A model for the evolution of the Weald Basin

DAVID L. HANSEN, DEREK J. BLUNDELL & SØREN B. NIELSEN

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The Weald Basin developed through the Jurassic–Lower Cretaceous as an extensional basin founded upon E–W trending low-angle faults that were probably Variscan thrusts, subsequently reacti-vated as normal faults. Later, the basin was inverted and uplifted into a broad dome, whilst the London Basin to the north, and the Hampshire–Dieppe Basin to the south, subsided as flanking basins during the late Palaeocene–Eocene. Seismic sections across the Weald indicate that inver-sion resulted from north-directed stress. A stratigraphic reconstruction based on a N–S profile across the Weald and flanking basins serves as a template for a forward, 2D thermo-mechanical model that simulates the evolution of the Weald Basin through crustal extension and its inversion, and subsidence of the flanking basins, through compression. The model provides a physical expla-nation for this sequence of events, requiring a region of crust of reduced strength relative to its flanks. This weak region is the location of crustal-scale Variscan thrusts that have been reactivated subsequently. The strong crust on the flanks is essential for the development of flanking basins during inversion and uplift of the Weald.

Keywords: Basin inversion, lithosphere, thermo-mechanical modelling, finite elements, visco-elas-tic-plastic, sedimentation, erosion.

David Lundbek Hansen [*david@geo.aau.dk*] *& Søren Bom Nielsen, Department of Earth Sciences, University of Aarhus, Finlandsgade 6, DK-8200 Aarhus N. Derek J. Blundell, Department of Geology, Royal Holloway, University of London, England. 15 January 2001.*

The major structural framework of southern England was formed during the Variscan Orogeny around 300 Ma, when the Armorican crustal block of Brittany pushed northwards towards the Midland Craton of central England (Lefort & Max 1992). In the intervening region of the Channel and southern England, crustal-scale, north-vergent thrusts and associated folds were developed, with a dominant E–W trend. These were offset by lateral ramps of NE–SW trend towards the west and NW–SE trend towards the east of the region, which created a compartmentalisation that was exploited in subsequent tectonic movements (Chadwick 1986). Post-orogenic collapse and extension in the Permian initiated the Wessex Basin, which developed across southern England and the central Channel, encompassing a set of sub-basins which evolved throughout the Mesozoic within the compartmentalised Variscan structural framework (Underhill 1998). As explained by Lake & Karner (1987), Variscan thrust faults were reactivated as low-angle extensional detachments, with new, steeper short-cut normal growth faults rooting down to them. Permo-Trias depocentres in the west migrated eastwards where they were superseded during the Jurassic and Cretaceous. The Weald Basin, covering SE England, the eastern Channel and the Boulognais area of northern France (Fig. 1), was initiated in the lower Jurassic as an easterly prolongation of the Wessex Basin. It developed as an extensional basin, subsiding by means of normal growth faults of mainly E–W trend, the most active of which were close to its northern margin against the London Platform, a stable crustal block forming part of the London–Brabant Massif that had acted as the undeformed foreland to the Variscan orogen. Thus the Weald Basin developed during the Jurassic mainly as an asymmetric basin with strong down-to-S normal faults along its northern margin, founded upon the reactivated Variscan thrusts within the basement, which acted as low-angle extensional detachments (Fig. 2). An element of trans-tensional fault movements during this period is marked by the en echelon geometry of the normal faults in plan view and the presence of associated WNW–ESE trending faults.

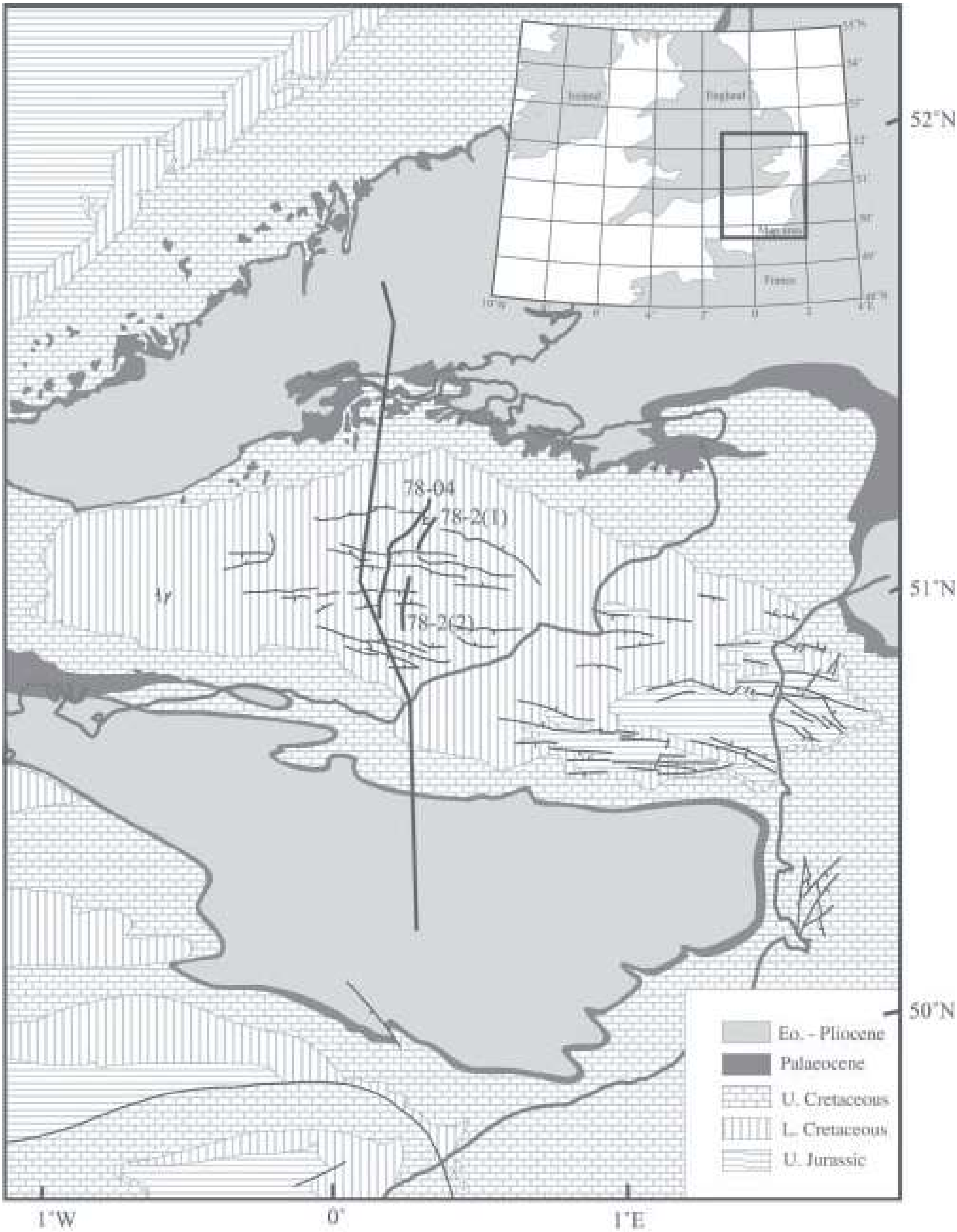


Fig. 1. Simplified geological map of SE England and locations of two seismic lines (Fig.2) and the BGS cross-section (Fig.3).

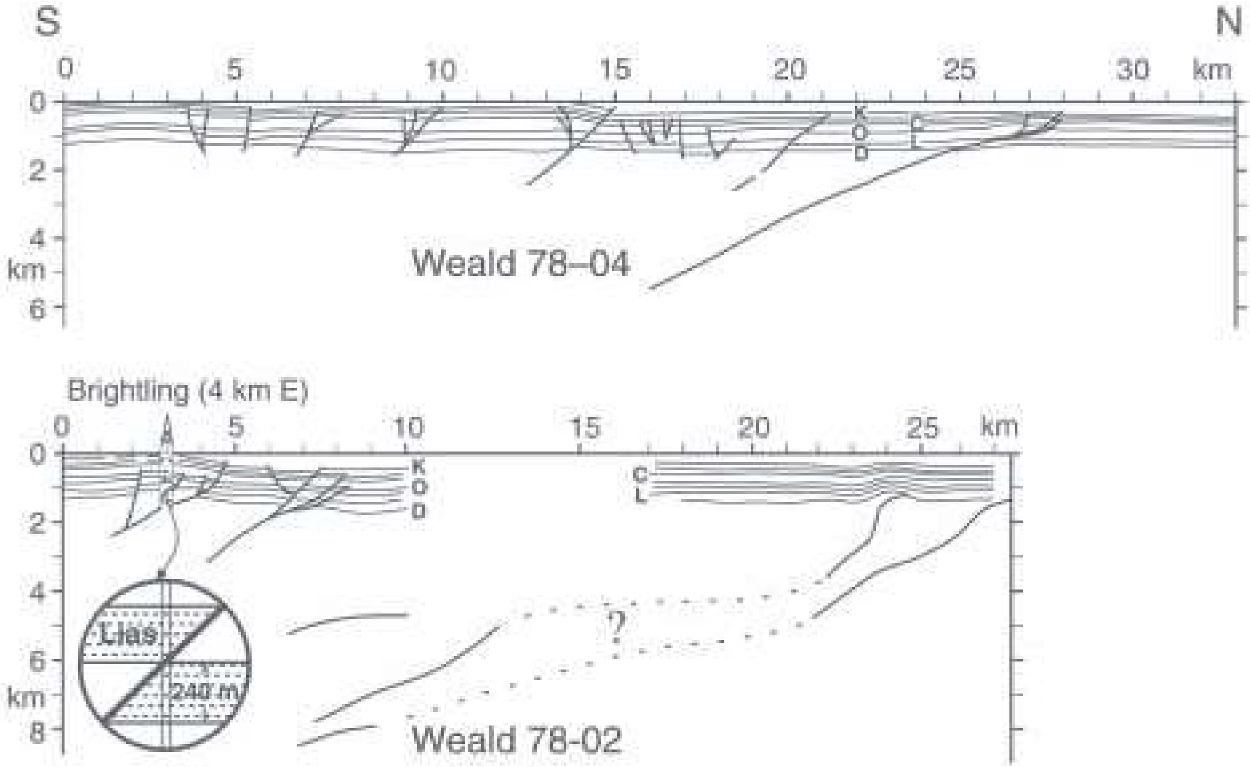


Fig. 2. True depth cross-sections based on the interpretation of seismic stack sections C78–02 and C78–04 across the Weald Basin, with stratal horizons depth converted using interval velocities derived from velocity analyses and faults migrated in the vertical plane of section. Stratal horizons are identified by reference to the nearby Brightling 1 well.

As the basin subsided it was filled with a Jurassic sequence in which carbonate rocks predominated, laid down in a shallow marine, low energy, wave-dominated environment, interspersed with mudstones. The Weald Basin became the major depocentre of the Wessex Basin during the Upper Jurassic and Lower Cretaceous, with phases of active faulting and intervening thermal relaxation. Sandstones deposited in the Upper Jurassic, sourced from the London Platform, formed as near-shore sand bars. These are overlain by Lower Cretaceous sabka-type evaporites and a sequence of shore-line sandstones and mudstones. Faulting ceased prior to Aptian time (124 Ma) and thermal subsidence followed. The Weald was covered by between 400 and 500 m of chalk during the Upper Cretaceous, which extended across the whole of southern Britain, northern France, and beyond.

Inversion of the Weald and formation of the London and Hampshire–Dieppe Basins

The youngest Chalk found in southern England is of Campanian age (74 Ma). A time gap of 16 Ma before the deposition of the oldest beds in the London and Hampshire–Dieppe basins, unconformably upon the Chalk, marks a period of uplift and erosion, the extent of which is difficult to quantify. Jones (1999) estimates that a regional uplift across southern England, most marked in Devon in the west and across the central Weald in the east, of some 500 m and erosion of 350 m of Chalk occurred between 68 and 60 Ma. Amounts of uplift and erosion varied, with about 60 m differential erosion of Chalk during this period. Uplift of the central Weald from the late Palaeocene to early Oligocene (60–30 Ma) was accompanied by subsidence and marine incursion of the London Basin to the north and the Hampshire–Dieppe Basin to the south. For much of this time the central Weald was emergent and being eroded, although marine encroachment around 53 Ma, which deposited the London Clay, was virtually complete across the

Weald. During the early Eocene the London and Hampshire–Dieppe basins were initially filled with alluvial and marginal marine deposits, followed in the late Eocene by the marine transgression that deposited the London Clay. In the Oligocene, regression led to the deposition of shallow marine near-shore deposits and freshwater limestones. Evidence of coeval erosion of the Weald and the Central Channel High, which followed a similar history, is found from clasts in the Eocene deposits. Examining the Eocene sequence of the Hampshire Basin exposed on the Isle of Wight close to a Chalk pericline associated with an inverted fault, Gale et al. (1999) were able to conclude that uplift occurred in a succession of short-lived pulses, individually of less than 1 Ma duration, at rates up to 100 m per Ma. These were accompanied by rapid erosion and sedimentation. The London and Hampshire–Dieppe basins both subsided passively as sag basins, with the accommodation space fully filled with sediment. Sedimentation ceased in these basins in the early Oligocene. Further inversion is evident in localised tectonic disturbances during the Miocene that resulted in uplift, erosion and, at least on the Isle of Wight, rotation of Eocene strata to the vertical. In the London Basin, for example, a small pericline formed post-London Clay raised Chalk to surface to create the hill on which Windsor Castle now stands, no doubt the surface expression of an underlying north-directed thrust. Sedimentation only resumed in the late Pliocene following a marine transgression from the southern North Sea in the east. This inundated a land surface of low relief that was being gently tilted towards the east and deposited shallow marine sediments.

Evidence from residual soils and planation surfaces across southern England, recently reviewed by Jones (1999), led him to conclude that an extensive sub-Palaeogene surface has been preserved as an etchplain, which currently stands at elevations which range between +200 m across the chalklands of the Weald and over +300 m in the west of England. The preservation of the residual soils for 60 Ma implies a land surface across much of southern England throughout the tertiary of low elevation and low relief, except that, in the last 3 Ma it has been elevated by 250–400 m. The cause of this uplift is unclear, although it may possibly be linked with contemporary subsidence of up to 700 m in several sub-basinal areas of the southern North Sea Basin. Kooi et al. (1991) modelled this subsidence as resulting from reactivation of strike-slip faults and the formation of pull-apart basins.

Modelling the evolution of the Weald Basin

The starting point for modelling is the present day cross section of the Weald and the flanking London and Hampshire–Dieppe basins taken from the BGS1:250,000 series of Solid Geology maps of Dungeness–Boulogne and the Thames Estuary (British Geological Survey 1988, 1989). A simplified version of this cross-section is shown in Figure 3. Whilst the detailed mechanism of Jurassic extension and subsequent Late Cretaceous–Palaeogene/Neogene inversion within the Weald may well be due to fault movements, there is, none the less, a distributed deformation which resulted in the overall basin shape during subsidence and the subsequent compression, with the uplift of the Weald and the coeval downwarping of

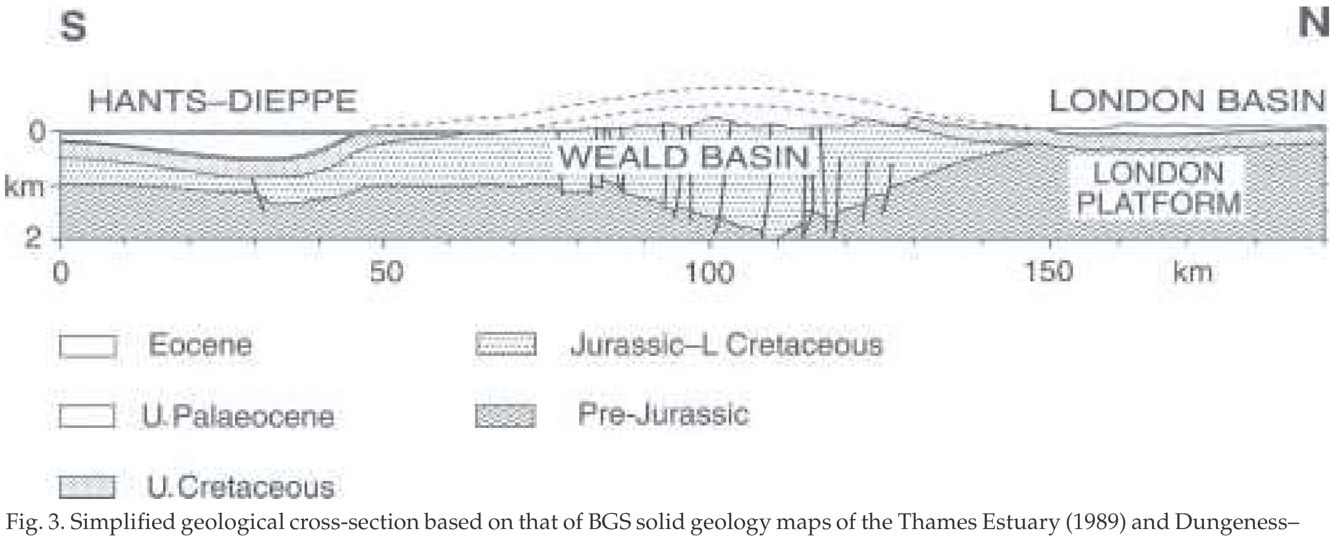
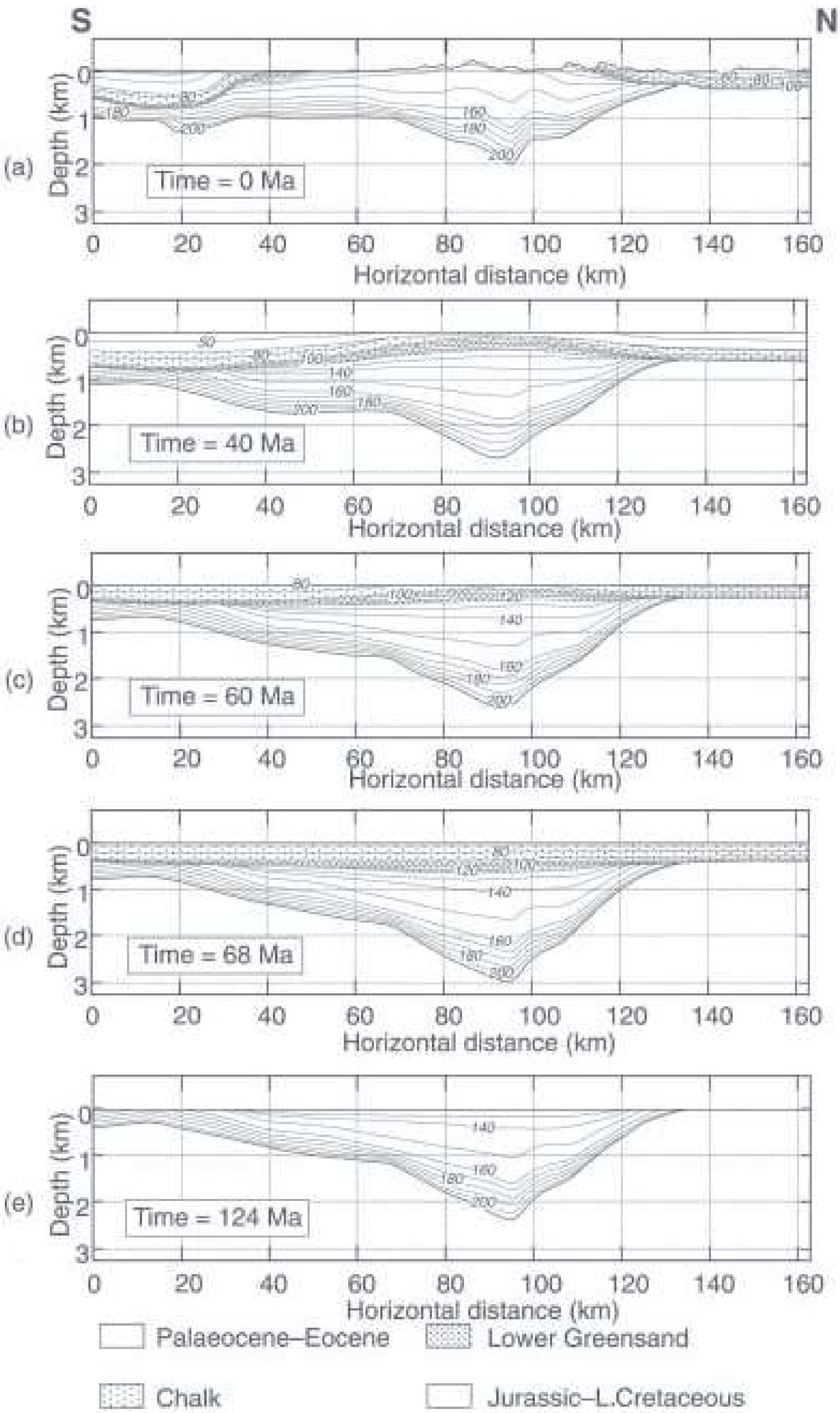


Fig. 3. Simplified geological cross-section based on that of BGS solid geology maps of the Thames Estuary (1989) and Dungeness–Bologne (1988).

Fig. 4. (a) adaptation of the geological cross section of Figure 3 to show isochrons; (b) reconstruction of cross-section at 40 Ma; (c) reconstruction of cross-section at 60 Ma; (d) reconstruction of cross-section at 68 Ma; (e) reconstruction of cross-section at 124 Ma.



the flanking Palaeogene and Neogene basins. In order to understand this process, the movements of individual faults have been replaced by bulk shear as the basis for performing the stratigraphic reconstruction. Critically for the forward modelling, the deep, crustal-scale faults provide a zone of low strength in the crust, laterally confined below the Weald basin, with relatively strong crust beneath the flanking basins. The stratigraphic reconstruction provides the template for a numerical forward model.

Stratigraphic reconstruction

The cross-section of Figure 3 was first adapted, by the removal of individual faults, to yield the present day cross-section shown in Figure 4a. On to this, isochrons have been drawn in order to illustrate the time sequence of the basin evolution. Using a knowledge of Paleogene and Neogene stratigraphy and landscape evolution (reviewed by Jones, 1999), the cross-section has been reconstructed back to the mid-Eocene (40 Ma, Fig. 4b), at which time the flanking basins had subsided to a maximum extent, to the late Paleocene (60 Ma, Fig. 4c) when the flanking basins began to subside, together with the broad domal uplift of the Weald, to the Late Cretaceous (68 Ma, Fig. 4d), when deposition of the Chalk had been complete and uplift and erosion began, and finally back to the mid-Cretaceous unconformity at 124 Ma (Fig. 4e). The Weald Basin was initiated at the beginning of the Jurassic (208 Ma). In making these reconstructions, account was taken of the compaction of the Jurassic–Lower Cretaceous sequence as a whole when buried beneath the full thickness of Upper Cretaceous beds. No account of compaction was made for the Upper Cretaceous and Tertiary beds.

Forward numerical modelling

A 2-dimensional thermo-mechanical evolutionary model developed by Hansen et al. (2000) and Nielsen & Hansen (2000) has been applied to the Weald cross-section, working forwards from 210 Ma to simulate the cross-sections created from the stratigraphic reconstruction. The numerical model operates on a finite element mesh of the crust and upper mantle to a depth of 100 km, with a dense mesh for maximum detail in the uppermost 18 km, a slightly less dense mesh between 18 km and the Moho at 34 km depth, and a coarse mesh within the mantle (Fig. 5). At each point of the mesh the rheological properties of the model are defined according to functions dependent

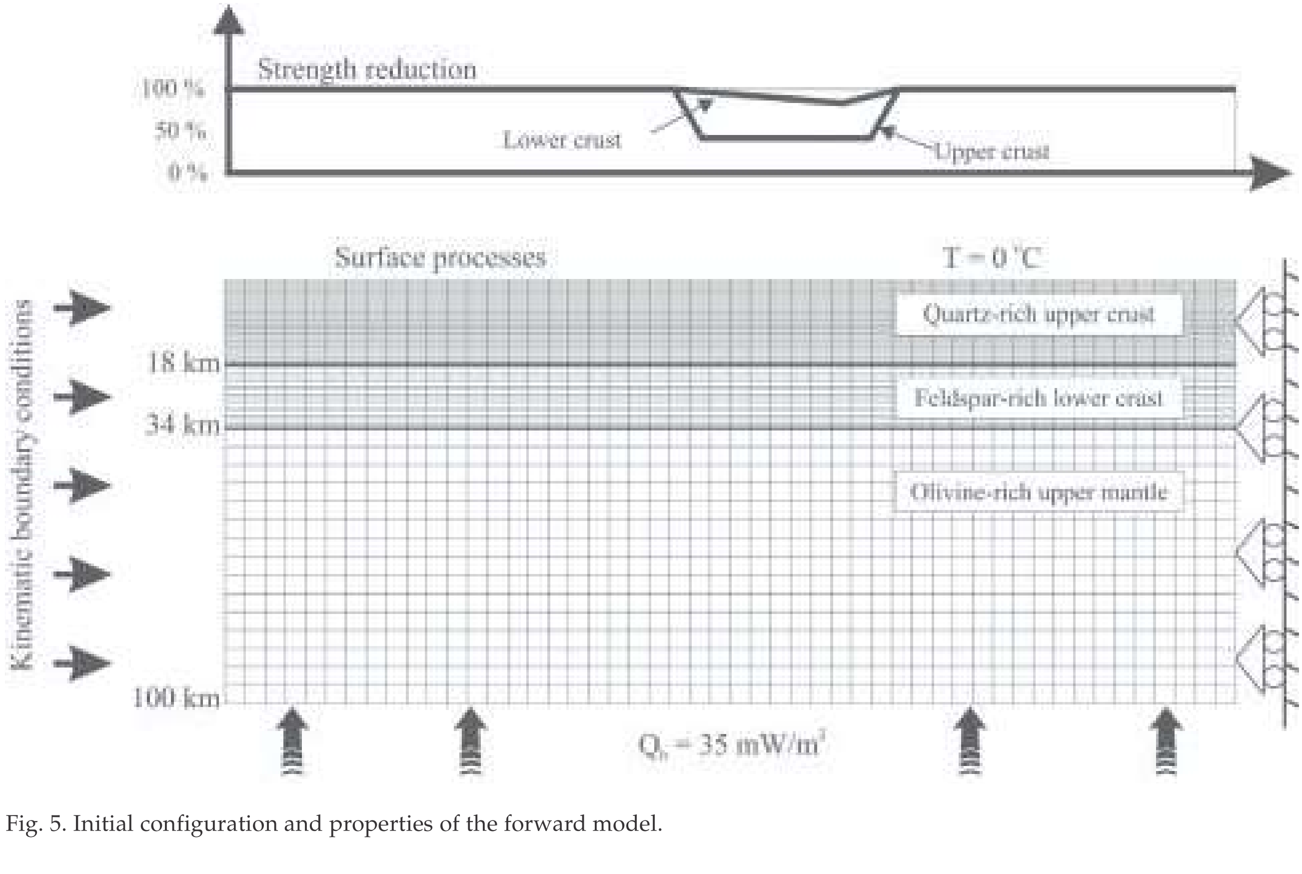


Fig. 5. Initial configuration and properties of the forward model.

on temperature, pressure, material composition and strain rate, creating fields within the model in which the material responds to stress in an elastic, plastic or viscous manner. As the stress and thermal fields within the model change in time, so, too, does the configuration of the rheological properties.

Displacements are found when solving the mechanical equilibrium equations :

$$\frac{\lambda\sigma_{ij}}{\lambda xj} + \rho X_i = 0$$

where σ_{ij} is the Cauchy stress tensor, x_j represents spatial coordinates, ρ is density and X_i represents body-forces in the i'th direction (e.g. gravity).

Rock viscosity is given by the following empirical function:

$$\eta = B[E_{2D}]^{(l-n)/2n} \exp\left(\frac{Q}{nRT}\right)$$

where E_{2D} is the second invariant of the deviatoric strain rate tensor, T is temperature, R is Boltzman's constant and n, B, Q are empirical creep parameters as given in Table 1.

Maximum rates of erosion and sedimentation are defined parameters within the model. Buoyancy forces resulting from density contrasts at the basement/sedimentary basin boundary, the Moho and base lithosphere are included in the model, which maintains isostatic equilibrium throughout. Eustatic sea-level changes (Haq et al. 1987) are also incorporated into the model. For further details on the physical basis of the model we refer to Hansen et al. (2000).

Applied to the Weald Basin, an initial crustal cross-section (Fig. 5) is set up with a mid-crustal boundary at 18 km and the Moho at 34 km depth. In the centre of the section, the yield strength of a 100 km width of the upper crust is reduced to 40% of that on the flanks, to simulate the crustal-scale faulting, and the underlying lower crust is reduced in strength asymmetrically to 85% of that on the flanks. The asymmetry is necessary to create the observed asymmetry of the basins. A horizontal tensional stress is applied at 210 Ma, which stretch the model at a rate of 100 $mMyr^{-1}$ for 40 Myr (210–170 Ma). This is increased over 5 Ma to 500 $mMyr^{-1}$, then maintained for 10 Ma, and then reduced to zero over a further 10 Ma (170 Ma–145 Ma). From 145 Ma until 60 Ma, the vertical axis are horizontally fixed but thermal relaxation is allowed to occur. At 60 Ma a horizontal compressive stress is applied that shorten the model at a rate increasing from zero to 250 $mMyr^{-1}$ over a 10 Ma period, which is maintained for 30 Ma (until 20 Ma). This is reduced over the next 10 Ma to 100 $mMyr^{-1}$ and held at this level to the present. The response of the sedimentary part of the model to this sequence of events is shown in Figure 6 at the same times as those of the reconstruction of Figure 5. Although the match is not exact, and could be improved by further adjustments to the forward model, there is a sufficiently close resemblance for useful geological inferences to be drawn.

Discussion

A number of seismic profiles were shot in the late 1970's in the search for oil, the data from which are now available for research purposes from the UK Onshore Geophysical Library. Interpretation of two seismic sections, shown in Figure 2, indicates south-dipping low-angle faults reaching to at least 8 km depth in the basement. The low-angle nature of these faults, and their E–W trend, suggest they originated as

Table 1. Model parameters. Creep parameters are from Nielsen & Hansen (2000).

Symbol	Meaning	Mantle Olivine	Lower crust Wet Feldspar	Upper crust Wet Quartzite	Sediments Wet Quartzite
E [Pa]	Young's modulus	10^{11}	10^{11}	10^{11}	10^{11}
ν	Poisson's ratio	0.25	0.25	0.25	0.25
n	Creep parameter	4.48	3.20	3.10	3.10
B [MPa $s^{-1/n}$]	Creep parameter	0.2628	12.28	208	208
Q [kJ/mol]	Creep parameter	498	239	135	135
T_0^e [MPa]	Tensile strength	26.2	13.1	13.1	8.73
T_0^c [MPa]	Comp. strength	52.4	26.2	26.2	17.5
ρ [kg/m^3]	Density	3300	2900	2700	2700*
k [W/m/K]	Conductivity	4.0	2.3	3.0	2.0
c [J/kg/K]	Specific heat	1000	900	850	1000
A [$\mu W/m^3$]	Heat prod. rate	0.01	0.3	1.3	1.3

*sediment porosity decreases with burial according to $\phi=0.6\exp(-z/2000m)$ where z is maximum burial depth.

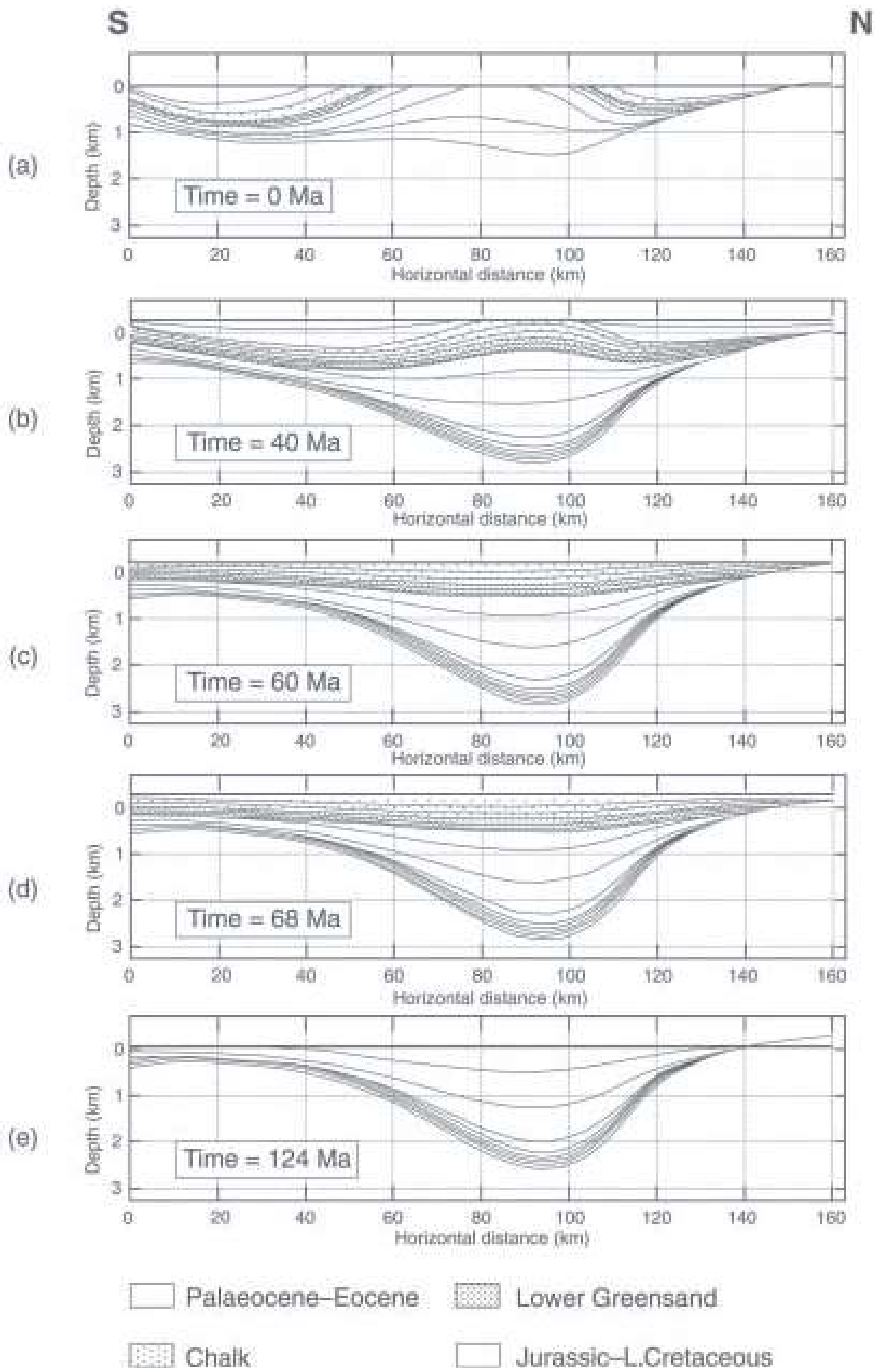


Fig. 6. (a)–(e) Cross-sections directly comparable with those of Figure 4 computed using forward modelling, as described in the text, at 0 Ma, 40 Ma, 60 Ma, 68 Ma and 124 Ma.

Table 2. Kinematic boundary conditions. v is velocity of left vertical axis. Positive values indicate extension, negative values indicate compression.

Period [Ma]	v [mm/yr]	Meaning
210–170	0.1	Slow ext.
170–155	0.1–0.5	Accel. ext.
155–145	0.5	Rapid ext.
145–130	0.5–0.0	Decel. ext.
130– 60	0.0	Quit period
60– 50	0.0– -0.25	Accel. comp.
50– 20	-0.25	Rapid comp.
20– 10	-0.25 – -0.1	Decel. comp.
10– 0	-0.1	Slow comp.

Variscan thrusts and are listric to a mid-crustal, horizontal detachment, such as that observed underlying the Wessex basin further to the west (Chadwick 1986). They were reactivated as normal growth faults during the Jurassic when the Weald Basin developed as an extensional basin. They were subsequently inverted during the tertiary, thereby creating localised uplift structures, with intense folding in the overlying strata above the fault tips. Evidence from a nearby borehole (Brightling 1) shows the repetition by faulting of 240 m of Liassic rocks, implying a reverse movement of the fault of at least 350 m. Movement of the hangingwall sediment up the low-angle, deep-seated segments of the faults, under north-directed compressive stress, would have created a broad uplift. Thus the longer wavelength doming of the Weald and the localised intense folding observed at surface outcrop can both be explained as features of the inversion of a set of linked, deep-seated low-angle faults. All the indications are that doming and fault movements took place at various times from the Palaeocene through to the Miocene. By analogy with the observations by Gale et al. (1999) relating to the Isle of Wight, it is likely that individual fault movements, and associated denudation of uplifted ground and sedimentation in nearby basins, occurred in a succession of short pulses of less than 1 Ma duration.

The sequence of stretching, followed by thermal relaxation, of the forward model simulates the subsidence of the Weald basin and its asymmetric geometry, including the unconformable nature of isochrons on its margins at 124 Ma, as reflected in the stratigraphy. The model simulates continuing subsidence during the Upper Cretaceous, the broad domal uplift of the Weald and subsidence of the flanking basins between 60 and 40 Ma, and then further uplift and erosion, and a tightening of structures, since 40 Ma.

The London and Hampshire–Dieppe basins formed as compressive sag basins as an essential accompaniment to the uplift of the inverted Weald Basin, based on the thermo-mechanical response of the lithosphere to the horizontal compressive stress. Their presence was predetermined by the reduction in yield strength beneath the Weald basin and the higher strength on the flanks, in addition to the variability with depth. This is probably a measure of the weakness created by the presence of crustal-scale faults beneath the Weald Basin and the lack of such faults beneath the London and Hampshire–Dieppe basins, all of which are a legacy of the Variscan orogeny. The total extension during the period between 210 and 145 Ma, according to the model, is 13 km and the total shortening, between 60 Ma and the present, is 11.5 km. Because the whole of the stretching and shortening is ascribed to distributed shear, and faulting is not invoked, these figures are likely to be about double the actual amounts of extension and shortening. For the purposes of the modelling, constant rates of stretching or shortening, held for long periods, are used to represent the integration over time of numerous short pulses of movement that are actually recorded in the stratigraphic record, exemplified by the work of Gale et al. (1999) on the Isle of Wight.

Although not evident in Figure 6, the forward model deploys rates of sedimentation which ensures that sedimentation keep pace with subsidence, maintaining shallow water depths consistent with depositional environments deduced from observed lithologies and sedimentary structures. Rates of erosion used in the model ensures that erosion keep pace with uplift so that a low elevation, low relief landscape is maintained during the past 60 Ma, consistent with the evidence from residual soils and planation surfaces (Jones 1999). The model indicates erosion of the London Basin sediments and uplift of its northern margin in the past 40 Ma are in part a result of the eustatic fall in sea level, according to Haq et al. (1987) of around 100 m since the Miocene. It does not include the elevation observed during the past 2 Ma that has created the modern topography of southern Britain.

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