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Environmental baseline monitoring for shale-gas development: Insights for monitoring ground motion using InSAR analysis

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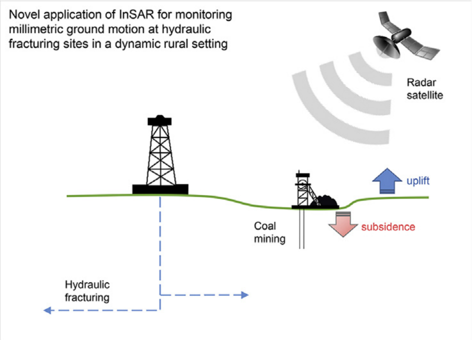
HIGHLIGHTS

- InSAR was used to monitor baseline and ongoing ground motion at UK hydraulic fracturing sites.
- Ground motion during and soon after hydraulic fracturing was unchanged compared to the baseline.
- The research successfully demonstrates InSAR for monitoring motion at rural shale gas operations.

GRAPHICAL ABSTRACT



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ABSTRACT

Shale gas operations can be contentious, with a degree of uncertainty regarding the effects that they may, or may not, have on the environment. Several countries have moratoria on hydraulic fracturing until its potential effects can be understood better. One area of debate is whether operations could cause ground motion at the surface. This research monitored ground motion prior to operations and compared that baseline to the situation during and after shale gas operations. The test sites are the Vale of Pickering (North Yorkshire) and the Fylde (Lancashire) in the UK. Planning permission was granted in May 2016 to undertake hydraulic fracturing near Kirby Misperton (Vale of Pickering) and in August 2018 at Preston New Road in Lancashire. Hydraulic fracturing has only taken place at Lancashire as it was the only site to also get the hydraulic fracturing plan approved. Complementary Interferometric Synthetic Aperture Radar (InSAR) techniques were used to process archive and current satellite images to detect relative ground motion with millimetric accuracy in rural and semi-urban landcover. The SBAS, ISBAS and RapidSAR processing for the period from 1992 to 2019 (extending 24 years prior to hydraulic fracturing) identified broad regions with little or no surface motion, along with discrete zones of uplift or subsidence. Analysis of the average velocities and time-series data revealed that the motion, where it occurred, related to factors including compressible ground, groundwater abstraction and underground coal mining. This research concluded that the shale gas operations in Lancashire did not alter the baseline ground motion dynamics to date, as detected by InSAR. The successful application of InSAR for detecting and monitoring ground motion at shale gas sites in rural landcover in the UK, where radar coherence has traditionally been a major challenge, serves as a precedent for other regions where baseline monitoring is required.

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1. Introduction

There is speculation whether shale gas development has the potential to cause motion or deformation at the ground surface. This paper describes independent ground motion research conducted in The Fylde, Lancashire and the Vale of Pickering, North Yorkshire (UK). The effects of hydraulic fracturing in The Fylde are assessed, and a baseline of motion prior to shale gas operations at the Vale of Pickering is outlined as part of an environmental monitoring research programme.

In the context of this research the term 'ground motion' does not refer to seismicity, which is the frequency, intensity and distribution of 'shaking' associated with earthquakes (induced or otherwise) in an area. The authors use 'ground motion' to mean the gradual movement of the surface of the landscape upwards (uplift), downwards (subsidence) or sideways (horizontal/lateral), which can be detected by spaceborne geodetic sensors.

It has been shown that conventional oil and gas operations have resulted in subsidence above compacting oil and gas reservoirs (Geertsma, 1973; Fielding et al., 1998), and a recent study suggests that surface uplift in eastern Texas, USA, was due to wastewater fluid injection at four disposal wells (Shirzaei et al., 2016). These studies do not imply that shale gas operations at depth will cause ground motion at the surface. Thus far, there is a paucity of information whether shale gas operations cause surface uplift, subsidence or lateral motion, despite being associated with seismic events (Davies et al., 2013). A key question is to what extent shale gas operations might alter the earth surface processes and stress conditions. This is especially important given public perceptions of shale gas development in the UK and internationally (Whitmarsh et al., 2015). Given that some countries (or states) have imposed temporary or long-term moratoria on shale gas operations, but it is ongoing in the UK, this research provides an opportunity to develop and test monitoring techniques that are globally noteworthy.

When considering a monitoring system, it is important to account for the dynamic nature of the earth's surface i.e. there may be pre-existing displacement due to either natural or induced factors. Definitive knowledge of baseline ground motion conditions, compared with those during/after shale gas operations, enables the provision of impartial and objective information on whether they may have affected the ground surface. Undertaking objective and authoritative environmental baseline monitoring helps to determine pre-operational environmental conditions in order to identify impacts of shale-gas development, should they occur. If undertaken impartially, a baseline survey can also perform the task of providing reassurance to stakeholders, including the public, that appropriate independent monitoring of potential environmental impacts is in hand.

A broad range of in situ and remote techniques (discussed further in Section 3) have the potential to monitor surface ground motion, depending on a range of factors including timing, precision, spatial coverage, site access and cost (Jin et al., 2013). For the purpose of this research, the satellite-based Interferometric Synthetic Aperture Radar (InSAR) technique was utilised to determine rates of historic and ongoing ground motion. InSAR provides a relative measure of ground motion in Line of Sight (LOS) from the satellite sensor as determined by signal phase differences in interferograms produced between co-registered SAR images acquired over the same location at different times (Rosen et al., 2000).

Primary amongst the reasons for choosing the InSAR method is the archive of satellite data extending back to 1992, which provides the potential to determine an historic record of ground motion. Furthermore, the satellite imaging technology can provide nationwide results (Costantini et al., 2017; Kalia et al., 2017), allowing identified ground motions to be understood in the context of both regional and local natural and anthropogenic processes. Nevertheless, the application of InSAR in the UK can still pose a significant challenge due to the rural vegetated landcover, which generally provides poor results due to temporal decorrelation and loss of phase coherence (e.g. Zebker and Villasenor, 1992; Cigna et al., 2014).

2. The study areas

This study addresses two sites in the UK, (i) Preston New Road (in the Fylde), where hydraulic fracturing has been conducted (October–December 2018) and (ii) Kirby Misperton (Vale of Pickering), where permission is still awaited to hydraulically fracture a shale gas well (Fig. 1). The Preston New Road (PNR) shale gas development site is situated in Lancashire to the east of Blackpool, in the northwest of England. The InSAR ground motion assessment encompasses the Greater Manchester urban area to the south, as well as the Forest of Bowland to the north. The area is predominantly low-lying in the west rising gently to the Pennines in the east. The 2012 CORINE Land Cover dataset indicates that the area is predominantly agricultural, forest and peatland with lesser urban fabric cover.

Kirby Misperton lies to the northwest of Malton within the Vale of Pickering in North Yorkshire. The Vale is low to moderate relief, rising northwards to the North York Moors. The land cover in the Vale is dominated by agriculture (arable and pasture) with forestry and peatland on the moors. There is limited urban fabric in the region.

The sites are highly applicable for research into the use of InSAR for ground motion analysis because (i) they are both primarily rural and vegetated (a particular challenge for InSAR); (ii) the Vale of Pickering has GNSS stations that can be used to validate the InSAR results; (iii) they both have appropriate stacks of archive radar data; (iv) the Vale of Pickering was used primarily to develop and test the efficacy of InSAR for baseline monitoring whilst the Lancashire site underwent shale gas operations thereby enabling, as far as we are aware, the first assessment of InSAR for monitoring ground motion pre- and post-shale gas operations in Europe.

3. Methodology

There are numerous techniques that have the potential to detect and monitor ground surface motion, summarised in Table 1. Techniques range from in situ systems, where sensors are installed either on or under the ground surface, to remote systems that can utilise airborne or space borne sensors. Each of the systems has inherent advantages and limitations specific to monitoring potential shale gas sites in the UK. For example, the necessity for frequent site access could potentially have been a challenge here where (i) access could have been affected by 'anti-fracking' protesters and (ii) installing equipment on site may have been problematic if it implied lack of impartiality. Nevertheless, the primary reason to exclude in situ systems is that they did not pre-exist in Preston New Road (PNR) or Kirby Misperton, therefore only a relatively short baseline of data would have been available had they been installed in 2015 when this research began, and prior to the start of hydraulic fracturing at PNR in October 2018.

The main aim of the research was to obtain baselines of ground motion and to determine if they were subsequently affected by shale gas development. It was concluded that this would be best-achieved using imagery from satellites that have been collecting data over the UK since 1992 and processed with InSAR techniques. Reviews of InSAR (e.g. Kalia et al., 2017) have outlined its success for monitoring displacement derived from processes such as landslides, coastal subsidence, karst processes, groundwater abstraction,

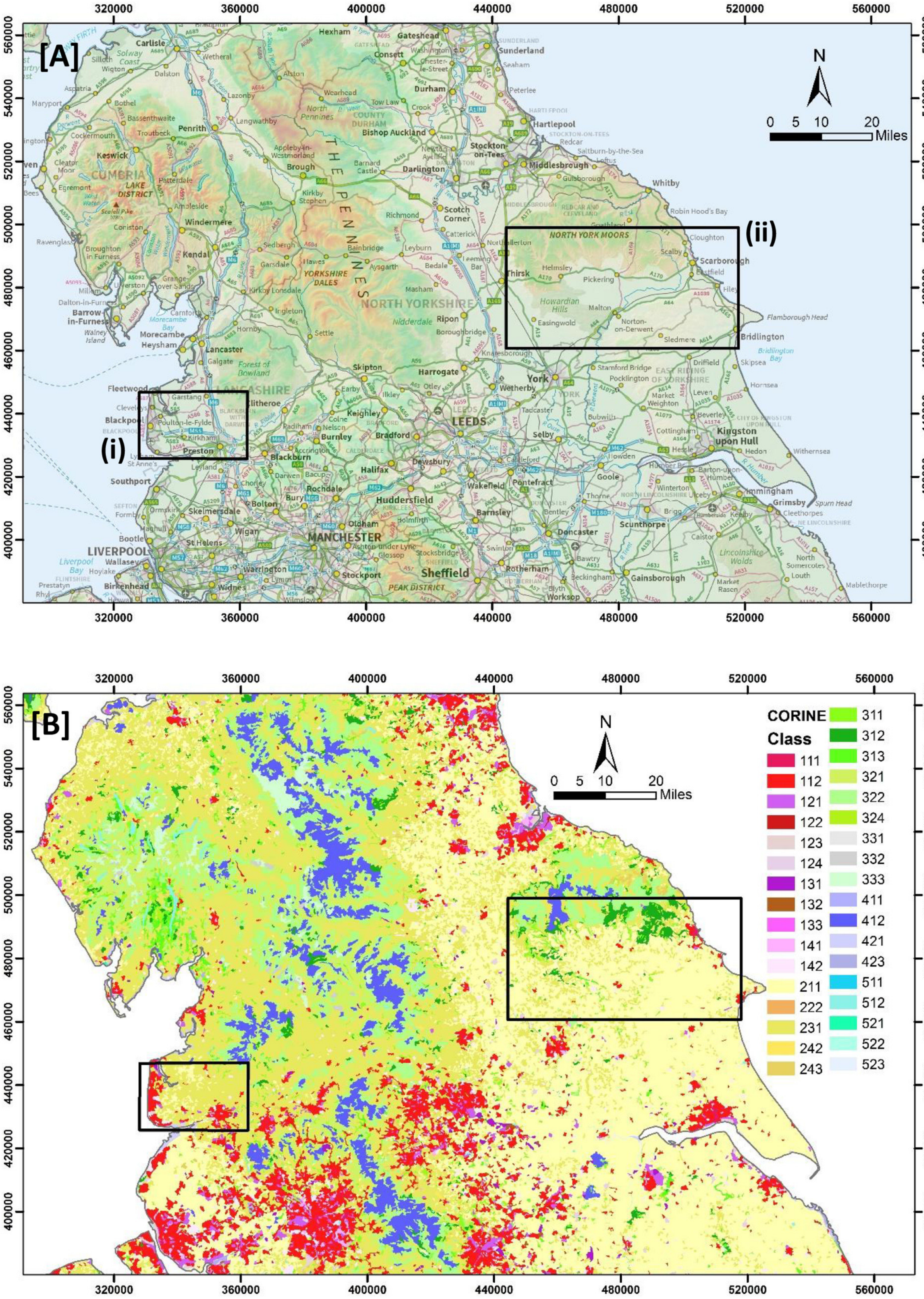

Fig. 1. Location of the two sites (i) Preston New Road, Lancashire and (ii) Vale of Pickering, Yorkshire overlaid onto [A] OS OpenMap 1:100k and [B] CORINE Land Cover Map 2012 (CLC2012). CLC classes as follows: EEA (2012): 111 Continuous urban fabric; 112 Discontinuous urban fabric; 121 Industrial or commercial units; 122 Road and rail networks and associated land; 123 Port areas; 124 Airports; 131 Mineral extraction sites; 132 Dump sites; 133 Construction sites; 141 Green urban areas; 142 Sport and leisure facilities; 211 Non-irrigated arable land; 222 Fruit trees and berry plantations; 231 Pastures; 242 Complex cultivation patterns; 243 Land occupied by agric. and natural vegetation; 311 Broad leaved forest; 312 Coniferous forest; 313 Mixed forest; 321 Natural grasslands; 322 Moors and heathland; 324 Transitional woodland shrub; 331 Beaches dunes sands; 332 Bare rocks; 333 Sparsely vegetated areas; 411 Inland marshes; 412 Peat bogs; 421 Salt marshes; 423 Intertidal_fats; 511 Water courses; 512Water bodies; 521 Coastal lagoons; 522 Estuaries; 523 Sea and ocean. Contains Ordnance Survey data © Crown copyright and database right (2015). CLC2012 © European Environment Agency.

Table 1
Comparison of remote and in situ ground surface motion monitoring techniques. (Modified from Ward et al., 2018.)

Monitoring technique	Advantages	Limitations
InSAR	Measurements are made remotely (non-invasive) Measurements can be made using historic data to gain a baseline prior to operations. Imagery can cover large areas simultaneously. Entire deformation field can be imaged, rather than individual points.	Conventional techniques have difficulty in vegetated areas. High magnitudes of motion (greater than the satellite detected phase difference) cannot be measured. Temporal and spatial resolution is limited by satellite set up and orbital parameters. Affected by steep topography (shown not be an issue in most of the UK).
GNSS	High precision. Does not require line of sight between benchmarks. Continuous site can operate without frequent human interaction.	Equipment can be stolen/vandalised/damaged. Requires site access for installation and maintenance. Sampling of deformation fields is limited to individual points; several points are required. Requires at least 4 satellites in view simultaneously. Limited to the location of stations at the outset
Tiltmeters	High precision. Does not require line of sight between benchmarks. Continuous site can operate without frequent human interaction.	Equipment can be stolen/vandalised/damaged. Requires site access for installation and maintenance. Sampling of deformation field is limited to individual points. Complex installation (e.g. in boreholes) – several tiltmeters are required.
Total Stations/ site levelling	High precision. Continuous sites can operate without frequent human interaction.	Requires line of sight between benchmarks. Systems that are operated manually require repeat site visits.

mining, natural gas production and earthquake-induced displacements. To date the opportunity has not arisen to apply the technique to an area in Europe undergoing active shale gas operations.

3.1. The InSAR process

Synthetic Aperture Radar (SAR) is an active microwave imaging system that can penetrate clouds and operate at night time. It is possible to measure sequential changes of the Earth's surface with millimetric accuracy and metric resolution by measuring the phase difference between satellite images (Pepe and Calò, 2017). Processing a stack of images acquired over a particular time period can provide an average of ground motion as well as a time series showing if the point or distributed scatterer has moved relative to the previous and subsequent images.

The InSAR process has been refined since early applications over 25 years ago (e.g. Massonnet et al., 1993) to include techniques such as Persistent Scatterer Interferometry (PSI) (Ferretti et al., 2001), Small Baseline Subset (SBAS) (Berardino et al., 2002), SqueeSAR (Ferretti et al., 2011), Intermittent SBAS (ISBAS) (Bateson et al., 2015; Sowter et al., 2016) and RapidSAR (Spaans and Hooper, 2016).

3.2. Data sources and processing

Tables 2 and 3 list the InSAR data sets acquired to establish the ground motion situation for the Vale of Pickering and Lancashire. The raw satellite data were processed with two InSAR techniques: RapidSAR (Spaans and Hooper, 2016) and SBAS/ISBAS (Sowter et al., 2013; Bateson et al., 2015). The RapidSAR results were supplied by Satsense Ltd., whilst SBAS/ISBAS results were processed either by BGS or by Geomatic Ventures Ltd., as detailed in Tables 2 and 3.

Table 2
InSAR data processing for the Vale of Pickering, including whether BGS or commercial providers Satsense Ltd. or Geomatic Ventures Ltd. undertook the processing.

Satellite	Time period	No. of scenes in the stack	Processing mode	Processed by
ERS-1/2	1992–2000	72	SBAS	BGS
ERS-1/2	1992–2000	72	ISBAS	BGS
ENVISAT	2002–2009	25	SBAS	BGS
ENVISAT	2002–2009	25	ISBAS	BGS
SENTINEL-1	2015–2016	36	SBAS	GVL
SENTINEL-1	2015–2016	36	ISBAS	GVL

Table 3
InSAR data processing for Lancashire, including whether BGS or commercial providers Satsense Ltd. or Geomatic Ventures Ltd. undertook the processing.

Satellite	Time period	No. of scenes in the stack	Processing mode	Processed by
ERS-1/2	1992–2000	63	SBAS	BGS
ERS-1/2	1992–2000	63	ISBAS	BGS
Sentinel-1 (Asc)	2015–2019	175	ISBAS	GVL
Sentinel-1 (Desc)	2015–2019	177	ISBAS	GVL
Sentinel-1 (Asc)	2015–2019	178	RapidSAR Urban	SatSense
Sentinel-1 (Asc)	2015–2019	178	RapidSAR Rural	SatSense
Sentinel-1 (Desc)	2015–2019	164	RapidSAR Urban	SatSense
Sentinel-1 (Desc)	2015–2019	164	RapidSAR Rural	SatSense

RapidSAR provides two results (i) 'RapidSAR urban' where the full Sentinel-1 resolution and point density is retained, and (ii) the lower resolution 'RapidSAR rural' where the detected motions are averaged for each cell in the radar image. The latter has the advantage that the effects of multiple weaker signals (which would not normally become a measurement point) are combined to create a signal that is sufficient to be a measurement point. The results are measurements within rural areas, which do not exist in the RapidSAR urban result. ISBAS provides more measurement points than RapidSAR rural over vegetated areas, but with a lower accuracy. Therefore, the combination of these multiple techniques can eliminate the inherent limitations of a single method, play a complementary role, and greatly improve the capability to detect ground displacements across different UK landcover types.

For both sites, the ground motion baseline has good temporal coverage from 1992 to 2000 and from 2015 onwards. Data from the 2000's and 2010's is more limited due to the lack of satellite SAR data coverage from the European Space Agency (ESA). However, at least 12 years of ground motion time series data for each site is sufficient to characterise natural and anthropogenic motion occurring prior to hydraulic fracturing activities.

3.3. Data interpretation

The InSAR process delivers two types of output (i) an average measurement of ground motion over the time period of the image stack and (ii) a time-series graph showing the relative displacement of each pixel at the date of the satellite image acquisition. These outputs may indicate ground stability or instability. Interpreting the results is a vital step to determine the potential or most likely cause(s) of the motion. Fig. 2 illustrates the process developed and followed throughout this research to interpret InSAR-determined motion (Ward et al., 2017). It utilises geological and

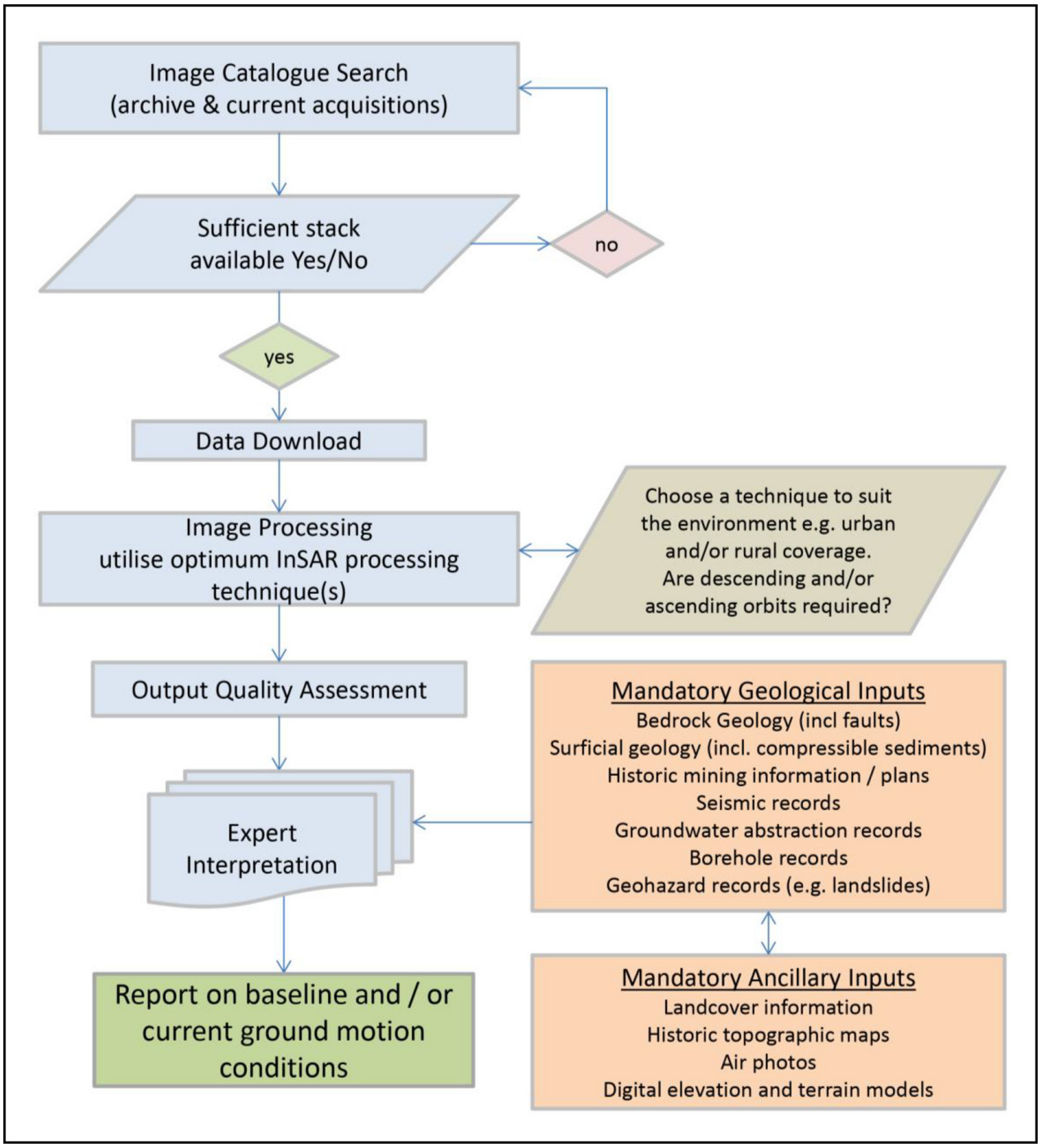

Fig. 2. Flowchart of the approach and data utilised for the ground motion InSAR monitoring.

non-geological ancillary datasets to characterise natural and anthropogenic earth surface processes and to determine factors such as whether an area is (i) underlain by compressible ground, and therefore may be prone to subsidence (ii) affected by mining operations (iii) undergoing groundwater abstraction (iv) a mass movement area, or (v) whether there were building works on site.

4. Results

4.1. Vale of Pickering ground motion baseline

The InSAR results from the ERS-1 satellite show that the Vale of Pickering site was predominantly stable between 1992 and 2000 (Fig. 3a). The SBAS result in this time period shows a small discrete zone of subsidence north of Whitby (in the Loftus area), which is likely related to historical potash mining but this is outside the Vale of Pickering monitoring area. The higher measurement density ISBAS ERS results (Fig. 3b) confirms the area of subsidence near Loftus and the overall stability elsewhere.

Twenty-five ENVISAT images were available for the 2000–2009 period. This relatively small stack limits the ability of the InSAR algorithms to statistically remove atmospheric effects, resulting in an element of noise in the results. Regardless, results were obtained (Fig. 3c and d) showing the areas with high continuous coherence to be stable, whilst areas with a lower coherence typically exhibit an uplift signal (Fig. 3d). The zones of uplift are dispersed and do not correlate with known geological causes, which suggests that they represent noise related to the low number of scenes and intermittent coherence or atmospheric effects.

Thirty-six Sentinel-1 images (a relatively low number) were used to assess the ground motion baseline for May 2015 to August 2016, using the SBAS and ISBAS algorithms (Fig. 3e and f). This data, once again, reveals the area to be predominantly stable, however the ISBAS results show a mild uplift signal in the lower-lying rural areas. For the majority of these, the signal relates to either increased noise due to the intermittent coherence or a signal derived from changes in vegetation over the year (only 1 years' worth of Sentinel-1 data has been processed in this case). There is a stronger and more defined area of uplift (of ~5-10 mm/yr) in the western sector of the Vale of Pickering, between Pickering

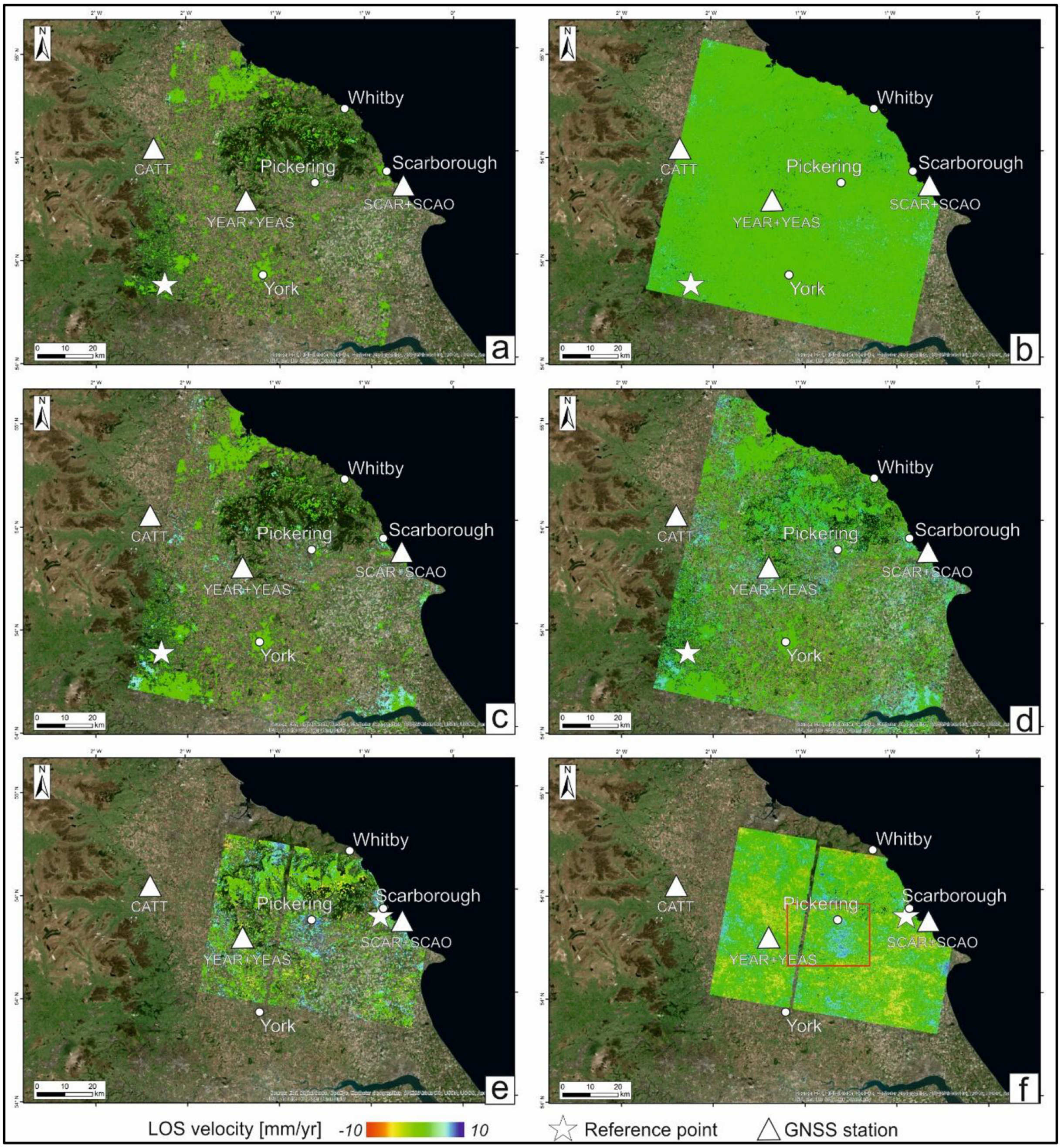

Fig. 3. InSAR results for the Vale of Pickering area, showing average rates of ground motion: red = subsidence, green = stable, blue = uplift. [a] ERS SBAS, [b] ERS ISBAS, [c] ENVISAT SBAS, [d] ENVISAT ISBAS, [e] Sentinel-1A SBAS, and [f] Sentinel-1A ISBAS. The red rectangle represents the Vale of Pickering area of interest (see Fig. 4). Location of GNSS stations and reference point are indicated with a white triangle and star, respectively. Insets [e] and [f] are © Geomatic Ventures Limited (GVL) 2019, insets [a], [b], [c] and [d] copyright BGS © UKRI. Background imagery: ESRI - World Imagery basemap. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and Malton (Fig. 4). The uplift is constrained to the north and south by the Quaternary clay and silt lacustrine deposits, which exceed 20 m thickness, derived from the Glacial Lake Pickering (BGS, 2000; Evans et al., 2016).

Possible explanations for this uplift relate to the wet winter of 2015–2016. The limestone to the North and South of the Vale of Pickering (Fig. 4b.) may allow a groundwater flow, which recharges the aquifer at depth, thereby increasing the pressure. Alternatively, the uplift may relate to shallower processes; the increase in surface water may have led to a swelling of the glacio-lacustrine clays, which are responsible for the flat topography of the Vale. Fig. 5 illustrates the change in average displacement following heavy rainfall in January 2016.

The InSAR data for the Vale of Pickering was compared to time-series GNSS data in the region to validate the magnitude and timing of ENVISAT and Sentinel-1A motion (Fig. 6). Two stations from the British Isles continuous GNSS Facility (available at www.bigf.ac.uk) were used. Note that the SCAR station (from 05/01/03 to 09/02/09) was renamed to SCAO (from 20/02/09) and the YEAR station (from 24/05/04 to 22/01/09) was renamed to YEAS (from 16/04/09 to 10/03/16), see Fig. 3 for location of GNSS stations.

The displacements at the two GNSS stations, at rates of −0.54 mm/yr for SCAO-SCAR and −0.56 mm/yr for YEAR-YEAS, are in agreement with the subsidence observed at the closest ISBAS points for the equivalent time span, confirming the validity of the InSAR results.

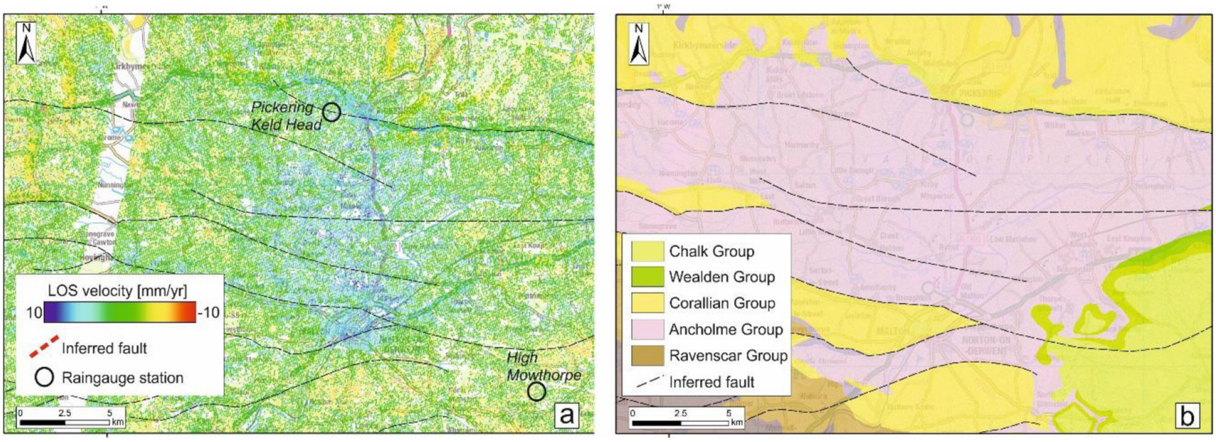

Fig. 4. [a]: ISBAS InSAR results for the Pickering area of the Vale of York. Blue areas are undergoing uplift whilst green/yellow areas are stable. Contains InSAR © GVL 2019 and Ordnance Data © Crown Copyright and database rights 2017. [b] BGS Bedrock geology and faults for the Pickering area of the Vale of York (BGS, 2000). Pink areas are clays from the Quaternary glacial lake; green represents chalk whilst the yellows and browns to the North and South are mainly limestones and sandstones. Contains British Geological Survey materials © UKRI 2019. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

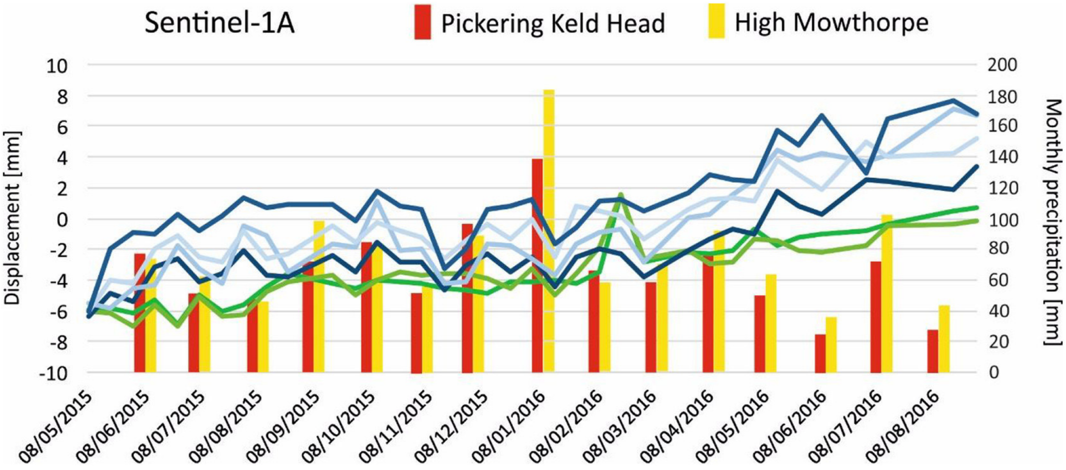

Fig. 5. ISBAS InSAR Time series for the Pickering (green) and Malton (blue) areas and rainfall data (see Fig. 4a for the location of the rain gauge stations). Contains Environment Agency information © Environment Agency. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4.2. Lancashire ground motion baseline (prior to shale gas operations)

Two temporal baselines have been produced for Lancashire (see Table 3); one from 1992 to 2000 and the second from May 2015 to January 2019. The second phase of InSAR results includes the period from October 2018 onwards when hydraulic fracturing started at Preston New Road (PNR).

ERS1/2 data were processed for the entire radar frame, revealing ground motions that occurred both within and outside the study area. The results highlight the potential for InSAR to detect a range of motion including discrete areas of subsidence and uplift, as well as confirming the stability of large areas (Fig. 7a–b).

Two significant areas of motion are identified outside the Fylde. A discrete area of uplift (blue points) northwest of Salford is due to the rise in groundwater levels following cessation of water pumping in abandoned coalmines (Cigna and Sowter, 2017). There is also an area of subsidence to the south-west of this uplift, in the Bickershaw-Goldborne-Leigh region. This is likely due to mining activity in the Bickershaw-Goldborne-Leigh collieries including water abstraction (Arrick et al., 1995). This subsidence has resulted in the formation of the Pennington Flash.

Two areas of subsidence in the Fylde study area in the 1992–2000 baseline ERS data correspond to 'peat and blown sand' on the published geological maps. Boreholes from the area indicate the presence of 'sand and peat' at the top of the stratigraphy (Fig. 8) suggesting that the subsidence is most likely caused by the existence of compressible ground.

Sentinel-1 data for the 2015–2019 period reveal similar patterns of baseline motion to the 1990's data. Over the entire area processed using the RapidSAR persistent scatter based algorithm (see Fig. 7c) we observe areas of stability over the built up areas, which is also where we expect high coherence. The discrete area of uplift in the centre of Fig. 7c is the Pennington Flash, which was subsiding in the 1990's. The motion signature has therefore switched from subsidence to uplift. Similar patterns of ground motion (subsidence following by uplift) are commonly observed over areas of coal mining in the UK (e.g. the Durham coalfield, Gee et al., 2017) and elsewhere in Europe (Przyłucka et al., 2015). They represent the transition from subsidence linked to active groundwater pumping, to surface uplift that is related to the influx of groundwater, and an increase in pore pressure after pumping ceases when coal mines are abandoned.

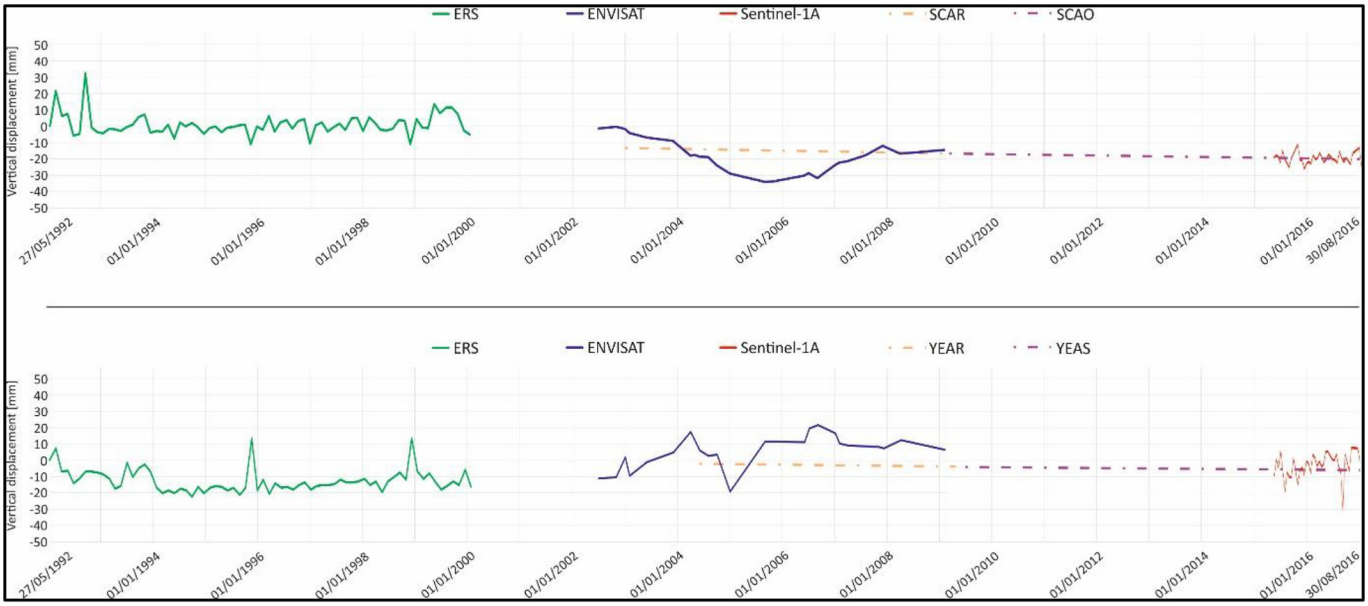

Fig. 6. Non-linear time series for selected ISBAS points compared with available GNSS data. The solid lines represent the ISBAS non-linear vertical displacements for the different acquisitions and the dotted lines represent the GNSS linear and vertical displacements. It is worth noting that the InSAR time series reported were generated considering a linear displacement velocity in the temporal gaps between the ENVISAT and Sentinel-1A datasets. From Ward et al. (2017).

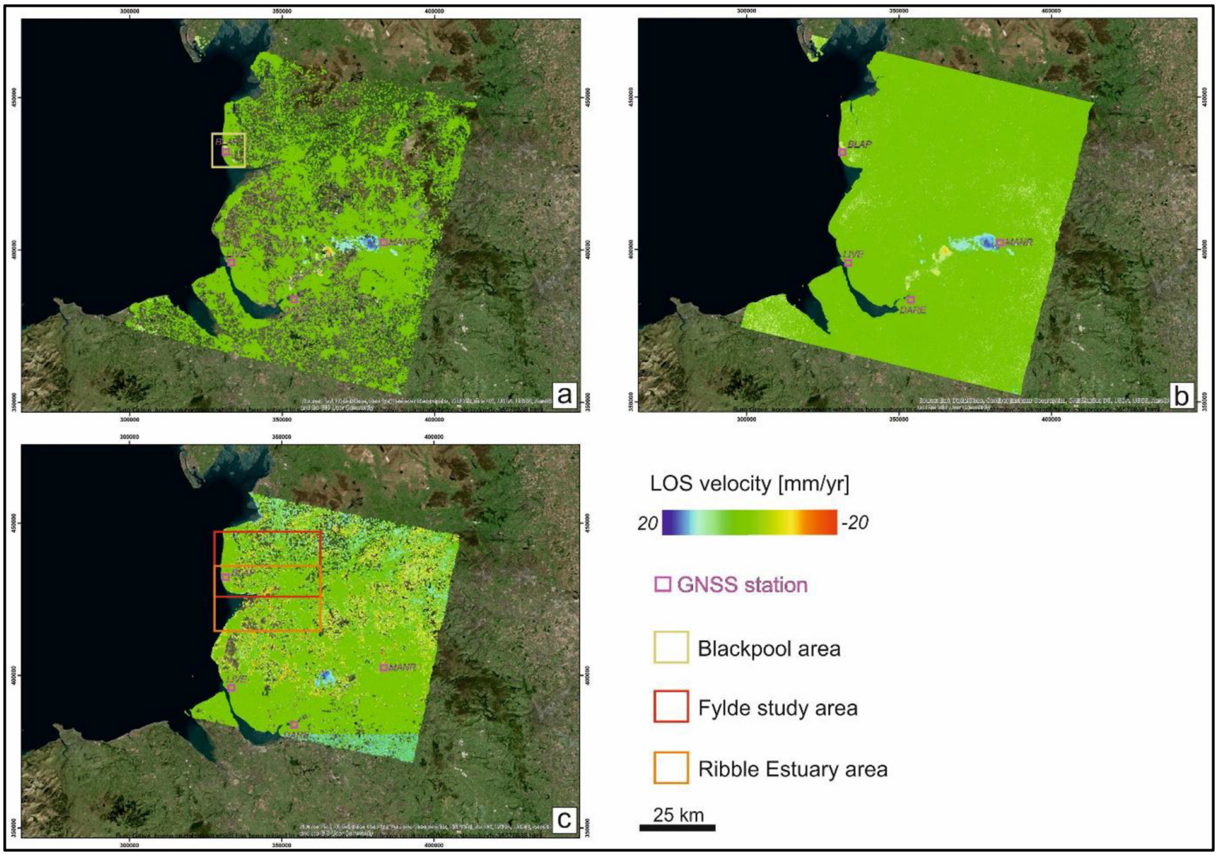

Fig. 7. [a] SBAS ERS descending average annual velocities for 1992–2000 copyright BGS © UKRI. [b] ISBAS ERS descending average annual velocities for 1992–2000 copyright BGS © UKRI. [c] SatSense RapidSAR Rural Sentinel-1 descending average velocity for 2015–2019. Yellow box indicates Blackpool area (see Fig. 8). Orange box indicates Ribble Estuary area (see Fig. 9). Red box indicates Fylde study area (see Fig. 10). Background imagery: ESRI - World Imagery basemap. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

In Fig. 7c rural areas appear, at this scale, to exhibit many yellow and red coloured points, suggesting subsidence. However, the point density in these areas is far lower than the stable areas and the points are given unequal weighting by the mapping software, thereby over-representing the subsidence signatures in the overall plots see Fig. 9. These apparent subsidence signatures

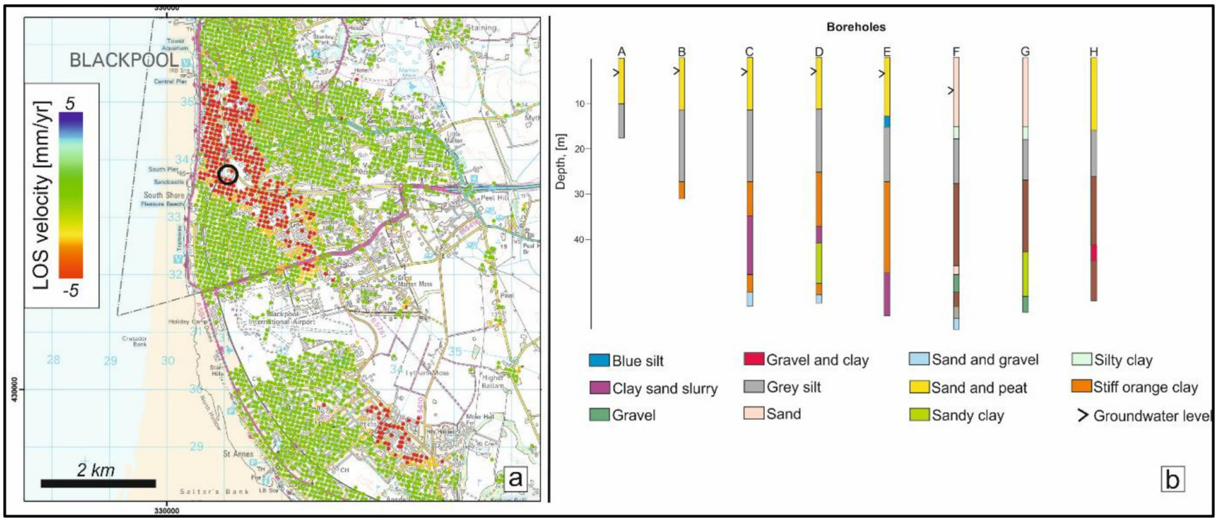

Fig. 8. [a] SBAS ERS descending average annual velocities for 1992–2000s for the Blackpool area. Black circle indicates the location of boreholes. [b] BGS borehole data showing the presence of sand and peat at the surface, copyright BGS © UKRI. Basemap contains Ordnance Data © Crown Copyright and database rights 2017.

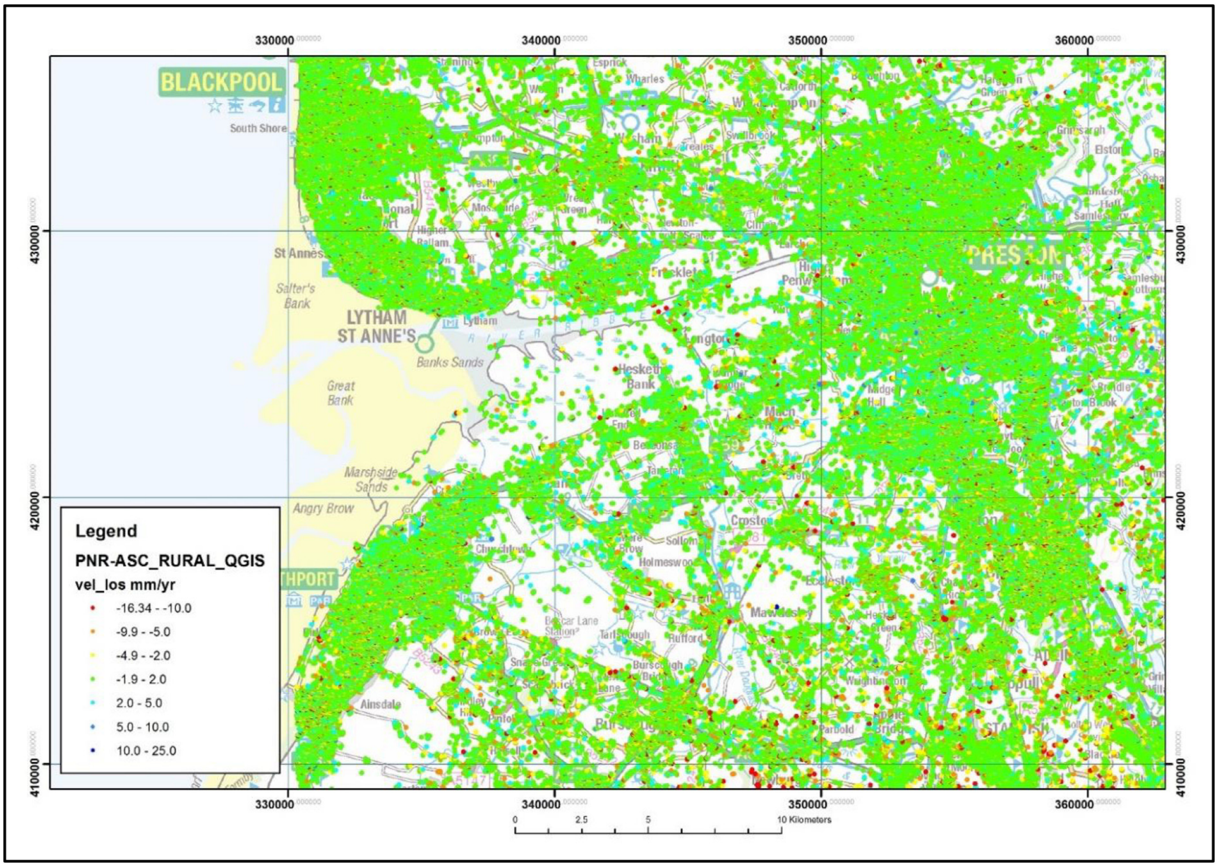

Fig. 9. RapidSAR rural Sentinel-1 ascending average annual velocities of the Ribble Estuary – at this scale the subsidence seen in Fig. 7 is not as apparent. Contains Ordnance Data © Crown Copyright and database rights 2017.

are therefore noise in the less coherent areas. This is a good example of the caution needed when visually interpreting InSAR data.

RapidSAR high resolution data (Fig. 10a) for the Lancashire study region reveals the average annual velocity for the study area to be stable for the 2015–2019 period prior to hydraulic fracturing. The Sentinel-1 ISBAS data (Fig. 10b) for the same area and period also shows the Lancashire study area to be stable, especially around the PNR site. However, the ISBAS data does identify two areas of subsidence to the south of Blackpool, in a similar position to the subsidence identified in the ERS data (see Fig. 8). The two identified in the 2015–2019 data are located over golf courses and it is proposed that the superficial geology of sand and peat along with water management at the golf courses led to this motion.

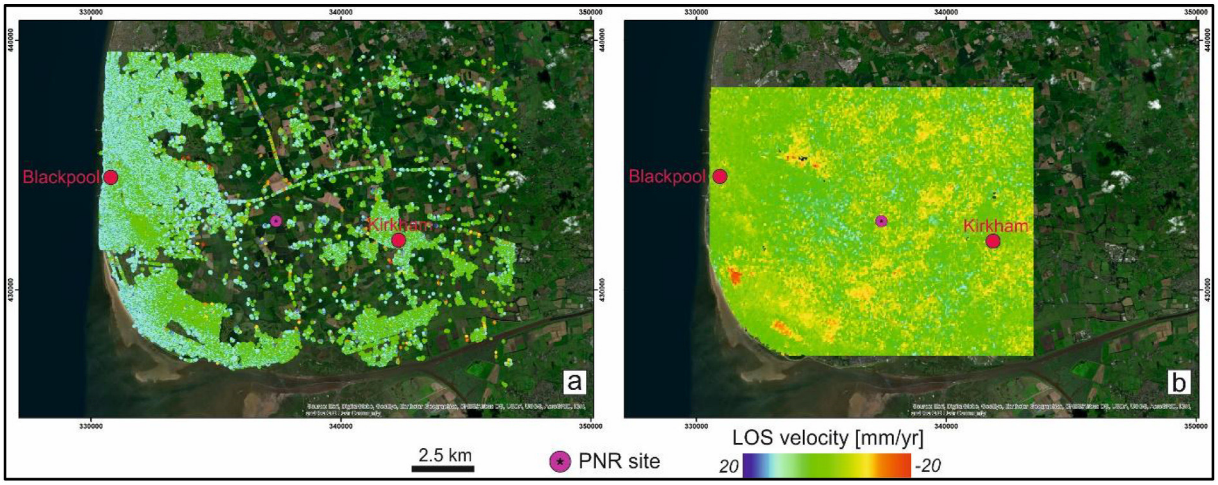

Fig. 10. 2015–2019 Fylde InSAR average velocities highlighting the Preston New Road site location [a] RapidSAR Sentinel-1 ascending high resolution results [b] Sentinel-1 ISBAS Sentinel-1 descending results. ISBAS data © GVL 2019. Background imagery: ESRI - World Imagery basemap.

4.3. Post baseline ground motion at the PNR site

Hydraulic fracturing of the shale surrounding one of the two horizontal wells drilled at the PNR site started in October 2018 and was completed by mid-December (Environment Agency, 2019). Flow testing occurred during January 2019. The InSAR time series for points at or near to the PNR site were examined in detail to establish if hydraulic fracturing activities produced detectable ground motions. Refer to Fig. 10 for average velocities around the PNR site. In particular, the Sentinel-1 time-series motion patterns for the period October 2018–February 2019 were compared to the Sentinel-1 baseline of May 2015–September 2018.

Although the average annual velocities in the region of the PNR site for the Sentinel-1 data indicate that it is stable over the 2015–2019 period, variations are evident in the ISBAS time series, acquired from the InSAR point directly over the site (Fig. 11). The variations represent natural fluctuations and measurement noise, which are part of the baseline for this area. Therefore, any motion caused by the hydraulic fracturing would need to either exceed this variation or represent a change in the established style of the baseline variation for it to be attributed to shale gas activities. For the PNR site the baseline variation in motion is approximately 20 mm, whilst the standard deviation is 11 mm (Fig. 11). During the hydraulic fracturing operations, the variation from the baseline mean is approximately 15 mm, which is greater than one standard deviation (10 mm for this point) but still within the baseline variation observed in the baseline period; the pattern of ground motions have not changed during the hydraulic fracturing.

The RapidSAR time series were also examined to assess whether ground motion was detected at the time of the seismic events that were coincident with the hydraulic fracturing. Fifty-seven seismic events occurred during the first period of hydraulic fracturing

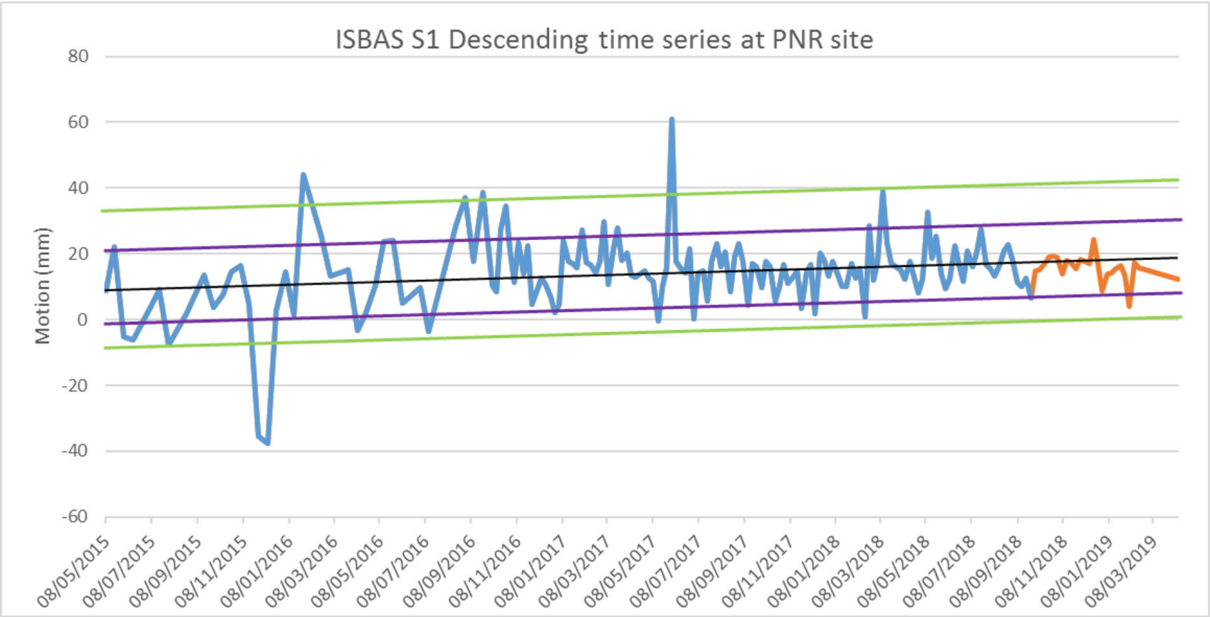

Fig. 11. ISBAS time series for a measurement point over the PNR site. The time series for the pre-fracturing baseline (blue line) and the continuation for the period of interest (orange line) are shown. The black trendline shows the average motion whilst the green lines mark the maximum and minimum deviations from the mean, the purple lines indicate one standard deviation from the average trend line. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(http://www.earthquakes.bgs.ac.uk/earthquakes/dataSearch.html). The largest seismic event took place 11th on December 2018 with a magnitude of 1.5 ML at a depth of 1.6 km. The second largest event, 1.1 ML, took place on 29th of October 2018 at a depth of 2.9 km. Both of these events occurred at approximately the same location (largest purple circle on Fig. 12). The largest seismic events occur under arable fields; the closest RapidSAR points are approximately 500 m to the south (green square on Fig. 12).

The RapidSAR time series show no evidence of a change in ground motion at the time of the seismic activity compared to the preceding period. Fig. 13 shows the time series for the pre hydraulic fracturing baseline (blue line) and the period when hydraulic fracturing took place (orange line). The black trend line shows the average motion whilst the green lines mark the maximum and minimum deviations from the mean. The blue vertical line marks the date of the strongest seismic event. InSAR continues to detect ground motion during the hydraulic fracturing period, and at the time of the seismic events, but the motion is no larger than the variation observed during the baseline period, and the trend of the average motion (i.e. uplift) is unchanged (Fig. 13).

5. Discussion

5.1. Vale of Pickering ground motion

The Vale of Pickering ground motion analysis included processing three stacks of ERS-1/2, ENVISAT and Sentinel-1 radar satellite data using SBAS and ISBAS techniques (i.e. six levels of analysis in total). The 2002–2009 ENVISAT data (24 radar scenes) SBAS analysis indicated that the urban areas were predominantly stable. The areas of dispersed motion in the SBAS and ISBAS analyses are most likely due to atmospheric effects rather than genuine ground surface motion. Nevertheless, the zone of more discrete subsidence in the south of the monitoring area correlates with compressible ground deposits.

The 1992–2000 ERS-1/2 results (72 radar scenes) were less affected by atmospheric conditions. The SBAS analysis revealed that the urban areas and connecting roads were stable i.e. they were not affected by regional subsidence or uplift. The ISBAS analysis also indicates that the area was predominantly stable apart from three zones that display dispersed uplift. Experience of this type of dispersed result elsewhere in the UK is that it is not due to geological motion (which is more discrete) but it is most likely due to vegetation changes and agricultural practices.

The Sentinel-1 data extends the ground motion monitoring to the present day and beyond. Since April 2015, there have been sufficient Sentinel-1 scenes to carry out InSAR investigation for this area of the UK. The Sentinel-1 InSAR processing provides a higher concentration of measurement points using both the SBAS and ISBAS techniques, compared to ERS and ENVISAT InSAR results. For this research, the Sentinel-1 image stack was curtailed to 2015–2016 due to the fact that shale gas operations were not ongoing in Yorkshire. The Sentinel-1A InSAR results display a pattern of uplift in the Vale of Pickering, which is most likely linked to groundwater fluctuations, whether at shallow or greater depths.

A baseline from 1992 to 2016 has been established for ground motion in the Vale of Pickering. Shale gas operations are currently on hold in the area, therefore the InSAR analysis has not been extended to the present day, nor has it included the RapidSAR pro-

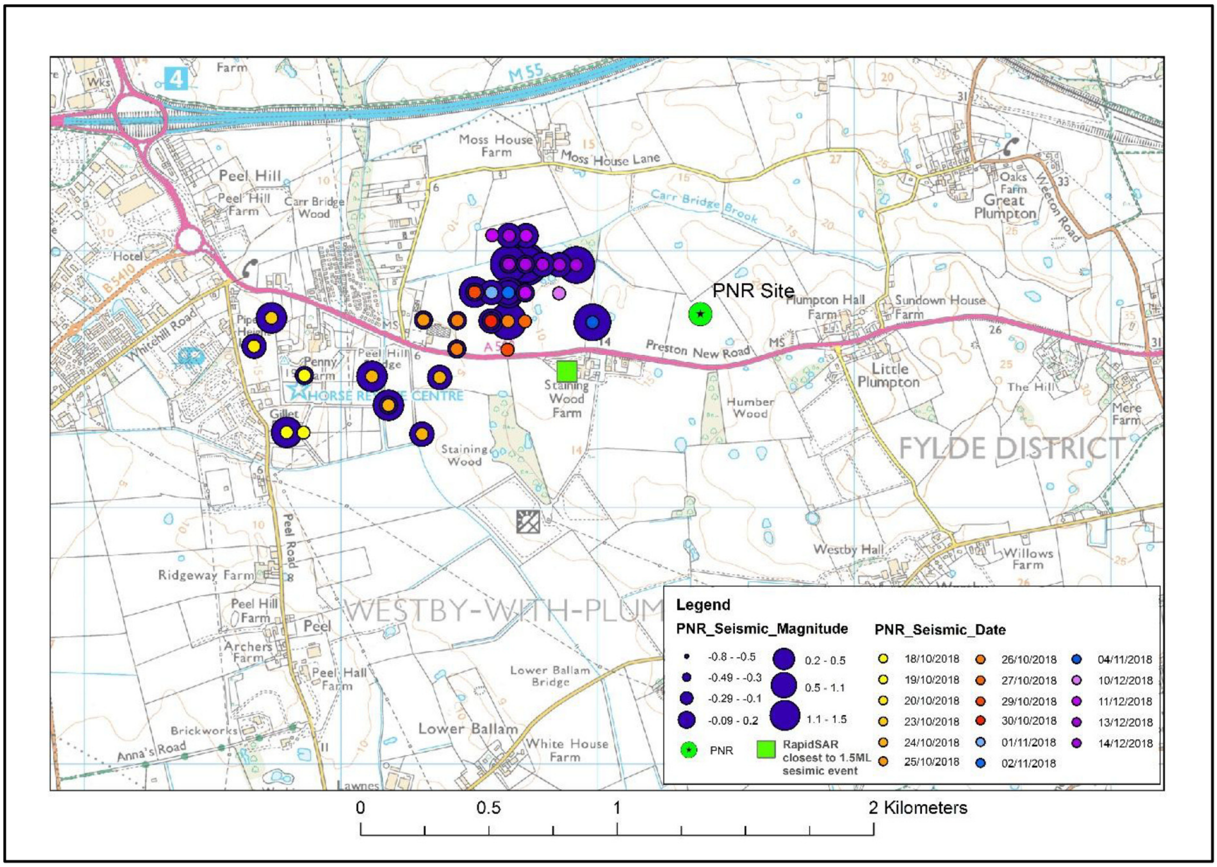

Fig. 12. PNR site showing location, date and magnitude of seismic events and location of the InSAR time series shown in this figure and Fig. 13. Contains Ordnance Data © Crown Copyright and database rights 2017, Seismic data © BEIS. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

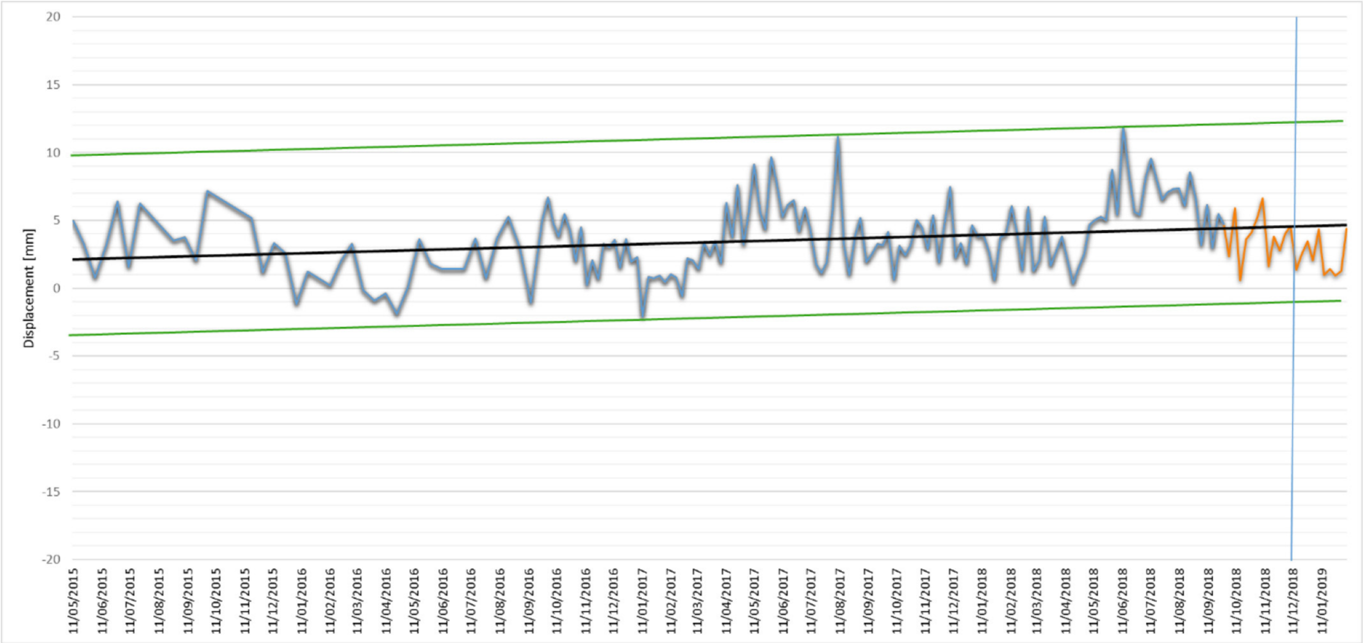

Fig. 13. Filtered InSAR time series for RapidSAR Sentinel-1 points on Fig. 11. Vertical blue line on graph indicates date of seismicity. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

cessing. The research has demonstrated that InSAR monitoring could be extended with Sentinel-1 data if and when operations start.

5.2. Lancashire ground motion

The Fylde InSAR ground motion baseline analysis utilised ERS-1/2 and Sentinel-1 data. The stack of ERS-1/2 data (covering the period from 1992 to 2000) was processed using SBAS and ISBAS techniques (i.e. two levels of analysis in total). The assessment indicates that the majority of the full region covered by the satellite image stack was stable, however discrete zones were affected by ground motion. The uplift and subsidence in the Manchester area relates to coal mining (Cigna and Sowter, 2017), whilst the subsidence in the west of the Fylde is related to compressible ground. These examples, corroborated by GNSS in this research, provide validation of the ground motion determined by InSAR in the region.

Two sources of InSAR ground motion data for the period from 2015 to 2019 were processed and interpreted for the Preston New Road site and wider area i.e. Sentinel-1 ascending and descending. Two InSAR processing techniques (i.e. ISBAS and RapidSAR) were used to ensure that the best coverage of measurements was obtained both spatially and temporally. This approach was designed to provide the best chance of capturing motion that could be related to hydraulic fracturing.

Outputs from the InSAR process include average measurements of ground motion over the time covered by the image stack, and a time series graph showing relative displacement between image acquisitions. Interpreting the results is still largely a manual process, following a protocol refined in this research with mandatory and ancillary input datasets (Ward et al., 2017).

Analysis of Sentinel-1 InSAR data for the pre-hydraulic fracturing period (2015–2018) reveal that the motion patterns observed in the 1990's data are still evident, although their locations have shifted slightly (compressible ground to the west of the Fylde) or the signal pattern has switched from subsidence to uplift (Leigh) due to changes in groundwater pumping related to past mining activities. Examination of the time series for the hydraulic fracturing period (October 2018–December 2018) shows no evidence of change compared to the baselines established in both the Sentinel-1 and ERS baseline time series. Examination of the Sentinel-1 time series for points closest to seismic events also showed no evidence of change at the time of those events.

Examination of the ERS and Sentinel-1 time series reveals a variability about the mean trend of the ground motion. Any meaningful syn- or post-hydraulic fracturing ground motion signals would therefore need to exceed this variability or change the 'pattern of motion recorded. No such variance from the baseline was revealed in this research.

6. Conclusions

Significant conjecture relating to whether shale gas operations could cause ground motion signifies the importance of objective monitoring for all stakeholders. It was apparent at public engagement events held in Lancashire and the Vale of Pickering for the BGS Environmental Baseline Monitoring Programme that there was a large degree of concern that hydraulic fracturing operations would case ground motion. Moreover there is some confusion between seismic activity (which has been correlated with shale gas operations) and ground motion. Many of the attendees assumed that if there is seismic activity there must be ground motion, and vice versa.

It is important to communicate impartially the situation regarding baseline ground motion and also provide evidence regarding the opportunities for detection and monitoring in order to allay public fears and objectively inform an open discussion. Establishing ground motion baselines and monitoring the situation throughout any shale gas operations is vital. Baselines allow an understanding of how the natural (and anthropogenic) processes can lead to small scale ground motions. The baseline provides evidence that ground motion is not uncommon and it may not normally impact on day to day life. It also offers reassurance to the public that there is a record of the existing conditions so that if operations start there is a baseline with which to compare the up-to-date information.

C-band SAR data were used in the Vale of Pickering and Lancashire to collect a baseline of ground motion measurements over a 25 year period, and subsequently to characterise the deformation. This baseline shows that overall the regions have been stable, whilst zones of natural and manmade ground motion were identified. These are correlated with compressible ground, ground water level changes and underground mining activities.

At Preston New Road (Lancashire) comparison of the InSAR time series for the period when hydraulic fracturing took place (October 2018 to December 2018) with the established baseline reveals that the ground motion to date does not deviate from the pattern observed in the baseline. Furthermore, examination of the InSAR time series for points closest to seismic events that occurred in October, November and December 2018 shows no significant ground motion at the time of the events.

Utilisation of InSAR for continued monitoring of ground motion is recommended. Further research will improve site characterisation and increase the capacity to recognise and evaluate potential impacts of shale gas operations in rural vegetated terrains. Impartial monitoring will help to provide a solid evidence base for stakeholders including the public, regulatory bodies and energy companies.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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