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Use of SAR interferometry for monitoring illegal mining activities: A case study at Xishimen Iron Ore Mine

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ABSTRACT

The development and application of the "digital mine" concept in China depends heavily upon the use of remote sensing data as well as domestic expertise and awareness. Illegal mining of mineral resources has been a serious long term problem frustrating the Xishimen Iron Ore Mine management. This mine is located in Wu'an county in Hebei province, China. Illegal activities have led to enormous economic losses by interfering with the normal operation of the Xishimen mine and have ruined the surrounding environment and the stability of the Mahe riverbed the crosses the mined area. This paper is based on field reconnaissance taken over many years around the mine area. The ground survey data are integrated with Differential Synthetic Aperture Radar Interferometry (D-InSAR) results from ALOS/PALSAR data to pinpoint mining locations. By investigating the relationship between the resulting interferometric deformation pattern and the mining schedule, which is known a priori, areas affected by illegal mining activities are identified. To some extent these areas indicate the location of the illegal site. The results clearly demonstrate D-InSAR's ability to cost-effectively monitor illegal mining activities.

1. Introduction

The price of iron ore has been rising along with the development of fierce competition in the commodity metal market. Attracted by the tremendous profit, many illegal or secret iron ore mines are increasing their production. The destructive and disorderly operation of these iron mines results in the formation of mined out sections that then create hidden troubles for legal mining companies. Moreover, this underground mining might be carried out directly under the pit later causing a large subsidence across the mining area. It ruins the surrounding environment.

Xishimen, an iron ore mine owned by China Minmetals Corporation and located in the south of the Hebei, Hanxing Mining District in China, was the primary test site for the research described here. In the past few years, more than one hundred secret iron ore mines have existed around this mine. Since 2006, the Xishimen Iron Ore Mine has spent nearly 1 million RMB a year for restoring the environment that was destroyed by these illegal mines. A typical case is the subsidence over the Mahe riverbed. The unexpected collapsed pit occurred beyond the normal underground working sections and led to enormous economic losses as it would have ruined the whole underground working section had remedial measures related to the affected riverbed not been carried out in time. Unfortunately, the location of such illegal mines and the devastation caused by them is very difficult to identify. Inevitably, passive remedial work replaces initiatives for monitoring the illegal mining activities. Handling these secrete iron mines in developing countries with their particular economic and sociological needs is a challenging, but not intractable, problem.

Satellite borne, repeat pass differential synthetic aperture radar interferometry (D-InSAR) has already proven its potential for ground deformation monitoring. This is because of its high precision and high spatial resolution. D-InSAR has been successfully used for different applications including the monitoring of volcanic activity, earthquakes, glacier dynamics, landslides, and mine subsidence [1–9]. In many cases D-InSAR has demonstrated its capability for measuring surface movements on the order of centimeters. However, D-InSAR techniques have rarely been used for detecting illegal mines, especially in China.

This study is performed using field reconnaissance collected over many years around the mine area. The D-InSAR results are obtained using ALOS/PALSAR data.

2. Geological and environmental setting

The geological setting and features of Xishimen include a contact metasomatic magnetite deposit of skarn iron, which was deposited in the Wu'an area of the southern Taihang Mountains. Most of this ore conformation is massive, dense, and dip-dye, with

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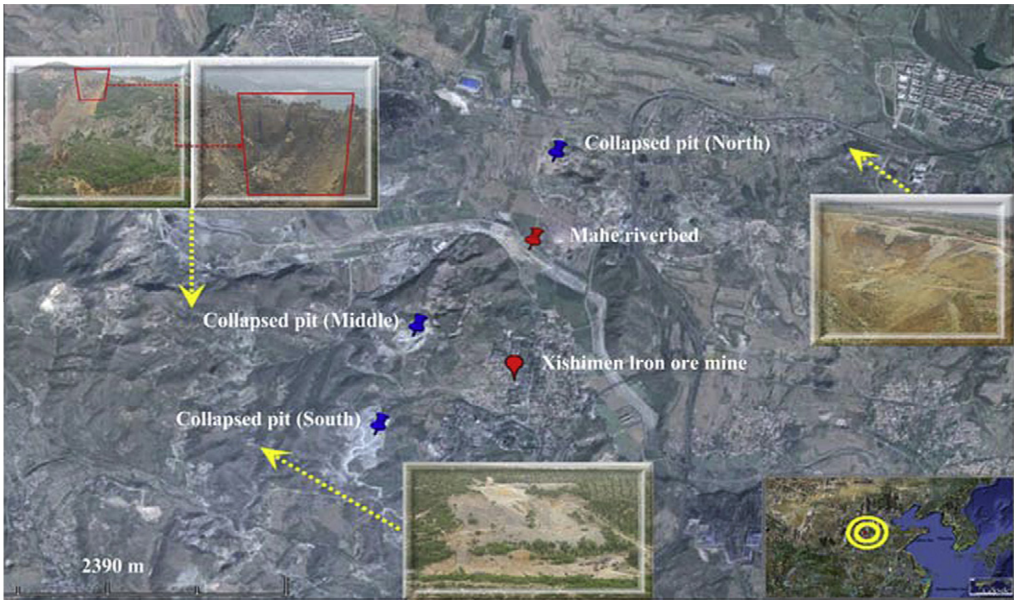


Fig. 1. Location of the Xishimen Iron Ore Mine and the distribution of collapsed pits.

Table 1
PALSAR interferometry data.

Date	Track	Frame	Heading	Polarization	Center lat	Center lon	Look angle	RSR
14/06/2007	453	73	A	HH	36.907714	114.118595	34.3	16
30/07/2007	453	73	A	HH	36.909423	114.125156	34.3	16
14/09/2007	453	73	A	HH	36.910152	114.12994	34.3	16
15/12/2007	453	73	A	HH	36.906573	114.144811	34.3	32
30/01/2008	453	73	A	HH	36.910069	114.146878	34.3	32
01/05/2008	453	73	A	HH	36.911305	114.150053	34.3	16
16/06/2008	453	73	A	HH	36.934061	114.051312	34.3	16
17/12/2008	453	73	A	HH	36.906774	114.102173	34.3	32
01/02/2009	453	73	A	HH	36.905699	114.107765	34.3	32
20/12/2009	453	73	A	HH	36.904281	114.120356	34.3	32

Table 2
ALOS repeat-pass interferometric pairs.

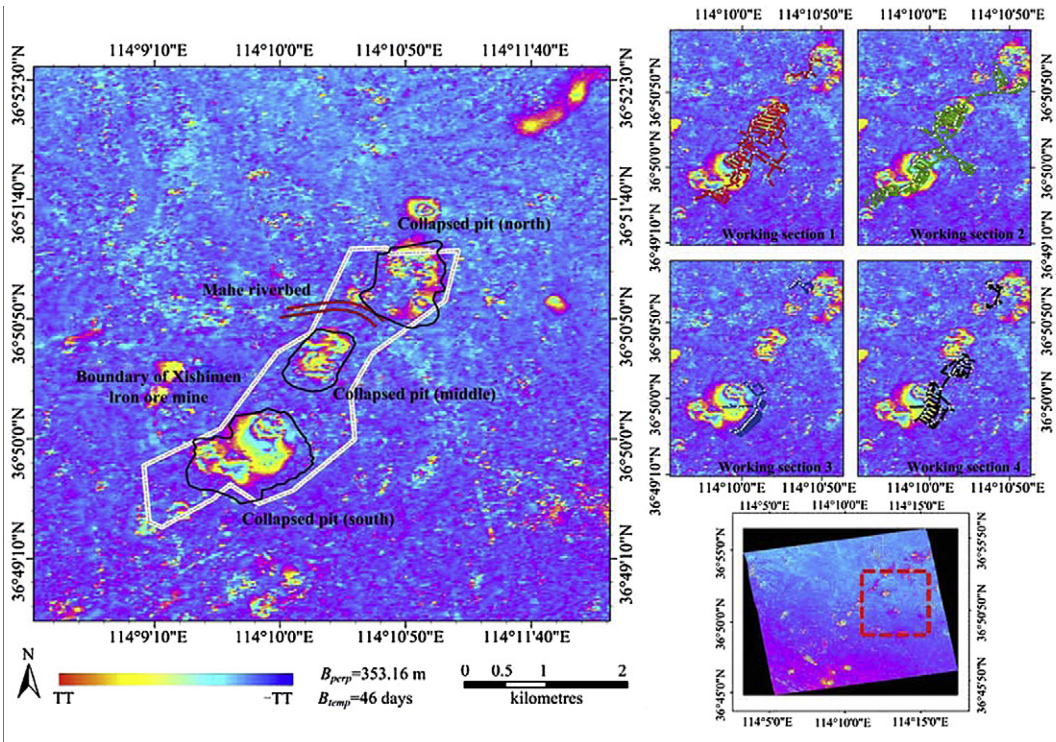
Pair No.	Master (date)	Slave (date)	Temporal baseline (day)	Perpendicular baseline (m)
1	15/12/2007	30/01/2008	46	353.16
2	17/12/2008	01/02/2009	46	526.91
3	01/02/2009	20/12/2009	322	1684.11

a compact structure. The ore body is mainly original magnetite with an average ore grade of 43.26%. The configuration that exists in the contacting cingulum, composed of limestone of the middle Ordovician period and corroded diorite, is complex. The majority of the roof of the ore body is limestone and the foot wall is corroded diorite. Due to the characteristics of skarn, which is low strength and easily softened by water, the stability of the surface and the protection of the environment is a serious issue at the Xishimen Iron Ore Mine [10].

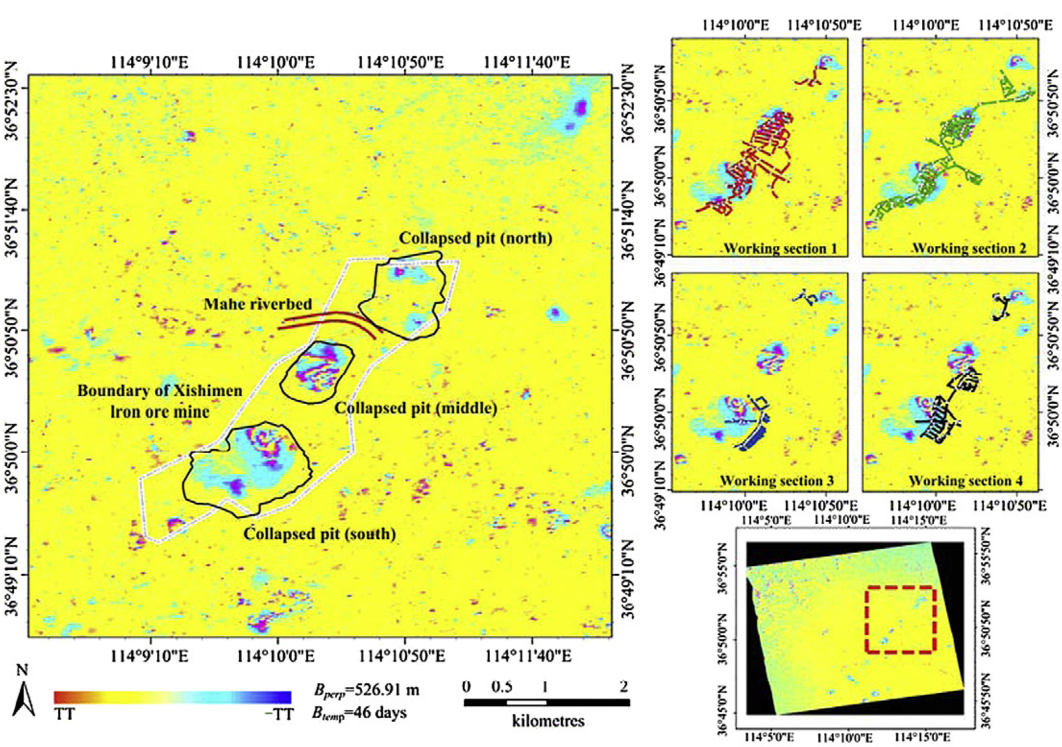
The mining area is divided into three areas, the north, the middle, and the south, based on the location on a geographical map. Three huge collapsed pits were formed in each mining area due to the long term underground activities (Fig. 1). The volume of the northern collapsed pit is about 7 million m^3 in a shape that is approximately square: 300 m North–South by 270 m East–West by 90 m average depth. The middle collapsed pit is one of the biggest areas that should be filled by mixed material or gravel in a quantity of nearly 8 million m^3. Here the average depth of the back fill is 80 m. The southern collapsed pit consists of several small pits and fractures of the Earth's surface.

Generally, the collapsed pits formed by underground mining activity are permitted. The deformed region will be estimated prior to proper exploitation. However, in recent years, disorganized small local small mines driven by short term interests have aggravated the area covered by deformation. The area now already exceeds the original boundary of the collapsed pits.

In addition to these collapsed pits the surface deformations beyond the limits of the large scale surface deformations have had an effect on portions of the Mahe riverbed. The Mahe crosses the mining area and is a seasonal river. A nearly 200 m wide safety pillar exists under the river bed protected from underground mining. Unfortunately, riverbed subsidence induced by destroying this safety pillar during illegal mining activity over the past few years



(a) 15 December, 2007 and 30 January, 2008, HH mode

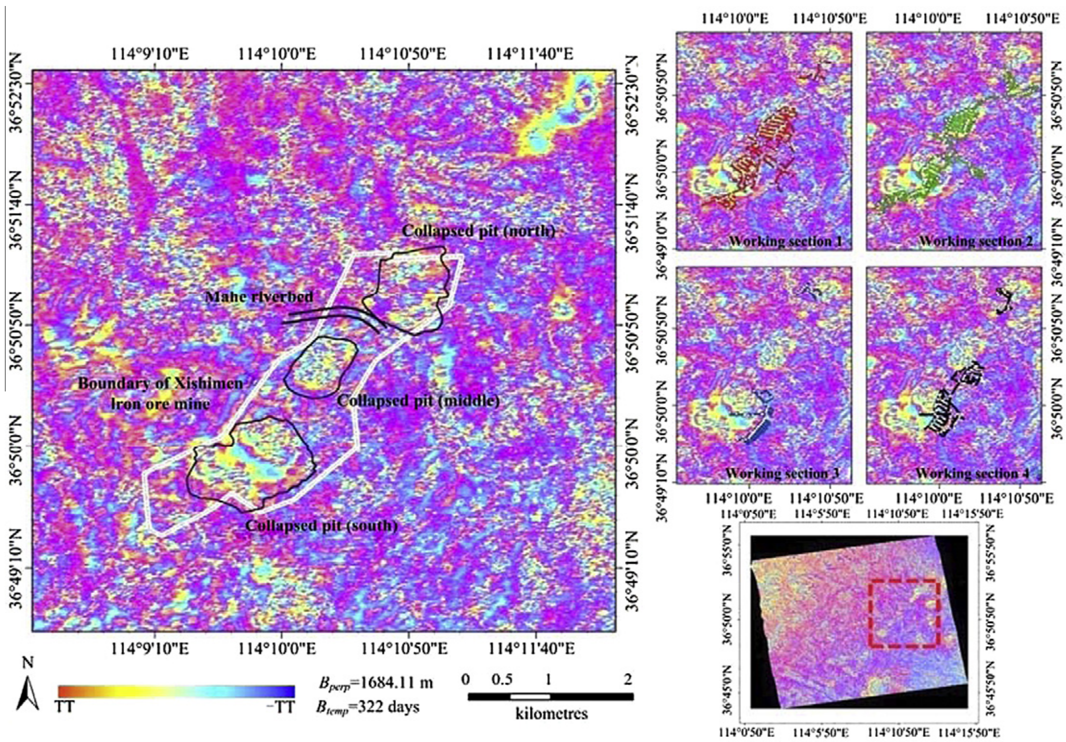


(b) 17 December, 2008 and 1 February, 2009, HH mode

Fig. 2. D-InSAR interferogram. (a) 15 December, 2007 and 30 January, 2008, HH mode. (b) 17 December, 2008 and 1 February, 2009, HH mode. (c) 01 February, 2009 and 20 December, 2009, HH mode.

has created a serious long term problem that frustrates the Xishimen mine. Preventing further destruction from the illegal mines and maintaining the riverbed directly relates to normal mine production.

In general, it is quite difficult for traditional monitoring methods to identify whether the subsidence area is caused by proper exploitation or by the activity of illegal mines. Moreover, limited human resources and limited funds often hamper further research



(c) 01 February 2009 and 20 December 2009, HH mode

Fig. 2 (*continued*)

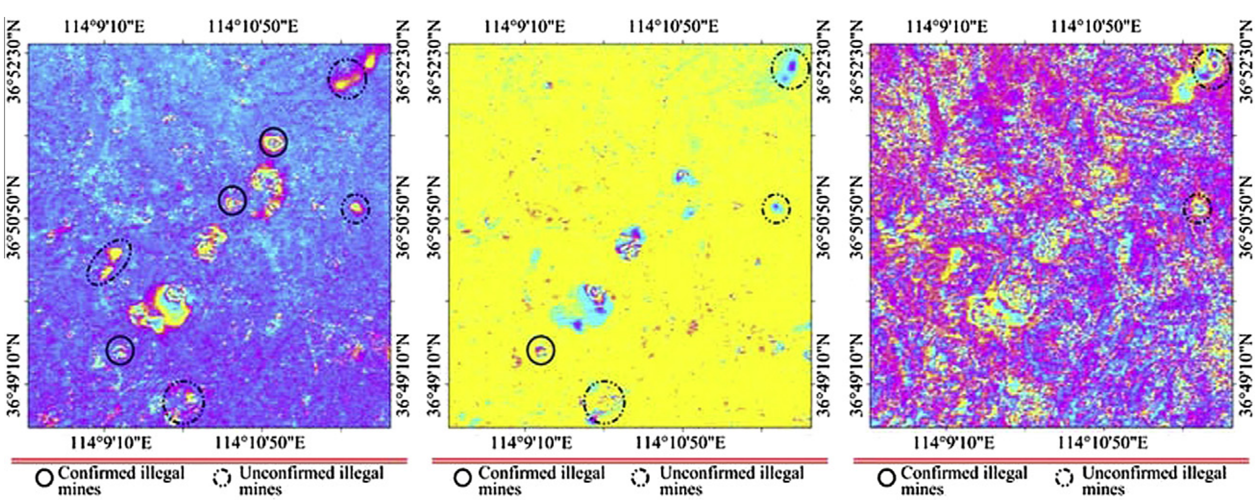


Fig. 3. Distribution of confirmed illegal mines near Xishimen mine.

related to prevention as these are preferentially used in performing remedial measures. The subsidence of the Mahe riverbed has made preventing illegal mines an urgent problem for the Xishimen Iron Ore Mine.

3. D-InSAR measurements

The conventional surveying methods used for mine subsidence monitoring, such as the leveling, total station, or GPS methods, are less useful than the satellite D-InSAR technique. This is true because the D-InSAR method is more accurate over a wider range with less labor and time. The abundant data from Synthetic Aperture Radar (SAR) satellites ensure long term surveillance for site specific monitoring.

A search of the PALSAR project on-line catalog (https://ims1d.palsar.ersdac.or.jp) for available interferometry data for the Xishimen region provided the results, listed in Table 1, that are appropriate for this study.

The usefulness of the data was determined from image acquisition date, baseline errors, atmospheric error, phase trends, and decorrelation noise.

The phase difference from two SAR images acquired over an identical region can be written as:

$$\Delta\phi = \phi_{\text{Topo}} + \phi_{\text{Defo}} + \phi_{\text{Atmos}} + \phi_{\text{Orbit}} + \phi_{\text{Noise}} \quad (1)$$

where $\Delta\phi$ is the phase difference between the two images; ϕ_{Topo} the phase introduced by topography; ϕ_{Defo} the phase introduced by displacement of the point; ϕ_{Atmos} the phase from atmospheric

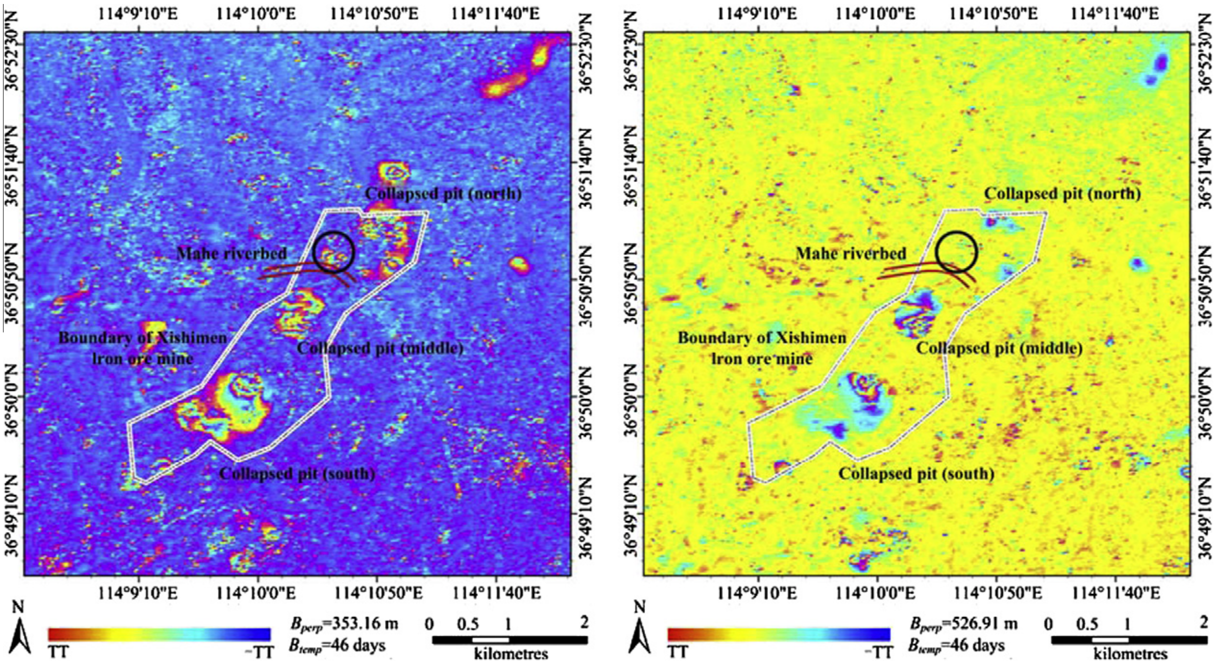


Fig. 4. Location of an illegal mine and the collapsed pit it caused.

disturbance; ϕ_{Orbit} the phase from orbit error; and ϕ_{Noise} the phase due to de-correlation noise.

In this study the standard two pass D-InSAR processing method was used to measure the ground subsidence. However, the quality of the data significantly reduced the number of scenes that were used in D-InSAR processing. Three combination pairs yielded a successful differential interferogram showing the mining related subsidence (Table 2).

Illegal mines were identified in a D-InSAR interferogram by several obvious characteristics. First, ground collapse always occurs in an area located above an underground mine. The 2D view of the subsidence is typically a round or oval shape that can be clearly identified in a D-InSAR interferogram. Second, the absolute values of the deformation gradient near the subsidence are larger than in nearby areas where no deformation is occurring. The direction of the gradient vector points, approximately, outside the subsidence area with the tail pointing toward the subsidence center [11]. The 2D gradient is expressed as a complex number where the magnitude represents the strength of the gradient and the phase indicates its direction:

$$\nabla f(x,y) = \frac{\partial f(x,y)}{\partial x} + i\frac{\partial f(x,y)}{\partial y} \qquad (2)$$

It becomes easy to distinguish patterns of collapse from underground mining using the D-InSAR results because of these characteristics.

4. Results and discussion

Three ALOS satellite radar images with dual polarizations were used to generate a D-InSAR interferogram that included topographical features only. The full scene ALOS/PALSAR data cover a 70 km by 70 km region but the data presented herein are limited to the vicinity of the Xishimen Iron Ore Mine boundary (see Fig. 2).

The data was filtered and multi-look processed to improve phase statistics so the phase fringes are clearly identified at the left side of the differential interferograms as a result. The boundary of the Xishimen Iron Ore Mine and three collapsed pits are seen in the images. Four different levels of the mine working area are in the top right corner imaged by the D-InSAR interferograms. The region of ground subsidence in this area can be evaluated and correlated with the related gallery and goafs known to exist there. An area of subsidence located within or nearby the iron ore mine boundary where no underground stope exists implies the existence of illegal mines. Supplemental information such as field reconnaissance and monitoring then allows identification of the illegal iron ore mine.

The first two pairs of 46 day interferograms were generated with perpendicular baselines of 353.16 and 526.91 m, respectively, see Fig. 2a and b. These two interferograms have much clearer fringes compared to the third interferogram. This is because of the shorter temporal, 46 versus 322 days, and perpendicular 353.16 and 526.91 versus 1684.11 m baselines. Abnormal ground subsidence regions are easily identified, see Fig. 3. The limited budget and available labor prevents the identification of all the illegal human activities happening far from the Xishimen mine. Further investigations may be carried out related to the unconfirmed illegal mines shown in the images presented here.

Note that on 17 February, 2008, an explosion occurred near the collapsed pit indicated by a black circle in Fig. 4. This location was an illegal mine and this collapsed pit was formed by long term illegal underground mining activities. Moreover, ground subsidence in the same area did not develop further after the illegal mine was closed. This may be recognized from pre- and post-event interferometric pairs. This example clearly demonstrates that integrated SAR interferometry is an effective way to detect the location of illegal mines.

5. Conclusions

The results presented herein confirm the applicability of D-InSAR technology for identifying mine induced surface deformation. This information may be used to identify unknown, illegal underground mining activity. The PALSAR data was processed, and differential interferograms obtained, from SAR images. The surface subsidence over time as derived from D-InSAR data was confirmed by field reconnaissance and monitoring.

This is a successful case and the method can be widely used to safeguard the sustainable development of iron ore and other mines, not only in China but also in other parts of the world.

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