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Author comments on Referees comments for paper “Surface movement above an underground coal longwall mine after closure”, A. Vervoort

Dear Editor

First of all, I would like to thank both referees for their comments and suggestions (no other comments were posted by the scientific community). Overall, I consider their reviews as positive. Below I write my reaction, point per point, on their points of criticism and on their suggestions. Mostly, I agree with them and I have made already the necessary changes in the manuscript (see file attached), although this was not required yet.

I have used the following color code: the text by referees is in black; my comments are in blue and the changes made in the manuscript are in red.

I hope that you agree with the changes that I have made. However, if you would still like further improvements, please let me know.

Kind regards,
André Vervoort

Anonymous Referee #1

Received and published: 2 June 2016

The presented topic is of high significance. It addresses environmental impacts of underground coal mining after closure in terms of residual subsidence and uplift and contributes as such to after mine care and safety. The paper is well presented and structured, includes a thorough analysis of spatial data leading to new insights into mechanisms controlling vertical ground movements after mine closure.

I thank the first referee for the positive global evaluation.

From the reviewer’s point of view, view minor changes may support the contribution:

1) It is advised to use passive voice consistently in the text, no use of we

I know that this point is often a point of discussion and that some journals prefer the passive form and others the active one. I have checked some papers in nhess and I see both forms being published. So, I have made in the revised version no changes to the manuscript on this point. However, if the editor would insist on the passive form, please let me know and I will the necessary changes.

2) Lines 143 – 146 appear to the reader a bit unclear (overlap in time zones) – this could be rewritten more clearly

I accept this suggestion and I have reformulated this part, so that it is better formulated. The new text is as follows:

In a similar way, it was observed that, at the start of the second period of observation (from December 2003 through October 2010), certain reflectors were still undergoing downward movement. Therefore, **in first instance, we looked at 5- year time zones in each observation period, which can be considered to be characterized by a pure downward movement (for the first observation period from mid-August 1992 through mid-August 1997) or a pure upwards movement (for the second observation period from mid-September 2005 through mid-September 2010). The remaining part of each observation period was also studied and for comparison purposes, a length of 2.5 years was chosen, i.e. the last 2.5 years of the first period and the first 2.5 years of the second period. These two 2.5-year time zones were from July 1998 through December 2000 and from December 2003 through June 2006, respectively. As the total first observation period was longer than 7.5 years and the second shorter,** there was a gap between the time zones of 5 and 2.5 years in the first period and a small overlap in the second period, but the main advantage of doing so was that all time zones could be compared more easily.

3) At the beginning of section 3 the reader may already ask himself about the sequence of mining as it may likely influence the timely subsidence/uplift behaviour. Although discussed later in section 4, it may help to introduce basic mining parameters (depth, thickness, and mining sequence) already in the introduction section next to the description of geology. A map containing years of production of the panels may help visualising a possible link between ground movement and extraction sequence.

I have tried to build the paper in a systematic order, whereby the analysis of the data on the surface movement is the central and most important part, followed by an interpretation of the observations. On the other hand, the basic mining parameters were already mentioned in the introduction:

At a certain X-Y position within the mined area, one to eight different coals seams were mined. The combined mining height of the several seams varied from 2.0 to 12.3 m within this area. The height of the mining of individual panels varied from 0.9 to 2.7 m, and, normally, about 10 to 40 cm of it were layers of waste rock. In some cases, either no waste rock was mined or only a few centimeters were mined, but, in other cases, almost 1 m of waste rock was recorded as having been mined. As the map indicates, certain zones were not mined. Apart from the zone around the vertical shafts (around the coordinates of Latitude 51.025°N and Longitude 5.370°E), these unmined zones mainly were areas around faults. The latter were composed of a predominant set of NNW - SSE striking normal faults with subordinate N-S to NE-SW striking thrust faults. In the later decades of production, a typical longwall panel had dimensions of 200 by 800 to 1,000 m. The main and tail gates were immediately adjacent to the panel, and they were just single tunnels with a horseshoe cross-section. So, no barrier or remnant pillars existed between the

longwall panels. In the area that we studied, the mining depth varied from 539 to 967 m, and the mining occurred between 1932 and 1992. However, most of the panels were mined in the 1960s and 1970s. In Sect. 4, more details of the mining characteristics are provided, and their possible influences on the surface movements are discussed.

So, I would like to keep it this way.

Regarding the remark on adding the year of production to each individual panel on Fig. 1: I understand the referee, but I have tried this before but this leads to, on the one hand, an overloaded map with too much information and, on the other hand, not all information can be made visible. The main reason is that up to 8 panels are mined above each other. In fact one needs to see it in 3D. So, the presentation of the information in Tables (see Table 3 and 4) seems me to be the best option, although it is less visual.

4) Sentence in line 185 related to EW section could be left out (Ideally, : : :), since no section is presented.

The word 'section' has been replaced and the sentence starting with 'Ideally' has been taken out. The new text is as follows:

To better visualize the map of reflectors, **the movement along** a north-south **line** is presented in Fig. 4a. **To have a sufficient amount of reflectors along this line**, a north-south zone was selected for Longitude between 5.37°E and 5.38°E, about 700 m wide **in the east-west direction**.

5) Formulation in line 263 appears unfortunate: Better: 'It becomes obvious that an uplift over the entire area took place'

I assume the referee refers to line 213. I have changed the sentence as suggested.

In the five-year time zone from mid-September 2005 through mid-September 2010 at the end of the second observation period, **it becomes obvious that an uplift over the entire area took place** (Fig. 5a).

6) General question on section 3: Does the author suspect that when using different time periods (e.g. 2010 – 2013 or before 1992) results may differ, especially with respect to the rate of residual subsidence and uplift, e.g. due to the extraction sequence? In other words, is the comparison between 2 x 5 year periods just a snapshot or can observations be generalized? A short discussion may address this issue (partly later answered in section 4.3).

This is an interesting and important point that the referee raises. The period of 5 years is not chosen at random. It is based on earlier research (see Vervoort and Declercq, 2016), in which annual increases in movement were studied in detail. This showed that during both periods of about 5 years there was either only subsidence (first observation period), or only uplift (second observation period). So, that means that if we would have chosen 4 years instead of 5 years, we would have also a pure downward or upward movement, but this would be not the case by

choosing 6 or 7 year time zones. In the latter cases, the movement would change direction during the entire period (at least at a significant amount of reflectors).

The first sentence of section 3 has been changed and the changes made following comment 2 (see above) should also help to clarify this point.

Earlier research (Vervoort and Declercq, 2016) **looked at annual increases in surface movement.**

For your information, the paper Vervoort and Declercq, 2016 is in the mean time accepted for publication. This has also been indicated in the list.

Vervoort, A., and Declercq, P.-Y.: Surface movement above old coal longwalls after mine closure. **Accepted (May 6th 2016) for publication in** Int. J. of Min. Sc. and Techn., 2016.

7) Interpretation lines 356-359: Note that especially in the centre of the field, considered the x and y coordinates for min and extensive mining activities are rather close. From the map the distance appears to be less than the area of influence. Movements may be superimposed and the ground movement behaviour at a min location is most likely affected by the subsidence from a neighbouring panel. Thus the ground movements of points which are close to each other may not be interpreted independently. Conclusions drawn can be associated with some fuzziness, which would reflect the limit of this study by not taking the spatial nature (i.e. angle of draw of 45 degrees and superimposition of effect of multiple panels) into account.

I fully agree with the comments by the referee. If one would consider the zone of influence of all panels, nearly all points within the area studied are within the zone of influence of at least one panel, of course sometimes a very old panel. An angle of draw of 45° means that the extent of the zone of influence beyond the edge of the panel is the depth of the panel. By considering the maximum depth at a certain location, the zones of influence are about 700 to nearly 1,000 m wider than the panels (e.g. on Fig. 1).

On the other hand, theory tells us that the maximum subsidence is of course larger above the mined out area than at the edges of the zone of influence. In one way, this is also logic. However, by looking at residual subsidence this cannot be clearly concluded, which is one of the main findings of this research.

To address the point raised by the referee, a sentence has been added in Sect. 4.2:

By looking at the map of the exploitation (Fig. 12), this means that nearly the entire area studied is within the zone of influence of at least one longwall panel.

Also, earlier (section 4.1), I have added the following sentences:

Table 3 provides a summary of some basic information on the exploitation just underneath the two locations. **The surface movement is of course not only affected by the mining directly below, but also by the mining around the locations. For an angle of draw of 45° the extent of the zone of influence is even equal to the depth of mining. However, the impact decreases when moving away from a panel, which justifies considering the exploitation in the immediate vicinity.**

This point is further addressed under comment 8, below. It would also be worthwhile to conduct in future research a similar investigation as the one presented, but whereby data are public on the initial subsidence too, so that a comparison can be made between initial subsidence, residual subsidence, uplift and mining parameters.

8) Conclusions: One main conclusion is that there is obviously no one-to-one relation between some parameters and the effects of residual and uplift. A suggestion may be added to further research on this multi-variate problem using techniques including unsupervised learning and supervised learning.

This is a very good suggestion and the following sentence and reference has been added in the Conclusions:

As for this area, no one-on-one relationships could be clearly identified between the surface movement and the mining characteristics, future research of this multi-variate problem could benefit by using techniques including unsupervised learning and supervised learning (Noack et al., 2014). Best would be to have data on the initial subsidence, the residual subsidence and the uplift, combined with data on the mining characteristics.

Noack, S., Knobloch, A., Etzold, S.H., Barth, A., and Kallmeier, E.: Spatial predictive mapping using artificial neural networks. In: Proceedings of the International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XL-2, 2014 ISPRS Technical Commission II Symposium, Toronto (Canada), 79-86, 2014.

9) Note on line 492: Much research has been conducted and published (mostly in German or Polish language) on complex mining geometries and multi-seam mining in the Polish and German hard coal industry by e.g. H. Kratzsch or A. Sroka. Only some references are available in English language.

This is a good suggestion. I have added the following reference (as part of the discussion in Sect. 5 on the various approaches worldwide):

Preusse, A., Kateloe, H.J., and Sroka, A.: Subsidence and uplift prediction in German and Polish hard coal mining. *Das Markscheidewesen* 120, no. 1: 23-34, 2013.

Anonymous Referee #2

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General comments Very interesting article, especially since the issue of the residual subsidence and the uplift of the area after mining activity in Europe is increasingly important due to the fairly widespread liquidation of active underground European mining. The paper address relevant scientific and technical questions within the scope of NHESS. The paper present new

data and results. There is up to international standards. The methods and assumptions are valid and clearly outlined. The results are sufficient to support the interpretations and the conclusions. The author reaches substantial conclusions. The description of the data, the method and the results obtained is sufficiently complete and accurate to allow their reproduction by fellow scientists.

The title clearly and unambiguously reflect the contents of the paper. The abstract provide a concise, complete and unambiguous summary of the work and the obtained results. The title and the abstract are pertinent, and easy to understand to a wide and diversified audience. The overall presentation is well structured, clear and easy to understand by a wide and general audience. The length of the paper is adequate. The technical language is precise and understandable by fellow scientists. I am not English but in my opinion the English language is of good quality, fluent, simple and easy to read and understand by a wide and diversified audience.

[I also thank the second referee for the positive global evaluation.](#)

Specific comments

1) It is interesting how accurate is the method of interferometry especially for just such analysis. It would be interesting, if possible, to compare the measurement results with the results of measurements of the classical levelling method.

[I understand the referee. It is a remark which is often made and justified. Therefore, the following text has been added at the end of section 2, referring to other published research by us:](#)

[An accuracy of 1 mm/year was confirmed \(Vervoort and Declercq, 2016\) by comparing the INSAR-data to the GPS-reference points of the Belgian National Geographic Institute \(NGI\), linked to the reference stations of the Flemish Positioning Service \(FLEPOS\). For example the reference point HQ10 of NGI, situated 20 cm above the ground level, within the same coal mine basin was compared to the three closest reflectors surrounding this reference point and situated at a maximum horizontal distance of 35 m. For a 5-year period of uplift, 31.0 mm was measured at the NGI reference point, while the INSAR-reflectors showed a movement of respectively 25.5 mm, 29.1 mm and 29.9 mm. As the location of the reference point and the three reflectors are different \(plus different size between reference point vs. reflectors\), it is normal that the four values are different, but the difference is small, showing that the INSAR-data are precise for the purpose of this research.](#)

2) Conclusions are interesting but also intuitive. If uplift is associated with swelling of clay minerals that should be linked to the phenomenon of rising water levels and the occurrence of these minerals in the geological layers. As noted in an article in Carboniferous there are no clay layers. These occur in the overburden. Therefore, uplift should be associated with the liquidation of depression cone throughout its previous range, befor mining activity has been finished. Uplift should occur actually in the area where there is no mined out coal seams - that is just around the

shaft because there is still a safety pillar of the vertical shaft. The caving above exploited coal seams serve as ways of spread of water.

Therefore, one should not expect the uplift especially above areas of former mining operation. Subsidence and uplift there are independent phenomena, only slightly linked by the mining operation. This is somewhat due to the paper, and was confirmed by the Author of the article.

I fully agree with the last two sentences: the referee confirms one of the main findings of the research, i.e. there is no direct link between residual subsidence and uplift.

Referring to the remark about the clay layers, there is a misunderstanding. When talking about the swelling of clay minerals, I refer to the swelling of clay minerals in argillaceous rocks, like siltstone and shale. These are present in the coal strata. So, I am not referring to clay layers in the overburden. I have checked the entire paper and I have changed the wording in the Abstract, the Introduction and the Conclusions, as the old formulation could have lead to confusion:

the clay minerals in the **argillaceous rocks in the coal strata**

I have also changed slightly the geological description of the coal strata:

The waste rock within these coal strata is composed mainly of **argillaceous rocks, like shale and siltstone**, and of sandstone and thin (unmined) coal layers.

I don't want to go as far in formulating conclusions as the referee does, by stating that the shaft pillar is the main cause for creating large uplift values. I prefer to first follow in future research the suggestion by the first referee on the multi-variate problem (see Comment 8 of first referee and my reaction).

3) It would be interesting to analyse the uplift of the ground in respect to the rising of water levels in different aquifers.

This comment is, at least partly, linked to the misunderstanding about the clay and the depression cones formed (see previous point). On the other hand, comparing the uplift with the water level in the deep underground would have been interesting. As mentioned in the paper, the water level in the deep underground is on the Belgian side of this coal basin not measured; however, it has been sufficiently observed in the Dutch studies of the same coal basin, which are mentioned and discussed in the paper (see references Bekendam and Pöttgens, 1995; Caro Cuenca et al., 2013; de Vent and Roest, 2013).

The suggestion by the referee, i.e. a comparison of the surface movement with a change in water level in the aquifers would of course be interesting, but this is not directly the topic of this research,

4) The phenomenon of the residual subsidence is time dependent, it is obvious and has been stressed in the article. Therefore, it is difficult to assess real residual subsidence above the area of different mine panels, each of which ended its activity at different periods of time. On the contrary, the assessment of uplift is associated with a rise of the water and it can be well assessed after 1992 when pumping of the mine water has been finished.

I agree with the referee, but I assume the referee is not suggesting here that something must be changed or added.

5) It is not easy to understand the sequence of Figures 3a and 3b, and 6a and 6b. In Fig. 3a and 3b the phenomena are presented chronologically and 6a/6b contrariwise, it is very difficult to interpret. Perhaps it makes sense but I have not found a justification for such order.

This is in fact the same remark as Comment 2 by the first referee, although it is formulated differently. I assume that the changes made following Comment 2 by the first referee (see above) gives the necessary justification for the order. In addition and to make sure that the readers will understand it correctly, I have added some sentences in the discussion of Figs. 2-3, respectively Figs. 5-6:

In sect. 3.1

It also justifies the choice of first considering the first 5 years instead of the entire observation period.

and

As mentioned earlier, all scales were halved to make the comparison easier and the main reason for considering two time zones was that we expected already a significant number of reflectors with uplift at the end of the first observation period.

In sect. 3.2

Only six of the 1,808 reflectors had a slight downwards movement over this time period.

This justifies the choice of first looking at the last 5 years of the second observation period.

and

There was a clear difference between the start and end of the second observation period, justifying the splitting of the entire observation period in two.

6) In the list of references there is no one position of Polish literature. Knothe theory, which was crucial for the prediction of subsidence has been recalled from Chinese literature, what is curious (587-589).

What the referee calls Chinese literature is a paper published in Int. J. of Rock Mech. Min. Sc in 2015. In the latter the authors refer to a publication of 1953 by Knothe. As I do not expand the theory by Knothe, I do not think it is necessary to include the original reference by Knothe,

Technical correction

1) Figures 3 and 6 are difficult to read. Probably the coloured symbols would be better. And perhaps Author should use some other symbols to display the different settlement and uplift classes?

I can be wrong, but I assume that the referee has looked at a black & white print of the paper. As it is an electronic journal, I assume that the large majority of the readers will look at the digital format, which is in color. So, I have not made any changes, but of course if the editor would like me to make changes, please let me know.

2) To assess whether there is a relationship between the operation and the residual subsidence and uplift in Figures 3 and 6 the contours of operation should be shown. Without this the assessment is very difficult;

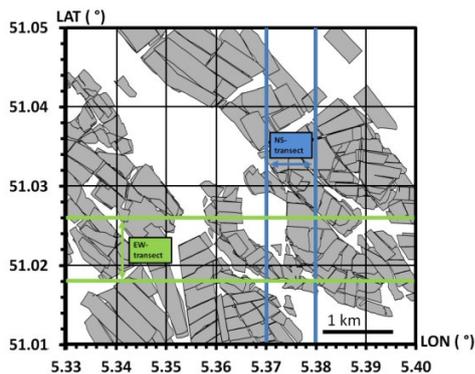
One always has to try to find a compromise between presenting as much information as possible on a graph and keeping everything visible and clear. The various maps (Figs. 1, 3, 6 and 12) are all plotted on the same scale, with the same axes and the same gridlines; this has been done, just to make it possible to compare the various maps.

By integrating Fig. 1 into Figs. 3 and 6, one does not improve or facilitate the assessment of possible relations between the mining characteristics and the surface movement, as the mining characteristics cannot be easily plotted on a 2D map. And also just the contours of operation is only one aspect of the mining (others are number of seams, total mining height, depth interval, time interval, etc.). To assess the various relations, I have opted to present the information in Table format for various locations and study the relationship on this basis. Again what referee 1 suggested (see comment 8 above) on the multi-variate problem could indeed improve the assessment, but I consider this as future research (and I assume referee 1 too).

3) On the Figures 1, 3 and 6 there is no section line drawn. It is a pity, because it would make easier the interpretation of the results presented on Figures 4, 7 and 8;

This could be done, but I would then only do on Figure 1, plus I would repeat this Figure (i.e. a new Figure before the old Figure 4) and not overloading the original Fig.1 with various lines; similar to Fig. 12, which is Fig. 1 plus the position and labels of the various locations considered in the analysis of relationships.

This new Figure would look like the following, which so far I have not yet integrated in the revised paper:



I am rather in favor of not including this new Figure, but I leave it up to the editor to decide on it.

1 Surface movement above an underground coal longwall mine after closure

2
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4
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8
9 **Abstract.** The surface movement in an area of about 22 km² above the underground coal mine of
10 Houthalen was analyzed based on Interferometry with Synthetic Aperture Radar (INSAR)
11 measurements. After its closure in 1992, a residual subsidence was observed over a period of
12 several years, followed by an uplift of the surface above and around the past longwall panels,
13 whereby the rate of movement was, in absolute terms, of the same order for the two types of
14 movements. The processes behind these movements are different. The process of subsidence is
15 caused by the caving of the roof above the mined out area and is mainly a mechanical stress-
16 deformation process, including time-dependent aspects. However, the process of uplift is most
17 probably caused by the swelling of the clay minerals in the **argillaceous rocks in the coal strata**
18 after the flooding of the underground workings. Hence, the areas in which there is the greatest
19 risk of damage to the surface infrastructure are not the same for the hazards linked to subsidence
20 and uplift. For example, the zone in which the maximum uplift occurs clearly is at a different
21 location from that of the zone with the maximum residual subsidence. There is no clear sign that
22 the amount of mining underneath affects the residual subsidence, and there is no indication that
23 the process of uplift is linked directly to the mining characteristics. It is more likely that uplift as
24 the result of flooding is initiated at, or close to, the vertical shafts.

25
26 **Keywords:** coal mining; surface movement; subsidence; uplift; radar-interferometry

27 28 29 **1 Introduction**

30
31 Most research of the movements of the Earth's surface above underground mines has focused on
32 the direct impact of mining, i.e., the impacts that occur during the lifetime of the mine. This is
33 entirely logical because the largest amount of movement occurs during that period. Also, during
34 that period, the mining company can limit the hazards, e.g., by selecting a different mining
35 method (e.g., room and pillar instead of longwall), by backfilling the mined-out area instead of
36 creating a goaf, or by changing the mining geometry. However, by introducing the concepts of
37 sustainable mining, the long-term impact of mining on its surroundings has been receiving
38 greater attention. This means that the period after the mine's closure is a period that should not
39 be neglected. Surface movements after closure, which is the topic of this study, should be
40 investigated in detail. In the past decades, not only individual mines in Western Europe have

41 been closed, but coal production stopped in entire coal basins. As a consequence, the deep
42 underground was flooded because access to the underground facilities was sealed off, and the
43 underground pumping stations were dismantled. This created a new hazard, i.e., the uplift of the
44 surface caused mainly by the swelling of clay minerals in the **argillaceous rocks in the coal strata**
45 (Bekendam and Pöttgens, 1995). Although the order of magnitude of the movements in such
46 uplifts is smaller than the subsidence that occurs during mining, cases have been reported in
47 which uplifts have damaged buildings and the surface infrastructure (Baglikow, 2011; de Vent
48 and Roest, 2013; Caro Cuenca et al., 2013). So, studying this phenomenon is more than a pure
49 scientific exercise. To date, other researchers have focused mainly on understanding the
50 phenomenon (e.g., Herrero et al., 2012) and identifying general trends, whereby the link with the
51 rise in water level was an important issue (Caro Cuenca et al., 2013; Devleeschouwer et al.,
52 2008). In this study, we tried to provide better quantification of the movement after closure and
53 the difference between the residual downward movement and the ultimate uplift of the surface.
54 To accomplish this, we studied the past mining directly underneath the observation points.
55 The underground coal mine of Houthalen, Belgium, was closed in 1992. For a period of nearly
56 two decades (from 1992 through 2010), we analyzed the movements of the surface above the
57 mine based on radar-interferometry or Interferometry with Synthetic Aperture Radar (INSAR)
58 measurements. The production of coal in this mine began in 1939, and, in 1964, the mine was
59 merged (and connected underground) with the Zolder coal mine, which is situated to the west of
60 the Houthalen mine. Production was stopped in both mines in 1992, and the access was sealed
61 off. Hence, the underground pumps also were stopped, causing flooding of the underground
62 work areas, the surrounding rock mass and caved zones.

63 Longwall mining with goaf was the method used in the mines, and different coal seams were
64 mined. The area in which the detailed study of surface movement was conducted is situated from
65 Latitude 51.01°N to 51.05°N and from Longitude 5.33°E to 5.40°E, an area of approximately 5.0
66 (EW) by 4.4 (NS) km² (Fig. 1). At a certain X-Y position within the mined area, one to eight
67 different coals seams were mined. The combined mining height of the several seams varied from
68 2.0 to 12.3 m within this area. The height of the mining of individual panels varied from 0.9 to
69 2.7 m, and, normally, about 10 to 40 cm of it were layers of waste rock. In some cases, either no
70 waste rock was mined or only a few centimeters were mined, but, in other cases, almost 1 m of
71 waste rock was recorded as having been mined. As the map indicates, certain zones were not
72 mined. Apart from the zone around the vertical shafts (around the coordinates of Latitude
73 51.025°N and Longitude 5.370°E), these unmined zones mainly were areas around faults. The
74 latter were composed of a predominant set of NNW - SSE striking normal faults with
75 subordinate N-S to NE-SW striking thrust faults. In the later decades of production, a typical
76 longwall panel had dimensions of 200 by 800 to 1,000 m. The main and tail gates were
77 immediately adjacent to the panel, and they were just single tunnels with a horseshoe cross-
78 section. So, no barrier or remnant pillars existed between the longwall panels. In the area that we
79 studied, the mining depth varied from 539 to 967 m, and the mining occurred between 1932 and
80 1992. However, most of the panels were mined in the 1960s and 1970s. In Sect. 4, more details

81 of the mining characteristics are provided, and their possible influences on the surface
82 movements are discussed.

83 The coal strata in the Campine basin in northeast Belgium belong to the Upper Carboniferous
84 strata (Westphalian unit), the time of the formation of many coals fields in Europe (Langenaeker,
85 2000; Vandenberghe et al., 2014). The top of the Upper Carboniferous strata generally occurs at
86 depths of approximately 400 to 600 m. The waste rock within these coal strata is composed
87 mainly of **argillaceous rocks, like** shale and siltstone, and of sandstone and thin (unmined) coal
88 layers. The sandstone is classed as medium-strong, with a typical Uniaxial Compressive Strength
89 (UCS) of 90 MPa (Caers et al., 1997). However, values up to 160 MPa also have been measured.
90 The other types of rocks are classified as weak rock, e.g., siltstone was tested with an UCS-value
91 from 17 to 68 MPa with an average of 46 MPa, and coal with an UCS-value from 6 to 10 MPa
92 with an average of 7 MPa. The average values of Young's modulus for these three types of
93 rocks were determined as 28 GPa for sandstone, 9 GPa for siltstone, and 1 GPa for coal (Caers et
94 al., 1997). Overall, the successive strata are relatively thin (on the order of dm to m in scale). The
95 overburden is composed of weak to very weak geological material (e.g., sand, clay, and chalk).
96 Several aquifers and aquitards are present over the entire section of the overburden.

97
98

99 **2 Radar-Interferometry data**

100

101 Radar-interferometry or Interferometry with Synthetic Aperture Radar (INSAR) is a recent
102 remote sensing technique that allows the study of large time series of surface movements (Akcin
103 et al., 2010; Herrera et al., 2009; Hongdong et al., 2011; Jung et al., 2007; Zhenguang et al., 2013).
104 The movement of reflective surfaces (i.e., the so-called permanent scatterers) is followed during
105 successive cycles of the satellite. There is high spatial coverage of the areas studied, at least if
106 the area corresponds to a built environment. In comparison to conventional leveling methods, the
107 advantages of radar-interferometry include (i) large areas can be covered for the same effort
108 (e.g., a full concession area of a mine), (ii) measurements are conducted on a regular and
109 frequent basis (i.e., one measurement per satellite revolution (35 days for the datasets used in this
110 research)), and (iii) a dense network of reflectors is available (sometimes every 10 to 20 m). One
111 of the disadvantages is that, when no reflective surfaces are identified in a specific zone, no
112 information is available on the movement of the surface. For example, this was the case for the
113 area studied in the zones composed of agricultural land, woodland and unused or semi-natural
114 land. Other problems were that 1) the recorded movement corresponds to the reflection of a
115 surface area of 4 x 20 m and not of a discrete point and 2) that the recordings are not of the
116 Earth's surface but of reflective objects, which can be hardened surfaces, such as the roofs of
117 buildings (for the most part), as well as parking lots and roads. This means that for buildings the
118 type and depth of the foundation and the structure itself affect the movement of the reflector
119 (Dang et al., 2014).

120 In this study, the European C-band ERS1/2 and ENVISAT-ASAR satellite images were used,
121 which were available for research through a European Space Agency (ESA) research proposal
122 (Devleeschouwer et al., 2008). The recorded periods were for both sets from August 1992
123 through December 2000 (87 cycles of 35 days) and from December 2003 through October 2010
124 (72 cycles of 35 days), respectively. Generally, it is accepted that the linear velocities can be
125 estimated with accuracies of about 1 mm per year (Marinkovic et al., 2009; Sousa et al., 2009).
126 However, these values depend significantly on the number of images and the conditions in which
127 they were obtained as regards baselines, Doppler centroid distribution, selected pixel density,
128 how they are connected, and the presence of atmospheric effects. **An accuracy of 1 mm/year was**
129 **confirmed (Vervoort and Declercq, 2016) by comparing the INSAR-data to the GPS-reference**
130 **points of the Belgian National Geographic Institute (NGI), linked to the reference stations of the**
131 **Flemish Positioning Service (FLEPOS). For example the reference point HQ10 of NGI, situated**
132 **20 cm above the ground level, within the same coal mine basin was compared to the three closest**
133 **reflectors surrounding this reference point and situated at a maximum horizontal distance of 35**
134 **m. For a 5-year period of uplift, 31.0 mm was measured at the NGI reference point, while the**
135 **INSAR-reflectors showed a movement of respectively 25.5 mm, 29.1 mm and 29.9 mm. As the**
136 **location of the reference point and the three reflectors are different (plus different size between**
137 **reference point vs. reflectors), it is normal that the four values are different, but the difference is**
138 **small, showing that the INSAR-data are precise for the purpose of this research.**

139

140

141 **3 Analysis of surface movement**

142

143 Earlier research (Vervoort and Declercq, 2016) **looked at annual increases in surface movement.**
144 **It** showed that, in this area at the end of the first period of observation (from August 1992
145 through December 2000), uplift had already been initiated in certain zones or for certain
146 reflectors. In a similar way, it was observed that, at the start of the second period of observation
147 (from December 2003 through October 2010), certain reflectors were still undergoing downward
148 movement. Therefore, **in first instance, we looked at 5- year time zones in each observation**
149 **period, which can be considered to be characterized by a pure downward movement (for the first**
150 **observation period from mid-August 1992 through mid-August 1997) or a pure upwards**
151 **movement (for the second observation period from mid-September 2005 through mid-September**
152 **2010). The remaining part of each observation period was also studied and for comparison**
153 **purposes, a length of 2.5 years was chosen, i.e. the last 2.5 years of the first period and the first**
154 **2.5 years of the second period. These two 2.5-year time zones were from July 1998 through**
155 **December 2000 and from December 2003 through June 2006, respectively. As the total first**
156 **observation period was longer than 7.5 years and the second shorter,** there was a gap between the
157 time zones of 5 and 2.5 years in the first period and a small overlap in the second period, but the
158 main advantage of doing so was that all time zones could be compared more easily. Hence, all
159 scales for the graphs that correspond to the 2.5-year time zones are halved.

160 In this research, downward movement has a negative sign, and uplift has a positive sign; the
161 same convention was used for the rate of movement (e.g., per year). However, when discussing
162 the smallest (minimum) movement or the largest (maximum) movement, we considered the
163 absolute value of the movement; in other words, when discussing the minimum rate, we did not
164 apply the pure mathematical definition of minimum. For the area studied, no public data were
165 available for the subsidence that occurred prior to the satellite observations.

166

167 **3.1 First observation period, characterized, on average, by subsidence**

168

169 In the five years from mid-August 1992 through mid-August 1997, the area studied was
170 characterized by an overall downward movement (Table 1 and Fig. 2a). Only two out of 1,073
171 reflectors were characterized by small upward movements, i.e., 3 and 6 mm. In the overall
172 picture, these can be neglected. **It also justifies the choice of first considering the first 5 years**
173 **instead of the entire observation period.** Among the reflectors, 69% underwent residual
174 subsidence ranging from -20 to -40 mm over the five-year time zone (Fig. 2a). The average
175 subsidence was -33 mm, corresponding to an annual subsidence rate of about -6 mm. The
176 maximum rate for the studied area was about -16 mm per year (or a total of -80 mm). The
177 distribution was slightly positive, i.e., a long tail for the larger subsidence movement. Also the
178 spread (e.g., maximum minus minimum) was relatively large, i.e., 85 mm. Earlier research
179 showed that the variation was even larger if one considers the annual increases, i.e., the
180 subsidence for each individual year, and not the total subsidence divided by five years (Vervoort
181 and Declercq, 2016). For the time zone considered, the maximum increase per individual year
182 was about -33 mm, i.e., five times the average rate over the five years (-6 mm/year) and about
183 twice the maximum average rate over the five years (-16 mm/year).

184 If one looks at the spatial variation of the total surface movement over the five-year time zone, it
185 is apparent that the largest residual subsidence occurred in the northern Central part of the area
186 studied (Fig. 3a). Unfortunately, the reflectors were not evenly spread over the entire area. There
187 were several zones with dimensions of a kilometer wide in which there were no reflectors at all.
188 These zones, in this particular case were farm land, woodland, unused land, and a lake. The
189 combination of large zones without reflectors and the large fluctuation between neighboring
190 points motivated us to present the individual reflectors instead of calculating a contour map. The
191 latter would result in too much loss of detail and would result in large uncertainties for certain
192 sub-zones.

193 Fig. 3a shows that, although large movements may occur next to small movements, clustering is
194 present. For example in the western and southeastern parts of the area studied, the reflectors were
195 characterized mainly by a residual subsidence of -20 to -30 mm over the five years. Most
196 reflectors with a total residual subsidence over the five years of -60 mm or more correspond well
197 with the mined out area underneath (Fig. 1). In Sect. 4.2, a more detailed analysis is presented
198 with the past exploitation. To better visualize the map of reflectors, **the movement along** a north-
199 south **line** is presented in Fig. 4a. **To have a sufficient amount of reflectors along this line, a**

200 north-south zone was selected for Longitude between 5.37°E and 5.38°E, about 700 m wide in
201 the east-west direction. A slightly longer transect was chosen, as shown in Figs. 1 and 3. No
202 exploitation took place more to the north than Latitude 51.05°N in the transect selected or its
203 immediate surroundings; the same is true more to the south than Latitude 51.005°N (Van
204 Tongeren and Dreesen, 2004). In the northern and southern part the residual movement was still
205 a subsidence but the values were small. In the zone between Latitude of 51.015°N and 51.050°N,
206 mainly movements of -20 mm and more were observed, with the largest values situated between
207 51.035°N and 51.045°N. The variation of the observed values was about 20 mm. This can be
208 explained by the inaccuracy of the method, by the variation in the east-west direction, and by the
209 local variation between neighboring points.

210 For the same (first) observation period, the last 2.5 years also were analyzed (Table 1 and Fig.
211 2b). As mentioned earlier, all scales were halved to make the comparison easier and the main
212 reason for considering two time zones was that we expected already a significant number of
213 reflectors with uplift at the end of the first observation period. About 8.5% of the reflectors
214 underwent uplifts during this time zone of 2.5 years (Fig. 2b). Fig. 3b presents the locations of
215 the corresponding reflectors. It is very clear that these locations are complementary to the zone
216 of the largest residual subsidence observed in the first five years (Fig. 3a). The maximum
217 subsidence rate observed was about the same as during the first five years, i.e., about -16
218 mm/year. The average rate was much smaller, i.e., -3.6 mm/year instead of -6.5 mm/year.
219 When looking at the north-south transect (Fig. 4b), large subsidence values occurred in a similar
220 area as in the five-year time zone. A peak was observed at a Latitude of about 51.04°N. The
221 variation of the observed values remained about 20 mm. As illustrated above, there was a non-
222 negligible number of reflectors characterized by uplifts, also above the unmined areas.

223

224 **3.2 Second observation period, characterized, on average, by an uplift**

225

226 In the five-year time zone from mid-September 2005 through mid-September 2010 at the end of
227 the second observation period, it becomes obvious that an uplift over the entire area took place
228 (Fig. 5a). Only six of the 1,808 reflectors had a slight downwards movement over this time
229 period. This justifies the choice of first looking at the last 5 years of the second observation
230 period. The smallest movement was -10 mm (Table 2). About 75% of the reflectors underwent
231 uplifts that ranged from 30 to 60 mm. The largest movement of all reflectors was 84 mm,
232 corresponding to an average rate of about 17 mm per year, while the global average movement
233 was 44 mm or nearly 9 mm per year. This means that the rate of uplift was larger than the
234 residual subsidence rate in the five-year time zone following the closure of the coal mine (e.g.,
235 an average rate of -6 mm/year vs. 9 mm/year). The shape of the distribution was negatively
236 skewed, which means that only a few reflectors were observed with small values. As for the first
237 five years in period 1, the variation in the increase of the uplift per individual year was larger
238 than the average rate over the five-year time zone. The maximum individual annual increase was
239 31 mm.

240 There was a clear difference between the start and end of the second observation period,
241 **justifying the splitting of the entire observation period in two.** Fig. 5b shows the distribution of
242 the increase in surface movement over the 2.5 years between December 2003 and June 2006.
243 About 6% of the reflectors still had undergone a subsidence (in comparison to 0.3% in the last
244 five years). The classes between 5 and 20 mm of total increase (corresponding to an average
245 annual rate between 2 and 8 mm per year) contained about 71% of the reflectors for the first 2.5
246 years, while the classes for the same annual rate (i.e., from 10 to 40 mm total increase) was only
247 about one third at the end of the second observation period.
248 The map of the reflectors in the area studied now shows a completely different picture (Fig. 6a)
249 in comparison to the first observation period. The largest uplift values were observed mainly in
250 the central to southern part. In the northern part, where the largest residual subsidence was
251 recorded, small uplift values were observed. In the 2.5-year time zone, from December 2003
252 through June 2006, numerous reflectors still had undergone subsidence in that northern part (Fig.
253 6b). In the eastern part (longitude larger than 5.39°E) of the southern half, subsidence was still
254 recorded, while this part was characterized by relatively small residual subsidence in the first
255 observation period. (Compare Fig. 3a with Fig. 6b.)
256 Fig. 7 presents north-south transects that are similar to those for the first observation period. In
257 the last five years of observation (Fig. 7a), the maximum uplift was observed at a Latitude of
258 about 51.024°N. Less than 10 mm of uplift were recorded farther to the south than 50.994°N and
259 farther to the north than 51.050°N. These zones were not situated above exploitation panels;
260 however, it is still worthwhile to note that there were uplifts in these areas. As for the subsidence,
261 a variation of about 20 mm for a specific coordinate was observed again. Overall the curve is
262 relatively symmetric. For the first 2.5 years of the second observation period (Fig. 7b), the values
263 along this north-south transect confirm what was mentioned before, i.e., most downward
264 movement was situated in the northern and southern parts, while the peak in uplift became
265 visible somewhere between 51.02°N and 51.03°N.
266 In comparison to these north-south transects, the east-west transects had a smaller variation,
267 except, of course, that the movement evolved to zero away from the exploitation in the east. In
268 comparison to the east of the area studied, where there was no exploitation, the exploitation of
269 the Zolder mine bordered the exploitation of the Houthalen mine in the west. So, this clearly
270 affected the movement. As an example, an east-west transect is presented in Fig. 8 for a Latitude
271 between 51.018°N and 51.026°N, which corresponds to the maximum uplift in the north-south
272 transect. More to the east than a Longitude of 5.41°E, no reflectors were available as there is
273 over a distance of about 3.5 km a nature reserve (without buildings or infrastructure). Although
274 the variation is small between a Longitude of 5.33°E and 5.39°E, the earlier chosen north-south
275 transect (5.37-5.38°E) was at or close to the east-west maximum.

276
277

278 **4 Discussion of results**

279

280 **4.1 Location of maximum residual subsidence vs. location of maximum uplift**

281

282 As mentioned above, the movement is more complex than can be represented by a single value.
283 Hence, one should be careful in replacing the individual measured values by an average or by a
284 smoothed curve. However, for comparison purposes, such smoothed curves were drawn for the
285 north-south transects, presented above. For the smooth curves of both of the five-year time zones
286 that were studied, the following observations were made (Fig. 9a):

287 - The absolute movement over five years is the same order of magnitude as the residual
288 subsidence and the uplift.

289 - The maximum observed movements were at different locations. In the phase of residual
290 subsidence, the maximum was situated around a Latitude of 51.04°N, while for the uplift phase,
291 the maximum was observed around 51.020°N to 51.025°N. This is in agreement with the maps
292 in Figs. 3a and 6a.

293 - To the northern and southern end of the chosen transect, the movements evolved towards zero,
294 away from the exploitation.

295 - The curve of the uplift is very symmetric, which is not the case for the curve of the residual
296 subsidence. In Sect. 4.3, the mechanism behind the uplift is further discussed.

297 All these points are also visible when looking at the smoothed curves for both 2.5-year time
298 zones that were studied (Fig. 9b). The only difference is that, in the southern part (more to the
299 south than a Latitude of 51°N), on average, there already was an uplift in the first observation
300 period, while a subsidence was observed, on average, in the second observation period.

301 When looking in detail at the movements at the locations of both maxima, the above can be more
302 quantified (Table 3 and Figs. 10 and 11). Around both maxima, the 10 nearest reflectors were
303 selected. The reflectors were not necessarily the same for the two observation periods, but they
304 were the same within each of the two observation periods. The amount of 10 reflectors is a
305 compromise between zooming in on a particular area and having enough data to be statistically
306 representative. Table 3 presents the minimum, maximum, and average of the total vertical
307 movement over the five-year time zone. The variation of these values as a function of time is
308 plotted in Figs. 10 and 11. As could be expected based on Fig. 9a, the difference between the two
309 groups of curves is clear. For the first observation period, there was a small overlap between the
310 two groups, i.e., the minimum of the residual subsidence of the location of the maximum residual
311 subsidence was slightly smaller than the maximum of the other location studied, but the
312 difference between the two averages was 27 mm over the five-year time zone. For the second
313 observation period, there was no overlap between the two groups. The difference between their
314 averages over the five years was 20 mm.

315 Table 3 provides a summary of some basic information on the exploitation just underneath the
316 two locations. **The surface movement is of course not only affected by the mining directly below,
317 but also by the mining around the locations. For an angle of draw of 45° the extent of the zone of
318 influence is even equal to the depth of mining. However, the impact decreases when moving
319 away from a panel, which justifies considering the exploitation in the immediate vicinity.** Fig. 12

320 indicates both locations. Under the maximum of the residual subsidence, the mining was more
321 recent than under the maximum of the uplift. Mining took place in the periods of 1968-1982 and
322 1939-1959, respectively. However, 1982 was still 10 years before closure (and the start of
323 observation). A corner of a panel, which was mined in 1992 at a depth of 820 m, is situated at
324 about 250 m to the west of the location $\text{Max}_{\text{RES SUBS}}$. This means that this location is within the
325 zone of influence of that panel. However, on the E-W transect (across the panel), we did not
326 observe any maximum in residual subsidence above the most recent panel. When comparing the
327 mining depth, mining height, and the number of panels mined underneath the two locations, the
328 mining characteristics were rather similar. So, this means that, apart from possibly the time of
329 mining, there was no clear indication concerning the causes of the difference between the
330 movements of the two locations. In the next two paragraphs, more locations are compared, which
331 will indicate whether the effect of the time of mining is significant.

332

333 **4.2 Influence of mining characteristics on residual subsidence after closure**

334

335 Mining by the longwall method results in caving above the mined-out areas, creating the goaf
336 area. A roof height of two to eight times the mined height generally is considered to be sufficient
337 to fill up the mined height, plus the caved height (Peng, 1986). In the Campine basin, an average
338 value of five times normally was assumed, corresponding to a bulking factor of 1.2. The caved
339 zone is composed of blocks of broken material and includes a large amount of small and large
340 cavities. Hence, Young's modulus of this caved material is several orders of magnitude smaller
341 than that of the original intact layers (Galvin, 2016). Over time, this volume is compressed
342 progressively, but it will never reach its original state. Apart from the caving of the immediate
343 roof layers, the rock further away fractures and sliding along the induced fractures occurs. Still
344 further away from the mining depth (i.e., closer to the surface), plastic and elastic deflections of
345 layers also occur. All these phenomena result in the occurrence of subsidence at the surface. A
346 typical trough shape is created, e.g., above and around a single panel that has been mined. The
347 zone of influence at the surface is larger than the dimensions of the panel itself. By considering
348 an angle of draw of 45° , as was often done for the Campine coal basin, the width of the zone of
349 influence is about the depth of mining, which varied from 539 to 967 m in the area studied. **By**
350 **looking at the map of the exploitation (Fig. 12), this means that nearly the entire area studied is**
351 **within the zone of influence of at least one longwall panel.** For the coal basin that we studied,
352 typical subsidence rates were 30 to 60 mm/month in the months following the mining.
353 Unfortunately, for the area studied, no public data were available for the subsidence that
354 occurred prior to the satellite observations. Worldwide, the maximum subsidence ranges from 40
355 to 90% of the total mining height (Wagner and Schumann, 1991; Sheorey et al., 2000). In the
356 Campine basin, values of 80 to 90% normally are used. This means that, for the area studied with
357 a mining height varying from 2 to 12.3 m, a subsidence of 1.6 to 11.1 m could have occurred.
358 There is no reason to assume that the general rules of the amount of residual subsidence
359 following years or decades after mining would be any different from what can be considered as

360 the globally accepted knowledge, e.g., more subsidence for larger mining heights and less
361 subsidence for deeper longwalls (Galvin, 2016).

362 To study the possible link of the residual subsidence with the original mining characteristics in
363 more detail, several groups of locations were selected (Fig. 12). First, three locations were
364 selected where, underneath, no mining had ever taken place (Table 4a). Second, two locations
365 with a small amount of mining, i.e., two panels only and with a total mining height of 2 and 2.5
366 m, respectively (Table 4b). Third, three locations were selected with extensive mining, i.e., 7 or 8
367 panels and a total mining height of 9.2 to 10.3 m (Table 4c). As for the two locations with
368 maximum movement (Table 3), the 10 reflectors in the most immediate vicinity were studied. It
369 was not easy to find an adequate number of locations so proper analyses could be done, i.e.,
370 enough reflectors had to be present in both observation periods at a close distance, and the same
371 mining conditions had to exist underneath these reflectors.

372 When one looks at the average total residual subsidence over the five-year time zone, one gets -
373 29/-26/-37 mm (no mining), -36/-23 mm (limited mining), and -29/-46/-33 mm (extensive
374 mining), respectively. Hence, one cannot conclude that the amount of mining underneath a
375 relatively small area is affecting the residual subsidence, certainly if we also point out that
376 location Ext_B (-46 mm) was situated very close to the location of the overall maximum of the
377 residual subsidence in space. When looking at the minima or maxima, also no distinction is
378 observed between the three groups of the amount of mining. This confirms what was observed
379 when comparing both locations of maximum movement (Sect. 4.1).

380 By looking at the data of Tables 4b and 4c as a function of the mining depth, no clear trend is
381 observed. For the two locations with a limited amount of mining, the most shallow mining
382 resulted in the largest residual subsidence, while, for the three locations with extensive mining,
383 the largest residual subsidence was for the deepest exploitation.

384 When comparing the two locations of maximum movement in Sect. 4.1, there was the possibility
385 that more residual subsidence occurred directly above the more recent longwall panel. This
386 would be logical. Therefore, Table 5 classifies the various locations as a function of the most
387 recent longwall panel underneath. Taking into account the large number of possible parameters
388 that influenced the results, the trend of these seven locations is indeed that the locations above
389 the most recent panels resulted in larger residual subsidence. However, it must be pointed out
390 that the location with the second most recent mining has undergone, on average, less movement
391 than one of the locations without mining underneath (i.e., No_C with -36.8 mm). So, it certainly
392 cannot be concluded that there is a simple one-on-one relationship with the time since
393 exploitation. Two different panels were mined in 1990 and 1992, respectively, but,
394 unfortunately, no reflectors or insufficient reflectors were present above these panels.

395 When comparing the residual subsidence in the north-south transect (Fig. 9a) with the map of
396 longwall panels, one can observe that the zone of influence is larger than expected based on the
397 normally-used values of the angle of draw. Based on the latter values and the depth of
398 exploitation, the influence zone during the phase of subsidence should be limited to the zone
399 between Latitude 50.995°N and 51.06°N, since no exploitation took place any further north than

400 Latitude 51.05°N in the transect selected or its immediate surroundings or any further south than
401 Latitude 51.005°N (Van Tongeren and Dreesen, 2004). This was confirmed in the northern part
402 of this transect. However, as far south as 50.98°N, residual subsidence clearly was observed, i.e.,
403 1.5 km further away than the theory would predict.

404

405 **4.3 Influence of mining characteristics on uplift after closure**

406

407 What was explained in previous section is the process that was initiated by the caving process,
408 and it can be seen as a mechanical stress-deformation process that includes time-dependent
409 aspects. However, once the underground activities ceased and the underground access was closed
410 off, including dismantling of the pumping installations, the underground begins to be flooded
411 (Bekendam and Pöttgens, 1995; Caro Cuenca et al., 2013; de Vent and Roest, 2013). In the
412 beginning, the water finds its way through various pathways, including open roadways,
413 permeable faults, and volumes of loose blocks. But there is no reason the rock mass adjacent to
414 the mined area or between mined areas would not be submerged, and this leads to new processes.
415 In the literature (Herrero et al., 2012), the swelling of clay minerals of argillaceous rocks under
416 the influence of water is considered to be the main factor for inducing uplift. Swelling is
417 governed by the swelling pressure and is, therefore, linked to the mining depth. Caro Cuenca et
418 al. (2013) showed clearly the direct correlation between the increase of the water level in the
419 underground areas and the uplift. In all cases, the groundwater levels showed even a very high
420 correlation (~ 0.97) with surface displacements. Apart from the uplift, Herrero et al. (2012)
421 pointed out that, due to the flooding, the mechanical properties of argillaceous rocks are affected
422 significantly by water, resulting in a decrease of 60 to 80% of their strength, which reactivates
423 the downward settlement.

424 For the same average locations, as for the first observation period, the minimum, average, and
425 maximum uplift of the five-year time zone for 10 reflectors are given in Table 4. By considering
426 the three groups as a function of the amount of mining, one gets average uplifts of 30/8/46 mm
427 (no mining), 54/52 mm (limited mining), and 60/43/60 mm (extensive mining), respectively.
428 Hereby, it must be pointed out that the average value of 8 mm was recorded at the far NE of the
429 study area, outside the mining area, and at a distance of about 3 km from the location with the
430 maximum uplift. Although the two smallest of these eight average values were for the group
431 without mining and the two largest were for the group of extensive mining, one should be very
432 careful in linking the amount of uplift with the amount of mining directly underneath. Earlier
433 research also indicated that there is not a clear link between the uplift rate and mining (or the
434 absence of mining) directly underneath (Vervoort and Declercq, 2016).

435 Often, one links the largest uplift to zones with the largest subsidence and estimates the total
436 uplift as 3 to 4% of the total subsidence (Herrero et al., 2012). Bekendam and Pöttgens (1995)
437 also concluded that, generally, the uplift is 2 to 4% of the subsidence; the latter conclusion is for
438 the same Campine basin, but above the Dutch coal mines to the east. This cannot be confirmed
439 by the area studied here and, of course, for the time periods considered; only the residual

440 subsidence rate is known. As pointed out earlier, no public data were available for the subsidence
441 that occurred prior to satellite monitoring, but by applying the rule of thumb for estimating the
442 total subsidence, one could estimate that the subsidence was from about 1.5 to 11 m in the area
443 studied, and 3% of this would mean that a total of 45 to 330 mm of uplift finally would occur
444 above the mined out area. If this were correct, then the uplift during the second observation
445 period (until 2010) would have reached only the bottom part of this predicted range; in other
446 words, one can still expect more uplift above the mining area and immediate surroundings.
447 As discussed in Sect. 4.2, the influence zone during the phase of subsidence should be limited to
448 the zone between Latitudes 50.995°N and 51.06°N . In the northern part of the north-south
449 transect that was considered, this was confirmed for the residual subsidence, but, in the south, the
450 influence was about 1.5 km more to the south. For the uplift until 2010 (Fig. 9a), the zone of
451 influence (e.g., an uplift of more than 5 to 10 mm) corresponded well with the limits of 50.99°N
452 and 51.06°N . However, after 2010, the extent of the uplift zone could have increased.
453 Based on all of the information that was collected, there is no indication that the process of uplift
454 is directly linked to the mining characteristics. It is more likely that the uplift as a result of the
455 flooding is initiated at or close to the shafts, where most likely the deepest point is situated and
456 where the pumping station was situated. From that central location, further flooding (in the
457 horizontal direction) and rise of mine water (in the vertical direction) are extended, creating a
458 further uplift at that central location and an initiation of uplift further away from the central area.
459 Of course, the fact that mining and caving have taken place has an effect. It is the main reason
460 that water flows into the underground workings. However, the local situation (e.g., the depth,
461 extent, or time of mining) does not seem to have a very significant influence on uplift. When
462 looking at the interpolated curve of Fig. 9a, no local irregularities are noted; the curve itself also
463 is very symmetric, much more so than the curve of residual subsidence (Fig. 9b).

464
465

466 **5 Conclusions**

467
468 Most research of surface movement above underground mines focuses on the direct effect of
469 mining, i.e., within the lifetime of the mine, and less attention is given to the long-term impact of
470 mining on surface movements. As at the end of the last century, several coal basins were closed
471 in Europe, and researchers began to observe a new phenomenon, i.e., the uplift of the surface as a
472 consequence of the flooding of the underground workings (Bekendam and Pöttgens, 1995). Also,
473 cases were reported of damage to buildings and infrastructure during the uplift phase (Baglikow,
474 2011; de Vent and Roest, 2013; Caro Cuenca et al., 2013). During that period, satellite images
475 with frequent and detailed measurements of the surface movement over large areas became
476 available, so this topic could be studied further. To date, the focus has been mainly on
477 understanding the phenomenon (e.g., Herrero et al., 2012) and identifying general trends, like for
478 example the link with the rise in the water level (Caro Cuenca et al., 2013; Devleeschouwer et
479 al., 2008). In this study, the residual subsidence after closure, as well as the initiation and further

480 evolution of the uplift were investigated for an area of 22 km² above the Houthalen coal mine,
481 which was closed in 1992. We tried to better quantify the movement after closure and the
482 difference between the residual downward movement and the ultimate uplift of the surface by
483 considering past mining directly below the observation points. All this has led to the following
484 conclusions:

- 485 - In the first five years following the closure of the coal mine (between mid-August 1992 and
486 mid-August 1997), the area studied was still characterized by an overall downward movement;
487 the average residual subsidence was -33 mm over five years, corresponding to a rate of about -6
488 mm per year. The maximum rate for the studied area was about -16 mm per year (or a total of -
489 80 mm).
- 490 - Although large residual movements may occur next to small movements, clustering was
491 present, and it resulted in areas with, on average, smaller residual subsidence and other areas
492 with larger values; certainly when looking at the north-south sections, there was a clear zone in
493 which the maximum residual subsidence occurred.
- 494 - In absolute terms, the rate of uplift was about the same order of magnitude as the residual
495 subsidence, but, in fact, it was slightly larger; an average rate of uplift of 9 mm/year was
496 observed for the period between mid-September 2005 and mid-September 2010, in comparison
497 to the average rate of -6 mm/year in the five years following the closure.
- 498 - The zone in which the maximum uplift occurred was clearly at a different location from the
499 zone with the maximum residual subsidence.
- 500 - The curve of the uplift along the north-south sections was very symmetric, which was not the
501 case for the curve of the residual subsidence.
- 502 - There was no clear sign that the amount of mining underneath a relatively small area had an
503 effect on the residual subsidence. However, there was some indication that the locations above
504 the most recent panels resulted in larger residual subsidence values. There is not a simple one-
505 on-one relationship with the time since exploitation. The zone of influence was larger than one
506 would expect based on the normally-used values of the angle of draw and depth of mining.
- 507 - Based on all of the information that was collected, there was no indication that the process of
508 uplift was directly linked to the mining characteristics. It is more likely that the uplift as a result
509 of flooding was initiated at or close to the shafts; from that central location, the additional
510 flooding (in the horizontal direction) and rise of mine water (in the vertical direction) were
511 extended, creating additional uplift at that central location and initiating uplift further away from
512 the central area.

513 Most concepts that one finds in textbooks dealing with surface subsidence above longwalls
514 considers either the impact of mining a single panel or a relatively-simple mining geometry
515 and/or mining sequence (e.g., mining a single seam with adjacent panels, which are mined in a
516 successive sequence). The latter is certainly typical for several countries, including the large coal
517 producers, such as Australia, South Africa, and the USA. In Europe, the situation was often
518 different (Preusse et al., 2013). For the mine studied, a total of 10 seams were partly mined over
519 a time period of 60 years (between 1932 and 1992) at depths varying from 539 to 967 m.

520 However, the situation was not significantly different when a shorter time is considered. For
521 example, in the 1970s, seven seams still were being mined at depths varying from 556 to 824 m.
522 As one also observes on the map of longwall panels (Fig. 1), there was no systematic geometry
523 or a systematic approach of mining the different panels. These observations probably explain
524 why no clear link has been established between mining characteristics and residual subsidence.
525 The entire area was rather in movement. For the amount of uplift, such one-on-one relationships
526 were nonexistent. As illustrated above, one can best visualize the uplift as starting at or close to
527 the shafts, whereby a further uplift occurred in the following years at that central location, and
528 uplift was initiated farther away from this central area. This seems to be in accordance with the
529 process of flooding the underground and the systematic rise of the water level. It will be
530 interesting to investigate the further evolution of the uplift, when more recent satellite data
531 become available.

532 The process of subsidence and the one of uplift are entirely different. The first is caused by a
533 caving process and is mainly a mechanical stress-deformation process, including time-dependent
534 aspects, while the process of uplift is caused by the swelling of the clay minerals in the
535 **argillaceous rocks in the coal strata**, due to flooding. Hence, one cannot assume that the areas
536 where one has the greatest risk for damage to infrastructure due to subsidence are the same areas
537 for the hazards linked to the uplift process.

538 **As for this area, no one-on-one relationships could be clearly indentified between the surface**
539 **movement and the mining characteristics, future research of this multi-variate problem could**
540 **benefit by using techniques including unsupervised learning and supervised learning (Noack et**
541 **al., 2014). Best would be to have data on the initial subsidence, the residual subsidence and the**
542 **uplift, combined with data on the mining characteristics.**

543

544

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680 **Fig. 2.** Distribution of total surface movement (in mm): a. Period 1, 5-year time zone, from mid-
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684 **Fig. 3.** Spatial variation of total surface movement in the area between Latitude 51.01°N and
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727 **Fig. 12.** Indication of selected locations on map of exploitation panels in area studied (between
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740 **Table 3.** Information on the two locations, corresponding to the zones with approximately
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749 **Table 5.** Information on residual subsidence of the locations considered in Table 3 and Table 4,
750 re-ordered as a function of the most recent exploitation panel.

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Figures

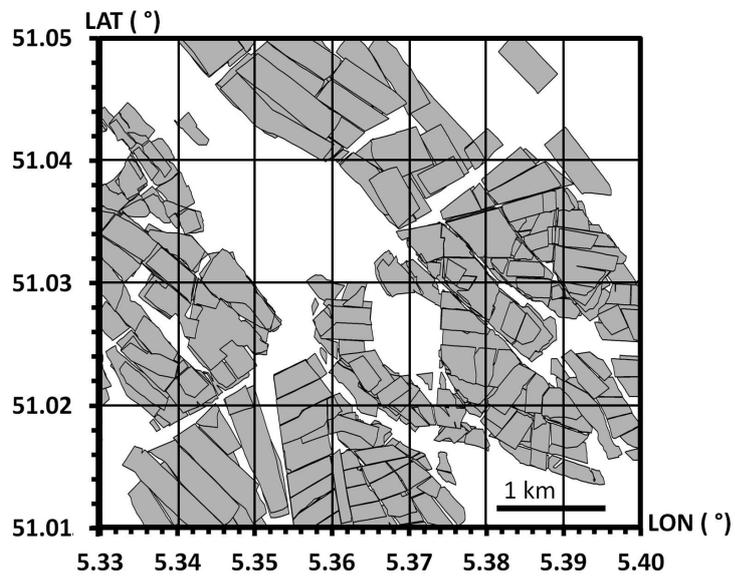


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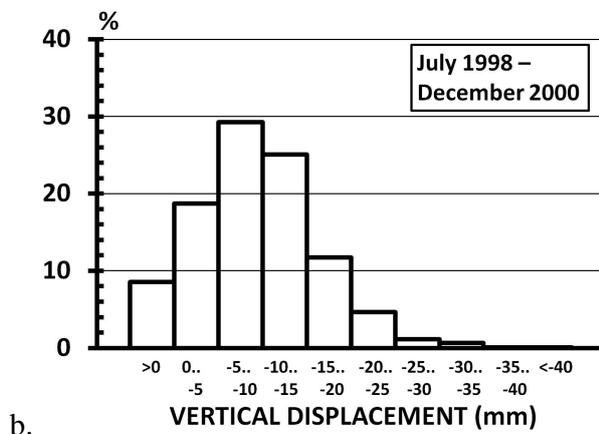
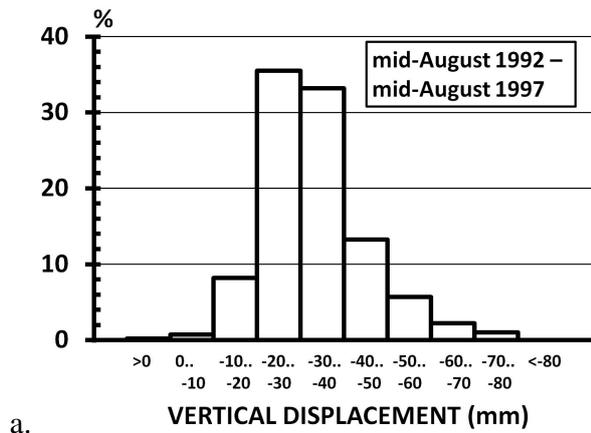


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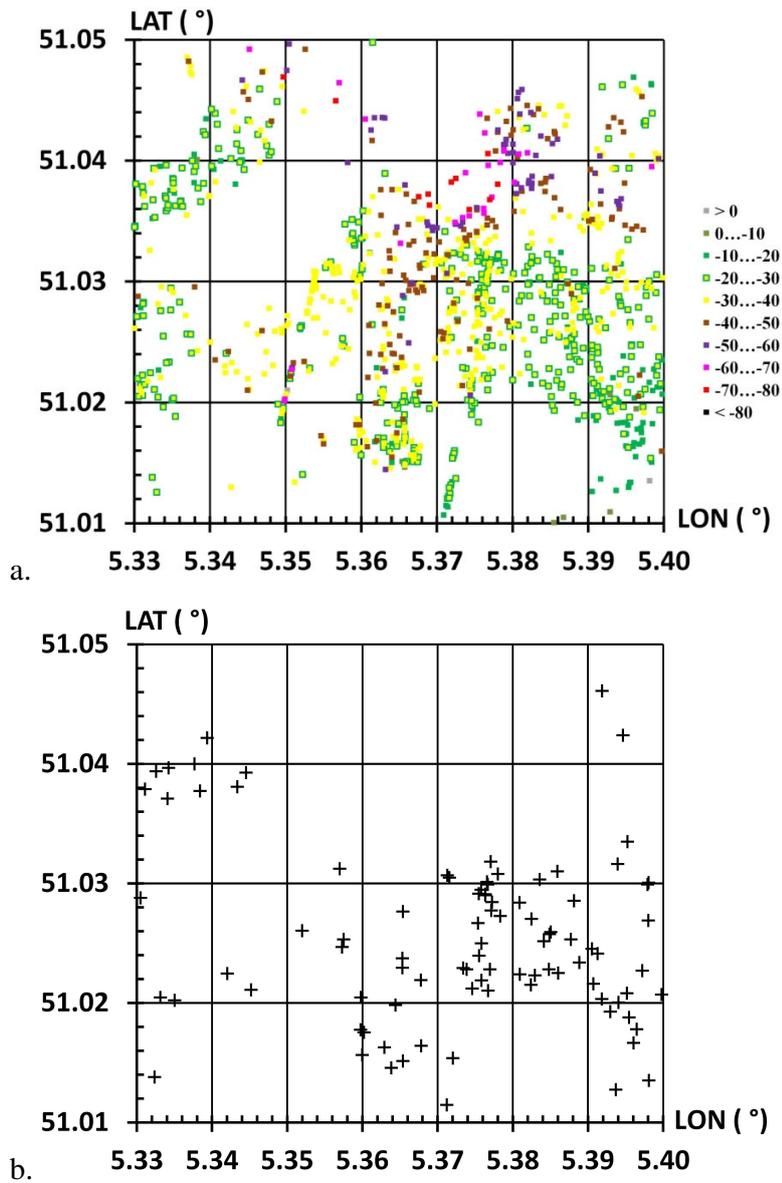


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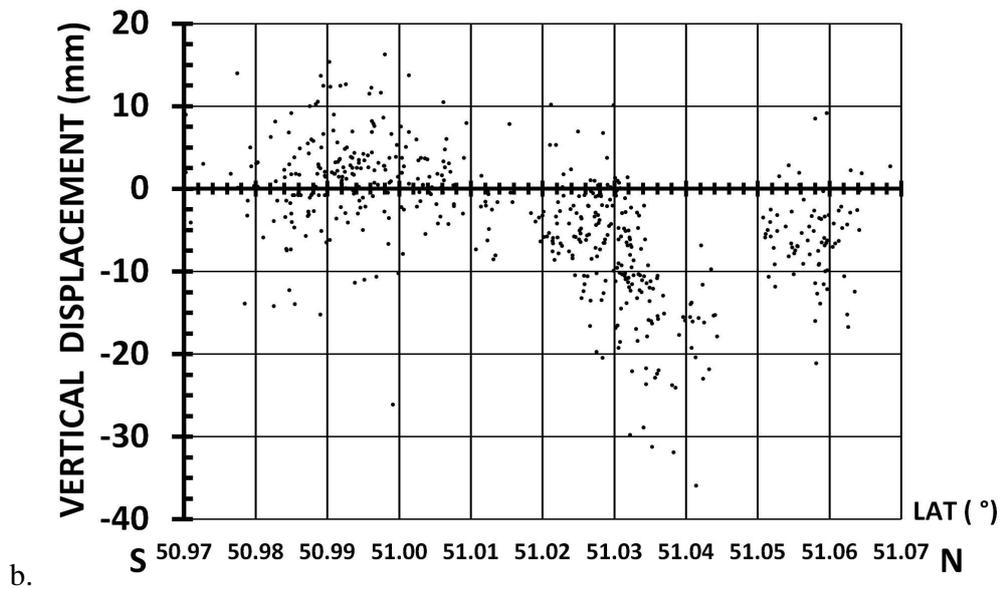
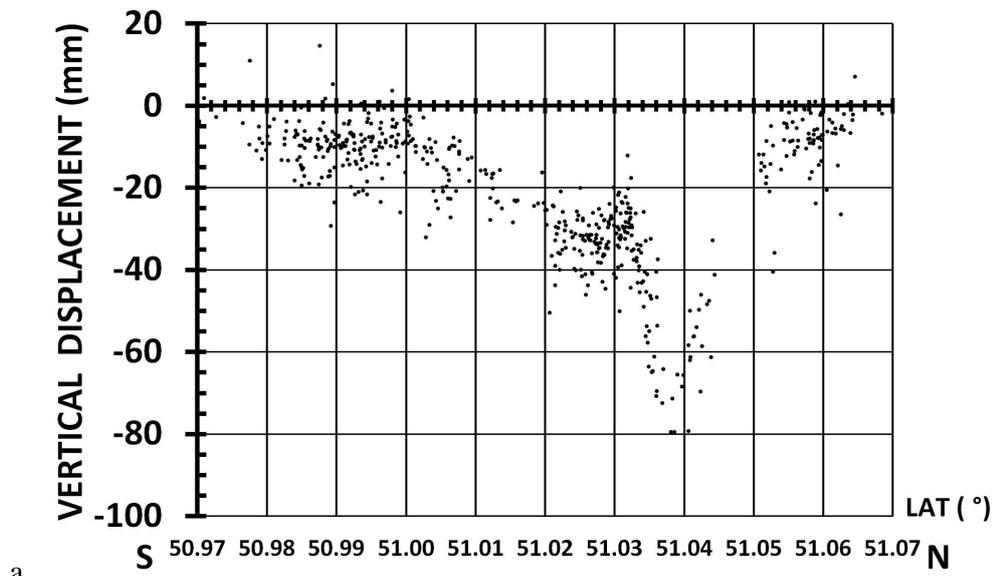


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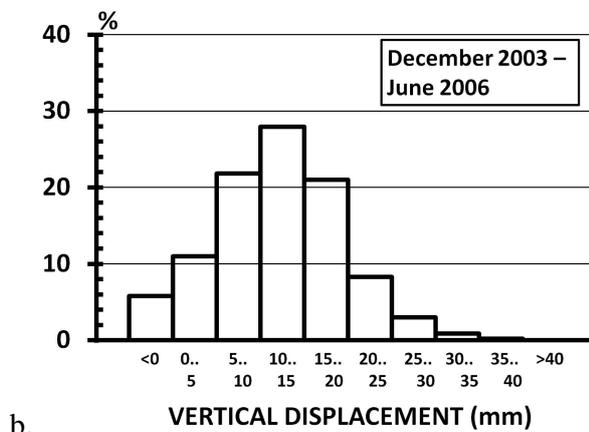
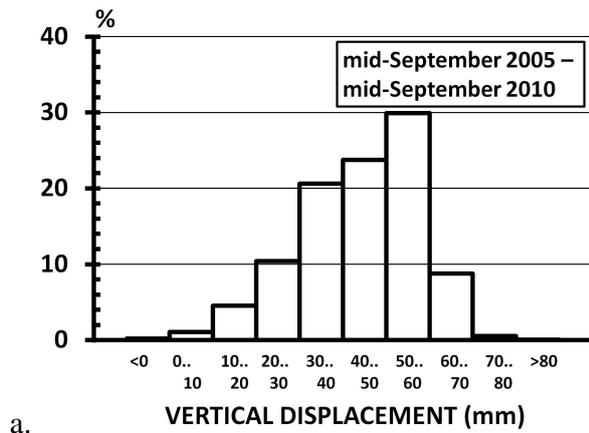


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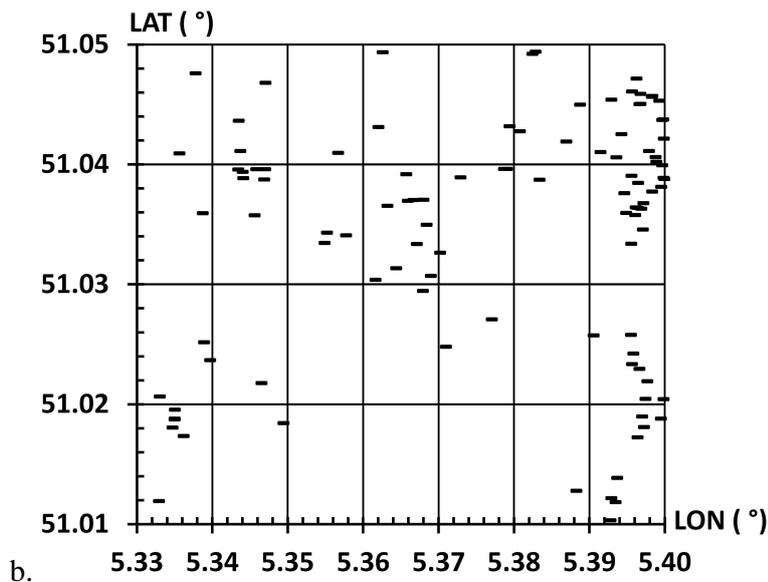
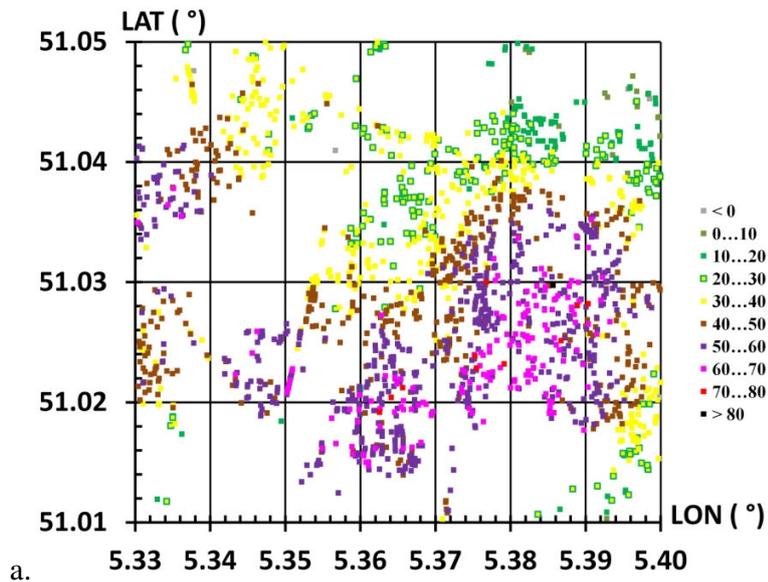


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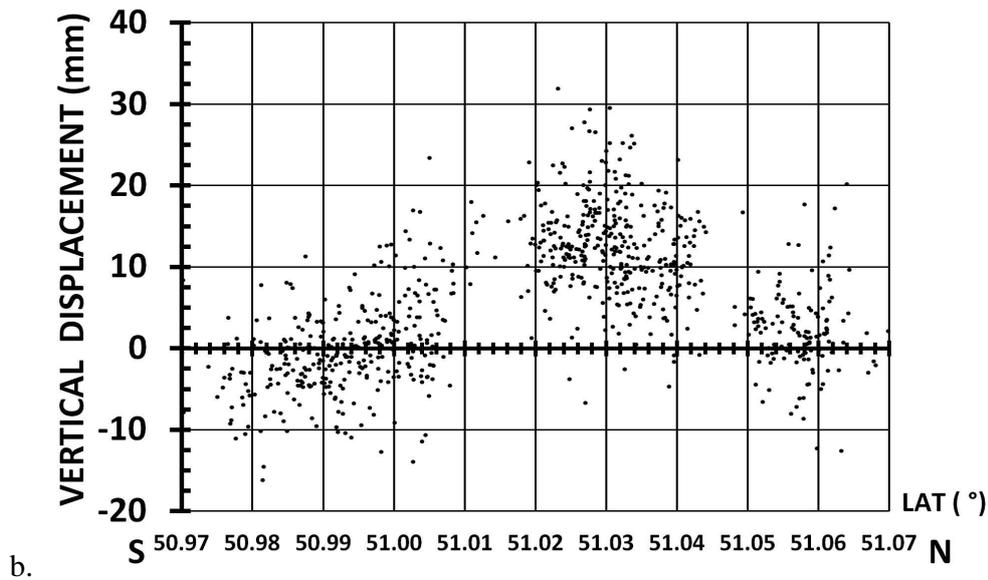
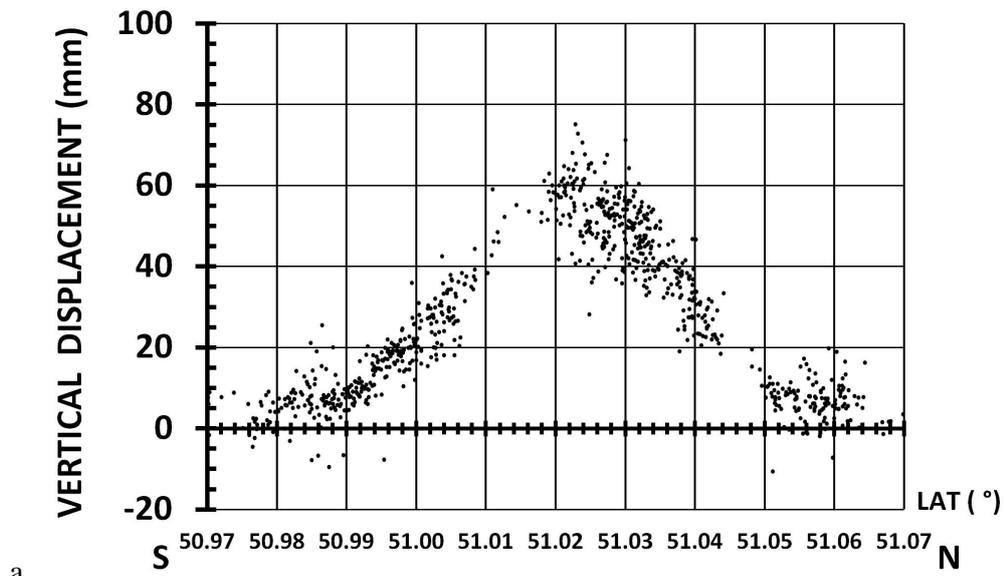


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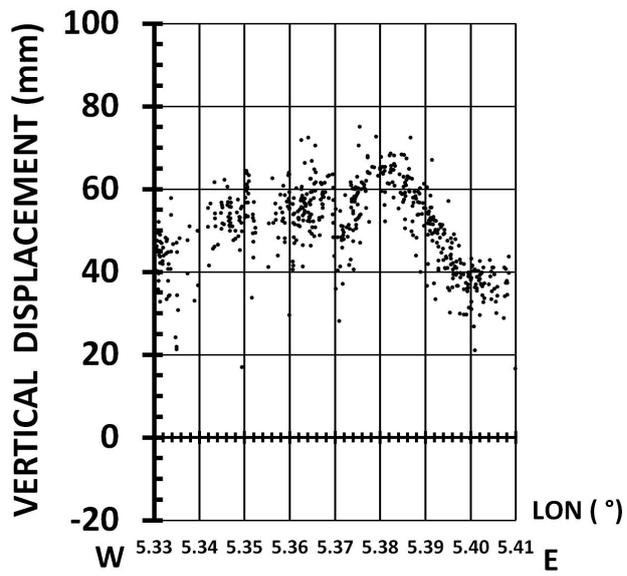
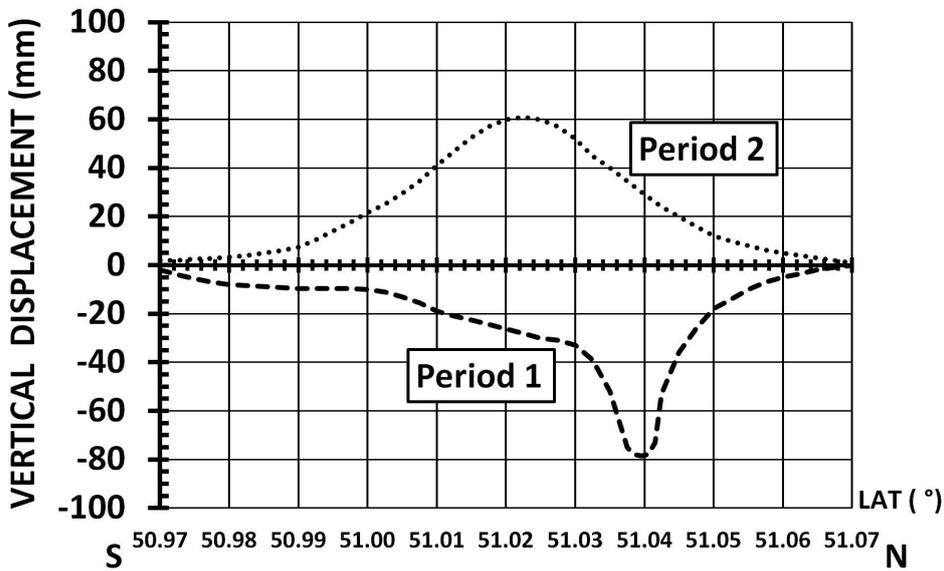
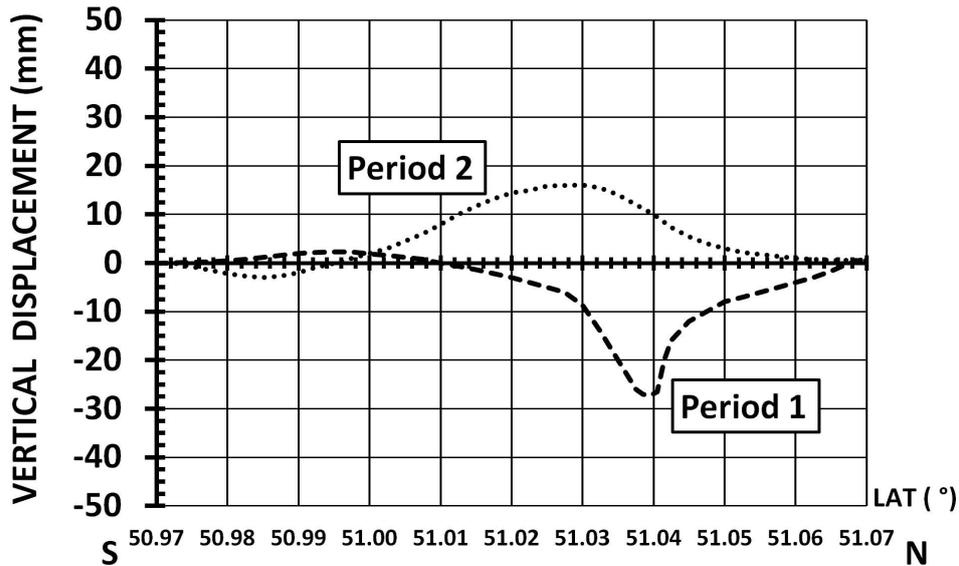


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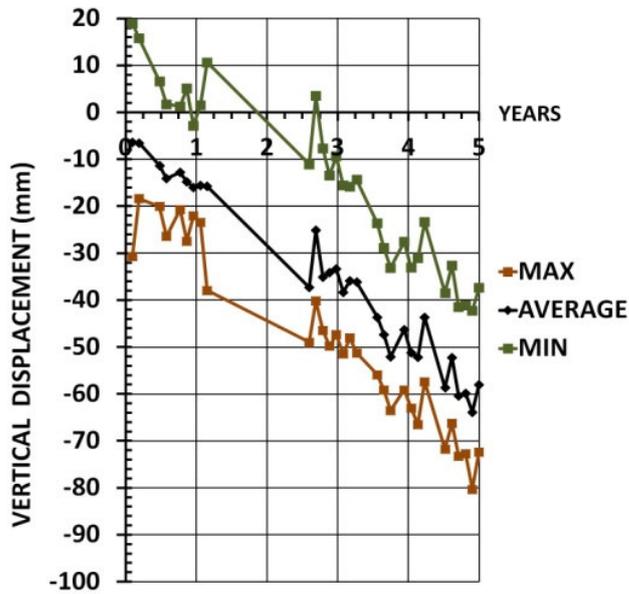


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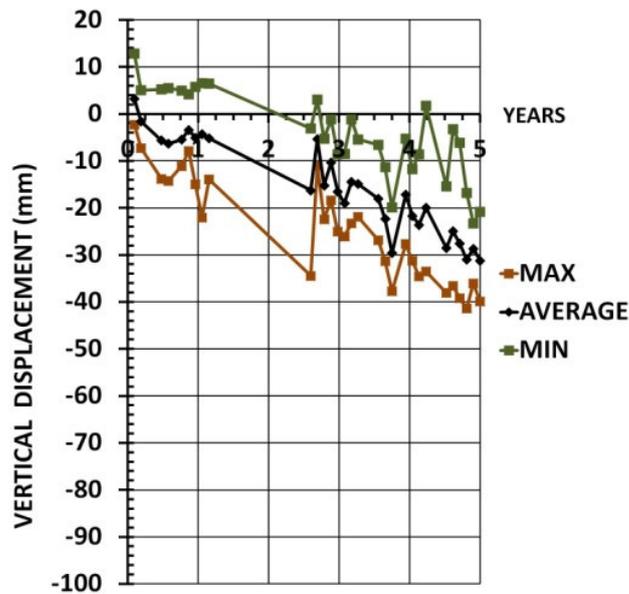


b.

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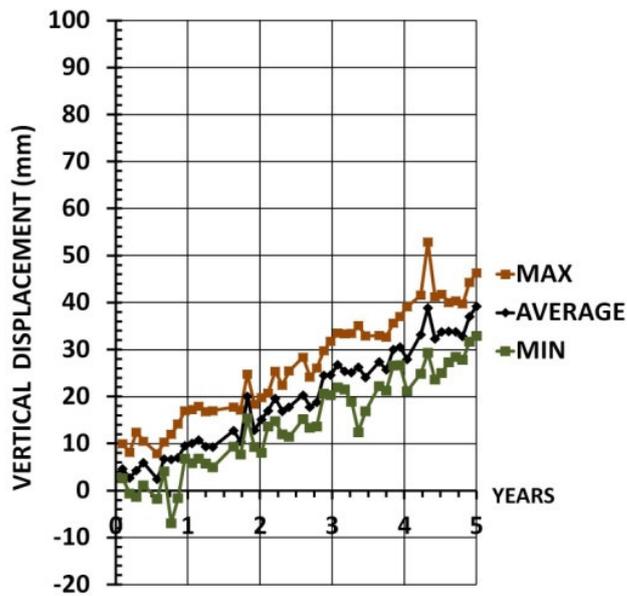


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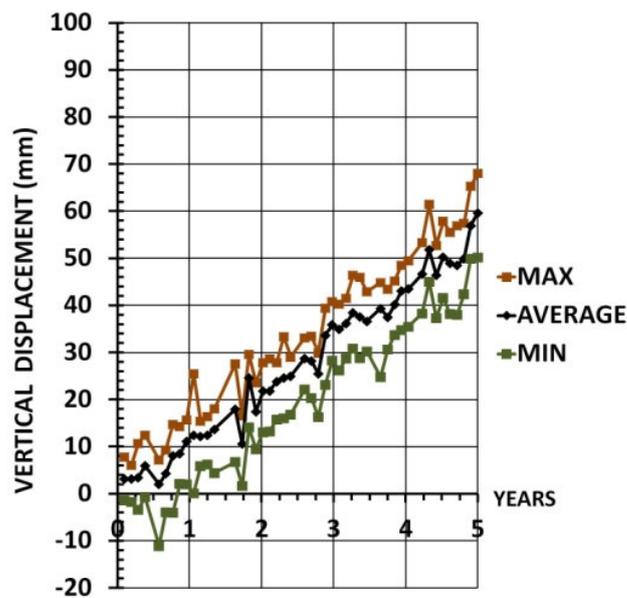


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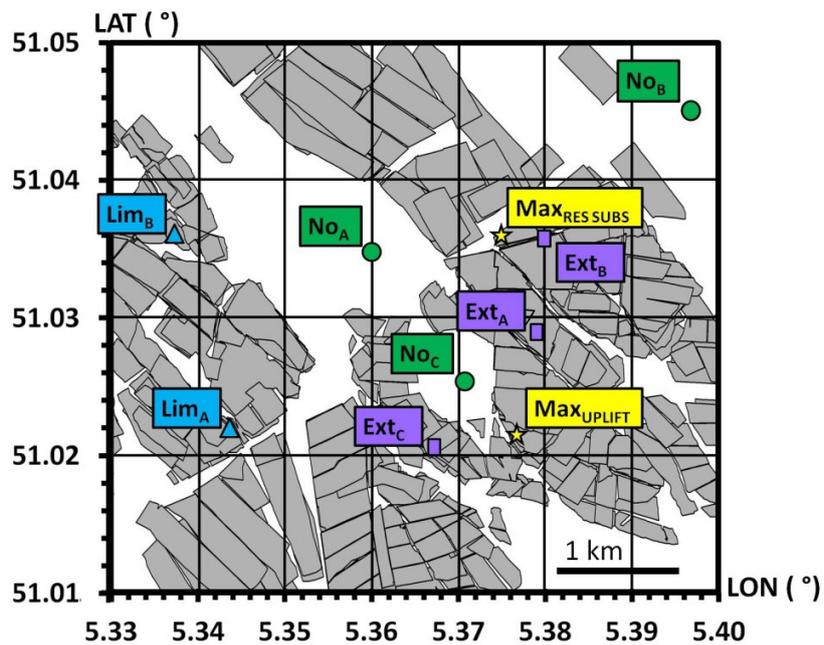


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Tables

Table 1. Information on total surface movement during the two times zones of 5 and 2.5 years considered in the first observation period for the total area studied.

	Period 1, 5-year time zone, mid-August 1992- mid-August 1997	Period 1, 2.5-year time zone, July 1998- December 2000
Number of reflectors	1,073	1,073
Minimum	5.8 mm	14.9 mm
Average	-32.9 mm	-9.0 mm
Maximum	-79.5 mm	-40.5 mm
Standard Deviation	11.8 mm	7.2 mm
Skewness (*)	0.83	0.24

(*) Positive skewness means a long tail for large values, i.e. large subsidence in the first observation period.

Table 2. Information on total surface movement during the two times zones of 5 and 2.5 years considered in the second observation period for the total area studied.

	Period 2, 5-year time zone mid-September 2005 - mid-September 2010	Period 2, 2.5-year time zone December 2003 - June 2006
Number of reflectors	1,808	1,808
Minimum	-9.9 mm	-21.7 mm
Average	43.9 mm	11.8 mm
Maximum	83.5 mm	37.1 mm
Standard Deviation	13.8 mm	7.6 mm
Skewness (*)	-0.58	-0.19

(*) Negative skewness means a long tail for small values, i.e. small uplift in the second observation period.

Table 3. Information on the two locations, corresponding to the zones with approximately largest residual subsidence in first period ($\text{Max}_{\text{RES SUBS}}$) and largest uplift in second observation period ($\text{Max}_{\text{UPLIFT}}$): information on total movement of 10 reflectors around coordinates given in 5-year time zones studied and data on exploitation below these locations.

LOCATION		$\text{Max}_{\text{RES SUBS}}$	$\text{Max}_{\text{UPLIFT}}$
Coordinates,	LAT	51.036°N	51.022°N
	LON	5.375°E	5.377°E
Vertical movement over 5 years:			
first period:	MIN	-37.4 mm	-20.9 mm
	AVERAGE	-58.1 mm	-31.2 mm
	MAX	-72.4 mm	-40.0 mm
second period:	MIN	33.0 mm	50.2 mm
	AVERAGE	39.3 mm	59.7 mm
	MAX	46.3 mm	68.0 mm
Exploitation:			
NUMBER OF LONGWALLS		4	6
OLDEST YEAR		1968	1939
MOST RECENT YEAR		1982	1959
MIN DEPTH		686 m	565 m
MAX DEPTH		796 m	712 m
TOTAL MINING HEIGHT		7.0 m	9.3 m

Table 4. Information of selected locations, i.e. movement of 10 reflectors around coordinates given over 5-year time zones in both observation periods and mining characteristics underneath locations: a. No exploitation; b. Limited exploitation; c. Extensive exploitation.

a.

LOCATION		No _A	No _B	No _C
Coordinates,	LAT	51.035°	51.045°	51.025°
	LON	5.360°	5.397°	5.371°
Vertical movement over 5 years:				
first period:	MIN	-24.3 mm	-14.5 mm	-27.9 mm
	AVERAGE	-28.7 mm	-25.7 mm	-36.8 mm
	MAX	-34.6 mm	-40.4 mm	-46.0 mm
second period:	MIN	22.9 mm	-6.6 mm	28.2 mm
	AVERAGE	29.8 mm	8.4 mm	45.6 mm
	MAX	42.5 mm	24.6 mm	54.8 mm
Exploitation:		None	None	None

b.

LOCATION		Lim _A	Lim _B
Coordinates,	LAT	51.022°	51.036°
	LON	5.344°	5.337°
Vertical movement over 5 years:			
first period:	MIN	-27.9 mm	-10.1 mm
	AVERAGE	-35.7 mm	-22.7 mm
	MAX	-42.3 mm	-33.7 mm
second period:	MIN	46.7 mm	41.7 mm
	AVERAGE	54.0 mm	52.2 mm
	MAX	62.3 mm	61.9 mm
Exploitation:			
NUMBER OF LONGWALLS		2	2
OLDEST YEAR		1954	1933
MOST RECENT YEAR		1977	1938
MIN DEPTH		613 m	688 m
MAX DEPTH		736 m	743 m
TOTAL MINING HEIGHT		2.5 m	2.0 m

c.

LOCATION		Ext _A	Ext _B	Ext _C
Coordinates,	LAT	51.029°	51.036°	51.021°
	LON	5.379°	5.380°	5.367°
Vertical movement over 5 years:				
first period:	MIN	-22.8 mm	-24.9 mm	-26.8 mm
	AVERAGE	-28.9 mm	-45.9 mm	-32.8 mm
	MAX	-34.7 mm	-79.5 mm	-50.4 mm
second period:	MIN	51.1 mm	35.8 mm	48.9 mm
	AVERAGE	59.6 mm	43.3 mm	59.7 mm
	MAX	67.6 mm	48.9 mm	70.5 mm
Exploitation:				
NUMBER OF LONGWALLS		7	8	7
OLDEST YEAR		1941	1943	1947
MOST RECENT YEAR		1968	1971	1965
MIN DEPTH		633 m	629 m	585 m
MAX DEPTH		888 m	965 m	735 m
TOTAL MINING HEIGHT		9.9 m	10.3 m	9.2 m

Table 5. Information on residual subsidence of the locations considered in Table 3 and Table 4, re-ordered as a function of the most recent exploitation panel.

Most recent year of exploitation	Minimum residual subsidence	Average residual subsidence	Maximum residual subsidence	Location
1938	-10.1 mm	-22.7 mm	-33.7 mm	Lim _B
1959	-20.9 mm	-31.2 mm	-40.0 mm	Max _{UPLIFT}
1965	-26.8 mm	-32.8 mm	-50.4 mm	Ext _C
1968	-22.8 mm	-28.9 mm	-34.7 mm	Ext _A
1971	-24.9 mm	-45.9 mm	-79.5 mm	Ext _B
1977	-27.9 mm	-35.7 mm	-42.3 mm	Lim _A
1982	-37.4 mm	-58.1 mm	-72.4 mm	Max _{RES SUBS}