

# Detection of Subsidence by Radar Interferometric Data in the Seruci-Nuraxi Figus Coal Mine Area (Sardinia, Italy)

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## Abstract

In the present work, an Advanced Differential Interferometric Synthetic Aperture Radar (DInSAR) technique has been used to measure deformations related to Seruci-Nuraxi Figus underground coal mine, located in the Carbonia-Iglesias mining district (Sardinia region, Italy). Specifically, COSMO-SkyMed (CSK) data, obtained in the framework of the Third Not-ordinary Plan of Environmental Remote Sensing project by PSP-IFSAR technique, have been used to analyze the deformations occurring between 2011 and 2014 in the study area to improve the phenomenon knowledge. Availability of images acquired in ascending and descending geometries has permitted to calculate the vertical displacement component. Accordingly, a maximum subsidence of about 25 cm has been measured in the time span 2011–2014. Furthermore, time-lapsed vertical deformation profiles have also been carried out to analyze the dynamic ground-deformation development. DInSAR measurements have allowed obtaining information on the spatial and temporal development of a

phenomenon, very useful to the cause-effect mechanism understanding aimed to improve the resources management.

## Keywords

InSAR • Coal mine • Monitoring • Subsidence • Underground mining

## 1 Introduction

Extraction activities are usually related to deformation phenomena which can mainly result in mine collapses and subsidence (Ng et al. 2012). Mine subsidence can also involve buildings (Bell 1992; Clarke et al. 2006) or infrastructures, impact groundwater and induce economic and life losses. Thus, the management of the consequences of mining activities represents a major concern issue (Raucoules et al. 2007). Several countries worldwide can be cited where coal mining provoked subsidence, like Poland, United Kingdom and Belgium (Graniczny et al. 2015), Illinois, Pennsylvania and Virginia (Pickering and Owen 1994). Mining activities can also have consequences after their cessation as occurred in the upper Silesian coal basin in Southern Poland (Graniczny et al. 2015) or in Belgium (Vervoort 2016). Therefore, monitoring of active or abandoned mining areas is a key point as to detect and forecast potential and actual geological hazards, or to improve their environmental rehabilitation (Winterhalder 1996). In the last years, Advanced Differential Interferometric Synthetic Aperture Radar (A-DInSAR) techniques have been effectively used to measure surficial deformations related to underground mining activity (Herrera et al. 2010; Tomás et al. 2014; Yerro et al. 2014; Fan et al. 2015; Przyłucka et al. 2015) being very useful to identify the extension of the area of influence also for longwall mining (Duro et al. 2013). Longwall mining represents a total extraction method which can result in failure, depending on the mine geometry as well as on the coal

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physical properties (Gee et al. 2017). In fact, this method results in the immediate collapse of the roof and overlying rock into the obtained void and this can have as consequence a ground areal subsidence.

In this work, an A-DInSAR technique has been used to study the surficial deformations occurred between 2011 and 2014 in the Seruci-Nuraxi Figus area (Carbonia-Iglesias, Sardinia region, Italy—Fig. 1), where a large underground coal longwall mine was active until 2013. For this study, COSMO-SkyMed data (2011–2014) obtained in the framework of the Third Not-ordinary Plan of Environmental Remote Sensing project (Piano Straordinario di Telerilevamento Ambientale, PST-A-3 in Italian) promoted by the Italian Ministry for the Environment, Land and Sea (Costantini et al. 2017; Di Martire et al. 2017) have been used. Specifically, 99 images (41 and 58, respectively acquired in ascending and descending geometries) were processed by PSP-IFSAR algorithm (Persistent Scatterers Pair Interferometry SAR—Costantini et al. 2008) and has allowed first analyses of the deformations measured in the

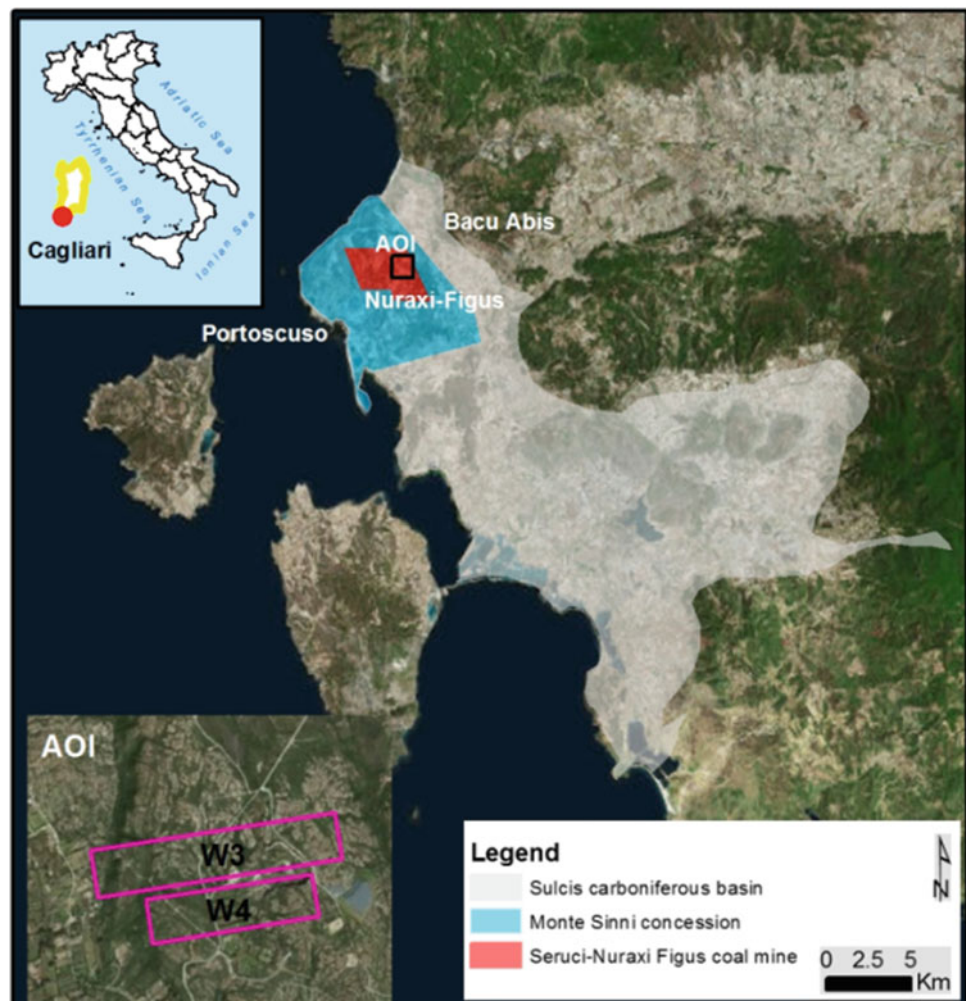
study area. At first, deformation measurements, projected along the satellite Line of Sight (LoS) direction (ascending and descending acquisitions), have been combined together to obtain vertical deformation maps and profiles. The availability of such kind of data can be very useful to the cause-effect mechanism understanding in order to improve the active deformation phenomena monitoring.

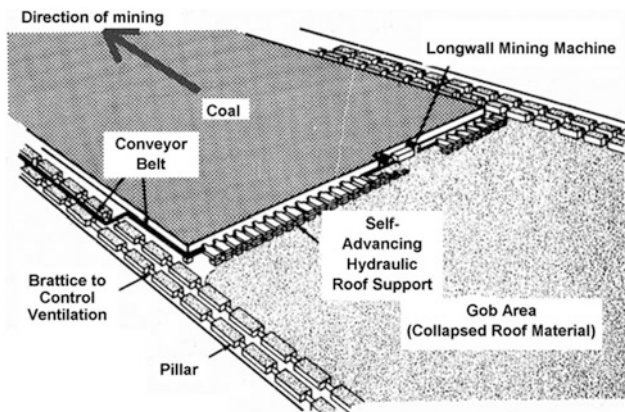
## 2 Study Area

### 2.1 History of Mining District

The Seruci-Nuraxi Figus coal mine is located in a historic coal mining district, which was active since the 1850 (Fig. 1). In the Seruci-Nuraxi Figus area the underground mining started at the end of the 1950. Since the 1976 the mining license has been owned by Carbosulcis S.p.A., which mined the coal seams in several sectors of the Seruci-Nuraxi Figus concession (also named “Monte Sinni”

**Fig. 1** Location of the study area





**Fig. 2** Longwall mining technique scheme

concession) until 2012, to supply coal fuel to the nearby thermal electric power station, owned by ENEL. Between 1996 and 2012, Carbosulcis S.p.A. mined several panels by using the longwall technique (Fig. 2).

Panels W3 and W4, within the Area of Interest (AOI, Fig. 1), are located at a depth of about 500 m below the ground surface, having average extent of about 0.1–0.2 km<sup>2</sup> (length of 500–900 m, width of 200–250 m) and height of ca. 3 m. According to the mining activity records reported in the Carbosulcis S.p.A. website, panels W3 and W4 were mined before and during the InSAR monitoring time-window, object of this study. In detail, panel W4 was completely mined out between 2008 and 2011, whereas panel W3 was only partially mined in the period 2011–2013. Between March 2013 and June 2015 the extraction activities of the W3 panel had to stop for long periods of time due to technical reasons, which prevented any further excavation of the panel and allowed only to carry out limited maintenance works to the main and tail tunnels.

On 1th October 2014, at the end of a EU procedure aimed to reveal if illegal state aid had supported the Carbosulcis operations in Sardinia, the European Commission finally approved a closure plan of the Seruci-Nuraxi Figus coal mine, which intends to definitely stop coal mining before the end of 2018 and to complete an environmental remediation plan before the end of 2027 (<http://www.carbosulcis.eu/>). Thus, from April to October 2014 the coal production was minimised and the activities were mainly focused on the maintenance and safety measures without new tunnel excavations.

## 2.2 Geological Setting

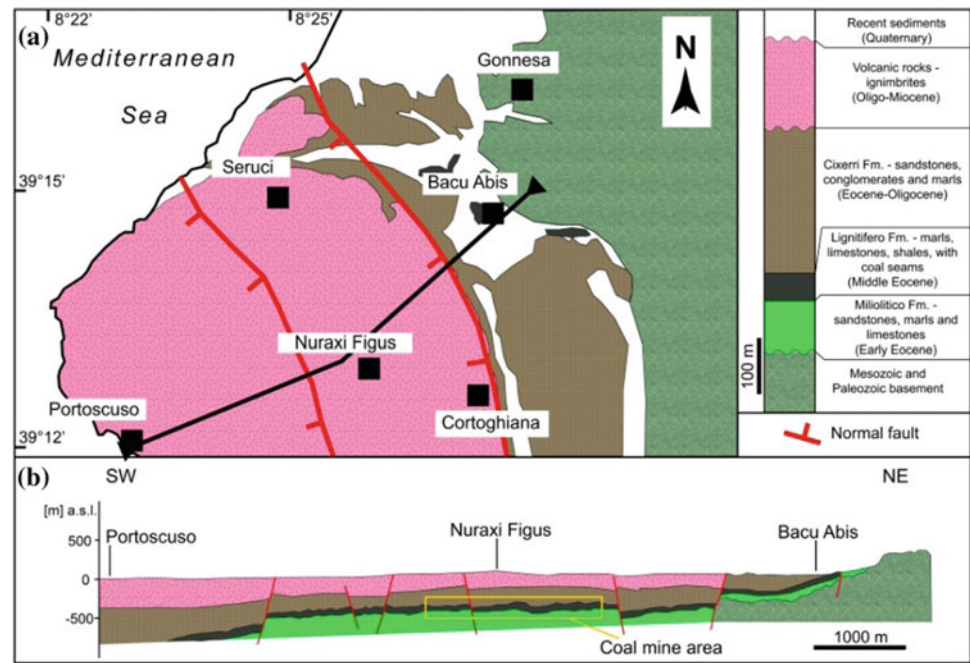
The Seruci-Nuraxi Figus coal mine is geologically located in the so-called “Sulcis carboniferous basin”, a tectonic depression covering an area of ca. 100 km<sup>2</sup>, which in the

Paleogene (66–23 Ma before present) was filled by a thick (up to 700 m) pile of continental-marine sediments (Fig. 3a). The basin is surrounded by Paleozoic to Mesozoic rocks (the basement), which mainly crop out on the eastern and northern borders of the basin (Pasci et al. 2012). The sedimentary succession filling the basin, uncomfortably covering the basement, can be subdivided from the bottom to the top, in four Formations of Paleogene age: *Calcari a Macroforaminiferi* Fm., (limestones—identified only in very deep drill holes); *Miliolitico* Fm., consisting of sandstones, marls and limestones (20–70 m thick; Early Eocene age); *Lignitifero* Fm., an association, 70–150 m thick, of clays, marly limestones, bituminous limestones, marls and conglomerates, interbedded with coal seams (Early-Middle Eocene age), and *Cixerri* Fm., consisting of sandstones, conglomerates and marls (average thickness = 300 m) (Eocene-Oligocene age; Pasci et al. 2012). The Lignitifero Fm., coal seams have a thickness comprised between 1 and 10 m, and consist of pure coal layers commonly 10 cm thick, rarely reaching 30–50 cm of thickness, interbedded with clays. In the Seruci-Nuraxi Figus area, the mined horizon is located at 350–450 m below the surface (Fig. 3b). Sedimentary rocks are covered by 100–300 m of volcano-pyroclastic rocks and ignimbrites (Oligocene-Miocene age; Fadda et al. 1994; Pasci et al. 2012). This area is crossed by several regional faults which seems not have interacted with the cultivation activities.

## 3 Satellite Data

In this work, the PSP-IFSAR algorithm (Costantini et al. 2008) has been applied to 41 high-resolution CSK images acquired in ascending and 58 in descending orbit modes, respectively covering the periods May 2011–January 2014 and May 2011–March 2014. InSAR results consist of LoS-projected deformation maps, profiles and time series (TS). The 2011–2014 subsidence rate (projected along the LoS) for the AOI is presented in Fig. 4a, while the LOS-projected deformation TS of the points labeled in Fig. 4a have been plotted in Fig. 4b. It is important to note that, in the central part of the monitored area, deformation velocities exceed the detection limits (Massonnet and Feigl 1998) and no satellite-based measurements are available (Fig. 4a). Cumulated satellite-based LoS displacements vary between –131 and +29 mm (until January 2014) and between –293 and +22 mm (until March 2014) in ascending and descending geometries, respectively. Specifically, cumulated measured displacements (for each observation period) are of  $-6 \pm 16$  mm (ascending) and of  $-13 \pm 32$  mm (descending) on average for the whole study area. According to Fig. 4a, as expected, the highest deformation rates (>5 cm/year) are observed in the center of the

**Fig. 3** Geological sketch map (a); geological cross-section (b)



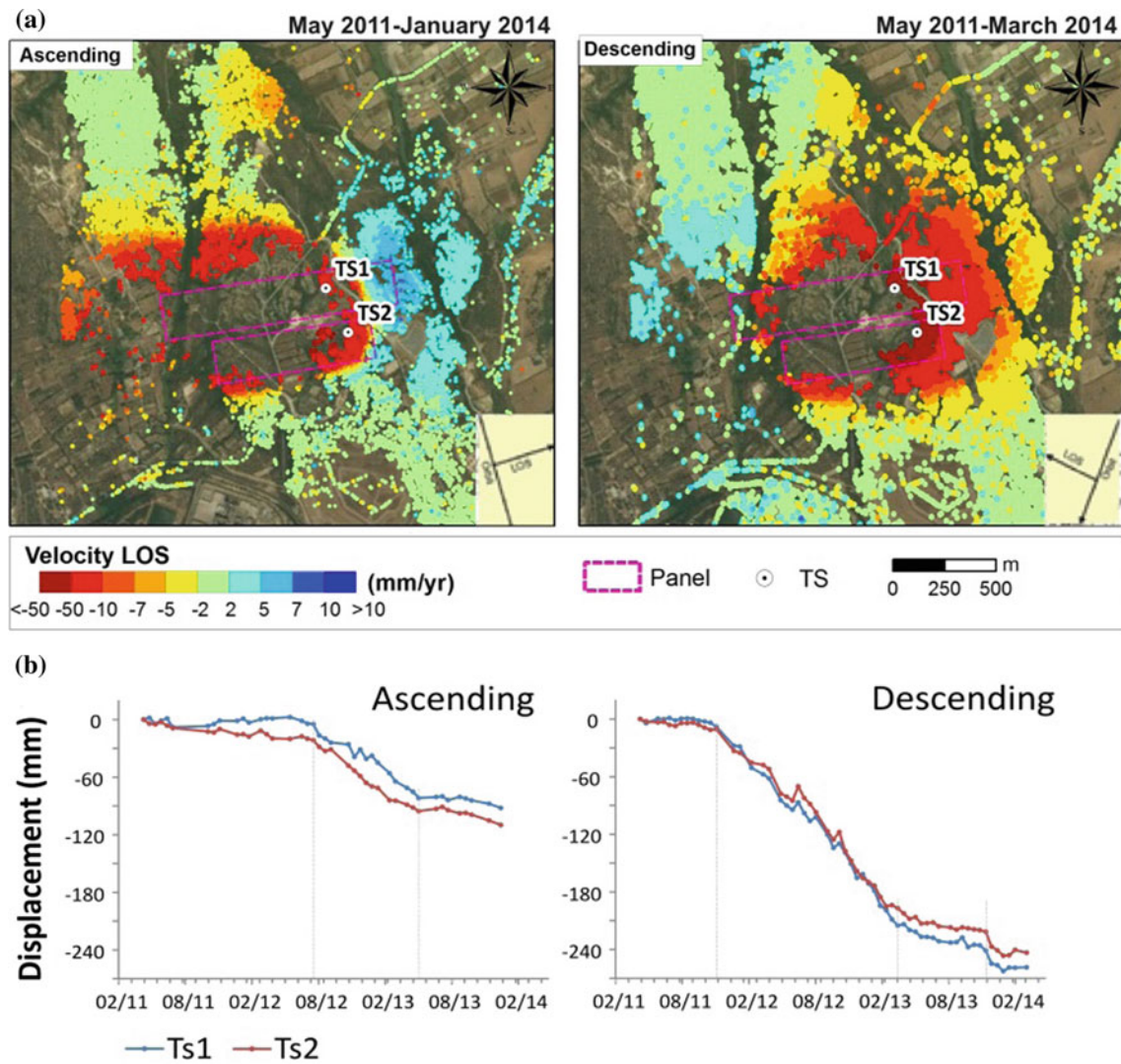
subsiding area, circumscribed to the mined panels W3 and W4. TS reported in Fig. 4b show several deformation trend changes during the monitoring windows; after a first stable period (until December 2011), an acceleration can be observed until May 2013; then the deformation rate decreased until December 2013 when a rapid settlement of about 3 cm has been detected by descending data.

## 4 Results and Discussion

Longwall mining activities are characterized by a special ground deformation behaviour due to the excavation technique; in fact, longwall face advances induce a strong movement pattern in the excavation surrounding area (Duro et al. 2013). In Seruci-Nuraxi Figus coal mine, in spite of the high thickness of the cover (Fig. 2b), an aerial subsidence has been detected by means of satellite-based measurements in correspondence of W3 and W4 panels (Fig. 4a). The availability of both ascending and descending acquisition geometries has permitted to obtain a vertical projection of displacement data, reported in Fig. 5. Maximum cumulated vertical displacements are of about 3 cm until January 2012, 14 cm until January 2013 and 24 cm until January 2014 (Fig. 5). As previously observed (see Sect. 3), no data in correspondence of the center of the panels are available; this issue does not allow to fully characterize the phenomenon and an integration with complementary InSAR techniques is needed to correctly estimate the maximum subsidence in the center of the study area.

Furthermore, as a first simplified analysis aimed to verify the possible causes of the observed phenomenon, the theory described in O'Reilly and New (1982) concerning the relations between tunneling depth and settlement geometries has been used. Specifically, by considering DInSAR deformation profile B–B' (orthogonal to the excavation direction), it is possible to obtain the length of the deformed area, the maximum displacement and the settlement inflection point. Such geometrical profile characteristics are related to the depth of the deformation causes which, in this case, has resulted located at –380 m to the ground. Of course, especially for the great error related to the maximum displacement in the central part of the profiles, further analyses will be carried out.

Nevertheless, to support this hypothesis, the observed deformation trend changes showed in Fig. 4b seem to be related with the excavation development. In fact, W3 panel was mined from 2011 to 2013 and the highest deformation velocities have been detected between December 2011 and May 2013; then, just a possible collapse has been observed by satellite in December 2013. Also in this case, the interferometric fringes integration would allow to better understand the event. Moreover, accordingly with Peng (1992), considering the deformation mechanisms upon a mined area, 4 zones can be identified where a proportion with the panel height ( $H$ ) can be found: (a) caving zone ( $2\text{--}8 H$ ); (b) fractured zone ( $30\text{--}50 H$ ); (c) bending zone; (d) soil zone. Taking into account such relations, for the Seruci-Nuraxi Figus area (see Fig. 3b), upon the mined horizon (located at 380 m below the surface), the caving zone “a” should be



**Fig. 4** InSAR mean velocity maps along the LoS direction in the ascending (left) and descending (right) acquisition geometries (a); TS of deformation (b)

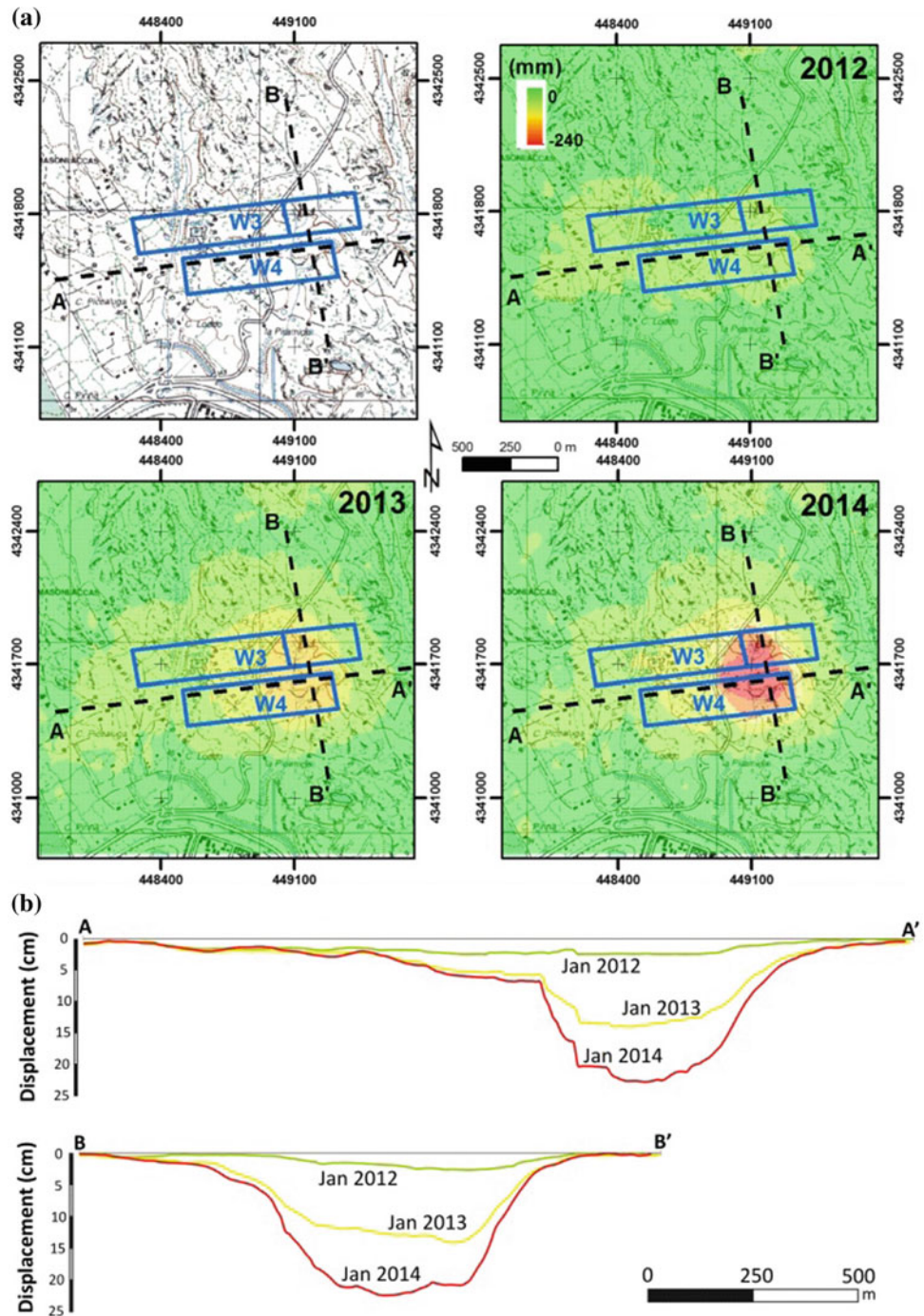
completely included in the Lignifero formation, while the fractured zone “b” should affect a part of the Cixerri formation; a residual part of Cixerri formation and the Volcanic-pyroclastic rocks should belong to bending zone “c”. Further analyses will be needed in order to found the specific relations for the geological settings of Seruci-Nuraxi Figus area.

## 5 Conclusions and Future Goals

Recently, the improvement of satellite and sensor technologies, the easier access to the data and the higher acquisition frequency have brought to an increase in the use

of remote sensing for Earth Observation (Tomás and Li 2017). A-DInSAR results (i.e. deformation velocity maps, profiles and TS) have turned out to be very useful for the hazard management. In this preliminary study concerning the possible deformation related to longwall coal mining, satellite-based measurements have allowed to identify a possible extension of the area of influence, deformation trend changes and vertical profiles. In the following of the present work, A-DInSAR processing will be performed with a coherence-based technique and deformation monitoring updated nowadays; then, in order to obtain displacement information at the centre of the longwall panels, where probably movements exceed the detection limits, InSAR fringes will be integrated. To analyse in depth the observed

**Fig. 5** InSAR vertical deformation maps (a) and vertical deformation profiles (b) cumulated in the periods May 2011–January 2012, May 2011–January 2013 and May 2011–January 2014; black dashed lines in the figure represent the profiles cross-sections



phenomenon and better understand the cause-effect mechanism, external data should be acquired; as usual, also in situ surveys should be carried out to improve the knowledge of the nature of the ground motion and interpret the areas where predominantly horizontal and vertical components have been observed. Accordingly to existing regulations, mines monitoring is mandatory also after their closure. DInSAR could

be considered as a complementary tool to detect existing potential risks and to plan possible rehabilitations.

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