Detecting and monitoring small-scale discrete ground movements across London, using Persistent Scatterer InSAR (PSI)

Detection et contrôle de mouvement de terrain à petite échelle à travers Londres, en utilisant PSInSAR

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ABSTRACT The geology of London is surprisingly poorly understood and, until recently, has been accepted as that of an unfaulted subsiding intraplate basin. The detection of deformation in such quiescent intraplate regions is, however, rather difficult since the movement rates are at least an order of magnitude less than those at plate margins. Growing evidence from across the capital indicates that London's ground conditions are considerably more complex than expected and that faulting is almost always involved.

PSInSAR is a developing technique widely used to detect and monitor ground subsidence, especially in urban settings, the movements of which may be up to tens of millimetres. This work focuses on the detection of smaller scale ground movements (of a few millimetres), which we believe are caused by fault-controlled intraplate adjustments, using PSInSAR.

The London PSInSAR dataset derives from an imaging SAR archive spanning 18 years (1992 - 2000 and 2001 to 2010). Our preliminary findings have revealed systematic patterns of both vertical and horizontal ground displacement. These displacements appear to be fault constrained and fit the predicted framework of Caledonian, Variscan/Alpine structures known to exist across southern Britain. More detailed analysis has revealed some surprising patterns, which hint at discrete movements rather than continuous 'creep' over the 18 year period; we believe these are driven by basement faults beneath an inverting London basin.

RÉSUMÉ La géologie de Londres est étonnamment mal comprise et, jusqu'à récemment, le consensus s'établissait autour d'un bassin intraplaques en affaissement et sans failles. La détection de déformations au sein de telles zones intraplaques quiescentes est en effet difficile car les taux de déplacement sont au moins un ordre de grandeur en dessous de ceux aux frontières de plaques. Des données de plus en plus nombreuses provenant de toute la capitale indiquent que la situation du terrain londonien est bien plus complexe qu'attendue et des failles ou fractures sont presque toujours impliquées.

PSInSAR est une technique en développement déjà largement utilisée pour détecter et surveiller la subsidence du sol, en particulier dans les zones urbaines où les mouvements correspondant peuvent êtres de l'ordre de la dizaine de millimètres. Grâce à cette technique, cette étude se concentre sur la détection de mouvements du sol de plus petite magnitude (de quelques millimètres), que nous pensons être causés par des ajustements intraplaques contrôlés par failles.

La série de données PSInSAR de Londres provient d'une archive d'images SAR [radar à synthèse d'ouverture] couvrant 18 ans (1992-2000 et 2001-2010). Nos résultats préliminaires ont révélés des profils systématiques de déplacement du sol verticalement et horizontalement. Ces déplacements paraissent contraint par des failles et correspondent au cadre prévu de structures calédoniennes, varisques/alpines dont l'existence est connue au sud de la Grande Bretagne. Une analyse plus détaillée a révélé des schémas surprenant qui suggèrent des mouvements discrets plutôt qu'un rampement continu pendant les 18 ans. Nous pensons que ce phénomène est dû à des failles au niveau du socle sous un bassin londonien en inversion.

1 INTRODUCTION

The London Basin is a wedge-shaped asymmetric depression extending from Newbury to Rochester and Great Yarmouth in southern England. It has experienced no significant geological activity in the last 50 Ma (Ellison et al., 2004) and has one of the lowest probabilistic seismic hazard assessments in Great Britain (Musson, 2007) (Figure 1). Nonetheless, it is one of a number of post-Variscan sedimentary basins (Busby and Smith, 2001), others of which were inverted during the Neogene (Chadwick, 1993). These Permo-Triassic basins opened by reverse movement above Variscan-age basement transcurrent (strike-slip) and thrust faults (Chadwick and Evans, 1995) and, while each opened at different times, they were generally depositional during the Mesozoic. NW-SE trending basement faults were reactivated as dextral transcurrent faults at various points in the Palaeogene and Neogene, causing inversion of the Hampshire and Weald basins (Blundell, 2002; Chadwick, 1993). The Weald, for example, has been uplifted by more than 1500 m since the Cretaceous (Jones, 1999). The inversion is likely a result of the combined compressive effects of the Alpine collision and North Atlantic ridge push (Musson, 2007). The London Basin was thought to have been unaffected by inversion but a reappraisal of the evidence indicates recent and ongoing inversion of the basin (Royse et al., 2012; Ghail et al., 2015).

Conventional GPS monitoring provides neither the temporal coverage nor the spatial density of observations necessary to resolve such small scale ground movement patterns. We therefore turn to PSInSAR, which was developed initially to detect and monitor ground subsidence, on a scale of 10s of millimetres, especially in urban settings. Using PSI we focus on the detection of smaller scale ground movements (of only a few millimetres) which we believe are caused by fault-controlled intraplate adjustments, using PSInSAR; a technique which we refer to as MicroPSI or MPSI.

Our MPSI investigations of London have been driven by numerous cases of unexpected ground conditions encountered at various site investigations across the capital. These unexpected conditions usually reveal more structurally complex geology than was expected, and in most cases the materials are faulted and fractured to a surprising degree. Our geological understanding, based on field evidence, borehole logs, geophysical survey data, Quaternary geology and fluvial evolution, has led us to believe that the ground movements we have detected are caused by discrete tectonic events on basement faults beneath an inverting London basin.

1.1 Background geological setting

The London Basin (Figure 1) differs from other sedimentary basins in southern England by lying north of the 'Variscan Front', on the margin of the Midlands microcraton, and in having a distinctive wedge-shape, bounded by the chalk hills of the Chilterns and the North Downs. It was a subaerial high throughout much of the Mesozoic but underwent complex and rapid deformation during the late Palaeogene (Knox, 1996), since which time it has remained subaerial and quiescent (Gibbard and Lewin, 2003). Although Wooldridge (1923) recognised its structural complexity nearly a century ago, the prevailing simple synclinal model (Sherlock, 1947) persisted into the 1990s (Sumbler, 1996). Faults are rarely recognised in London (Aldiss, 2013) and evidence for recent fault displacement is rarer still. Yet countless site investigations have revealed brittle failures in Palaeocene materials all over London. A Neolithic trackway, dating from between 1520 and 1100 BC, unearthed in 1993 in Beckton [TQ 427 820] was found to be cut by a fault which is infilled with clay (Greenwood and Maloney, 1994), implying a significant London earthquake within the last 3000 years. The Colchester Earthquake of 1884, which occurred at the NE edge of the London Basin, was probably the most damaging in Britain in the last 400 years (Musson and Winter, 1996).

The surface drainage network and connectivity within the chalk aquifer in London reflect a complex pattern of faulting (de Freitas, 2009) related to Variscan basement fractures. The many instances of unexpected ground conditions, encountered in London since Victorian times (Chandler et al., 1998; Lenham et al., 2006; Mortimore et al., 2011; Newman, 2009) also point to greater structural complexity. A variety of Pleistocene (Berry, 1979; Hutchinson, 1980) and Holocene features (Akeroyd, 1972) mask deeper tectonic changes but nonetheless, a regional uplift of at least 0.07 mm a^{-1} across the Thames valley in the last

900 ka has been detected (Maddy et al., 2000), with perhaps a higher rate in the last 400 ka, despite recent deglaciation (Nunn, 1983). A reappraisal of new and existing data (Royse et al., 2012; Ghail et al., 2015) in light of these observations indicates incipient inversion of the London Basin.

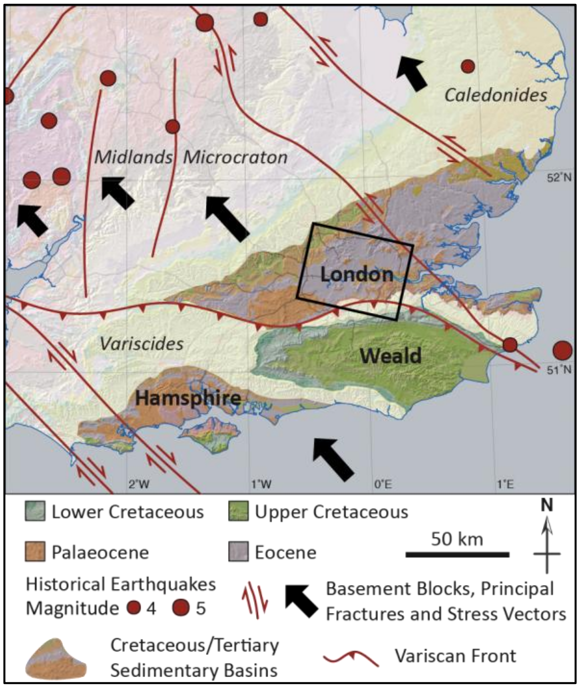

Figure 1. The Cretaceous/Tertiary transtensional basins and Variscan basement fractures of southern England. The region is historically aseismic but nonetheless influenced by north-directed Alpine stresses. Black rectangle indicates approximate coverage of the London PSI dataset. (Developed from Musson 2007, with Geological Map Data BGS © NERC 2013 and Ordnance Survey Data © Crown copyright/database right 2012. An Ordnance Survey/EDINA supplied service)

1.2 Persistent Scatterer InSAR

Persistent or Permanent Scatterer Interferometry (PSI) is the most advanced development of Differential Interferometric Synthetic Aperture Radar (DInSAR) and provides millimetre scale measurements of vertical ground movements on an approximately monthly timescale (Ferretti, 2001, Tele-Rilevamento Europa, 2013). The technique is well established and is ideal for detecting small, gradual (and abrupt) ground movements. PSI is widely used for detecting and monitoring ground subsidence, is increasingly being used for monitoring landslide (Collesanti et al, 2003; Ng, 2012; Meisina et al., 2006, 2007 & 2008) and fault movements, especially in earthquake prone areas (Ferretti et al. 2006). PSI has also been used to estimate rates of sea level change along the Thames estuary (Bingley, 2008) for long-term flood risk and to characterise subsidence along the Jubilee Line extension (NPA & ESA, 2006).

The main advantage of PSI is that it compares a very large stack of interferograms (usually a minimum of 14) which reduces noise and error considerably (Tele-Rilevamento Europa, 2013). The technique requires the identification of a selection of permanent or persistent scatterers (PS), which involves comparing the pixels in several acquisitions of the same scene, initially selecting those with stable amplitude using an amplitude dispersion index (Ferretti et al. 2001). A time series analysis of pixel phase values is then used to identify any remaining candidate pixels (Ferretti, 2001).

A great advantage of PSI is its ability to record vertical as well as eastward or westward movements (Eastward on the ascending orbit from a ‘right-looking’ aperture, and westward ('left-looking') on the descending orbit) (Wright, 2004). Movements towards or away from the sensor can, however, only be detected in the line of sight. It is therefore not yet possible to measure North-South movement, which would require images from at least 3 different viewing geometries and look angles (Tele-Rilevamento Europa, 2013).

Once identified, the persistent scatterers are used as spatial reference points between acquisition dates, from which to detect small displacements toward or away from the SAR antenna (the orbital geometry of which is known precisely). In this way different observations of the same area can be compared even with very large baselines or from images with different radar band properties. Using this large image dataset allows for a significantly better correction for the different factors that normally cause decorrelation between SAR acquisitions (Tele-Rilevamento Europa, 2013).

The main influences on PSI data quality include the spatial density and quality of the persistent scatterers, the weather conditions during and between acquisition and the distance between a measurement point and its nearest reference point. The precision of PSI is much greater than that of DInSAR and is typically able to detect a ground displacement rate of <1 mm a^{-1}, and individual displacements of ~5 mm (Tele-Rilevamento Europa, 2013). The errors are lowest in central London where the PS point density is greatest.

2 MPSI ANALYSIS OF THE LONDON DATASET

The London PSInSAR dataset is collected from an imaging SAR archive spanning 18 years (1992 - 2000 and 2001 to 2010). Each PSI dataset contains the ground movement of permanent scatterers over several years, their average velocity (in the line of sight) over those years and errors for both height and velocity measurements. The earliest of the two datasets covers the period from 5th May 1992 to 12th January 2001 and contains 760,274 permanent scatterers measured on 68 irregularly spread dates; its baseline is the 5th May 1992 and later measurements are relative to the measurements of that date. The second dataset covers the period 13th December 2002 to 17th September 2010 and contains 45 measurements on irregularly spread dates, and 1,048,575 permanent scatterers; its baseline is the 13th December 2002.

The left-looking PSI data covering the two time periods were obtained from the descending orbits of ERS (1992-2001) and ENVISAT (2002-2010). In addition, right-looking PSI data were obtained from the ascending orbit of ERS only, which covers the 1992-2000 period, although these data were only available for the northern half of the study area. Buildings and other structures make urban areas particularly suitable for PSI data and consequently there is a particularly high concentration across the London region but parks and other open areas are notably absent in the PS data. Locally, the displacement velocities and directions (towards or away from the satellite) obtained at PS points can vary considerably as a result of construction, road resurfacing, localised settlement, etc. but small-scale regional patterns are discernible geographically regardless of these high magnitude changes.

The PSI data points are irregularly distributed and the scatterers in the ERS and ENVISAT datasets are not necessarily located at the same geographic position. To compare velocities between these datasets continuous velocity surfaces were produced by interpolation of the point velocity values of each acquisition, using an automated inverse distance weighted (IDW) method. The interpolated surfaces were produced at 10 m spatial resolution and the interpolation was restricted to an area of 140 m radius around each input PS point to prevent the prediction of unrepresentative values in data gaps. One interpolated raster is made for each date of measurement thus producing 113 velocity surfaces over the 20 year period.

The PSI velocity rasters were then clipped, to reduce 'noise' or 'speckle' (related to movements caused by construction, etc.), removing values of more than ±3 mm a^{-1}. This seemingly arbitrary cut-off was chosen on the basis of the 1997 to 2005 data (Bingley, 2008), which indicated natural ground movements in the range approximately from +0.5 to −2.5 mm a^{-1}, and is relevant for this dataset only.

2.1 *Detecting lateral and vertical movements*

The SAR imaging geometry allows us to derive rates of east-west displacement from right- and left-looking ERS PSI data. Values that are positive in the left-looking data and negative in the right-looking data indicate eastward ground motion (towards 098N), and those which are negative in left-looking and positive in right-looking indicate westward motion. Values that are positive or negative in both datasets indicate vertical displacement only with no horizontal movement. The latter are likely related to changes in groundwater level, construction, and other non-tectonic effects, which have been illustrated in the PanGeo interpretation of PSI data for London (Cigna et al, 2014).

To highlight the lateral component we colour-coded the ERS PSI values to indicate pixels with consistent westward motion in red, and consistent eastward motion in blue (Figure 2). This reveals surprisingly consistent patterns in which large blocks show relatively uniform eastward or westward movement. When the known arrangement of fault orientations is considered (Ghail et al., 2015), these patterns of movement seem to fit very well into lozenge-shaped blocks bounded by strike-slip and thrust faults (see also Figure 5).

To highlight vertical (and temporal) changes in the direction of ground displacement, the interpolated ERS and ENVISAT PSI data were combined and colour-coded such that red areas show continuous positive displacement of the ground surface (uplift, toward the sensor), blue areas show continuous negative displacement (subsidence, away from the sensor), and green areas reveal uplift in one dataset and subsidence in the other (Figure 3).

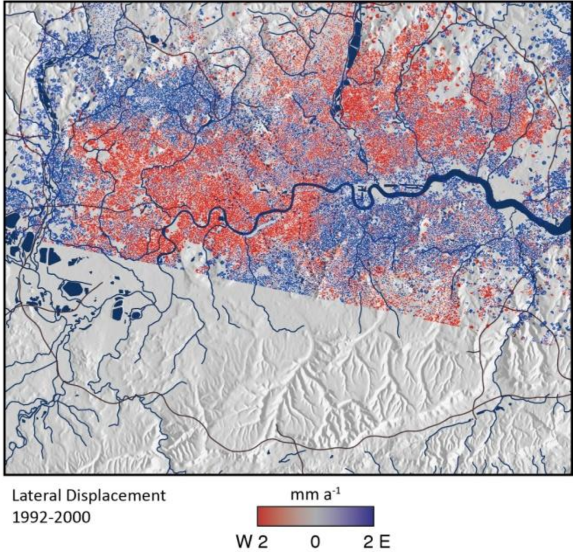

Figure 2. PSI lateral data - ascending and descending mode ERS data combined to isolate the east-west component of displacement. Two large west-moving blocks are identified in the west and NE, and two east-moving blocks in the NW and SE; patterns of displacement in the centre and far SE are less clear.

The latter are therefore rising and falling periodically in response to seasonal and annual changes in surface levels, probably as a result of groundwater changes and the presence of recent compressible materials. The more persistent vertical displacements (either positive or negative) are inferred to result from inversion of the London Basin, caused by dextral movement on basement transcurrent faults, and blocked by thrust faults parallel to the Variscan Front. These (expected) low rates of horizontal displacement are difficult to measure by conventional methods, particularly given that the faults themselves have, in general, not yet been identified (Aldiss, 2013).

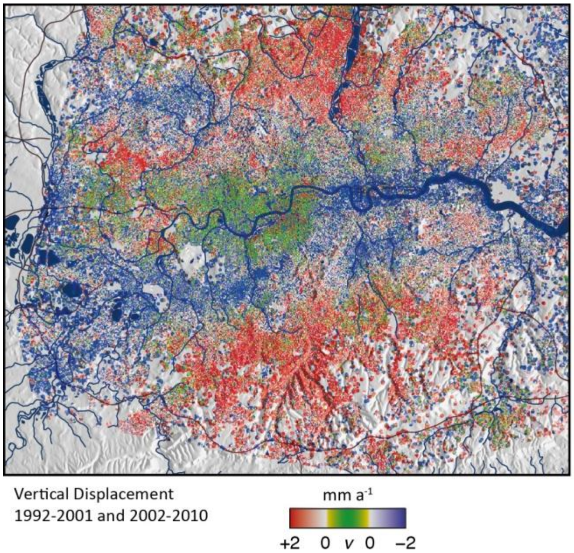

Figure 3. PSI vertical data - differences in vertical displacements over two decades reveal a consistent pattern of subsidence in the Thames valley, with uplift in the north, south and west. A mixed signal (v, in green) in west central London indicates uplift in one time period and subsidence in the other.

Particularly noticeable are the contiguous blocks of movement in a consistent direction (either up or down), see Figure 3. The hills to the south and NE are consistently uplifting over the 20 year period, whereas the east and parts of Surrey and NW London, are consistently subsiding. Subsidence in the Thames Gateway may also be partly attributable to compressible ground materials. Again central London rises and falls periodically (seasonally).

2.2 *Detailed analysis of ground movements*

Detailed analysis of the individual PSI velocity datasets, allowing monthly measurements to be examined in some cases, revealed a complex pattern of movements. Unsurprisingly these prove to be far more difficult to interpret and show gradual but occasionally consistent fluctuations within confined zones; these zones coincide with inferred fault block boundaries in many cases. Comparison with rainfall data reveals extremely complex patterns which may never be fully understood. There is no obvious correlation between the fluctuations of ground movements and the rainfall records (which are considered here as a partial proxy for groundwater).

There are however several data intervals which show more abrupt changes and which hint at periodic discrete movements that might be fault controlled. The most notable of these occurred in 2005, between October and December 2005, when a significant drop in ground level, of unusual spatial geometry, occurred across central, eastern and northern London. Subsidence of between 5 mm and 12 mm in less than 4 months has been detected (Figure 4). The driving force is unclear but the change is too sudden to be explained simply by seasonal groundwater changes. Between December 2005 and May 2007 there is a gradual and complex rebound, in some but not all areas, of as much as 20 mm. It is possible that construction-related groundwater pumping is at least partially responsible for such changes but clearly further investigations are necessary to verify any interpretations. Although the ground movements in these individual acquisitions are comparable in magnitude to the predicted PSI errors, any systematic movements or movements which are consistent over large areas, and especially those with sharp boundaries, can be considered to reflect real movements rather than stochastic noise.

3 GEOMORPHOLOGICAL SIGNIFICANCE

The mean displacement rates of the blocks identified in the PSI lateral and vertical data (Table 1) are consistent with independent data derived from GPS monitoring (Teferle, 2009). Assuming that the PSI-derived lateral movements are generated by displacement on NW-SE oriented basement transcurrent faults, the true mean dextral displacement vector is 1.6 ± 2.3 mm a^{-1} to 326N ± 12°; the GPS derived mean rate is 0.7 ± 1.6 mm a^{-1} to 323N ± 15° after correction for the absolute plate motion vector of 24 mm a^{-1} to 051N. These rates are of comparable magnitude and are at least an order of magnitude lower than plate boundary rates, yet they are still fault controlled.

Table 1. Mean rates of ground displacement across London

Region	Vertical	Lateral
North east	+0·17 ± 0·46 mm a^{-1}	1·06 ± 1·60 mm a^{-1} W
Estuary	−0·61 ± 0·74 mm a^{-1}	1·09 ± 1·48 mm a^{-1} E
South east	+0·09 ± 0·53 mm a^{-1}	1·01 ± 1.49 mm a^{-1} W
West	+0·28 ± 0·52 mm a^{-1}	0·99 ± 1·41 mm a^{-1} W

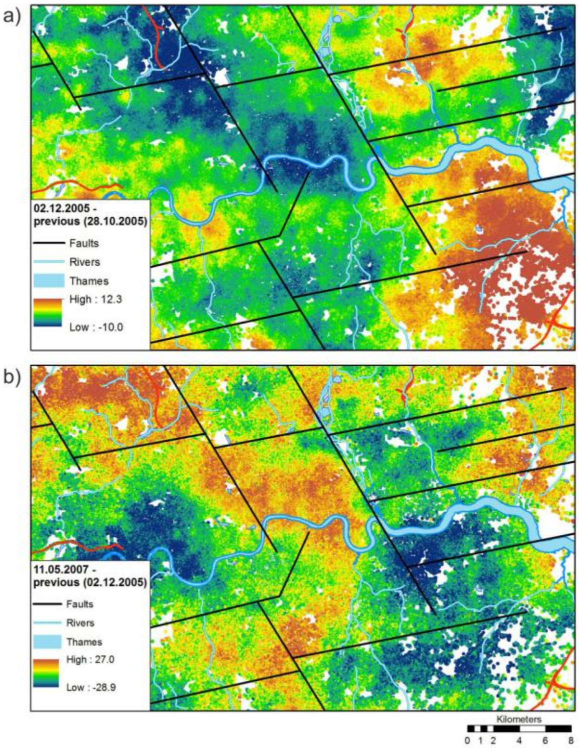

Figure 4. PSI vertical velocity rasters showing differential ground movement in central London in the intervals between a) October and December 2005 and b) Dec2005 and May 2007. A ground subsidence movement begins in October 2005 and is most noticeable in December 2005 (the relative drop is as much as 20 mm in places) and then uplifted again by May 2007 (rising again by as much as 30 mm in places). Black lines indicate the approximate positions of block-bounding faults (Ghail et al., 2015)

In addition to a range of expected patterns, caused by sediment compaction, ground water abstraction, etc., the data demonstrate differential vertical displacement of 1 mm a^{-1} or more across the Wimbledon fault and its lateral extensions, in line with previously inferred long-term trends (Maddy, 2000).

Our interpretation of the complex PSI patterns of ground movement across London, based on horizontal and vertical displacements, and supported by 3D modelling from borehole records, limited seismic interpretations and field observation, points towards a fascinating pattern of geological and geomorphological changes over the past ~400 ka (Figure 5).

The distribution and ages of Quaternary river terrace deposits reflects fault control on the migration of the Thames over that time; they mainly lie to the north of the modern Thames and to the NW of the River Lea (Figure 5a). The time-variant PSI vertical changes suggest uplift and subsidence caused by fluctuations in the depth of the lower aquifer (especially near A, Figure 5b). In the east (green shading at B, Figure 5b) the Thames appears to be 'ponding' in a consistently subsiding area, and with the older river sediments to the north and younger to the south.

The sharp bend in the Lea valley (south of C, Figure 5b) occurs at the junction of the river and a boundary between areas of subsidence and uplift, i.e. a fault boundary, and is caused by block tilting. Similarly, the Lea valley river sediments all lie to the NW of the river north of the sharp bend in its course at C (Figure 5a) indicating SE migration of the river over the last 400 ka. In the west, the marked southward displacement of the Thames over the last ~420 ka (indicated by the arrow at D, Figure 5b) may result from fault-bounded block tilting, causing uplift north of the M4 and subsidence to the south, and progressive deposition of younger sediments southwards in this area.

The PSI data are consistent with interpreted a pattern of block displacements, defined by dextral transcurrent faults oriented NW-SE and ENE-WSW oriented normal faults (possibly reactivated as reverse faults and often with oblique slip); these form the boundaries of uplifting or subsiding blocks (Figure 5b).

4 CONCLUSIONS

The displacements detected here all occur within the interior of the European plate, more than 1500 km from the plate boundary at the mid-Atlantic ridge, and are therefore genuinely intraplate displacements. Globally, similar intraplate tectonic ground movements may be occurring in other seismically quiet regions, even those intensively investigated by conventional means.

Our results demonstrate the effectiveness of bidirectional PSI at discriminating the very low rates of horizontal and vertical ground deformation in intraplate areas; rates impossible to measure by conventional means. PSI is more effective than long-term GPS monitoring and is the only way to resolve patterns, and therefore boundaries, between areas of consistent movement, i.e. the fault lines which are responsible for the deformation. Our preliminary PSI investigations of the London area are consistent with

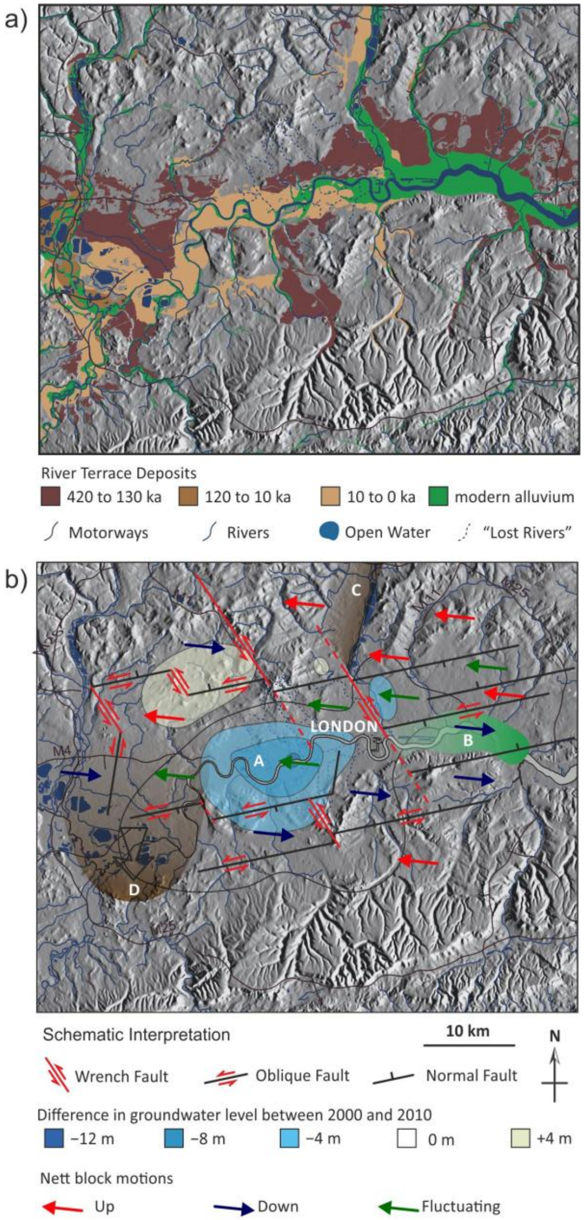

Figure 5. Geological change in the London region. a) River terrace and loess deposits of the last 420 ka nearly all lie to the north of the modern Thames and to the NW of the upper Lea. (b) Interpretive cartoon of the major features observed in Figures 2, 3 and 4 and in (a) above (adapted from Ghail et al., 2015).

a wide range of other evidence for fault controlled geological activity (and basin inversion) in the relatively recent past. PSI is particularly effective in urban areas, which are sensitive to such small but long-term changes, and the technique could therefore be developed to complement existing risk models for other cities in intraplate regions.

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