THE SUBSIDENCE OF THE NORTH SEA BASIN AND THE GEOMORPHOLOGY OF BRITAIN

by

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Summary

The North Sea basin is subsiding and Britain is tilting, up in the north-west and down in the south-east. These two related effects may be caused by a mantle current which rises at the mid-Atlantic ridge and descends in the vicinity of the Alps. Such a current, impinging on the thicker continental crust, would cause distortion at the edge of the continent, particularly in the projecting lobe which contains Britain and in the even more exposed Iberian peninsula.

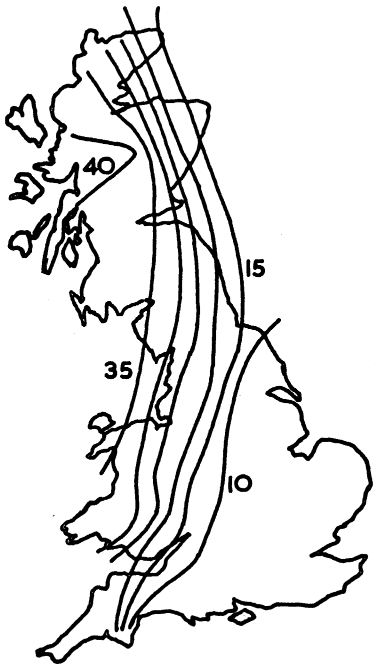
I am a firm believer that without speculation
there is no good original observation.

C. Darwin to A.R. Wallace 1857

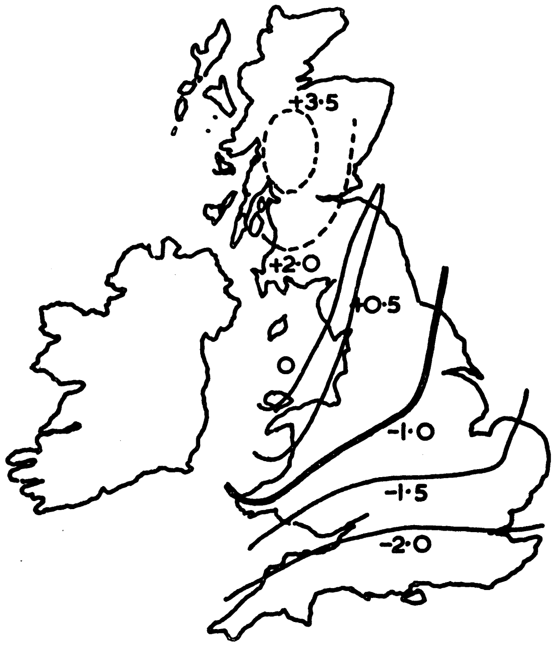
Introduction

L.C. King (1966, p. 396), in his treatise on the morphology of the earth, described a map by Linton (1951) as the basic document for the study of British geomorphology. This map is part of a paper concerning problems of Scottish scenery and, according to King, it demonstrates two things: (a) that summit altitudes in Britain represent in a general way a formerly existing summit topography of low relief; and (b) that this former topography has hinged along a north-south axis passing through East Anglia, giving progressively more uplifted country towards the west and a depressed area to the east. This second fact, the tilt of Britain, appears to be the critical fact determining the present face of the country. Depression to the east and denudation to the west have led to a particular pattern of exposed strata with, in general, older rocks outcropping to the west. A sketch map based on Linton's summit topography map is shown in Text-fig. 1.

Further evidence for the existence of the tilt and an indication that it is still continuing can be derived from papers by Valentin(1953)and Churchill(1965). Text-fig. 2 is based on a map by Valentin; it shows present vertical movements of the British Isles in relation to mean sea level, in mm./year. To obtain true crustal movements, the amount of present sea level rise must be added to all figures; if this is taken to be 1mm./year then the pivot line is the -1 line (this is given special emphasis in Text-fig. 2). The map indicates uplift to the north and west and subsidence to the south and east. The same pattern of crustal movement is apparent from the map produced by Churchill. Text-fig. 3 is based on the Churchill map; it shows the general trend since 6500 B.P., the figures expressing vertical distances in feet. The data for this map were derived from peat



Text-fig. 1. Summit altitudes in Britain; heights in hundreds of feet (after Linton 1951).



Text-fig. 2. Present vertical movements in the British Isles, according to Valentin (1953), in relation to mean sea level. Positive numbers–uplift; negative number–subsidence, in mm./year.

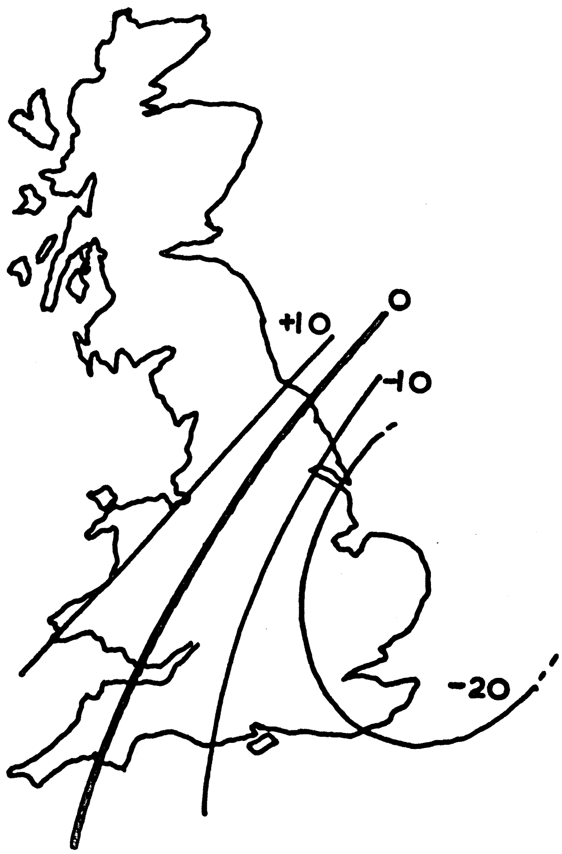
deposits which had been formed at sea level and could be dated by radiocarbon methods. This appears to be a method preferable to that of Valentin, who had to rely on tide-gauge data and who described the bulk of his results as "probable" or "conjectural". The Churchill investigations only concerned southern Britain, but they serve to establish the important pivot line.

Vertical movements of shorelines in Highland Britain have been considered by Walton (1966), but he offers neither elucidation of overall trends nor an acceptable mechanism of crustal upwarping. The Walton paper served as an introduction to a symposium on vertical displacements of shorelines; it is apparent, from the papers presented at that symposium, that rising and falling sea levels during the Pleistocene make the whole situation very complex. Work on raised beaches yields data on relative sea-level changes but, with the absolute sea level changing, it is difficult to discern absolute crustal movement. This applies not only to the Highlands but to most other areas as well. On the other hand, by working on a site close to the pivot line, it is possible to study eustatic changes of sea level with the minimum of disturbance from changing land levels. For Pleistocene and Recent tilting the pivot line suggested by Churchill is probably the most reasonable. This passes very close to the raised beaches and strandlines investigated by Orme (1960) in South Devon.

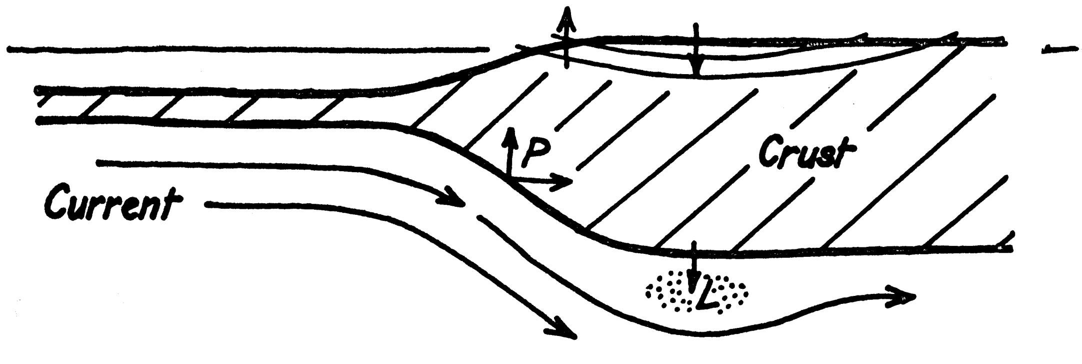
To the south and east of the pivot line Britain is sinking; this subsidence is directly related to the more widespread subsidence of the North Sea basin and both of these crustal movements are caused by the same mechanism. The present North Sea occupies only the most westerly part of a much larger sedimentary basin, which is believed to have come into existence in Upper Permian times. Brouwer (1963) described it as being bordered to the north by the Precambrian Baltic shield, to the east by the Russian platform, and to the south by a number of Palaeozoic massifs. Umbgrove (1945) defined it as being enclosed on its western and eastern sides by two axes of elevation, the Pennines and the axis of Erkelenz. L. C. King (1966, p. 404) suggested that the North Sea basin did not exist during the Jurassic and quoted, in support of this statement, a contention of Arkell's that the deltaic Bajocian and Bathonian deposits of N. E. Britain were derived from the Scandinavian shield. The basin, according to King, subsided intermittently during the late Mesozoic, the Oligocene, and the Plio-Pleistocene. The subsidence of the Netherlands part of the basin and its implications have been considered in some detail by Faber (1962).

The tilting of Britain and the subsidence of the North Sea basin are results of the same basic crustal movement. The cause of the crustal movement lies probably beneath the crust, in the upper mantle. Action in the mantle causes crustal movements which are seen in the tilting and the subsidence. Since the upper mantle is still inaccessible, it is only possible to speculate about the nature of processes occuring in this part of the earth. There does, however, appear to be considerable and growing support for the idea of convection currents in the mantle, giving rise to continental displacement. Evidence for continental drift and the presence of convection currents in the mantle has been presented in a recent symposium (Blackett, Bullard and Runcorn, 1965); the evidence for drift has also been considered in some detail by Bullard (1964) and in more general articles by Wilson (1962) and Dietz (1966). It was suggested by Runcorn (1962) that the system of convection currents has fairly recently (in geological time) undergone a change from a four-cell arrangement to a five-cell arrangement. Some calculations by Coode (1966) have provided support for this theory, but it should be noted that Wilson (1966) has suggested a feasible, alternative convection system which does not require multiple cells. Wilson envisaged a single cell upwelling along the mid-ocean ridges to form young ocean crust and reabsorbing older ocean floors by downwards flow under trenches. He suggested that the convection pattern was a self-altering one, requiring no hypotheses about the growth of the core to explain the succession of different orogenies, as the Runcorn (1962) theory requires.

The currents in the mantle do appear to have a direct effect on the configuration of the crust and a recent change in the convection pattern provides a likely starting point for the crustal movements under consideration. Various current directions have been proposed; the suggestions outlined in this paper depend on a current which rises at the mid-Atlantic ridge and travels in a generally south-easterly direction, as indicated on the maps of Girdler (1965) and Wilson (1962). The interaction of the current with the thickening continental crust causes the crust to deform slightly; the current provides the endogenetic forces which give rise to certain structures and landforms.



Text-fig. 3. Tilt of Britain occurring since 6500 B.P.; vertical distances in feet; positive numbers-uplift, negative numbers-subsidence (after Churchill 1965).



Text-fig. 4. An ideal current-crust interaction system. P-high pressure zone causing uplift; L-low pressure zone causing subsidence.

Mechanism

Vening Meinesz (1954) proposed a mechanism to account for the subsidence of the Netherlands part of the North Sea basin. He suggested that, in the study of crustal movements in the Netherlands, two great phenomena are important. These are the postglacial rising of Fennoscandia, which may be expected to bring about a sinking in the surrounding area, and the rising of the Alpine foreland,which has given a recent upward movement in the Rhineland, the Ardennes and Limburg. Vening Meinesz stated that it is fairly certain that the rising of the Alpine foreland has already had a profound influence on the southern part of Holland,as well as the greater part of Belgium and a great area further south. He invoked this foreland uplift because his model required that subsidence take place over a broad belt of northern Europe, whereas it is in fact only found on the northern and north-western margins.

A fundamental tectonic mechanism is required which can cause pre- and post-glacial crustal movements. This mechanism can be considered as a complement to the Vening Meinesz mechanism, or possibly as an alternative. The Vening Meinesz mechanism could only contribute to postglacial subsidence and it does not appear to explain the tilt of Britain. The mechanism suggested here relies on the presence of a current in the upper mantle which interacts with the crust to produce certain effects. The sectional diagram in Text-fig. 4 shows a suggested flow adjustment pattern,which would take the south-east flowing convection cell current under the thickening European continental crust. It is considered that the current is tending to push the whole continental mass towards the south-east. At the edge,considerable upward stress is exerted and the crust responds to this if it can. In the case of Britain, as shown in Text-fig. 5, there is effectively a lobe projecting from the main continental mass and,due to its exposed position,this feels the effect of the upthrust more than the main continental body. The other major projection from the continent is the Iberian peninsula and this appears to have been bent back by the impinging current, towards Africa. This has the effect of producing what Carey (1958) calls a sphenochasm, the Bay of Biscay. The goodness-of-fit investigations by Bullard, Everett and Smith (1965) and the palaeomagnetic investigations reported by Irving (1964, p. 254) suggest that this readjustment of the continental periphery probably occurred.

It is further considered that the same force which caused the lateral movement has uplifted the western edge of Britain. The flow is diverted downwards by the thickening crust and there is a zone of readjustment where the original direction is restored. A sub-crustal low pressure zone is caused (at point L in Text-fig. 4); the isostatic balance is disturbed; and at this point the crust tends to sink, resulting in the subsidence of the North Sea basin.

If this is indeed the mechanism responsible for the crustal deformations, the tilting and subsiding must have been going on,possibly at varying rates, since the convection cell first became active; if it is still active, the crustal movements are still going on. This would mean that the optimistic view of Vening Meinesz,that the subsidence of the Netherlands would end at about 6800 A.D., after another 3.5 m. of subsidence, was unjustified and that subsidence might be expected to continue until a new arrangement of convection currents is formed, or some crustal readjustment, perhaps by faulting, occurs.

The Time Factor

There is a school of geomorphological thought which considers that the most normal type of landscape is one in which the rate of crustal uplift more or less keeps pace with denudation and erosion, thus leading to a landscape of moderate relief (see C.A.M. King, 1966, p. 8). This appears to be the case for Britain; a slow, continuing Penckian uplift yields the sort of landscape relief indicated in the Linton (1951) sketch map shown in Text-fig. 1. An aspect of the process which needs to be investigated is the problem of when the uplift of the west began; this would presumably coincide with the beginning of subsidence in the east.

L.C. King (1966, p. 397) has criticized Linton's choice of a starting point for the tilting process. Linton chose a Cretaceous (pre-Cenomanian) landsurface for the ancestral planation. King suggested that the ancestral summit topography must be younger than the early-Cainozoic lavas of Mull and Antrim and must belong to a Cainozoic cycle of erosion which would pass over them. The parent land-surface would thus be of Cainozoic age; from it the existing cyclic topography has been carved. It seems more likely that the Linton choice is the right one; the Mull and Antrim lavas were released when the Irish Sea fault was formed - some time after the beginning of the tilt process. It could be that the event which marked the end of the Cretaceous period was the starting of the tilt.

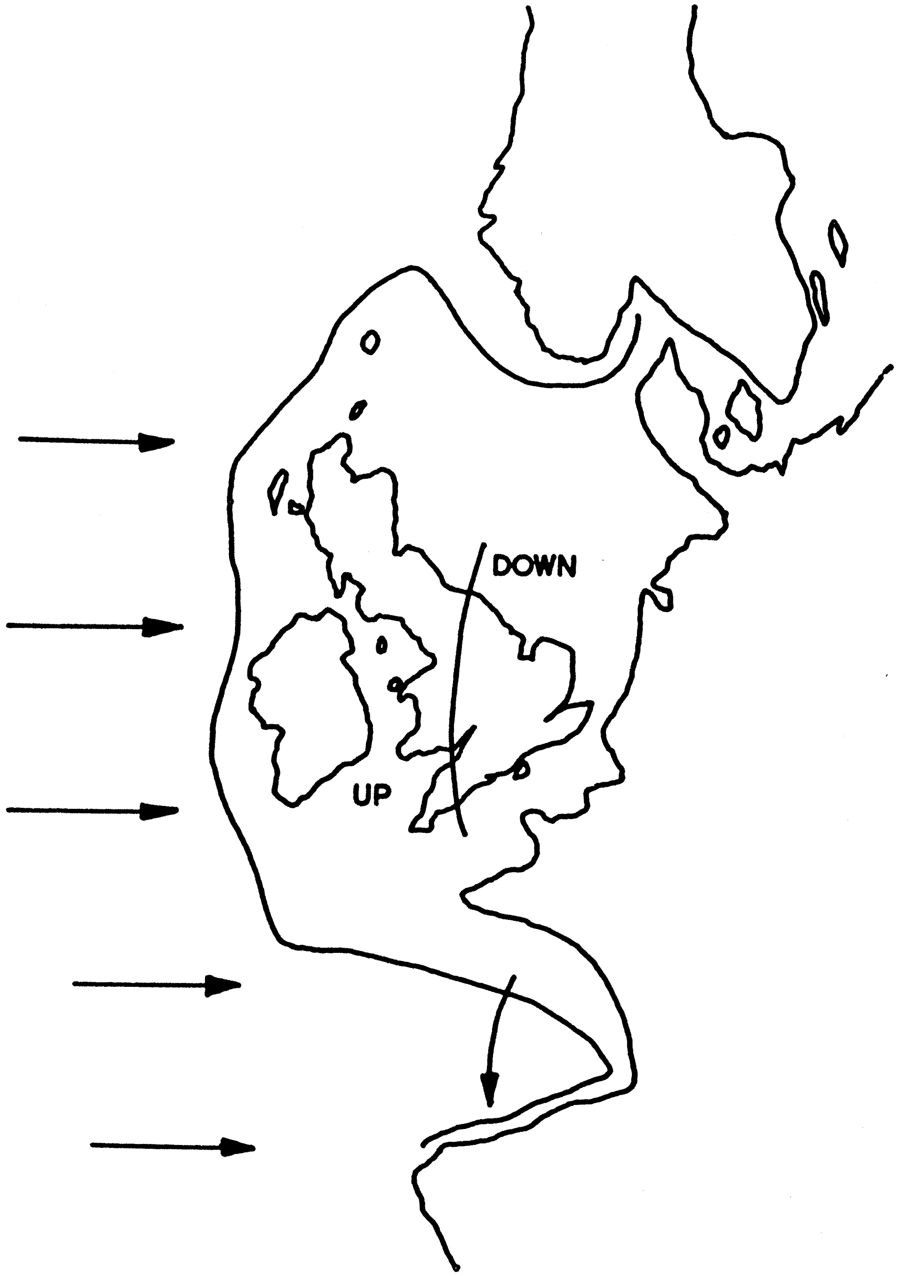
Linton explained the features of his summit topography map by referring to a hypothesis by Cloos (1939). From a study of areas where large scale rifting is prominent, Cloos concluded that rifting was a consequence of an upward bulging of part of the earth's crust. Linton believed that Britain and Ireland were situated on such a bulge, Britain being on the eastern flank and the roof of the dome having collapsed to form the Irish Sea. C.A.M. King (1965, p. 15) has referred to this dome as a cymatogenic arch. The Cloos theory or the cymatogenic arch concept (L.C. King 1966, p. 657) provide unsatisfactory explanations of the tilt of Britain; the major deficiency is an inability to explain the subsidence of the eastern part of the country and the North Sea basin as a whole. The proposed arch structures do, however, offer a mechanism for the formation of the Irish Sea by the collapse of the overstrained crustal material at the crest of the arch.

The current interaction theory accounts for the subsidence and the tilt; and this mechanism can be invoked to explain the formation of the Irish Sea. The convex upwarping of the crust would cause the upper part to be subjected to severe tensile stresses and the crest of the uplifted part would collapse, forming the sea basin. Linton's map of the earliest British rivers is based on the theory that the tilting is caused by Britain's position on the flank of a cymatogenic-type arch, giving a general west to east drainage direction. If the tilt is caused by the current interaction mechanism, the drainage directions may be expected to be more towards the south-east.

Various facts and opinions must be correlated before an attempt can be made to date the beginning of the crustal movement which has led to the tilting and the subsidence. The presence of the chalk strata over the down-warped part of Britain suggests that the tilt is post-Cretaceous; it would have to be fairly well developed before sufficient stress would have built up, in the upper layers of the crust, to cause the Irish Sea to form by the collapse of the arch crest. Mitchell (1960) proposed that the process of formation of the Irish Sea occurred during the Tertiary, and was completed in the Lower Pleistocene.

Girdler (1965) has suggested that the changeover in structure from geosynclinal to block faulting in the south-western United States indicates that there has been a change in the mantle convection pattern in the last 50 million years. If this change did occur and a recently formed mantle current was responsible for the crustal movements in Britain and the North Sea basin, then, if Girdler's time assessment is correct and can be applied to the Atlantic currents, the crustal movement began at some time in the last 50 MY. The change in mantle convection pattern involved could possibly be the change from a four-cell to a five-cell system; this would give a world-wide change in current arrangements. Alternatively the change could occur within the framework of the Wilson model and presumably be more localised. If the change in the current system detected by Girdler affected Britain and the North Sea basin and if his time limit were extended slightly, it seems possible that the change in convection pattern could have coincided with the end of the Cretaceous period.

There are indications then, but unfortunately no real evidence, that the crustal warping began about 50-60 MY ago, with a new mantle current providing the driving force for the process. For the theory advanced here and, in particular, the starting date to be at all convincing, the presence of Permian deposits in the North Sea basin must be explained. The question arises whether the presence of the North Sea basin was required for these sedimentary deposits to form. It seems likely that the subsidence started after the formation of some sediments; in this case some pre-Tertiary sediments. Thus the Permian and Jurassic deposits were submerged beneath the Cretaceous sea, covered by Cretaceous material, and then subjected to a general post-Cretaceous movement as the crustal processes which produced the North Sea basin were initiated.



Text-fig. 5. The continental lobe containing Britain and the estimated convection current direction. Pivot line is after Churchill (1965).

Geomorphology

Walther Penck (1924), in his approach to geomorphology, required that the surface features of the earth should give some indication of the nature of the forces acting within the earth. In this paper, the opposite position is adopted and the nature of the upper mantle forces is invoked to explain the morphology of the observed landforms. The basic approach is, however, Penckian; the traditional cyclic Davisian theory, of uplift followed by erosion, will not apply because uplift and erosion have proceeded simultaneously. The endogenetic forces are represented by the interaction of the upper mantle current with the thickening continental crust; the exogenetic forces are the normal forces of denudation and erosion; and to date these have been almost in balance, yielding a landscape of relatively low relief. The forces are, however, slightly out of balance, so that the land appears to be slightly uplifted.

The question inevitably arises as to whether the observed landforms indicate the presence of a sub-crustal convection current, i.e. the Penckian position as stated above (see Simons 1962), or whether the interaction of the proposed current with the material of the continent provides an acceptable and satisfactory explanation of the observed landforms. The aim of this paper is to give an affirmative answer to the second of these queries, but the questions are, in fact, inseparable. It is known that a current flowing over a step structure produces a pressure distribution as shown in Text-fig. 4; thus a current flowing under the crust would tend to produce the observed landforms.

The problem of determining the main geomorphological trends and influences in the shaping of Britain is one of discarding the confusion brought about by glaciation and its aftermath. The main source of confusion is the rise and fall of sea level; this can make the absolute measurement of upwarping and downwarping of the land difficult, if the measurements are based on beach deposits.

The basic shaping of the surface of the British Isles is considered to have been accomplished as follows:-

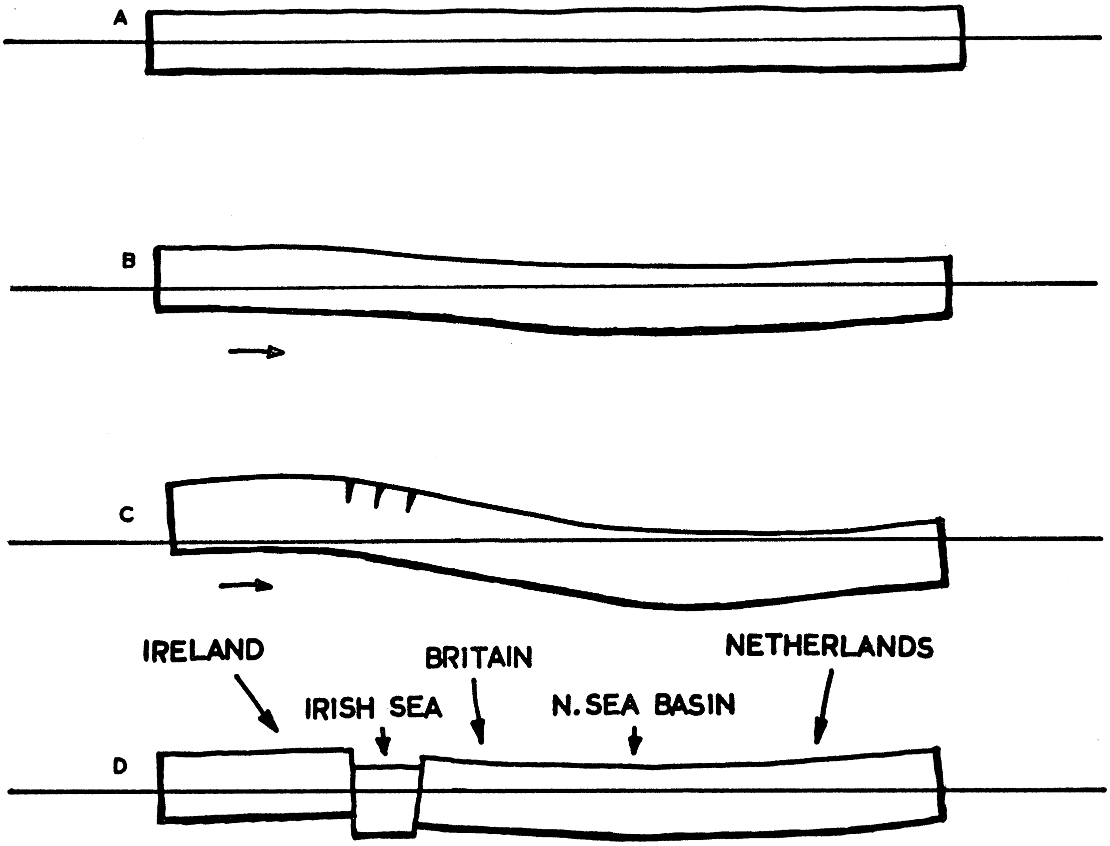
1) A convection current system developed in the mantle which caused the Atlantic Ocean basin to open. This current system possibly came about by a change from a four-to a five-cell arrangement in the mantle, or by readjustment of part of a world-wide single cell system.

2) The edge of the European continental mass was affected by the current; the Iberian peninsula was pushed around towards its present position and the western parts of the British Isles were uplifted.

3) These crustal changes began when the new convection current began to interact with the crust; and they perhaps became more apparent when the continental mass had reached equilibrium with the forces due to the current, after movement had been initiated by the current.

4) When sufficient upwarping had occurred, a critical level of tensile stress was developed in the upper part of the crust and a graben-type fault formed. This released some of the stresses and there was some crustal readjustment. The graben forms the Irish Sea. With considerable tectonic activity going on then, this seems the best time for the appearance of the Tertiary lavas of Northern Ireland and west Scotland.

5) To the east of the fault zone, crustal movement continued much as before. The western part of Britain was uplifted and eroded; the North Sea basin subsided and sediments were deposited there. These processes are continuing and this is the situation at present.



Text-fig. 6. Diagrammatic representation of the response of a section of continental crust to a cell current flowing from left to right. This ideal crustal section is at the surface and at the edge of the continent (for explanation see text).

An attempt has been made to illustrate the essentials of this sequence of events in Text-fig. 6; this is purely diagrammatic; it represents an ideal portion of crust, initially horizontal and undisturbed (A); the current starts up and slight deformation occurs (B); maximum deformation occurs and tensile failure is imminent (C); then the graben fault forms and some readjustment occurs (D).

The tilting process envisaged would produce a general uplift in the west. As the initial plain was uplifted, it would be affected by the forces of weathering; these would not act uniformly and some mountains would remain. Brown (1960, p. 3) has suggested that the present mountains of Wales were carved out below the level of a plain, rather than uplifted to their present altitudes; although he does describe a rather more Davisian mechanism, with the plain uplifted and then eroded, the essential observation is that required by the tilt mechanism. On the sink side of the pivot line, observations should reveal gradients sloping down towards the east. In the case of the East Midlands, Kellaway and Taylor (1952) found the downwarping towards the North Sea basin, which they expected and which the tilt mechanism discussed here would provide.

To decide whether the suggested mechanism is feasible and whether it serves to explain the basic geomorphology of Britain, three 'observational' and one 'synthetic' conclusions have to be reached. The three 'observational' conclusions can be stated thus: there are convection currents in the earth's mantle; a particular crustal movement, which has been going on since approximately the end of the Cretaceous, has caused Britain to tilt and the North Sea basin to subside; and thirdly, currents in the mantle do interact with the crust, causing exposed portions to move relative to the main continental mass.

The third required conclusion is the critical one and the most difficult to provide evidence for. Since much crustal movement is observed as glacial after-effects, it is difficult to distinguish crustal movement of the sort which may be caused by current interaction. Charlesworth (1957, p. 1353) states that the Tertiary diastrophic rhythm doubtless continued into the Quaternary Era and is still continuing. If there was a change in convection current pattern at about the end of the Cretaceous period, this would tend to dominate all Tertiary tectonic activity. In the North Atlantic basin the rising current, diverging at the mid-Atlantic ridge, would tend to cause uplift at the edge of the shield areas of N. Europe and N. America. Charlesworth has indicated that this sort of tectonic uplift has occurred; he states that the centre of uplift on either side of the North Atlantic is not that of the glaciated region but of elevated areas of much older date. He also suggests that the present sinking of the north-west German coast is tectonic in origin and goes back in time at least to the Zechstein (c. 200 MY ago).

The 'synthetic' conclusion represents a synthesis of the three required 'observational' conclusions; an Atlantic basin convection current, interacting with the edge of the European continental mass, has resulted in the tilting of Britain and the subsidence of the North Sea basin.

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REFERENCES

BLACKETT, P.M.S., BULLARD, E. and RUNCORN, S.K. (Organizers) 1965. A Symposium on Continental Drift. Phil. Trans. Roy. Soc. Lond., Vol. A258, pp. 1-323.

BROUWER, A. 1963. Cainozoic history of the Netherlands. Verh. Kon. geol. mijnb. genoot. Geol. ser., Vol. 21-1, pp. 117-148.

BROWN, E.H. 1960. The Relief and Drainage of Wales. Cardiff: University of Wales Press. 186 pp.

BULLARD, E. 1964. Continental Drift. Quart. J. geol. Soc. Lond., Vol. 120, pp. 1-33.

BULLARD, E., EVERETT, J.E. and SMITH, A.G. 1965. The fit of the continents around the Atlantic. Phil. Trans. Roy. Soc. Lond., Vol. A258, pp. 41-51.

CAREY, S.W. 1958. A tectonic approach to continental drift. in Continental Drift: A Symposium (convener; S.W. Carey). University of Tasmania Press, pp. 177-355.

CHARLESWORTH, J.K. 1957. The Quaternary Era. London: Methuen. 1700 pp.

CHURCHILL, D.M. 1965. The displacement of deposits formed at sea-level 6500 years ago in southern Britain. Quaternaria, no. 7, pp. 239-249.

CLOOS, H. 1939. Hebung, Spaltung, Vulkanismus; Elemente einer geometrischen Analyse irdischer Grossformen. Geol. Rdsch., Vol. 30, pp. 400-527.

COODE, A.M. 1966. An analysis of major tectonic features. Geophys. J. Roy. Astronom. Soc., Vol. 12, pp. 55-61.

DIETZ, R.S. 1966. Drifting continents. Analog, Vol. 77, no. 2, pp. 58-76.

FABER, F.J. 1962. Past, present and future subsidence. Geol. en Mijnb., Vol. 41, pp. 151-160.

GIRDLER, R.W. 1965. The formation of new oceanic crust. Phil. Trans. Roy. Soc. Lond., Vol. A258, pp. 123-136.

IRVING, E. 1964. Palaeomagmetism. New York: Wiley. 399 pp.

KELLAWAY, G.A. and TAYLOR, J.H. 1952. Early stages in the physiographic evolution of a portion of the East Midlands. Quart. J. geol. Soc. Lond., Vol. 108, pp. 343-376.

KING, C.A.M. 1966. Techniques in Geomorphology. London: Arnold. 342 pp.

KING, L.C. 1966. The morphology of the Earth. 2nd ed. Edinburgh: Oliver & Boyd. 726 pp.

LINTON, D.L. 1951. Problems of Scottish scenery. Scot. Geogr. Mag., Vol. 67, pp. 65-85.

MITCHELL, G.F. 1960. Pleistocene history of the Irish Sea. Advanc. Sci., Vol. 17, pp. 312-325.

ORME, A.R. 1960. The raised beaches and strandlines of South Devon. Field Studies, Vol. 1, no. 2, pp. 109-130.

PENCK, W. 1924. Die morphologische Analyse. Stuttgart: J. Engelhorn's Nachfolger. (English translation, Morphological analysis of Landforms, 1953, London: Macmillan, 429 pp.

RUNCORN, S.K. 1962. Palaeomagnetic evidence for Continental Drift and its Geophysical Cause. in Continental Drift (editor:S.K. Runcorn). New York: Academic Press, pp. 1-40.

SIMONS, M. 1962. The morphological analysis of landforms: a new review of the work of Walther Penck. Trans. and Papers Inst. Brit. Geographers, Vol. 31, pp. 1-14.

UMBGROVE, J.H.F. 1945. Periodical events in the North Sea basin. Geol. Mag., Vol. 82, pp. 237-244.

VALENTIN, H. 1953. Present vertical movements of the British Isles. Geogr. J., Vol. 119, pp. 299-305.

VENING MEINESZ, F.A. 1954. Earth-crust movements in the Netherlands resulting from Fennoscandian postglacial isostatic readjustment and Alpine foreland rising. Proc. Kon. Ned. Akad. v. Wet., Vol. 57, pp. 142-155.

WALTON, K. 1966. Vertical movements of shorelines in Highland Britain: An Introduction. Trans.and Papers Inst. Brit. Geographers, Vol. 39, pp. 1-8.

WILSON, J.T. 1963. Continental Drift. Sci. American, Vol. 208, no. 4, pp. 86-100.

1966. On a possible explanation of the earth's crust and movements. Proc. Geol. Soc. London, no. 1630, pp. 42-43 (Abstract).

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