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TERRAFIRMA PRODUCT

Interpretation Report

V1.1

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Northumberland

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1 SUMMARY

This report presents the findings of the BGS value adding of the Persistent Scatterer Interferometry (PSI) ground motion data for the Northumberland region of the UK. PSI results have been produced, by FugroNPA, using descending ERS and Envisat data. The availability of ascending data was insufficient to produce PSI results therefore DifSAR analysis has been carried out for these datasets.

The Northumberland and Durham area in the North East of the UK is a region with a long history of coal mining. As such the UK Coal Authority is interested in investigating techniques for the verification of mining-related subsidence claims in this area. The PSI technique offers a means of measuring terrain motion over wide areas and therefore has possible applications to the verification of mining-related subsidence claims. The Terrafirma study area extends for 50 km from Durham in the south to Ashington in the north; it is 20 km wide and includes Newcastle upon Tyne, Sunderland, Gateshead and South Shields.

The geological sequence of interest includes bedrock of Carboniferous strata, including the Westphalian Coal Measures, and Permian strata comprising the basal Permian Yellow Sands Formation and overlying Zechstein Group. The Carboniferous rocks dip gently eastwards and are overlain unconformably by the Permian rocks. The continuity of the outcrops of these units is interrupted by a number of normal faults. Quaternary (drift) deposits mantle almost the entire district and, except in a few places, conceal the bedrock.

The coal-bearing strata dip gently to the east, part of the coalfield being concealed beneath the Permian strata to the south of the River Tyne and the coalfield extends beneath the sea. The coalfield has a working history dating back to Roman times. Over twenty coal seams have been mined underground and the coalfield has been one of the major sources of opencast (surface-mined) coal in Britain. The geological structure of the area determined the development of the coalfield with faults, in particular, serving to divide the area into zones of 'take'. The working of deeper and deeper coal; seams, including those beneath the Permian, led to the need to pump mine water.

PSI data were retrieved for two radar datasets; 50 ERS (European Remote sensing Satellite) descending images from track 137 between the dates of 19 April 1995 to the 14 December 2000 were processed to produce 115 555 PS points. 21 descending ENVISAT scenes from the 3 December 2002 to the 7 October 2008 produced 71 899 PS points. Ascending data from ERS and ENVISAT were found to be unsuitable for PSI analysis therefore DifSAR processing was carried out. ERS PSI data cover approximately 50% of the processed area; the ENVISAT data produced fewer points for the same area and therefore has a lower density.

PSI data were checked for geocoding accuracy, residual orbital trends, and the location of the reference points before the data were loaded into the project GIS. PSI data were integrated with all data available to BGS such as geological mapping, borehole data, coal mining records, other mining records, BGS GeoSure ground stability data, topographic maps and aerial photography. Interpretation first took place in a general sense; overall trends in both the ERS and Envisat data were analysed and compared to the geology. No direct relationship was found to the bedrock geology although the geological structure of the area was found to relate to several areas of motion – especially for the ERS data. Relationships were also found between areas of thick superficial deposits and motions in the ERS PSI data, these relationships were less clear in the Envisat data. An overall comparison between ERS and ENVISAT PSI datasets was carried out. In the south of the study area large differences in the average motion rate occur between the ERS and Envisat time frames. When the difference is compared to the geological structure it is found that areas of greatest difference appear to be constrained by the faulting.

Study areas were then chosen to carry out more detailed case studies of the relationship between the motion and the geological data. The Team Valley illustrates the relationship between areas of thick superficial deposits, the compression of these deposits by buildings and de-watering through surface sealing and water abstraction and the occurrence of subsidence. The Houghton-Le-Spring and Ryhope areas illustrate that a complex relationship appears to exist within the time frame of the ERS PSI data. It is possible that remnant mining collapse and ground water level changes are leading to ground motion with the motion accommodated through faults and fissures in the area.

Motions observed in the Envisat PSI data appear to be more regional in both extent and reason; the interpretation of this wide area uplift is unclear but thought to be related to ground water level change.

The PSI and DifSAR datasets represent a vast dataset with a complex motion history, therefore it has only been possible to examine the broad relationships and select a few examples for more detailed analysis.

BGS do not hold all the data necessary to make a full informed interpretation for some of the areas addressed in this report. Therefore a suggested hypothesis of the reasons for the motions is given and suggestions are made as to further lines of investigation. In some areas, the Houghton-le-Spring area for example, more information is available and tentative conclusions are drawn based on this. However it should be noted that the information in this report is tentative and is likely to be supplemented and possibly amended following discussion and collaboration with the Coal Authority.

2 AIM OF THE STUDY

The Coal Authority is interested in investigating techniques for the verification of mining-related subsidence claims. The PSI technique offers a means of measuring terrain motion over wide areas and therefore has possible applications to the verification of mining-related subsidence claims.

This Terrafirma study has been established to investigate ground motions in the Northumberland region of the UK. This is a region with a long history of coal mining.

FugroNPA are the ‘PSI Supplier’, the BGS are the ‘Value Adding Supplier’ and the Coal Authority is the ‘Recipient’. The Coal Authority will be delivered an Advanced Terrain Motion Mapping (ATM) product. This will consist of the PSI data and a geological interpretation carried out by the value adding organisation. This report comprises part of the value adding process and details the work that has been carried out by the BGS in checking the PSI data, integrating it with geological information and interpreting the data.

2.1 Description of the Product

This Terrafirma ATM product involves new InSAR data processing and interpretation specifically tailored to mine applications, obtained by integrating the results of PSI processing, aerial-photos and geological information. The PSI processing for ATM products involves dual-mode (ascending and descending) integrations of SAR data acquired by three ESA missions; ERS-1 (91-96), ERS-2 (95 - present), and ENVISAT (01 - present), giving motion measurements from a possible 1991 to the date of the last archived acquisition (not all available radar data must be used, but rather a data-stack appropriate to the aims of the processing). For details of the radar data used see section 4 of this report.

The value adding activity relates to GIS mapping, geological and structural interpretation of subsidence due to the mining activity.

The ATM product for Northumberland consists of the following:

- PSI data
- DifSAR results
- Value adding geological interpretation report (this document)
- PowerPoint presentation of the results and interpretation
- GIS files resulting from the interpretation, such as polygons outlining areas of motion.
- Excel file of PSI time series plots for many areas of interest.
- PowerPoint files containing the DifSAR time series images
- Difference image of the PSI results obtained from ERS and Envisat
- A meeting with the Recipient to explain the interpretation both as a presentation and live demo of the data.

3 INTRODUCTION TO THE AREA OF INTEREST

3.1 Geological Background

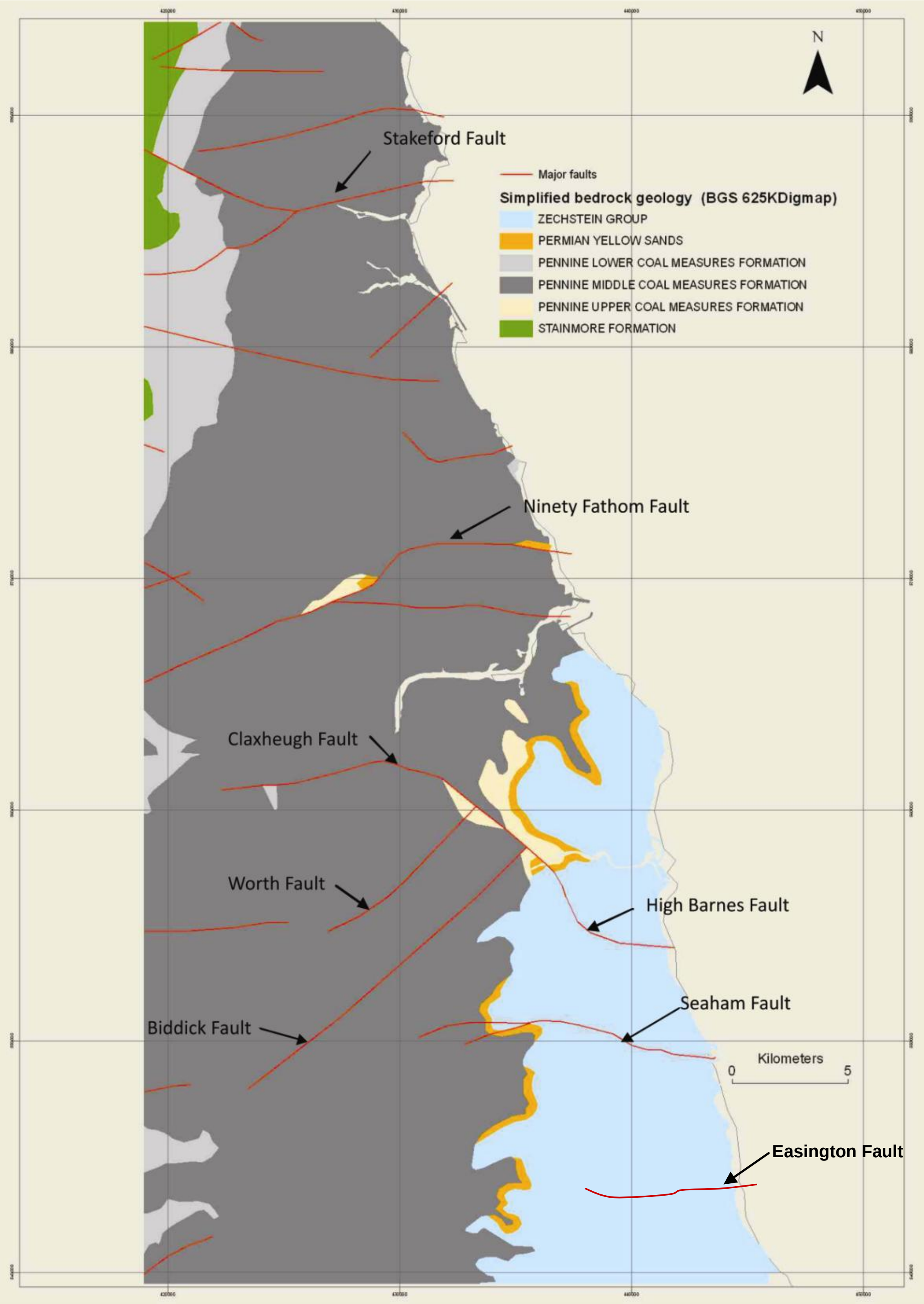


Figure 1: Generalized geological map showing major faults (based on BGS Digmap625 data)

The geological sequence of interest includes bedrock of Carboniferous strata, comprising the Westphalian Coal Measures Group and the Namurian Stainmore Formation overlain by Permian strata comprising the basal Permian Yellow Sands Formation and overlying magnesian limestone formations of the Zechstein Group (Figure 1). The Carboniferous rocks dip gently eastwards and are overlain unconformably by the Permian rocks. The continuity of the outcrops of these units is interrupted by a number of normal faults. The edge of the Zechstein Group outcrop is typically marked by a prominent scarp feature overlooking the lower lying ground of the Coal Measures Group.

Quaternary (drift) deposits mantle almost the entire district and, except in a few places, conceal the bedrock. The outcrop of the Permian rocks, particularly the magnesian limestones of the Zechstein Group, is distinguished by a generally thinner cover of superficial deposits, with areas of the limestone virtually free of such deposits.

3.1.1 Bedrock

Figure 2 illustrates the bedrock geology based on BGS 50k Digmap data. The oldest strata in the district are the Stainmore Formation deposits that are present only in the north-west of the study area. The topmost part of the Stainmore Formation, present in the study area, is typical of the “Millstone Grit” facies comprising coarse-grained sandstones with large-scale cross bedding separated by thin argillaceous sequences that include seatearths and some thin coals.

The Stainmore Formation is overlain by the Pennine Coal Measures Group (formerly called ‘the Coal Measures’) comprising the Lower, Middle and Upper Coal Measures formations. The Lower and Middle Coal Measures are the typical coalfield sequences of mudstones and siltstones in cyclic sequences with seatearths, coals and sandstones. They contain numerous named coals, many of which are locally cut out by erosive sandstone units. Coals may split into two or more seams or die out, but the major named seams are generally laterally persistent throughout the district. With the exception of one or two thick sheet sandstones, the other lithological units are impersistent, many cyclothems being incomplete owing to their deposition in deltaic, lacustrine and semi-terrestrial environments where local rather than regional factors determined lithologies.

The Upper Coal Measures are present only in the much-faulted Boldon Syncline on the western side of Sunderland, where the Coal Measures sequence has a total thickness of 850 m and in isolated occurrences on the northern (downthrown) side of the Ninety-Fathom Fault (Figure 1).

Mudstones are generally silty, slightly micaceous and thinly bedded. Ironstone, in nodules and thin beds, is common. Sandstones are sub-arkosic with dominant quartz and subordinate feldspar. Two different geometric forms can be recognised in the sandstones. Sheet sandstones are generally less than 5 m thick, are fine- to medium grained, thinly bedded with cross bedding and with interbedded siltstone and mudstone at top and base. Channel sandstones may be up to 30 m thick, massively cross-bedded with a meandering ribbon shape in plan, with limited lateral extent. Their thickness is very variable. Their bases are generally erosive and in places they cut down through the underlying coals giving washouts in the seams. The two geometrical forms are not mutually exclusive and many are composite.

Seatearths resemble other Coal Measures mudstones mineralogically, kaolinite and illite being the dominant clay minerals, but they show a complete lack of bedding and usually contain numerous plant roots. They have an irregular fracture along curved, near vertical, polished listric surfaces. Ironstone nodules are common.

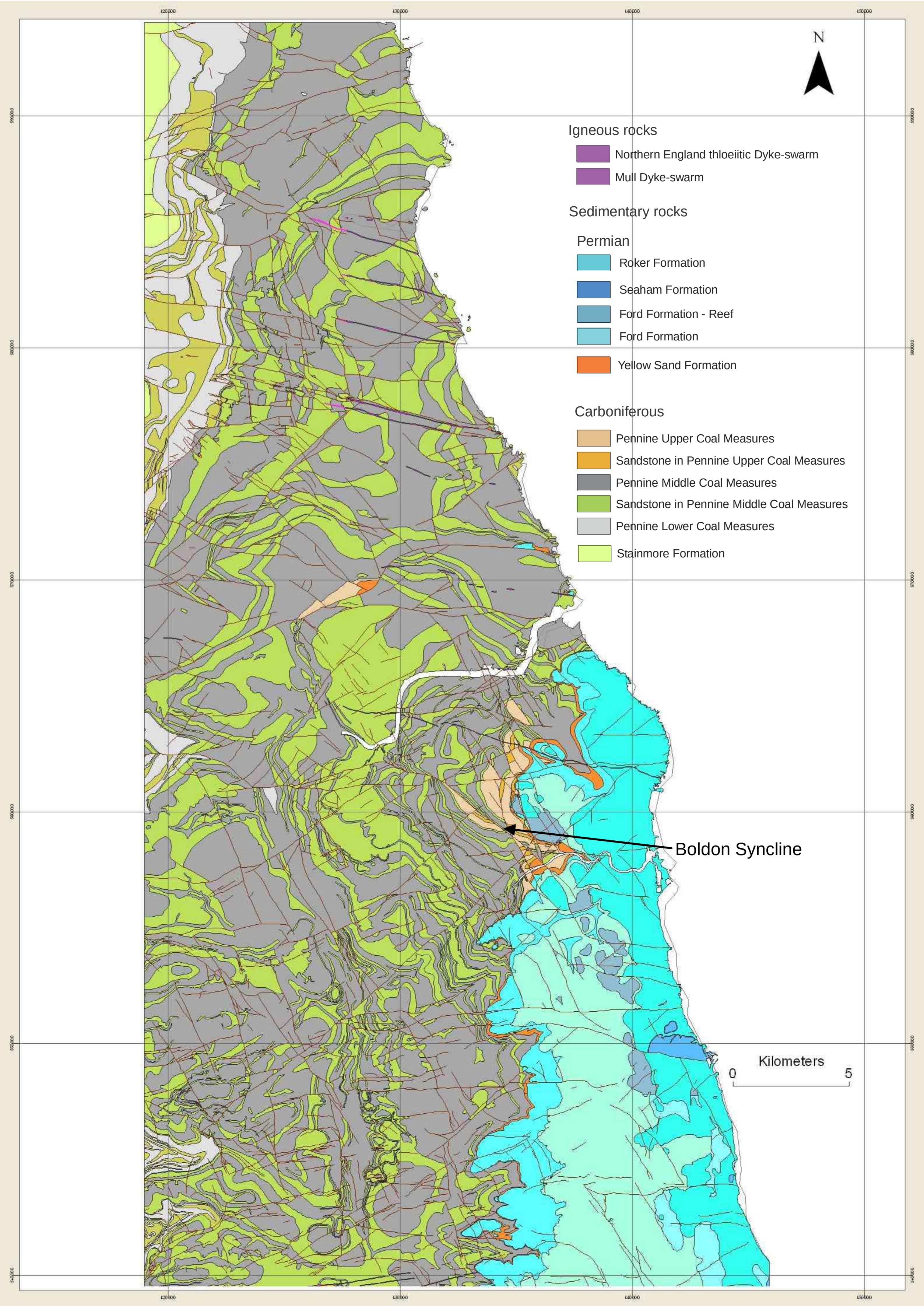


Figure 2: Bedrock geology (based on BGS Digmap50k)

3.1.2 The Permian sequence

The Pennine Coal Measures are unconformably overlain by the Yellow Sands Formation of Permian age comprising weakly cemented, aeolian sandstones, distributed in ridges that represent sand dunes that were subsequently buried beneath the Zechstein Group. The sands are followed unconformably by a thin (less than 2 m) dark grey mudstone called the Marl Slate Formation which laps around them. This is in turn unconformably overlain by the interbedded magnesian limestones and marls of the Permian Zechstein Group (Table 1), further explanation of the sequence stratigraphy of the succession is provided in Tucker, 1991. These magnesian limestones include the Raisby, Ford, Roker and Seaham formations, which comprise dolomitic limestones and dolostones that form the main aquifer bodies in the area, collectively and informally referred to as the Magnesian Limestone or the Magnesian Limestone aquifer. The limestones also include patch and shelf edge reef facies in the Ford Formation. The interbedded marls are commonly anhydritic or gypsiferous with significant sequences of evaporite in the south and south-east.

Table 1: The Classification of the Permian rocks in the area

Geological System	Group	Previous Name	Current Name	Maximum thickness	English Zechstein Cycle
Upper Permian	Zechstein Group	Upper Magnesian Limestone	Seaham Formation	33 m	EZ3
			Roker Formation (including Concretionary Limestone)	200 m (116 m)	EZ2
		Middle Magnesian Limestone	Hartlepool Anhydrite	As a residue	EZ1
			Ford Formation (including the Reef)	116 m	
		Lower Magnesian Limestone	Raisby Formation	76 m	
		Marl Slate	Marl Slate Formation	6 m	
Lower Permian	Rotliegendes Group	Yellow Sands and breccias	Yellow Sands Formation	60 m?	

3.1.3 Igneous intrusions

In addition to faulting and folding, the Carboniferous sequence is also cut by several igneous dykes, which may compartmentalise the hydrogeology of the coal-bearing sequence.

3.1.4 Structure

The Carboniferous rocks exhibit a gentle regional easterly dip rarely exceeding 10°. This comparatively simple structure is interrupted in places by shallow synclinal and anticlinal structures.

The faults that intersect the Carboniferous rocks are mostly east-north-east trending, but there are a number that trend east-south-east. These faults displace the strata by variable amounts. Several major faults have been identified (Figure 1). These include east-north-east – trending Ninety Fathom Dyke. This forms part of the Ninety Fathom - Stublick Fault System that bounds the Northumberland Trough on its southern side, separating it from the structural unit of the Alston Block to the south. This fault throws down to the north at between 200 and 280 m, and locally has a hade of up to 45°. Faults within the Coal Measures mostly exhibit displacements of 25 m or less, but those up to 70 m, are recorded for a few faults. Many faults terminate against cross-faults, whereas others die out gradually as their throw reduces or as they pass into several fractures, commonly with opposing throws.

The Durham Memoir (Smith and Francis, 1967) describes the Durham coalfield north and south of the Easington Fault as occurring in two situations. North of the Easington fault, the average dip of the coal measures exceeds that of the unconformity so that successively higher beds crop against the base of the Permian. South of the fault, the unconformity dips more steeply than the coal measures and this, together with the difference in strike between the Permian and Carboniferous strata, results in a closure of the coalfield towards the east. The memoir also notes that almost all faults of more than about 10 ft (3 m) displacement in the coal measures are reflected in the overlying Permian rocks cropping out along the coast; either as clean, relatively simple breaks having a dip of about 70 degrees, or as nearly vertical shatter belts up to 20 to 30 ft (6-9 m) wide. In both cases the displacement in the Permian strata generally appears to be considerably less than in the underlying coal workings.

In addition to the reactivation of the faulting, Tertiary earth movements caused renewed folding along pre-existing axes in the Carboniferous strata. The Permian strata were deformed into broad folds while the underlying folds in the Carboniferous strata were tightened.

Like most limestone formations, those of the Zechstein Group of County Durham are typically cut by a number of more or less vertical or steeply inclined joints. Young and Culshaw (2001) reported a conjugate pattern of joints, the most prominent directions of which were approximately WSW-ENE and WNW-ESE, in limestones of the Raisby Formation, the lowest limestone unit of the Zechstein Group in the Houghton-le-Spring area. It may be assumed that well-developed jointing is present throughout the limestones of the area. Many of these joints are likely to have developed as a result of tectonic stressing during the earth movements which folded and faulted the Permian rocks. Stress relief during the development of the present topography may have widened some joints, may have created some new joints, and modification of pre-existing joints may have been induced by periglacial processes during late Quaternary times (Young and Culshaw, 2001). Subsidence over underground coal workings has almost certainly caused widening of many joints.

3.1.5 Quaternary deposits

The unconformity which separates the solid and drift deposits in north-east England represents a very long period of geological history during which perhaps as much as 2000 m of Mesozoic strata, and some Upper Carboniferous rocks, were removed by erosion. It is likely that the district experienced several periods of glaciation during the Pleistocene, though the deposits seen today date only from the latest (Late Devensian) glaciation. Any deposits formed during earlier glaciations have either been removed or recycled by subsequent glaciations.

The till (formerly called boulder clay), which covers more than half of the area, is largely an overconsolidated lodgement till, thought to be the product of a single late-Devensian glacial episode (Figure 3). It is in excess of 60 m thick in places. Where unweathered, the till is typically a stiff, grey to greyish brown, silty, sandy or stony clay. Thin sand lenses and partings of sand, gravel, silt and clay are common throughout. Included cobbles and boulders consist chiefly of Carboniferous rocks, mainly sandstone with subordinate amounts of limestone, siltstone, mudstone, ironstone and coal. Areas of glaciofluvial sand and gravel are present in the west and south of the area. Glacial lake deposits are present and consist of silt and clay, usually laminated, stone-free and with inter-calated very fine-grained sand lenses and partings. The surface deposit called the Pelaw Clay is mapped, generally 1 to 2 m thick, locally up to 5 m. It overlies other glacial deposits, notably a considerable thickness of laminated clay in places and may be a product of weathering.

Postglacial and recent deposits accumulated during the warmer, wetter climate of the last 10 000 years. During this time the modern drainage pattern has developed. River terrace sands and gravels and alluvium occur as narrow, discontinuous tracts flanking rivers and small streams throughout the district. The alluvial deposits do not usually exceed 3 m in thickness and consist generally of laterally variable clay, silt and fine sand. Lacustrine deposits infill small flats and hollows. This lacustrine alluvium may reach in excess of 8 m in thickness and comprise sand with pebbly, silty and clayey partings. Peat occurs in places filling small hollows or the sites of former lakes. Made ground, worked ground and infilled ground overlie the natural deposits. Worked out opencast (surface-mined) coal sites are numerous. These have generally been backfilled and reinstated using waste rock previously excavated as overburden from the workings. In some places spoil from deep coal mine spoil heaps has been employed as backfill; other areas of deep mine coal spoil have been landscaped. Several old quarries have been filled with industrial and domestic waste.

Borehole evidence suggests that the rockhead surface has an appreciably greater relief than the till plain that forms the present-day surface. Pre-existing, possibly pre-glacial, valleys coincident with or marginally offset from, the present-day valleys of the major rivers are largely infilled with glacial deposits (Figure 4).

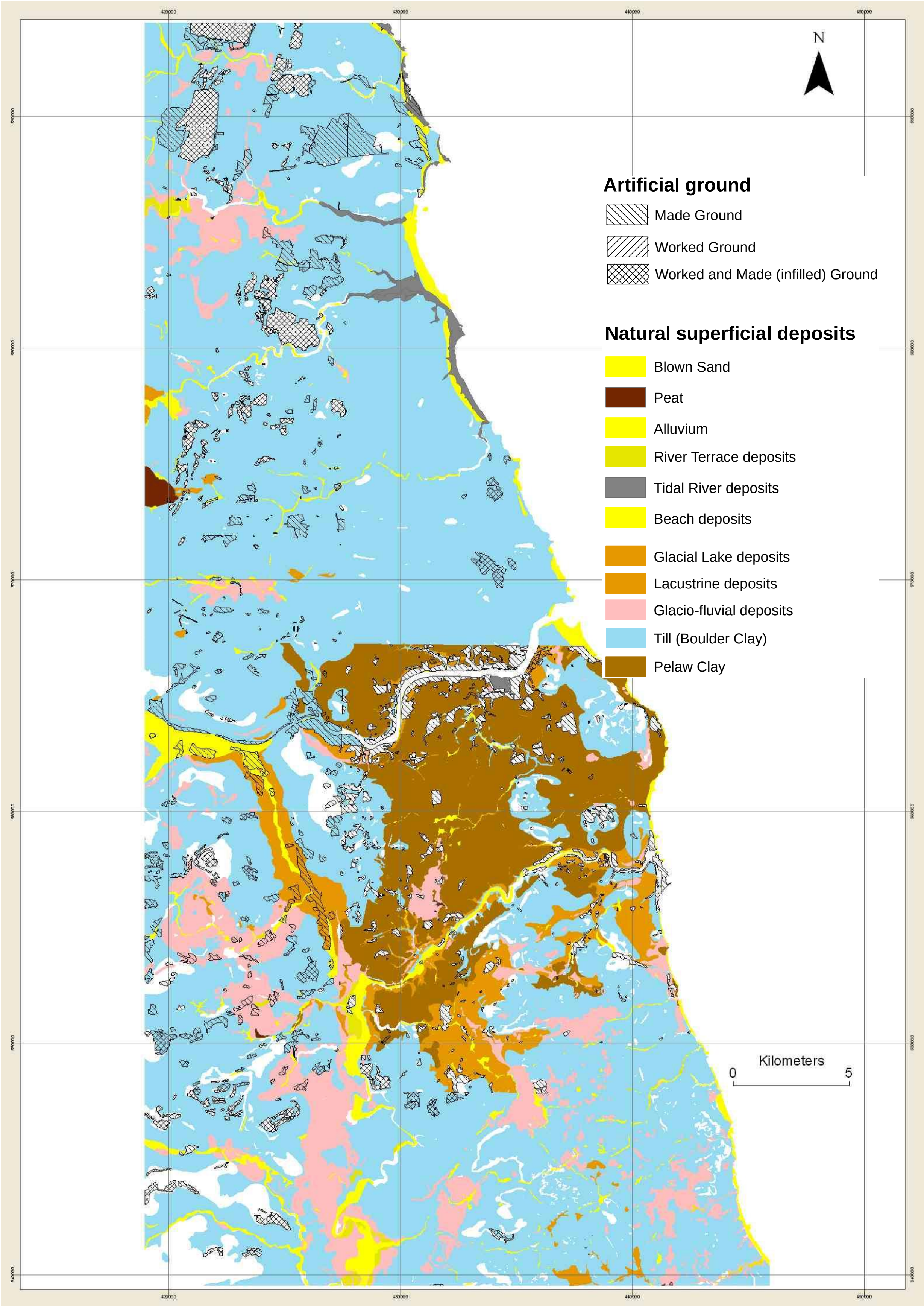


Figure 3: Superficial deposits (based on BGS Digmap50k)

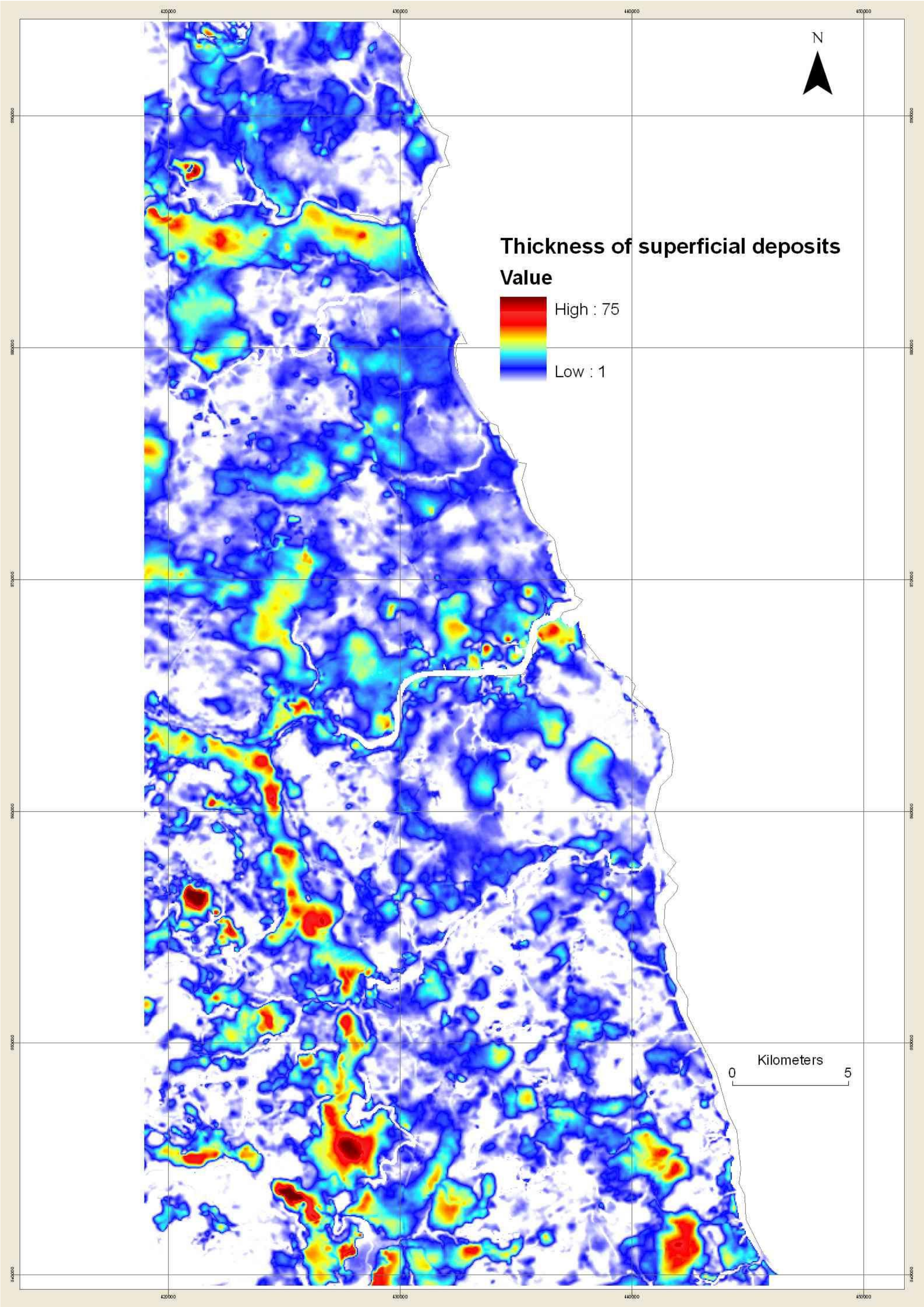


Figure 4: Thickness of superficial deposits (derived from BGS Advanced Superficial Thickness Model – ASTM)

The BGS Geosure ground stability dataset provides general information to identify each of six natural geohazards in great Britain, viz. compressible ground, shrink swell, collapsible deposits, landslides (slope instability), soluble rocks (dissolution) and running sand (Booth et. al, 2010).

Only the first two of these are identified as being of potential relevance to this study area. Although the Permian deposits contain limestone and other soluble material, field investigation has shown that limestone dissolution does not appear to have a significant role in the formation of collapse features.

3.1.5.1 Compressible deposits

Some types of ground may contain layers of very soft materials like peat or some clays. These may compress if loaded by overlying structures, or if the groundwater level changes. This compression may result in depression of the ground surface, potentially disturbing foundations and services.

3.1.5.2 Shrink Swell

Swelling clays can change volume due to variation in moisture; this can cause ground movement, particularly in the upper two metres of the ground that may affect many foundations. Ground moisture variations may be related to a number of factors, including weather variations, vegetation effects (particularly growth or removal of trees) and the activities of people. Such changes can affect building foundations, pipes or services.

It could be anticipated that areas containing such deposits, either at the surface or within a sequence of thick superficial deposits, might show ground movement related to change in loading or variation in water content over time (section 5.4.1).

3.1.6 The Northumberland and Durham Coalfield

The coal-bearing strata dip gently to the east, part of the coalfield being concealed beneath the Permian strata to the south of the River Tyne; the coalfield extends beneath the sea. The coalfield has a working history dating back to Roman times. Over twenty coal seams have been mined underground and the coalfield has been one of the major sources of opencast (surface-mined) coal in Britain. The geological structure of the area determined the development of the coalfield with faults, in particular, serving to divide the area into zones of ‘take’. The working of deeper and deeper coal; seams, including those beneath the Permian, led to the need to pump mine water.

Systematic pumping of mine water ended with the abandonment of underground mining. However, as part of a strategy to control and monitor mine water within the now abandoned coalfield, the Coal Authority continued to pump minewater from a number of sites within the coalfield. Recent years have seen a progressive reduction in the number of pumping sites and groundwater levels within some eastern parts of the coalfield have recovered to levels close to the base of the Permian rocks. It is known that in order to eliminate potential contamination of the important aquifers within these rocks, pumping of groundwater from a new facility at the former Horden Colliery, approximately 8 km south of the study area, began in July 2004 (Personal communication, Environment Agency).

3.1.7 Field observation of ground movement and collapse features on the Permian plateau.

Young and Culshaw (2001) described and figured widespread evidence of fissuring in the Magnesian Limestone (Zechstein Group) and underlying Coal Measures rocks of the Houghton-le-Spring area, City of Sunderland. Evidence of structural damage, related to this fissuring, was also described. Whereas local movement along some fissures was noted during the course of this investigation, the dateing of the initiation of surface features, or of movements associated with them, was possible in only a few localised instances. In their discussion of the possible mechanisms of fissuring, Young and Culshaw (2001) concluded that fissure formation and resultant surface collapse was still active and may be related to renewed subsidence or reactivated movement associated with the Houghton Cut Fault. The collapse features recorded exhibit considerable similarities to surface fissuring reported from nearby locations elsewhere on the Zechstein Group outcrop, notably in the Coxhoe, Houghton-le-Spring and Sunderland areas (Goulty and Kragh, 1989; Wigham, 2000; Young and Culshaw, 2001; Cuss and Beamish, 2002; Young and Lawrence, 2002; Young, 2003). These authors have demonstrated a close spatial relationship between surface disturbance and individual faults or areas of faulted ground within the underlying Permian rocks. Most of the disturbance reported from these areas appears to lie in the hangingwall, or downthrow side, of the associated faults. Collapse features at Seaham were also concentrated within comparatively narrow belts within the hangingwall zones of known faults.

Fissuring at Houghton-le-Spring was particularly noticeable in areas free of superficial deposits, or where such cover was comparatively thin. However, more recent work in the Sunderland area suggests that such fissuring may propagate to the surface through substantial thicknesses of superficial cover, perhaps in excess of 10 m.

In their detailed review of the likely causative mechanisms of fissuring in the Houghton-le-Spring area, Young and Culshaw (2001) demonstrated that:

- Surface collapse is still active and is associated with damage to land and structures.
- Many examples of surface collapse are closely related to instability in the underlying Magnesian Limestone.
- Instability in the Magnesian Limestone may be due to the widening of joints, particularly within the hangingwall zone of faults.
- Surface collapses are most commonly seen in areas with a comparatively thin cover of superficial deposits.
- Collapse features are commonly concentrated in belts up to 300 m wide along known zones of faulting.

They concluded that processes such as landslipping, cambering and dissolution of limestone do not offer realistic explanations of the observed phenomena. They proposed that renewed or continuing subsidence of coal mine workings, or reactivation of known faults, may be major factors in the formation of surface fissures and that rising minewater levels within abandoned coal workings may be a causative factor in this renewed subsidence or fault reactivation.

4 THE PS DATA USED IN THE STUDY

4.1 Data received:

Four datasets were delivered by FugroNPA:

1. ERS descending PSI data (1995 – 2000)
2. ENVISAT descending PSI data (2002 – 2008)
3. ERS Ascending DifSAR data (1992 – 2000)
4. ENVISAT Ascending DifSAR data (2002 – 2009)

ERS descending PSI data

A PSI point dataset was derived by analysis of 50 ERS scenes from the 19 April 1995 to the 14 December 2000 (Table 2). 115 555 PS points were identified, an overall average annual motion rate of +0.407 mm/yr was found. Two dbf files were received; one containing the average annual velocities and one containing the time series data. The derived average annual velocity can be seen in Figure 5.

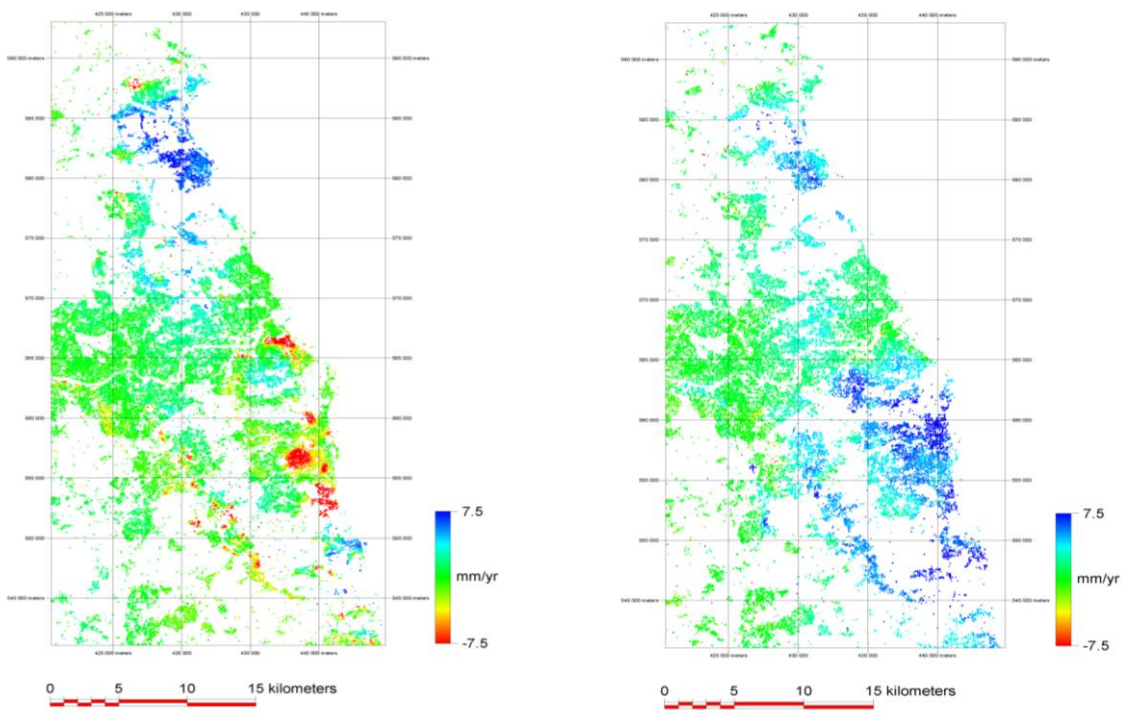


Figure 5: PSI Average annual velocities for ERS 1995 to 2000 (left) and ENVISAT 2002-2008 (right)

ENVISAT descending PSI data

A PSI point dataset was derived by analysis of 21 ENVISAT scenes from the 3 December 2002 to the 7 October 2008 (Table 3). 71 899 PS points were identified; an overall average annual motion rate of +2.47 was found. Two dbf files were received; one containing the average annual velocities and one containing the time series data. The derived average annual velocity can be seen in Figure 5.

ERS Ascending DifSAR data

PSI analysis was not possible with the ascending data therefore DifSAR analysis was carried out on all image pairs with a baseline of less than 250 m. Between the 8 July 1992 and the 10 June 2000 55 DifSAR interferogrames were produced from the ERS ascending data.

ENVISAT Ascending DifSAR data

PSI analysis was not possible with the ascending data therefore DifSAR analysis was carried out on all image pairs with a baseline of less than 250 m. Between the 7 December 2002 and the 5 December 2009 28 DifSAR interferogrames were produced from the ENVISAT ascending data.

Table 2: ERS descending images used for PSI analysis (1995 – 2000)

Interferograms used for analysis			
Master Date	**Slave Date**	**Bperp (m)**	**Temporal Separation (days)**
19 April 1995	19 April 1995	0	0
19 April 1995	24 May 1995	-42.211	35
19 April 1995	25 May 1995	-121.125	36
19 April 1995	02 August 1995	484.26	105
19 April 1995	03 August 1995	443.204	106
19 April 1995	07 September 1995	-887.042	141
19 April 1995	11 October 1995	686.026	175
19 April 1995	12 October 1995	1017.475	176
19 April 1995	21 December 1995	389.916	246
19 April 1995	29 February 1996	846.422	316
19 April 1995	03 April 1996	-75.392	350
19 April 1995	04 April 1996	-137.391	351
19 April 1995	09 May 1996	645.932	386
19 April 1995	22 August 1996	-558.009	491
19 April 1995	31 October 1996	1166.9	561
19 April 1995	05 December 1996	-549.325	596
19 April 1995	09 January 1997	72.921	631
19 April 1995	13 February 1997	-289.767	666
19 April 1995	20 March 1997	91.252	701
19 April 1995	24 April 1997	-332.646	736
19 April 1995	29 May 1997	-87.85	771
19 April 1995	03 July 1997	-98.641	806
19 April 1995	07 August 1997	256.627	841
19 April 1995	11 September 1997	567.875	876
19 April 1995	16 October 1997	244.816	911
19 April 1995	20 November 1997	602.13	946
19 April 1995	25 December 1997	53.053	981
19 April 1995	29 January 1998	135.327	1016

19 April 1995	05 March 1998	-427.22	1051
19 April 1995	09 April 1998	-123.579	1086
19 April 1995	14 May 1998	832.865	1121
19 April 1995	18 June 1998	955.891	1156
19 April 1995	23 July 1998	-314.454	1191
19 April 1995	27 August 1998	215.946	1226
19 April 1995	01 October 1998	798.765	1261
19 April 1995	05 November 1998	1099.354	1296
19 April 1995	10 December 1998	-757.647	1331
19 April 1995	18 February 1999	1273.17	1401
19 April 1995	25 March 1999	-248.675	1436
19 April 1995	12 August 1999	1226.741	1576
19 April 1995	16 September 1999	-191.733	1611
19 April 1995	21 October 1999	-104.289	1646
19 April 1995	25 November 1999	336.077	1681
19 April 1995	30 December 1999	449.705	1716
19 April 1995	03 February 2000	-461.272	1751
19 April 1995	09 March 2000	148.993	1786
19 April 1995	13 April 2000	529.17	1821
19 April 1995	18 May 2000	738.926	1856
19 April 1995	09 November 2000	620.002	2031
19 April 1995	14 December 2000	276.974	2066
Number of PS identified		115555	
PS density (PS/km2)		~128	
Point motion statistics (mm/year classes)		**% of points in each mm/year class**	
-max to -3.5		6.73	
-3.5 to -1.5		8.70	
-1.5 to +1.5		56.19	
+1.5 to +3.5		18.93	
+3.5 to +max		9.45	
Average annual motion rate of the entire processed area		0.407	
Standard deviation of average annual motion rate		3.070	

Table 3: ENVISAT descending images used for PSI analysis (2002 – 2008)

Interferograms used for analysis			
Master Date	**Slave Date**	**Bperp (m)**	**Temporal Separation (days)**
20 June 2006	03 December 2002	306.2603	-1295
20 June 2006	11 February 2003	-309.227	-1225
20 June 2006	14 October 2003	634.6362	-980
20 June 2006	18 November 2003	-1044.12	-945
20 June 2006	23 December 2003	-13.3503	-910
20 June 2006	06 April 2004	763.4986	-805
20 June 2006	11 May 2004	-644.176	-770
20 June 2006	20 July 2004	104.1008	-700
20 June 2006	24 August 2004	-6.6103	-665

20 June 2006	02 November 2004	32.093	-595
20 June 2006	11 January 2005	-845.863	-525
20 June 2006	09 August 2005	-164.587	-315
20 June 2006	13 September 2005	-352.551	-280
20 June 2006	22 November 2005	243.2619	-210
20 June 2006	27 December 2005	271.6952	-175
20 June 2006	07 March 2006	85.493	-105
20 June 2006	20 June 2006	0	0
20 June 2006	03 October 2006	-869.226	105
20 June 2006	16 January 2007	580.8819	210
20 June 2006	20 February 2007	-33.1091	245
20 June 2006	07 October 2008	-168.143	840
Number of PS identified		71899	
PS density (PS/km2)		~80	
Point motion statistics (mm/year classes)		**% of points in each mm/year class**	
-max to -3.5		0.24	
-3.5 to -1.5		0.89	
-1.5 to +1.5		40.23	
+1.5 to +3.5		28.58	
+3.5 to +max		30.05	
Average annual motion rate of the entire processed area		2.47	
Standard deviation of average annual motion rate		2.31	

Table 2 and Table 3 show that within both the ERS and ENVISAT PSI datasets the majority of points are within the -1.5 mm/yr to +1.5 mm/yr 'stable' class. If this class is ignored then a general bias towards uplift is seen in both datasets, however the proportion of uplifting points is far greater in the more recent ENVISAT data (~60% Vs ~30% for ERS). The ENVISAT PSI dataset shows very little subsidence; with just over 1% of the points subsiding by more than 1.5 mm/yr. ERS has a greater proportion of PS points exhibiting subsidence at ~15%. These observations are supported by the overall average annual motion rate for the whole area which for ERS is +0.4mm/yr and for ENVISAT is +2.3 mm/yr.

From the 1995-2000 data there is therefore a pronounced shift to an overall regime of uplift as shown by the 2002-2008 data, areas which were shown to be subsiding by the 1995-2000 data are seen to be uplifting in the 2002-2008 ENVISAT data.

It should be noted that the ERS dataset is based on more input images (50 Vs 21 for ENVISAT); in theory this should make the ERS data statistically more accurate.

All data were delivered with a British National Grid projection.

4.2 Validation of PSI results

Upon receipt of the PSI data there was concern that an error had occurred in the processing, this was due to the dramatic difference in motion patterns between the ERS (1995 to 2000) and ENVISAT (2002 to 2009) datasets.

BGS were happy with the ERS data since this was comparable to ERS data we had received in a previous (non-Terrafirma) study carried out 10 years ago. In this study the area was processed by FugroNPA, but using a different PSI software chain. There are a few subtle differences in the average annual velocity but the period processed in the earlier study was longer.

Further reassurance was found by comparison to PSI and SBAS processing carried out by a PhD student working with BGS and the University of Nottingham. The students' work used both the Gamma PSI processing chain and an SBAS Processing technique to produce InSAR data for a subset of the Newcastle area for both ERS and ENVISAT data. The results of the student's processing from both softwares were comparable to this Terrafirma result.

Although the availability of both ERS and Envisat ascending data was insufficient to produce PSI datasets it was possible to produce many DifSAR images. These were used as a further source of validation of the PSI datasets. There is good agreement between the descending PSI results and ascending DifSAR results.

We are therefore happy that the motion revealed from the ERS and ENVISAT processing is the true PSI derived motion for the areas processed.

4.3 Choice of the reference point

The reference points for ERS and ENVISAT processing were chosen by FugroNPA, a dbf file of their location was supplied to BGS. The reference points were plotted in the project GIS and their location checked with respect to the BGS GeoSure and other geological datasets. The location of both reference points shows a low potential for all hazards identified in the GeoSure datasets.

4.4 Geo-referencing check

The georeferencing accuracy of the PSI datasets can be difficult to quantify, especially with PS datasets resulting from ENVISAT and ERS processing due to their lower spatial resolution compared to the newer high resolution radar satellites. It is often difficult to identify exactly what object is acting as the scatterer, if the scattering object is identified it is then difficult to determine which part of the object is scattering. The PSI processing report received from FugroNPA states a +/-10 m XY accuracy. We have assessed this and found it to be a fair assessment of the positional accuracy.

The approach taken to assess the geo-referencing is to identify prominent and isolated objects and study the PS point distribution about these objects. Objects were selected from the north, south, east, west and the centre of the areas processed. Examples of the georeferencing accuracy are given in Figure 6 and Figure 7.

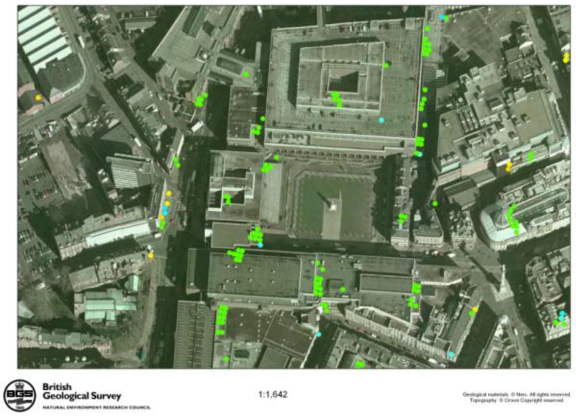
<table>
<tr><td>North; Lynemouth Power Station</td><td>South; Durham University</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>East; Tynemouth pier</td><td>West; A1 and hotel</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>Central: Newcastle city centre</td><td></td></tr>
<tr><td>
</td><td></td></tr>
</table>

Figure 6: Examples of the georeferencing accuracy of the ERS PSI dataset. If accurately referenced the PS points will be coincident with strong radar reflectors such as built structures.

North; Lynemouth Power Station	South; Durham University
	
East; Tynemouth pier	West; A1 and hotel
	
Central: Newcastle city centre	
	

Figure 7: Examples of the georeferencing accuracy of the ENVISAT PSI dataset. If accurately referenced the PS points will be coincident with strong radar reflectors such as built structures.

Any offsets between the location of a PS point and the structure it is thought to represent are within 10 meters, for example the ENVISAT points along the liner structure at Lynemouth Power Station (Figure 7) are offset to the northwest, and the offset is approximately 7 metres.

4.5 Residual Orbital Trends in the PSI data

Residual orbital trends or “tilts” can be a feature of PSI processing that arises from uncompensated orbital inaccuracies used within the PSI processing chain. They appear as a general tilt from uplift to subsidence across the image of average annual velocities.

Inspection of the average annual velocities for both ERS and ENVISAT shows that trends are not present in either the ERS or ENVISAT data.

5 VALUE ADDED PRODUCT RESULTS

5.1 Comparison & integration methodology

The Persistent Scatterer (PS) point data held in the average_annual_displacement_rates.dbf files were loaded in to a Geographical Information System (GIS). This allows the location of a PS point to be accurately studied. The GIS environment enables PS points to be visualised in relation to other spatially referenced data which can provide information on the cause of the motion. Given the large number of PS points and their high spatial density, the PS points are commonly colour-coded for visualisation purposes (section 5.1.1.1). It is essential to ensure that all the files are in the same projection so that they can be properly aligned in a GIS environment; in this case the British National Grid was used.

5.1.1 Loading and displaying the data:

Firstly the ENVISAT average annual motion dbf file (ENV_D_PSI_BNG_average_annual_motion.dbf) was loaded into ArcMap using the 'Tools/Add XY data' facility. Upon loading it was necessary to specify the Easting column of the dbf table as the X Field and the Northing column as the Y field. The coordinate system was specified as British National Grid, the same projection system as the PSI datasets were delivered in. The points were drawn in ArcMap in the correct geographical location, but all points displayed as the same symbol and same colour.

The dbf file was then exported from ArcMap as a shapefile. The original dbf file was removed and the shapefile created was the file used for further analysis.

5.1.1.1 Symbology and colour ramps

The average annual motion of all PS points as revealed by ENVISAT is +2.47 mm/yr. This overall uplift signal makes it important to display the data correctly.

Commonly a linear colour ramp (Figure 8) is applied to PSI data, when doing this it is common to exclude the extreme positive and negative values. The common colour ramp applied ranges from red for areas experiencing negative motion, passes through oranges and yellows and into green and then through light blue with dark blue representing positive motions. If the overall average motion for the processed area is close to zero then green colours represent stable areas.

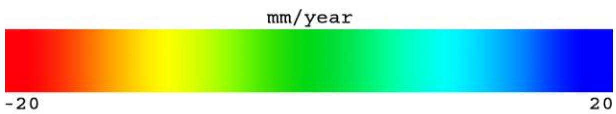


Figure 8: An example of the colour ramp commonly applied to PSI average velocities

If a colour ramp such as previously mentioned is directly applied to a PSI Dataset which has a positive bias in its average annual velocities, the colour ramp will be biased in favour of the positive values. This would result in the greens, normally associated with stable areas, actually representing areas of uplift. Since much of the interpretation of these datasets relies on the recognition of areas of colour it is important to ensure that the colours are applied to the data in such a manner as to avoid these biases.

The following guidance for applying the colour ramp to the PSI data was followed:

1. Right-click the town name>_average_annual_displacement_rates layer in table of contents in ArcMap and click “Properties”. The “Layer Properties” window is displayed (Figure 9)
2. Click the “Symbology” tab.
3. Click “Quantities” and “Graduated colours”.
4. Select the red to blue colour ramp.
5. Use the “VEL” field as the “Value” for the colour ramp.
6. Click the “Symbol” column heading and click “Properties for all Symbols” from the pop-up menu. This step is used to remove the black outline from each point. If this is not done then the black outline to each point obscures the colours where points overlay.
7. Click the “Classify” button to alter the class boundaries. It is sometimes necessary to alter the class boundaries so that the colour ramp can be distributed around the “stable” values and ensure that green colours are applied to stable points.
8. The manual method of classification allows the user to click and drag the class boundaries (blue lines on the distribution graph; Figure 10). It was decided to apply a green colour, representing stable ground, to all average annual velocities between -1 and +1 mm/yr. The other class boundaries were then defined in an interactive manner; the aim was to make the variations in the data as clear as possible
9. The display style defined above was saved as a layer file.
10. This layer file was then applied to the other PSI data including the time series data and the ERS Descending data. This ensures that all datasets are displayed in the same way.

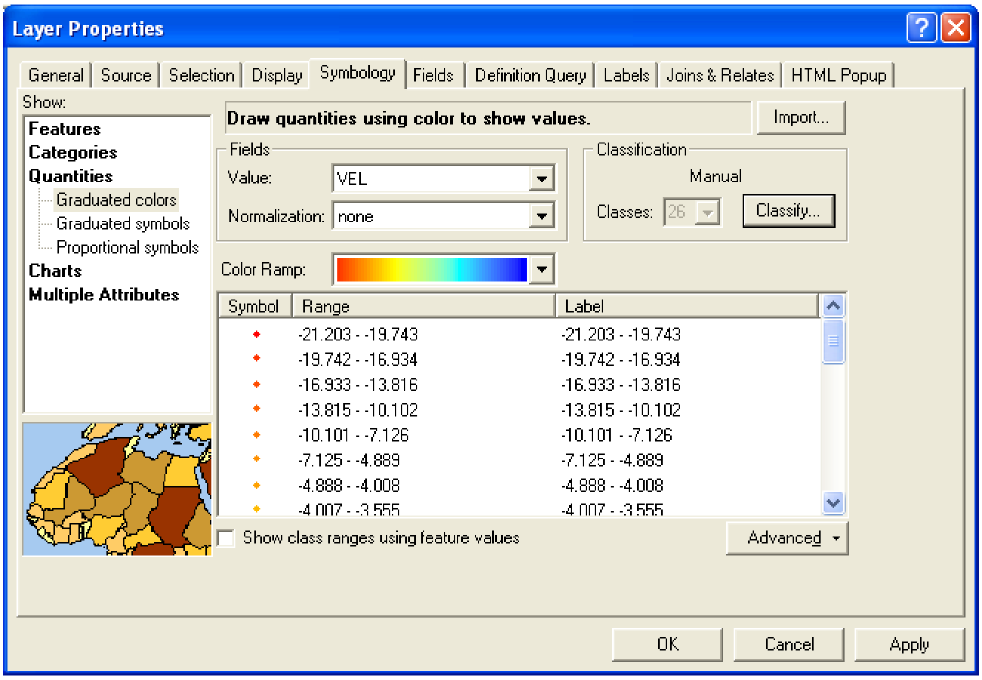


Figure 9: PSI point display properties in ArcGIS

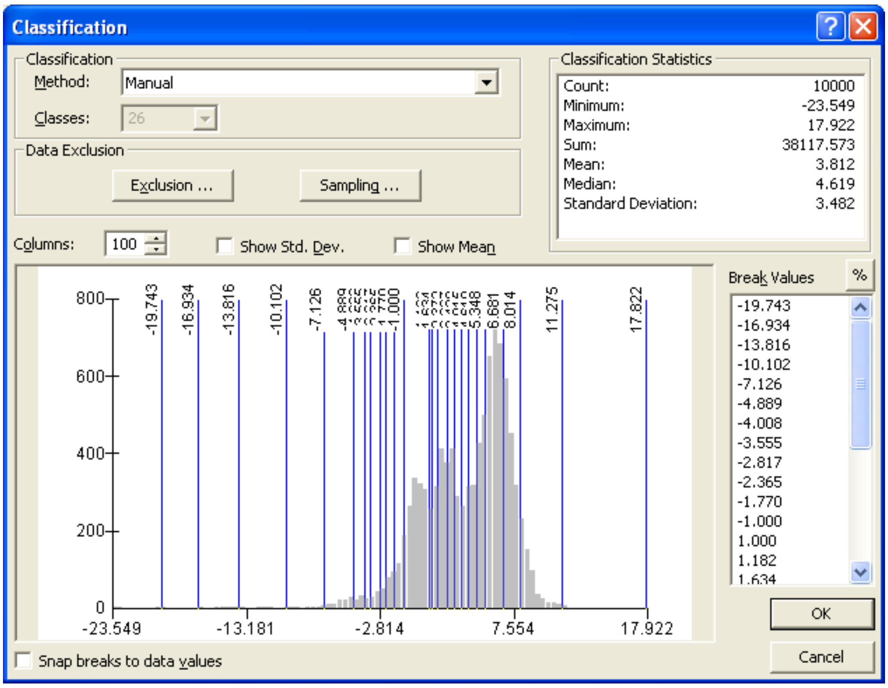


Figure 10: Interactive assignment of the colour ramp to the PSI point data.

5.1.2 Ancillary Datasets

The following datasets were integrated with the PSI data in the GIS.

- **Topographic Maps** - Relevant Ordance Survey topographic maps of the Northumberland area used for interpretation were colour 2D raster layers at 1:10 000, 1:50 000, 1:250 000 and 1:1 000 000 scales.
- **Geological Maps** - Solid, superficial, artificial geology and structural geology vector 2D layers were visualised at scales of 1:10 000 and 1:50 000.
- **Thickness of superficial deposits –** A grid dataset of the thickness of superficial deposits has been produced, by the BGS, from rockhead elevation and borehole data.
- **Borehole Data** - Borehole data held at the BGS has been extracted from our Single Onshore Borehole Index (SOBI) and is visualised as a 1:10 000 scale vector 2D layer. Information is provided on the length of the boreholes and these are categorised into 0-10m, 10-30m, >30m and includes locations of borehole with unknown length.
- **Coal Mining** - Information was obtained from a 1:50 000 scale vector 2D layer detailing the spatial extent of open cast coal mining activities and from the BGS ‘Coal Map’ 2D vector dataset showing areas of underground mining. The coal map data set also shows sites of active mining.
- **Mining hazards, not including coal data** – a dataset of all mining and quarrying in the UK, this does not include data relating to coal extraction.
- **Karst Geohazard dataset –** A BGS digital vector dataset of hazards relating to karst. This includes building damage, cavities, dolines, springs, and stream skink points
- **Hydrogeological Property Maps** - Permeability of bedrock geology, superficial geology, artificial ground and mass movement are visualised as 1:50 000 scale vector 2D layers. The layers were colour coded based on the maximum permeability of the units.
- **Remote Sensing Imagery** – Aerial photography from UK perspectives. NEXTMap Britain 5 m resolution Digital Surface Model (DSM).

- **GeoSure National Ground Stability Data -** A series of 1:50 000 scale vector 2D layers have been generated by the BGS that identify and assess the potential geohazards threatening the UK landscape. The GeoSure layers generated by geologists, geotechnical experts and information developers at the BGS provide an indication of the hazard, rated through an A-E classification of increasing hazard, from collapsible ground, compressible soils, running conditions, shrink-swell clays, dissolution and slope instability. They comprise:
    - Collapsible Ground: rocks or soils that are prone to collapse when they are loaded or become saturated
    - Compressible Soils: characterised by ground that contains layers of very soft materials like peat or clay that can become compressed if loaded or if the groundwater levels change
    - Running Sand: loosely packed sandy layers in the rock with a potential to become fluidised by water flowing through them
    - Shrink-Swell: clays that change volume in response to variations in moisture, such as caused by weather variations, vegetation growth or removal and anthropogenic activity
    - Dissolution: more soluble rocks such as salt, gypsum, chalk and limestone are prone to dissolution to produce an irregular bedrock surface and subsurface voids that may collapse or subside
    - Slope Instability: occurs when particular slope characteristics, such as geology, gradient, source of water, drainage and anthropogenic activity, combine to produce an unstable slope and cause downslope movement of materials
- **Geophysical Aeromagnetic Data**: This information is held by the BGS as a 1:250 000 scale raster 2D layer. Areas of magnetism are coloured from red to blue in decreasing amounts of magnetism.
- **The BGS National Landslide Database**. A database of all reported landslides in the UK. The majority of these have been verified by BGS staff members others have been reported by the public and are in need of verification.

5.2 Overall relationships of PSI average motion to geological data

A first pass was made in determining whether the general pattern of average movement over time could be related to properties of the superficial and bedrock geology as defined by the overall geological structure. Uncertainties when predicting the extent of zones with no InSAR data makes it difficult to define overall zones of movement within the area. A rectangular area enclosing the point data can be seen in : – point coverage accounts for approximately 50% of the onshore area – emphasising the difficulty and limitations of generalising links with geology by extrapolating from the known points. There is a need to avoid creating imaginary links with the geology, particularly because is it easy to be visually misled. In order visualise the data, the scenes (1995-2000 ERS Descending PSI results and 2002-2008 Envisat Descending PSI results) were divided into classes according to average annual motion: Up > 5; Up 2 to 5; Up 2 to down 2; Down 2 to 5; Down greater than 5; Area with no recorded points.

s

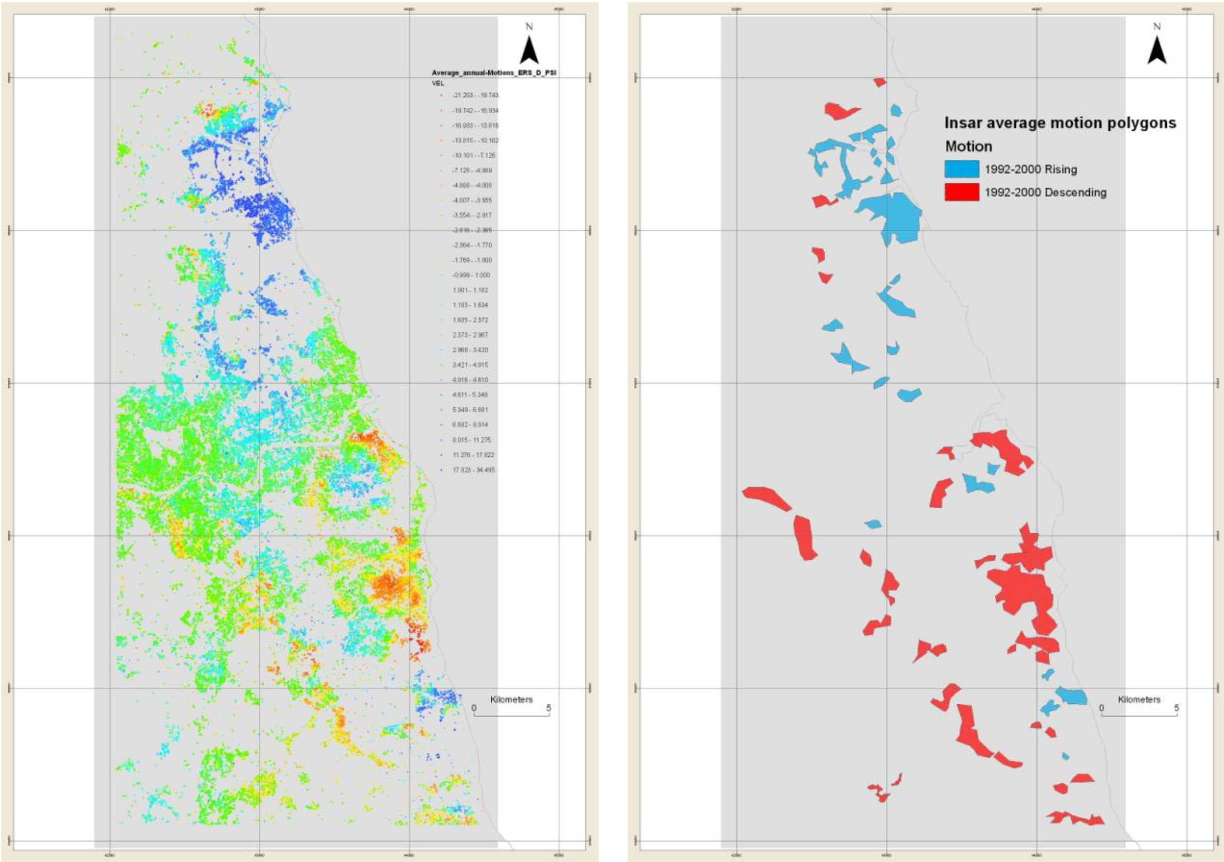


Figure 11: Derived general motion polygons for ERS data

These were produced by attribute selection from arc. Sets were then produced by giving points 100 m buffer and dissolving. After viewing these areas, polygons were digitised in order to demarcate regions for overlay against geological considerations in the following categories: 1995-2000 Descending, 1995-2000 Ascending; 2002-2008; Descending, 2002-2008; Rising >2; 2002-2008 Rising >5 (: and Figure 12).

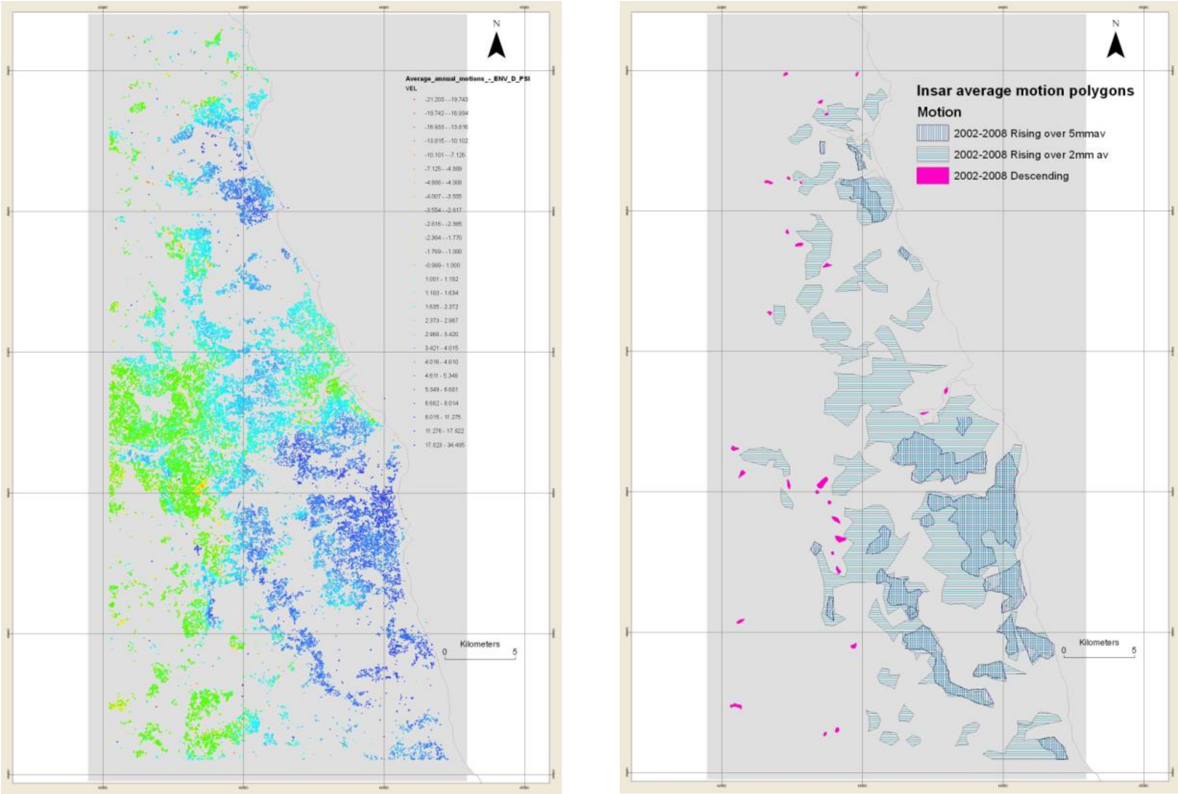


Figure 12: Derived general motion polygons for ENVISAT data

5.2.1 Overall relationship between average annual motion and Bedrock Geology

There is no obvious relationship between the bedrock geology and the ERS or Envisat PSI data, i.e., there is no evidence to suggest that certain geological units are responsible for areas of uplift or subsidence.

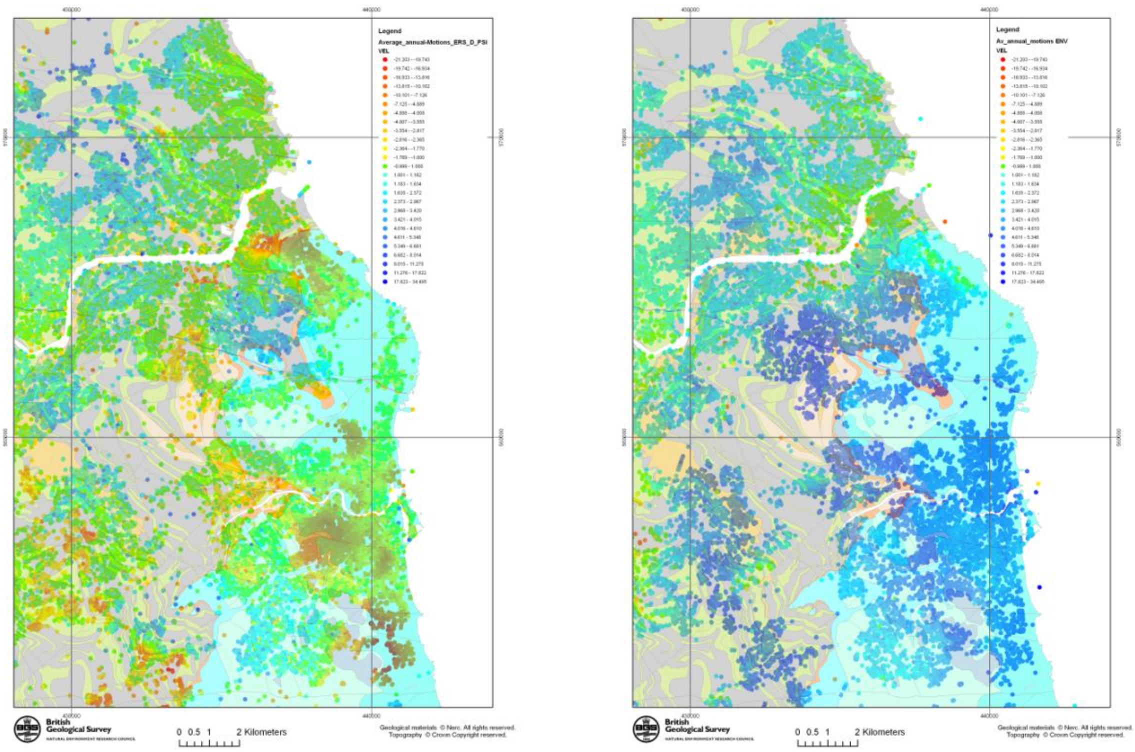


Figure 13: Bedrock geology and ERS (left) and Envisat (right) average annual motions for the Newcastle and Sunderland areas. Key for geology as for Figure 2.

5.2.2 Relationship between PSI motion and geological structure.

A comparison of average movement with bedrock structure shows that it is possible that patterns of movement can be associated with areas defined by major geological faults (Figure 14). The relationship between the motion and faults is discussed in more detail with in the case study sections of the report.

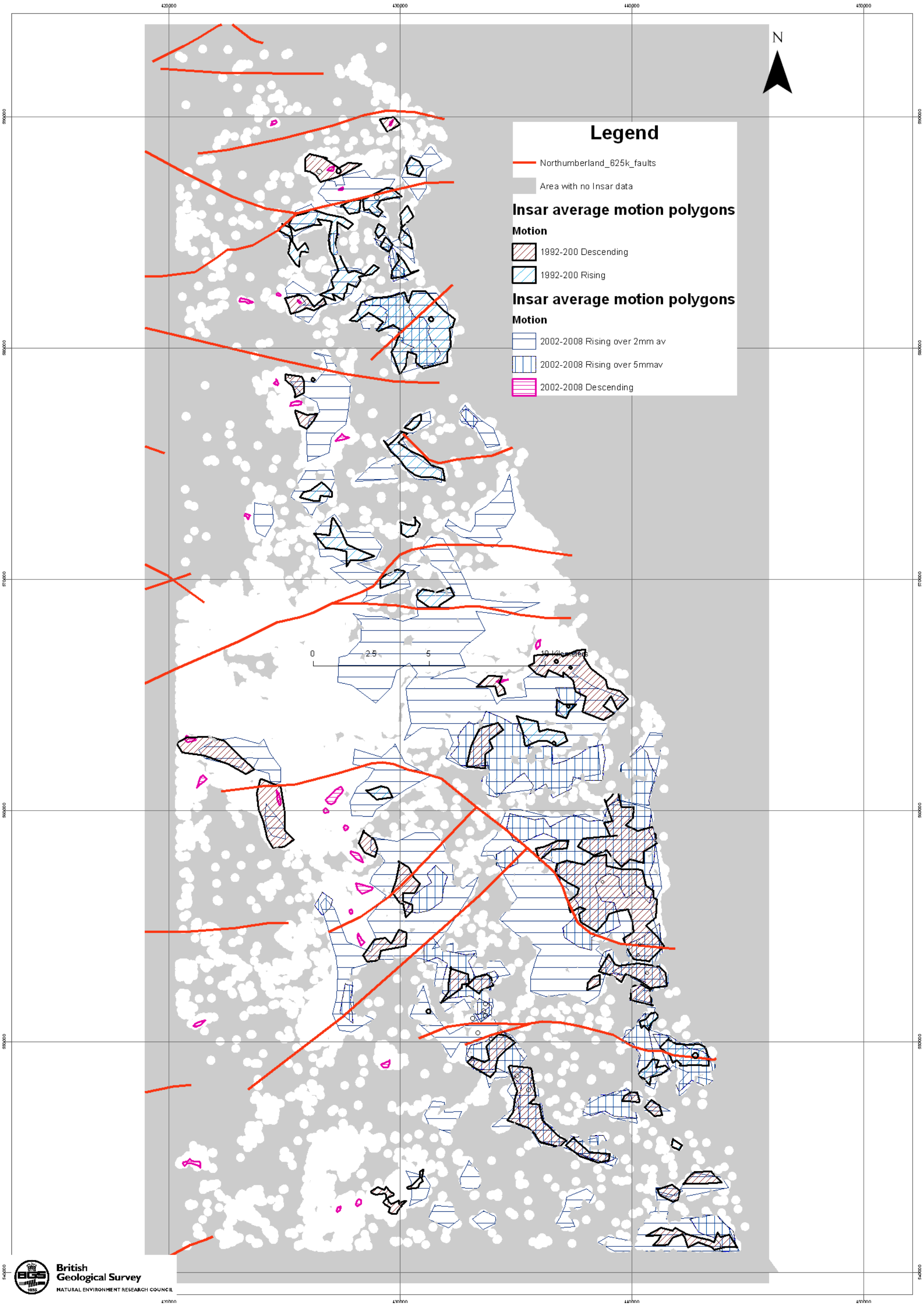


Figure 14: Relationship between areas of motion and major geological faults.

Figure 15 illustrates the relationship between the ERS average annual velocity and the major geological faults in the area. Black circles highlight areas of motion which appear to be constrained by the major faults. It would appear that although the faults are not directly responsible for the motion they are influencing the motion, either by accommodating the motion or constraining it.

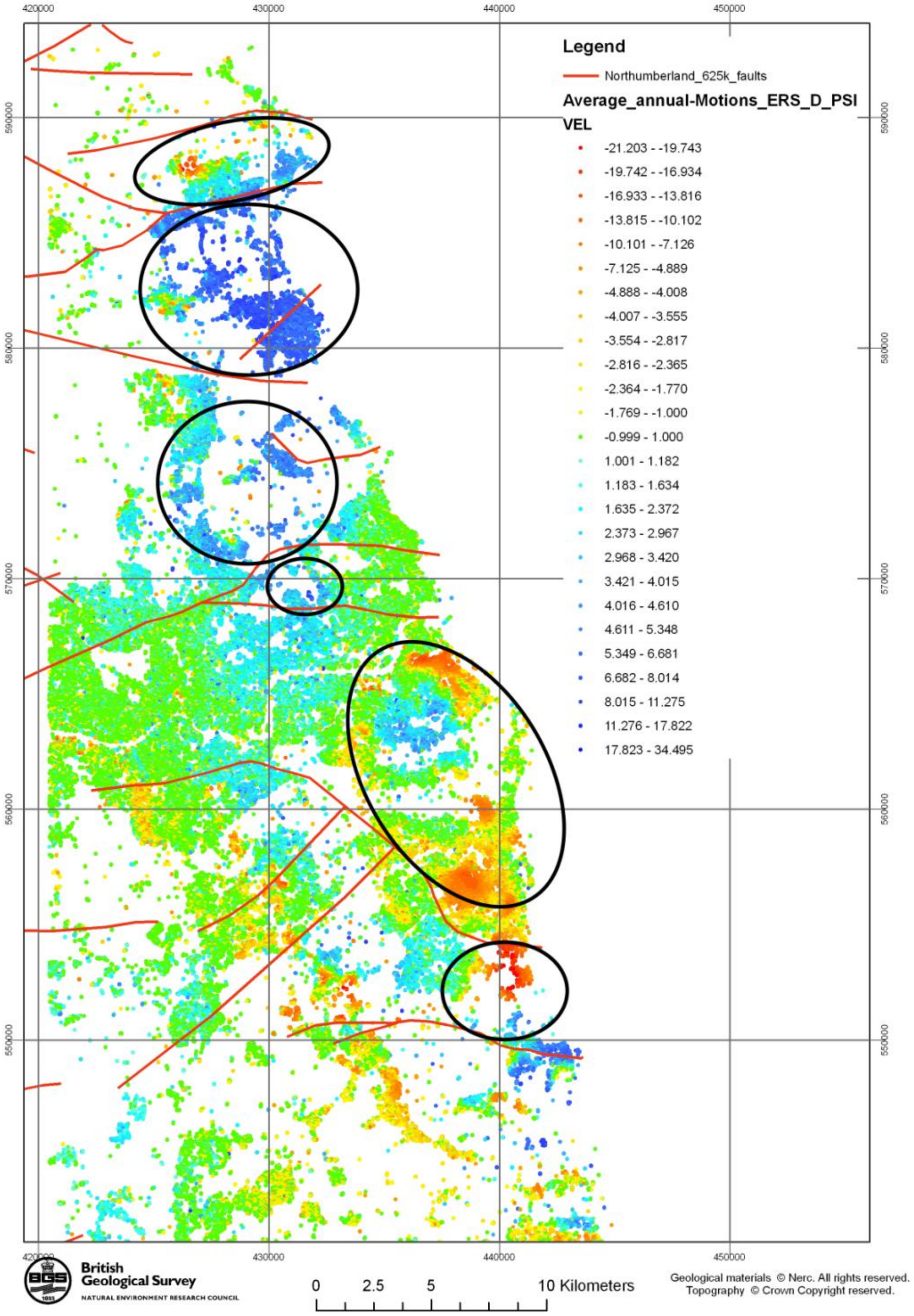


Figure 15: ERS average annual Velocity and major faults

The relationship of the 2002-2008 average motion and faulting is less pronounced (Figure 16). This is attributed to the overall change in the pattern of motion in the south of the area from subsidence to uplift. It would appear that the uplift in the south is less constrained by the faults than in the north, possibly suggesting a more regional reason for the uplift in the south. 2002-2008 average motion in the north still appears to be constrained by the faulting, as shown by the black circles in Figure 16.

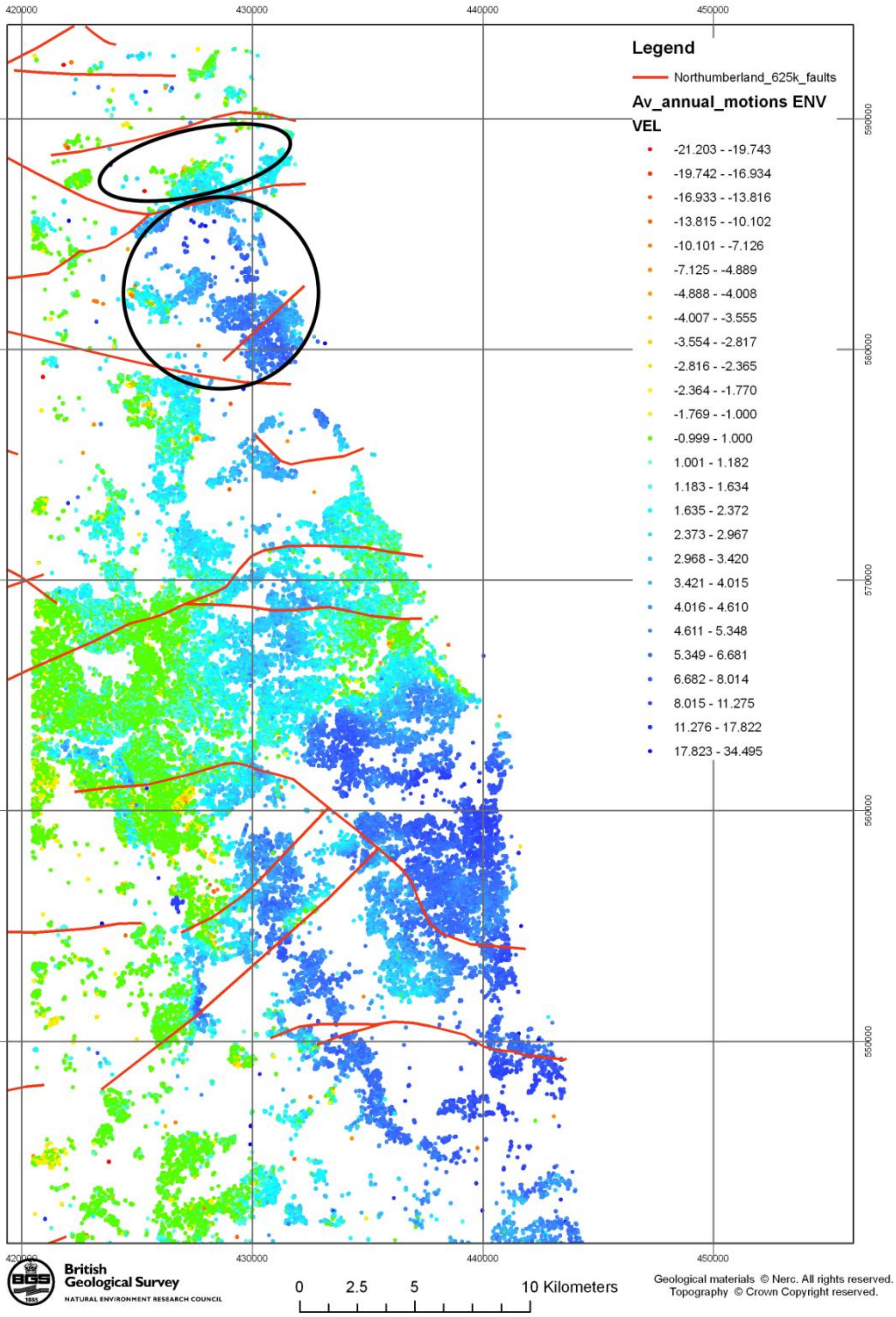


Figure 16: ENVISAT average annual velocity and major geological faults.

5.2.3 Overall relationship between average annual motion and superficial deposits.

Comparison of average motion with the distribution of superficial deposits (particularly compressible deposits and those with potential for shrink-swell) and their thickness shows that, in general, there is little correlation. The major exception is in the region of the buried valley of the rivers Tyne and Wear in the areas indicated in red on Figure 17. It should be noted that the motion changes from descending to ascending between the two processed periods. This area is known as the Team Valley and is discussed further in section 5.4.1.

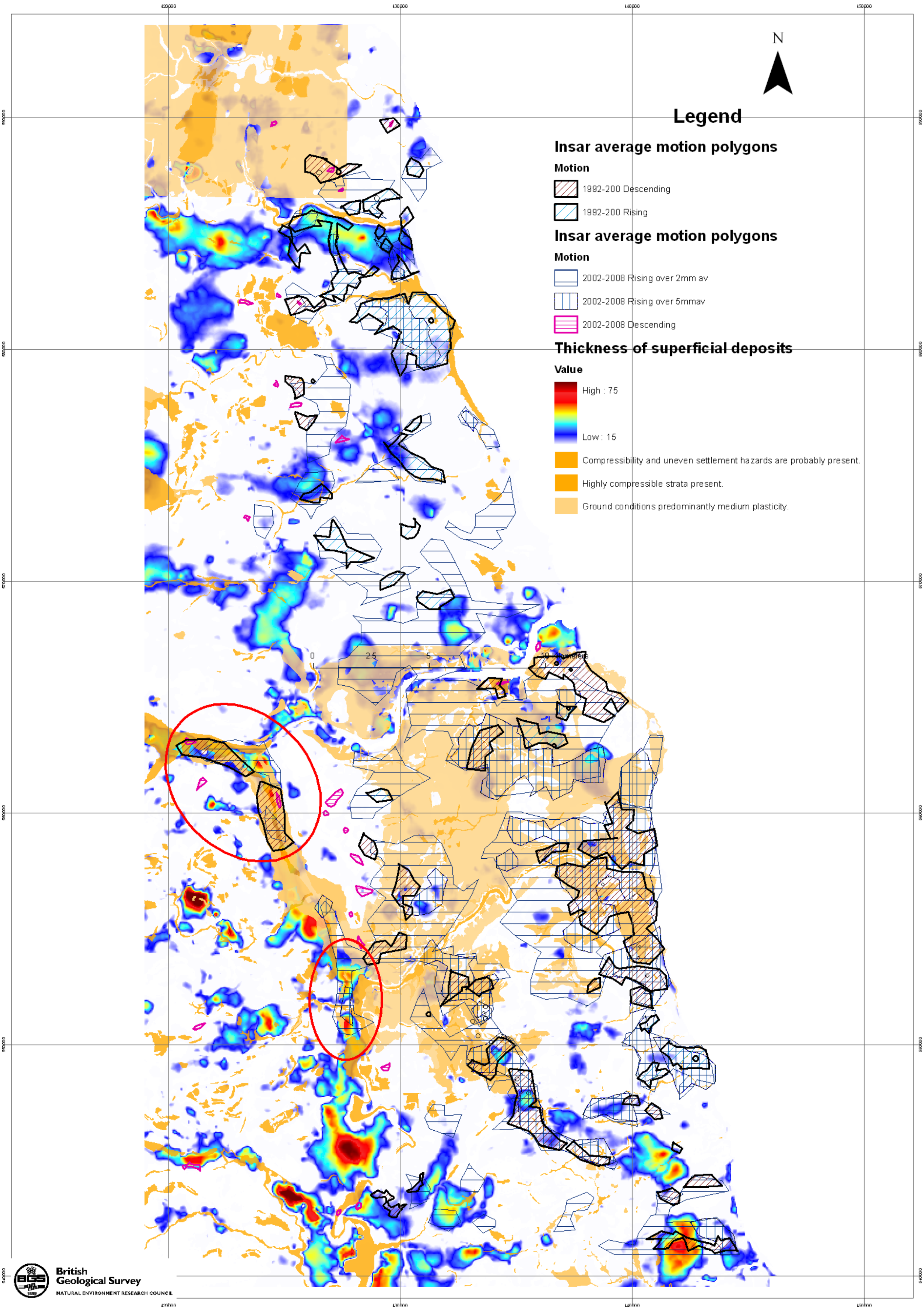


Figure 17: Derived general PS motion polygons superimposed on map showing thickness and nature of superficial deposits.

5.2.4 Overall motion and areas of mining

Figure 18 shows areas of deep and shallow undermining. The whole of the study area has been undermined in the past; it is therefore difficult to draw any relationship based on this dataset other than to say that observed ground motions might be related to mining.

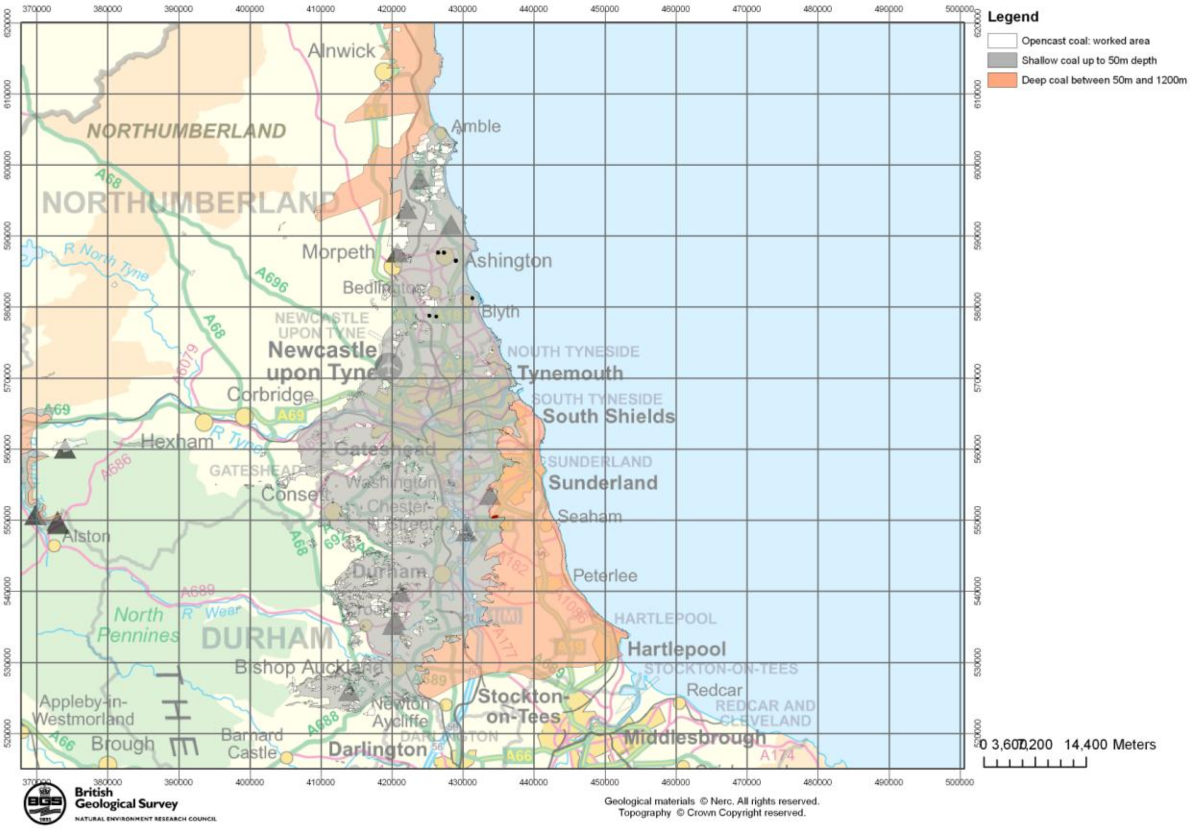


Figure 18: Areas of Deep and shallow coal mining in the study area.

5.2.5 Relationship of ground motion and groundwater levels

In our experience large areas of uplift indicated on PSI data, such as seen to the North of Newcastle in the ERS data and to the north and south of Newcastle in the ENVISAT data (Figure 5) is often the result of an increase in the level of groundwater, as would occur following the cessation of pumping in an area of in-active mining.

It is our hypothesis that the dramatic change in motion between the ERS (1995 to 2000) and ENVISAT (2002 and 2008) periods is due to a reduction in the amount of water pumped from the in-active mines. However BGS hold limited data on how the ground water levels in the region have responded to any change in the pumping of mine water from in-active mines. This makes it difficult to draw any conclusions on the observed motions and the water pumping history. ***We would urge the Coal Authority to investigate possible groundwater extraction and recharge as causes of ground subsidence and uplift respectively.***

BGS have also observed areas of subsidence, as shown by PSI, in the Merton area of South West London. This has been related to the extraction of groundwater (Bateson et al, 2009). Modelling has shown that the average motion measured by the PSI technique is in good agreement with the average motion derived through a geological model written to predict the expected motion for a given lowering of the ground water level.

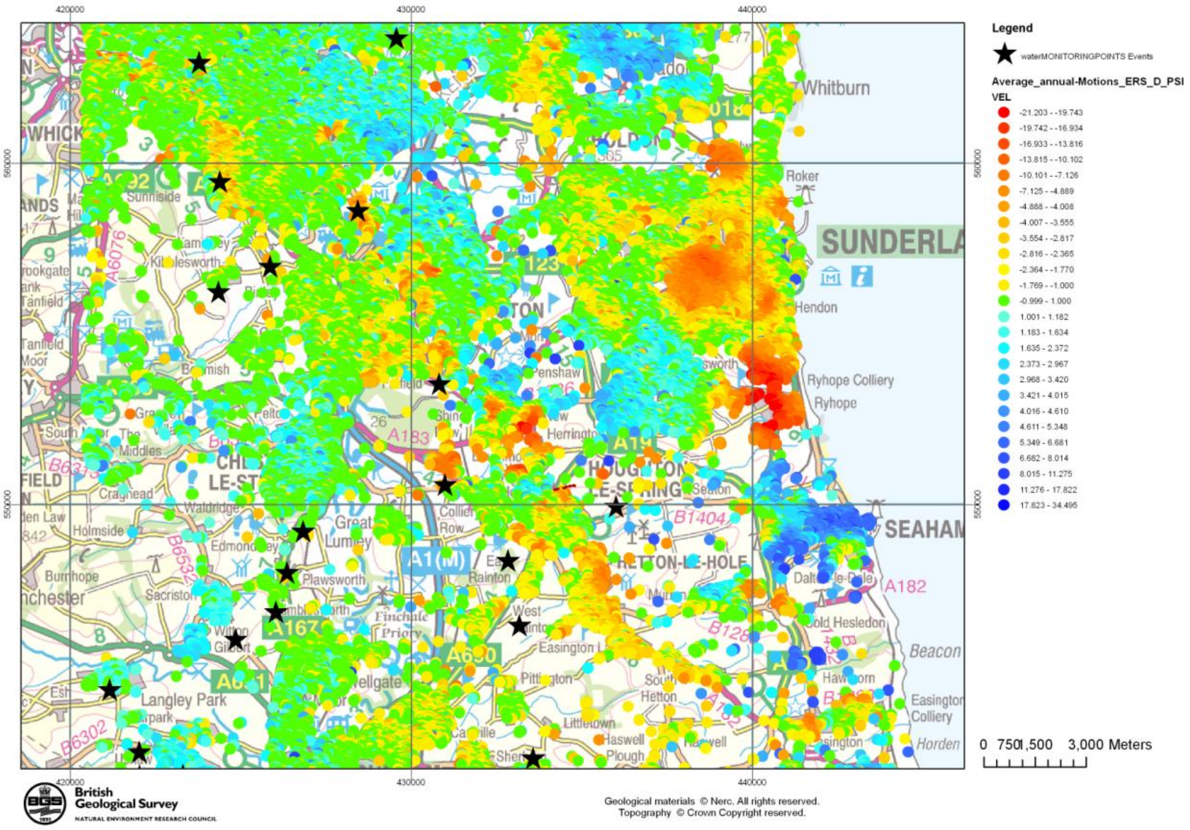


Figure 19: ERS Average annual velocity and the sites of Environment Agency groundwater monitoring boreholes.

Figure 19 shows that there are ground water monitoring boreholes in the area, the location of some of these is coincident with areas of subsidence between 1995 and 2000. BGS do not hold sufficient data to investigate this fully.

5.3 Overall comparison of ERS and ENVISAT motions

The PSI datasets from the two satellites correspond to two different periods of time; 1995 to 2000 and 2002 to 2008. As shown in Figure 5 there is a striking change in the character of motion in several areas between the two time frames. The most striking change occurs in the Sunderland and surrounding areas. In 1995 to 2000 the overall character of motion is subsidence, in the 2002-2008 data this area appears to be undergoing uplift.

Motion polygons extracted from the ERS (Figure 11) and ENVISAT (Figure 12) PSI data can be compared and contrasted to study how the motion has changed from one period to the next. The results of this comparison can be seen in Figure 20. Virtually all the area that was rising on average in 1995-2000 continued rising in 2002-2008, but there was very limited correlation between areas that were descending in the 1995-2000 data.

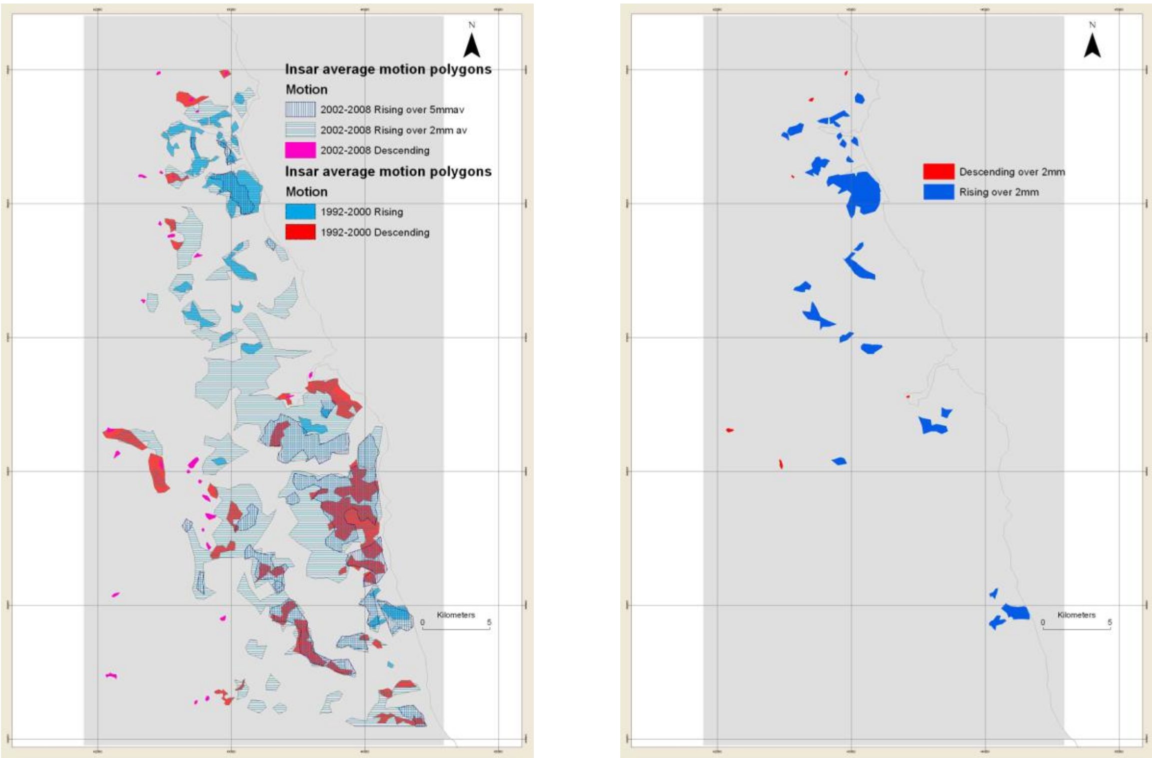


Figure 20: Comparison of derived general average motion polygons for ERS and ENVISAT data

To help identify areas of change between the two processed date ranges a difference image has been calculated (Figure 21). In order to calculate the difference in average motions it was first necessary to convert the point dataset into a raster image. PS point locations are not coincident between the ERS and Envisat datasets therefore it was also desirable to fill in some of the gaps between points during the process of converting the points to a raster. A kriging algorithm was used to produce a raster with 100 m grid cells for the ERS and Envisat average annual velocities. These two images were then differenced and the resulting difference image colour coded so as to highlight areas of change, as seen in Figure 21.

The meaning of the colour coding of the difference image in Figure 21 can be summarised as:

- Reds represent areas where the motion trend has switched from subsidence to uplift

- Yellows are where subsiding areas have become stable or stable areas have started to uplift
- Light blues are where the rate of uplift has become less or stable areas have started to subside
- Dark blues are where the motion trend has switched from uplift to subsidence.

Table 4: Meanings of the colours seen in Figure 21

Colour in difference image	ERS motion	ENVISAT motion
Red	strong subsidence	strong uplift
Yellow	strong subsidence	stable/slight uplift
	mild subsidence	uplift
	stable	strong uplift
Light Blue	strong uplift	slight uplift/stable
Dark Blue	stable	subsidence
	uplift	subsidence

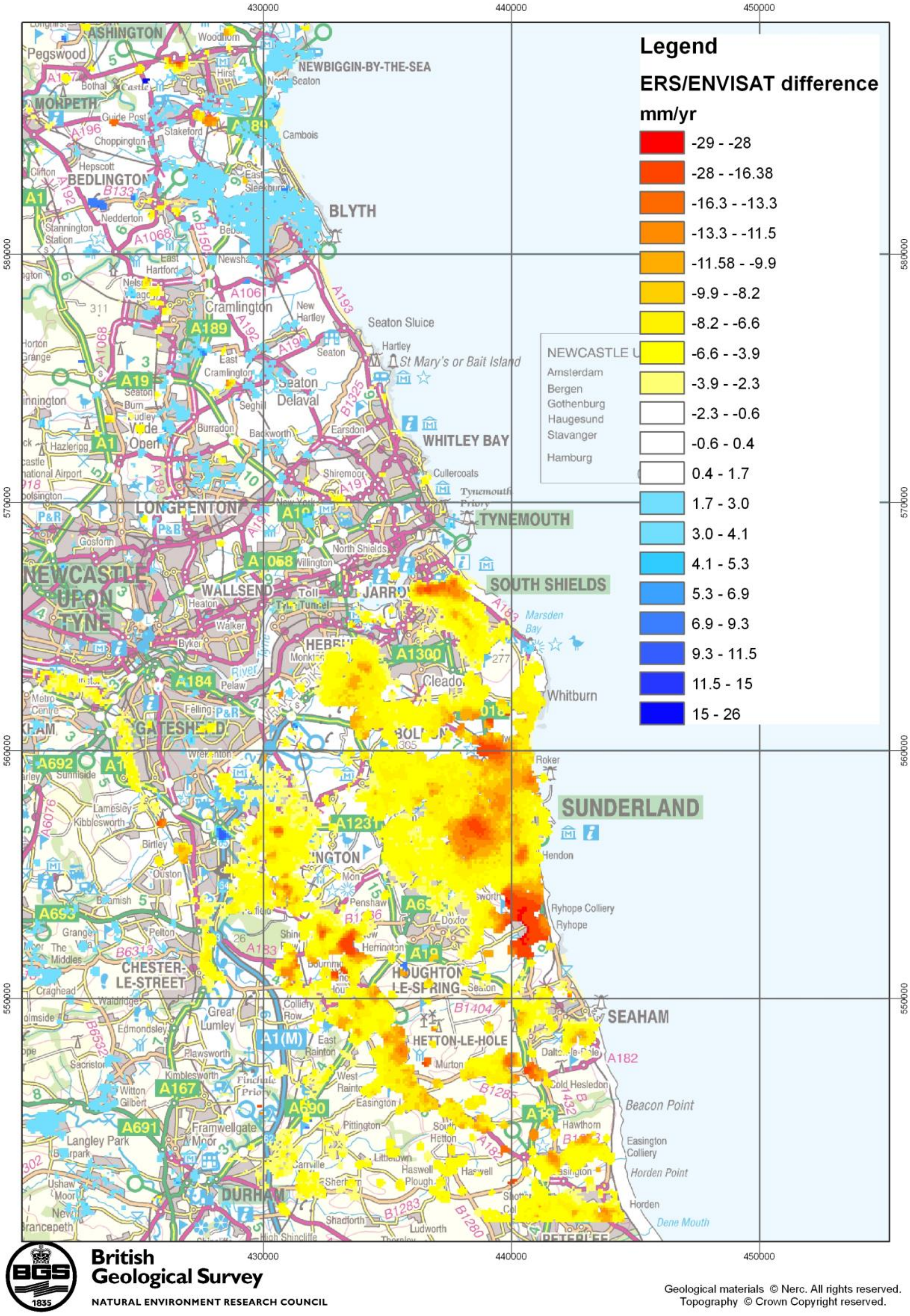


Figure 21: Difference image between the ERS average annual velocities and the ENVISAT average annual velocities. Areas of red and blue represent the greatest difference between the ERS (1995 – 2000) and ENVISAT (2002-2008) datasets. See Table 4 for an interpretation of the colours.

The overall message from the difference image and comparison of motion polygons is a decrease in the rates of uplift in the north and a pronounced switch from subsidence to uplift in the south of the processed area. The magnitude of the decrease in uplift rates as shown by areas of light blue are relatively small, the total change in rate is 2-4 mm/yr. The switch from subsidence to uplift is more pronounced with several areas changing by a total rate of over 15 mm/yr.

5.4 Case Studies

5.4.1 Team Valley, Gateshead.

Analysis of time-series data for clusters of PS points associated according to surface superficial geology has been undertaken within in the area covered by Figure 22, which includes the Team Valley area of Gateshead and the immediately adjacent area of the River Tyne to the north. The area is everywhere underlain by Coal Measures rocks from which several coal seams have been extracted by underground mining. All such mining has been abandoned for several decades. Over much of the area the Coal Measures rocks are concealed beneath a mantle of superficial deposits comprising till with deposits of laminated clay and alluvial deposits in the Team Valley and the adjoining Tyne valley.

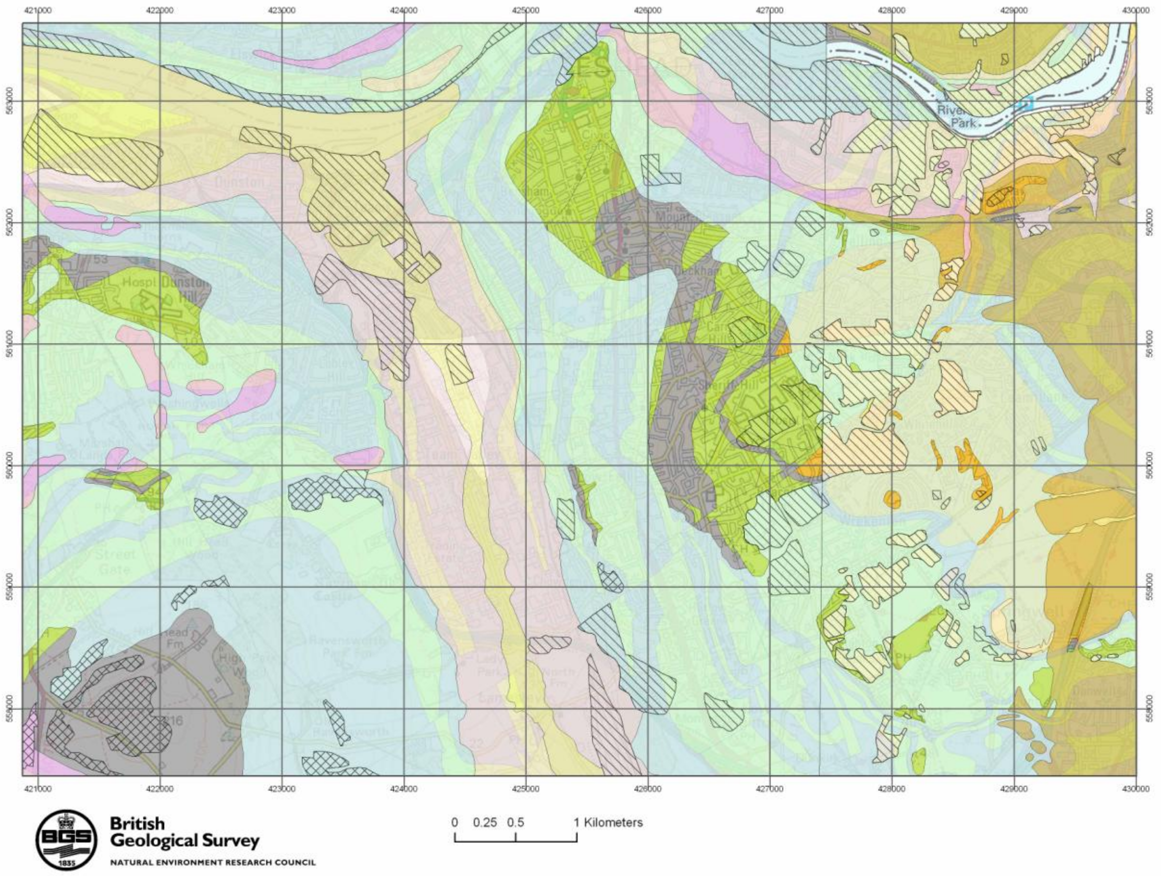


Figure 22 Superficial and bedrock geology of the Team Valley area, key as Figure 2 and Figure 3, hatched areas indicate artificial (man-made) ground at the surface.

The Team Valley is of interest as providing one of Britain's finest examples of a misfit valley. The valley is the pre-glacial channel of the River Wear, which, prior to its diversion following the Devensian glaciation, flowed northwards through the Team Valley to join the Tyne near Dunston. An abundance of site investigation borehole records enabled Mills and Holliday (1998) to construct a very clear picture of the rockhead topography of the Team Valley (Figure 23). These authors have demonstrated that the valley is locally excavated to below -46 metres OD. In this area the surface alluvium is coincident with the centre-line, deepest part, of the buried valley, where the alluvium overlies an interlensing complex of glacial clays, laminated-clays, silts and sands

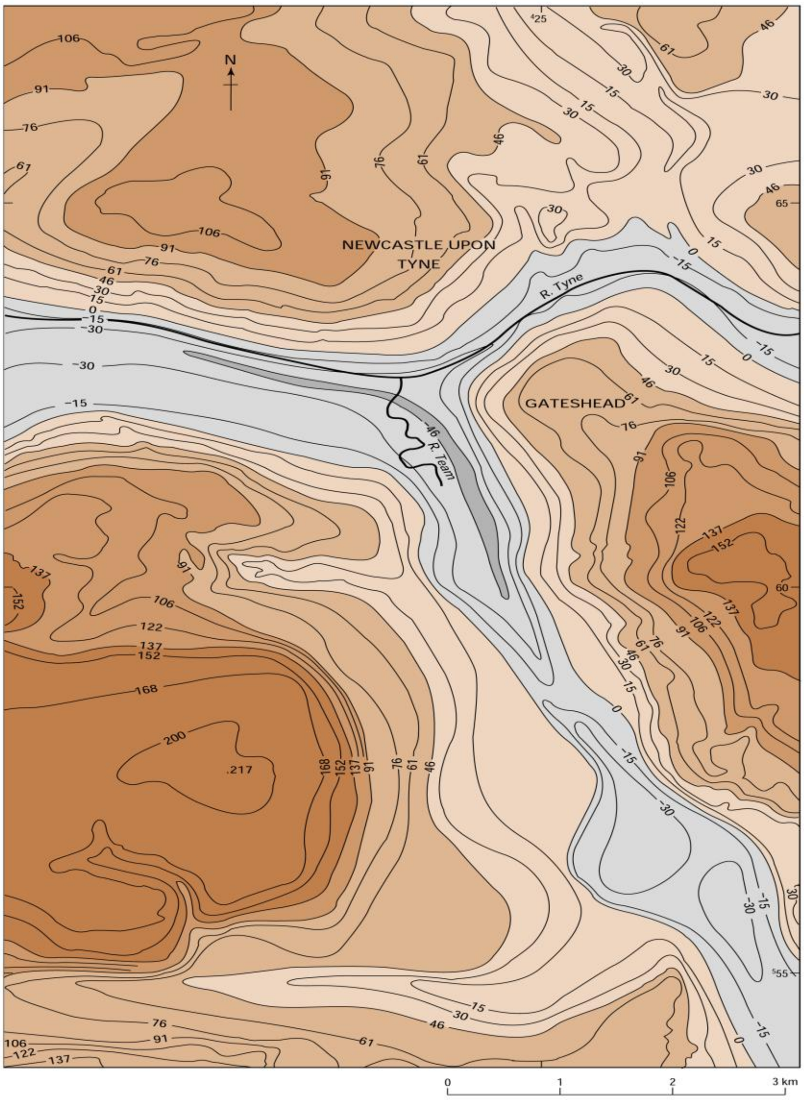


Figure 23: Rockhead topography of the Team Valley area (after Mills and Holliday, 1998).

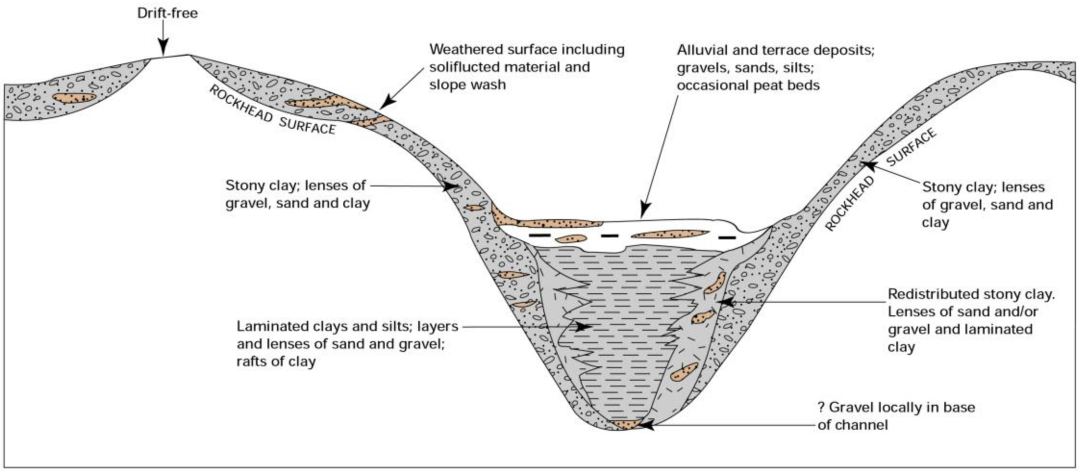
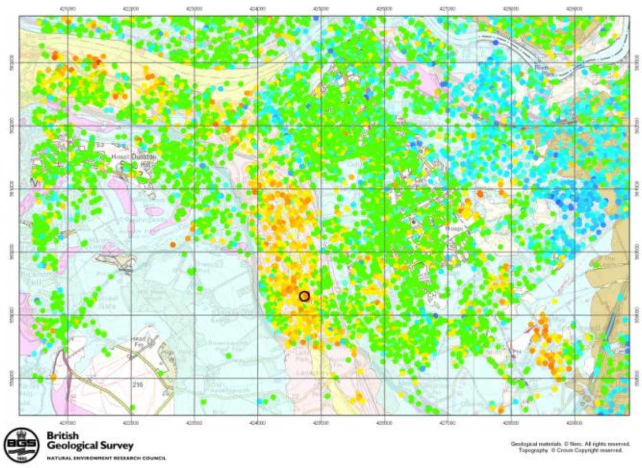
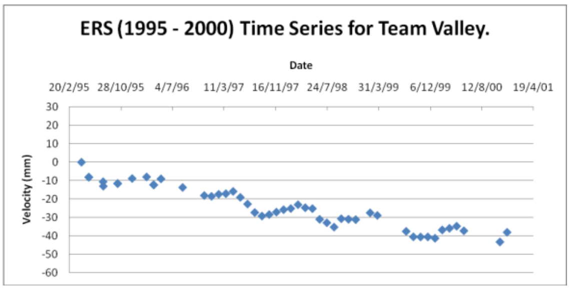
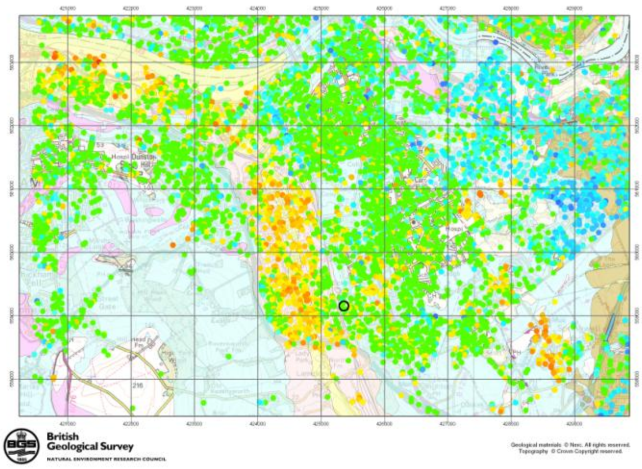


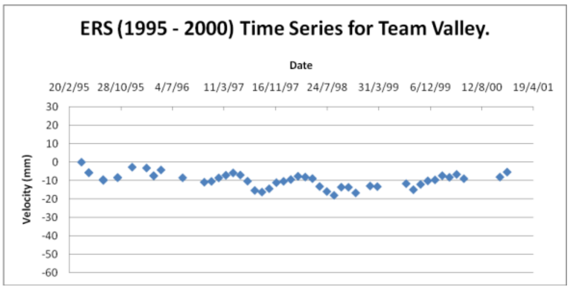
Figure 24: The fill of an abandoned river channel such as the Team Valley



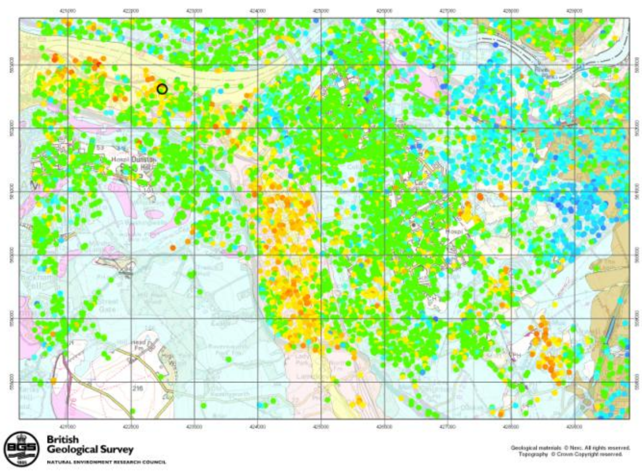


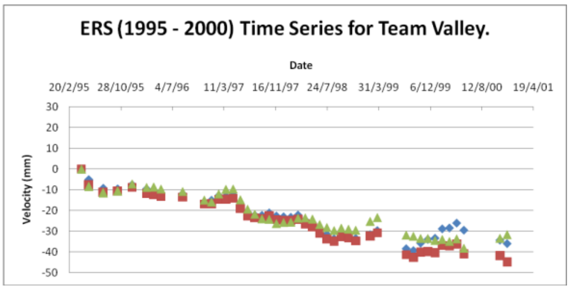
PS cluster 1.





PS cluster 2.





PS cluster 3.

Figure 25 ERS motions for PS points in Team Valley. On the left of the figure are average annual velocities; on the right are PS point time series data for selected points (highlighted by black circle on the left hand image, PS point cluster 1 at the top, 2 middle and 3 bottom). The striking areas of subsidence (yellow to orange shades on images) revealed by PSInSAR coincide extremely closely with the thick infill of the Team Valley.

The three ERS PS clusters (Figure 25; areas 1, 2 and 3) show distinctive time-related subsidence profiles (1995 to 2000). Clusters 1 and 3, in the deepest part of the buried channel, showing a general negative trend throughout the period, Cluster 2, on glacial till overlying Coal Measures rocks beyond the margins of the buried channel is, by comparison, relatively stable.

Preliminary examination of the available data, including a wealth of geological and geotechnical data held by the BGS, suggest that progressive compaction and consequent subsidence of these deposits must account for the striking PS image. Such apparent subsidence could be due to a variety of related causative factors, which merit close examination and critical analysis. Settlement of areas of extensive underground coal extraction would be expected to affect both the Team Valley and surrounding areas. The PS images do not support this. The area affected coincides with an extensive area of industrial development in the Team Valley and Gateshead Metro Centre, with large areas covered by buildings, roads, paving and associated drainage. Very substantial areas of ground are thus effectively sealed from recharge from rainfall. A combination of loading, albeit from comparatively light-weight structures, and progressive 'drying out' of hitherto wet sediments may be a significant factor in creating subsidence. De-watering of Quaternary sediments within the Team Valley may be accentuated by pumping of mine waters as part of a continuing programme of ground water control in this part of the former coalfield.

A comparison of Figure 25 with Figure 26 shows that, for the most part, the pronounced subsidence in the Team Valley area shown in the ERS data has ceased and in places changed to upward motion in the Envisat data. An examination of groundwater data for this area should be undertaken. It might be that groundwater level change is responsible for the change from subsidence to uplift.

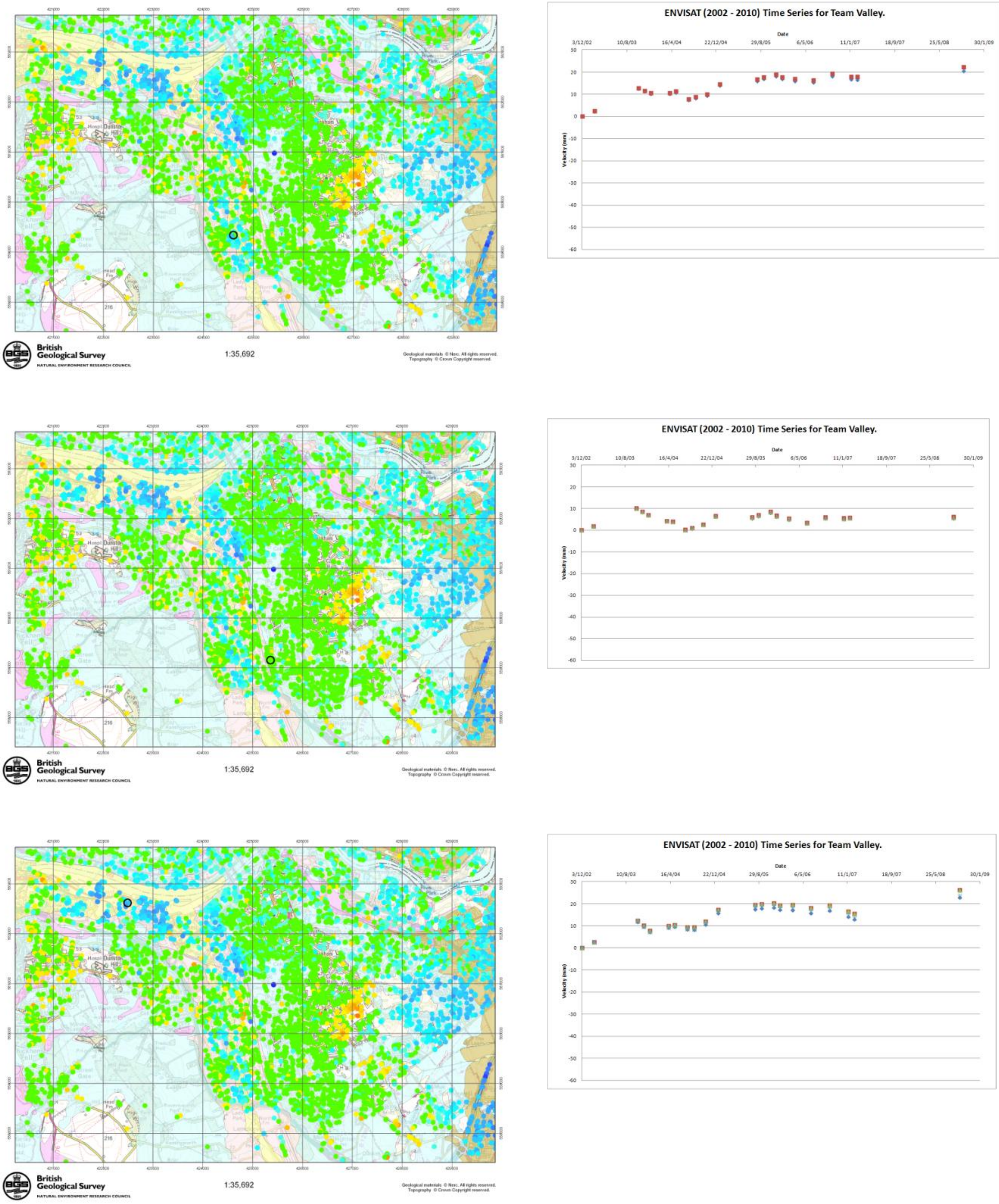


Figure 26 ENVISAT motions for PS points in Team Valley. On the left of the figure are average annual velocities; on the right are PS point time series data for selected points (highlighted by black circle on the left hand image

5.4.2 Houghton-le-Spring

It is known from BGS work on fissuring in the Magnesian Limestone (Zechstein Group) of the Sunderland area, that several parts of the city are markedly susceptible to active open surface fissuring. This fissuring in places exhibits some spatial relationship with known faults. Such ground movements are reported from the Doxford Park area of the city and from the area to the east of Roker. Similarly, work by Young and Culshaw (2001) in the Houghton-le-Spring and Seaham areas demonstrates a clear relationship between active surface fissuring and known lines of faulting. However, it is difficult to determine a linear relationship between such PS points and known lines of faulting, although this could be due to an absence of PS data in appropriate areas (e.g. see Figure 27 and Figure 28). Displacement of areas of Magnesian Limestone between individual fault blocks could conceivably result in relative rotation of blocks of limestone between individual faults. Such movement in an area of complex fault intersections, such as that beneath the city of Sunderland could well result in a cumulative displacement leading to a pattern of PS points indicative of movement.

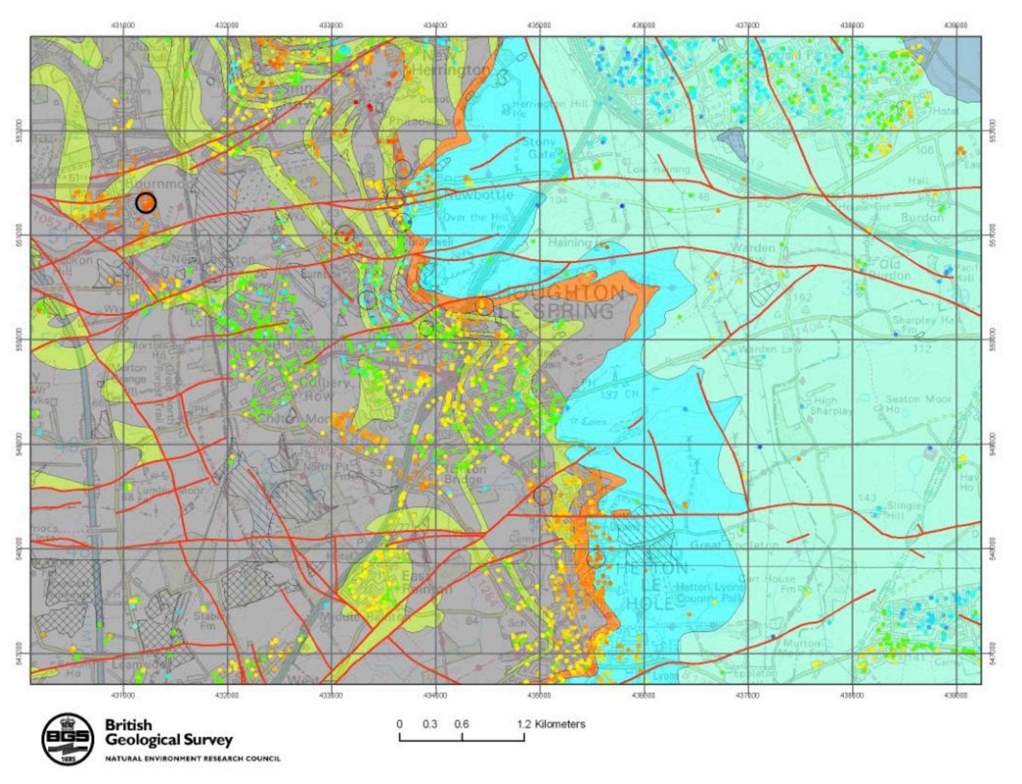


Figure 27: ERS motion in the Houghton-le-Spring area superimposed on bedrock geology

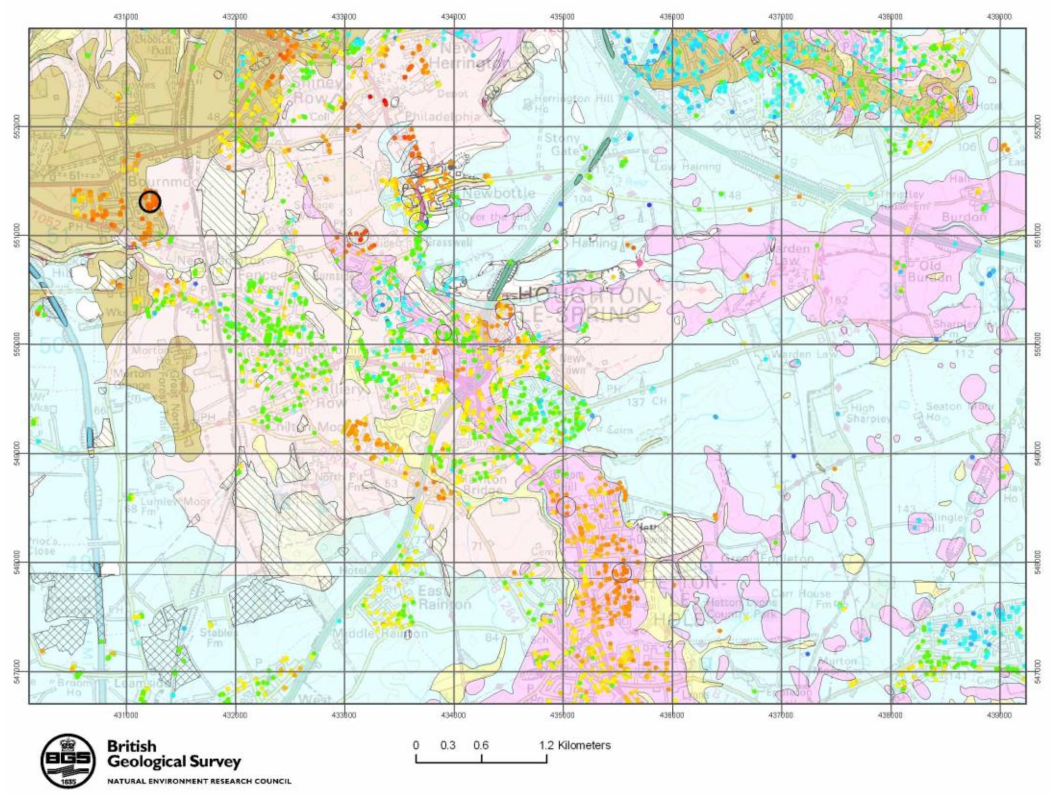


Figure 28: ERS motion in the Houghton-le-Spring area superimposed on superficial geology

Field investigations by Young and Culshaw (2001) and Young and Lawrence (2002) have mapped and catalogued recent fissures and Crown holes in the Houghton-le-Spring area (

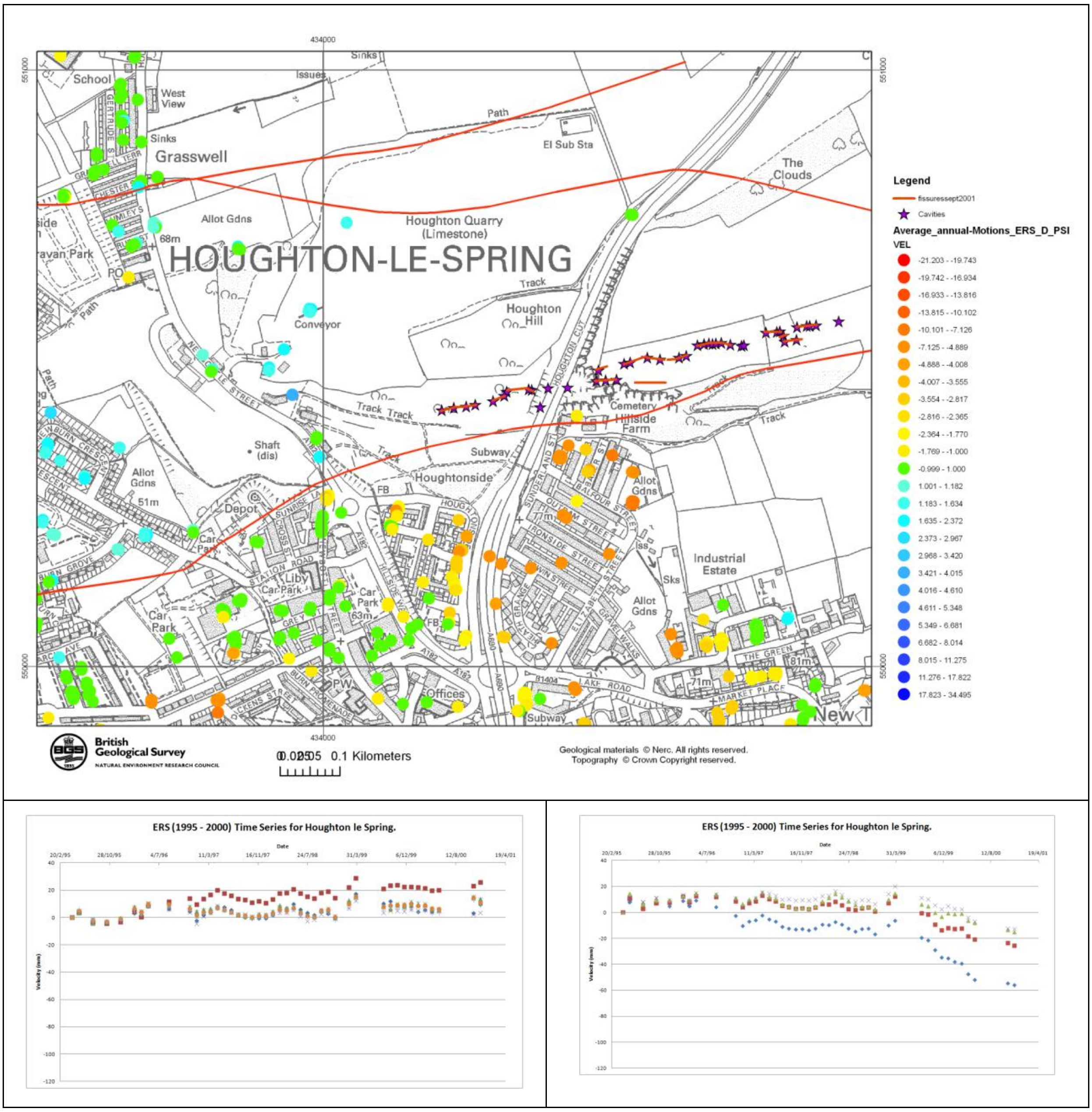


Figure 29). Although these are not coincident with the distribution of PS points in the area the ERS PS data does support the notion that differential motion is taking place across faults.

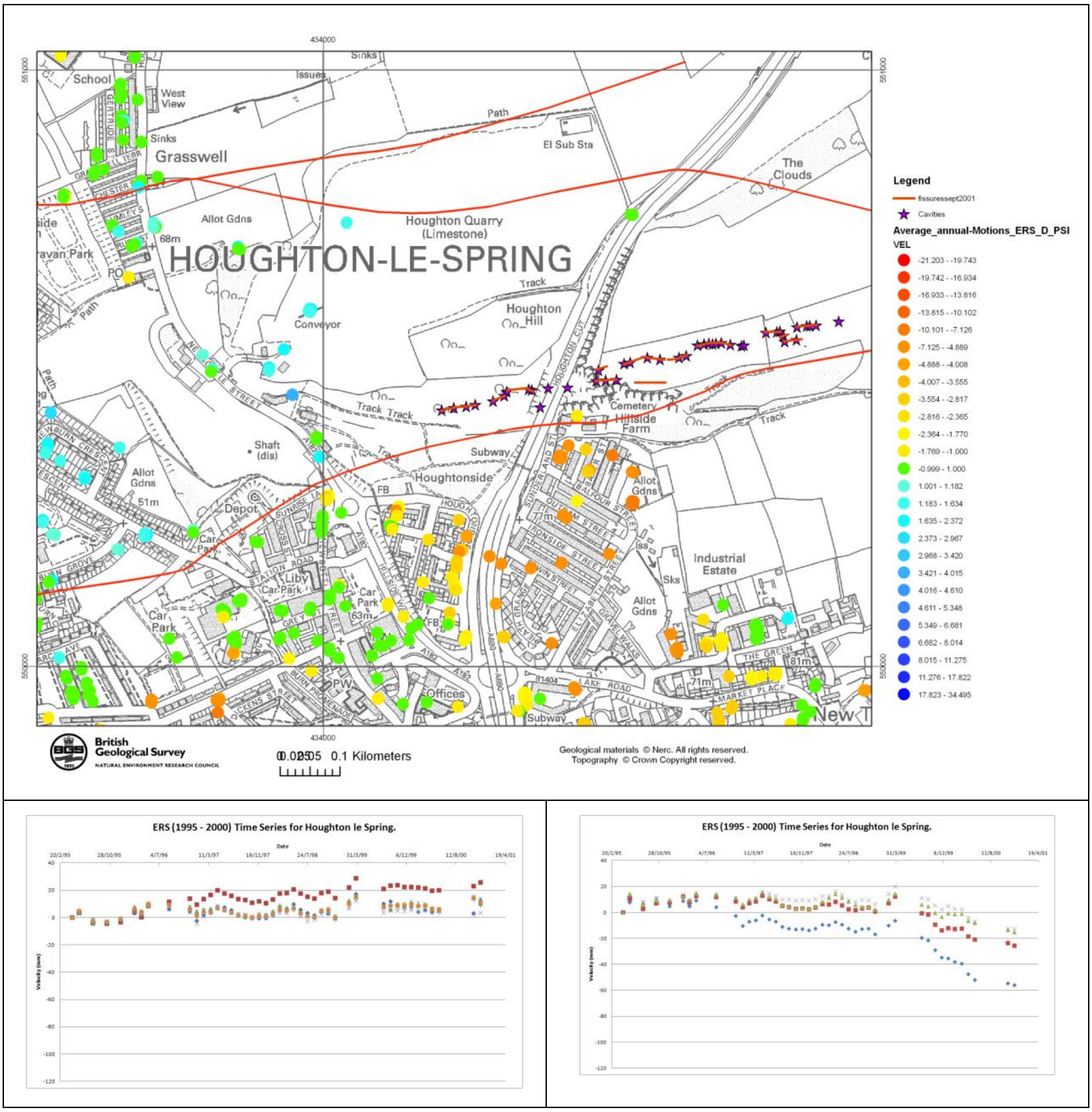


Figure 29 shows the ERS average motions for the Houghton-le-Spring area, to the south of the mapped fault (Houghton Cut Fault) the PS points are indicating subsidence and uplift is shown to the north of the fault.

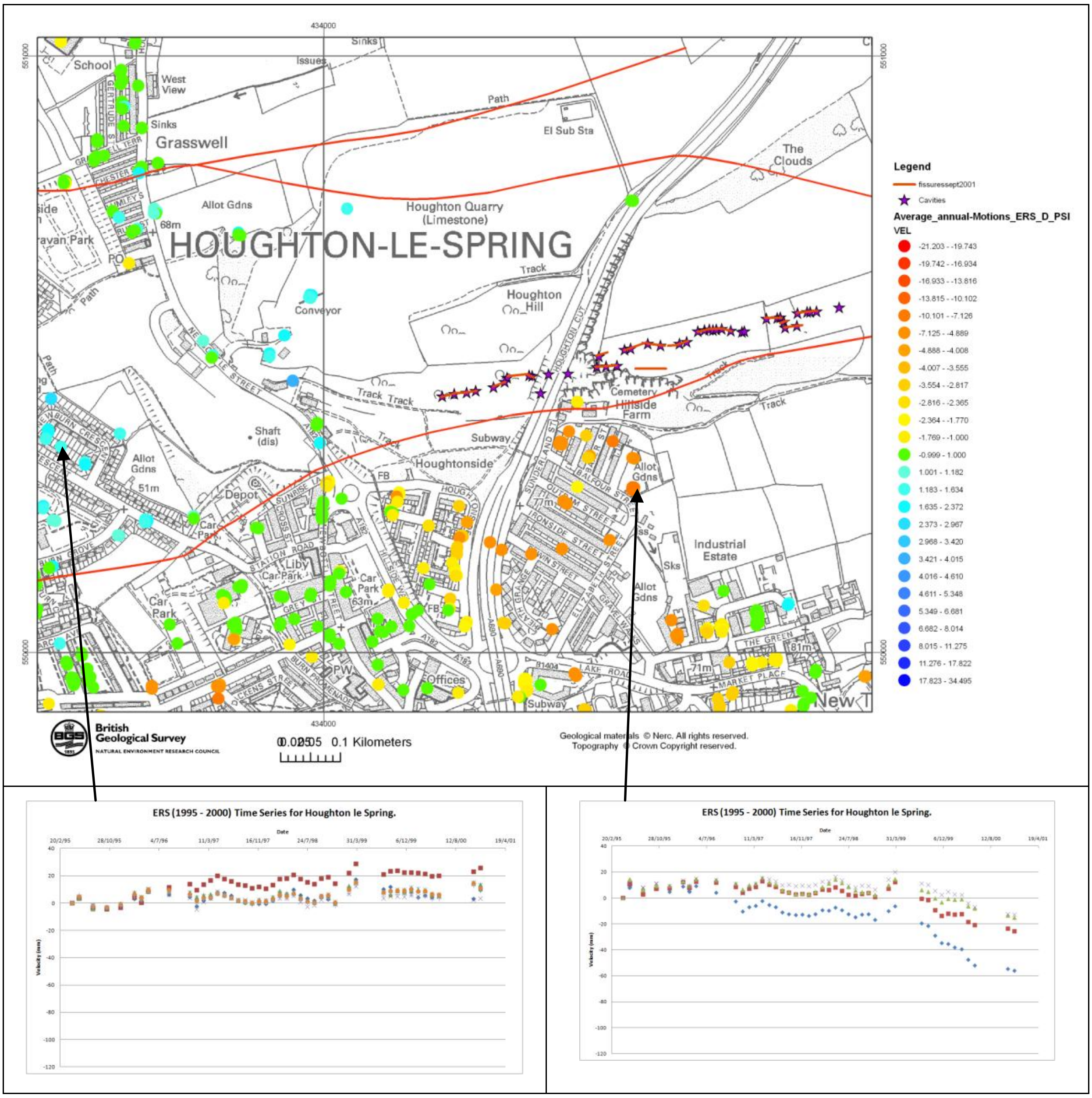


Figure 29: Top: Field observations of cavities and fissures in Houghton-le-Spring. 1:50 000 scale faults and ERS average motion points area also shown. Bottom: ERS time series plots showing the history of motion across the fault.

Examples of the fissures and resulting road damage are shown in Figure 30.

	
Houghton Cut. Crack in S-bound carriageway of A690. Open fissure in Raisby Formation visible beyond figure to W of N-bound carriageway. Photographed April 2000.	The Old Cemetery, Houghton - le - Spring. Prominent, wide, N-dipping open fissure in Raisby Formation in W end of cemetery. For location see 'Cemetery' marked on the map in Figure 29.

Figure 30: Photographs of the effects of the fissuring in the Houghton-le-Spring area, south of Houghton Hill. Images taken from Young and Culshaw (2001).

The Houghton colliery opened between 1823 and 1827 and closed in 1981. During production the following seams were worked: Bottom and Top Busty, Harvey, Hutton, Low Main, Maudlin, Main and Five-Quarters. These seams represent a total coal thickness of approximately 10m. Mining abandonment plans (Figure 31) indicate that the Top Busty was worked form the late 1960's to mid 1970s in this area. The abandonment plans show that workings of the Busty coals from Houghton Colliery lie south of the Houghton Cut Fault which appears to have acted as a northern boundary to the workings. The plans indicate pillar and stall workings beneath the built up area of Houghton-le-Spring area: a note on the abandonment plan records "underground water" in the area immediately east of Hillside Farm.

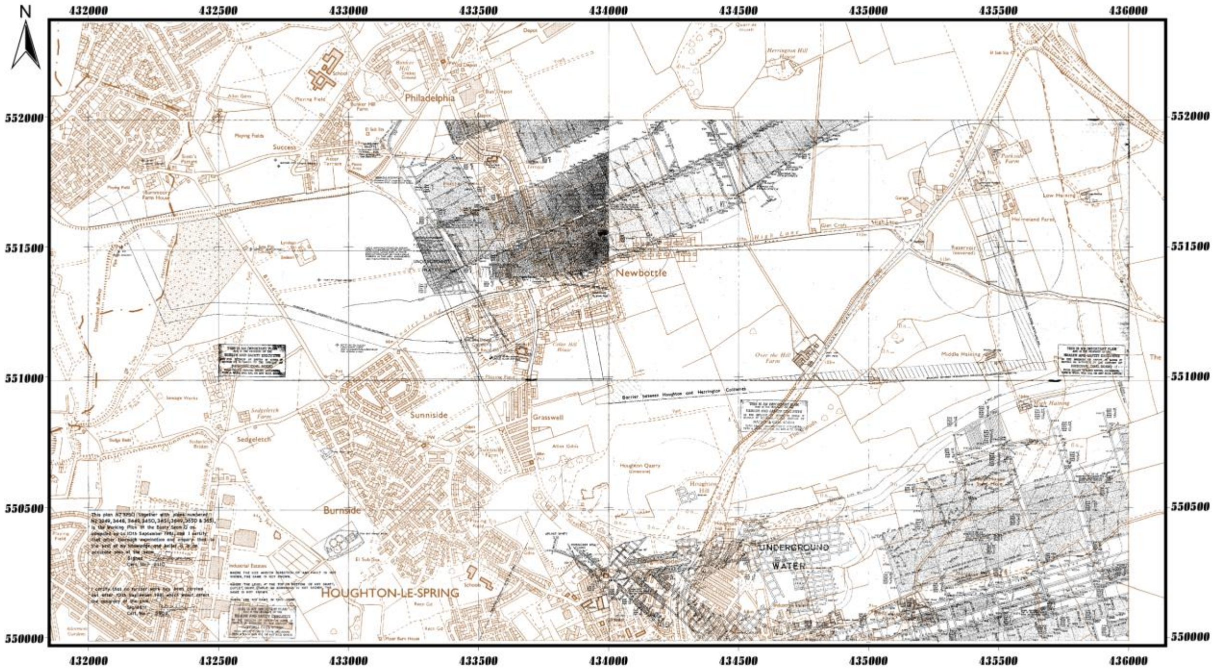


Figure 31: Mining abandonment plan for the Top Busty seam in the Houghton area.

It is interesting that the workings in the Top Busty seam were bound to the north by the Houghton Cut Fault and that the ERS PSI motion also appears to be bound to the north by the Houghton Cut Fault. Young and Culshaw (2001) say the following about mining subsidence in the area, note this was said in 2001:

"It is generally assumed that subsidence over modern 'longwall' workings, of the sort likely to be most widespread in this area, is completed within a few years of the cessation of mining. However, the collapse of pillar and stall workings is a much less predictable matter and may continue intermittently for many years after the end of working. Extensive areas of pillar and stall workings are known to be present within a number of seams at Houghton Colliery.

Wigham (2000) attempted to demonstrate a coincidence between surface collapse and disturbance features in the Magnesian Limestone and the configuration of areas of coal extraction in underground workings. No such clear relationship has been demonstrated during the present investigation of the Houghton-le-Spring area. However, it should be noted that in this area the major boundaries of coal extraction, as revealed by mine plans, tend to coincide with known faults."

They go on to point out the close proximity of the fissuring to the Houghton Cut Fault and the similarity in orientation. The relationships seen in the Houghton-le-Spring area and the overall correlation of faulting and PSI motion as noted in section 5.2.2 leads the authors to hypothesise that ground motion is occurring as a result of the combination of any remnant mine collapse, possibly from collapse of areas of pillar and stall, and groundwater level change brought about by pumping of groundwater. The effects of these processes are accommodated by the reactivation of faults in the area and the creation of fissures. The faults and fissures are effectively compartmentalising the area. This compartmentalisation leads to different 'blocks' undergoing different motions as shown in the ERS PSI data.

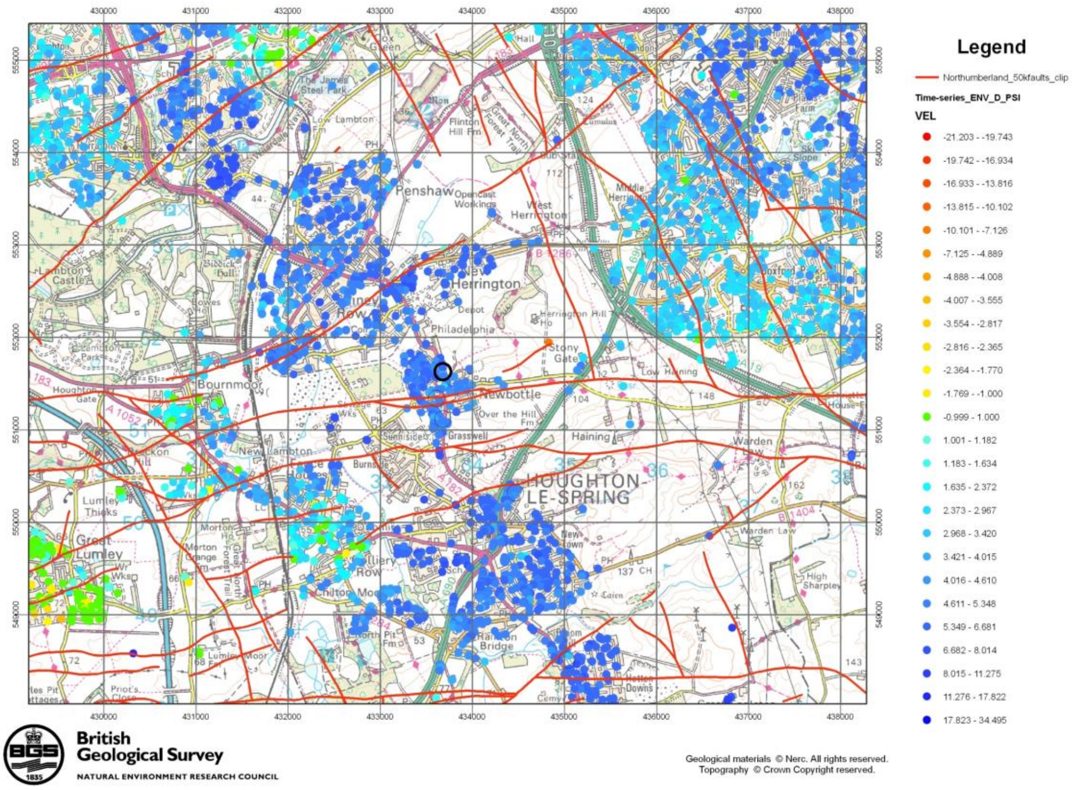


Figure 32: Envisat motion in the Houghton area.

From 2002 to 2008 the Envisat PSI data (Figure 32) indicates uplift across much of the area around Houghton-le-Spring. The more recent motion appears to be far less associated with the pattern of faulting and would appear to be part of a more regional pattern of uplift. The reason for this is unknown; the authors believe a detailed study of the minewater pumping history and its effect on groundwater levels would be very interesting.

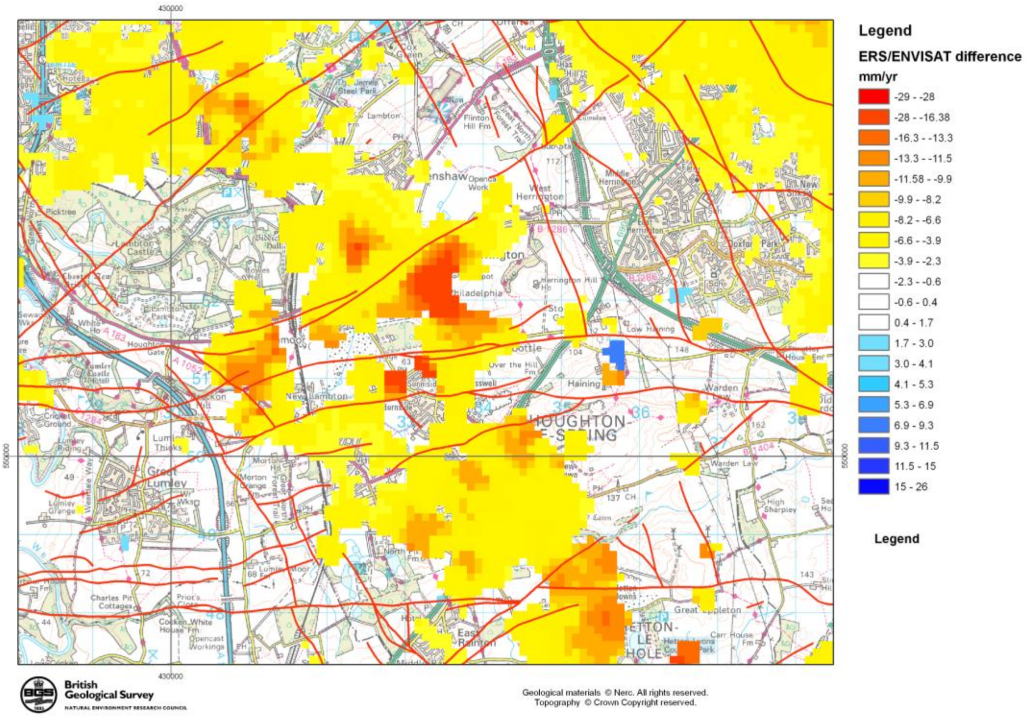


Figure 33: The ERS/Envisat average motion difference image (Figure 21) for the Houghton-le-Spring and Newbottle area with geological faults overlaid in red.

It is clearly demonstrated in the Houghton and Newbottle area that areas undergoing the maximum change in motion between the ERS and Envisat data, red areas on Figure 33, are bounded by the faulting in the area. This further suggests that faulting is accommodating the motion.

5.4.3 Ryhope

Between 1995 and 2000 Ryhope was subsiding by as much as 21 mm/yr. From 2002 to 2008 the same area was experiencing average uplift rates of up to 8 mm/yr.

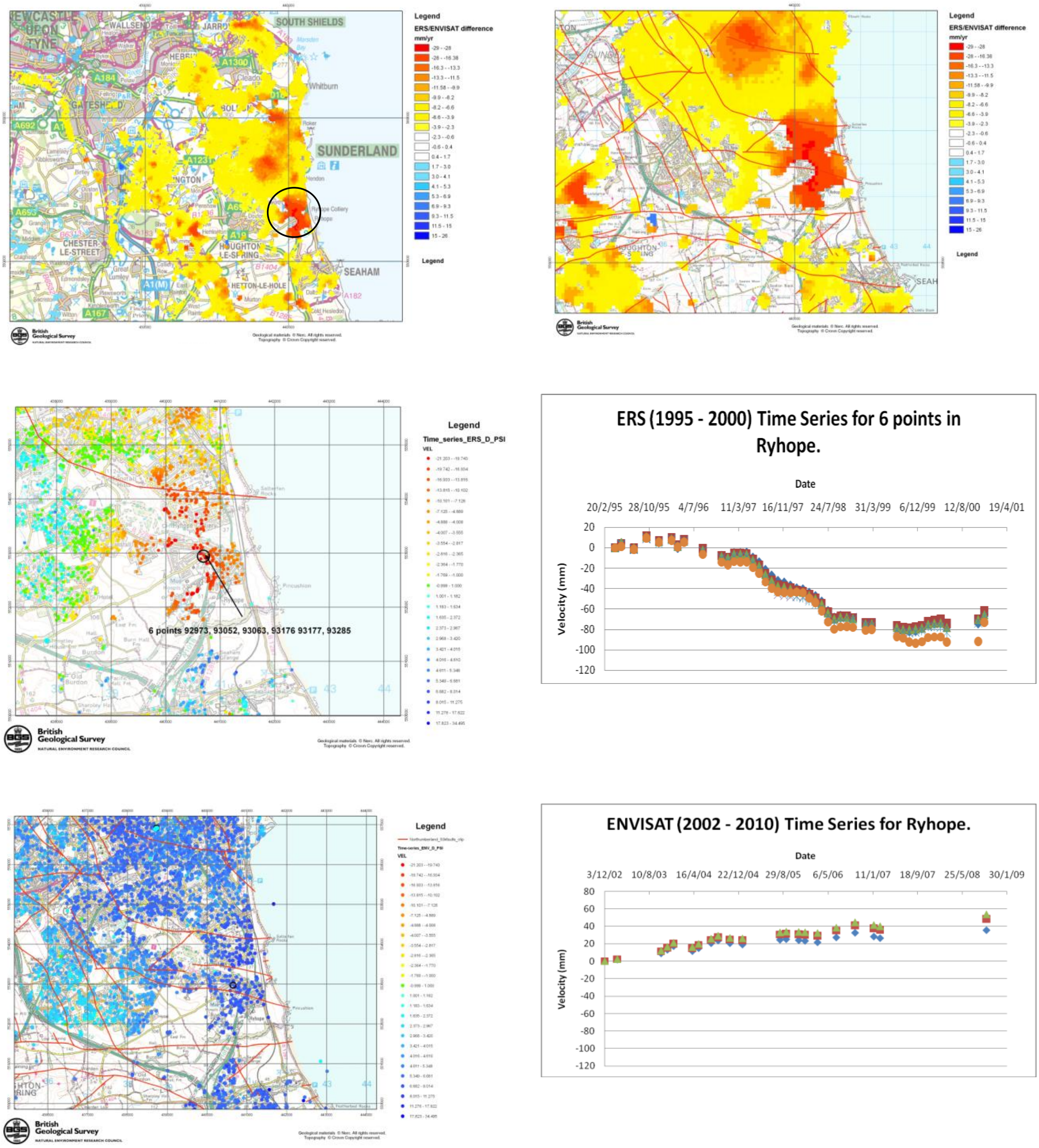


Figure 34: ERS (middle) and ENVISAT (bottom) motions for PS points in Ryhope. On the left of the figure are average annual velocities; on the right are PS point time series data for selected points (highlighted by black circle on the left hand image). Top right is close up of the difference image for the Ryhope area with geological faults overlaid in red.

Figure 34 indicates that the majority of subsidence in Ryhope took place between March 1997 and August 1998. Within this period of maximum subsidence there appears to have been two phases of more rapid subsidence, with a period of stability in November 1997.

The time series plot for the ERS data reveals that uplift (as seen in the ENVISAT data) actually started towards the end of 2000 and continued until the end of the dataset in 2008. The uplift appears to have taken place in ‘steps’, with periods of more rapid uplift between October and December 2003, April and July 2004 and January and October 2006. The top right of Figure 34 shows how the area of maximum change in motion is associated with the geological faults supporting the theory that faulting is accommodating this motion.

Figure 35 illustrates an area of Ryhope, where subsidence is apparently defined by two E_W faults, but slightly offset to south. This is as would be expected if subsidence related to an area of mining - the position of the faults being at rockhead (or base of Permian), not at position of mining.

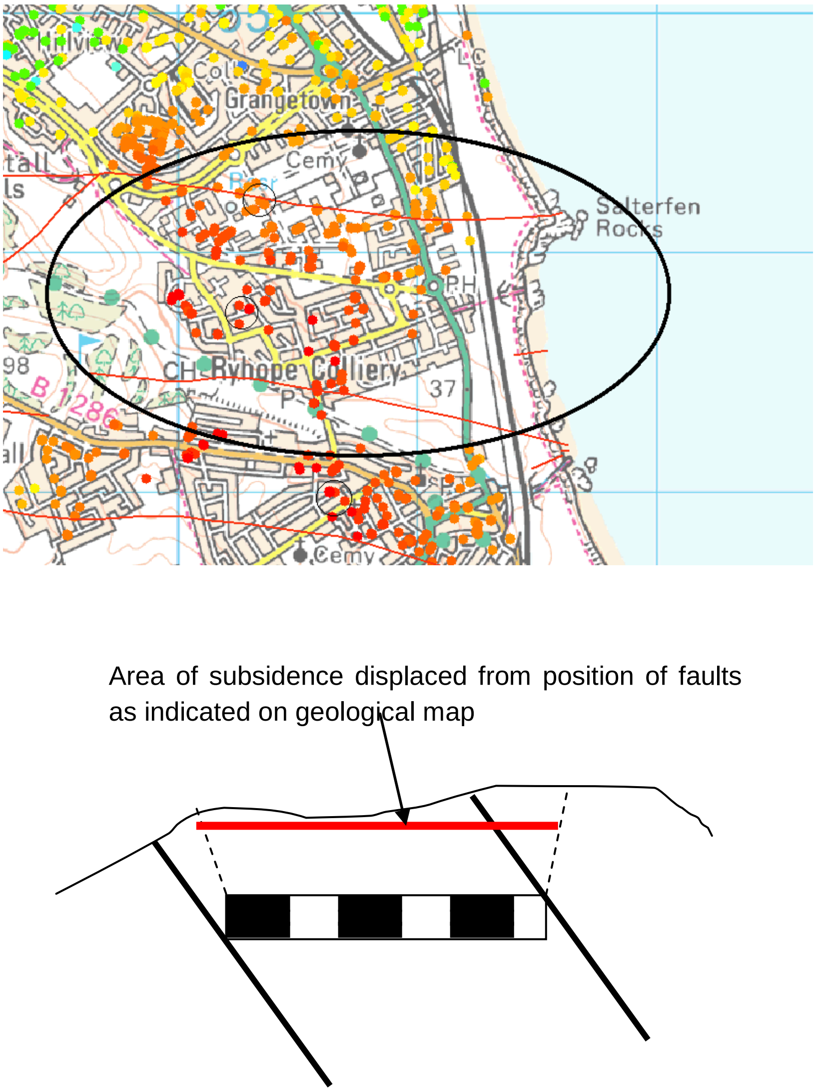


Figure 35: Top: ERS PSI average annual velocities for the Ryhope area. Bottom: Geological explanation for the apparent offset of the motion to the faults which are thought to be controlling the motion

The Ryhope Colliery was closed in November 1966. Any motions relating to the collapse of mine working would be expected to have taken place before the start of the PSI dataset in 1995. It would therefore be interesting to study the type of mine working used in the Ryhope colliery to see if this might have led to collapse at a later date and to try and understand how the period of maximum subsidence from March 1997 and August 1998 occurred. It would also be interesting to study the groundwater levels for this area to see if water inundation of old workings has caused degradation and movement in the mined area.

5.4.4 Sunderland and South Shields

The motion history of Sunderland (Figure 36) is similar to that seen in Ryhope, namely subsidence in 1995 to 2000 followed by uplift in 2002 to 2008. Once again it would be interesting to see groundwater level data for this area to see if a relationship exists with the motions revealed by the PSI data.

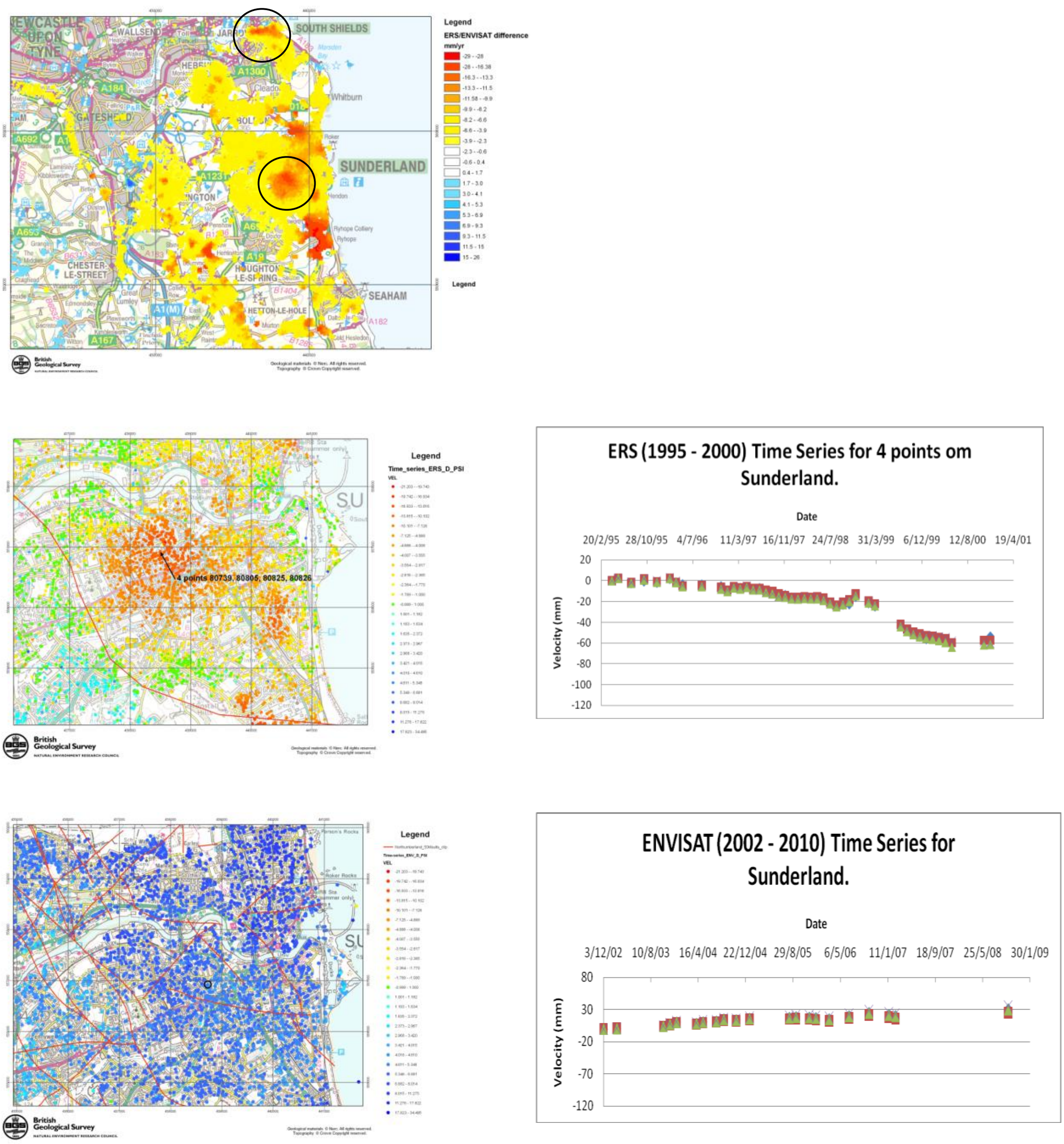


Figure 36: ERS (middle) and ENVISAT (bottom) motions for PS points in Sunderland. On the left of the figure are average annual velocities; on the right are PS point time series data for selected points (highlighted by black circle on the left hand image).

In the 1990s Newcastle University undertook a study for the Environment Agency, 'Predicting Mine Water Rebound' (Environment Agency, 1999). Additionally, the Coal Authority commissioned work to to better understand the hydrogeological regime and the effect of changes in pumping following the closure of mines in the Northumberland and Durham region. This enabled the area to be described in terms of a series of underground 'ponds' holding water at different levels and either rising or lowering, largely dependent on pumping. The ponds were, for the most part, interconnected and allowed flow between areas. From limited information that was made available to the BGS approximately between 1999 and 2003, the position of the ponds appeared to be controlled by the geological structure, particularly faults. Figure 37 shows the mine water 'ponds' in relation to the ERS average annual motion. It is believed that Pond 10 is where the mine water is deepest, this corresponds to the area where subsidence is occurring in South Shields and Sunderland. It is possible that the mine water is deepest as the pumping of water is greatest here. If the pumping is greatest then this might account for the subsidence.

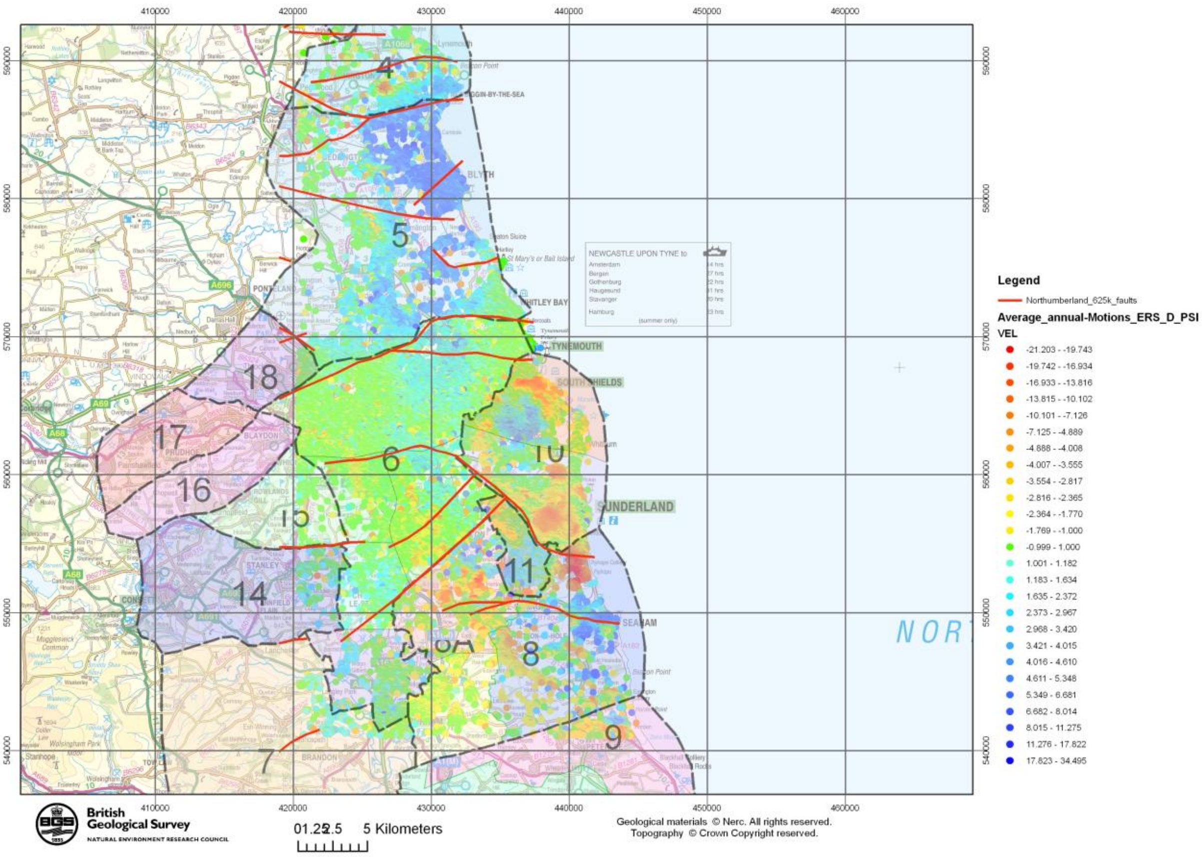


Figure 37: ERS average motion and the Minewater 'ponds'.

It would be instructive to examine this further using the data held by The Coal Authority.

5.4.5 Ellington; motion in relation to active coal mining

BGS active mining records for the area indicate no obvious relationship between areas of motion and the location of active mines. There were five mines active in the area at various times within the period of interest:

Four surface (opencast) mines:

1. Priors Close North,
2. Herrington colliery,
3. Pegswood Moor Farm,
4. Stobswood,

One deep mine:

1. Ellington, which closed in January 2005. Ellington colliery was therefore active for much of the study period.

It is not expected to find PS points relating to opencast workings since the removal of material leads to a loss of coherence between radar images, therefore a permanent scatterer cannot be detected in the area.

Examination of the ERS data for the Ellington site (Figure 38) shows that the area in the immediate vicinity of the mine is mainly stable. There are however several points within 1 km which show a negative average annual velocity of 2.5 to 4 mm/yr. Approximately 2 km to the southeast of the colliery is an area showing more constant negative motions. ***It would be interesting to compare the location and timing of these motions with the coal seam exploitation plans of the Ellington mine. These observed motions could be related to mining activity and should be investigated further by the Coal Authority in light of the more detailed data that they hold.***

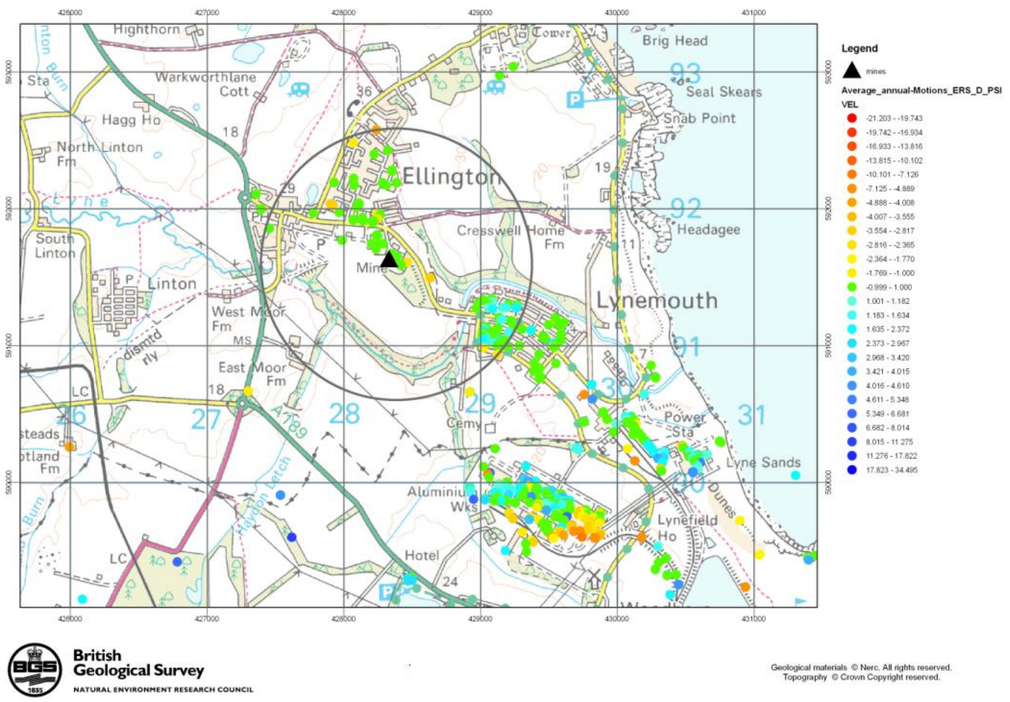


Figure 38: Ellington Mine closed 2005. ERS average annual velocities show that the area is mainly stable.

Examination of the ENVISAT data for the Ellington site (Figure 39) shows that between 2002 and 2008 the site exhibited stable behaviour to the north west of the mine. Moving in a south east direction the nature of the motion becomes that of uplift, with rates up to 2.5 mm/yr. Once again it would be interesting to compare the dates of mining with the temporal range of the motions.

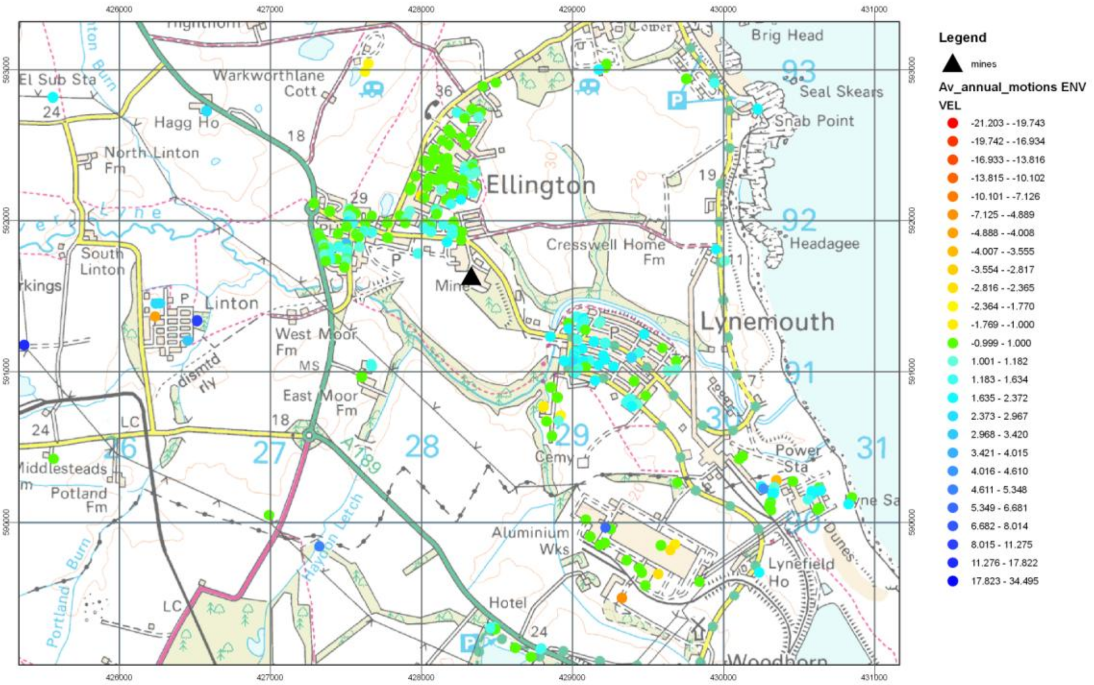


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Figure 39: Ellington Mine closed 2005. ENVISAT average annual velocities show that the area is mainly stable or uplifting.

6 OBSERVATIONS

6.1 Assessment of impact and benefits

The PSI data have revealed ground motions, in this area, that the BGS were unaware of. It has also revealed that the motion history from 1995 to 2000 for the southern part of the study area is very complex. This is a great benefit as it shows that a single model for subsidence, at this time, in this area would not be applicable.

This study has also highlighted the fact that ground motion is a very time dependant phenomenon as evidenced by the dramatic change of motion in the southern part of the study area.

6.2 Critical analysis of utility for end-user organisation

BGS believe this data should be of use to the Coal Authority. No other technique offers the capability of providing a historic record of the ground motions over a very large area covered by the coal field. This should offer the Coal Authority the chance to better understand how motions in the area relate to natural processes and processes relating to the extraction of coal. Analysis of the data in conjunction with the Coal Authorities' database of subsidence claims made against them may allow a relationship to be established between the geological conditions, timing and method of coal extraction, water pumping and the amount of resulting ground motion which has led to a claim for damage resulting from subsidence. This information may then contribute to the understanding of the management of abandoned mining.

6.3 Comparison with alternative services and information sources

There is no other service or technique which would offer the same type of measurements over such a wide area. Levelling and GPS are the obvious techniques which offer millimetric level measurements comparable to those of PSI. Although levelling and GPS are arguably better accepted techniques neither GPS or levelling offer the same opportunistic or historic capabilities as PSI does. It is necessary to place a measurement device on the location where it is required and if it has not been carried out for the dates of interest then the data does not exist. PSI offers the opportunity of historical measurements from 1992 onwards.

6.4 Recommendations for product improvements

PSI datasets contain a great deal of information, when separate PSI datasets are delivered for both ERS and Envisat data then the amount of data for an area become huge. This requires a great deal of time and expertise to analyse fully and properly. In this instance it was not possible to use the ascending data for PSI analysis; if this had been possible then the interpretation would have been very lengthy indeed.

DifSAR data is not as accessible as the PSI datasets. This is due to the nature of its presentation as images. Trying to detect, understand and interpret motions on over 50 DifSAR images is a difficult task. Therefore the BGS did not make as much use of this data as would have been ideal.

Now that the PS technique has become more mature perhaps an effort on making the data more accessible and therefore easier to interpret is required. As a first pass the average annual velocity is an important visual guide to areas that might be undergoing motion. However as with all averages, trends in the underlying time series can be hidden. For example if, with the time period processed, an area undergoes subsidence and then uplift the overall average motion might be close to zero. When carrying out the interpretation this area may well be overlooked as an area which, on first glance, appears to be stable. It would be valuable to develop a visualisation technique whereby the user can step through the time series in a visual manner and hence pick up all trends of motion no matter their time span.

We also point out within this report that approximately 50% of the Northumberland study area is covered by the PS points. While for areas with sufficient PS point coverage it is relatively easy to see the overall trends in motion it can be difficult to push the geological interpretation to areas with insufficient PS point coverage. This becomes harder when you have a result such as the southern half of the ERS result for Northumberland where the motion characteristics area changing over short distances. It would therefore be beneficial to have a method of filling these gaps in the PS coverage – perhaps with a different ‘flavour’ of InSAR.

6.5 Record of complaints, problems, resolutions

None to report.

7 CONCLUSIONS

It can be difficult to recognize generalised patterns because PSI data is only present in discrete areas. However, it has been possible to make some general correlations between geology and PS motion, but it seems that in most cases it will be necessary to provide specific explanations for localised motion.

It is also apparent that a PSI dataset contains a great deal of information for many different areas and underlying reasons for the motion observed. To complete a full interpretation of this data would require a great deal of time and resources. The BGS also recognises that we do not hold all the data necessary to fully interpret the ground motions in this area. The Coal Authority do hold this data. The interpretive work reported here will provide a good basis to build upon in the light of more in depth data on: the dates and method of coal extraction, ground water pumping histories (both amount and timing of), groundwater levels and claims made against the Coal Authority for subsidence related damage.

General conclusions which have been drawn from this work are:

1. Although already known, it has highlighted that the pattern of ground motion can substantially change through time.

2. Rather than having a single PSI result for the whole study period it can be beneficial to obtain two or more PSI results since it allows motion patterns to stand out when the average annual velocity is displayed.

Conclusions drawn from the ERS PSI motion:

1. The information does not appear to show a direct relation to variation in bedrock geology

2. The pattern of motion can be related to the thickness of superficial deposits in some areas

3. Motion appears to be controlled by the faulting, both at the regional scale and smaller scale

4. Some areas of subsidence might be related to areas of depressed minewater (deepest minewater ponds and hence pumping).

5. Some areas of subsidence might be related to remnant mine collapse

6. It is likely that many areas of subsidence seen in the ERS data area is a result of the combination of points 2, 3 and 4 above. That is that subsidence is likely to be a result of the complex relationship between remaining collapse of old workings (although most should have occurred by now), pumping of the ground water to prevent flooding of workings and therefore contamination of the ground water supply and the accommodation motion caused by the above factors by the faults fissures and joints in the area.

Conclusions drawn from the Envisat PSI motion:

1. Dramatic change in the south from strong subsidence to strong uplift.

2. No direct relation to bedrock geology

3. Areas of subsiding motion relating to compressible sediments in the ERS data appear to be uplifting – possibly a result of a regional rise in ground water levels.

4. Some areas appear to be related to faulting – but fewer than for ERS period

5. The uplift, in both the north and south, does not appear to be controlled to a great extent by the faulting and appears to be a regional phenomenon, especially when compared to the typical subsidence characteristics.

6. The regional scale and other characteristics suggest a water table related cause for this uplift.

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