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ORIGINAL ARTICLE

Monitoring of coal mining subsidence in peri-urban area of Zonguldak city (NW Turkey) with persistent scatterer interferometry using ALOS-PALSAR

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Abstract This paper presents the results of spatiotemporal monitoring of surface subsidence over a mining area in Zonguldak Province of Turkey using Synthetic Aperture Radar (SAR) data, providing maps of subsidence rates in the radar line of sight direction. A total of 18 SAR images, acquired between January 2007 and June 2010 by the Japanese Advanced Land Observing Satellite, have been used to map the surface displacements using the Persistent Scatterer Interferometry technique. The use of Phased Array Type L-band Synthetic Aperture Radar data has proved useful for avoiding signal decorrelation and estimating surface deformation in the heavily vegetated study region. The technique enables the monitoring of continuous small displacements over a large area. Our findings present that many Persistent Scatterers were located on the vegetation cover. The results reveal areas of ground surface subsidence up to 44 mm/year that are well correlated with the underground coal mining galleries particularly in the Gelik region where the Karadon mining galleries are present.

Keywords InSAR · Persistent scatterer · Coal mining · Land subsidence · Time series analysis

Introduction

Zonguldak province located along the Black Sea coast northwest of Turkey, has the largest underground hard coal mine in Turkey. Mining was initiated in the mid-19th century and is still active today. More than 150 years of intense mining extraction duration, approximately 400 million ton coal was produced (Akcin et al. 2010). In Turkey, hard coal is produced under the competence of Turkish Hardcoal Enterprises (THE). In the area, coal reserve researches were completed under −1,200 m from the surface, and approximately 305.2 million and 412.5 million tons of hard coal have been estimated in Üzülmez and Karadon, respectively, by THE (Turkish Hardcoal Enterprise Annual Report 2012). Hard coal is used especially in the iron and steel industries that are important for the national economy. Besides, subsidence has been monitored during the intense and constant mine production in the past (Akcin et al. 2010). Urban and rural areas suffered due to the mining and several damages occurred in Zonguldak (Turer et al. 2008; Akcin et al. 2010; Can et al. 2011, 2012). Moreover, due to subsidence, many legal problems have occurred between the public and the mining administration (Can et al. 2012). Results of this study may disclose these problems. Furthermore, in the area, there are many illegal mining activities that also affect the environment (Turer et al. 2008). Additionally, natural

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environment and both surface and underground drainage systems are disturbed (Can et al. 2011). In this context, it is important to monitor the deformation and specify the subsidence rate for this region.

In the study area, the actual rate of deformation and its spatial distribution in time are not known due to the lack of conventional measurements such as GPS and leveling. In addition, these methods have disadvantages as being short period measurements and rare network of points. On the other hand, Differential InSAR (DInSAR) has become an important tool for measuring displacements over wide areas. It has been proved by many researches that DInSAR is capable of detecting small-scale deformations. It has been successfully applied for mining related deformation (Akcin et al. 2010), earthquakes (Cakir and Akoglu 2008), landslides (Strozzi et al. 2005), and volcanic studies (Pagli et al. 2006). Beside potentiality of using conventional DInSAR, large baseline geometry or atmospheric inhomogeneity loss of coherence may occur due to temporal decorrelation. For this purpose, to reduce the effects of these decorrelations, new approaches known as persistent scatterer interferometry (PSI) have been proposed (Ferretti et al. 2001; Mora et al. 2003; Hooper et al. 2004; Kampes 2006). It is introduced that several investigations have been done by persistent scatterer interferometry (PSI) to figure out the deformation phenomena on large scales such as mining-induced subsidence (Guéguen et al. 2009), earthquakes (Arikan et al. 2010), volcano (Hooper et al. 2007), water withdrawal (Osmanoğlu et al. 2011), landslide (Greif and Vlcko 2012) and land subsidence (Aly et al. 2012).

Previous studies have presented subsidence in the study area by DInSAR method using different sensors such as RADARSAT, JERS and ALOS images for different and shorter time span. According to their results, 204 mm/4.5 months and 30–40 mm/1.5 months deformation rates were monitored for a short time period by JERS and ALOS, respectively (Deguchi et al. 2007; Akcin and Kutoglu 2010). As a result of their studies they have reached the conclusion that, for the same area, C-band RADARSAT was not able to achieve monitoring subsidence due to lack of coherence at vegetated area (Deguchi et al. 2007; Akcin et al. 2010).

In this paper, Stanford Method for Persistent Scatterer (StaMPS) method which has advantages over rural areas (Hooper et al. 2004) was used. As a preliminary study, deformations in Zonguldak region were presented with C-band data, which were gathered in both ascending and descending paths of ENVISAT images (Abdikan et al. 2011). However, due to vegetation at rural areas and gaps in dataset, slight densities of PS points were extracted. This work focuses on applying PSI analysis on a peri-urban and vegetated area to determine the relevant deformation where underground coal mines are located. ALOS/PALSAR scenes are applied to monitor the potential ground subsidence.

Here, we report the results of long time subsidence monitoring by PSI analysis over the mining area in Zonguldak. Furthermore, a temporal evolution of deformation velocity with InSAR time series was performed. This study reveals a subsidence rate of 44 mm/year as maximum at the mining area of the Zonguldak province. This technique has given the opportunity to determine the temporal evolution of the subsidence phenomena at a peri-urban area.

Study area

The study area is located at the coastline of Zonguldak city in NW Turkey. Urbanization is mostly located along the coastline, and peri-urban area is dispersed because of topographical structure and mining regions. The area has a hilly topography with 56 % of the area being composed of mountains, and the altitude changing between 0 and 986 m (Fig. 1). Forest covers 52 % of Zonguldak where mean humidity is approximately 70 %. The region has an oceanic climate, thus precipitation can be seen nearly in all seasons.

In the center of Zonguldak there are three mines belonging to THE, namely Kozlu, Karadon and Üzülmez mining areas. Kozlu mine is located at the coastline over Kozlu town. In this study, we focused on an area of about 110 km^2 covering only Karadon and Üzülmez mines. These mines are located at peri-urban area which lies on the east of Zonguldak city center. Karadon mine is located between Kilimli and Gelik cities, and 15 km east of Zonguldak city center. Mining operations are continuing at 11 galleries which range between 160 and −540 m elevations. The Üzülmez mine is located south of Karadon and southeast of Zonguldak city center. Currently seven mining galleries range between 38 and −320 m of elevation in Üzülmez. Due to constant subsidence, a subsidence influence area and a potential subsidence area were defined by THE (Fig. 1).

In Zonguldak region the lithological units were comprised in Paleozoic, Mesozoic, and Cenozoic era. Main four systems which were formed from up to bottom are Cenozoic–Quaternary, Mesozoic–Cretaceous, Mesozoic–Cretaceous and Paleozoic–Carboniferous respectively. The coal seams were formed in Westphalian and Namurian stages of Paleozoic–Carboniferous system (Fig. 2).

The rate and the spatial expansion of subsidence regarding the coal mining can be affected by many parameters such as thickness of seam, depth of mining, dip angle of mining, geology (Lee et al. 2013). In the area, coal seams are not uniform and thickness of coal seam varies. This is not favorable for the subsidence calculation (Duzgun 2005; Can et al. 2011, 2012). Mining techniques have

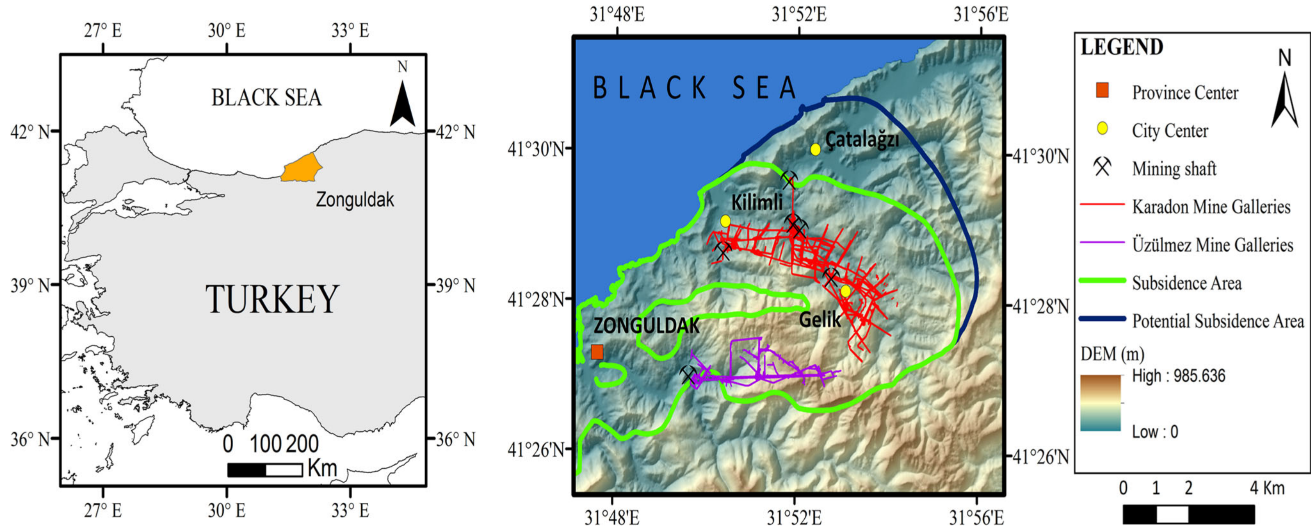

Fig. 1 The location of the study area and the mining galleries

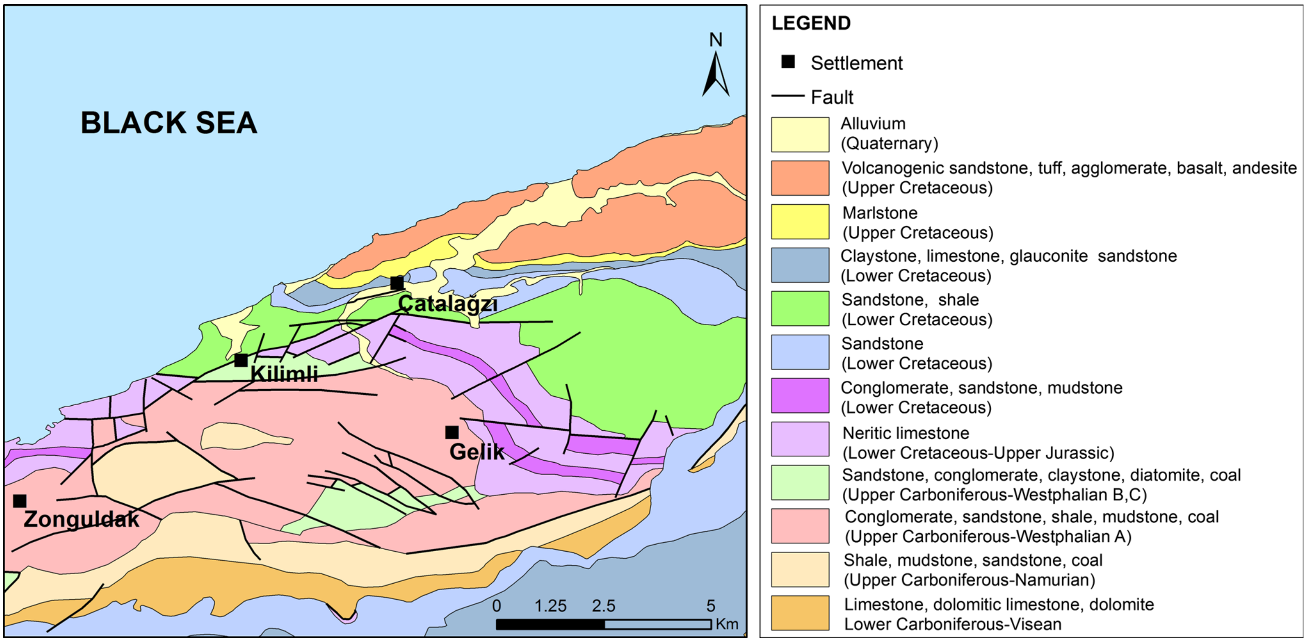

Fig. 2 The geological map of the study area (adapted from Alan and Aksay 2002)

different effect on the magnitude of subsidence. Longwall mining method, for instance, generates larger displacement compared to that of pillar and Room mining methods (Lee et al. 2013). In the study area coal extraction is carried out at different horizons in two collieries simultaneously. According to the distinctive characteristics of the coal seam, roof and floor conditions, any mining method can be solely operated (Güney 1967; Duzgun 2005; Can et al. 2012). Conventional longwall advancing and retreating methods have been used most commonly at the coalfield (Güney 1967; Duzgun 2005).

In the study area, approximately 893.000 ton coal/year in Karadon and 535.000 ton coal/year in Üzülmez was extracted between 2007 and 2010 (Fig. 3). The graph shows that in Karadon, the coal extraction fluctuates from 2007 to 2010. First 2-year amounts were closer to each other just over 800.000 ton. It considerably rises up more than 200.000 ton in 2009 and then slightly drops around to 900.000 ton in 2010. For the same time span extraction in Üzülmez slowly declines from 2007 to 2008 and then increases approximately to 100.000 ton in 2009 and then gradually increases in next 2 years. The coal extraction was

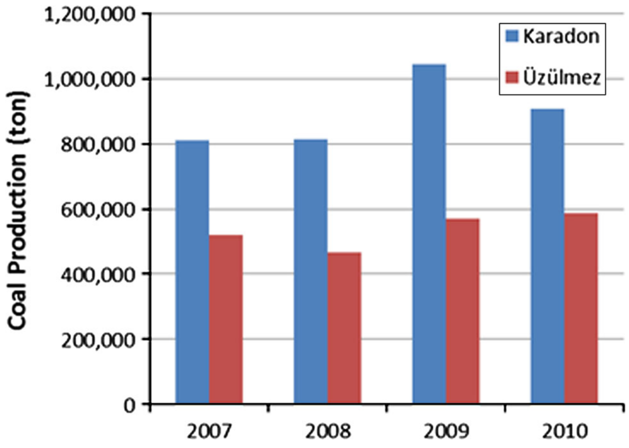

Fig. 3 Coal production in the study area between 2007 and 2010

not increasing linearly; however the subsidence might occur long after mining operations (Ng et al. 2009; Yue et al. 2011).

Observations and PSI time series analysis

In this paper, repeat-pass Phased Array-type L-band Synthetic Aperture Radar images of Advanced Land Observing Satellite (ALOS) which is provided by the Japanese Aerospace Exploration Agency (JAXA) were used. Phased Array Type L-band Synthetic Aperture Radar (PALSAR) has a wavelength of 23.6 cm that can penetrate to the surface better than C-band images (Agustan et al. 2010). This feature is important for our case study because our aim is to identify mining collapses in rural and densely vegetated areas. Since previous InSAR applications over this region had some limitations, it is verified the superiority of the usage of ALOS in this study (Deguchi et al. 2007; Abdikan et al. 2011).

18 raw (Level 1.0) ALOS images were acquired along the ascending path with 34.3 off-nadir angle in both Fine Beam Single (FBS) and Fine Beam Dual (FBD) modes between January 2007 and June 2010 time span. The dataset consisted of 12 FBS HH polarized and 8 FBD HH/HV polarized images. FBD images have two times worse range resolution than FBS images. Raw images were focused to produce single look complex images (SLC) by ROI_PAC (Rosen et al. 2004). For the process of all HH polarized images together, FBD images were converted to FBS images during the focusing by ROI_PAC (Sandwell et al. 2008). Interferograms were calculated from SLC images with DORIS software (Kampes et al. 2003). A 3-arcsecond (∼90 m) posting Shuttle Radar Topography Mission (SRTM) DEM was used to remove the effects of topography from the interferograms. Precise DORIS satellite orbits were gathered from European Space Agency (ESA) to correct the satellite positions.

The PSI technique was applied using StaMPS (Hooper et al. 2007) to detect the ground subsidence. The PSI method uses multi-temporal SAR data to generate a stack of interferograms generated from a common master image which was acquired on 23 July 2008. The temporal and perpendicular baselines of slave images with respect to the master image were shown in Table 1. Large temporal and perpendicular baselines cause decorrelations which effect the InSAR measurements negatively (Ferretti et al. 2001). Table 1 shows the perpendicular baselines are quite small (Sandwell et al. 2008), and for the temporal baselines 690 days was accepted as maximum.

In this assumption, deformation and phase are correlated in space. The main concept of PSI technique used by StaMPS is based on identification of single persistent targets which are spatially correlated in long time period.

Some PS techniques such as Ferretti et al. (2001), Lyons and Sandwell (2003) merely use amplitude images where PS pixels are extracted from strong returns of surface (Riddick et al. 2012). Besides, StaMPS has proven being reliable over the natural terrains (Hooper et al. 2007). First, it uses amplitude dispersion index, defined to identify the PS candidates (Ferretti et al. 2001). Then, the approach identifies the persistent scatterers (PS) using the dispersion index and phase stability. Here a threshold value 0.4 was considered for the dispersion index. The PS points were extracted in the processes with respect to a reference point (Fig. 2). The

Table 1 ALOS imagery (track: 604, frame: 820) used in the PSI analysis

No.	Date	B_{tem} (days)	$B_{\perp}$ (m)	B_{Dopp} (Hz)
1	18 January 2007	−552	−1,407	−11.61
2	5 March 2007	−506	383	10.50
3	5 June 2007	−414	518	47.99
4	5 September 2007	−322	1,301	15.24
5	21 October 2007	−276	1,602	05.75
6	6 December 2007	−230	1,793	−00.15
7	21 January 2008	−184	2,262	−15.78
8	**23 July 2008**	**0**	**0**	**0**
9	23 October 2008	92	−1,961	05.56
10	8 December 2008	138	−1,736	−03.02
11	10 March 2009	230	−716	01.59
12	26 July 2009	368	−449	−22.51
13	10 September 2009	414	89	−07.15
14	26 October 2009	460	395	03.88
15	11 December 2009	506	632	−02.39
16	13 March 2010	598	1,842	05.71
17	28 April 2010	644	1,895	10.35
18	13 June 2010	690	1,905	40.07

residuals due to topography has been estimated and removed. High-pass and low-pass filters were applied on time and space respectively to remove the phase of atmospheric delay. At the end of process a mean velocity map of PS points along the line of sight (LOS) direction was yielded.

Results and discussions

A PSI map based on 17 interferograms was generated from ALOS dataset. The temporal baseline was shorter than a 2-year period, and the perpendicular baseline was ranging between 89 and 2,262 m (Table 1). PSI derived LOS displacements of 18 images show subsidence in space and time (Fig. 4). A significant subsidence pattern was monitored in the center of the study area where the Karadon and Üzülmez mines galleries are located.

The amount of PS points was reaching up to 24,036 in total. Over the study area 218.51 points/km^2 was identified as the average value. In the analysis, it was noticed that the distribution of the points were not limitedly observed over settlement areas. Through the coastline and port, also large amounts of points were present over vegetated peri-urban areas and hills. A close rate to zero (−6 to 6 mm/year) was determined for most of the distributed points. These points were reflecting constant areas (Fig. 4).

However, PSI displacement rates have been increasing in the north of Gelik and southeast of Kilimli. Denser points and spatially larger areas were identified at Karadon mining area than Üzülmez mining area in comparison to a previous study (Abdikan et al. 2011). In the north of Gelik region, LOS subsidence rates were mostly monitored between 30 and 40 mm/year. In Kilimli region, subsidence rates have been reaching up to 35 mm/year. The displacement rates mostly have been changing from 20 to 30 mm/year within a small area around Üzülmez mine. Moreover, towards the northeast of Üzülmez mine, the rate of subsidence amount was <25 mm/year. The highest deformation rate was extracted at Karadon mine as 44 mm/year with a few points from ALOS/PALSAR result. Note that these figures are highly correlated with the coal production amounts given in Fig. 3. Namely, the coal

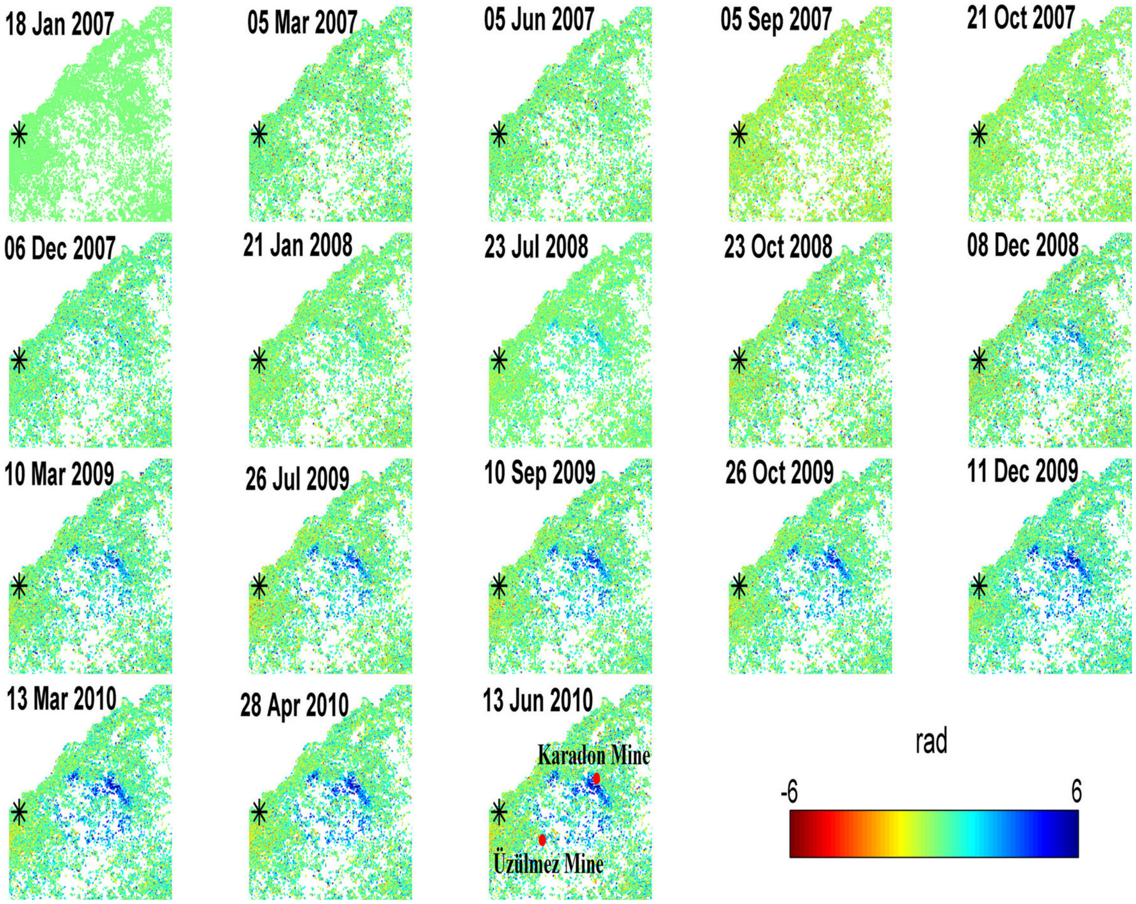

Fig. 4 Estimated cumulative LOS displacements (rescaled to 18 January 2007) over the study area where *asterisk* refers to the selected reference point that has a stable phase overtime. The locations of Karadon and Üzülmez mines are indicated on the image of 13 June 2010

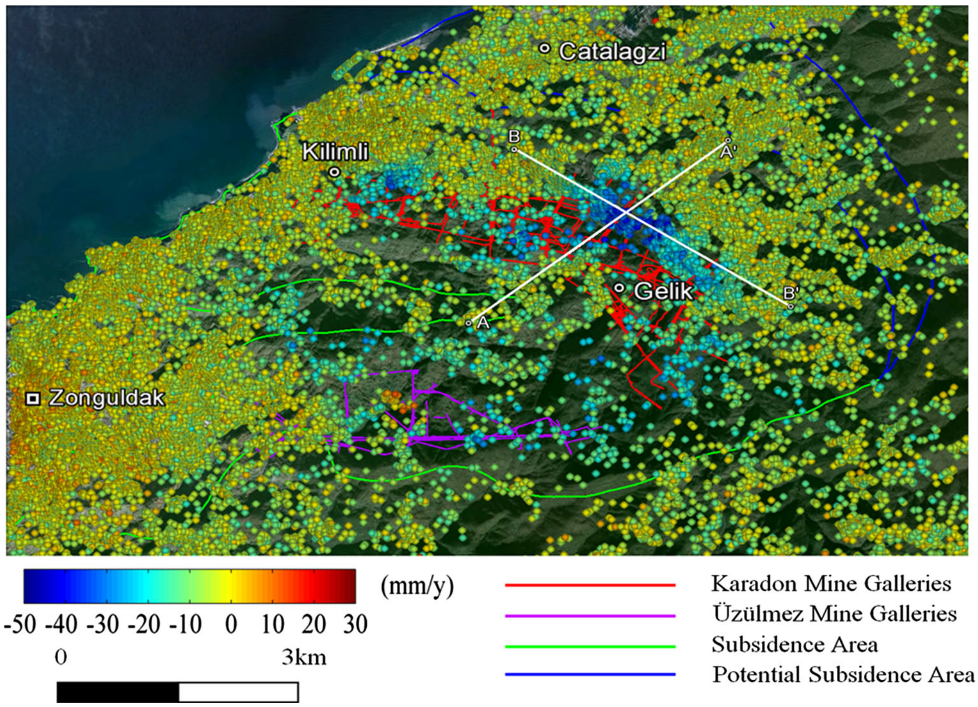

Fig. 5 LOS average displacement velocity map overlaid on Google Earth. Deformation rates in mining area between January 2007 and June 2010 monitored using PSI analysis of 18 ALOS/PALSAR images. Locations of cities and AA′ and BB′ cross-sections were also represented

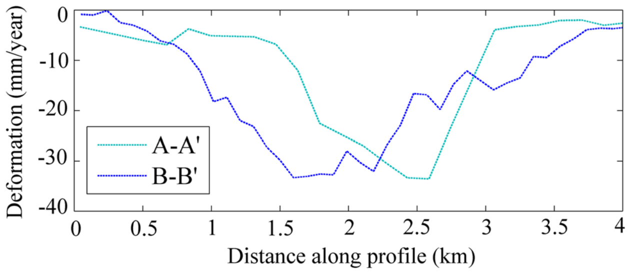

Fig. 6 The spatial profiles over the study area along lines AA′ and BB′

production and the subsidence rate are higher in Karadon whereas they are smaller in Üzülmez. Meanwhile cross-section analyses were applied to determine the subsidence in space. Two cross-sections of AA′ and BB′ were placed over the Karadon mine to show the deformation (Fig. 5). The mining related subsidence bowl was clearly determined in space in both profiles of 4 km long (Fig. 6). The PSI method allows us to investigate the PS displacement over the selected time period. The evolution of the deformation over 3.5 year's period was determined by time series analysis.

For this purpose, two peri-urban areas where subsidence patterns were clearly monitored were selected nearby Gelik (Fig. 7a) and Kilimli (Fig. 7b) cities. In both selected areas, the ground is covered by vegetation and forest. In Fig. 7b there are more city structures as buildings and roads. In two areas, two points were analyzed to interpret the evolution of subsidence in time. In Fig. 7, evidence of the evolution of deformation was observed in time within Gelik and Kilimli regions.

In the first area at Gelik, approximately 125 and 84 mm deformation were measured at PS1 and PS2 points respectively (Fig. 7c). In the second area at Kilimli approximately 101 and 80 mm deformation at PS1 and PS2 points were measured respectively (Fig. 7d). A non-linear characteristic of deformation were achieved from the time series analysis of PS points.

InSAR studies on this area were previously published by Deguchi et al. (2007), Akcin and Kutoglu (2010), and Akcin et al. (2010). In their studies, conventional DInSAR method was used with C-band RADARSAT. This method failed in the vegetated areas. Because L-band studies were applied for the short time period in their study, it was not sufficient to understand the subsidence phenomena. In our study, PSI method was applied successfully and it was observed that the number of PS points was dramatically increased over vegetated areas comparing to the previous C-band InSAR results (Akcin et al. 2010; Abdikan et al. 2011).

It is noticed that the deformation rates are higher in Karadon than in Üzülmez. Surface subsidence related to the mining activities may confirm these results. In Karadon, more hard coal was exploited during a 3.5 years period from Jan 2007 to June 2010. The Karadon and Üzülmez mines are still active and continuing to produce hard coal. During the period of ALOS data acquisition, approximately 3.5 and 2.1 million tons of coal were produced in Karadon and Üzülmez mines, respectively.

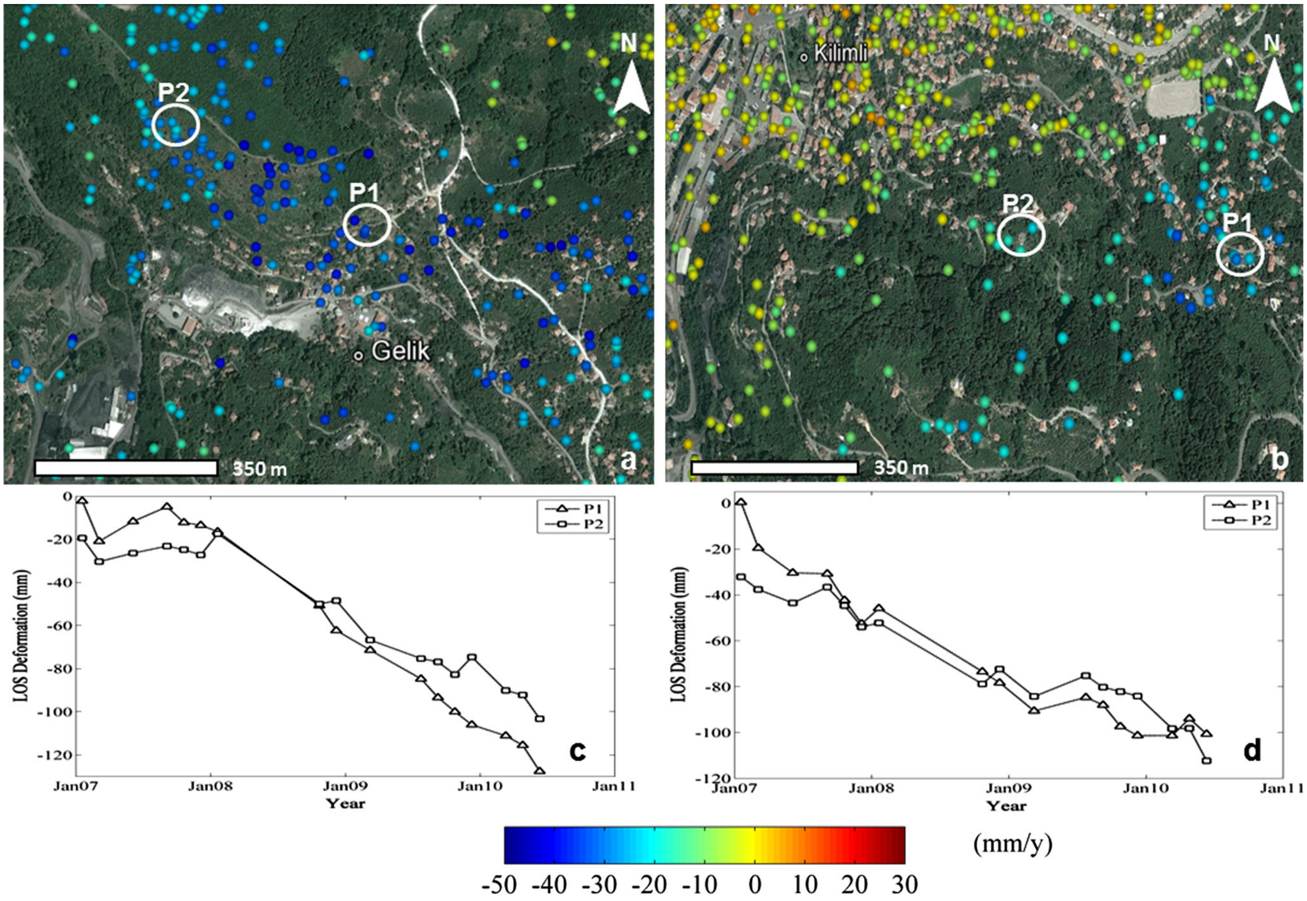

Fig. 7 Sub-area selected in, **a** Gelik, **b** Kilimli, **c** Time series of PS located in **a**, **d** Time series of PS located in **b**. (PS points were overlaid on Google Earth imagery)

Between June 2010 and July 2012, 1.25 and 0.86 million tons of coal were produced in Karadon and Üzülmez mines, respectively.

The number of PS points is not only high in urban areas due to the several man-made structures but also high at natural terrain. The spatial density of the determined points gives an important interpretation about the boundaries of the subsidence area. Hence, the strategic locations could be under management. A better knowledge of surface subsidence and its evolution is essential in order to estimate further risk assessment. Characterizing the deformation and understanding the variation of the Earth's surface over a long time period is very important for the assessment of vulnerability risks. Thus it will be possible to guide the growth of urbanization and to protect the environment more carefully.

Conclusions

In this study, ground surface deformation at the largest mining area of Turkey is investigated. Over the past decades, the city of Zonguldak has had problems such as collapsed settlements and other structures. The PSI technique was applied to derive the subsidence occurred in a long time period at the selected area. Although the study area is surrounded dominantly by vegetation and forest-covered hills, the technique was able to observe underground-mine-induced surface deformation.

Time series were analyzed for the evolution of deformation in time from archived ALOS data between the years 2007 and 2010. Average point density of 218.51 points/km^2 was observed. The results verify the previous C-band ENVISAT results, and it has been improved with denser PS points which gives higher deformation rates. A zone of major deformation was detected in Karadon mine by PSI. In the study area, the deformation was generally rated as 30–40 mm/year in Karadon mine and 20–30 mm/year in Üzülmez mine.

The PSI method has the capability to evaluate time series of surface deformation. In the study area, a non-linear behavior of deformation was detected from the time series analysis of selected points. The results show that PSI method contributes to identify significant improvements for the monitoring of coal mining subsidence over wide peri-urban areas of Zonguldak. PSI can provide updated displacement information via regular monitoring even in the absence of conventional ground measurements. Further studies will continue to monitor the deformation that is associated with the coal mining in both rural and urbanized areas for management of hazard.

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