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DISCUSSION OF THE RELATION OF PALAEOGENE RIDGE AND BASIN STRUCTURES OF BRITAIN TO THE NORTH ATLANTIC

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The evidence of Tertiary ridges, basins and volcanicity in Britain is at variance with a simple relation to the Atlantic opening as proposed recently by Hallam. The structural complexity of the continental margin off Britain needs further investigation before its development can be related satisfactorily to the several phases of opening of the North Atlantic. In particular, Mesozoic and Tertiary basins and ridges do not consistently show the elongation and asymmetry required by Hallam's model, and many were initiated too early to be related to the Reykjanes spreading.

1. Introduction

Hallam [1] has suggested that during the last 60 my Western Britain has suffered the imposition of asymmetrical horst and graben structures trending parallel, and from comparison with other areas genetically related, to the Reykjanes Ridge. He claims to recognise other phases of structural evolution during the earlier growth of the North Atlantic.

We think that Hallam has omitted or misconstrued some aspects of the structure of Western Britain in an attempt to justify a model which is itself uncertain. He also begs the question of the age of some of the structures he regards as Palaeocene.

2. Validity of the models and their relevance to Britain

Despite much recent research [2, 3], the problem of whether the deep crustal structure of the southern part of the Red Sea area is essentially continental or oceanic remains unsolved. Hallam's block-fault model of Britain is based primarily on Hutchinson and Engel's interpretation [4] of the structure of the topmost 5 km of crust in the Danakil area derived from geological (mainly lithofacies) and topographic evidence. Their hypothesis has been restated recently [5] with additional offshore data from further north.

By contrast, Lowell and Genik's synthesis of data from the southern Red Sea results in a model [6, fig.5] in which the topmost 5–10 km of thinned continental crust is broken into horsts and grabens by normal faults without any obvious asymmetry. A seismic reflection profile figured by Hutchinson and Engels [5, fig. 5] overlaps Lowell and Genik's profile but misses the block-faulting. Thus, whatever the validity of Lowell and Genik's model for the deep crustal structure of the region, it is probable that the tilted fault-block model of Hutchinson and Engels is over-simple. It is relevant to note here that the graben structures parallel to the Red Sea axis extend only 150 km onto the continent. The undoubted complexities of the deep structure (eg. [7]) should be sufficient, in addition to the above, to rule out any attempt at a viable comparison of most of British ridge-and-basin development with that of the southern Red Sea.

The Otway Basin in South Australia trends parallel to the continental margin and extends 150 km from the mainland onto the continental slope [8]. The Mesozoic infill is 4–5 km thick, dipping landward, and is separated from up to 2 km of seaward-dipping Tertiary sediments by one of three well-marked, basinwide unconformities. The regional structure of sub-Tertiary tilted fault-blocks is inferred to have developed as a result of the separation of Australia from Antarctica, in which pre-drift doming and erosion of the crust led, after separation, to isostatic subsidence and normal faulting contemporary with continuing sedimentation.

Comparison of this region with British structures may be made, therefore, over a continental margin of about 150 km width, and the inferred mechanism may be valid if the crust within this area can be shown to be thinning oceanwards. The former restriction would limit the area to the shelf west of the Shetlands, Orkneys and Outer Hebrides, but possibly including the Minch; the latter restriction as suggested by the regional rise in Bouguer anomaly [9, fig. 2], more or less confines application of the mechanism to the continental slope.

3. Tectonic patterns in the British area

The following paragraphs discuss, successively from north to south, the evidence of ridge and basin structures in Britain (refer to fig. 1). It is often impossible to decide, on present evidence, whether sedimentary basins are basins of deposition or synclines/grabens (or both). This difficulty will be apparent in the regional analysis that follows and is not entirely satisfactorily resolved by our conclusion that those areas where the stratigraphy is better known are often sites of recurrent basin development with intervening periods of inactivity or uplift and erosion. Faults which have originally bounded areas of sedimentation tend to move again during any later episode of deformation.

Certain features of the geology of the shelf west of the Shetlands are indeed somewhat similar in form to those of the Otway basin; for example the sedimentary trough marked by gravity "low" E of Bott and Watts [9]. Supposed Mesozoic and Tertiary sediments within this basin dip gently away from the continental margin, are strongly down-faulted against the SE. margin, and are overlain unconformably by flat-lying Quaternary sediments [10, figs. 9 and 16]. However the basin shown by "low" C, only 50 km from the edge of the shelf and to the SW of "low" E, is the mirror image of the latter in being faulted on its NW margin only, with the Mesozoic-Tertiary infill dipping NW, not SE [10, fig. 12]. The ages of the Mesozoic infill of both the Scottish continental shelf basins and the Otway basin are broadly similar, but infilling of the Scottish troughs

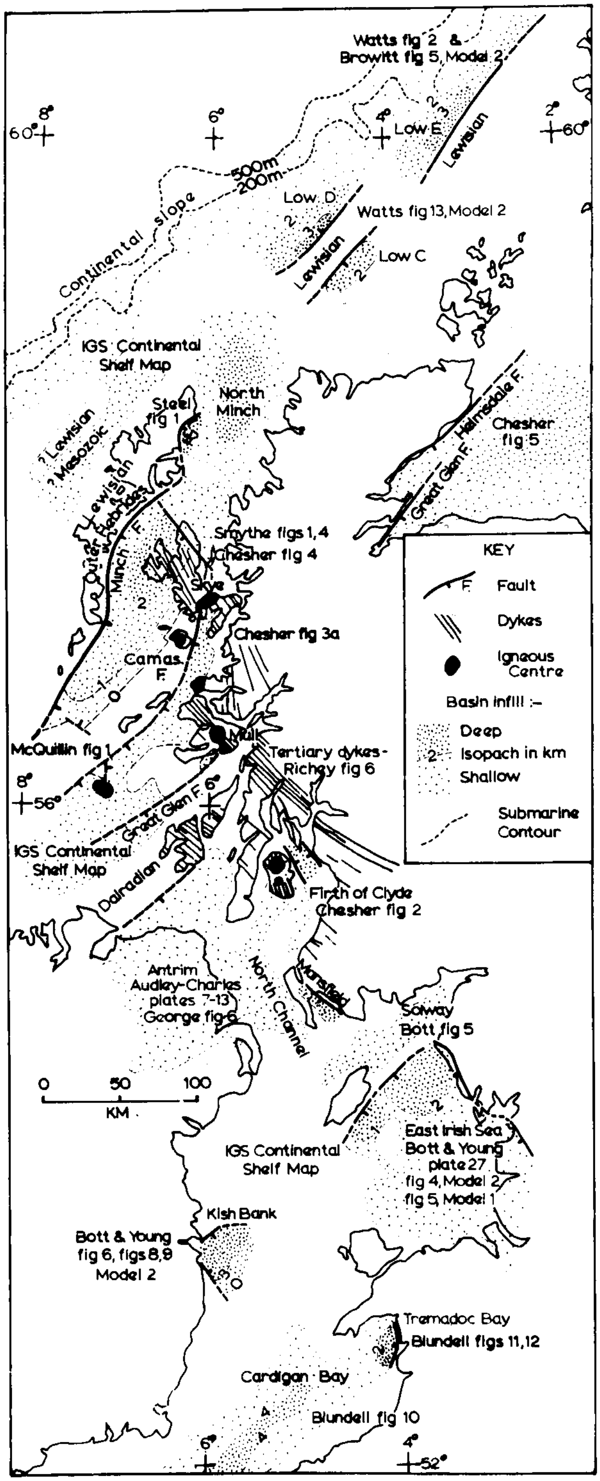

Fig. 1. Sedimentary basins in western Britain. Names refer to relevant publications: Audley-Charles [25]; Blundell et al. [27]; Bott [34]; Bott and Watts [9]; Bott and Young [26]; Browitt [13]; Chesher et al. [15]; McQuillin and Binns [14]; Mansfield and Kennett [35]; Richey [36]; Smythe et al. [12]; Steel [11]; Watts [10].

probably began earlier, in New Red Sandstone times, as suggested by extrapolation from the Little Minch area [11–13]. In the Australian example it can only be stated that "sedimentation was initiated at least as early as the Late Jurassic" [8, p. 70]. But it is clear that here a considerable thickness of pre-Tertiary sediment accumulated in asymmetric grabens overlain by flat-lying Cainozoic sediments, whereas in the Scottish waters discussed above the Tertiary trough sedimentation was merely a continuation of a much older history of subsidence, whether deposition was interrupted by periods of erosion or not. Both examples therefore serve to demonstrate that the initiation of ridge and basin structures, *pace* Hallam [1, p. 174], cannot be related simply to their respective most recent periods of spreading, but rather appear to pre-date the separation by a considerable time.

There are two Minch basins, not one. Comparatively little has been published concerning the larger North Minch basin (though commercial exploration has been carried out), but it appears to be strongly down-faulted on its NW margin with its SE margin ill-defined [14]. Most of its several kilometres depth of infill is probably the same age as the Stornoway formation which, on a recent sedimentological re-examination [11], is correlated with New Red Sandstone rather than Old Red Sandstone or Torridonian. This younger age is strongly supported by seismic velocity measurements in the Hebrides (unpublished work of the authors). It is probable that the North Minch trough is early Mesozoic, if not older, in origin.

The NNE, trending basin just described is separated from the Little Minch trough by a major NW–SE ridge of Torridonian [15]. The deepest portion of this trough is bounded to the NE by a fault trending NW or NNW [12] which is hidden by the relatively thin blanket of Jurassic sediments of northern Skye. Most of the infill must be Triassic or older and was deposited almost certainly in an actively subsiding trough, possibly still discernible though of wider extent in Middle Jurassic [16]. A gentle syncline of rather indeterminate trend was formed in the younger Mezosoic rocks before the effusion of Tertiary tuffs and lavas, the overstep of which is depicted on the I.G.S. 1″ sheet of North Skye. However the general structure of the younger rocks of the basin, the marine area included, is one of radial dips towards northern Skye rather than one of NNE elongation [15, fig. 4]. The Minch fault system forms the NW limit of the basin, throwing down to the SE [14]. In SE Skye, according to an earlier account by Hallam [17], the large NE–SW Camasunary fault preserves Middle and Upper Jurassic rocks, together with Upper Cretaceous, on its SE side. Both faults show that the asymmetry here is opposite to that expected by Hallam's recent interpretation but similar to that of the North Minch basin.

Dykes and normal faults in northern Skye trend NNW–SSE, and a similar trend of such tensional structures is clear throughout much of the Tertiary igneous province. Further, there is some evidence (Simkin, 1965, Ph.D. thesis Princeton, unpublished) that the sills of the area (and probably also the lavas) were fed from faults of this trend, which is almost perpendicular to that of the Reykjanes Ridge. Hallam's model would predict that volcanic activity, if any, should occur through fissures mostly sub-parallel to the associated spreading axis.

The NW margin of the Little Minch and North Minch basins, the normal Minch Fault system, tends to follow, just offshore, the eastern coastline of the Outer Hebrides [12, 14, 15]. There is an obvious spatial correlation (and so possibly a genetic relationship), not with an as yet unlocated transcurrent fault [18], but with the Outer Isles Thrust, both the inner and outer coastlines of the Outer Hebrides, and the swing from NE–SW to N–S of the continental margin bordering the northern end of the Rockall Trough.

Thus the supposed predominance of a NE–SW trend in either Mesozoic or Tertiary structure is quite unreal in this area, and if there is any consistently developed asymmetry in the basins it is converse to that proposed by Hallam. It is the adjacent Rockall Trough, probably floored by oceanic crust [19], and of still-debated history, that is likely to be more relevant to the development of sedimentary basins in NW Britain than the Reykjanes Ridge spreading.

The Firth of Clyde and North Channel areas are dominated by NW–SE basins of Carboniferous and New Red Sandstone age (not simply 'post-Hercynian') with some later subsidence, probably in Tertiary times [20, 21], superposed on a NE–SW Midland Valley rift.

The Antrim lava plateau is faulted downwards towards the North Channel on its NE margin; this NW trend is clear in the preservation of Upper Basalts towards the east coast. The middle Tholeiitic Basalts wedge out to the south, and contours on the base of the lava pile in the Lough Neagh basin show asymmetry in the opposite sense to that expected by Hallam. This evidence is summarised by George [22], who shows that the Lough Neagh basin has a long history going back to pre-Triassic warping. In particular, although Hallam's assertion that "Antrim was evidently no more a Mesozoic basin than Mull" [1, p. 175] does not contradict the District Memoirs [23, 24], detailed isopachytes for successive divisions within the Triassic [25] suggest that NE Ireland was at that time a subsiding basin. The general outline of the present outcrops of Mesozoic and Tertiary rock is square with margins aligned NE–SW and NW–SE.

There are two gravity "lows" in the East Irish Sea basin [26], the main one caused by Permo-Trias and Carboniferous sediments between 3 and 6 km thick, and extending SE into Lancashire without great reduction in thickness. The NE margin in western Cumberland is downfaulted and so is the NW margin, as suggested by the steep gravity gradient of up to 7.3 mgal/km. The smaller "low", just off the Isle of Man, is slightly elongated NE–SW and is also faulted on its NW margin. In the western Irish Sea, the Kish Bank gravity "low" is interpreted by the same authors as a roughly rectangular basin, elongated NE–SW, 40 km by 30 km. It is probably faulted on its NW and SW margins by faults of NE–SW and NW–SE trend, respectively. The depth of infill, probably Mesozoic, is up to 4 km thick.

The Cardigan Bay basin and the subsidiary Tremadoc Bay basin differ from most of those described above in having an appreciable thickness of Tertiary sediment [27]. The smaller basin is asymmetrical, fault-bounded on its E and SE margins, with an infill of just over 2 km, of which the upper half km is Tertiary. The Cardigan Bay basin is a broadly symmetrical downwarp aligned NE–SW and probably faulted on both sides [28]. Much of the 6 km or more of infill is Permo-Trias and Jurassic, while Chalk is apparently absent. Unconformably overlying these in the centre of the basin is up to 2 km of Palaeogene sediment which is in turn overlain unconformably by up to 200 m of horizontally stratified sediments. Thus, Tertiary deposition here has evidently occupied the same site as Mesozoic sedimentation, and has proceeded at a similar rate.

Hallam's section [1, fig. 3] across the Irish Sea gives an impression of regionally consistent asymmetry that is not justified by the above evidence.

By contrast with Hallam, we come to the following conclusions about Mesozoic and Tertiary tectonics in Britain.

(i) Tertiary structures and volcanism in the west and north-west are most often developed from, or controlled by, pre-existent weaknesses, of which those trending NW or NNW are just as important as those of NE trend.

(ii) The regional trend of the Tertiary dyke swarms suggests that crustal extension in the region of their intrusion is parallel, not perpendicular, to the trend of the Reykjanes Ridge.

(iii) Virtually the same 'basement' fractures controlled early and late Mesozoic basins, on which superimposed but similarly controlled Tertiary structure is relatively minor.

(iv) There is no consistently developed asymmetry in Tertiary structure, except that

(v) the major Tertiary structure in the British area is the tilt towards a subsiding North Sea, wherein is preserved some 3 km of Tertiary sediment [29] with depth contours running mainly NNW–SSE.

(vi) The development of the north-western margin

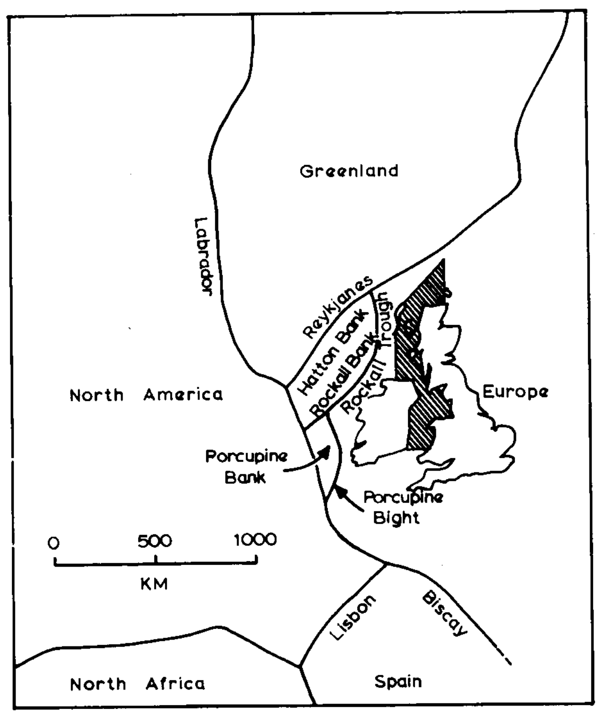

Fig. 2. Pre-Atlantic reconstruction mainly after Bullard et al. [37] with area under discussion shaded.

of the British shelf area cannot be considered independently of that of the Rockall Trough.

(vii) Some of the areas considered by Hallam are as close to the continental margin SW of Britain as to that NW of Britain. The two margins have different trends (see fig. 2) and have probably had dissimilar histories [30, 31].

(viii) We except from some of the above conclusions the only area that appears to fit Hallam's model – the 50 km adjacent to the continental margin west of the Shetlands.

4. The development of the North Atlantic

4.1. *Hallam's model*

We are puzzled by the supposed relationships of Hallam's model to the three phases of Atlantic opening he mentions. The model and our interpretation of his correlation of it with phases of sea-floor spreading are summarised in table 1. Spreading axes are identified in fig. 2.

The three phases do not correlate with successive stages of the model, nor are all stages evident for each phase. Perhaps stage A of phase 2 is supposed to link with stages B and C of phase 3: this is implied by Hallam since the obvious alternative – of each phase having stages A, B and C with either one or two of them undetected - is precluded by the back-dating of a potential A of phase 3 (the postulated base Tertiary unconformity of Stride et al. [32]) to the Middle Cretaceous. The onus is on Hallam to support his reinterpretation by explaining why unconformities observed on the adjacent shelf are absent from the slope. A base Tertiary unconformity could lead to a link with stages B and C of phase 3 neatly tied to Reykjanes Ridge spreading – at least in the extreme NW of the British shelf, and secondly it would, with B and C, match the time period of the model. Instead, Hallam chooses to regard A as so early that the time period (from Middle Cretaceous to late Tertiary) is about three times that of his model and includes episodes of North Atlantic opening with directions of spreading varying through large angles.

A major problem in relating British shelf structure to Atlantic opening is our present lack of knowledge of the relative effects of differently orientated spreading axes at given distances from an area of anisotropic crust. However, even if this knowledge were available, the inverse problem – that of resolving the direction of maximum strain for a particular epoch (as revealed by shelf structure) into two or more directions of inferred stress – does not necessarily have a unique solution. Hallam's two-dimensional crustal model cannot cater for this unavoidable three-dimensional complexity.

TABLE 1

Hallam's model

Time my BP	Observation	Stage
30	Uplift; incipient rifting	A
	Asymmetrical graben/horst features controlling volcanism; structures parallel and up to 80 km from central rift.	B
0	Sea floor spreading; central subsidence; asymmetrical graben/horst features extend up to 150 km from new continental edge	C

Application of the model to western Britain

Time my BP	Phases 1	2	3	Hallam's observations	Interpreted stage
180				"Early Mesozoic" basins	B, C
100– 130				"Significant epeirogenic movements"	A
80	Africa/N. America ↓	Labrador Sea ↓			
60			Reykjanes ↓	Volcanism	B
40				Asymmetric subsidence extending into Neogene	C
0					

4.2. *Continental evidence of North Atlantic growth*

Currently, we are unable to correlate separate structural features of the continental margin of Britain with particular episodes in the growth of the North Atlantic, because of the problem of inferring stress patterns from deformation of an anisotropic crust; the temporal overlap of spreading phases with different trends adjacent to the margin; the possibility of extension of continental crust in the direction but beyond the end, of an oceanic spreading axis; and, not least, the limited knowledge of the stratigraphy of the shelf, slope and adjacent ocean basins.

We recognise the need for the following advances in knowledge, which are being actively pursued:

(i) Variation with distance of stress patterns in the lithosphere away from a constructive plate margin to be added to the analyses of gravitational instability [33], resulting in quantitative estimates of the distance over the shelf within which the formation of post-spreading extensional structures would be significant.

(ii) Theoretical substantiation of estimates from other areas, of the lateral extent of pre-spreading uplift and consequent graben formation: the Nubian swell suggests that uplift may extend over 1000 km but within it the zones of continental rifting have a cumulative width of little more than 300 km (the half-width of 150 km limits the lateral extent of Hallam's model, as pointed out above).

(iii) Obtaining a detailed stratigraphy of the shelf around Britain (including the North Sea) for which geophysical work and bedrock sampling must be backed up by deep drilling. The various continental slopes, the Rockall Trough and similar ocean bights require drilling to remove the ambiguities of present geophysical interpretation.

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