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Localized Quaternary uplift of south–central England

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Abstract: The Early Quaternary of south–central England is characterized by uplift, as is indicated by the river gravels that extend intermittently from Oxfordshire, through Northamptonshire, to Lincolnshire. The earliest of these gravels contain abundant quartz and quartzite clasts derived from Lower Triassic conglomerates in the West Midlands, but later deposits contain progressively larger amounts of locally derived Jurassic sediments. This compositional change is associated with the incision of the rivers that flowed eastwards from the West Midlands. Subsequently, the headwaters of some of these rivers were diverted towards the Bristol Channel and their suspended material was deposited on the outer parts of the UK continental shelf and slope. The area of incised drainage (Gloucestershire to Lincolnshire) did not extend to East Anglia (in the east) or to Somerset (in the west). Both these coastal regions contain several marine horizons showing that the area of uplift did not include the whole of southern England. The uplift cannot therefore be attributed to eustatic changes in sea level. The area of uplift is centred on the broad topographic depression of the English Midlands and corresponds approximately to the outcrop of thick (*c.* 1 km) Upper Triassic and Lower Jurassic mudrocks. We have used an Ordnance Survey 50 m × 50 m topographic 'grid' to estimate the amount of mudrocks that has been removed from the depression and 2D flexural unloading models to calculate the tectonic uplift that resulted, for various assumptions of the effective elastic thickness (which is determined by the flexural rigidity) of the lithosphere. The amount of material removed is in accord with what is known of the volume of Quaternary deposits offshore, and the uplift accounts for the incised plateau surfaces of the flanking Cotswold Hills and the high ground of Northamptonshire to the east, and the Forest of Dean and the hills of Herefordshire to the west.

Keywords: Quaternary, isostasy, flexure, landform evolution.

It has long been known (e.g. Buckland 1823) that the quartz and quartzite clasts in the Quaternary river gravels of the Upper Thames Valley were derived from the Triassic conglomerates in the West Midlands. With the exception of the study by Wills (1948) and the more recent work of Maddy (1999), there has been little discussion of the implications of this observation. Not only must drainage patterns during the earlier Quaternary have been radically different from those of today, but there has been no satisfactory explanation of the uplift, erosion and sedimentation history of the Quaternary or of its relationship to the present-day landscape of south–central England.

In recent years, great strides have been made in understanding the sequence stratigraphy of the Quaternary. It is now known, for example, that the Quaternary comprises several scores of glacial events that are related to Milankovitch cycles. These cycles can, in turn, be related to climatic changes seen in the oxygen isotope record preserved in deep-sea sediments. Unfortunately, the relationship of marine sequences to non-marine sequences is still not definite. The non-marine sequences of southern England contain some terrestrial plants, insects and vertebrates, but most of them cannot be dated by palaeontological means. Marine and estuarine sequences have more varied faunas (including many molluscs) and so should, in principle, be dated more precisely than fluvial sequences.

Marine and estuarine sequences of Quaternary age occur in East Anglia and Devon and Somerset, where they lie within *c.* 25 m of present-day sea level. By contrast, the presence of quartz and quartzite detritus that is derived from Triassic conglomerates of the West Midlands has been deposited over wide areas of East Anglia (e.g. Wroxham Crag and Bytham Formations), Northamptonshire and Oxfordshire (e.g. Northern Drift Formation); this suggests that some inland areas of southern England were uplifted during the Quaternary.

Today, most river gravels are found on terraces that border the modern river systems. The highest terrace in the Northern Drift Formation, for example, is now located at heights of *c.* 130 m above modern river levels (Hey 1986). Gibbard (1999) considered the Northern Drift to be older than Oxygen Isotope Stage (OIS) 12 (*c.* 450 ka). This formation contains almost no locally derived material and was deposited prior to most of the valley incision. It follows, therefore, that the oldest (and highest) river gravels were deposited on a surface with little or no relief. Subsequent terraces occur at progressively lower levels, forming a 'staircase' pattern, until the most recent are close to the height of the modern river systems.

The origin of the river terraces has been a subject of much debate. Early interpretations (see, for example, the discussion by Jones 1981, pp. 138–139) favoured a eustatic control. According to this interpretation, the terraces formed during sea-level 'stillstands' that were separated by falls. Subsequently, Wooldridge & Linton (1955) proposed a tectonic control that involved 'warping' and 'flexuring' of the crust. More recently, Maddy *et al.* (2001) suggested that aggradation and incision in river valleys can be explained by climate-induced changes in sediment and water supply. However, as Maddy *et al.* (2000) and Veldkamp & van den Berg (1993) have pointed out, climatic changes cannot

†Deceased. This paper was in review when W. S. McKerrow died on 12 June 2004. Many aspects of his wide-ranging interests are reflected in this study: geomorphology, stratigraphy and palaeontology, and geodynamics. It is hoped that this paper will stimulate increased communication between workers in these fields, in addition to providing a healthy debate on the tectonic evolution of the British landscape.

explain the progressive aggradation and incision of the landscape by rivers, as recorded by terrace 'staircases'. These features require a net fall in sea level, tectonic uplift of the land, or some combination of these factors to explain them.

Despite the evidence for repeated advances of the ice and widely distributed river activity in the recent geological past, the present-day landscape of south–central England is not smooth. The gently dipping Mesozoic beds consist of harder beds of sandstone and limestone alternating with softer mudrocks that combine to produce a distinct 'scarp and vale' scenery. The scarps reach heights of >300 m in the Cotswold Hills and >250 m in the Chiltern Hills, whereas the intervening clay vales lie mainly below *c*. 100 m above sea level. These geomorphological features, in themselves, suggest recent uplift of the landscape. If there had been no uplift, the topography would not be as marked and the whole of south–central England would be flat.

Another indicator of uplift is the change in the strike of the Mesozoic beds. In south Yorkshire and Lincolnshire, the strike is north–south and appears to be related to subsidence in the nearby southern North Sea. However, southwards, in Northamptonshire, north Oxfordshire and Gloucestershire, there is a marked change in strike to NE–SW, followed by a further change back to a north–south strike in Avon and Somerset. Cope (1994) and White & Lovell (1997) have interpreted the strike change as the result of uplift caused by a mantle hotspot or magmatic underplating associated with the early opening history of the Atlantic Ocean.

Today, the English Midlands are *c*. 100 m above sea level and comprise a region where *c*. 1 km of soft Upper Triassic and Lower Jurassic mudrocks (the Mercia Mudstone Group and the Lower Lias Clays) crop out. Watts *et al*. (2000) suggested that the change in strike of the Mesozoic beds might be related, at least in part, to the removal by meltwater-charged rivers of large volumes of these mudrocks. Flexural unloading as a result of the removal of these sediments explains the broad topographic depression of the Midlands and the uplift and incision of the plateau-like topographic 'highs' that flank it. It also explains the 'switch' that occurred in the direction of flow of the major rivers from generally SE towards the London basin (e.g. Rose 1994) to SW towards the Bristol Channel.

Watts *et al*. (2000) pointed out that because the rivers were able to traverse much of south–central England more or less uninterrupted during the Early Quaternary it was unlikely that potential topographic barriers such as the Cotswold Hills were in existence then. Therefore, the Cotswold Hills, they argued, must be a relatively young feature compared with the Early Quaternary rivers.

The purpose of this paper is to re-examine the model of flexural unloading caused by river excavation and its applicability to the Quaternary of south–central England. The evidence for the source, flow directions and deposits of the rivers is first reviewed. We then use an Ordnance Survey (OS) 50 m × 50 m Digital Elevation Model (DEM) dataset to quantify the volume of material that may have been removed by the rivers and 2D flexural unloading models to calculate the areal extent of the resulting uplift. We argue that the maximum uplift, which is localized to the region of the Severn and Avon river valleys and their flanks, is generally in accord with what is known about the distribution of the Quaternary, both onshore and offshore in south–central England.

Sediment sources and river systems

The older and higher gravel deposits that make up the terraces of the Upper Thames Valley were assigned by Hey (1986) to the Northern Drift Formation. This formation contains detritus rich in rounded quartz and quartzite pebbles derived from Lower Triassic conglomerates of the Sherwood Sandstone Group (formerly the Bunter Pebble Beds). Triassic sediments were deposited in Devon and Dorset, in the Worcester graben (between Wales and the Anglo-Brabant massif) and, slightly more widely, in the north Midlands (Cope *et al*. 1992). In this narrow depositional region, quartzose conglomerates are strongly developed only in south Devon and the West Midlands. The conglomerates include clasts up to 50 cm which were deposited by fast-flowing rivers that eroded Palaeozoic quartzites from the Armorican mountains in Normandy and Brittany (Audley-Charles 1970, pp. 54–55 and plate 7).

In the Sherwood Sandstone Group, about one clast in a thousand contains Palaeozoic fossils that are diagnostic of Normandy and Brittany rather than England. In addition, there are a few clasts derived from the Lower Palaeozoic rocks of Wales and the Upper Palaeozoic rocks of the Pennines, showing that the regions to the west and north of the Worcester Graben were also being denuded during the Early Triassic. The clasts consist of highly durable material that was rounded during the Triassic while being transported the 500 km from Normandy and Brittany to the Birmingham area. Their much later Early Quaternary transportation from this area to the Thames Valley (*c*. 100 km) does not appear to have been so erosive. Some clasts in the gravels here have a hemispherical shape, indicating that a portion of well-rounded Triassic pebbles suffered comparatively little abrasion after they were split in half during the Early Quaternary.

Quartzite and quartz pebbles, reworked from Triassic conglomerates cropping out in the West Midlands, are now distributed over a wide region that extends from the East Midlands, through Lincolnshire, Northamptonshire and the Upper Thames Valley, to the North Sea (Rose 1994; Gibbard & Allen 1995; Smith & Rose 1997). Similar quartz and quartzite clasts in SW Hampshire (Allen & Gibbard 1994) appear to be linked to an entirely different river system, as they were deposited by rivers flowing from the west and thus from a source well to the south of the present-day Cotswold Hills.

It is still uncertain how many rivers were carrying the Triassic material east- and southwards from the West Midlands (Fig. 1). In addition to a 'Thames river' that flowed southeastwards from Shropshire, Smith & Rose (1997) discussed evidence for a 'Bytham river' (flowing eastwards across Leicestershire and Cambridgeshire) and a 'Kesgrave river' (flowing from Warwickshire to Essex). They also considered the possibility of a 'Letchworth river' flowing from Warwickshire, past Letchworth and through the Stevenage gap to join the Kesgrave river. There may have been many more such rivers flowing east and SE over this Early Quaternary eroded surface. The evidence from north Oxfordshire (Watts *et al*. 2000) suggests that most, if not all, of the river gravels assigned to the Northern Drift Formation were deposited on a gently tilted surface of eroded Mesozoic beds.

Throughout much of the Upper Thames Valley, the higher and older river gravels do not contain any significant amounts of locally derived material. By contrast, in the lower and younger gravels local Jurassic material becomes progressively more abundant through time (Hey 1986). This indicates that during deposition of the older river gravels there was little incision and the rivers were able to change course relatively frequently.

In Hertfordshire and East Anglia, gravels that are in a similar setting to the Hanborough Terrace contain up to 50% Mesozoic detritus at some localities (Smith & Rose 1997). This suggests that Early Quaternary uplift (involving erosion of the local rocks)

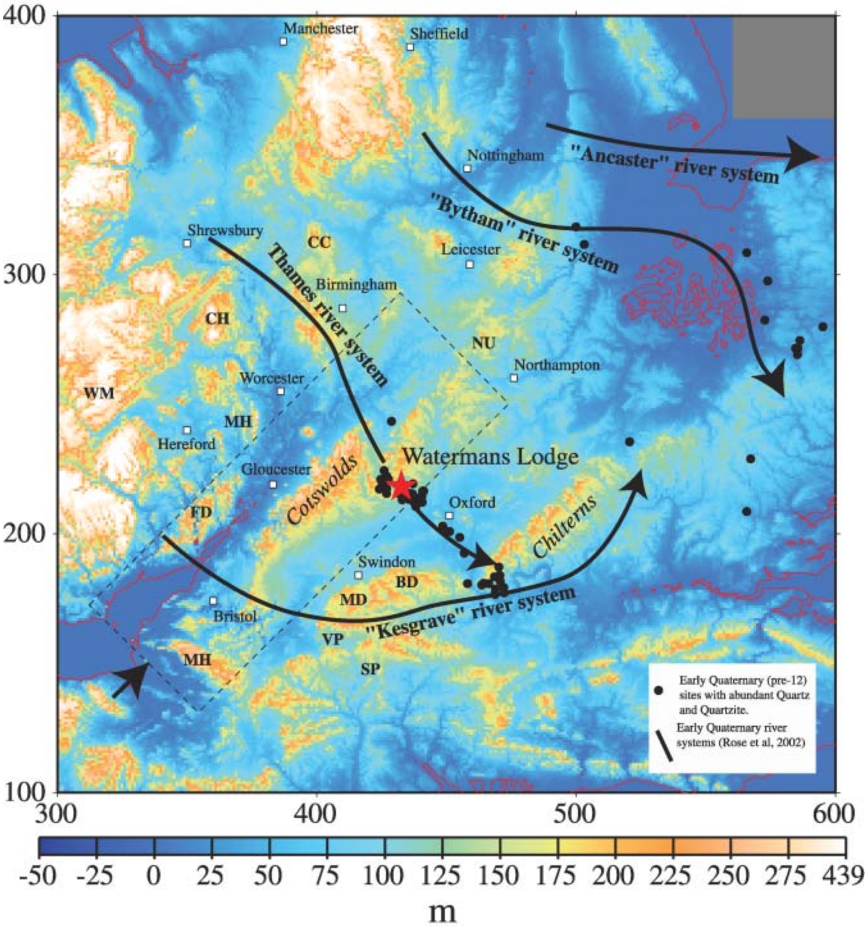


Fig. 1. Location map of south–central England showing main topographic features. Topographic data is based on an Ordnance Survey 50 m × 50 m 'grid'. NU, Northampton Uplands; SP, Salisbury Plain; FD, Forest of Dean; BD, Berkshire Downs; MD, Marlborough Downs; MH, Malvern Hills; MpH, Mendip Hills; VP, Vale of Pewsey; CC, Cannock Chase; CH, Clee Hills; WH, Welsh Marches. Bold lines show the Early Quaternary river systems according to Rose *et al*. (2002). ●, location of Early Quaternary sites with abundant quartz and quartzite clasts based on data of Arkell (1947), Hey (1986), Bowen (1999) and Smith & Rose (1997). The star indicates the location of Waterman's Lodge (Fig. 2). A perspective image of the topography within the boxed area (dashed lines) is shown in Figure 3.

occurred somewhat earlier in other parts of SE England than it did in mid-Oxfordshire. Similarly, the numerous 'rejuvenation events' cited byBridgland (1994, p. 7) may represent local uplift episodes in response to this erosion.

Ice origin?

The origin of the Northern Drift Formation has been the subject of much debate ever since Buckland (1823) first attributed it to a 'universal deluge'. Geikie (1877) and Pocock (1908), for example, suggested a glacial origin for the deposit. Arkell (1947) and Shotton *et al*. (1980), however, favoured a fluvial origin, at least for the lower members of the formation. Hey (1986) favoured a fluvial origin, even for the oldest and highest member of the formation, Waterman's Lodge, on the basis of the predominance of quartz over quartzite and that the deposits appear to be remnants of a single sedimentary unit. Recently, Simms (2001) suggested that Hey's observations are far more reminiscent of a glacial till than a fluvial deposit.

There is some uncertainty about the southern limits of the Quaternary glacial deposits of south–central England. The earlier deposits are not well dated, nor is it clear which deposits were actually deposited by ice. In Gloucester and Oxfordshire, the Middle Jurassic Cotswold Escarpment appears to mark the southern limit of the ice, at least in the later parts of the Quaternary. To the west (in Avon and Somerset), the escarpment swings to the south and the ice extended further south (Boulton 1994). To the east (in Northamptonshire and Buckinghamshire), the escarpment is less prominent and the ice extended further south, possibly to London (Boulton 1994). Lacustrine sediments that represent the deposits of pro-glacial lakes (e.g. 'Lake Harrison') are found in the East Midlands (e.g. Maddy & Lewis 1991). Coastal regions of East Anglia and Somerset and Devon, in contrast, are associated with marine and estuarine deposits.

We recently re-examined the Northern Drift Formation at the Waterman's Lodge locality in Wychwood Forest, where the gravels cap ground higher than 190 m. The gravels were extensively worked and are now obscured by vegetation. However, excavations showed no obvious bedding (Fig. 2). The gravels are clast- rather than matrix-supported, as claimed by Hey (1986) and cited (with no new observations) by Simms (2001). We have not observed matrix-supported gravels nor, for that matter, glacial striations on any clasts, although either may be present at localities no longer extant. Therefore, we agree with Hey (1986) and consider the highest (and oldest) member of the Northern Drift Formation, at least at the Waterman's Lodge locality, as a fluvial deposit.

River excavation, scarp retreat and flexural unloading

The English Midlands is a topographic depression that mainly corresponds to the outcrops of mudrocks of Late Triassic and Early Jurassic age. Surrounding this lowlying area are 'horsts' of Palaeozoic rocks, and outcrops of Triassic conglomerates that drain into the basins of the Trent, Warwickshire Avon and the Severn. The main depression follows the present-day course of

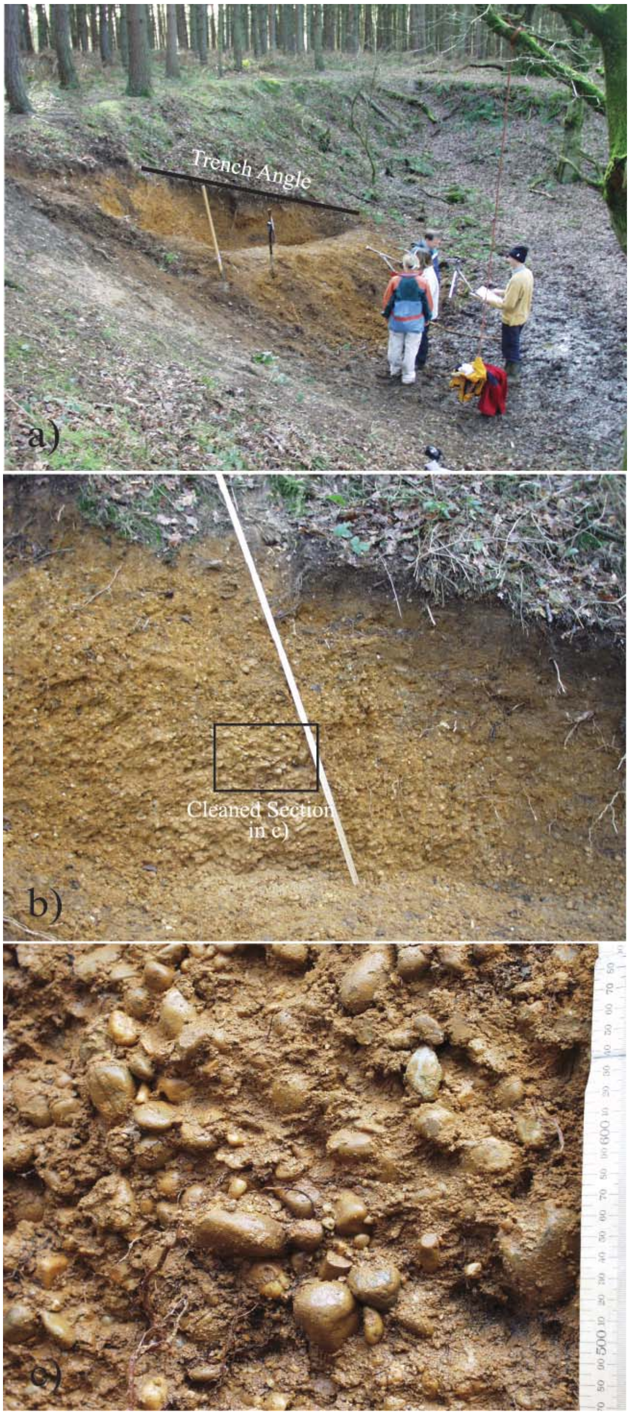


Fig. 2. The Waterman's Lodge site (Fig. 1) on Stag's Plain, Wychwood Forest, near Charlbury, Oxfordshire, which was excavated by the authors on 22 January 2002. The excavation revealed a 3 m section of the Northern Drift Formation at one of its highest occurrences, 198 m above sea level. Although no bedding can be discerned, the deposit is clearly clast supported and therefore more likely to be water-lain than a glacial till.

the Trent, Severn and Avon river valleys, and is bounded to the west by the Forest of Dean, Malvern Hills and the Clee Hills, and to the south and east by the Cotswold Hills and the Northampton Uplands.

Figure 3 is a perspective view of the Vales of Evesham and Gloucester and the flanking topography of the Cotswold Hills and Forest of Dean from above the Bristol Channel region. The figure shows the gently tilted plateau surface that characterizes the Cotswold Hills in north Oxfordshire and Gloucestershire. The surface is incised by 'dip streams' on its SE flank and deeply incised 'scarp streams' on its NW flank. There is evidence from physiographic maps (e.g. Green 1992) that the dip and scarp streams are separated in Gloucestershire by a drainage divide that roughly follows the crest of the Cotswold Hills and divides streams that flow mainly into Upper Thames Valley from those that flow directly into the Severn river valley.

Perhaps the most striking feature seen in Figure 3, however, is the steep escarpment that characterizes the NW-facing edge of the Cotswold Hills. The escarpment is segmented along strike, appearing to have retreated more to the SE and east in north Oxfordshire and south Gloucestershire and Somerset than in north Gloucestershire. The possibility of retreat is supported by the evidence of numerous landslips, as indicated on the more recent British Geological Survey maps of the region, and by the Jurassic outliers (e.g. Bredon and Dundry Hills) that appear to have escaped the excavation. The reasons why certain segments of the escarpment have retreated and, hence, have been excavated more than others are not clear. However, lithology of the underlying Mesozoic beds is likely to have played some role. For example, the region of the Cotswolds Hills that has shown the least retreat occurs where the thickness of Inferior Oolite is greater than 80 m compared with the NE in north Oxfordshire and south Gloucester and Avon and Somerset where the resistant limestones are thinner (Hallam 1992).

Watts *et al*. (2000, 2001), using 1D flexural unloading models, showed that the removal of sediments by river excavation from the English Midlands could cause isostatic uplifts in flanking regions of up to a few tens of metres, depending on the width, depth and symmetry of the excavated region and the effective elastic thickness of the lithosphere, T_e.

As Tucker & Slingerland (1994) have shown in their numerical models, flexure caused by, for example, erosional, mechanical and water unloading gives rise to a distinct landscape. In particular, flexure facilitates escarpment retreat by elevating topography in the vicinity of an eroding escarpment and helps to keep the locus of a drainage divide near an escarpment crest. The Cotswold Hills are characterized by a well-developed escarpment, as well as a drainage divide that NE of Stroud is located within a few kilometres to the SE of the escarpment crest.

An outstanding question is what triggered the postulated excavation? Watts *et al*. (2000) speculated that it was the locus of meltwater-charged rivers relative to the outcrop of soft Triassic and Liassic sediments of the English Midlands that was the initial cause of incision and, eventually, the removal of these sediments. The evidence for incision, however, is limited although there is evidence that quartz and quartzite pebbles are scattered over wide areas of north Oxfordshire and it is possible that some of the rivers that flowed across south–central England during the Early and Mid-Quaternary did so in relatively wide valleys.

What is clear is that the Cenozoic of south–central England, as a whole, was a time of much tectonic instability. We know, for example from present-day outcrop patterns, that the region was subject to post-Cretaceous uplift of up to 350 m, followed by a prolonged period of erosion to low relief. The uplift has been variously attributed to magmatic underplating (White & Lovell 1997), a mantle hotspot (Cope, 1994) or temperature anomalies

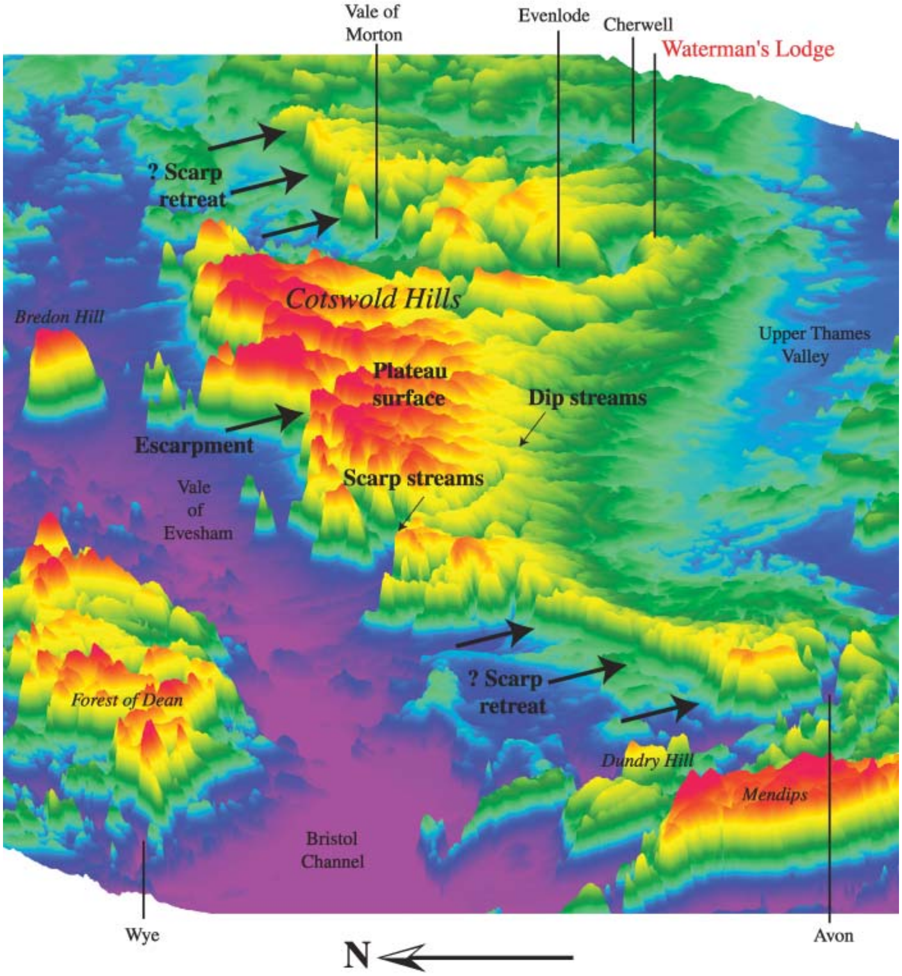


Fig. 3. Perspective view showing the excavated region of the Vales of Evesham and Gloucester and its associated flank uplift. Particularly prominent are the Cotswold Hills with their NW-facing escarpment and tilted, heavily incised, plateau surface. The long filled arrows highlight other escarpments in north Oxfordshire (Edge Hill) and south Gloucestershire and north Somerset that appear to have advanced further to the east and SE than the main Cotswold escarpment. Topographic features such as Bredon Hill and Dundry Hill are Jurassic outliers that appear to have escaped the main area of excavation. The Mendip Hills also appear to have to escaped the excavation, although they have a distinct plateau surface that dips gently to the east. The question marks indicate that the evidence for scarp retreat is uncertain. The short filled arrows highlight examples of the Cotswolds dip and scarp streams, which generally flow into the Thames and Severn respectively.

in the upper mantle (Bott & Bott 2004). During the Eocene, southern England (e.g. the Weald) experienced fault inversion, caused, it is believed, by far-field compression associated with the Alpine orogeny (Blundell 2002). Therefore, despite its location in the interior of a plate, south–central England has had a long history of tectonic movements, which, when combined with other factors such as eustatic sea-level changes, could have triggered at almost any time uplift, base level changes and river incision.

Flexure modelling

Methods

Unlike terrestrial volcanoes, where it is relatively easy to identify a surface load above the surrounding topography, it is difficult to estimate the amount of material that unloads the lithosphere by processes such as river excavation. The problem is that the present-day landscape reflects not only the amount of material that has been removed, but also the isostatic response of the crust (which includes the topography) to that removal.

To address this problem, we first carried out some simple tests using synthetic models for the topography. Then, a technique was developed that could be used to determine the amount of material removed using the observed topography. In this way, we have been able to evaluate the dependence of estimates of the amount of material removed on some of the parameters required in flexural unloading studies such as T_e.

Figure 4 shows a simple calculation of the flexural rebound that would be expected following the removal of sediments from a symmetric basin by processes such as river excavation. The rebound in the x–y plane is calculated using

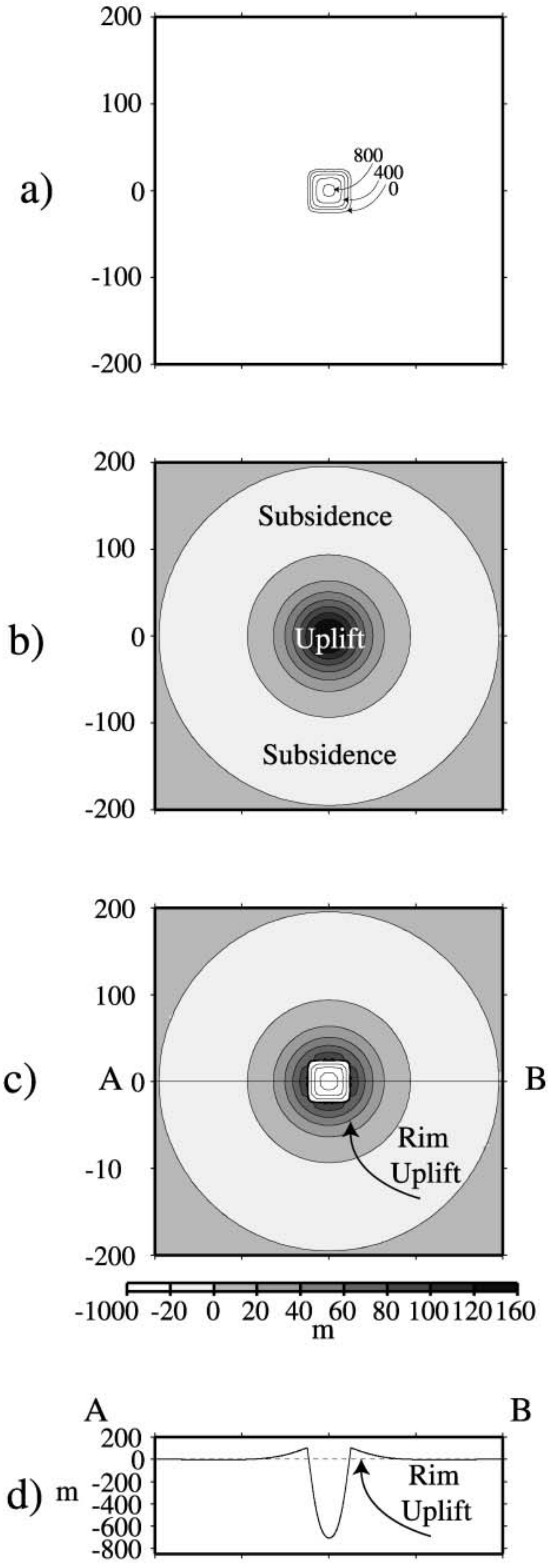
$$R(k) = S(k)\frac{\rho_{\text{sediment}}}{\rho_{\text{mantle}}}\phi(k)$$

where $R(k)$ and $S(k)$ are the Fourier transforms of the rebound and sediment distribution respectively, ρ_{sediment} and ρ_{mantle} are the densities of the sediment and mantle respectively, and $\phi(k)$ is given by

$$\phi(k) = \left(\frac{Dk^4}{g\rho_{\text{mantle}}} + 1\right)^{-1}, \qquad D = \frac{T_e^3 E}{12(1-\upsilon^2)}$$

where D is the flexural rigidity, k is the wavenumber vector $((k_x^2 + k_y^2)^{\frac{1}{2}})$, k_x is the wavenumber in the x-direction, k_y is the wavenumber in the y-direction, g is average gravity, T_e is the elastic thickness, E is Young's Modulus, and υ is Poisson's ratio.

The basin in Figure 4 is 50 km × 50 km in area and has a maximum depth after gridding of 856 m. The actual volume, V, is 1068.9 km^3. The sediments ($\rho_{\text{sediment}} = 2500\text{kgm}^{-3}$) are assumed to have been replaced by air (i.e. material with a density of 0 kg m^{-3}), and to have been unloaded from lithosphere with



T_e of 10 km. The figure shows a broad pattern of uplift that extends beyond the region of the original basin. The uplift affects surrounding regions, as well as the region where material has been removed, and so the resultant topography shows a deep basin that is flanked by rim uplifts. Flanking the uplift is a region of subsidence, with a magnitude that is less than 2% of the uplift.

To evaluate whether it is possible to quantitatively estimate the amount of material that has been removed from a landscape that already includes the flexural rebound, we set up a three-step analysis procedure (Fig. 5). First, the basin edge was used to locate the 'scarp edge'. Second, a 'plane' was selected from profiles of the rim flank uplift. Finally, the volume of material between the scarp edges and beneath the plane was calculated. This is the apparent volume, V_a, of material removed.

Figure 5d compares the ratio of the actual volume of material removed with the apparent volume for various values of T_e. For high values of T_e, the agreement between the two volumes is relatively small. This is because the rim flank uplifts for high T_e are small in amplitude and so the method of fitting a plane does not significantly underestimate the thickness of the material removed. For low T_e, however, the agreement is poor. This is because the amplitude of the rim uplift is large and the method of plane fitting significantly underestimates the amount of the load.

One consequence of underestimating the load is that the rim uplifts may appear higher than they actually are. This is because there is less load and hence a smaller reduction in the rebound in the immediate vicinity of the scarp edge. The width of the uplift, however, is less affected because it depends less on the magnitude of the load removed and more on T_e.

Local unloading. We first applied the approach outlined above to the OS DEM of the topographic depression of the Vales of Evesham and Gloucester and the Severn and Avon river valleys. First, the 'scarp edge' of the flanking uplift was picked from topographic contour maps. Then, a profile was constructed of heights along the scarp edge and the mean height and, hence, the 'plane' were calculated. The plane associated with the scarp edge plotted in Figure 6b is 128.9 ± 51.0 m. We attribute the high standard deviation of the data to the difficulty of picking the scarp edge in Avon, Somerset and Warwickshire and the heavy incision by scarp streams in the Cotswold Hills, Forest of Dean and Malvern Hills. The final step was to calculate the volume of material removed from the distance between the scarp edge and below the plane. We found that a plane of 128.9 m yields $V_a = 669.6\text{km}^3$. If the standard deviation of the plane is indicative of its total range, then V_a could be as low as 306.6 km^3 (for a plane of 77.9 m) or as high as 1072.6 km^3 (for a plane of 179.9 m).

Figure 6a shows the predicted flexural rebound that would result from the removal of a volume of 669.6 km^3 of sediment from the Vales of Evesham and Gloucester and the Severn and

Fig. 4. Simple 2D model for the flexural unloading of the lithosphere. The model is based on a thin elastic plate overlying an inviscid substratum with E = 100GPa, $\upsilon = 0.25$ and $T_e = 10\text{km}$. Other parameters are given in the text. (**a**) Original basin containing sediment. (**b**) Flexural rebound that results from the removal of the sediment. It should be noted that the region of uplift extends beyond the region of the original basin because of the strength of the plate. Also, the area of uplift is flanked by a region of subsidence. (**c**) Final basin topography obtained by superposition of the original basin on the flexural rebound. (**d**) Profile of final topography showing rim uplift

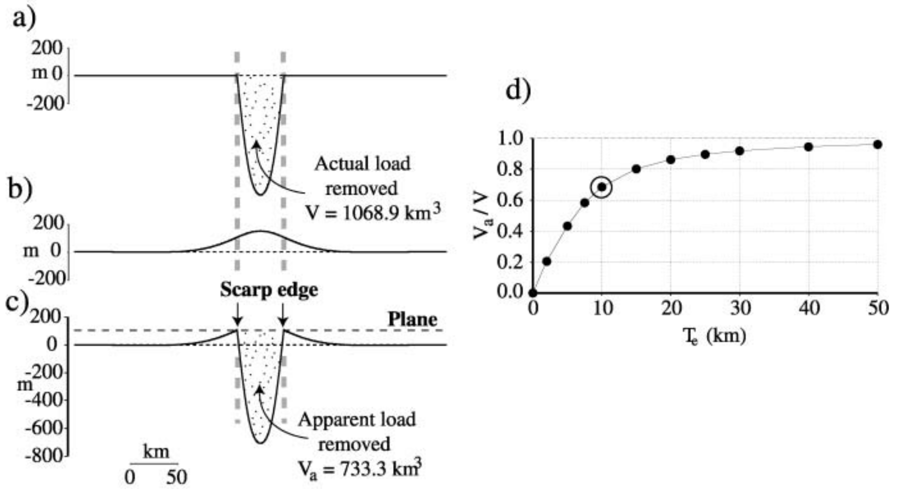


Fig. 5. Comparison of the ratio of the actual to apparent volume of sediment in the model basin as a function of T_e. The actual volume, V, is given by the original basin shape. The apparent volume V_a is obtained from the final basin topography by estimating the amount of material between the ‘scarp edges’ and beneath the ‘plane’. (**a**) Original basin showing the actual load removed. (**b**) Flexural rebound resulting from load removal. (**c**) Final basin topography showing the apparent load removed. It should be noted that use of the scarp edges and plane underestimates the amount of material removed, the amount depending on T_e. (**d**) plot V_a/V v. T_e.

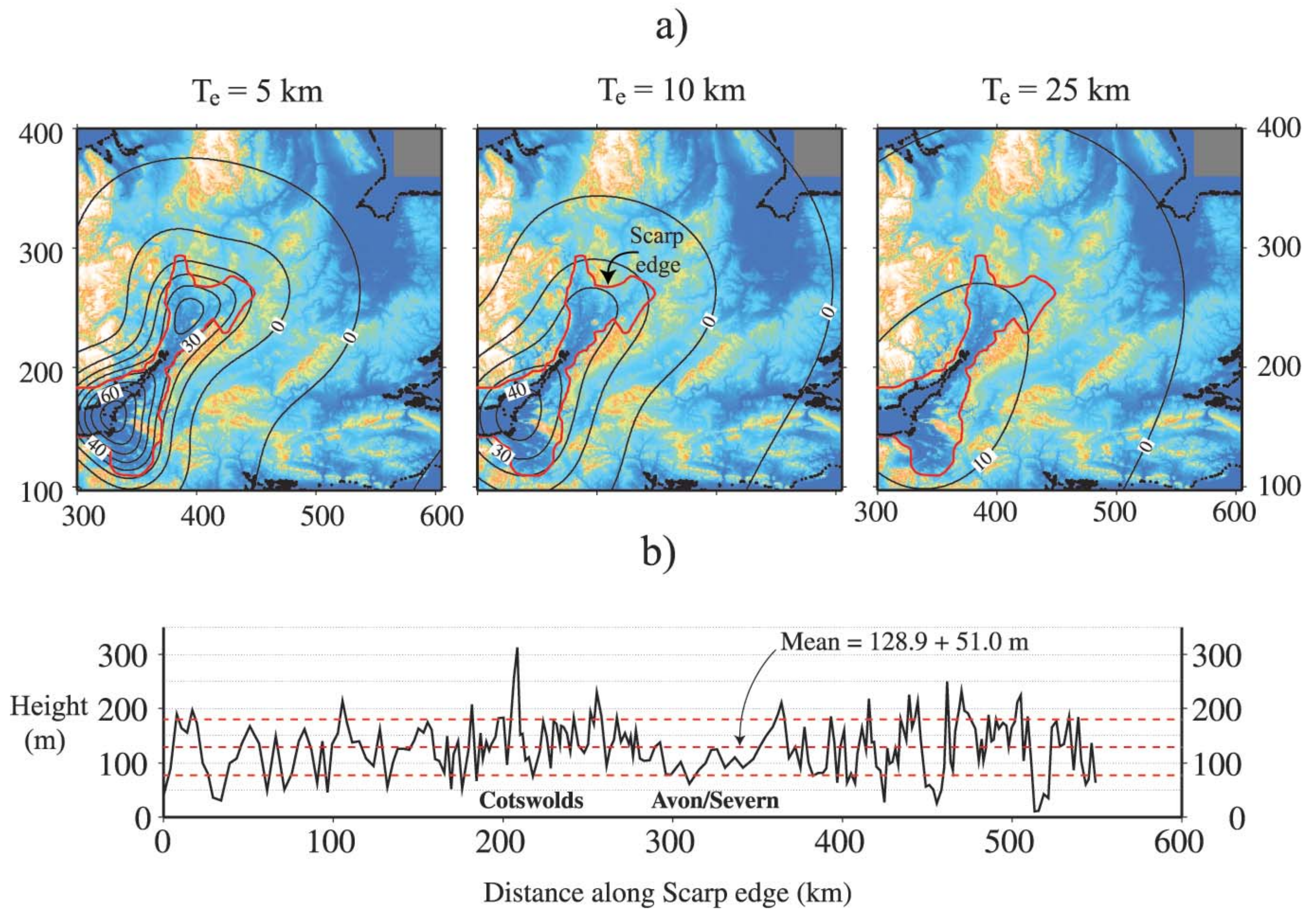


Fig. 6. Flexural rebound caused by removal of material from the Vales of Evesham and Gloucester and the Severn and Warwickshire Avon river valleys. The actual area excavated is defined by the scarp edge, which was chosen, wherever possible, to follow the crest of the escarpment. The calculations are based on a plane of 128.9 m (i.e. the mean of topographic heights along the scarp edge profile) and T_e values of 5, 10 and 25 km.

Warwickshire Avon river valleys. As expected, the pattern of rebound follows the general NE–SW trend of the vales where the largest loads have been removed. The maximum amount of the uplift depends on T_e, with T_e of 5, 10 and 25 km yielding values of 75.7, 45.8 and 18.7 m, respectively.

Wider region. The English Midlands is not the only topographic depression in south–central England. The depression is flanked by uplifts that are, in turn, flanked by other depressions. In the west, the depressions follow the Wye and Usk river valleys in the Forest of Dean. In the east, the depressions form the clay vales of the Upper Thames Valley (Oxford Clay) and the Vales of the White Horse and Aylesbury (Kimmeridge Clay).

We therefore repeated the ‘Cotswold’ unloading calculation, taking into account a wider region that included the topographic depressions to the west and east (Fig. 7). The scarp edge in the west was selected as the abrupt change in topography associated with the edge of the Welsh Marches. In the east, we used the Chiltern escarpment and its continuation into the Berkshire Downs and Salisbury Plain to define the scarp edge.

Figure 7 shows the wider region of flexural rebound for T_e of 10 km. The main trend of the rebound is similar to that plotted in Figure 6a, but the amplitude and wavelength of the uplift are now greater. The apparent volume of the material removed for a plane of 128.9 m is now 985.3 km^3 and is made up of contributions from a ‘Cotswold’ unload of 669.6 km^3, a ‘Wales’ unload of 123.1 km^3 and a ‘Chiltern’ unload of 192.6 km^3. The maximum uplifts for T_e of 10 km as well as 5 and 25 km are summarized in Table 1.

Discussion

We have shown in this paper that flexural unloading as a result of river excavation is capable of producing a broad regional uplift that, because it occurred in the geologically recent past, may still be evident in the landscape of south–central England. Our results have implications for the distribution of Quaternary deposits, both onshore and offshore the UK. They are also relevant to current debates on topics such as the origin of river terrace staircases and the T_e structure of continental lithosphere.

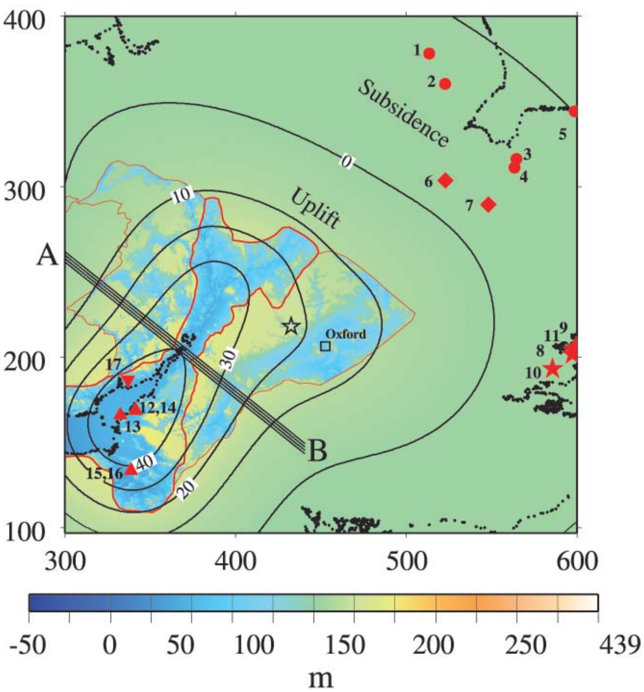


Fig. 7. Flexural rebound caused by removal of material from the Vales of Evesham and Gloucester and the Severn and Warwickshire Avon river valleys together with a region to the west and east. The western region extends the area of excavation to the foot of the Welsh Mountains. The eastern region extends the area to the Chiltern escarpment. The calculation is based on a T_e of 10 km. The symbols show the location of the Quaternary marine and estuarine sites summarized in Table 2. It should be noted that Sites 1–5 and 7–13 are located outside the region of the tectonic uplift and so are in accord with the model predictions.

Table 1. *Summary table showing maximum uplifts for the combined ‘Cotswold’, ‘Wales’ and ‘Chiltern’ unloads and various values of the plane and* T_e

Elastic thickness, T_e (km)	Maximum uplift (m)		
	(1)	(2)	(3)
5	42.3	76.0	111.7
10	25.2	**49.4**	77.9
25	10.2	24.2	43.7

(1) Plane = 77.9m; V_a = 350km^3; (2) plane = 128.9m; V_a = 985.3 km^3; (3) plane = 179.9m; V_a = 1870.3km^3. Bold value is the case illustrated in Figure 7.

Quaternary marine deposits onshore

The flexural unloading models are associated with a permanent, rather than transient, uplift of the crust and mantle and so the question is raised of whether the uplift is compatible with what is known on the distribution and facies of the Quaternary, particularly those beds that were deposited in a setting of subsidence rather than uplift.

Table 2 summarizes those sites in southern England that, according to the workers cited by Bowen (1999), formed in marine or estuarine environments. The location of the sites is shown in Figure 7, where they are compared with the predicted uplift based on a flexural unloading model with a plane of 128.9 m and T_e of 10 km. The table suggests that Sites 1–5 were probably at or near sea level during most of the Quaternary (OIS 12–5e according to Bowen (1999)). The figure shows that this is consistent with the model prediction in that Lincolnshire, Cambridgeshire and Norfolk are all located in a region of subsidence that flanks the main uplift. Sites 6–11, which are located in Essex, are located in the same region of subsidence. The main difference, however, is that the length of time that the sites were at or near sea level (OIS 12? to 9 for Sites 8–11 and OIS 7 for Sites 6 and 7) appears to have been shorter.

In contrast, Sites 12–17 are located within the main area of the uplift and so do not appear to fit the model. However, there are explanations for some of the sites. Site 12, for example, is a glacial marine deposit. It could have formed either at sea level or in a topographic depression below sea level. Irrespective, then if the age assignments of Bowen (1999) are correct, then the flexural uplift must post-date OIS 16. Alternately, the ice may have ‘pushed’ up the sediments at Kenn onto a surface that was already above sea level. In this case, the ages given by Bowen (1999) suggest that the uplift would already have taken place by OIS 16. Sites 13–17 are interesting because they indicate that at some time during OIS 7–5e, the region to the north and south of the Somerset Levels was at or near sea level. Therefore, if Site 12 was once at sea level, then this site together with Sites 13–17 bracket the age of the uplift to some time between OIS 16 and 7.

Today, Sites 12–17 are 6–12 m above sea level and so the question remains of why the evidence for uplift is not more apparent at these sites, given their location in the area of maximum uplift. Indeed, it is not at all clear why, if the uplift post-dates OIS 16, Sites 13–17 were at or near sea level by OIS 7–5e. There are two possibilities. Either the uplift has been opposed by a competing subsidence from sediment loading offshore or, more likely, north Somerset and south Breckonshire were regions of continuing excavation throughout much of the Quaternary, such that they were being maintained more or less at sea level, despite being located within the area of maximum uplift.

Table 2. *Quaternary marine and estuarine deposits in south–central England (Bowen 1999)*

Site number in Fig. 7	Page number in Bowen (1999)	Formation, Member	$\delta^{18}O$	Easting (m)	Northing (m)	Environment
1	11	Lowestoft	12	513300	378100	Estuarine
2	14	Bain Valley, Kirkby	5e	522460	360400	Marine till
3	18	Nar Valley, Nar	11	564300	316600	Marine
4	18	Nar Valley, Nar	11	563200	311400	Marine
5	18	Hunstanton, Morston	5e	598700	344100	Beach
6	44	March	7	523000	303600	Marine or brackish nearshore
7	44	March	7	548000	289500	Marine or brackish nearshore
8	57	Southend, Asheldham	9 or 12?	597300	201700	Estuarine
9	57	Southend, Asheldham	9 or 12?	599300	205700	Estuarine sediments
10	57	Southend, Shoeburyness	9 or 12?	585500	193400	Freshwater and estuarine
11	57	Southend, Tillingham	9–11	598000	204100	Freshwater and estuarine
12	75	Kenn, Kenn Court	>16	341400	168800	Glacial–marine
13	75	Middle Hope, Swallow Cliff	5e	332500	166100	Raised beach
14	78	Burtle, Kenn Church	7	341200	168600	Marine sands
15	77	Burtle, Greylake	7	338500	133600	Marine + freshwater
16	78	Burtle, Middlezoy	5e	338500	133600	Marine
17	90	Brecknockshire, Llanwern	5e	337000	187000	Marine gravels

We caution, however, that this discussion on the possible age of the uplift is speculative, as it is based only on the distribution of nearshore Quaternary deposits and many of the ages assigned to these deposits by Bowen (1999) are uncertain. There are fluvial deposits from within the region of uplift that might also bear on the problem. For example, Maddy & Lewis (1991) have described a series of Quaternary sands and gravels from the Snitterfield area, Warwickshire, that were deposited by a NE-flowing river, a tributary of which drained the Cotswold escarpment. The river would have been located on the NE flank of the uplift. The age of the deposits is uncertain, but geochronological dating of underlying and overlying sediments (Maddy & Lewis 1991) suggests that they were formed during OIS 10–15, which is within the range of our estimates for the age of the uplift. Other fluvial deposits are more difficult to explain. For example, Maddy *et al*. (1995) have described a series of Quaternary sands and gravels from the Lower Severn Valley between near Gloucester and Kidderminster that were deposited by a south-flowing river. If the oldest of these deposits is dated to OIS 10, as Maddy *et al*. (1995) suggested, then it is difficult to explain why a river system was flowing south towards the centre of the uplift unless other processes, such as sediment loading offshore, were operative so as to compete with the uplift and cause a net tilt down to the south.

Quaternary sediments offshore

If large volumes of material were removed from the English Midlands, an important question is: where has the material been deposited? Watts *et al*. (2000) speculated that most of the material was transported out from the English Midlands through the Bristol Channel and into the southern part of the Irish Sea. They cited Tappin *et al*. (1994) as showing that in the Celtic Deep, midway between Wales and Ireland, there is British Geological Survey (BGS) seismic reflection profile evidence of a thick sequence of Anglian and younger sediments that unconformably overlie Neogene and older strata.

Clayton (1996) used the BGS and other offshore datasets to estimate the volume of the UK offshore deposits of Quaternary age by dividing them into two groups: the relatively thin sediments that cover the continental shelf and the thicker sediments that occur beneath and beyond the present-day shelf break. He estimated that the total volume of Quaternary sediments in the Celtic Deep region is ‘just over 400 km^3’.

Our estimates of the apparent volume of material that has been removed from the English Midlands, V_a, are in the range 306.6–1870.3 km^3 (Table 1). V_a for the best-fit plane of 128.9 m is 985.3 km^3. The actual volume, V, depends on T_e (Fig. 5) and is 2345.9, 1407.6 and 1094.8 km^3 for a T_e of 5, 10 and 25 km, respectively. These volumes are therefore a factor of 2.5–6 higher than those estimated by Clayton (1996) from the Celtic Deep. This indicates to us that a significant part of the excavated material has bypassed the southern Irish Sea and made its way to the outer continental shelf and slope. Clayton (1996) estimated a combined volume for the shelf basins of the southern Irish Sea and continental margin shelf edge ‘wedge’ of 1857.9 km^3, which is approximately midway in the range of our estimates of the actual volume removed for a T_e of 5–10 km.

The river terraces

The elevation and estimated ages of the river gravel deposits of the Upper Thames Valley have been used by Maddy (1997) and Maddy *et al*. (2000) to calculate uplift rates. Using a simple linear model, Maddy *et al*. (2000) estimated rates of *c*. 0.07–0.10 m ka^{-1} for the terraces of the Upper Thames Valley, the highest of which is at Waterman’s Lodge and the lowest at Northmoor, Oxford. They were unable, however, to determine the cause of the uplift, except to say that erosional isostasy, glacio-eustasy, hydro-isostasy and far-field intra-plate stresses might all be involved.

Recently, Westaway *et al*. (2002) suggested that the terrace pattern might be a product of the cyclic loading of the crust by water (i.e. hydro-isostasy). They suggested that during a sea-level rise, the shelf exerts an excess pressure, which will act to drive a weak lower crust beneath adjacent onshore regions, thus causing uplift. During a sea-level fall, the process is reversed. They argued, however, that if the thermal state of the crust is also taken into account, then during a rise and fall cycle there is a net warming of the shelf crust and a net cooling of the onshore crust, with the consequence that sequential oscillatory sea-level changes will cause only uplift. Their model, however, excludes flexure and the isostatic effects of erosional unloading and sediment loading.

We have shown that flexural unloading as a result of river excavation gives rise to a broad region of uplift. The maximum uplift is localized to the present-day Severn and Avon river valleys, but extends into flanking areas, including the mid-Oxfordshire region between Waterman's Lodge and Oxford City. It is possible, therefore, that the uplift might contribute, at least in part, to the staircase pattern of terraces reported by Maddy and coworkers in the Upper Thames Valley.

To test this possibility, we computed the uplift between Waterman's Lodge and Oxford City for various values of T_e and compared it with the present-day difference in height between these localities. The model predictions for a plane of 128.7 m and T_e of 10 km is 4.6 m, which is much smaller than is observed (136.9 m). The calculated uplift increases if we increase the plane and/or decrease T_e. However, even when the highest likely plane is assumed, the calculated uplift contributes only *c*. 25% to the observed value.

These considerations suggest that flexural rebound as a result of river excavation is unable, by itself, to explain the staircase pattern of river terraces. However, our calculations ignore the loading effects associated with the deposition of the excavated sediments. Terraces that find themselves within the flexural depression of these sediment loads, for example, would undergo subsidence whereas sites that are within the flexural bulge would experience uplift. The result, in the case of sediment loading in the southern North Sea, would be to provide an additional up-to-the-west and down-to-the-east tilt to the interior of southern England, which could amplify any contribution to the terrace pattern that might be caused by flexural rebound caused by river excavation.

The elastic thickness of UK lithosphere

Figure 8 shows a comparison of observed and calculated topography profiles of the main region of flexural rebound. As expected, the calculated profiles vary according to the value of the plane and T_e that are assumed. The figure shows that there is little sensitivity of the observed profile to variations in the values of plane and T_e. However, a comparison of observed and calculated volumes of the material removed by river excavation suggests 5 km $< T_e <$ 10 km and Figure. 8 shows that the topography of the central region of rebound is compatible with this range of T_e.

There have been few published independent estimates of T_e for the British Isles region. Onshore estimates are limited to the Caledonian and Variscan sequences of Ireland and South Wales. Armstrong (1999) estimated T_e in the range 25–45 and 45–60 km for the Caledonian units of central and northern Ireland, respectively. The Variscan sequence of southern Ireland yielded results in the range 45–60 km. A similar estimate of 40 km was obtained by Burgess & Gayer (2000) for the Variscan foreland of South Wales and Avon and north Somerset. Offshore estimates, however, have generally been lower. In the North Sea, for example, Barton & Wood (1984) and Kusznir *et al*. (1991) estimated T_e of $<$5 km and 3–6 km, respectively. Similar estimates of $<$5 km have been reported by Watts & Fairhead (1997) for the Hatton Bank margin of the Rockall Plateau.

These results suggest that Caledonian and Variscan Britain may be associated with a T_e that is relatively high compared with the thickness of the crust. In contrast, regions that were modified by extension during the Jurassic and Cretaceous are associated with low values. Recently, Tiley *et al*. (2003) used an admittance technique of analysing free-air gravity anomaly and topography data and concluded that the British Isles, as a whole, are associated with a T_e of 5 ± 2 km.

Our results based on the wider region of unloading suggest a T_e of *c*. 5–10 km. However, we have observed that the tilted plateau surface is more apparent in the Cotswold and Chiltern Hills than it is in the Forest of Dean. This might be due to asymmetry in the excavated region, with more material being removed from near the Cotswolds, for example, than the Welsh Marches. Alternatively, it might be caused, at least in part, by the

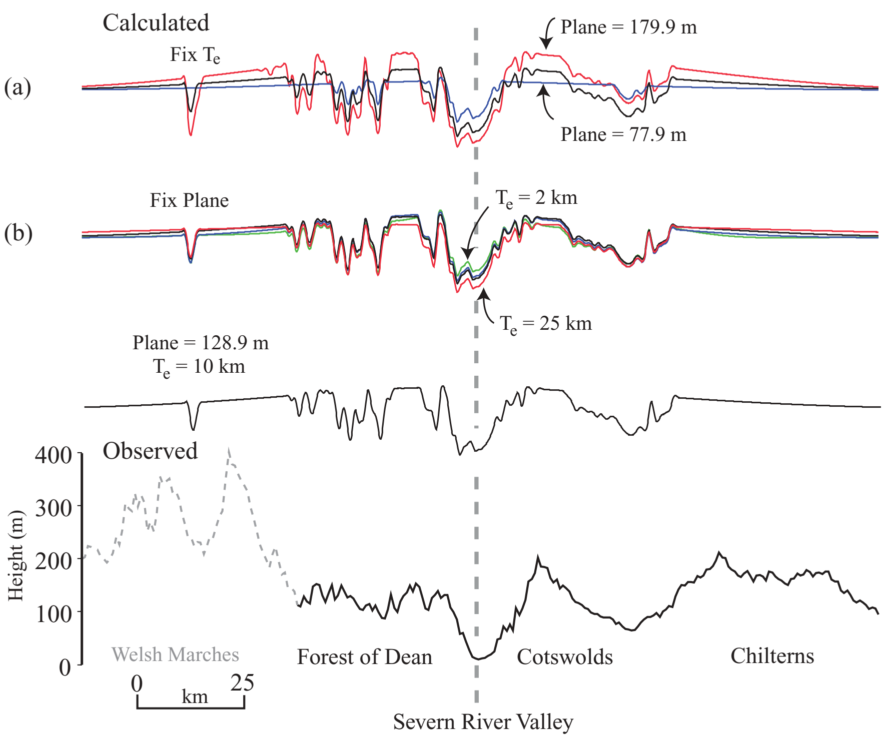


Fig. 8. Comparison of observed and calculated topography profiles across the Forest of Dean, the Severn River Valley, and the Cotswold and Chiltern Hills. The observed profile is based on an ensemble average of seven profiles located in Figure 7. The calculated profiles show the final topography based on various assumptions regarding the height (above sea level) of the plane and T_e. (**a**) T_e = 10km and a plane at 103.9, 128.9, and 153.9 m. (**b**) Plane = 128.9m and a T_e of 2, 5, 10 and 15 km.

differences in T_e between a relatively strong Caledonian and Variscan Britain and a relatively weak Jurassic and Cretaceous Britain, the mechanical boundary between them following approximately the line of the present-day Malvern and Clee Hills.

If T_e is a controlling factor, then it is perhaps surprising that the Quaternary unloading did not inherit the relatively high flexural strength of the Palaeozoic, as these rocks now underlie the Cotswolds and Chilterns Hills. The thickness of the Jurassic and Cretaceous cover sediments is relatively thin and the Variscan was the last major orogenic event to have affected the region. However, there is evidence of large amounts of extension in the Jurassic and Cretaceous sequence of the Wessex basin to the south (Lake & Karner, 1987) that could have significantly weakened the lithosphere over a broader region than the basin itself. This, together with the fact that the North Sea to the east and Rockall Plateau to the west also underwent extension during the Jurassic and Cretaceous, makes it likely that much of the lithosphere of south–central England is relatively weak.

Conclusions

(1) There is evidence that during the Early Quaternary, one or more river systems flowed eastwards across south–central England on an exhumed surface of Mesozoic beds with little or no relief.

(2) The rivers preferentially removed large volumes of soft Triassic and Liassic mudrocks, especially from the English Midlands, and deposited them offshore.

(3) Two-dimensional flexural modelling shows that the removal of these sediments would have caused a broad regional uplift, which reached its maximum height over the lower Severn and Avon river valleys, from Herefordshire to Northamptonshire.

(4) A consequence of the uplift was to raise the flanks of surrounding regions, which had an abrupt effect on drainage systems such that rivers that once flowed SE towards the London basin 'switched' to flow SW towards the Bristol Channel.

(5) The region of uplift is broadly consistent with what is known about the distribution of marine and estuarine Quaternary sediments in southern England. Sites in East Anglia were located outside the main area of uplift. Sites in north Somerset and south Wales maintained themselves near sea level, despite being within the main area of uplift.

(6) Our estimate of the volume of material removed is broadly consistent with what is known of the volume of Quaternary sediments now found on the UK continental shelf and slope.

(7) The best-fit T_e is 5–10 km, which is low compared with cratons, but is compatible with values elsewhere where extensional processes have modified the strength of the lithosphere.

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