Characterization of Longwall Mining Induced Subsidence by Means of Automated Analysis of InSAR Time-Series

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Abstract

We present an automated time series analysis of InSAR data for the characterization of ground subsidence induced by longwall mining at Metropolitan mine (New South Wales, Australia). The dataset derives from SqueeSAR™ processing of two Envisat radar data stacks of 44 images acquired from the ascending orbit and 43 from a descending orbit, acquired on a 35-day repeat interval in the period June 2006 to September 2010. Automated time series classification was carried out with PSTime, a specifically designed software that employs a sequence of statistical tests to classify the time series into the six different classes: uncorrelated, linear, quadratic, bilinear, discontinuous without constant velocity and discontinuous with change in velocity. Results highlight a cluster of bilinear trends with acceleration at the front of longwall panel progression and a cluster of bilinear trends with deceleration at the back. Linear trends are found at the centre of the subsidence bowl while outside most trends are uncorrelated. This picture is consistent with the evidence of acceleration in deformation trend when mining is approaching and a deceleration after extraction is completed and an essentially constant while mining takes place just underneath a specific point. Thus, time series analysis proved to be valuable for subsidence dynamics characterization, constraining in space and time the patterns of deformation trend in mining applications.

Keywords

Underground mining • InSAR monitoring • PSTime • Non-linear deformation • SqueeSAR™

187.1 Introduction

The coal mining industry represents a major economic resource in New South Wales, where several underground coals mine have been operative for more than a century. As a consequence of long-term extraction, land subsidence is quite significant (Cuenca et al. 2013). Several authors used InSAR technique to cost-effectively identify coal mining induced subsidence over large areas (Stow and Wright 1997; Ge et al. 2001, 2007; Ng et al. 2001; Cuenca et al. 2013).

Multiple longwalls mining induces complex surface subsidence, which often determines non-linear deformation trend. The knowledge of areas in acceleration and areas in deceleration can be used to discriminate areas where major

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subsidence can still be expected from areas were settlement is to be considered residual.

In this work, automated classification of InSAR time series was used in order to identify the extent, direction, and timing of surface subsidence over the longwall Metropolitan mine in New South Wales from in the period of June 2006 to September 2006 to 2010.

187.2 Case Study

The Metropolitan Mine is an underground coal mine located in the Southern Coalfields of New South Wales (Fig. 187.1c), about 40 km South of Sydney and operating since 1888. At present, about 3 m thick of coal are mined out from the Bulli Seam (DeBono et Tarrant 2011) using the longwall procedure. The Bulli Seam is stratigraphically the top seam in the Illawarra Coal Measures (Hutton 2009), and is overlain by the Narrabeen Group (late Permian late Triassic) consisting of about 300 m of sandstones, claystones and shales. The Middle Triassic quartz sandstone and Hawkesbury Sandstone are the upper formation extending over most of the area.

The depth of the cover varies from 400 to 520 m depending on the local surface topography (DeBono et Tarrant 2011).

The excavation of the mine layout presented in this study, started in July 1995 with the extraction of the longwall 1 and finished in April 2010 with the extraction of the longwall 18 (DeBono et Tarrant 2011; Morgan et al. 2013). Accordingly, the longwall mining progression is from South East to North West (Fig. 187.1). On the other hand, the extraction direction of each single longwall is from South West to North East (DeBono and Tarrant 2011).

187.3 Methods

Two stacks of ENVISAT radar imagery were used for the SqueeSAR™ analysis (Ferretti et al. 2011). The two data sets consisted of 44 images acquired along an ascending orbit and 43 images acquired on a descending orbit. Both data sets were acquired on a 35-day repeat interval and cover the time period from June 2006 to September 2010, corresponding to the extraction time of longwall 13 to longwall 18.

Automatic procedures for InSAR time series analysis are essential when different deformation dynamics are expected in space and time domain. To this end we used PS-Time (Berti et al. 2013) a statistically-based free software for time series analysis. PS-Time classifies deformation trends in 6 types: uncorrelated, linear, quadratic, bilinear, discontinuous

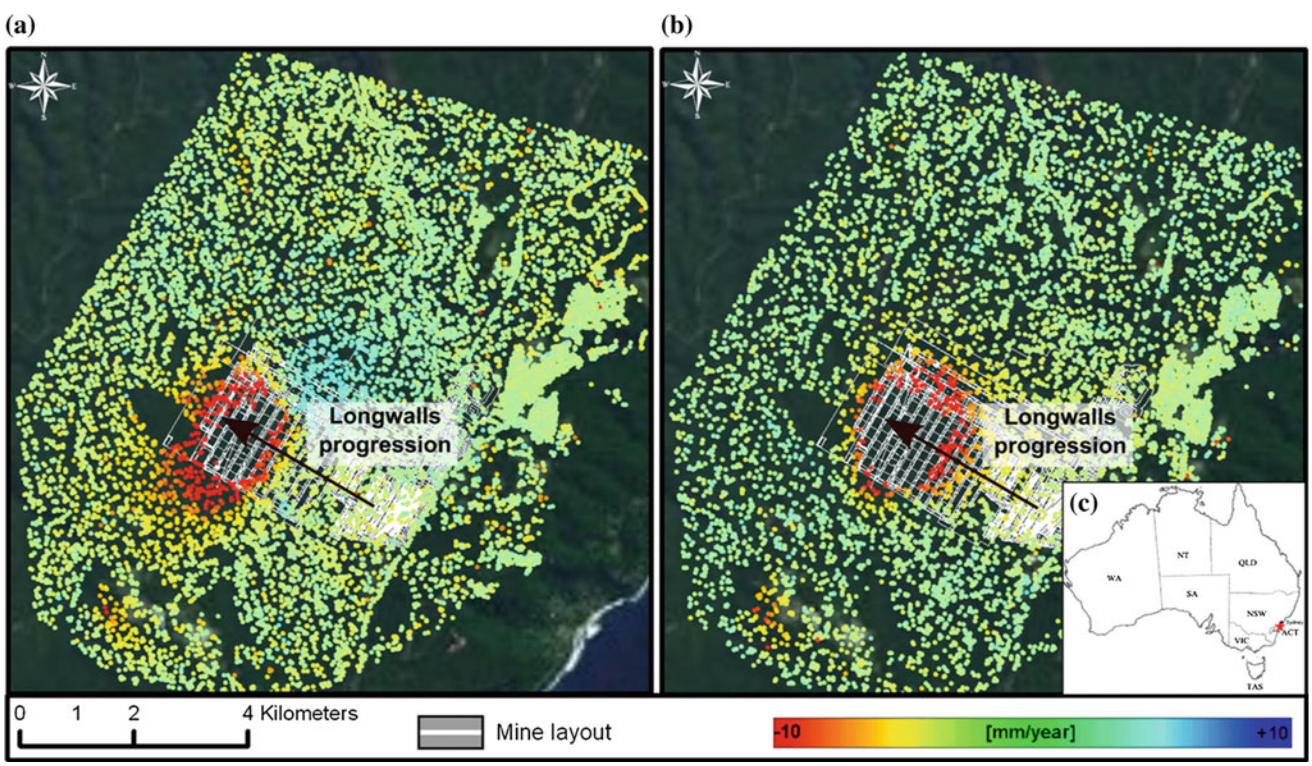

Fig. 187.1 Average annual velocity of the SqueeSAR™ **a** Ascending dataset and **b** Descending dataset. The *black arrow* indicates the direction of longwalls excavation progression. **c** Geographic location of the Metropolitan Mine (New South Wales, Australia)

Table 187.1 Statistics of time series types classified with PS-Time at the Metropolitan mine, for ENVISAT ascending and descending

	Ascending		Descending	
	N° PS	%	N° PS	%
Total dataset	17,795	100	12,561	100
Uncorrelated	10,075	57	7,876	63
Linear	1,337	8	576	5
Bilinear (acceleration)	1,126	6	540	4
Bilinear (deceleration)	1,140	6	840	7
Linear filtered out (±2 mm/year)	4,099	23	2,725	22

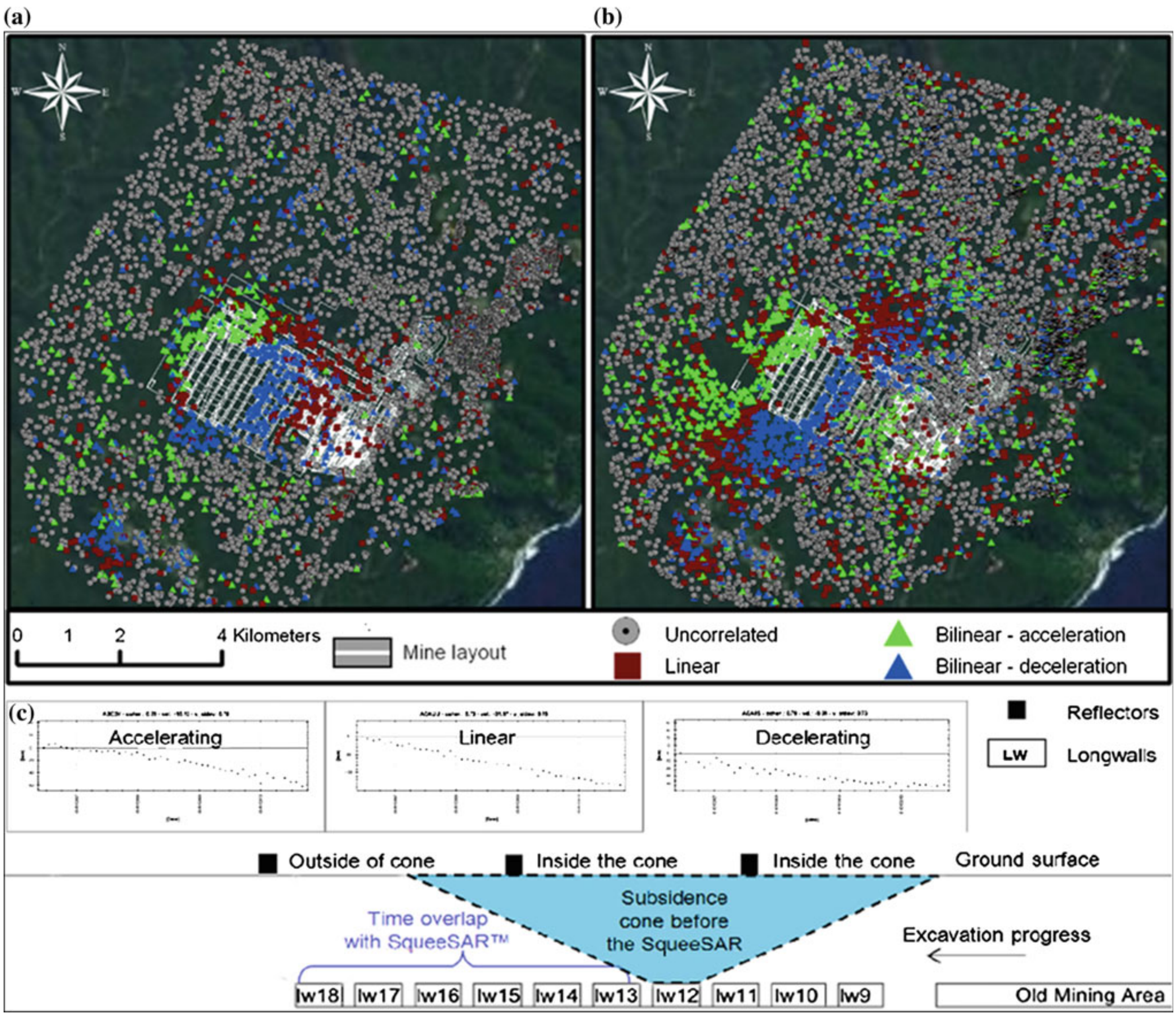

Fig. 187.2 Results of the time series classification with PS-Time of **a** Descending dataset and **b** Ascending dataset. Both geometries show a clear localization of measurement points showing acceleration (front of the mine excavation direction) while measurement points showing deceleration are located at the back of the mine layout, over old longwalls. **c** Schematic cross section of influence areas for each longwall during the InSAR monitoring dates. The cone represents the areas affected by subsidence at the beginning of the InSAR monitoring. Objects outside the cone and in front of the mine layout, will result in acceleration since reached by the subsidence cone after

without constant velocity and discontinuous with change in velocity. In addition, PS-Time returns descriptive parameters such as: date of change in motion, velocity before and after the change in motion, difference in velocity, amplitude and frequency of the time series.

As the main purpose of this work was to distinguish areas characterized by acceleration and deceleration trend, a simplified classification in 3 classes was used by grouping the "quadratic" and "discontinuous" classes with the "bilinear" class. Moreover, to improve the distinction between uncorrelated and linear, a filter based on a regional frequency analysis of time series classes was used. Berti et al. (2013) found that the class "uncorrelated" is represented by a Gaussian distribution with a modal value of zero mm/year and extreme values of ±2 mm/year. Similarly, in the analysed dataset the modal value of the class "linear" was found to be −2 mm/year, showing an overlap with the Gaussian distribution of the "uncorrelated" class. Thus, in order to clearly discriminate the classes, measurement points in the range ±2 mm/year were assigned to the "uncorrelated" class.

187.4 Results

Underground mining can induce large displacements in few weeks after panels are mined out. As a consequence, the loss of coherence in the interferograms leads to the lack of measurement points above the longwalls, which can be limited reducing the timespan between SAR image acquisitions. SqueeSAR™ analysis highlighted a kilometric subsidence bowl that in the surrounding area of the mine layout reached a cumulated displacement of over 150 mm (Fig. 187.1) in the 2006 to 2010.

On the other hand, the automated classification of time series shows very similar results for both the ascending and descending datasets (composed by 17,795 and 12,561 measurement points respectively) (Table 187.1). About 60 % of the measurement points show no correlation between time and deformation ("uncorrelated" class) and are predominantly located outside the subsidence bowl (Fig. 187.2a, b). About 7 % of the measurement points have a linear deformation trend. These points are mainly located along a NE-SW axis (near parallel to the longwalls) and centred on the subsidence bowl. Some measurement points with a linear deformation trend can also be found over old mining area, indicating that residual subsidence can lasts for about a decade. About 12 % of the measurement points are characterized by a bilinear deformation trend equally divided between points showing acceleration and points showing deceleration. As expected, points in acceleration are localized at the front of the mining layout (longwalls last extracted) while points in deceleration are localized at the mine back (longwalls previously extracted). The remaining 20 % are linear points which have been filtered out from the dataset using the procedure and assumptions referred to in Sect. 187.3.

Figure 187.2c explains the localization of various time series trend, in respect the influence area at different extraction date. In fact linear trends are found during the SAR acquisition in overlapping areas of influence.

187.5 Conclusions

Automatic time series analysis is essential when dealing with non-linear deformation, allowing to easily identifying area affected by similar deformation trend. This is particularly true where the deformation is space and time dependent, such as in the underground mining sector. The automated classification of time series using PS-Time allowed to identify different deformation domain: (a) stable areas outside the subsidence bowl, (b) linear deformation at the centre of the subsidence bowl and over the old mine, (c) accelerating deformation at the front of the mine layout, (d) decelerating deformation at the back of the mine layout. This highlights the potential of time series classification tools for extending the applicability of large InSAR datasets.

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