Proceedings of the Geologists' Association 125 (2014) 1–13

Contents lists available at ScienceDirect

Proceedings of the Geologists' Association

journal homepage: www.elsevier.com/locate/pgeola

Geological interpretation of current subsidence and uplift in the London area, UK, as shown by high precision satellite-based surveying

Don Aldiss [a,*], Helen Burke [a], Barrie Chacksfield [a], Richard Bingley [b,1], Norman Teferle [b,1,2], Simon Williams [c,3], David Blackman [c,3], Richard Burren [d,4], Nigel Press [d,4]

[a] *British Geological Survey (BGS), Keyworth, Nottingham, UK*
[b] *Institute of Engineering Surveying and Space Geodesy (IESSG), UK*
[c] *Proudman Oceanographic Laboratory (POL), UK*
[d] *Nigel Press Associates Ltd (NPA), UK*

ARTICLE INFO

Article history:
Received 1 March 2013
Received in revised form 17 July 2013
Accepted 20 July 2013
Available online 20 August 2013

Keywords:
PSI
Land level change
Holocene
Tectonic control
London

ABSTRACT

Long term planning for flood risk management in coastal areas requires timely and reliable information on changes in land and sea levels. A high resolution map of current changes in land levels in the London and Thames estuary area has been generated by satellite-based persistent scatterer interferometry (PSI), aligned to absolute gravity (AG) and global positioning system (GPS) measurements. This map has been qualitatively validated by geological interpretation, which demonstrates a variety of controlling influences on the rates of land level change, ranging from near-surface to deep-seated mechanisms and from less than a decade to more than 100,000 years' duration.

During the period 1997–2005, most of the region around the Thames estuary subsided between 0.9 and 1.5 mm a^{-1} on average, with subsidence of thick Holocene deposits being as fast as 2.1 mm a^{-1}. By contrast, parts of west and north London on the Midlands Microcraton subsided by less than 0.7 mm a^{-1}, and in places appear to have risen by about 0.3 mm a^{-1}. These rates of subsidence are close to values determined previously by studies of Quaternary sequences, but the combined GPS, AG and PSI land level change data demonstrate a new level of local geological control that was not previously resolvable.

1. Introduction

The general pattern of relative sea-level change around Britain has long been recognised from landforms such as raised beaches in Scotland and Wales, and 'submerged forests' and 'drowned' river valleys in southern England (Shennan, 1989). Typically, these are a consequence of changes in both absolute sea level and absolute land level, relative to the geoid. Latterly, it has been possible to estimate rates of land level change during the late Quaternary. Broadly speaking, such estimates have been based either on mathematical models of crustal behaviour, specifically glacio-isostatic adjustment (GIA), such as those of Peltier et al. (2002) and Bradley et al. (2011), or on the interpretation of radiometrically-dated horizons in late Quaternary coastal sedimentary sequences (Shennan, 1989; Shennan and Horton, 2002; Shennan et al., 2006; Gehrels, 2010).

Comparison of continuous global positioning system (CGPS) measurements of present-day absolute crustal motion with modelled predictions of GIA in the British Isles (comprising the UK and Ireland) show that the vertical elements of motion are highly correlated, implying that GIA (here related principally to the British ice-sheet) is the dominant process controlling absolute uplift and subsidence (Bradley et al., 2009). The GIA model of Bradley et al. (2011) predicts uplift of more than 0.8 mm a^{-1} in central Scotland, and subsidence of between 0.6 and 0.8 mm a^{-1} in most of southern and eastern England. Other GIA models find a similar pattern of land level change, but with different rates reflecting the different models of past ice distribution and of visco-elastic behaviour in the Earth's crust (Peltier et al., 2002; Bradley et al., 2009, and references therein).

The geologically-based studies show a generally similar pattern of uplift in Scotland and northern England and subsidence in southern Britain, although this variation is relative to sea level. Maximum rates of uplift, of 2.0 mm a^{-1}, are found in western Scotland, varying to subsidence of as much as 1 mm a^{-1} in Essex and maximum subsidence of 1.5 mm a^{-1} in western Ireland (Shennan and Horton, 2002; Gehrels, 2010). However, such

---

[*] Corresponding author. Tel.: +44 115 936 3129.
E-mail address: dta@bgs.ac.uk (D. Aldiss).
[1] Now Nottingham Geospatial Institute (NGI), University of Nottingham, UK
[2] Current address: Faculté des Sciences, de la Technologie et de la Communication, University of Luxembourg 6, rue Richard Coudenhove-Kalergi, L-1359 Luxembourg, Luxembourg.
[3] Now National Oceanography Centre (NOC), Liverpool, UK.
[4] Now NPA Satellite Mapping, CGG, Crockham Park, Edenbridge, Kent, UK.

0016-7878/$ – see front matter
http://dx.doi.org/10.1016/j.pgeola.2013.07.003

determinations of local sea level change are commonly based on data from several localities at some distance from each other, the rates of change are typically non-linear, and, as pointed out by Gehrels (2010), late Holocene sea level curves for the British Isles are subject to various global, regional and local processes that can influence sea level change. These factors all present difficulties to the interpretation of geologically-based Holocene sea level curves as indicators of land level change at the present day.

These two methodologically independent approaches to this topic provide comparable results: they are, within their limitations, robust and successful (Bradley et al., 2011). However, neither method provides a level of detail that is sufficient to demonstrate (A) the actual rate of absolute or relative land level change at the present time, or (B) how changes in land level might vary through the region, both of which are required for assessments for the long term planning of flood risk management, as along the Thames estuary. For example, local geological controls on spatial variation in the rates of present-day land level change have been found in the Venice area of north-east Italy (Tosi et al., 2009), and in the Segura River Basin of south-east Spain (Tomas et al., 2011).

A study to determine rates of change in land level and in relative sea level around the UK was undertaken from March 1997 to December 2005 (Bingley et al., 2007, 2008). This project determined the average 'background' rate of sea-level change in British coastal waters, decoupled from changes in land level, i.e. the component of sea level change that includes the consequences of global climate change, which was found to be a rise of about 1 mm a^{-1}. The project also determined the absolute rate of land level change in the London and Thames estuary area. The relative rate of sea level change in the Thames estuary at the present time can thereby be separated into its two components. Relative rates of ground motion (as determined from geological observations) can be approximately compared with absolute rates of ground motion (determined by modelling or by instrumental observation) by allowing for this absolute rate of sea level change, although that rate will have varied through time.

On a national scale, the project involved the serial measurement of land levels by absolute gravity (AG) (Williams et al., 2001) and global positioning system (GPS) methods. For this project, requiring the measurement of millimetric changes in land level, two different approaches to the GPS data processing were used (Bingley et al., 2007; Teferle et al., 2009). On a regional scale, the project also used serial measurements from GPS, but in addition it included the determination of ground velocity for about 950,000 points using PSI (persistent scatterer interferometry) techniques. The PSI data were corrected using the AG/GPS determinations to provide a measure of absolute ground motion, relative to the geoid (Bingley et al., 2008).

This paper presents a geological interpretation of the AG/GPS-aligned PSI land level change data, demonstrating (A) that the PSI data is non-random, and so is a valuable tool for assessing patterns of modern ground movement, especially when aligned with measures of absolute ground movement, (B) local and regional patterns of ground movement and (C) probable mechanisms controlling those movement patterns.

2. Geological setting of London and the Thames estuary area

The geological setting of the London and Thames estuary area is described by Sumbler (1996) and Ellison et al. (2004). It is dominated by the synformal London Basin, which is bounded to the north-west and to the south by the Chalk Group and by older Cretaceous formations (Fig. 1). The main part of the London Basin is underlain by Palaeogene deposits, of which by far the most extensive is the London Clay Formation. That is underlain in turn by the Lambeth Group, also mostly composed of clay although with some sands and gravels, and by the Thanet Sand Formation, which is dominantly composed of silts and fine-grained sands. The London Clay is locally overlain by sands of the Bracklesham Group, here represented by the Bagshot Formation.

These bedrock formations are extensively covered by a variety of superficial deposits of Quaternary age. On the higher parts of the Chiltern Hills and the North Downs, the Chalk is partly overlain by the clay-with-flints, a clay-rich *remanié* deposit largely derived from a previous cover of Palaeogene sediments. The southern limit of the Anglian ice sheet lies within the north of London, and much of the northern part of the study area is underlain by clay-rich till, with some glaciofluvial deposits. River terrace deposits are, however, the most widespread type of superficial deposit, forming discontinuous flights at various levels. The youngest terrace deposits, dating from the late Devensian, are partly covered by Holocene alluvial sediments laid down on the flood plains of the River Thames and its tributaries (Ellison et al., 2004).

The natural land surface has been anthropogenically modified in various ways. Made ground is widespread, both in engineered embankments for transport routes, flood defence and so forth, and also as broad spreads within well-established urban areas. Much of central London, for example, is underlain by several metres of made ground. Mineral workings are fairly common, and in some cases have been infilled by waste. There are extensive areas of reclaimed land on either side of the Thames estuary, and in some cases the ground surface there has been artificially raised for development.

No seismic surveys of the geological basement in the London area are available, so its structure is revealed only by the regional geophysical fields, corroborated by the few boreholes that penetrate the base of the Cretaceous strata in this region (Ellison et al., 2004, Fig. 2). Variations in the regional Bouguer gravity anomaly field in the London area largely relate to geological formations occurring beneath the Chalk Group, mostly of Palaeozoic or Proterozoic age. The gravity data were processed using standard techniques, such as gravity stripping, to enhance these variations (Aldiss et al., 2006). The resulting map shows portions of three geological terranes within the pre-Mesozoic basement underlying the study area (Fig. 2). (The regional magnetic map was also considered but was found to provide little additional useful information, in part because of incomplete coverage, and electrical interference from anthropogenic sources.)

The north-western part of the study area is underlain by the Midlands Microcraton, where Proterozoic rocks occur at relatively shallow depths, and which has been relatively tectonically stable during the Phanerozoic. Structural trends are complex. The north-eastern part of the area is underlain by a portion of a Caledonide fold belt, formed during mid-Palaeozoic times, in which the dominant structural trends are north-west to south-east. The southern part of the area includes the northern margin of a Variscan fold belt, formed in late Palaeozoic times. This terrane is represented by arcuate structural trends, oriented approximately east-west (Lee et al., 1993). The Variscan fold belt was the site of basin subsidence during the Mesozoic and basin inversion during the Cenozoic, whereas the Midlands Microcraton and the Caledonide foldbelt (together forming the London Platform) remained relatively stable during that time. Note that the exact position of the northern margin of the Variscan fold belt, the Variscan Front, is uncertain, although the location shown in Fig. 2 has been shown to be plausible by Busby and Smith (2001). Ellison et al. (2004) ascribe the area of the large gravity 'low' in the south of the study area (Fig. 2) to 'a zone of transition between the London Platform and the Variscan fold belt'. This gravity low is taken to mark a very thick sequence of post-Caledonide strata, probably of Devonian age. It is separated from the Midlands Microcraton by a zone of north-east to south-west trending basin margin faults, as indicated by linear features in the gravity field (Fig. 2). This basin