Measurement of ground movements in Stoke-on-Trent (UK) using radar interferometry

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Abstract: Stoke-on-Trent (UK) and the nearby towns make up a large industrial conurbation known as 'The Potteries,' famous for its pottery and china manufacture. The area was also well known for iron and steel manufacture. These industries were based on the local availability of clay, ironstone and coal. To the northwest is the UK's largest halite field where salt extraction continues to the present. The other minerals are no longer extracted, coal mining having finished in the 1990's.

Coal was mined by both partial total extraction methods. In addition, opencast working has taken place with the abandoned pits being reclaimed by infilling with domestic and other waste material. Ground movement (subsidence) was common while underground mining was going on but declined thereafter. However, as minewater levels have risen following abandonment, further some further (often substantial) subsidence has taken place, particularly adjacent to major faults.

In the last decade the development of satellite radar interferometry (InSAR) and improvements in processing techniques have allowed the data from radar satellites to be analysed to produce millimetric measurements that can be related to ground movements. The raw data can be processed in various ways producing either interferograms for areas of ground movements or movement time series for points on the ground (PSInSAR). The time series covers more than a decade of measurements. However, the techniques do have limitations.

The radar data has been processed for The Potteries as part of a European Space Agency project (TERRAFIRMA). The data shows ground movements both towards (uplift) and away from (subsidence) the satellite in various areas that may be related to coal and salt extraction, compressible alluvial deposits and infilled waste disposal sites. The paper provides possible interpretations of the movements observed and discusses applications for, and limitations in, the use of this new and exciting technique.

Résumé: Stoke-on-Trent (Royaume-Uni) et les villes avoisinantes constituent une grande conurbation industrielle appelée « The Potteries », célèbre pour sa fabrication d'articles en céramique et en porcelaine. La région est également connue pour son industrie sidérurgique. Ces industries découlaient de la présence locale de l'argile du minerai de fer et du charbon. Au nord-ouest se trouve le plus grand gisement de sel gemme (halite) du Royaume-Uni où l'extraction du sel a toujours lieu encore aujourd'hui. Les autres minerais ne sont plus extraits, l'exploitation du charbon ayant pris fin dans les années 1990.

Le charbon était exploité par des procédés d'extraction du type partiel ou total. Par ailleurs, la transformation des mines à ciel ouvert a repris, les puits abandonnés ayant été réhabilités par remplissage avec des ordures ménagères et autres déchets. Courant lorsque les mines souterraines étaient exploitées, le mouvement de terrain (affaissement) a diminué par la suite. Toutefois, avec une augmentation des niveaux des eaux de mine suite à l'abandon, d'autres cas d'affaissement (souvent important) ont eu lieu, en particulier à proximité des failles majeures.

Au cours des dix dernières années, le développement de l'interférométrie radar satellite (InSar) et les améliorations des techniques de traitement ont permis aux données provenant des satellites-radar d'être analysées pour produire des mesures millimétriques pouvant être rapportées aux mouvements de terrain. Les données brutes peuvent être traitées de différentes manières pour produire des interférogrammes pour des zones de mouvements de terrain ou des séries de mouvements dans le temps pour des points sur le sol (PSInSAR). Les séries dans le temps couvrent plus d'une décennie de mesures. Toutefois, ces techniques ont des limites.

Les données radar ont été traitées pour la région « The Potteries » dans le cadre d'un projet de l'Agence spatiale européenne (TERRAFIRMA). Les données montrent des mouvements de terrain vers (soulèvement) et à distance (affaissement) du satellite dans différentes zones pouvant se rapporter à l'extraction du charbon et du sel, aux gisements alluvionnaires et aux sites d'élimination des déchets par enfouissement. L'article fournit des interprétations possibles des mouvements observés et discutent les applications, et les limites, de l'utilisation de cette nouvelle technique passionnante.

Keywords: coal mining, abandoned mines, land subsidence, remote sensing, subsidence, urban geosciences.

INTRODUCTION

The city of Stoke-on-Trent forms part of a larger conurbation in the Midlands of England that includes the towns of Newcastle-under-Lyme, Hanley, Longton, Fenton, Burslam and Tunstall (Figure. 1). The area is better known, collectively, as 'The Potteries' because the main industry is the manufacture of pottery and china. The area was made famous, worldwide, by the author Arnold Bennett, through his novel "Anna of the five towns" (Bennett, 1902).

Newcastle-under-Lyme lies outside The Potteries and, strictly, is not a Potteries town and Fenton is a sixth Potteries town, omitted by Bennett. In this paper, 'The Potteries' should be taken to include all the towns in the conurbation. The Potteries has an area of around 72 km^2 (15 by 4.8 km) and a population of more than 250 000. In addition to pottery manufacture, the area's other main industries included mining (coal, clay and ironstone) (now ended), iron foundries (in decline) and brick and tile making. Halite (salt) is still extracted in the Cheshire salt fields to the north west of the conurbation.

Figure 1. Location of the Potteries in Great Britain.

This industrial heritage, together with a geological environment that has experienced phases of tectonic stressing and destressing throughout its history, has resulted in the occurrence of ground movements that can be measured at the surface. The amount of movement ranges from a few millimetres to as much as 2 m in the worst affected areas (Donnelly 1994, Donnelly & Rees 2001). These movements were originally mostly associated with mineral extraction, mainly coal and often resulted in damage to property. However, it is likely that there were other causes, such as poor foundation design and construction, which would have caused damage, though these may not have been recognised at the time. Since the decrease in coal mining activities, and ultimately, its cessation, ground movements have continued (Donnelly & Rees 2001). Similar movements have been observed elsewhere in the UK, for example in the Lancashire, Yorkshire, Durham and Northumberland Coalfields (Donnelly 1994) and in the Nottinghamshire and Leicestershire Coalfields of the East Midlands (Donnelly 2000). Usually, these ground movements are noticed only when they cause damage; this occurs when the amount of movement exceeds the threshold necessary to cause damage in a given building or structure. However, while some movements are relatively sudden, others a gradual, taking place incrementally over several years. These movements can be hard to detect because they may be at the lower end of the resolution of conventional ground-based surveying methods. Also, there would be little justification to carry out a relatively expensive survey if no damage had taken place.

In May 1991 the first radar satellite to provide publicly available data became operational. This satellite (ERS-1) was operated by the European Space Agency (ESA). Subsequently, further radar satellites (ERS-2 [in April 1995] and ENVISAT [in March 2002]) were also launched by ESA. The satellites carry a Synthetic Aperture Radar system (SAR), which is a microwave imaging system, which looks at the same target from different positions. The system allows the accurate measurement of the travel path of the electromagnetic radiation transmitted from the satellite and the reflection received back. Initially the data were used to investigate the potential of SAR interferometry for digital elevation modelling (DEM) and ground surface movement monitoring. The method combines two successively acquired radar images. The radar signal is complex; its amplitude is influenced by the physical and geometrical properties of the ground surface, while its phase is directly linked to the distance between the satellite and the ground. By subtracting the phase signals from the two images an image is created of the difference of distances between the satellite and the ground. This phase difference is known as an 'interferogram.' As it depends upon both the topography and possible ground movements occurring between two satellite acquisitions, 'removal' of the effect of topography leaves an image that shows ground movements alone. By 'stacking' several differential interferograms an improved image can be produced. Graham (1974) described the principles of differential interferometry (DInSAR). More recently, detailed reviews of the principles have been provided by Gabriel, Goldstein & Zebker (1989), Massonnet & Feigl (1998) and Hanssen (2001).

An alternative method of processing SAR data is known as the Permanent Scatterers technique (PSInSAR). In this method radar reflections from millions of points on the ground (for a 100 x 100 km square scene) are combined for repeat passes of the satellite. Errors associated with atmospheric effects can be estimated and removed because they are not correlated in time whereas slight movements of the position of reflectors usually do show temporal correlation because movement is often gradual. The data is processed and phase changes between repeat passes of the satellite are analysed to create a velocity history for those points with 'coherence', that is repeated reflections. Where coherence is less, an average rate of ground movement only will be obtained, rather than a full linear velocity history. Ferretti, Prati & Rocca (2000), Ferretti et al. (2001) and Colestanti, Locatelli & Novali (2002) described the technique in more detail. Crosetto, Crippa & Biescas (2005) provided an overview of both techniques, including an application to subsidence caused by dissolution of soluble rocks in Sallent in northeast Spain.

In The Potteries, PSInSAR data for an area of 1111 km^2 were analysed and this resulted in the identification of 178 109 permanent scatterer points with an average velocity (Figure 2). 68 509 (38.5%) of these had a full linear velocity history. The data obtained were compared with a range of spatial geoenvironmental information to try to identify the causes of the observed ground movements over the period from 1992 to 2004. The paper describes the geology of the area, explains why the movements may be occurring and briefly discusses limitations of the technique that need further research and development for them to be overcome.

PHYSICAL GEOGRAPHY, GEOLOGY AND MINERAL RESOURCES OF THE POTTERIES

The Potteries lies in low Pennine foothills near the edge of the Cheshire Plain (Figure 1). The highest point is just to the east of Burslem with an elevation of a little over 210 m. Natural drainage is mainly via the River Trent which rises just to the north of the Potteries, near Biddulph, and flows to the east through the city of Nottingham, reaching the North Sea via the Humber Estuary near Hull.

The geology of the area has been described in detail by Rees & Wilson (1998). The northern half of the area is directly underlain by Coal Measures of Carboniferous age, lying in the deep Potteries Syncline and containing 60 mined horizons (mostly coal with some ironstone) distributed through over 1100 m of rock strata. Generally, beds on the western limb of the fold dip more steeply than those on the eastern limb. In the south, the mudstones and siltstones with seatearths and coals and occasional sandstones of the grey Coal Measures are overlain by dominantly red Barren Measures, which consist mainly of reddish brown mudstones with occasional sandstone bands and are lacking coals of workable thickness. However, workable coal seams lie beneath these Barren Measures and these were worked until the last colliery, Silverdale, closed in 1998, thus ending a history of over 700 years of coal mining first recorded in 1282 in Tunstall.

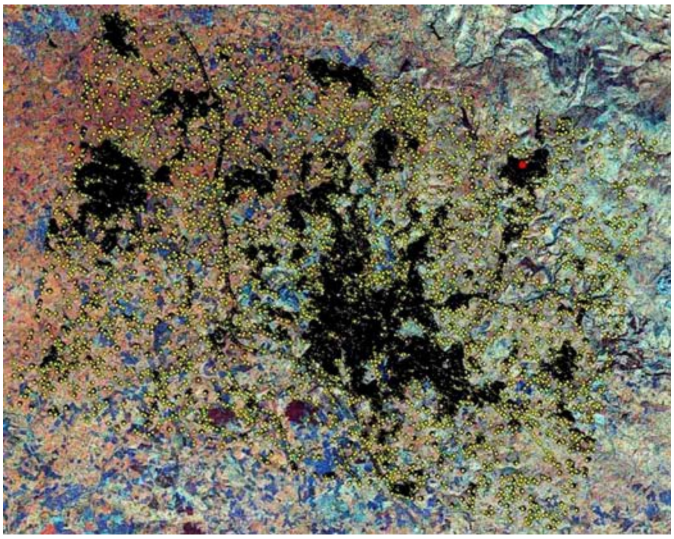

Figure 2. Permanent scatterer points (in yellow) displayed on a false colour Landsat image. Reference point shown in red.

Above the Carboniferous strata are beds of Triassic age, comprising thick, permeable sandstones of wind-blown origin containing beds of conglomerate, which are used for public water supply. These rocks are overlain by mudstones and siltstones of the Mercia Mudstone Group, which were deposited in arid conditions.

The bedrock is overlain by glacial tills from the Devensian glaciation; the tills are thickest towards the northwest where the ice was thicker. Sands and gravels deposited by pro-glacial melt waters are also found. Holocene deposits consist of sand and gravel of alluvial fans and river terraces, alluvium on floodplains consisting of clay, silt, sand and gravel, and a few landslides.

Extensive areas of artificial deposits are found throughout the Potteries. These consist of made ground and materials infilling the many former mineral excavations. The material varies from inert hardcore and brick and tile waste to ironworks slag, colliery waste, ceramic rejects and domestic and industrial waste that may be a source of methane.

The area has been rich in mineral resources, principally, coal, ironstone and clays for brick and tile manufacture. The Sherwood Sandstone is an important aquifer adjacent to the urban area. Coal was the most important resource with between 6 and 7 million tons a year being extracted in the first 70 years of the 20th century. Coal was mined from so-called ‘footrail mines’ in which access was by inclined tunnels and partial extraction methods were employed with pillars of coal left to support the roof, and from deep mines by total extraction from areas where the seems were deeper and accessed from vertical shafts. Till the end of the 20th century, coal was also extracted from opencast sites. Ironstone was also extracted from the Coal Measures but this has long been exhausted or abandoned. Clay for manufacture of bricks and tiles was extracted from opencast sites in the mudstones of the Etruria Formation and the Coal Measures. Sand from weathered sandstones of the Sherwood Sandstone Group and Glacial Sands and Gravels are sources of sand and aggregates but are currently little exploited. Methane is drained from several abandoned mines and there has been research in the Potteries into methods of extracting methane from unworked seams.

Table 1. Simplified litho-stratigraphy of The Potteries

Stratigraphy		**Lithology**
Quaternary - Holocene	Artificial deposits	Hardcore, bricks and tiles, colliery waste, foundry slag, ceramic rejects, domestic and industrial waste
Quaternary - Holocene	Alluvium	Clay, silt, sand, gravel
Quaternary – Pleistocene/Holocene	River Terrace and Alluvial Fan Deposits	Sand, gravel
Quaternary - Pleistocene	Glacial Till; Glacial Sand and Gravel	Clay, silt, sand, gravel, cobbles, boulders; sand, gravel
Permo-Triassic Mercia Mudstone Group	Lower Mudstone Division	Mudstones and siltstones
	Denstone Formation	Mudstones, siltstones, sandstones
Permo-Triassic Sherwood Sandstone Group	Helsby Sandstone Formation	Sandstones with occasional conglomerates
	Hawksworth Formation	
Carboniferous Barren Measures	Keele Formation	Mudstones and siltstones with occasional sandstones
	Newcastle Formation	
	Etruria Formation	
Carboniferous Coal Measures	Upper Coal Measures	Mudstones and siltstones with coal seams and occasional sandstones
	Middle Coal Measures	
	Lower Coal Measures	

ENVIRONMENTAL LEGACY

As indicated above, the Potteries area has a considerable legacy of ground-related environmental issues resulting from the natural geology and the industrial activity of the last 200+ years. These can all cause ground movement to occur.

- Coal mining subsidence. As underground mining has ceased, subsidence has reduced in recent years. However, underground mining was still active for much of the period for which PSInSAR data was available (1992 to 2004). This is particularly true in the southern part of the Potteries where mining did not end till 1998.
- Minewater rise. To enable mining to take place groundwater levels need to be lowered to below seam levels by pumping. Once a mine is closed, pumping usually ceases and groundwater returns towards its historical level as water levels rise the level of the ground surface may also rise. In the northern part of the coalfield mining ceased many decades ago and water levels have risen considerably from their lowest levels.
- Fault reactivation is associated both with active mining and with the post-mining period as the ground stabilises and minewater levels recover. Donnelly (1994) and Donnelly & Rees (2001) have studied this in the Potteries and have recorded substantial ground movements of many hundreds of millimetres.
- Salt extraction subsidence. Salt is still extracted by controlled pumping in the Cheshire Basin to the north west of the Potteries. Subsidence associated with natural salt dissolution processes is continuing.
- Dereliction and the presence of artificial ground may cause ground movement due to poor compaction and chemical reaction.
- Infilled quarries/waste disposal sites are subject to ground movements as waste materials settle producing subsidence or as material decays, possibly producing methane, which may cause temporary rises in the surface level.
- A few landslides have been mapped in the Potteries. Further slipping may cause lateral and vertical ground movements.
- Compressible valley alluvium. Some of the river valleys are infilled with weak and compressible alluvial deposits. Settlement of the surface is likely due to both self-compaction and artificial loading (for example from foundation loads).

USE OF PSINSAR DATA FOR GROUND MOVEMENT OBSERVATION IN THE POTTERIES

PSInSAR processing

Two principal variants of the PSInSAR processing method are available:

- The Standard Permanent Scatterers Analysis (SPSA) method is used for large area applications (minimum 100 km^2). The method is suitable for mapping urban conurbations and regions, to identify stable areas and to highlight possible hazardous areas (for example, affected by landslides, subsidence, seismic faults, etc.). Permanent Scatterers (PS) are detected and their average velocity is then estimated by an automatic and cost-effective procedure, allowing the processing of large amounts of data in a short period of time. The method can be further streamlined if it is assumed that the ground movement is linear, that is, the rate of movement is fairly constant. Where it is not, non-linear processing should be carried out, but this is more time-consuming.
- The Advanced Permanent Scatterers Analysis (APSA) method is used for high-resolution applications on limited areas (minimum 1 km^2). The method is appropriate for small areas where a full exploitation of the information content of the satellite data is required. Typical applications include landslide detection and monitoring or stability assessment of individual buildings or structures (dams, industrial plants, etc.). It is a very sophisticated and time-consuming analysis, requiring strong interaction with skilled personnel. The procedure is specific for each area.

Linear processing using the SPSA method was carried out for the Stoke-on-Trent area.

Interpretation of the PSInSAR data

The spatial geoenvironmental information compared with the PSInSAR data is listed in Table 2.

Table 2. Spatial information available for comparison with PSInSAR data

Main spatial information type	Specific spatial datasets
Digital geology at 1:250,000, 1:50,000 and 1:10,000 scale	• Bedrock and superficial deposits geology (1:25,000) • Distribution of borehole and shafts (1:25,000) • Surface Mineral Resources (1:25,000)
Ordnance Survey topographical data, 1:250,000, 1:50,000, 1:10,000, 1:2,500 and 1:1,250 scale	
NEXTMap elevation data (DEM) (radar derived)	• 5-metre cell size elevation dataset with a 1 metre vertical accuracy, acquired via SAR interferometry.
Derived geological data (1:50,000 scale)	• Superficial deposits thickness • Rockhead elevation
Geohazard data (1:50,000 scale)	• Shrink Swell • Compressibility • Dissolution • Running Sand • Slope Stability
Engineering geological data (1:25,000 scale or larger)	• Artificial Ground • Engineering characteristics • Hydrogeology • Undermined areas • Ground stability constraints • Leachate and gas constraints • Fault reactivation
Geophysical data	• Magnetics • Gravity
PhD study of Donnelly (1994)	• Ground optical surveying data

A geographical information system (GIS) was created in ArcMap 8.3 using the PSInSAR point data, interpolated PS data and the data shown in Table 2. PS data were interpolated using an inverted linear distance interpolation algorithm. This GIS was used to examine the spatial relationships between the various datasets. Overall, PSInSAR results showed a large area of uplift to the north of the Potteries and two large areas of subsidence to the south, as seen on Figure 3. There is no relationship between the elevation data and the PS.

Association with geological faults and seismic activity

The spatial association with fault lines suggests that movement along the faults may well accommodate the observed ground motion. Several of the areas experiencing ground motion are either fault bound or areas of heavy fracturing (Figure 4). However, faulting is not the primary reason for the motion. Seismic activity (of a magnitude of 1

– 2 on the Richter scale) has been observed in the area and this correlates especially well with the area of uplift (Figure 4).

Association with geohazard data

Overall there seems to be very little obvious spatial correlation with the following geohazard datasets:

- Areas prone to shrink-swell
- Running sand
- Slope instability

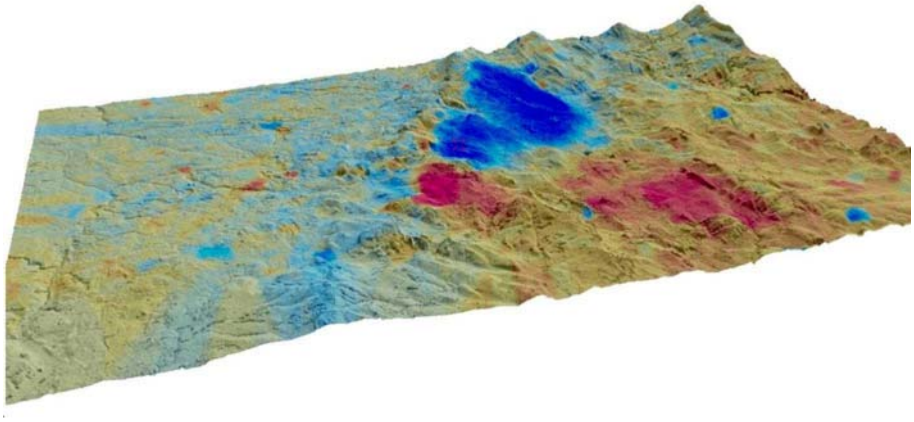

Figure 3. Interpolated PS data overlain on the NEXTMap elevation dataset. Blue indicates areas of uplift, red areas of subsidence.

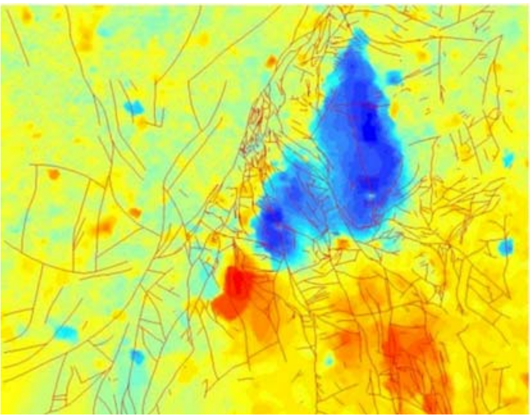

Figure 4. Interpolated PS data with Faults (red lines) overlain and seismic magnitude shown as green circles.

There is a spatial correspondence between the rate of uplift and compressible soils. Figure 5 shows that the uplift rate seems to be less over a valley filled with compressible soils. It could be that the overall uplift of the area is slowed by settlement of buildings and structures founded on these soils.

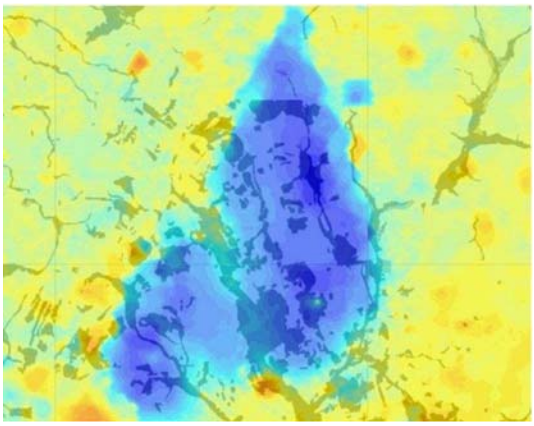

Figure 5. Interpolated PS data overlain on to compressible soils data. Dark shaded areas are more prone to compression.

Relationship with geological data

There is no obvious relationship between the stratigraphical geological units and the areas of ground motion. This lack of an obvious relationship extends to the engineering geology of hard rock and superficial deposits, ground stability, slope steepness or surface mineral workings.

Ground motion related to mining

The areas of ground motion observed around the Potteries, as shown on Figure 3, appear to be mainly related to undermining. In the south of the area subsidence appears to be prevalent, this corresponds with areas that were undermined most recently (Figure 6). It is thought that subsidence revealed by the PS technique is caused by the collapse of mine workings and reactivation of faults in the area of these workings. The notion that existing faults have been reactivated is supported by work carried out by Donnelly & Rees (2001) in the Barlaston and Crowcrofts area (Figure 7).

Donnelly (1994) carried out ten levelling surveys along Wedgwood Drive to the south of Crowcrofts from January 1992 to July 1993. The Crowcrofts Fault intersects this road at approximately 90° (Figure 8). A plot of the levelling data (Figure 8) shows the progressive movement associated with the fault.

The closest PS point to the levelling survey is on the western side of the Crowcrofts Fault and approximately 200 m north of the survey line. PS histories for this point show overall subsidence of approximately 130 mm over a 10-year period from Mat 1992 to November 2002 (Figure 9). However during the 1.5 years that the levelling survey was out carried (January 1992 to July 1993) the PSInSAR data indicates 25mm of total movement whereas the levelling data shows 130 mm of movement. There is an order of magnitude difference between the datasets.

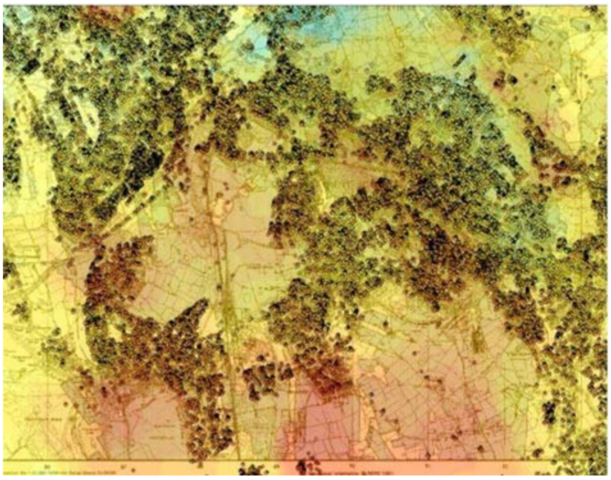

Figure 6. Subsidence to the south of Stoke is associated with recently undermined areas. This figure shows the PS points and interpolated PS data, which have been coded so that red is subsidence and blue uplift. The underlying map shows areas of mine workings (grey polygons) (Topographical data © Crown copyright).

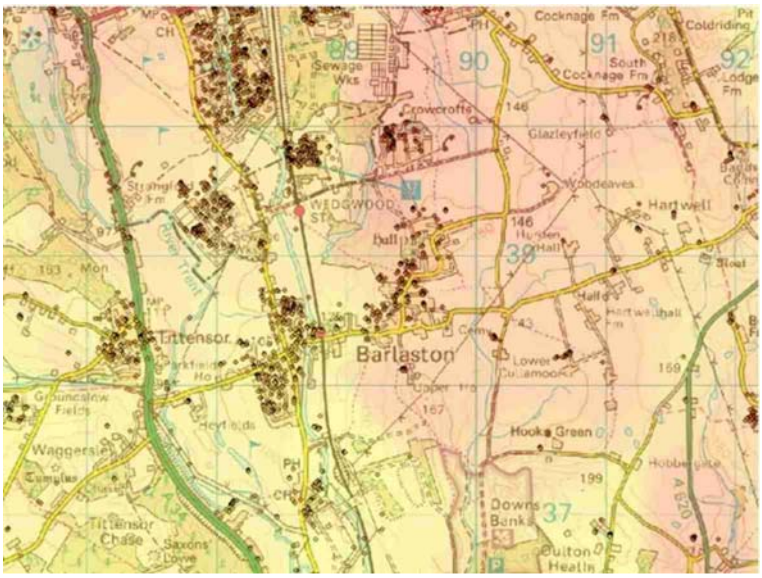

Figure 7. Location of Barlaston and Crowcrofts. Interpolated PS data (in pink) shows ground motion in the area (Topographical data © Crown copyright).

In the north of the area, many of the PSInSAR points showing uplift overlie areas of undermining. In this region of older mining activity uplift occurs rather than the observed subsidence in the south. The current hypothesis for this is that since the abandonment of the mines years ago groundwater has ceased to be pumped from the workings. The resulting influx of groundwater may account for the uplift, accommodated by fault reactivation, seen in this region.

Salt Dissolution

To the northwest of The Potteries the Wilkesley Halite Formation is found. The outcrop of this is extensive but has not been commercially worked. Rock salt such as this is readily soluble and has caused a long history of subsidence in the Cheshire Basin area, on which these deposits are on the edge. Figure 10 shows the Wilkesley Halite Formation (grey polygons) and areas of probable non-linear subsidence (brown areas) overlain by the interpolated PS data. A good spatial correspondence between the areas of probable non-linear subsidence and the PS derived subsidence can be seen.

Relationships with Made Ground

Differential ground motion is observed over a landfill site at North Crackley. This was formerly an opencast coal site and was variably backfilled at two different times. The southwest half was filled first and initially subsided (red interpolated areas on Figure 11) but is now more or less stable. PS data shows the northeast half is undergoing uplift (blue interpolated areas on Figure 11). Anticipation of likely ground motions over this site resulted in houses being designed with raft foundations. A recent inspection of this area showed no obvious problems with the buildings.

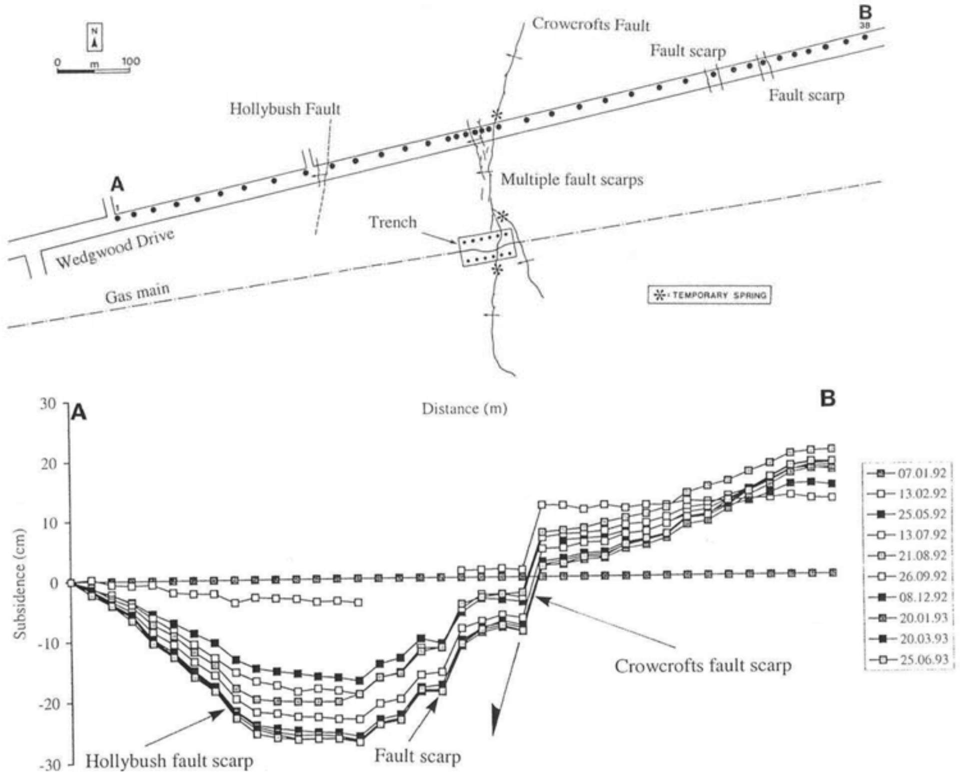

Figure 8. The levelling traverse along Wedgwood Drive and motion associated with the fault.

DISCUSSION AND CONCLUSIONS

The recently processed PSInSAR data for The Potteries area of England have shown that both subsidence and uplift have been taking place over the last 15 years. Uplift seems to be associated with the area of older mining in the northern Potteries where coal was extracted by partial extraction methods and where groundwater levels have returned towards their 'natural' levels. Subsidence was observed in the southern Potteries where deeper mining using total extraction methods ended less than ten years ago. Additionally, subsidence is associated with areas of landfill (but with subsidence varying depending upon the age of the infill), an area of compressible alluvial soils and areas underlain by highly soluble halite.

Because of these unsurprising associations, the PSInSAR technique would appear to be a potentially powerful tool for identifying and monitoring ground movements at local, regional and, indeed national scales. When combined with environmental geological spatial information it is possible to identify the likely causes of the observed ground motions. Therefore, the technique would seem to have many applications for those charged with managing the urban environment and the service infrastructure of roads, railways, pipelines etc. However, the technique probably needs further research and development before end users will readily accept it. Issues yet to be resolved include:

- the locational accuracy of PS points;
- uncertainty over the magnitude of the ground movements being observed;
- conversion of the observed movements (which are measured along the inclined line between the satellite and the ground reflector point) into three components;
- repeatability of the data processing between processing specialists because of variations in the methods and software used;
- cost: processing currently costs more then €10 000 for a scene and additional processing costs are incurred when new data is added from repeat satellite passes.

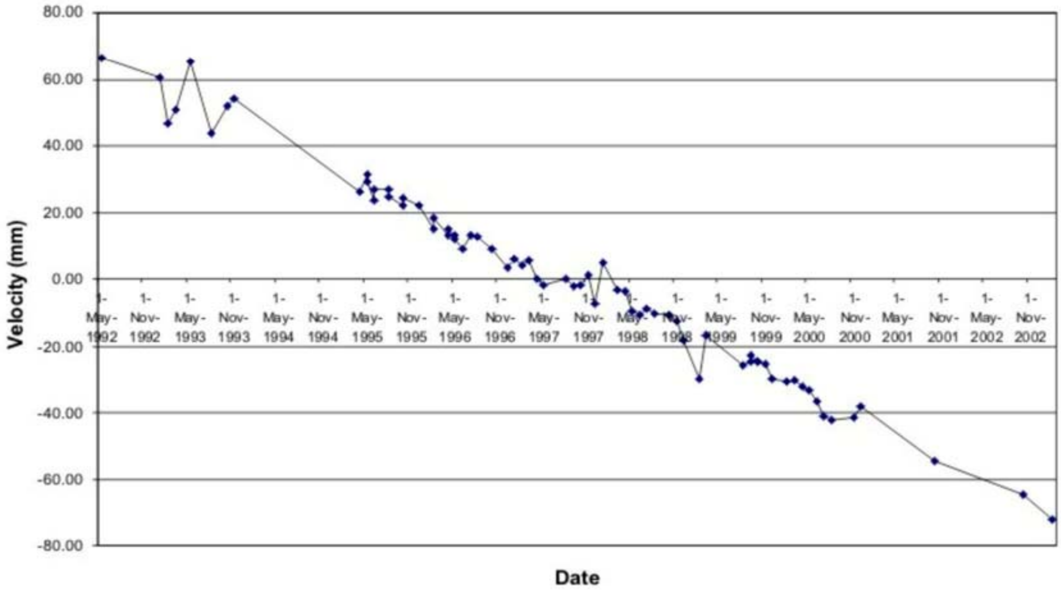

Figure 9. PSInSAR derived velocity for the point nearest to the Crowcrofts fault and the levelling data gathered by Donnelly (1994). The time period runs from May 1992 to November 2002. Horizontal lines are scaled 20 mm apart.

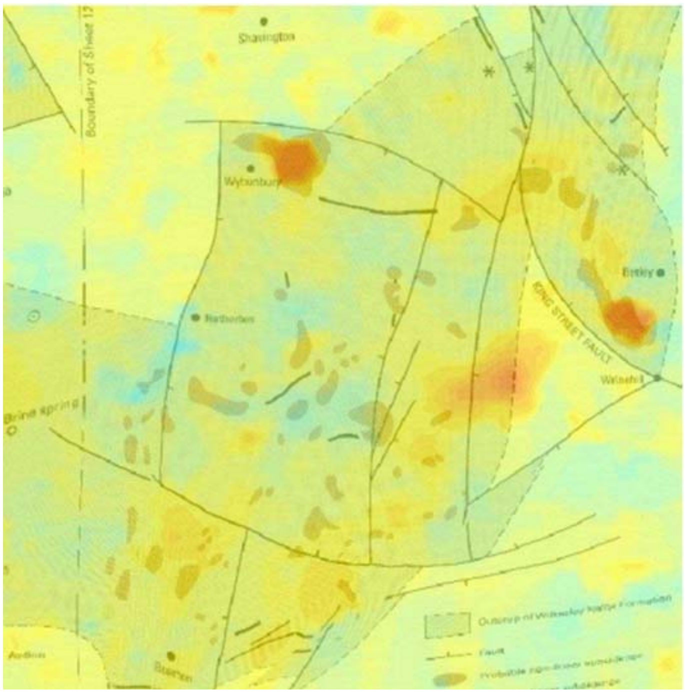

Figure 10. Wilkesley Halite Formation (grey polygons) and areas of probable non-linear subsidence (brown areas) overlain by the interpolated PS data.

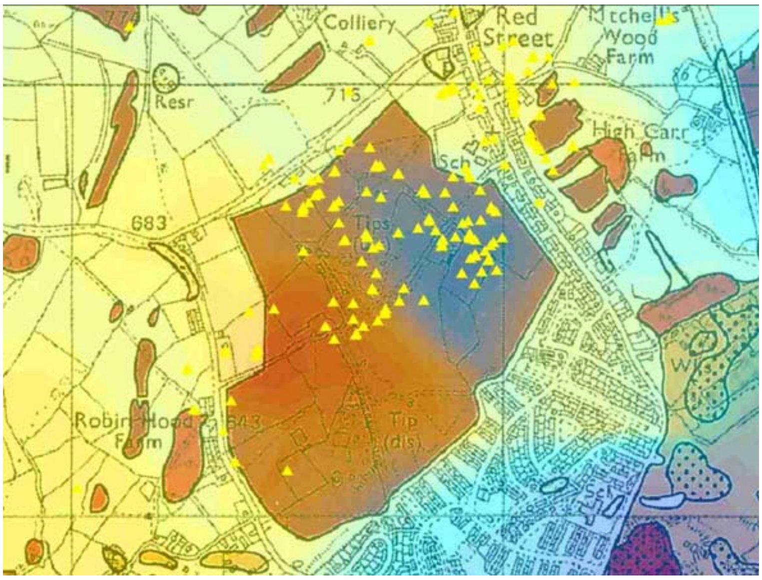

Figure 11. Differential movement over a waste site at North Crackley (PS Points shown as yellow triangles; red is subsidence, blue is uplift) (Topographical data © Crown copyright).

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