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MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

The Regional Setting

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Phil. Trans. R. Soc. Lond. A 1972 **272**, 81-86
doi: 10.1098/rsta.1972.0033

Phil. Trans. R. Soc. Lond. A. **272**, 81–86 (1972) [81]
Printed in Great Britain

THE EVIDENCE FOR SUBSIDENCE

The regional setting

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For the purpose of the present discussion, southeastern England will be understood to embrace East Anglia, the London Basin, the Weald anticline and the Hampshire Basin. However, because of the immediate practical importance of subsidence still apparently continuing, it will focus most attention upon the Thames Estuary and on London. The whole region is one in which the formations exposed at the surface are no older than Jurassic (about 160 million years (Ma)). They continue upwards through Cretaceous (Gault, Greensand, Chalk) and Tertiary to Pleistocene and Recent deposits.

The Mesozoic rocks rest upon a platform of much older rocks, ranging from Carboniferous (under Kent) through Devonian under London itself to lower Palaeozoic. Figure 1 shows the formations penetrated by representative boreholes through the Mesozoic cover. The platform of Devonian lies 300 m or less below surface under London (Sherlock 1962), but the upper boundary of the ancient rock descends to 1500 m or more under the Weald (Gallois 1965). Not enough information is available to enable the thickness and structure of these old buried rocks to be

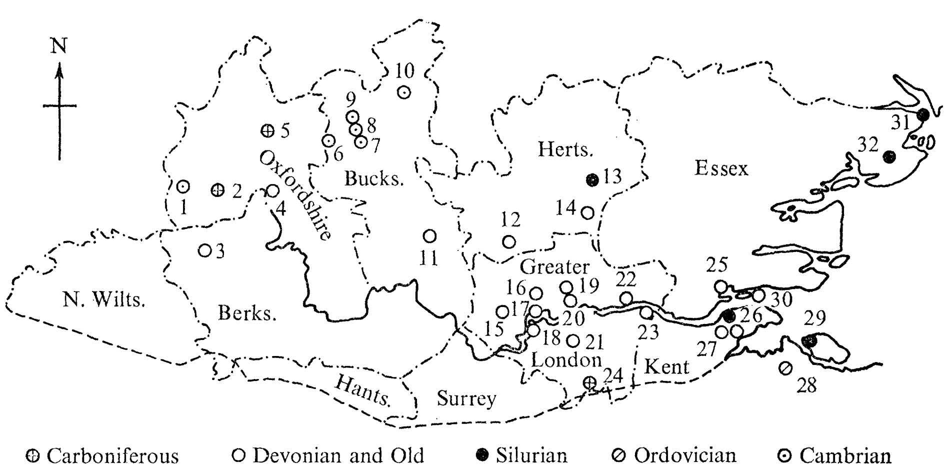

Figure 1. London and Thames Valley; key to boreholes.

1. Burford
2. Witney (Apley Barn)
3. Faringdon
4. Noke
5. Steeple Aston
6. Marsh Gibbon
7. Calvert
8. Charndon
9. Twyford
10. Tattenhoe
11. Little Missenden
12. Bushey
13. Ware
14. Turnford
15. Southall
16. Willesden
17. Chiswick
18. Richmond
19. Kentish Town
20. Tottenham Court Road, London
21. Streatham
22. Beckton
23. Crossness
24. Warlingham
25. Fobbing
26. Cliffe Marshes
27. Cliffe Nos 10 and 11
28. Bobbing
29. Sheerness
30. Canvey Island
31. Harwich
32. Weeley

worked out, but it is certain that they had been extensively folded by disturbances that culminated at perhaps 390–420 Ma ('Caledonian') and 280 Ma ('Hercynian'). For long periods of geological time, what is now the infrastructure of southeastern England formed part of a great mobile belt extending, according to current ideas, longitudinally across a continental mass which included Eurasia and America. The sedimentary rocks, which accumulated in troughs within the belt, reach great thicknesses and point to marked subsidence as the primary control of accumulation. The Lower Palaeozoic rocks from Cambrian to Silurian can be seen at the surface in Wales. The calculations of Jones (1938) indicate a maximum thickness of about 11.5 km of sediment accumulated in 270 Ma. A maximum figure for subsidence, assuming it was continuous (which it was certainly not), would give an average rate of 4.3 mm per century; but this takes no account of compaction, which in the type of sediment present here (shales and greywackes dominating) might well double this figure.

The uplands created by the Hercynian earth movements were eventually planed down to produce the London platform which forms part of the so-called Anglo-Brabant massif. Upon this erosion surface were deposited the Mesozoic sediments, and again the distribution and thickness of these was controlled by differential warping of the crust. Thus, the region which now forms the Weald of Kent subsided during Jurassic times to receive 1.5 km of shallow water, mainly marine sediments. A minimum rate of subsidence of 5.8 mm per century can be calculated for this period. The Wealden series of early Cretaceous time were deposited in a freshwater lake; three successive deltas were built up to water level so that they were able to support forests, but each was eventually buried under later sediments (Allen 1959). No clearer proof of continuing subsidence could be found. Meanwhile, however, the London platform remained an island. Later in the Cretaceous the very widespread Cenomanian marine transgression brought shallow sea over great areas of Europe including the whole of southeastern England and in this accumulated the white foraminiferal limestone of the Chalk. For Cretaceous times, the subsidence rate uncorrected for compaction appears to have been only about 1.4 mm per century.

The evidence from the stratigraphy and lithology of the sedimentary rocks underlying southeastern England shows the continuing instability of the Earth's crust with periods of continuous and intermittent subsidence relative to sea level interspersed with periods of positive upward movement followed by erosion. Such is indeed generally true of the crust; but the exact causes of these movements are difficult to discover. On the broadest scale, the recent concept of plate tectonics (McKenzie & Parker 1967; Morgan 1968) proposes that the lithosphere (the outermost shell of the solid earth) suffers strong deformation only along narrow mobile belts lying between more or less rigid blocks or plates. The thick sedimentation and subsequent distortion of the palaeozoic rocks can reasonably be explained, as indeed it was under the older Dana–Hall geosynclinal concept by the development of subsiding troughs extending through what is now east Greenland, Spitzbergen, Scandinavia, the British Isles and eastern north America from Cambrian to Silurian times with strong distortion in later Ordovician and late Silurian–early Devonian times; followed by the appearance of a new series of troughs running from east to west across Europe beneath London, through Cornubia and linking with the Appalachians in Devonian and Carboniferous times, terminated again by powerful distortion of the thick prisms of sediment that had accumulated. Within the relatively rigid blocks or plate themselves gentler warping and vertical movements undoubtedly took place; perhaps the plate tectonics concept tends to minimize these unduly.

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From late Cretaceous times two new factors about which more is positively known began to influence southern England. Rifting to the west of the British Isles, broadly oriented NNE took place, and drifting apart of the American and Eurasian continents started. The very strong evidence for this has already been summarized by Blackett, Bullard & Runcorn (1965). The apparent movement is explained by the formation of new oceanic crust by spreading of basaltic material from a median fissure-system (Vine & Matthews 1963; Vine 1966). The Atlantic continental margin to the west of Britain plays an inactive role (quite different from the Pacific margins where oceanic crust is being destroyed by subduction), but nevertheless as Smalley (1967) and Taylor & Smalley (1969) have suggested stresses are set up in the continental block which could explain features such as the Tertiary basin in the North Sea and the satellite basins under London, Hampshire and Paris. Bott & Watts (1971) indicate other connexions with sea-floor spreading, including steady-state creep of lower crustal material.

Whatever the cause, subsidence continued through earlier Tertiary (Palaeogene) times, during which the Reading and Woolwich beds and the London Clay were deposited in the London basin; and was renewed in late Tertiary and early Pleistocene (Neogene) times, when the Crag deposits, with clear evidence of changing shorelines, were laid down. For the Palaeogene, a subsidence rate averaging 1.8 mm per century (plus a compaction factor) is indicated.

Now followed a new situation, also initially leading to subsidence. The great ice-sheets of the Pleistocene which appeared about one million years ago caused depression of the continental crust upon which they rested and they extended at least as far south as the Thames Valley. This, the isostatic loading effect, was offset by a fall in sea level due to the removal of very large quantities of water from the oceans to form ice. Until the final retreat of the glaciers, these two factors, the isostatic and the eustatic were in competition with one another and with the tectonics effects associated with ocean floor spreading and other causes. It is difficult, if not impossible, to distinguish clearly between these effects; some or perhaps all of them are influencing the current situation. It is generally accepted that the continental shelf was produced by subaerial erosion coupled with marine planation, and that this indicates a low sea level of 200 m below present level at some stage in the Pleistocene. There is some evidence of a high sea level of about 200 m above present (Wooldridge 1960), but this is more controversial. It is, however, clear from the well-developed Boyne Hill and Taplow terraces of the Thames, that these were graded to sea levels respectively about 30 and 15 m above present. The fall of sea level relative to land continued until the lower or Flood Plain terrace of the Thames was formed. The bottom of the sand and gravel deposits forming this lies substantially below present sea level showing that the river was graded to a sea level at least 25 m below the present. Subarctic conditions are indicated by the fossils in the Flood Plain terrace, but the final amelioration of the climate leading to the present occurred after it had been formed, the time spanned being about 10000 years.

For the present inquiry, this, the Holocene period of geological history is of immediate interest. The detailed studies of Jelgersma (1971) in the Netherlands show from radiocarbon dating of peat deposits encountered in numerous borings, that Holocene times have been a period of subsidence of the land relative to sea level, the total extent being over 20 m. Other authorities agree that subsidence was continuous to 5000 to 3000 B.P. but some, for example Godwin, Suggate & Willis (1958) have claimed that there has been little or no change in the past 5000 years. Miss Jelgersma's data, however, for Holland indicates subsidence continuing to the present, though at a decreased rate from about 5000 B.P. onward. Her curves suggest an average subsidence of 500 mm per century between 8000 and 5000 B.P., reducing to 100 mm per century since 5000 B.P. It will be noted that these are far higher rates than the average rates deduced for the Tertiary and older sediments, but compaction of these recent deposits is by no means complete and direct comparison with the earlier rates of subsidence may not be entirely valid.

For southeastern England, unfortunately, only a few observations on dated peat beds buried below sea level are available at present. The data available has been used by Churchill (1965) to suggest a maximum subsidence, involving East Anglia, the Thames Estuary and Kent of 6 m in the last 6500 years, i.e. an average rate much the same as can be deduced from Miss Jelgersma's data for the same period in the Netherlands.

It must not be supposed that apparent subsidence is a general feature of the British Islands during the Holocene. It has long been known that physiographical evidence strongly indicates that much of Scotland probably with northwestern England has been rising. The late-Glacial raised beaches, particularly those at the '25 ft' (7.6 m) level backed by old sea cliffs, are perhaps the most striking testimony to this (Sissons 1967). It is very clear not only from the drowned topography of Orkney and Shetland, but still more from the submerged peat beds in the latter (Flinn 1964), that these parts of Scotland are, like southeastern England, subsiding. The magnitude of this effect is indicated by Sissons (1967) who in referring to the occurrence of submerged peat at Whalsay in the Shetlands, comments 'Since the peat was obtained from about 29 ft below high water mark, at least this amount of relative sea-level rise has occurred in this part of Shetland in the last 5500 years or so'. The dating being derived from five peat samples ranging in age from 5400 to 7000 years B.P. In contrast, the buried and submerged peats in the central areas affected by isostatic warping are above ordnance datum. For example, they are at +25 ft (7.6 m) O.D. in the west of the Forth lowlands whence they fall to well below ordnance datum in the regions peripheral to that affected by the isostatic uplift. Thus, the simple picture of a tilting movement, as deduced by Linton (1951) from physiography, Valentin (1953) from tidal observations, and Churchill (1965) from peat deposits, by which Scotland rises while southeastern England subsides, is not correct. The mechanism advocated by Smalley (1967) and Taylor & Smalley (1969) similarly takes no account of the subsiding north of Scotland, though a small modification could cover this. It can in fact be argued that the movements which appear to be in progress are producing an arching of Great Britain, with an axis more or less in the Caledonoid (NE) trend. The principal factors leading to this conclusion are briefly summarized in figure 2.

The hinge between the rising and subsiding areas in England has been placed along a line between the Tees and Pembrokeshire by Churchill. This is in accordance with the distribution of 'submerged forests', seen around the coast at exceptionally low tides. These first appear, coming southwards, at Berwick and are known at intervals around the coast of eastern and southern England and south Wales; it is certain that the sea has risen since the forest trees, the roots and boles of which remain, flourished.

It is not profitable, in the present inadequate state of geological information, to attempt to establish the cause or dominant control of subsidence in southeastern England. At present, nothing precise is known of the nature of the Earth's crust beneath the area below the limits of the boreholes, the deepest being about 1 km. Geological evidence of the position of the Mohorovicic discontinuity is lacking, though there is little reason to think this departs far from the 30 km proved in northwestern England. The evidence from buried peat deposits formed

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near sea level in the U.K. is inadequate. Leaving aside causes, the geological evidence can be extrapolated cautiously to suggest a current rate of subsidence of about 100 mm per century. It should not be expected that this is a uniform rate, and it is likely to vary from place to place. In certain areas like the Thames Estuary, the activities of man have undoubtedly affected the situation.

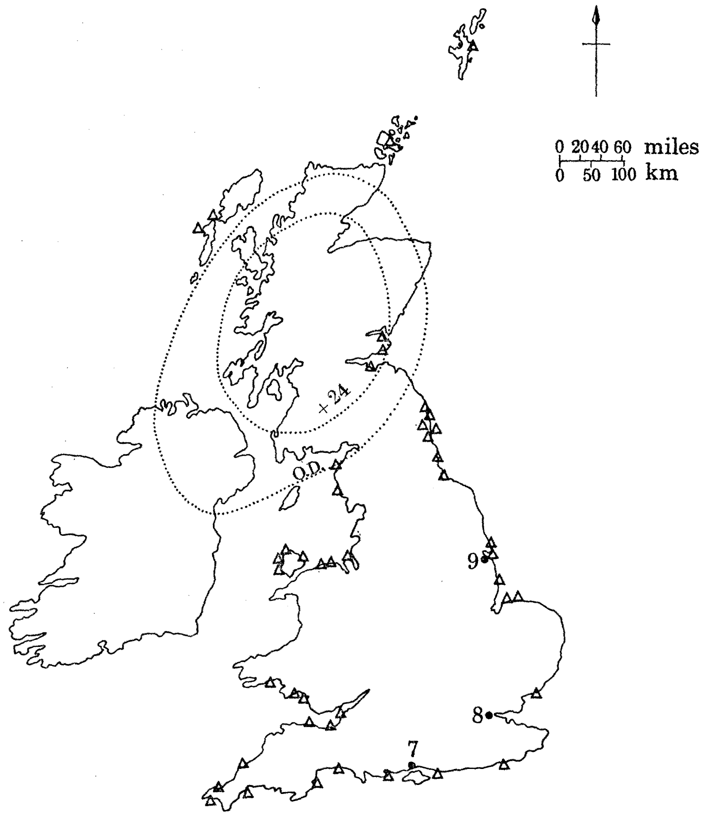

FIGURE 2. Outline map of Great Britain indicating the distribution of the principal data relevant to elevation and subsidence. · · · · +24, approximate limit of area in which late-Glacial raised beaches in Scotland occur at a level greater than 24 m above ordnance datum and · · · · O.D., approximate line along which outermost late-Glacial raised beaches pass below present sea-level. (After Sissons 1967.) ●, localities within southeastern England at which dated peats occur:

Site 7: oak wood from −7.5 m O.D. dated at 6358 ± 130 B.P.: overlying *Phragmites* clay dated at 6390 ± 124 B.P.

Site 8: *Phragmites* peat from −11 m O.D. dated at *ca.* 7000 ± 120 B.P. Wood at −8 m O.D. dated at 5790 ± 120 B.P.

Site 9: *Alnus* wood from *ca.* −9 m O.D. dated at 6681 = 130 B.P.
(After Churchill 1965.)

△, localities at which 'submerged forests' have been recorded on the foreshores. The ages of these peat deposits visible at low tide is known in only a few cases.

In the discussion which follows, critical examination is given to the evidence from Pleistocene land/sea-level changes, from structural geology, from sedimentation, from current sea-level observations, from coastal and estuarine sedimentation and from archaeology, before considering practical measures necessary to safeguard the Thames Estuary and London.

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