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Discussion on lithospheric flexure, uplift, and landscape evolution in south-central England

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J. C. W. Cope writes: The paper by Watts *et al.* contains interesting ideas on landscape evolution, but by concentrating their observations locally, and by overestimating post-Anglian erosion, they may have lost sight of more widespread effects that could have been major contributors to the features they describe, and thus their causative mechanisms may need re-examination.

Cope (1994) suggested that uplift centred in the Irish Sea explained the loss of >2 km of Mesozoic cover there, explaining apatite fission track analyses from the eastern Irish Sea and northwestern England. The southeasterly regional dip of the Mesozoic outcrop of the English Midlands could be attributed to this uplift; although a mantle plume was suggested as the cause, the same effect could be attributed to mantle underplating. Substantial igneous activity is known around the Irish Sea region before the earliest Antrim basalts. The Fleetwood dyke, in the Eastern Irish Sea is dated at 65.5 Ma (Arter & Fagin 1993) and similar ages are known from dykes in North Wales (Evans *et al.* 1973). Pre-basalt dykes exist in Northern Ireland whence Simms (2000) records dykes cutting Chalk and truncated by the basal Palaeogene lavas. Cope's (1994) reconstruction of the missing Mesozoic cover of the area from the Cheshire Basin southwards led him to suggest that the resultant average gradient imparted over the Midlands from the Cheshire Basin to the Chiltern scarp was 1: 87.5. What was incorrectly calculated from this figure by Cope (1994) was the angle of dip represented by that figure, which is 0.7° and not 2°. The former is close to that recorded by Watts *et al.* for the area of Oxfordshire they considered and this suggests that they may have overestimated the uplift caused by lithospheric flexuring.

There may be local tectonic effects that may have affected the regional dip, including locally pre-mid Albian (Late Cimmerian) movements. In the SE of their map (Watts *et al.* fig. 2b), Gault and Upper Greensand overstep Lower Greensand, and rest on Portland Beds (bright yellow on their fig. 2b, but omitted from their key). Around Oxford (but off fig. 2b) progressive overstep brings the Gault directly onto Kimmeridge Clay and Corallian Beds (coloured pale blue on their fig. 2b, but also omitted from the key), presenting clear evidence of Late Cimmerian warping and erosion. The Irish Sea uplift is well constrained to start around the Cretaceous–Palaeocene boundary and uplift and resultant erosion continued through much of the Palaeogene Cope (1994). It would undoubtedly have affected the Oxfordshire area as extrapolation to outcrops farther south demonstrates that *c.* 500 m of Jurassic and Cretaceous rocks have been eroded from what is now the top of the Cotswolds (Cope 1994, fig. 1). Thus a local southerly dip was imparted on the Jurassic rocks before the Pleistocene.

The equivalent of the Inferior Oolite is likely to have been present over the Eastern Irish Sea (Cope 1998) and so its scarp has retreated some 250 km to its present position in Oxfordshire. Cope (1994) suggested that much of the erosion that removed the Mesozoic rocks was within the Palaeogene. Assuming the removal took 40 Ma, under the tropical Palaeogene régime, the Inferior Oolite scarp would have retreated 6.25 mm per year. This rapid removal of so much Mesozoic rock must have caused much greater compensatory uplift than that suggested by Watts *et al*. Rates of erosion in the Neogene were probably much lower than in the Palaeogene as compensatory uplift ceased.

Cope (1994, fig. 3) suggested that the principal drainage directions, inherited from the post-Cretaceous uplift, would have been southeastwards in south-central England, with strike-parallel consequent tributary streams, at right angles to the principal drainage direction. Thus the proto-Thames once rose in the West Midlands and carried Welsh volcanic clasts southeastwards across the Middle Jurassic outcrops into the present west–east-striking valley in south Oxfordshire (Bridgland 1994; Hey 1986; Maddy 1999). This system was later beheaded by river capture, perhaps by a proto-Warwickshire Avon (the Baginton River of Shotton 1953), which in pre-Anglian times rose at Bredon Hill (the outlier of the Cotswold scarp at the mouth of the Avon valley in Watts *et al.*, fig. 1) and flowed northeastwards parallel with the Cotswold scarp (which must have been a significant topographical feature) to join the Soar and thence into the Trent/Humber system. Thus, significant amounts of erosion of the Warwickshire Avon valley are pre-Anglian. Similarly the lower Severn valley arose as a consequence of Miocene downwarping of the Bristol Channel. The proto-Severn flowed down the present lower Severn Valley and into the Bristol Channel and also eroded a substantial valley in pre-Anglian times. Thus the amount of Triassic and Lower Jurassic rock removed in post-Anglian times must have been smaller. Watts *et al.* variously estimated this at some 500 km^3 (p. 1172), up to 500 km^3 (p. 1173) and >500 km^3 (p. 1174). A recalculation made from their figure 1 and accepting their mean height of 150 m for the flanks gave 375 km^3—significantly less than the Watts *et al.* figures—and initiated much earlier than the Pleistocene. This make a significant difference to the Watts *et al.* calculations, as does narrowing the distance between the flanks along which their reported uplift has taken place from 200 km (Watts *et al.*, fig. 4) to 30 km which is closer to the maximum width across the Vale of Evesham. One piece of evidence which militates strongly against any flank uplift is that the summit of Bredon Hill (at 293 m) which sits astride the excavated area (Watts *et al.*, fig. 1) is actually higher than the top of the Cotswold scarp 12 km to the south (at 279 m). Any flank uplift would have shown the scarp to be significantly higher than a mid-valley outlier. Additionally flank uplift requires that the opposite flank dips in the opposing direction. There is no evidence within the area that Watts *et al.* consider where such an opposing dip is found. Indeed the regional dip over the whole area depicted in their figure 2 is approximately

0.7° to the south or SE. There seems nothing peculiar in the fact that the topography is not a dip-slope (Watts *et al.*, fig. 3) as the rocks involved are of approximately similar resistance, consisting predominantly of limestones with a few much thinner clay formations; it is only when the Oxford Clay is met that there is a major formation that eroded more readily.

The Pleistocene history of the Severn and Avon sytems is much more complex than Watts *et al.* suggest (Wills 1950; Maddy *et al.* 1991, 1995). For instance, at one stage, an ice-sheet in the Bristol Channel blocked drainage to the south. The water from the Severn and Avon systems, already augmented from the outflow from ice fronts in the north and east Midlands formed a large pro-glacial lake that ponded up against the Cotswold escarpment. When the Bristol Channel ice retreated, the lake drained through the Bristol Channel and it was then that the Warwickshire Avon developed its present course and much of the more recent excavation of the Mesozoic clays took place.

It thus seems that flank uplift has been much less significant in landscape development than Watts *et al.* propose.

12 December 2000

A. B. Watts, W. S. McKerrow & E. Fielding reply: We thank Cope for his contribution. He makes four main comments on our paper (Watts *et. al.* 2000), which we will address here.

Firstly, we agree with Cope that, in north Oxfordshire, a component of the dip of the Jurassic beds is pre-Anglian in age. In fact, we pointed this out in both the discussion (p. 1175) and conclusions (p. 1176) sections of our paper.

Secondly, we disagree with the suggestion of Cope that most of the excavation of the English Midlands was pre-Anglian. If there had been significant river excavation in the pre-Anglian, then the main rivers would have preferentially flowed *along* the NE–SW strike of the soft Late Triassic and Early Jurassic beds of the English Midlands. We recognize that the stratigraphy of the onshore pre-Anglian is poorly known. However, it is clear that in the case of the Warwickshire Avon, there could *not* have been any significant downcutting before the Anglian, otherwise detritus from the Birmingham area would have been unable to breach the Cotswold and Edge Hill escarpments and reach north Oxfordshire.

Thirdly, we disagree with Cope that we have necessarily overestimated the volume of material that was excavated and, hence, the amount of flank uplift. Cope's estimate of 375 km^3 is not 'significantly different', in our opinion, from our estimate of 500 km^3. This is because the volume estimates depend on assumptions about the area of excavation, the filtering parameters used to isolate the plateau surface and, the average height of the scarp. Besides, we did not actually use the volume estimates to calculate the flank uplift. Rather, the flexural response to the river excavation was calculated using 2-dimensional models.

We agree with Cope that the amount of flank uplift is dependent on the width that is assumed for the excavated region. The models in figure 4 of Watts *et al.* (2000) illustrate the sensitivity of the flank uplift to changes in the thickness of the excavated region and elastic thickness of the lithosphere but not to changes in width. Moreover, they are based on a symmetric unloading model in which there is an equal amount of material removed either side of the ancestral river. They therefore do not show the asymmetric case, which might be more appropriate to a region where the soft beds had already been tilted prior to excavation.

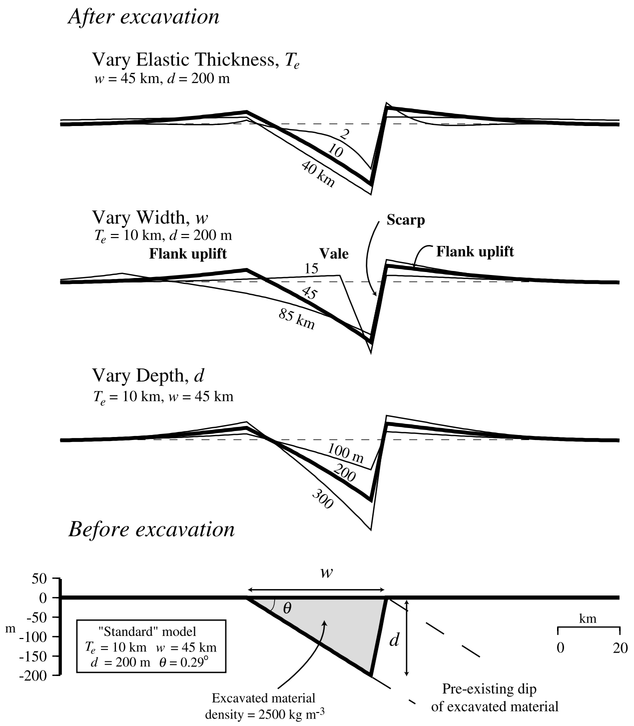

Fig. 1. Simple models of flexure due to unloading of the lithosphere by river excavation. The calculations assume two-dimensionality and that a state of isostasy exists before and after excavation. Heavy lines show the flexure due to a 'standard' model with d=200 m, w=45 km and T_e=10 km. Light lines show the flexure when d, w and T_e are varied within reasonable bounds. Other model parameters (e.g. Young's modulus and Poisson ratio) are as given in the caption of fig. 4 of Watts *et al.* (2000). We note that rim flank uplift is a feature of all flexure models. T_e controls both the amplitude and wavelength of the uplift, in contrast to d and w which control mainly the amplitude.

In order to address these points, we show in Figure 1 the calculated the flank uplift that would be expected for an asymmetric unloading model and a range of plausible values for the assumed depth of excavation, d, width of excavation, w and, elastic thickness of the lithosphere, T_e. The thick line in the figure shows the flank uplift that is associated with a 'standard' model with d=200 m, w=45 km and T_e=10 km. A width of 45 km was chosen because it is the approximate width of present-day outcrop of the soft Late Triassic and Early Jurassic beds between the Edge Hill [SO 981711] and Bromsgrove [SP 362458]. The figure shows that the 'standard' model produces a flank uplift of up to 45 m which agrees well with the relief of the plateau surface deduced by Watts *et al.* (2000) from the spectral averaging of topography profiles of north Oxfordshire. The thin lines in the figure show the sensitivity of the 'standard' model to variations in d, w and T_e. Increasing d and w, for example, increases the rim uplift. Since it is likely that both d and w exceed the values used in the 'standard' model (d because the region of excavation extends beyond Bromsgrove to the Severn river and w because the combined thickness of the Middle Trias mudstones, Upper Trias clays and Lower and Middle Lias clays and sands beneath the English Midlands exceed 450 m), the figure shows that flexure in response to excavation in the English Midlands is more than capable of producing rim uplifts in flanking regions, even regions as far afield as north Oxfordshire.

Finally, we disagree with Cope's remarks on the relative height of Bredon Hill compared to the Cotswold escarpment. We consider the opposing rim flank as in accord with the predictions of the flexure model. Bredon Hill is a Jurassic outlier which is located in the central area of uplift, yet has escaped excavation. We would expect therefore that Bredon Hill would be more elevated than the adjacent Cotswold escarpment. This is because the region of excavation, as a whole, experiences a greater flexural uplift than its flanking rims, irrespective of the value of T_e that is assumed. We pointed out in our paper (p. 1172) that the region of excavation will be flanked by rim uplifts, not only in north Oxfordshire but, also west of the Malvern Line (including the Abberley Hills and Forest of Dean) and the high ground around Birmingham (including the Lickey Hills). We also pointed out, however, that because of heavy river incision it might be difficult to easily see the surfaces of the opposing rim flank uplifts in topography data. Nevertheless, hints of a pronounced planation surface which caps the Forest of Dean at a height of about 200 m has been reported by Maddy (1997). The elevation of Bredon Hill and the Forest of Dean planation surface are therefore in accord with the predictions of the flexural unloading model and so might themselves be used as additional observational constraints on T_e and, hence, the flexural rigidity of the lithosphere.

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John C. W. Cope, Department of Earth Sciences, Cardiff University, PO Box 914, Cardiff CF10 3YE, UK (e-mail: copejcw@cardiff.ac.uk)

A. B. Watts & W. S. McKerrow, Department of Earth Sciences, Parks Road, Oxford OX1 3PR, UK (e-mail: tony@earth.ox.ac.uk)

E. Fielding, Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, California, USA

Scientific editing by Alex Maltman.