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Upward surface movement above deep coal mines after closure and flooding of underground workings

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ABSTRACT

After the mass closures of entire coal mine districts in Europe at the end of the last century, a new phenomenon of surface movement was observed—an upward movement. Although most surface movement (i.e., subsidence) occurs in the months and years after mining by the longwall method, surface movement still occurs many decades after mining is terminated. After the closure and flooding of underground excavations and surrounding rock, this movement was reversed. This paper focuses on quantifying the upward movement in two neighboring coal mines (Winterslag and Zwartberg, Belgium). The study is based on data from a remote sensing technique: interferometry with synthetic aperture radar (INSAR). The results of the study show that the rate of upward movement in the decade after closure is about 10 mm/year on average. The upward movements are not linked directly to the past exploitation directly underneath a location. The amounts of subsidence at specific locations are linked mainly to their positions relative to an inverse trough shape situated over the entire mined-out areas and their immediate surroundings. Local features, such as geological faults, can have a secondary effect on the local variation of the uplift. The processes of subsidence and uplift are based on completely different mechanisms. Subsidence is initiated by a caving process, while the process of uplift is clearly linked to flooding.

1. Introduction

After the mass closures of entire coal mine districts in Europe at the end of the last century, a new phenomenon of surface movement was observed—upward movement in the area above the past exploitation and in the immediate surroundings. Of course, most surface movement (i.e., subsidence) occurs in the months and years after mining by the longwall method [1]. This downward movement continues to occur at a smaller rate many decades after mining has been terminated when the water in the underground excavations is pumped to the surface. This is the case as long as a mine is in operation. However, after the closure and flooding of the underground excavations and the surrounding rock, this movement is reversed, and the surface is uplifted. A total uplift of about half a meter has been recorded to date. This phenomenon has been described in several different coal basins in Europe, for example, in Belgium, France, Germany, the Netherlands, and Poland [2–7]. To date, research has focused mainly on understanding the phenomenon and identifying general trends, whereby the link with the rise in water levels is an important issue [7,8]. There are several possible explanations, for example, the swelling of clay minerals in the argillaceous rocks in the coal strata [8]. However, decreases in the effective stresses also result in the relaxation or expansion of the rock, which induces an upward movement [9]. On the other hand, most coal strata rock is weakened upon contact with water and the increase in water pressure results in a decrease in the effective stress. Both aspects facilitate the fracturing of rock, which normally would result in further subsidence. So, the full explanation is complex. All of these aspects, including the long-term residual subsidence due to compaction under dry conditions, result in a net upward movement, as observed. The phenomenon discussed here is clearly different from the upsidence, sometimes observed on other continents [10]. When upsidence occurs, the rock near the surface bends and buckles upwards due to the overstressing of the floors of the valleys.

The phenomenon of upward movement was detected recently, so we do not understand all of the aspects of the underlying processes. Hence, each systematic analysis of data related to surface movement and mining characteristics should help to improve our understanding. Therefore, in this study, as in previous studies, the researchers' objective is to provide better quantification of the

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surface movement for a specific area [11,12]. This study focuses on coal mining in the Campine Basin in northeast Belgium (Fig. 1). The area that has been mined corresponds approximately to an east-west zone with a length of about 60 km and a north-south width of 5–10 km. Coal mining also has taken place to the east of this zone (in the Netherlands and in Germany).

As noted in Fig. 1, the study area in this paper is situated around a longitude of 5.495°E.

2. Case study of Winterslag and Zwartberg

A total of seven collieries were once active in the Belgian Campine Basin. Coal production started in this area in 1917 at the Winterslag Mine. The first mine closure was the Zwartberg Mine in 1966. The other mines were closed between 1987 and 1992. These mines produced more than 400 million tons of coal, with the highest annual production, about 8–10 million tons, occurring between 1950 and 1970 [13]. Longwall mining was the only mining method used in these mines. These longwalls had a single headgate and a single tailgate on each side of the panel, and, normally, no barrier pillars were left between the longwall panels. In general, the standard geometry of a panel was a rectangle that measured about 200 m by 800 m. In the early years of mining, smaller panels also were mined, and sometimes they had more complex geometries. Mining took place at depths between −450 and −1050 m. In European coal basins, a large number of longwalls in different seams were mined above each other, separated by waste rock. In the Campine Basin, this number could even be more than 10 seams. The mining height of most longwalls was between 1 and 1.5 m.

The largest variation in subsidence, as well as the largest variation in the upward movements, occurred predominantly in the north-south direction (perpendicular to the east-west axis of the entire zone mined (Fig. 1)) rather than the east-west direction. Specific local situations could be different due to the presence of faults and unmined zones. In this paper, we report the results of our study of portions of the surfaces above the Winterslag and Zwartberg mines (Fig. 2). The Zwartberg Coal Mine was active from 1920 until 1966. In 1966, production was stopped, and the underground was sealed off. Then, flooding of the underground started. The Winterslag Coal Mine began production in 1917 and was closed in 1988. The Zwartberg Mine was, on average, deeper than the Winterslag Mine. The main levels in the Zwartberg Mine were between −654 and −1010 m, whereas the main levels were between −600 and −850 m in the Winterslag Mine. Although there were no man-made connections between the two underground workings of the mines, water from the Zwartberg Mine flowed into the underground workings of the Winterslag Mine. The flow rate was estimated to be about 30 m^3/h. Therefore, it was assumed that the water level in the Zwartberg Mine stabilized at a depth of about −850 m. After the closure of the Winterslag Mine in 1988, its shafts were sealed off, and the mined-out area and the surrounding rock started to flood. At the same time, the water level in the Zwartberg Mine increased further. During the years of full production, about 7000 m^3/day of water was pumped to the surface in the Winterslag mine [14].

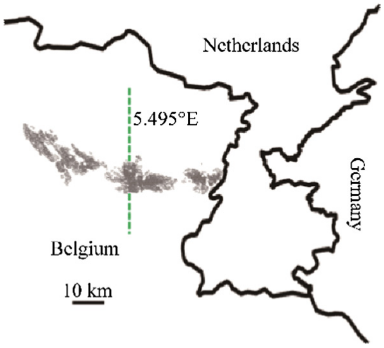


Fig. 1. Overall view of all longwall panels mined in the Campine Basin of Belgium in the 20 th century.

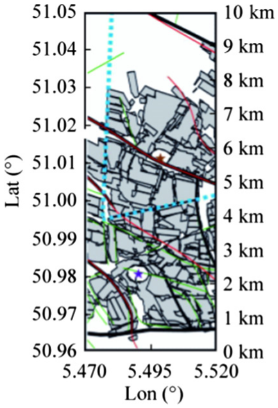


Fig. 2. Map of all longwall panels mined (presented superimposed) in part of the concession of the coal mines Winterslag and Zwartberg.

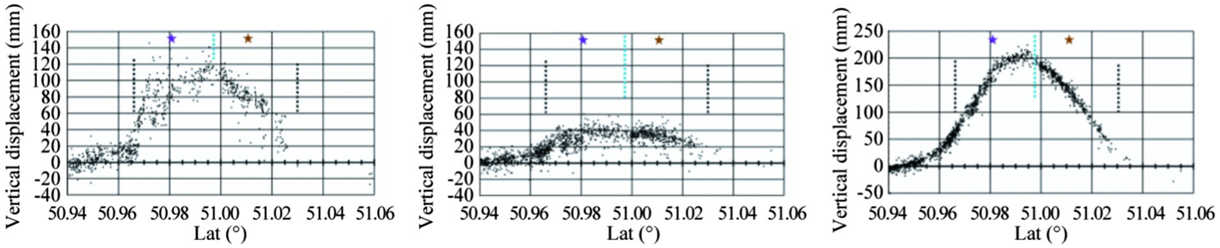
As noted in Fig. 2, blue dotted line is the concession limits, stars mean the average position of double central shafts (Winterslag in purple and Zwartberg in brown), longwall panels are superimposed in grey, and faults indicated in green, red and thick black lines.

In this paper, we concentrate our analyses on a north-south zone situated around the longitude of 5.495°E (Figs. 1 and 2). This zone is situated between the two shaft areas. Fig. 2 shows all of the longwall panels (superimposed) for an area of approximately 10 km by 3.5 km. This study is based on data from a remote sensing technique: radar-interferometry or interferometry with synthetic aperture radar (INSAR). It allows the study over a long period of time of the movement of reflectors situated in a large area. It provides measurements every 35 days at distances ranging from 10 to 20 m with accuracies of about 1 mm/year. More details are available in the literature [3,12,15,16]. The European C-band ERS1/2 and ENVISAT-ASAR satellite images made available for research through a European Space Agency (ESA) research proposal are used in this study. The images were recorded for two different periods: one period of nearly 8.5 years (87 cycles of 35 days each from August 1992 through December 2000) and one period of nearly 7 years (72 cycles of 35 days each from December 2003 through October 2010) [2].

3. Analyses of surface movement data

3.1. Global variation in the north-south direction

In the Belgian Campine Basin, two different trends have been observed for surface movement after the closures of the coal mines [2]. In the western part, residual subsidence still occurred for a period of about 10 years after the closures, but, in the eastern part, including the Winterslag Mine, upward movements already were visible at the beginning of the first observation period in August 1992, which was 4–5 years after the closures of the mines. The largest spatial variation occurred in the north-south direction. Therefore, we concentrated on a north-south transection. We took a central line that was situated between the two shaft areas and covered the concession of the Winterslag and Zwartberg mines. The central line corresponds to a longitude of 5.495°E (Fig. 2). The reflectors were not situated on a straight line, so we considered a



(a) Period 1 from August 1992 through December 2000

(b) Period 2 from December 2003 through October 2010

(c) Total period from August 1992 through October 2010, including interpolated part

Fig. 3. Variation of the total surface movement along a north-south transect, situated around a longitude of 5.495°E.

buffer zone with a certain width as a compromise between having sufficient data points and having limited scatter in the other direction. Thus, we opted for the zone between 5.486 and 5.504°E, which was about ±600 m wide around the central line.

Fig. 3a and b shows the total surface movements since the start of each observation period for all reflectors within the selected zone. Fig. 3c shows the total surface movements for the entire 18-year period from August 1992 through October 2010. To compose the latter, an interpolated curve was estimated for the first observation period and added to the surface movements of the second observation period, as the reflectors are different between both observation periods. In a similar way, the surface movements between December 2000 and December 2003 were estimated and also added. The representation of the total movements in the first observation period by a smoothed curve leads to less variation in Fig. 3c in comparison to Fig. 3a. The variation due to the inaccuracy of the method has, at least partly, disappeared; however, real local variations in the first observation period have most likely been smoothed out. Note also that the length of the zone in Fig. 3 is longer than that of the area presented in Fig. 2. In the next section, we provide a more detailed comparison of the exploitation characteristics, but, referring to Fig. 2, it is apparent that the past mining occurred between the latitudes of approximately 50.965 and 51.030°N. Before discussing these graphs, it should be noted that (1) there were nearly no reflectors further north than 51.027°N because this area was agricultural and semi-natural land and (2) the recorded values for reflectors at a certain latitude were situated within a band width of about 20 mm. Past experience showed that such a variation can be considered the normal scatter for these types of observations [12].

In Fig. 3, black dotted lines are the mining limits in N and S, blue dotted line is border between the two concessions, and stars mean the average position of double central shafts, specifically Winterslag in purple and Zwartberg in brown.

After about 8.5 years of observations, Fig. 3a shows clearly that the entire area above the mined-out zone has been uplifted. The maximum value recorded was about 150 mm, but most reflectors were situated between 60 and 120 mm. Surface movement was less towards the extremities of the mined-out area, but uplift also was recorded outside of the mined-out area. For example, in the zone between 50.945 and 50.965°N, which was south of the mining activities, on average, a total uplift of 10 mm was observed. This is a zone that is as far as 2.2 km south of the mining activities, which is about 3–4 times the maximum depth of the longwalls in the southern part of the Winterslag Mine. On average, one could say that the uplift corresponded to an inverse trough or bowl shape (see also further, Fig. 3c). To illustrate that the variation was the largest in the north-south direction, it should be noted, that, for a latitude of about 50.995°N, the uplift during the first observation period was situated mainly between 80 and 120 mm for a distance of more than 10 km in the east-west direction.

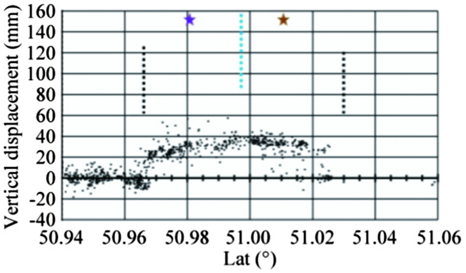


Fig. 4. Variation of the total surface movement along a north-south transect, situated around a longitude of 5.495°E for a 3-year period from August 1992 through August 1995.

Fig. 4 shows the surface movement that occurred during the first three years of observation, and it provides more insight concerning how the uplift was initiated. Outside the mined area, there was no indication of uplift yet. Even at the extremities of the mined area, there were many reflectors without any uplift, and some even indicated that subsidence was still occurring. For the remaining part of the transection (between the latitudes of about 50.965° and 51.025°N), the uplift tended to be situated around a constant value of about 30 mm.

Fig. 3b shows the total movement during the second observation period. The reflectors were not necessarily the same for both observation periods. On average, there were more reflectors selected in the second observation period than in the first because a more advanced satellite was being used. In the nearly 7-year period from December 2003 through October 2010, the rate of movement was clearly smaller, certainly for the zone above the mined-out area. For comparison purposes, the same vertical scale was used. Outside the mined area, a total additional movement of about 10 mm was recorded. In the second period, there were a few reflectors outside the mined area in the north, and they underwent an uplift of 10–20 mm. The additional uplift after December 2003 was almost constant over most of the mined area. At the extremities of the mined area, again, the amount of uplift was smaller in comparison.

Fig. 3c clearly confirms the inverse trough shape when looking at the entire 18-year period. It also shows a maximum just south of the concession boundary between both mines. This maximum corresponds to a total uplift of about 200 mm. Above other coal mines, we also observed an inverse trough shape with a distinct maximum in the curve, but this maximum was situated close to the shaft area [11]. For the concessions of the Winterslag and Zwartberg mines, the situation was more complex than for a single coal mine because the partial flooding of the underground of the Zwartberg Mine already had started in 1966, and there were two shaft areas along the north-south transection.

Figs. 3 and 4 show that there were variations in uplift depending on the position on the north-south coordinate and that the

Table 1
Average total surface movement for 20 reflectors since the start of each observation period for the first 3 and 6 years, respectively.

Latitude (°N)	Surface movement since August 1992 (mm)			Surface movement since December 2003 (mm)		
	After 3 years	After 6 years	Ratio	After 3 years	After 6 years	Ratio
50.965	2.3	11.9	5.2	4.6	8.3	1.8
50.975	26.3	52.6	2.0	14.2	24.1	1.7
50.990	29.1	71.8	2.5	18.1	30.2	1.7
51.005	34.1	67.7	2.0	17.3	31.2	1.8
51.015	28.9	52.6	1.8	16.1	28.3	1.8

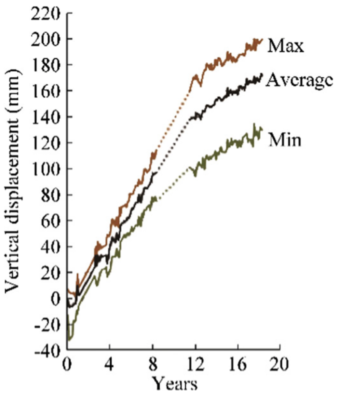


Fig. 5. Variation as a function of time of the total surface movement for 20 reflectors at and around a latitude of 50.990°N and a longitude of 5.495°E for both observation periods (reference date is August 1992).

variations changed over time. Therefore, some average values are given in Table 1 for five different locations. Each time, the average was calculated for the 20 reflectors that were closest to the selected latitude coordinate and that were within the zone that was being considered (between 5.486 and 5.504°E). As an example, Fig. 5 shows the variation as a function of time for both observation periods for the 20 reflectors at or near the latitude of 50.990°N. This latitude was situated in the zone where the largest uplift occurred. The period between the two observation periods was interpolated. In addition to the average, the minimum and maximum values for each date also are presented. The extreme values did not always occur at the same reflectors over the entire period or between both periods. Table 1 provides the total movement since the beginning of each observation period for the first three and six years respectively, which makes it easy to compare the results.

The latitude of 50.965°N corresponds approximately to the south border of the mining area. Between August 1992 and August 1995, on average, the uplift was negligible (less than 1 mm/year). The rate increased in the following three years, but it remained small (about 3 mm/year). In the second observation period, the rate was about 1–1.5 mm/year. For the other four latitude values, the total surface movements were much larger, and the largest values were recorded for latitudes 50.990 and 51.005°N. For the latitude of 50.990°N, the uplift accelerated during the first observation period. The ratio after three and six years was 2.5, while it was 2.0 or less for the other three locations. This difference was not observed in the second period; rather, the ratio after three and six years was in the range of 1.7–1.8, which indicated a decrease in the uplift rate. A comparison of the four similar locations during the first three years of both observation periods indicated that the rate clearly had decreased. In the first observation period, the average rate was 8.8–11.4 mm/year, but it was between 4.7 and 6.0 mm/year in the second period. Note that earlier research has shown that the annual increase for a single reflector can be several times the average of several reflectors, and, similarly, it can be several times the average over a number of years [12].

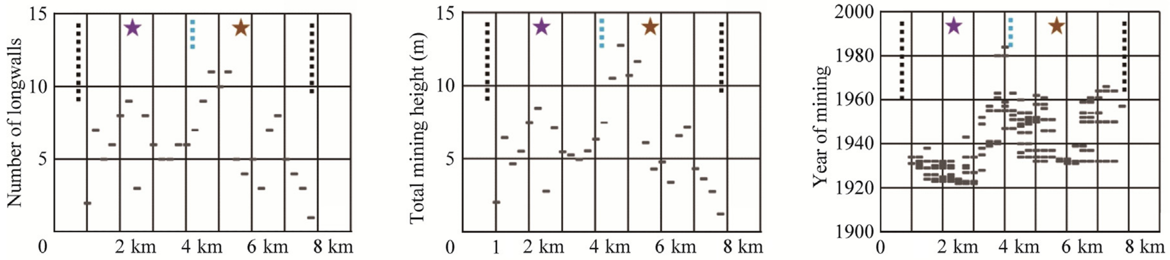
3.2. Comparison to mining characteristics

Fig. 6 shows four mining characteristics for the line that corresponds to a longitude of 5.495°E. Here, the distance is presented as a function of kilometers rather than degrees, as indicated by the right axis in Fig. 2. The data are plotted beginning at a latitude of 50.960°N. In Fig. 6, unlike Figs. 3 and 4, a distance of only 9 km is presented, which is slightly larger than the total length of both mines in this transection. The following mining characteristics are presented every 250 m: the number of seams mined (Fig. 6a), total mining height over all seams (Fig. 6b), the years these panels were mined (Fig. 6c), and mining depths of the different longwall panels (Fig. 6d). In Fig. 6e, the total surface movement in the first observation period is presented again but for the same 9 km as the other graphs in Fig. 6.

Along most of this line, the total mining height was between 4 and 8 m (Fig. 6b). Just north of the border between the two mines (at 4.2 km), more longwalls were mined in different seams, and the total mining height was about 10–13 m. Less mining was done at the southern-most and northern-most limits. The individual mining heights for the various seams and panels that were mined were between 0.67 and 1.46 m. Along this transection, only three panels were mined after 1966 (Fig. 6c). This means that nearly all of the panels were mined without full mechanization and certainly without using shield support. In the southern part of the zone that was studied, mining only took place in the first half of the last century. The Winterslag Mine stopped production more than 20 years after the Zwartberg Mine. However, along the transection studied, no mining took place in the Winterslag Mine after the closure of the Zwartberg Mine, except for three panels, close to the border with the Zwartberg Mine. Fig. 6d clearly shows that the depth of mining increased towards the north, which is logical given that, on average, the dip of the seams (about 10–15°) is towards the north.

Of course, in comparing surface movement with mining characteristics, it is important to remember that surface movement is a three-dimensional problem. Therefore, we also considered the mining characteristics at locations that were within 1 km to the east and 1 km to the west of the line in Fig. 6. 1 km is a conservative limit for the zones of influence since the maximum depth was −900 m, and most mining took place at depths of −700 m or less (Fig. 6d). By considering an angle of 45° for the zone of influence, 1 km is, indeed, larger than the depth. There are only two changes worth mentioning for the east-west variation. First, around the distance of 7 km, there were still three additional panels mined in 1965 and 1966, one of which was at a depth of −917 m. Second, just north of the border between the two mines, there were some other panels with a total mining height of 7.7 m. For the rest, the year of mining and the mining depth of the other panels fit within the ranges in Fig. 6c and d, respectively.

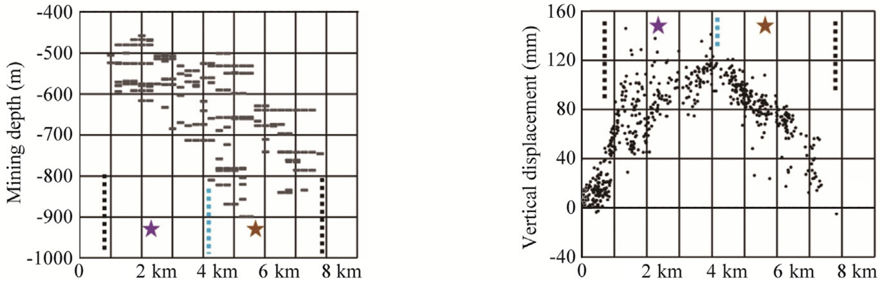
When comparing these mining characteristics with the observed uplift (Fig. 6e), one must exercise care to avoid formulating conclusions too quickly. The overall variation was a clear uplift



(a) Number of longwall panels

(b) Total mining height

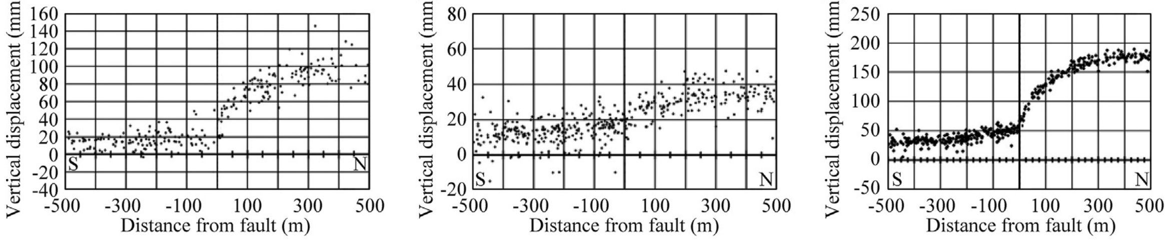
(c) Year of mining of the different longwall panels



(d) Mining depth of the different longwall panels

(e) Total surface movement during the first observation period (part of Fig. 3a)

Fig. 6. Mining characteristics along a north-south line corresponding to a longitude of 5.495°E and relative to a latitude of 50.96°N (distance of 0 km).



(a) Period 1 from August 1992 through December 2000

(b) Period 2 from December 2003 through October 2010

(c) Total period from August 1992 through October 2010, including interpolated part

Fig. 7. Variation of the total surface movement perpendicular to the Midi fault situated at the southern border of the exploitation between a longitude from 5.495 to 5.515°E.

above the mined-out area, but, towards the borders in the north and the south, the uplift decreased. Further than the mined-out area, some uplift was observed. Due to the presence of the shaft area in the Zwartberg Mine, all four mining characteristics decreased when the distance was between 5.5 and 6 km, but this was not visible on the graph of the uplift during the first observation period. Although, to a lesser extent, the same occurred for the shaft area of the Winterslag Mine, but, again, this was not apparent in the data of the uplift values. Of course, the mining depth, as well as the most recent year of mining, increased for a distance from 1 to 4 km, and over this distance there was also an increasing trend in the uplift. However, it is our opinion that it would be inappropriate to conclude that there is a proper correlation. The mining depth increased still further, from 4 to 5.5 km, without any further increase in uplift; rather, the uplift decreased. The largest total mining height and the largest number of longwalls clearly were situated around a distance of 5 km, but this did not correspond to the zone with the largest uplift. Taking past research into account, we concluded that there was no clear and direct link between the mining characteristics and the uplift values, apart from the fact that mining took place [11,12]. For each observation that supported a certain correlation, there were other observations to support the opposite relationship. Therefore, we see as the most realistic and correct conclusion that the shape of the uplift corresponds to an inverse trough or bowl shape situated over the entire mined-out area and the immediate surroundings, at least in the north-south direction. Such a shape is typical for a flooded zone or for a reservoir where the fluid pressure changes [9].

3.3. Local variation around the fault at the boundary of the mined zone

Although the accuracy of the measurements used generally was accepted to be within 1 mm/year, when one calculates the rate over a longer time period, the fluctuation between successive observations can be larger. Based on our experience, the latter is ±10 mm around an average as a function of the distance for the calculated total movement. In other words, we considered a local spread of 20 mm as the typical scatter for the images used by these two satellites [12]. For example, Fig. 3a shows that the local variation sometimes is larger than 20 mm, and we consider this to be significant. It is not the direct consequence of the measuring method. In other words, there must be a logical explanation based on local geology or other influential parameters. Since the whole process of residual subsidence and uplift undoubtedly is very complex, it is difficult to pinpoint the real causes of larger variations. For this particular site, we paid special attention as an example to the zone around the most southern fault, the Midi fault, which is also the boundary of the mining operations (Fig. 2). It has an

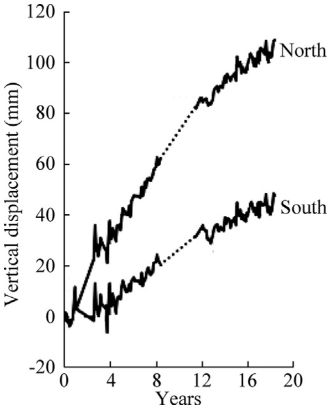


Fig. 8. Variation of the average surface movement as a function of time for all reflectors situated at a distance of 25–100 m from the Midi fault for both the zone in the south (no mining) and in the north (where mining occurred) between a longitude from 5.495 to 5.515°E.

east-west strike direction and a vertical displacement of 200 m or more along the fault. The coal seams to the north are situated deeper due to tectonic movement. During the Cretaceous and Cenozoic eras, the Midi fault was probably active, resulting in Midi fault displacements of the order of 10 m within these younger strata. The Midi fault in the coal strata is characterized by strong fracturing, and the total width of the fault, which is composed of crushed rock material, is 10 m or more. Also, this fault contains a lot of clay, which results in the fault having low permeability.

In Fig. 7a and b, the total surface movements in both observation periods are presented for all reflectors situated in a zone parallel to the fault between the longitudes of 5.495 and 5.515°E (a length of about 1400 m). Similar to Fig. 3c, the total estimated movements over the entire 18-year period are presented in Fig. 7c. The distance between each reflector and the fault was calculated, and the surface movements were presented as a function of the distance to the north or to the south. The graph is limited to a distance of ±500 m. Fig. 8 shows the variation of the average surface movement as a function of time for all reflectors situated at a distance of 25–100 m from the fault for both the zone in the south (no mining) and in the north (where mining occurred). For this graph, we did not consider the reflectors within a zone of ±25 m because there could be some inaccuracy concerning the exact position of the fault. As mentioned above, the width of the fault was considered to be at least 10 m. In Fig. 8, the period between the two observation periods was interpolated.

For the first observation period (Fig. 7a), the movement south of the fault was relatively constant over a distance of 500 m, and the uplift varied between 0 and 30 mm. At the other side of the fault, the uplift values closest to the fault were 40–60 mm, and they increased as their distances from the fault increased. The fault actually acted as a discontinuity in the movement. Even though no data are available for the water level, we interpret this graph as indicating that the water flowing from the north encountered the fault zone as a barrier. Of course, the absence of mining and caving to the south of the fault also helped in creating a barrier against the water flow. In the zone that we considered, between the longitudes of 5.495 and 5.515°E, no tunnels were excavated through the fault. More to the west (around the longitude of 5.490°E), a test panel was mined, and there were two tunnels constructed through the fault. For the surface movement that occurred during the second observation period (Fig. 7b), the effect of the fault location can still be observed, indicating that there was an approximately constant uplift to the south and an increasing uplift from the fault northwards. However, no discontinuity can be observed for the variation of movement. South of the fault and just north of the fault, the uplift during the second period was about 10–30 mm. The most logical explanation for the difference between both observation periods is that as the water level increases water starts to flow through the fault zone. The total surface movements over the 18-year period (Fig. 7c) clearly indicate the position of the fault at the extremity of the mined area.

In Fig. 8, the curves as a function of time show that the rate of surface movement north of the fault was larger than the rate south of the fault. Also, there were different delays in the initiation of the upward movement. Unfortunately, no data images were available for the period between October 1993 and March 1995. The upward movement in the north started about one year after the start of the measurements (August 1992), which is similar to what is shown in Fig. 5. In the south, the upward movement began after three years.

4. Discussion and conclusions

Currently, people in the mining industry are well aware that they must pay close attention to the impacts of their operations on the environment. Ongoing research to address the subsidence above and around caving operations, like the longwall method, should further be conducted to better quantify and monitor the movement of the surface [17]. A good understanding and quantification of the long-term impact also has increased in importance. This should allow reliable risk assessments, including assessing the period after the mine closes. The long-term impact certainly includes the residual subsidence, which can still take place many decades after the initial mining. However, recent observations above deep European coal mines showed that the surface movement can be reversed after closure of the underground access and the flooding of the deep underground areas. The rates of upward movement are of the same order of magnitude or larger than the residual subsidence rates [12]. The values of total uplift will always be less than the original subsidence values, but, since the two processes (subsidence and uplift) are two completely different processes, the maximum values occur at different locations [11]. The maximum differential movements and the maximum horizontal strains also occur at different locations. Subsidence is initiated by the caving process, and it can be seen as a mechanical-stress, deformation-driven process, including time-dependent aspects. The process of uplift clearly is linked to the increase in the underground water level, as shown by Caro Cuenca et al. [7]. The effect of the water is complex, and some impacts facilitate further subsidence, while others contribute to uplift. Since the phenomenon of upward movement was detected recently, not all aspects are fully understood yet. Crucial data often are missing, as is the case for the Campine Basin in Belgium, and they are needed to understand and fully explain the observed phenomenon of upward movement. For example, in our case study, past subsidence data were not publicly available, and no measurements were conducted on the variations of the water level in the deep underground after the closure of the mines. The latter also means that the water flow paths are not known. As many faults are present (Fig. 2) and the exploitation took place in two different mines, the flood water comes most likely from various sources. For example, we know that water flowed from the Zwartberg Mine to the south after the closure of the Zwartberg Mine in 1966, when the mine of Winterslag was still in operation. However, even that we have not a complete picture with all the information, a systematic analysis of satellite data on surface movement after closure helped to improve our understanding. For the areas above the two coal mines we studied, some worthwhile conclusions can be formulated.

A first conclusion is that, for this case study, uplift varied as a function of the north-south coordinate, and this variation changed over time. The overall spatial trend indicated that there was a clear uplift above the mined-out area and that the uplift decreased towards the borders to the north and the south. However, some uplift still was noted farther away than the mined-out area. The zone of influence was determined to be as far as 2.2 km south of the mining operation, which is about 3–4 times the maximum depth of the longwalls in the southern part of the mine. Therefore, the shape of the uplift corresponds to an inverse trough or bowl shape situated over the entire mined-out area and the immediate surroundings. This is a smoother shape than one would expect for the subsidence that occurs immediately after mining. The latter is much more affected by the location of the longwall panels and their collapsed zones as well as by the extent of the unmined zones, e.g., around the shaft areas. This effect, of course, is less pronounced if the longwall panels are situated deeper. Since the upward movement is linked to flooding, it is logical to expect that the shape of the uplift would be smoother. Water spreads out more evenly, while caving is more locally situated. At the beginning of the uplift, average rates of 9–11 mm/year were recorded in most parts of the mined area; however, a decade later, these rates were between 5 and 6 mm/year. Over a 20-year period, total uplift values of 140–220 mm were observed in certain zones.

A second conclusion is that no direct correlation can be established between the amount of uplift and the characteristics of the mining process (e.g., total mining height, mining depth, and time since the mining was done). For example, the zones in which the largest total mining height existed and the largest numbers of longwalls were excavated did not correspond with the zone of the largest uplift in the first observation period (approximately 4–12 years after the mine was closed). When we evaluated the uplift during the second observation period (approximately 15–22 years after the mine was closed), there was certainly no indication of any correlations, since the additional uplift was relatively constant over the largest part above the mined area.

A third conclusion is that, during uplift, major geological faults also can have an effect. For example, at the start of the uplift (first observation period), the fault at the southern border of the mining area clearly acted as a barrier to the water flowing from the north. A clear discontinuity was observed in the movement at the fault position. In the second observation period, the shape of the uplift was more continuous, but the upward movement was still smaller south of the fault where there had been no mining. In the immediate vicinity of the fault, 50 mm of uplift, on average, was recorded south of the fault over a 20-year period. For the same period, the uplift to the north was about 100 mm.

Globally, one can conclude that this case study, like others, has improved our knowledge about the upward movements of the surface, and that the quantification of the behavior has been improved. However, it is also apparent that more data and research are needed, e.g., to acquire information and data on the water levels in the deep underground and their variation over time. Accurately predicting the short-term impact of complex mining geometries is quite complicated [5,18], but the long-term impacts are even more difficult to describe well. As correctly pointed out by S. Peng in 2015: "time has been a forgotten factor in all ground control design, and, yet it is one of the most important behavior factors. All rocks exhibit time-dependent behavior including failure, especially sedimentary strata associated with coal mining, and some are fairly large in magnitude. But very few researches have considered this factor" [17].

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