OR/18/054 Dataset and methodology

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The SAR datasets belong to Single Look Complex products of different satellite constellations managed by the European Space Agency and available free of charge: ERS, ENVISAT and Sentinel 1 (S-1) Interferometric Wide swath acquisition mode.

These spacecraft follow near-polar orbits with azimuthal direction approximatively parallel to N–S that defines two acquisition geometries, according to the flying direction of the sensor: ascending (from south to north) and descending (north to south). All the measurements are 1D, detected along the sensor's Line of Sight (LOS) inclined at a θ angle with respect to the vertical direction, known as the incidence angle (Table 1).

Table 1 Properties of ERS, ENVISAT and Sentinel-1A IW SLC products. Rg = range (perpendicular to satellite flight direction) and Az = azimuth (parallel to satellite flight direction).

	ERS	**ENVISAT**	**S-1**
Pixel size	8 m (Rg) × 4 m (Az)	8 m (Rg) × 4 m (Az)	2.3 m (Rg) × 14.1 m (Az)
ϑ at the scene centre	~23.3°	~23.3°	~37.5°
Minimum revisit time	35 days	35 days	6 days

Three SAR stacks of approximatively 280 satellite images have been considered, covering an area of interest (AoI) of ~1,090 km^2 (Figure 1):

- ERS-1 and ERS-2 descending images from 1995 to 2001.
- ENVISAT descending images from 2002 to 2010.
- S-1 ascending and descending images from 2015 to 2017.

The investigation has been focused on a portion of the whole SAR scenes and centred on the proposed GGERFS borehole locations for phase 1 at Dalmarnock and Cuningar Loop (Figure 1). The area is typical of many towns and cities above abandoned coal mine workings, characterised by a labyrinth of disused mines hewed into the Coal Measures by coal miners in the 19th and 20th century (Monaghan et al., 2017[1]).

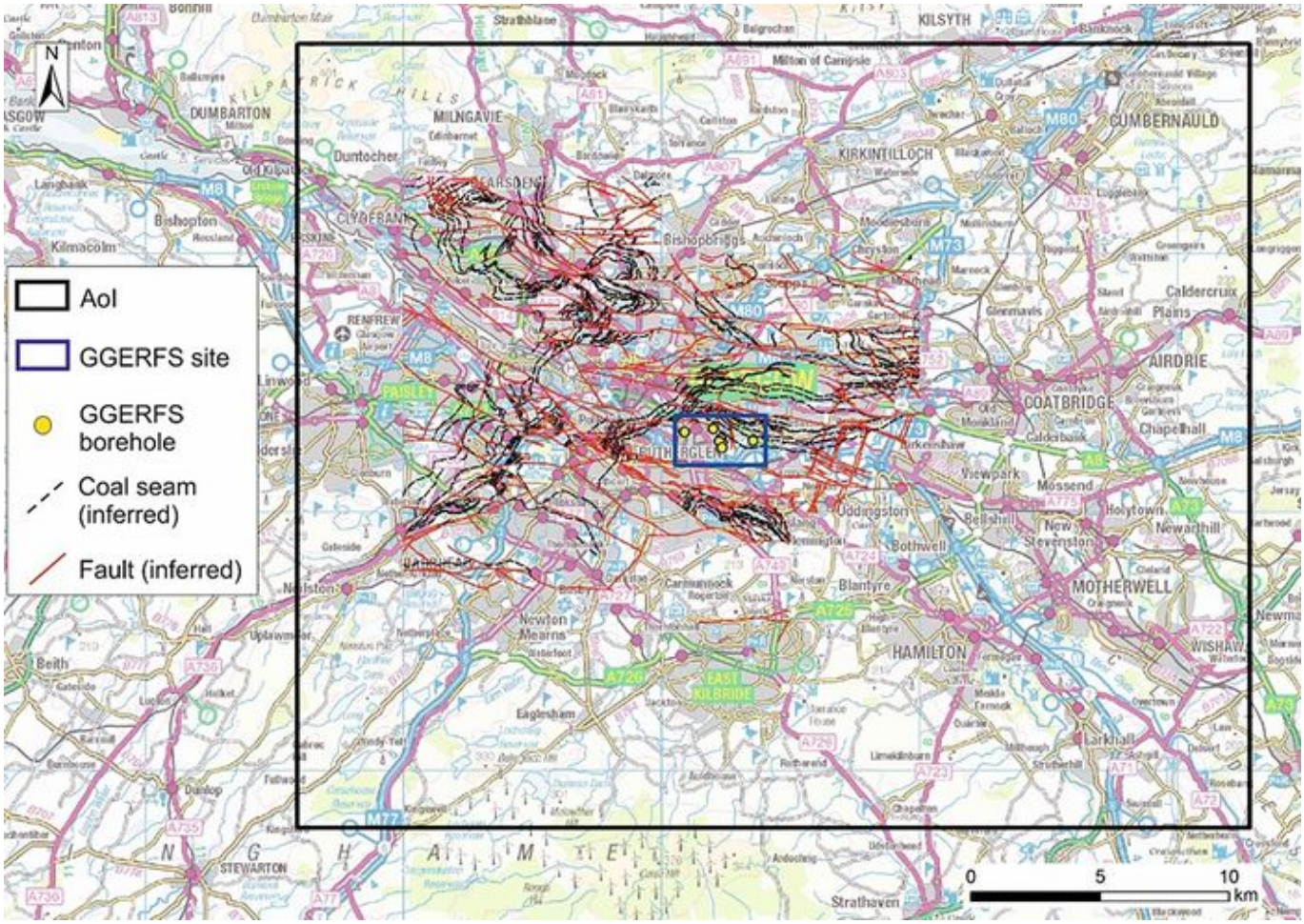

Figure 1 GGERFS site and the extent of the AoI processed with ERS, ENVISAT and S-1 SAR imagery. Coal seam and fault locations are shown for to the central part of Glasgow only. Contains Ordnance Survey data © Crown copyright and database right 2018, license number 100021290 EUL. Contains British Geological Survey materials © UKRI 2019.

The three datasets cover a time span of 23 years with a gap of almost one and a half years between ERS and ENVISAT and ~5 years between ENVISAT and S-1.

Spaceborne Interferometric Synthetic Aperture Radar (InSAR) techniques have been adopted for measuring surface deformation from the three satellite radar datasets. However, temporal changes in the scattering properties of the Earth's surface and changes in scattering properties with different look directions constrain the feasibility of InSAR measurements. Noise is introduced in to the ground displacement signal by both variation in atmospheric properties and inaccuracy in both satellite orbit and surface elevation determination. These sources of error can be addressed via the processing of multiple acquisitions in time, making it possible to obtain high precision measurements of ground displacement (Hooper, 2008[2]) for pixels that show correlation of the radar signal in time or a high radar signal return (e.g. buildings, rocky outcrops and linear structures).

The displacement measurements are relative in both space and time: they are spatially referred to a reference point, and temporally to the date of the first available satellite acquisition in the stack. Therefore all displacement measurements are relative to the reference point, which is assumed to be motionless and selected for its radar properties, with low phase noise in all the scenes of the imagery. For this study the chosen reference point is in the western part of the city.

In order to obtain the most complete investigation in terms of resolution and density of InSAR results, two InSAR methods to process the SAR datasets have been used for this study and, when possible, compared:

- Intermittent Small Baseline and Subset (ISBAS), a patent pending algorithm developed by © Geomatic Ventures Limited and whose IP belongs to the University of Nottingham — UK (Sowter et al., 2013[3]; Bateson et al. 2015[4]).
- SqueeSAR™, the proprietary multi-interferogram technique patented by TRE ALTAMIRA (Ferretti et al., 2011[5]).

Since all ground motion measurements derived using the InSAR methods are relative to a reference point it is important to understand the stability of this point. In the case of this study two reference points have been used:

- one for the ISBAS processed data (ERS, ENVISAT and Sentinel) at -4.256, 55.861
- one for the SqueeSAR™ processed data (ERS, ENVISAT and Sentinel) at -4.374, 55.858

These reference locations have been assessed against the BGS GeoSure datasets and show a low susceptibility to shrink swell, landslides, compressible ground, running sand, soluble rock and collapsible deposits. Additional confidence is given by the InSAR results themselves, if the reference point was not stable then it would manifest as differences in average velocity between the point and the rest of the measurements points. We do not observe any such differences associated with either of the reference points.

The spatial interpretation of InSAR results consisted of comparison against the following BGS datasets at 1:50 000 scale:

- The Digital Geological Map of Great Britain project (DiGMapGB), namely the geological map data of bedrock and superficial deposits down to 1:10 000 scale (www.bgs.ac.uk/products/digitalmaps/digmapgb_10.html).
- The BGS GeoSure dataset, which identifies and classifies the susceptibility connected to areas of potential natural ground movement in Great Britain due to collapsible deposits, compressible ground, debris flow, landslides, running sand, shrink-swell terrains and soluble rocks (Lee and Doce, 2017[6]). The GeoSure datasets are polygon (area) layers, which are described using a simple A to E potential hazard classification (A = Low, E = High).
- Coal Authority data has been accessed via the Coal Authority interactive map viewer accessible at: http://mapapps2.bgs.ac.uk/coalauthority/home.html. This provides information on the location of potential hazards relating to past coal mining such as old mine entries, areas of surface mining etc.
- The BGS superficial deposits thickness model (www.bgs.ac.uk/products/onshore//superficialThicknessModel.html), incorporating the youngest geological formations (less than two million years old).

For the S-1 dataset, the short revisit time allowed us to analyse the temporal evolution of the displacement rates through the classification of time series into distinctive predefined target models (e.g., uncorrelated, linear, discontinuous and seasonal) based on a conditional sequence of statistical test as defined in Berti et al. (2013)[7].

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