rische et al. 2023; Niederhuber et al. 2025b). These findings are consistent with analytical and probabilistic geomechanical calculations on slip tendencies that consistently reveal a low fault reactivation potential under the stress conditions applied (Allgaier et al. 2024). Thus, large faults with offsets > 10 m displayed in the 3D model of the Ruhr hard coal district are stable (Fig. 1c).

4.1.2 Saar hard coal district

Besides natural tectonic seismic events associated with the Hunsrück fault (Ahorner and Murawski 1975), only a few mining-induced seismic events were observed until 1990 (Fritschen et al. 2010). The detection of mining-induced seismic events with magnitudes $M_L > 3$ in May 2005 (3.3), June 2007 (3.6) and February 2008 (4.0), however, resulted in the abandonment of the Primsmulde excavation zone of the Saar mine followed by a two-phase mine flooding process initiated in March 2013 (Stemke and Wieber 2022). Seismic data are available until May 2018 covering the active and the post-mining phase of the Saar hard coal district (Fig. 4).

While the active mining phase is characterized by tens of events per month and magnitudes M_L up to 4.0 (Fritschen 2010; Alber and Fritschen 2011), the post-mining phase shows ≤ 16 events per month and magnitudes M_L typically < 2 (Fig. 4) (Alber et al. 2019, 2020; Quandt et al. 2026). Thus, during the post-mining phase less seismic activity is observed than during operational mining. The shallow depths of the post-mining events between 1.0 and 1.5 km (± 150 m) below mean sea level (Fig. 4) and their temporal occurrence during phases characterized by the highest flooding rates point to induced seismicity caused by increased pore fluid pressure.

Although the microseismic events are characterized by uncertainties of ± 250 m, seven microseismic clusters partly separated by > 1000 m can be distinguished. Indeed, some of these clusters seem to be concentrated below the edges of the excavation zone that mined the Schwalbach coal seam (Saar mine) that was also the focus of induced seismicity during active mining with the highest magnitude of M_L 4.0 detected in February 2008 (Fritschen 2010; Alber and Fritschen 2011), but no unambiguous conclusion can be made due to the high localization uncertainty.

Further seismic clusters without any spatial relation (i.e. distance > 1000 m) to any excavation zone may be related to reactivation of preferentially oriented (i.e. N-W striking) small-scale fractures with offsets < 10 m (Alber et al. 2019, 2020; Quandt et al. 2026). In contrast, large-scale faults with offsets > 10 m are stable as indicated by fault scaling relationships and consistently low slip tendencies < 0.5 calculated on 3D faults (Fig. 1e) under different stress scenarios to consider the poorly defined regional stress field in the area (Quandt et al. in 2026).

The spatiotemporal analysis of the occurrence of seismicity reveals a southwestward migration of seismicity over time. This may be due to progressive flooding of the northward dipping Schwalbach coal seam and the Primsmulde excavation zone (Quandt et al. 2026).

4.1.3 Ibbenbüren hard coal district

The last five years of active mining are characterized by a few hundred events per month and magnitudes $M_L < 3$. Published records of seismicity covering the period before 2014 state similar numbers of events per month and maximum magnitudes M_L up to 4.6 in 1991 (Cete et al. 1996; Bischoff 2010 (unpublished diploma thesis) (Fig. 4). After abandonment of the Ostfeld of the Ibbenbüren hard coal district in 2018 (Voß 2018), the number of seismic events decreased from a few hundred per month to < 10 per month.

From December 2020 onwards, mine water levels were continuously measured and document relative high flooding rates until June 2022 (Quandt et al. 2022a). In this period, the number of events per month varied between 0 and 20. With the decrease in flooding rate in June 2022, detected seismic events per month progressively decreased from 7 to 0. As the network used for monitoring consists of only three stations, seismic events are localized with an uncertainty of ± 1000 m. This does not allow any spatial analysis using the geological 3D fault model, which shows a complex setting of NW–SE and N/NE–S/SW striking faults that developed during Late Carboniferous Variscan orogeny and Late Cretaceous inversion tectonics.

4.2 Gas monitoring and geochemistry

4.2.1 Ruhr hard coal district

Based on historic and recent data, the Ruhr hard coal district shows a heterogeneous CH₄ outgassing pattern. In the eastern part at mine Radbod adjacent to mine Haus Aden, higher CH₄ contents up to 76 m³/t coal were measured in the year 1908 (Von Treskow 1985), whereas the western part is less CH₄-rich (Busch et al. 2017) (Fig. 1b). The contents significantly decreased to 10–40 m³/t coal by the proceeding mining until the 1980 s (Lommerzhelm 1994). The gases consist primarily of CH₄ and secondarily of CO₂ classifying as coal mine methane (NRW 2004; Thielemann et al. 2004).

Short-term soil gas measurements across two fault traces inferred from the 3D fault model for the water province Haus Aden and a geological map (Fig. 5a), respectively, showed localized positive anomalies of CO₂ (up to 13 Vol%), ²²²Rn (up to 105,000 Bq/m³) and negative anomalies of O₂ (up to 8 Vol%) across the modelled fault trace (day A in Fig. 5b). These anomalies were confirmed by repeated measurement (day B in Fig. 5b). The co-occurrence of these positive and negative anomalies indicates a structurally controlled migration of the gases and thus points to an exposed fault trace (Ukelis et al. 2023). Measured δ¹³C-CO₂ isotope compositions between $-22.9 \pm 0.3\text{‰}$ and $-24.6 \pm 0.3\text{‰}$ are in the range of both, typical C3 soil ($-25 \pm 3\text{‰}$ after Staddon 2004 and Rosenbauer et al. 2009), which corresponds to the soil type at the measurement locations, and coal mine methane δ¹³C-CO₂ isotope compositions (-7.5 to -33.7‰) known in the Ruhr area (Thielemann et al. 2004; FloodRisk 2023). Accordingly, measured CO₂ may be associated with one of these sources or a mixture, and thus, the source remains inconclusive.

The primary coal mine gas CH₄ was not detected. This was explained by its oxidative decomposition in the presence of water driven by microorganisms and resulting in the formation of CO₂ (Ukelis et al. 2023; Oest et al. 2019; Knittel and Boetius 2009). Newly developed sensor prototypes for permanent monitoring of soil gases (focus on CO₂) as well as for surface and underground temperatures were successfully applied for the duration of few weeks (Fig. 5c). The finalization and deployment of the prototypes came late in the flooding process and approx. 8 months after the first short-term measurements using commercial systems (Fig. 5b). The prototype measurements 8 months later did not confirm the CO₂ anomalies of the earlier short-term soil gas measurements (< 2.5 Vol% vs. up to 13 Vol%, Fig. 5b), also verified by repeated short-term measurements using commercial devices. These results therefore indicate temporally variable processes. Surface temperatures follow a typical day-night cycle. Underground temperatures show a similar curve that is damped and slightly phase-delayed because of the depth of 50 cm where the sensor is located. The maximum and minimum peaks of the CO₂ concentrations match the underground temperature peaks due to the expansion and compression of the soil gas volume and

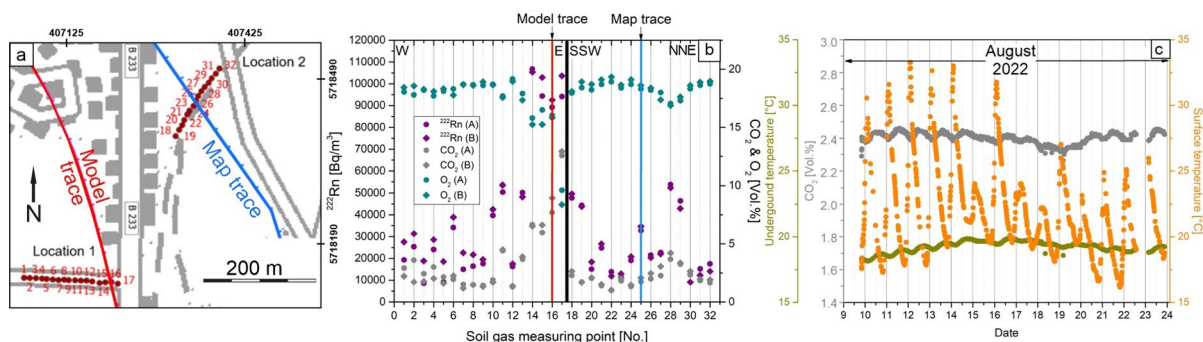


Fig. 5 a & b Short-term measurements of ²²²Rn, CO₂, and O₂ concentrations across modelled and mapped fault traces on two days (A, B) in November 2021 (modified after Ukelis et al. 2023). c Long-term CO₂ surface and underground (at 50 cm depth) temperature monitoring in August 2022 (FloodRisk 2023)

associated concentration changes (FloodRisk 2023). A deployment of the sensor prototypes beyond few weeks was not possible because of the insufficient robustness of used storage batteries in the outdoor environment. These challenges need further development efforts in the sensor concept.

4.2.2 Saar hard coal district

The Saar hard coal district is considered to have a higher outgassing potential than the Ruhr and Ibbenbüren hard coal districts. Accordingly, coal mine methane was produced during active mining periods (Wagner 2017; Thielemann 2002). Between 1998 and 2010, soil gas investigations in the Völklingen area (ca. 10 km WNW of Saarbrücken, Fig. 1d) showed outgassing of CH₄ and ²²²Rn with CH₄ considered to be a transport medium for ²²²Rn (Kemski et al. 2016). A highly significant positive correlation of both components was also shown in similar expert reports on the same study area (unpublished expert reports by Kemski and Partner 2010; Kemski and Klingel 1998a, b and 2005 all referenced in Kemski et al. 2016).

Recent short-term measurements were affected by rain-induced, increased soil moisture occluding the soil pore space and therefore hindered a complete short-term soil gas survey. Individual measurement spots unaffected by soil moisture did not show any (structure-controlled) gas anomaly (FloodRisk 2023). Considering the high outgassing potential in the Saar hard coal district and assuming a precise projection of the modelled fault to the surface, the results possibly indicate a localized and/or temporally variable outgassing process.

4.3 Ground displacements

4.3.1 Ruhr hard coal district

Geodetic investigations on the mines of the Ruhr hard coal district have been conducted in a series of expert reports. One of these expert reports was devoted to Bergwerk Ost in the eastern Ruhr area (Busch et al. 2017) that has also been studied in the framework of FloodRisk. Busch et al. (2017) considered the period December 18, 2003, to November 6, 2015, which is prior to the investigation period of FloodRisk. Based on ground displacements from InSAR and levelling before the end of active mining on September 30, 2010, subsidence rates of more than 100 mm per 2-year period were observed. Afterwards, subsidence decelerated but persisted throughout their investigation period. Between May 2012 and May 2014, the maximum observed subsidence was still about 40 mm.

4.3.2 Saar hard coal district

Available studies on ground movements in the Saar hard coal district are scarce. Samsonov et al. (2013) used InSAR to analyze ground movements in the Saar hard coal district and the adjacent French Lorraine hard coal district covering the observation period 1995–2009. Their results reveal areas of subsidence in the order of a few centimeters per year that transition into uplift over time. Changes in deformation rates were interpreted to be related to variations in mine water levels over time. Additionally, levelling time series measured in Warndt and Primsmulde (Saar mine, end of excavation in 2008) show examples of immediate uplift after initiation of flooding and examples where the uplift begins with a delay of almost two years (Heitfeld et al. 2016). A recent study (Modeste et al. 2025) of the mines in Lorraine presents InSAR line-of-sight measurements from November 2014 to January 2020, which is earlier than the period covered by the data investigated for this work. In addition, a comparison with levelling data is presented.

4.3.3 Ibbenbüren hard coal district

Between 1980 and 1999, Goerke-Mallet (2000) reported uplift of up to 101 mm in the Westfeld, where the final mine water level was reached in 1982. About 10% of the total uplift occurred between 1985 and 1999

(Goerke-Mallet 2000). Between December 2003 and February 2015, no significant displacements were observed with levelling and InSAR (Busch et al. 2016; Sroka et al. 2017) in the Westfeld. Sroka et al. (2017) assessed the possible effects of the future mine water rise. Among others, they conclude that a maximum uplift of 384 mm is to be expected and that no mining-related damage will be caused.

5 Results

5.1 Ground displacements in the eastern Ruhr hard coal district

The ground displacement analysis of the mine Heinrich-Robert in the eastern Ruhr hard coal district reveals a complex spatiotemporal displacement pattern for the observation period January 2018 to December 2022. The displacement field shows larger gaps over areas with vegetation because of decorrelation. Between January 2018 and August 2019, displacements can be described by a linear model (Fig. 6). Subsidence occurs above the excavation zones with the largest rates observed west of shaft Heinrich, where the deepest mine panels are situated. The areas without information correspond to vegetated or other surfaces without stable scattering properties. After August 2019, changes in displacement rates are observed (Fig. 7), which can be related to the spread of water along hydrological pathways.

The shafts are hydrologically connected at different depths (cp. Figure 2a): The connection between shaft Lerche and shaft Heinrich is at a depth of 1124 m below mean sea level (Klinger et al. 2023), wherefore the levels in both shafts develop in parallel after having surpassed this level (before the period considered here). Likewise, the western part of Heinrich-Robert is connected by galleries at this depth (Fig. 7). The flooding of the eastern part of Heinrich-Robert (mine panels near example measurement point (MP) D (Fig. 7)) starts when

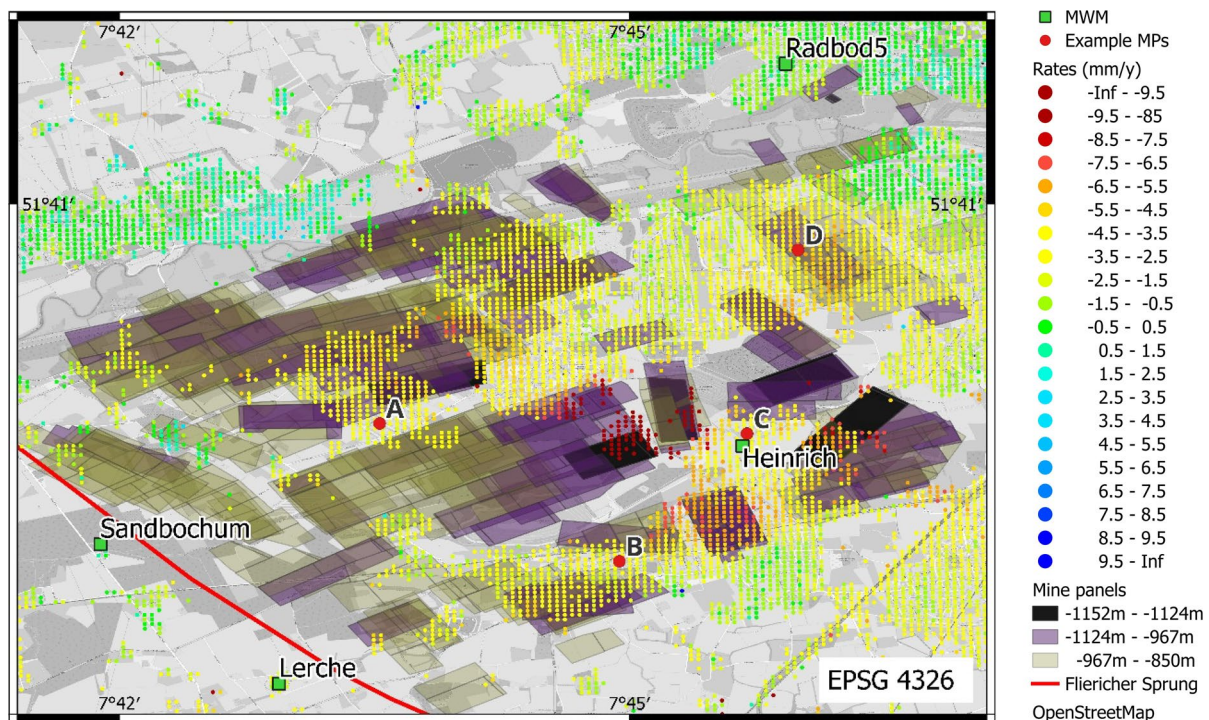


Fig. 6 Vertical displacement rates (mm/y) at mines Ost (Hamm) and Radbod for the period January 9, 2018–August 25, 2019. The mine panels are colored according to their vertical position. The darker the color the deeper the excavation. The positions of mine panels and shafts are from (BID 2025)

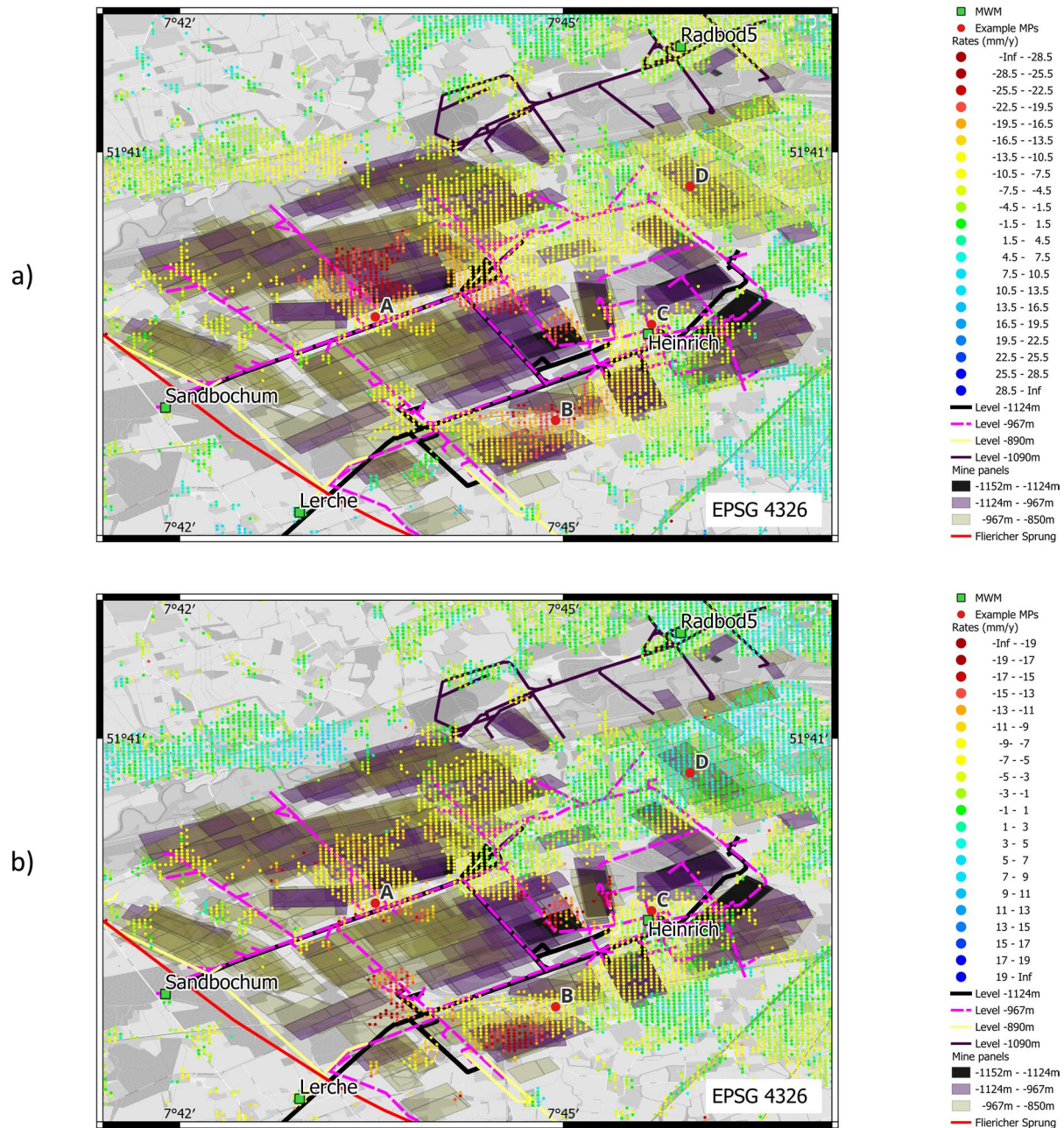


Fig. 7 Part 1 Vertical displacement rates during consecutive time intervals: **a** August 25, 2019–January 21, 2020, **b** January 21, 2020–July 11, 2020. Galleries at different levels constitute the main pathways for the flowing water. The mine panels are colored according to their vertical position. The darker the color the deeper the excavation. The positions of mine panels and shafts are from (BID 2025). The positions of galleries were provided by RAG. Part 2 Vertical displacement rates during consecutive time intervals: **c** July 11, 2020–November 21, 2020, **d** November 21, 2020–April 15, 2021. Galleries at different levels constitute the main pathways for the flowing water. The mine panels are colored according to their vertical position. The darker the color the deeper the excavation. The positions of mine panels and shafts are from (BID 2025). The positions of galleries were provided by RAG. Part 3 Vertical displacement rates during consecutive time intervals: **e** April 15, 2021–November 7, 2021, **f** November 7, 2021–December 23, 2022. Galleries at different levels constitute the main pathways for the flowing water. The mine panels are colored according to their vertical position. The darker the color the deeper the excavation. The positions of mine panels and shafts are from (BID 2025). The positions of galleries were provided by RAG

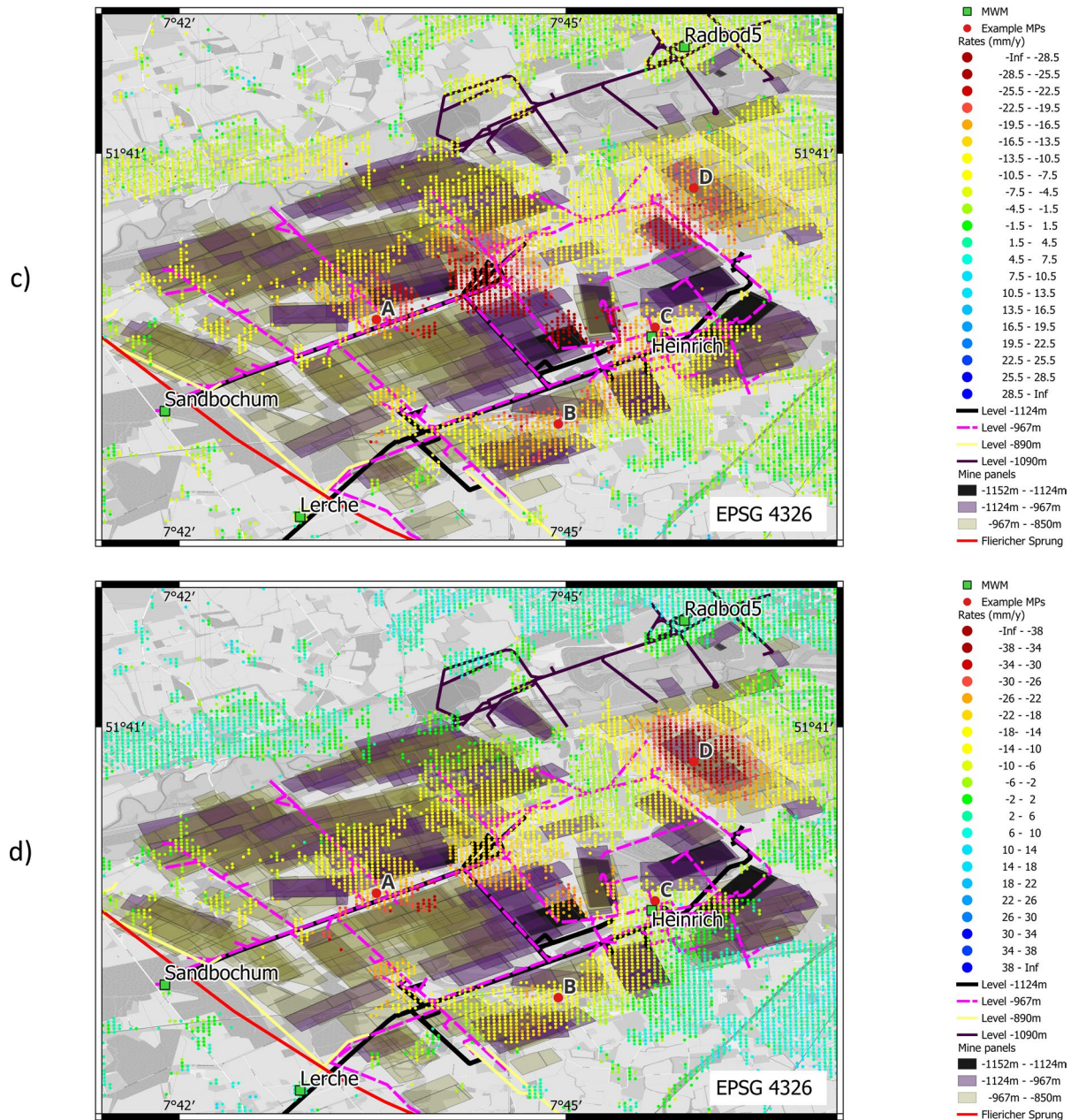


Fig. 7 (continued)

mine water levels reach 967 m below mean sea level (cp. Figure 2a, shaft Franz). This level had been reached at shaft Heinrich in mid-2020, when the level at Radbod 5 was still lower. At this time, also the hydrological connection between Lerche and Heinrich-Robert with Radbod 5 is made (cp. Figure 2a). Shortly afterwards, the water stagnates at Heinrich until it adjusts at Radbod 5, and from then on, both levels develop simultaneously (Niederhuber et al. 2025a).

The temporal development of displacements observed at the MPs A-D correlates with that of the mine water levels (Fig. 8). To go beyond individual example time series and to understand the whole spatio-temporal displacement field, the cluster analysis described in Sect. 3.2 has been applied. It has identified six clusters whose temporal centers subdivide the observation period into time intervals during which the displacement is approximately

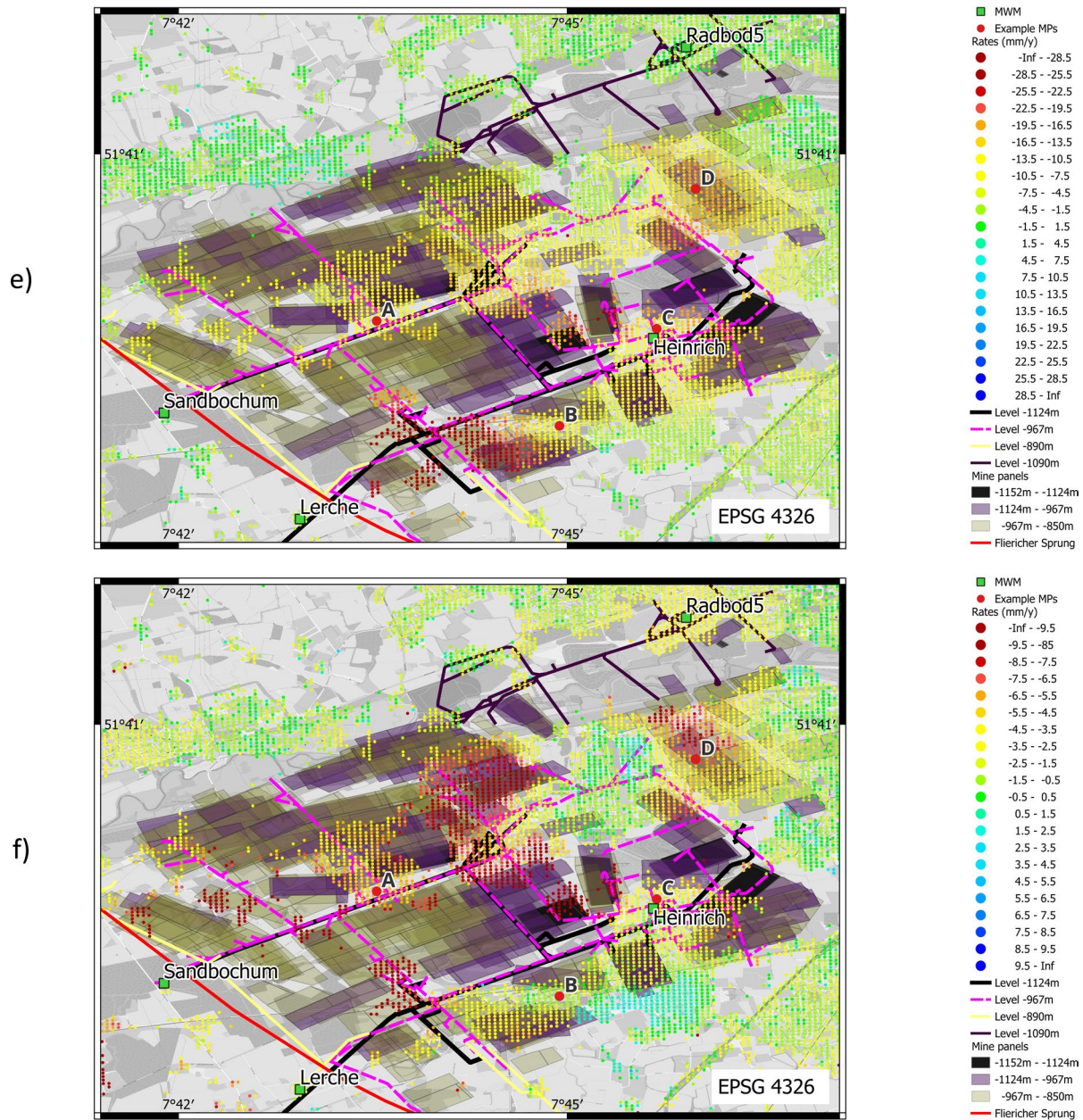


Fig. 7 (continued)

linear. The spatial pattern of displacement rates (Fig. 6 and 7) during these time intervals indicates a connection with the development of mine water levels at different locations.

While Fig. 6 shows moderate subsidence of about 4 mm/y near MPs A and B (period January 9, 2018, to August 25, 2019), the displacement rates during the second time interval near these points is up to 30 mm/y near MP A and up to 20 mm/y at MP B (Fig. 7, Part1a; please observe that the scales of vertical displacement vary between figures). This acceleration of subsidence correlates temporally with the acceleration of mine water rise (Fig. 8). Spatially the strongest acceleration occurs above the deepest excavations. The water enters them via galleries that are at a depth of 1124 m below mean sea level and are flooded in summer 2019. Between January and July 2020, when the mine water levels stagnate at shaft Heinrich, also the subsidence decelerates (Fig. 7, Part1b). The only exceptions are the deep mine panels a bit south of MP B, where displacement rates increase compared

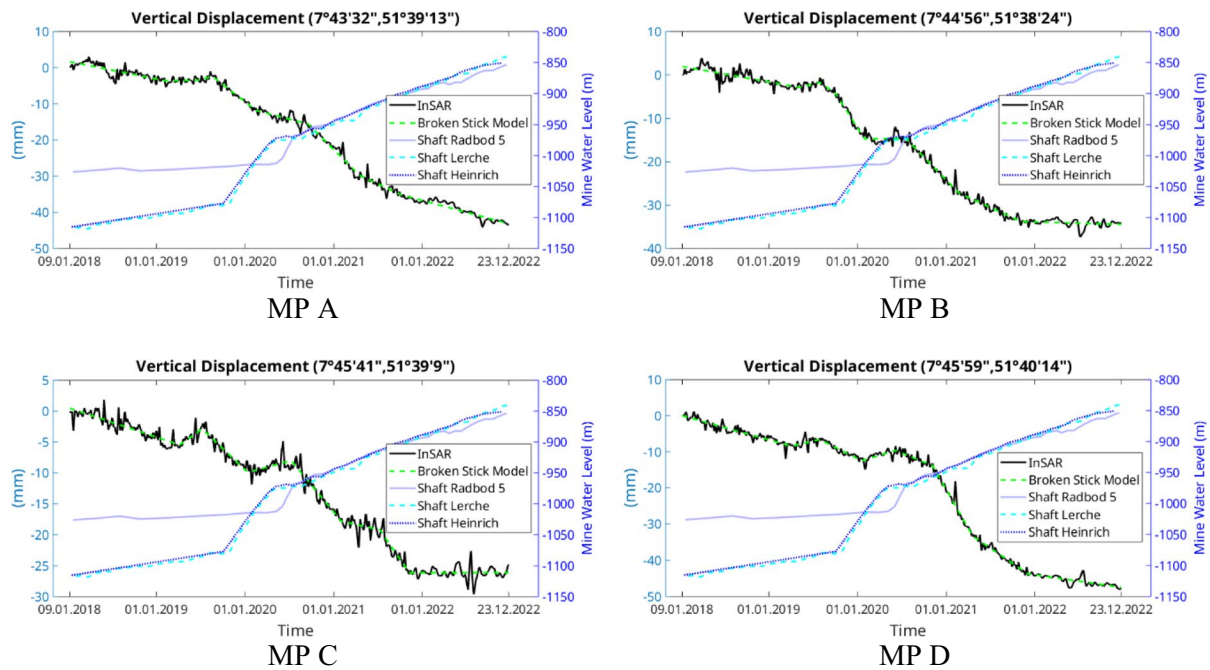


Fig. 8 Time series of vertical displacements of the example measurement points marked in Figs. 6, 7, and 9 together with the mine water levels with respect to mean sea level measured at the shafts Radbod 5, Lerche, and Heinrich likewise marked in Figs. 6, 7, and 9. The broken stick models of the time series are displayed in green

to the previous time interval. Around July 2020, when the mine water levels at the three shafts adjust, a second acceleration of subsidence begins at Bergwerk Ost and this time also a distinct acceleration of subsidence can be observed in the East of mine Heinrich-Robert near MP D (Fig. 7, Part2c), which is now hydrologically connected to the western parts of Heinrich-Robert by a gallery at a depth of 967 m below sea level. Between November 2020 and April 2021, strong subsidence of almost 40 mm/y is observed in the area around MP D (Fig. 7, Part2d). This is presumably caused by the ongoing flooding of the deep excavations at this location. In April 2021, subsidence decelerates (Fig. 7, Part3e). In fall 2021, subsidence decelerates further (Fig. 7, Part3f). Near MP B, the first signs of a turnaround to uplift appear. A map of cumulative vertical displacement for the complete observation period shows that the areas with the strongest vertical displacements of about 5 cm are situated above the mine workings with the deepest coal seams (Fig. 9).

5.2 Ground displacements in the Saar hard coal district

Sentinel-1 data of Lorraine and Saarland for the period November 2015 to February 2020 have been evaluated. The already flooded mines at Lorraine and Warndt show uplift with raising mine water levels (Fig. 10a blue). The area in the north characterized by subsidence (red) represents mine Luisenthal, which is situated on the non-flooded side of the hydraulic dam. Figure 11a–e show that vertical displacements near the marked shafts and mine water levels measured there correlate well. The mine water levels at these five shafts develop in parallel, which is an indication that the shafts are hydrologically connected. At Primsmulde (Saar mine, cp. Figure 1d), cumulated subsidence in the order of about 3 cm is spatially overlapping with the former excavation zones (Fig. 10b). Mine water levels at Nordschacht are – 1084 m at the beginning and – 1044 m at the end of the observation period (Fig. 11f). No spatial correlation between faults and ground displacements was found. Currently, subsidence is ongoing.

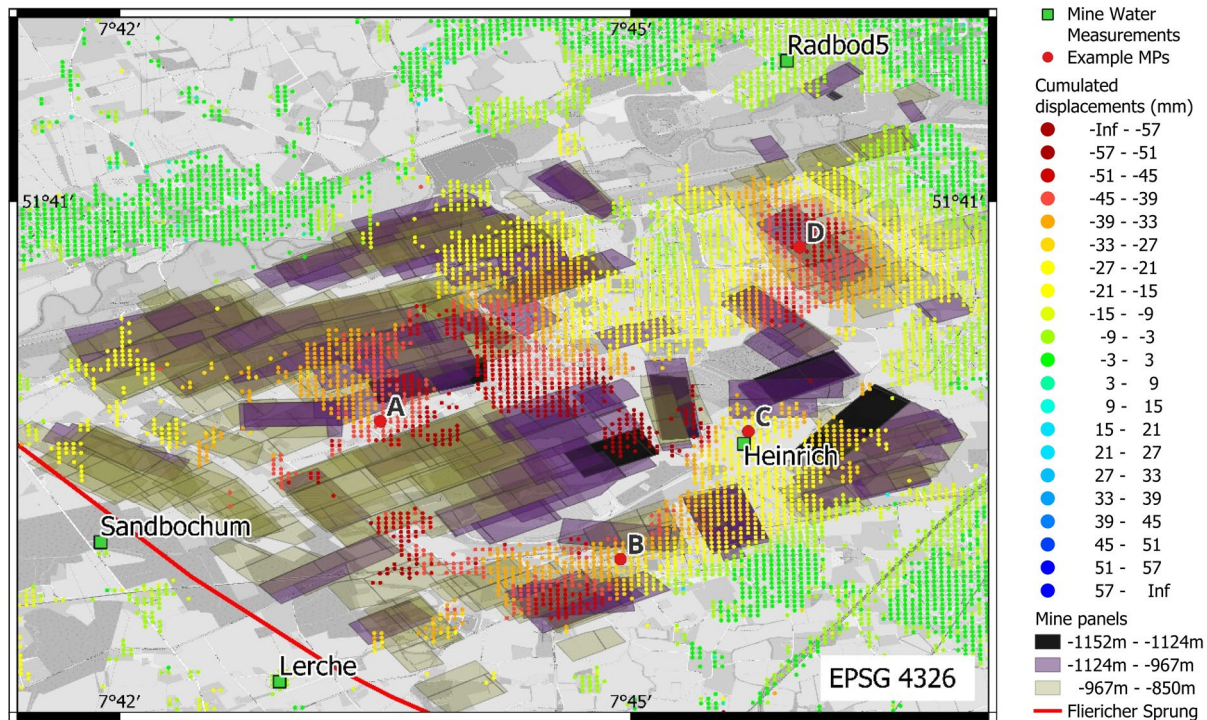


Fig. 9 Cumulated vertical displacement (mm) at mines Ost (Hamm) and Radbod for the period January 2018–December 2022. The mine panels are colored according to their vertical position. The darker the color the deeper the excavation. The positions of mine panels and shafts are from (BID 2025)

5.3 Ground displacements in the Ibbenbüren hard coal district

InSAR processing for the Ruhr area and Ibbenbüren has been done using the same Sentinel-1 interferograms. A broken stick model with seven breakpoints has been used for clustering the data. As the spread of break times for each cluster is small, we decided to represent the results with the help of maps of vertical displacement rates for the time intervals that are formed by the start time of the data, the medians of break times of the clusters, and the end time of the data (Fig. 12). In the first two maps (Fig. 12a–b), two centers of active displacement are recognizable: at the Beust field between the Beust and Fahlbach faults in the West and at the Theodorfeld and Morgensternfeld east of the Theodor fault. Both centers are characterized by subsidence on the scale of centimeters. These two centers correspond to the locations where the latest production of hard coal took place. Hard coal had been produced east of the Theodor fault (seam 78) until June 6, 2018, and between the Beust and Fahlbach faults in the west (seam 53) until August 17, 2018. The end of production in the area between the two centers had been on June 6, 2016 (seam 51) and thus before the observation period of this study. With ongoing time, this subsidence reversed to uplift on the scale of a few centimeters (Fig. 12c–g).

Discussing the subfigures of Fig. 12 one by one, (a) we find that the median break time that separates the first and second interval coincides quite well with the end of production at seam 78. Until this point in time, the maximum subsidence rates at the two centers are in the order of several decimeters per year. Afterwards, the displacement at seam 78 decelerates distinctly, while it stays high at seam 53. (b) The second interval ends about four months after the end of production at seam 53. But the break times of the time series readable from Fig. 13a–b agree quite well with the end of hard coal production between the Beust and Fahlbach faults on August 17, 2018. (c) During the third interval, only slight residual subsidence associated with the two centers can be observed. (d) The fourth interval starts on June 8, 2020, shortly after dewatering was stopped in June 2020 (Ministerium für Wirtschaft, Innovation, Digitalisierung und Energie des Landes Nordrhein-Westfalen 2020). The ensuing acceleration of subsidence with

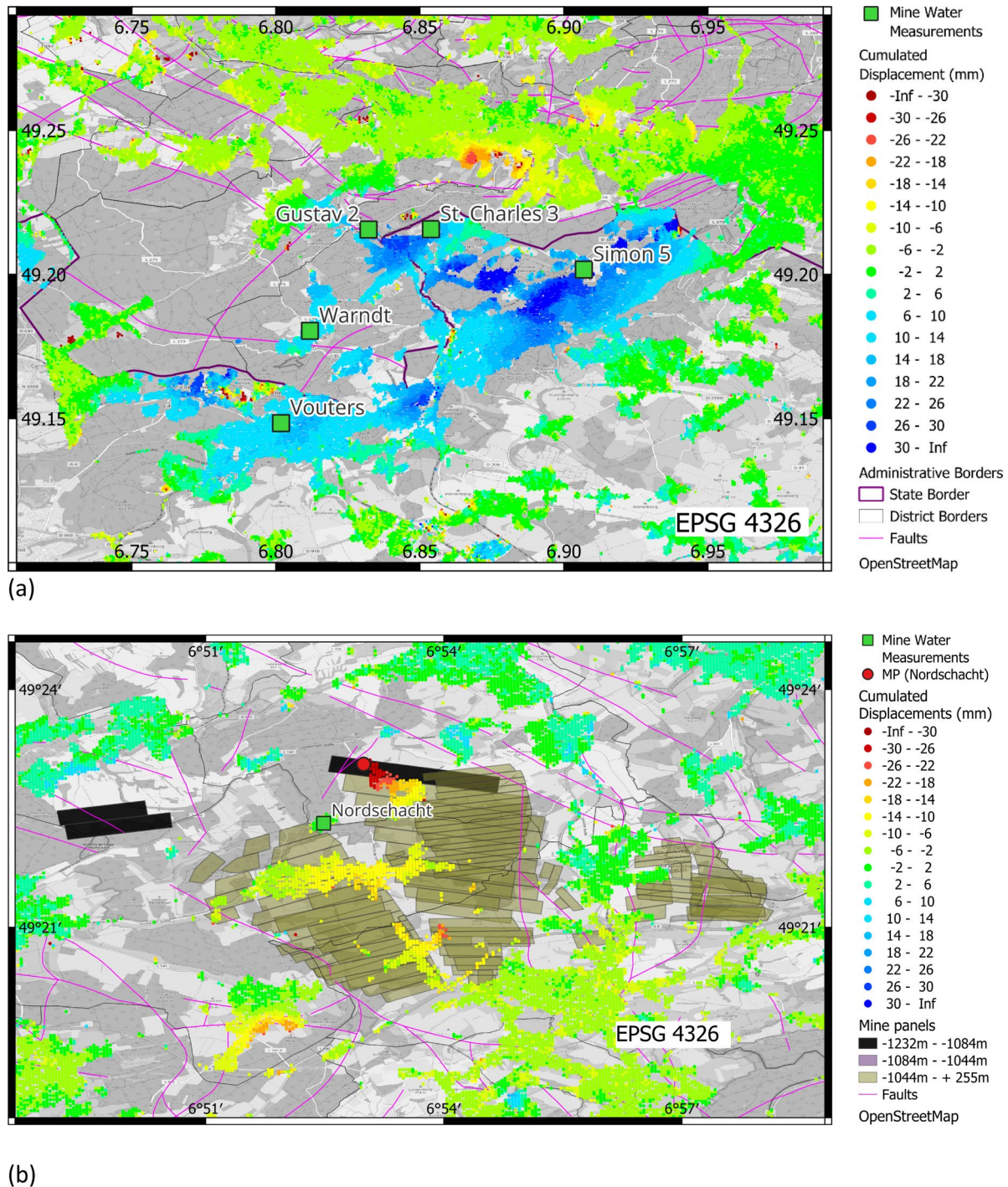


Fig. 10 Vertical cumulated displacements (mm) at **a** Lorraine (France) and Warndt (Saar hard coal district) and at **b** Primsulde (Saar hard coal district) for the period November 2015–February 2020. The mine panels are colored according to their vertical position. The darker the color the deeper the excavation. The positions of mine panels and shafts are from (BID 2025)

its center approximately above the center of the mine workings can be interpreted as a consequence of the rising mine water level. The first provided mine water level at Nordschacht is available on December 23, 2020, with a reported level of -1183.9 m NN (BID 2025). As the depth of Nordschacht is 1.545 m, there must have been a

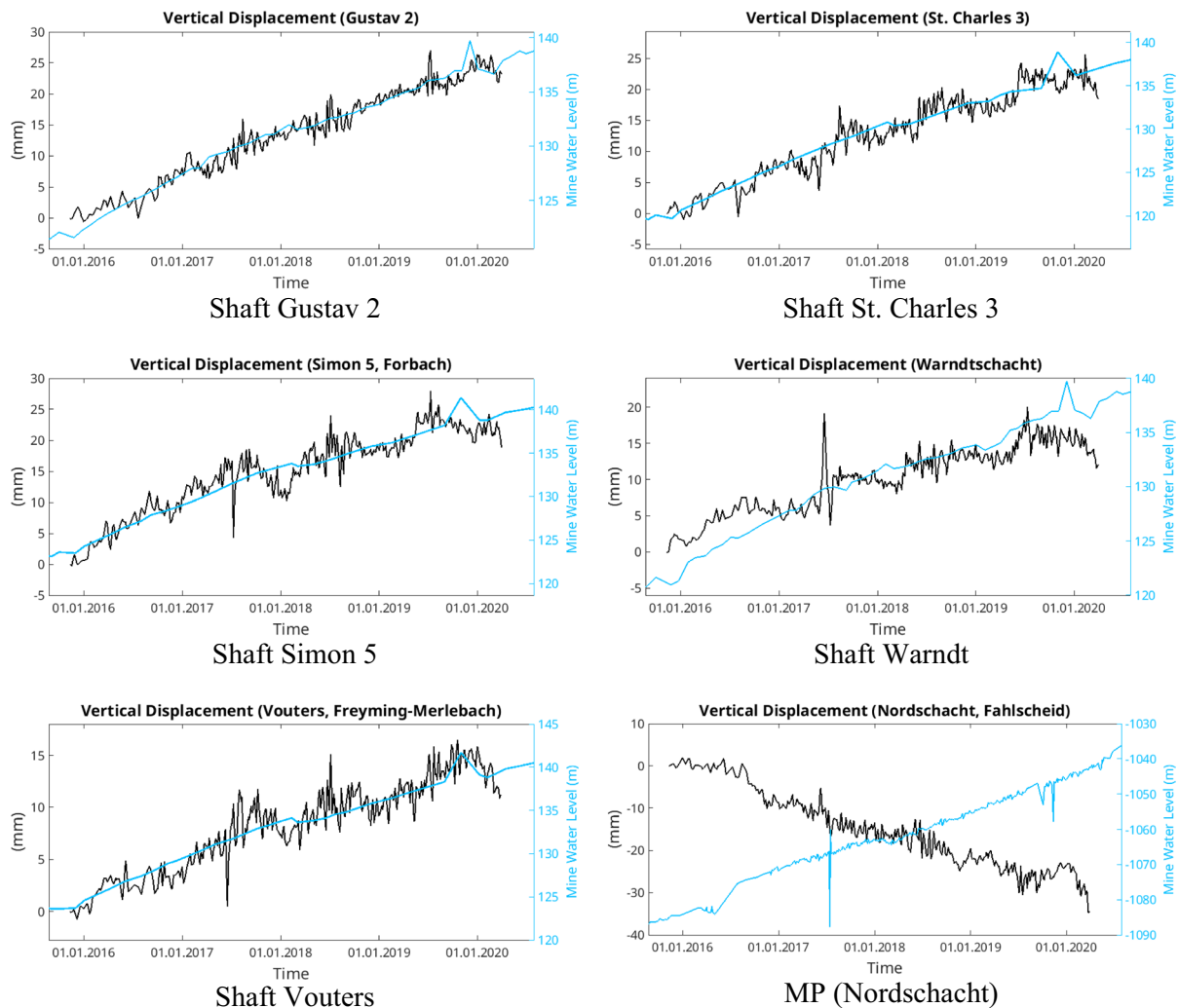


Fig. 11 Time series of vertical displacements together with the mine water levels with respect to mean sea level measured at the shafts (cp. Figure 10a) in Lorraine (France) and Warndt (Saar hard coal district) and at a MP near Nordschacht (cp. Figure 10b) at Primsmulde (Saar hard coal district)

considerable rise of mine water during a short time span after switching off the pumps. (e) During the fifth interval, a transition from subsidence to uplift can be observed. (f) Uplift accelerated distinctly after December 28, 2021, in coincidence with the steep rise of mine water that sets in about the same time. (g) Rate of uplift reduces again after June 25, 2022, corresponding to the lower rate of mine water rebound (cp. Figure 13).

The time series in Fig. 13 indicate that after the uplift starts, changes of uplift are proportional to changes of mine water levels. Generally, changing displacement rates can be temporally associated with mining and post-mining activities.

6 Discussion

6.1 Spatiotemporal occurrence of mine flooding-induced microseismicity in the study areas

In this study, we conducted a comparative analysis of three regions in Germany affected by post-mining and subsequent flooding. The three study areas are similarly characterized by induced seismicity during mining and during

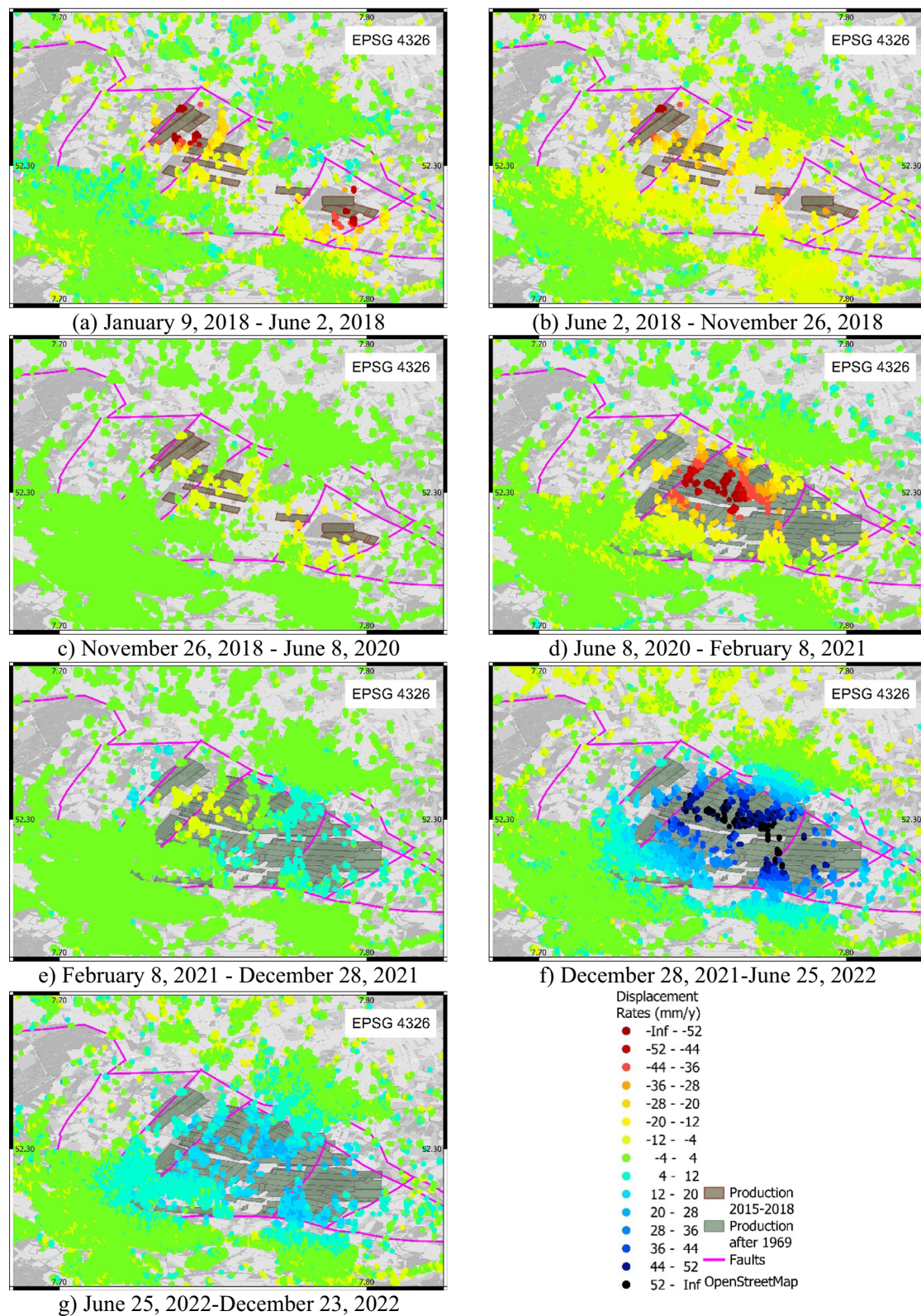


Fig. 12 Vertical displacement rates (mm/y) for the Ostfeld of the Ibbenbüren hard coal district for different time periods. Mine panels with production periods are from (BID 2025)

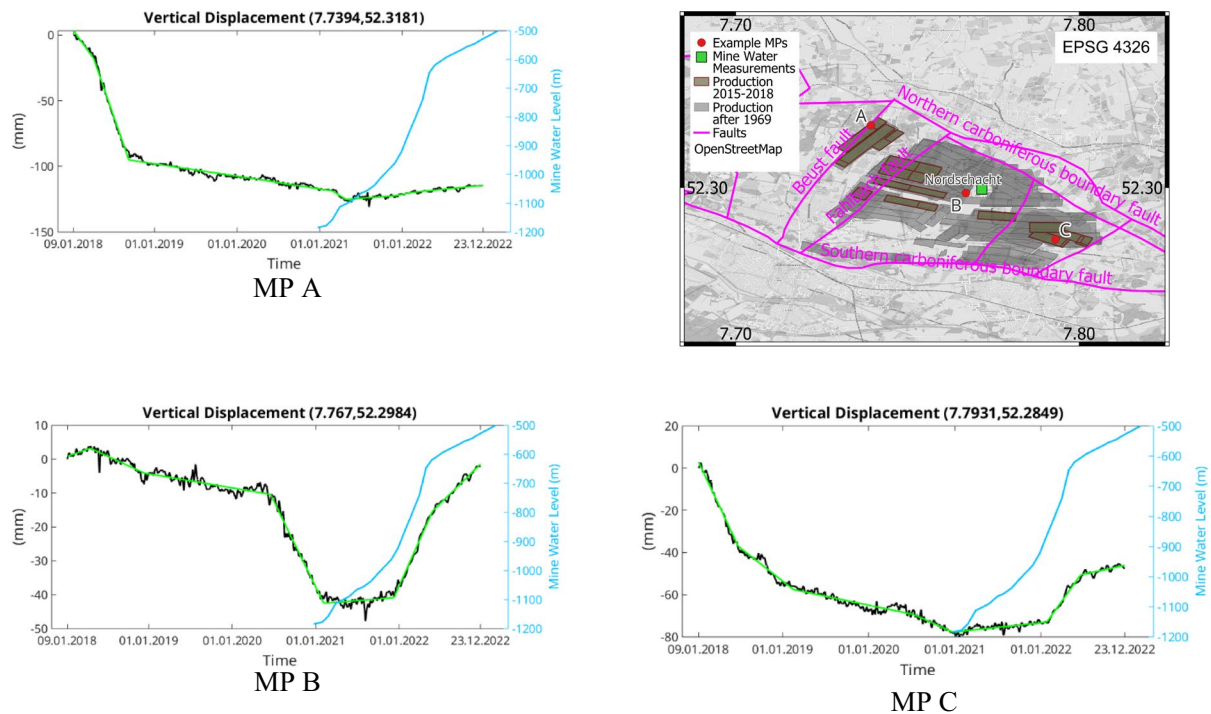


Fig. 13 Time series of vertical displacement for three example measurement points, where the latest mining in the Ibbenbüren hard coal district took place, together with mine water levels below mean sea level at shaft North. The fitted broken stick model is displayed in green

flooding. In the Ruhr and Saar hard coal districts, spatially shifting seismic clusters over time were observed. In the Ruhr hard coal district, the dense seismic network enabled to precisely and accurately attribute microseismic events to the area below mine workings (Rische et al. 2023; Niederhuber 2025b). Large-scale fault systems have not shown induced seismicity. Similar spatial correlations seem to be present in the Saar hard coal district but due to the poorer localization of events, conclusions remain ambiguous. Moreover, the microseismic events in the Ibbenbüren hard coal district are characterized by high localization uncertainties that only allow temporal analyses. This highlights the importance of high-resolution seismicity and 3D fault data. Induced seismic events are also observed during the flooding of old mines in France, Germany, Poland, and the Czech Republic as part of a study on hazard assessment within the European PostMinQuake project (Sokola-Szewiola et al. 2023). The observations at the sites are heterogeneous. Estimates of seismic hazard could only be provided where the events were evaluated with sufficient accuracy.

6.2 Spatiotemporal occurrence of soil gases

Repeated soil-gas measurements along the same transect in the Ruhr district lacked gas anomalies, indicating temporal variations of the outgassing rate into soil. One explanation for the absence of CH_4 and related CO_2 anomalies could be also rising mine water levels occluding gas pathways and/or past outgassing through artificial and natural degassers such as disused mine shafts and permeable fractures, respectively (Krause and Pokryszka 2013). Indeed, mine water levels at the Haus Aden dewatering site rose by about 40 m between the two measurement campaigns in November 2021 and July/August 2022 (BID 2025).

Taken together, the observations made in the Ruhr and Saar hard coal districts in comparison with literature data indicate that anomalous outgassing into soil represents temporally varying events as a function of diverse effects (e.g. weather, mine water levels, groundwater chemistry). Thus, considering geomechanics, pedology,

hydrology, and geology, commercial short-term soil gas measurement systems are capable of detecting structure-controlled and temporally variable soil gas anomalies in post-mining areas. Still, more transects along the same fault section need to be investigated to verify the spatial occurrence of gas anomalies in general. In addition, permanent monitoring of outgassing and environmental parameters will have to be studied to better understand the diverse impacts on gas concentrations. The developed modular gas sensor prototypes for permanent monitoring showed promising results as validated by the commercial short-term systems but need further optimization in terms of battery supply.

6.3 Spatiotemporal occurrence of ground displacements in the study areas

In the areas studied here, the displacement fields do not indicate an influence of faults. In contrast, studies on Belgium and Dutch hard coal districts suggested that ground displacements are controlled by faults, which may have acted as impermeable barriers against flooding (Caro Cuenca et al. 2013; Vervoort and Declercq 2018). However, considering that mine workings are also limited by faults, it remains unclear if a causal relationship exists. In general, permeability along fault zones may be reduced by clay smear. In the eastern Ruhr hard coal district, calculated shale gouge ratios indicative of clay smear revealed a heterogeneous clay distribution pattern along an exemplary fault zone (Allgaier et al. 2024). Thus, entire fault zones do probably not act as impermeable barriers.

Clear temporal correlations exist between ground displacements and mine water levels. These correlations were also observed in other hard coal districts (Caro Cuenca et al. 2013; Samsonov et al. 2013). In the Ruhr and Ibbenbüren hard coal districts, significant changes in displacement rates were detected after mine abandonment, onset of flooding, and change of rate of rise of mine water levels. Based on other hard coal mining districts that were already flooded and regarding the temporal development of the mine life cycle, five phases (1–5) can be distinguished (Rosner 2011; Heitfeld et al. 2016; Vervoort 2021) and are assigned to the areas studied here.

1. During active mining, subsidence is caused by excavation and dewatering (Harnischmacher and Zepp 2010, 2014; Malinowska et al. 2020). The exact amount of ground displacements depends on the depth, inclination, number and thickness of exploited coal seams, surface topography, presence of faults, and the composition of the overburden (Vervoort and Declercq 2017 and references therein).
2. Subsidence caused by mining can occur even decades after extraction has been terminated (Rosner 2011; Busch et al. 2017; Vervoort and Declercq 2017; Heitfeld et al. 2016).
3. During the first phase of the mine water rebound, usually no significant uplift can be observed. Nevertheless, Heitfeld et al. (2016) show examples of immediate uplift after the initiation of flooding and examples where the uplift begins with a delay of almost two years. Often, subsidence continues for some time as loosened rock still must be densified (Heitfeld et al. 2016). A short-term increase of subsidence might be caused by settlement due to saturation (Rosner et al. 2014) and as the result of a disequilibrium between the weight of the water column and the pore pressure within the surrounding (low-permeability) rock mass.
4. After a sufficient pore pressure has built up in the rock mass, expansion movements effect surface uplifts. This requires a certain impoundment depth. For North Rhine-Westphalia and South Limburg, impoundment depths of 300–600 m were reported (Heitfeld et al. 2016). The surface uplift during this phase parallels approximately the mine water rise (Sroka et al. 2017). Depending on the soil-mechanical properties of the overburden layers, the rate of surface uplift might increase when the water reaches the overburden. Heitfeld et al. (2016) add that the strongest uplift is observed, where the strongest subsidence occurred during mining. In total, post-mining uplift is in the order of several decimeters (Clostermann et al. 2020) or millimeters-centimeters per year (e.g. Banton et al. 2013; Caro Cuenca et al. 2013; Malinowska et al. 2020; Vervoort 2021; Declercq et al. 2023). Accumulated subsidence during mining is on the meter scale (e.g. Harnischmacher and Zepp 2014; Vervoort and Declercq 2018; Malinowska et al. 2020; Vervoort 2020).
5. When the final mine water level is reached, ground displacements may go on for some time, but they decelerate and finally fade out (Goerke-Mallet 2000).

The hard coal districts studied here can be categorized accordingly. The different phases correspond to site-specific flooding rates and hydrological conditions. During the observation period January 2018 to December 2022, mine Heinrich-Robert in the eastern Ruhr hard coal district showed subsidence in parallel to the development of mine water levels (phase 3). Since 2022, it has been locally transitioning into phase 4. Parts of the Saar hard coal district such as the Warndt and its French neighboring hard coal districts are in phase 4 or 5. Other parts of the Saar hard coal mining district, where flooding is currently ongoing, show localized subsidence (phase 2 or 3). At Ibbenbüren's Westfeld, where the mine water rebound ended in 1982, we have not observed any ground displacements that can be related to post-mining. In the Ostfeld, our data show the passage through phases 1–4. The actual maximum displacement rates during phase 1 are distinctly higher than those that could be deduced from the time series of vertical displacement (Fig. 13). One reason for this is the averaging that has been done during orbit combination. Maximum LoS displacements observed by us during this period were > 200 mm. A possible second reason could be that the sampling is not sufficient to unwrap the signal correctly. There is an upper limit to the spatiotemporal gradients that can be unwrapped correctly, which is hard to quantify because of the dependence on distribution and quality of the measurement points. Overall, our findings fit well to the phases described in literature (Rosner 2011; Heitfeld et al. 2016; Vervoort 2021).

The spatial pattern of displacements is in qualitative agreement with the theories of (Sroka et al. 2021 and references therein). Assuming that an infinitesimal quantity of mineral extraction corresponds to a subsidence trough at the surface centered above the volume element makes them capable of forecasting all mining-related ground movements (Sroka et al. 2021). More general, subsidence can be described as the convolution of a mining-related convergence function and an influence function, and this approach can with some modifications also be used for prediction of mine flooding induced uplift (Sroka et al. 2017). According to these theoretical approaches, both the influence areas of mining related subsidence as well as those of mine flooding induced uplift are largely determined by the geometry of the mine workings and the physical properties of the geological setting. The deepest excavations are flooded first, and the strongest displacements are observed on the surface above the locations where these deepest excavations are situated (Fig. 9). But other influence factors can be important as well, e.g. the hydrological conditions or the presence of fault zones and their permeability. An example is the observation of Rosner (2011) that the area of uplift at the Aachen coal mining district reaches more than 10 km beyond the area of former excavation because of the mine water rebound. In this case, indications for the presence of such phenomena can be obtained from discrepancies between modelling and InSAR analysis.

7 Main findings and outlook

In general, the active mining phase shows a higher activity of microseismicity (number and magnitude of events) than the post-mining phase, when progressing flooding controls the temporal occurrence of microseismicity. Thanks to the high resolution of the seismic network at eastern Ruhr hard coal district and geomechanical modeling, stress arch effects at pillars below the deepest mine workings could be identified as an important source of microseismicity. In contrast, no spatial correlation between occurrence of microseismicity and large faults was observed. This is in accordance with geomechanical investigations on large fault reactivation potential, which found low slip tendencies for the eastern Ruhr area and the Saar hard coal district (although with higher uncertainty for the latter).

Soil gas monitoring proved anomalous outgassing along fault zones, and prototypes of new, modular gas and environmental sensors were successfully deployed. Anomalous outgassing into soil constitutes a temporally variable process influenced by diverse environmental effects. Proving spatial occurrence and extending permanent monitoring by optimized modular sensors are relevant next steps to clearly correlate seismicity or displacement with anomalous outgassing.

Ground displacements in hard coal mining districts show higher magnitudes and gradients of ground displacements during active mining (phase 1) than during the post-mining phase (meter-scale vs. decimeter-scale). After

mine abandonment, residual subsidence goes on (phase 2). With the initiation of mine flooding, subsidence may re-intensify (phase 3). After the mine water reaches a certain impoundment depth, the subsidence reverses to uplift (phase 4). Eventually, ground displacements fade out, after the final mine water level is reached (phase 5). During the observation period, mine Heinrich-Robert (Ruhr) passed through phases 2 and 3 and the Ostfeld (Ibbenbüren) through phases 1–4. In the Saar hard coal district, the Warndt area is within phase 4–5 and Prims-mulde is in phase 2–3. Mine water is a significant factor influencing the occurrence of ground movements, but it is not sufficient to explain these movements over time. Only after a certain impoundment depth is reached, surface uplift is correlated to the mine water level. A new observation is the parallelism of mine water levels and subsidence during phase 3 at Heinrich-Robert. Spatially, the strongest displacements at the surface are situated above the largest flooded volumes of the mine workings.

These findings may help to better plan and monitor mining operations, the post-mining phase and potential re-use of mines. The interdisciplinary workflow (3D fault model, petrophysics, fault stress analysis, seismological, soil gas, and geodetic monitoring, mine plans, mine water levels) has proven to be an insightful approach if high-resolution seismic data and 3D fault models are available (e.g. Ruhr hard coal district). The wealth of subsurface data (3D fault models, drill cores, petrography, petrophysics) collected during the multidisciplinary project FloodRisk contributes to assess potential re-use concepts of post-mining sites (e.g. geothermal applications, gas storage, and unconventional gas production). In terms of mine water management, mine operators may adjust the flooding rate to control the magnitude of microseismicity and ground displacements. Future mine layouts may be sustainably planned from the beginning to mitigate the spatial occurrence of post-mining microseismicity.

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Declarations

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