COAL RANKS AND GEOLOGICAL HISTORY OF THE NOTTINGHAMSHIRE-YORKSHIRE COALFIELD

by

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Summary

The high-volatile bituminous coals of the Nottingham-Yorkshire coalfield vary systematically in rank. Both calorific values, ranging from 7800 kcal/kg to 8700 kcal/kg, and equilibrium moisture contents, ranging from 16 to less than 2 per cent, show progressive changes with depth. Calorific values, with depth gradients ranging from 700 kcal/kg/1000 m to 950 kcal/kg/1000 m, increase linearly with depth until values of 8620 kcal/kg are attained; after this the rate of increase diminishes. Moisture contents decrease linearly with depth until values of about 4 per cent are reached, after which the rate of decrease diminishes; the gradients show a variation of about 15 per cent from place to place. At any particular calorific value, the moisture content can vary by nearly 2 to 1. The variations of rank are related primarily to depth below the base of the Permian unconformity although the rank is not uniform at that level. The rank was attained under a cover of Permian and Mesozoic sediments, probably of the order of 1800 m thick and regionally increasing in thickness northwards. Detailed minor variations show a mainly systematic relation to pre-Permian structures, which clearly influenced the rank, presumably by affecting the pattern of geothermal temperatures and the paths through which moisture was expelled from the coals and intervening sediments.

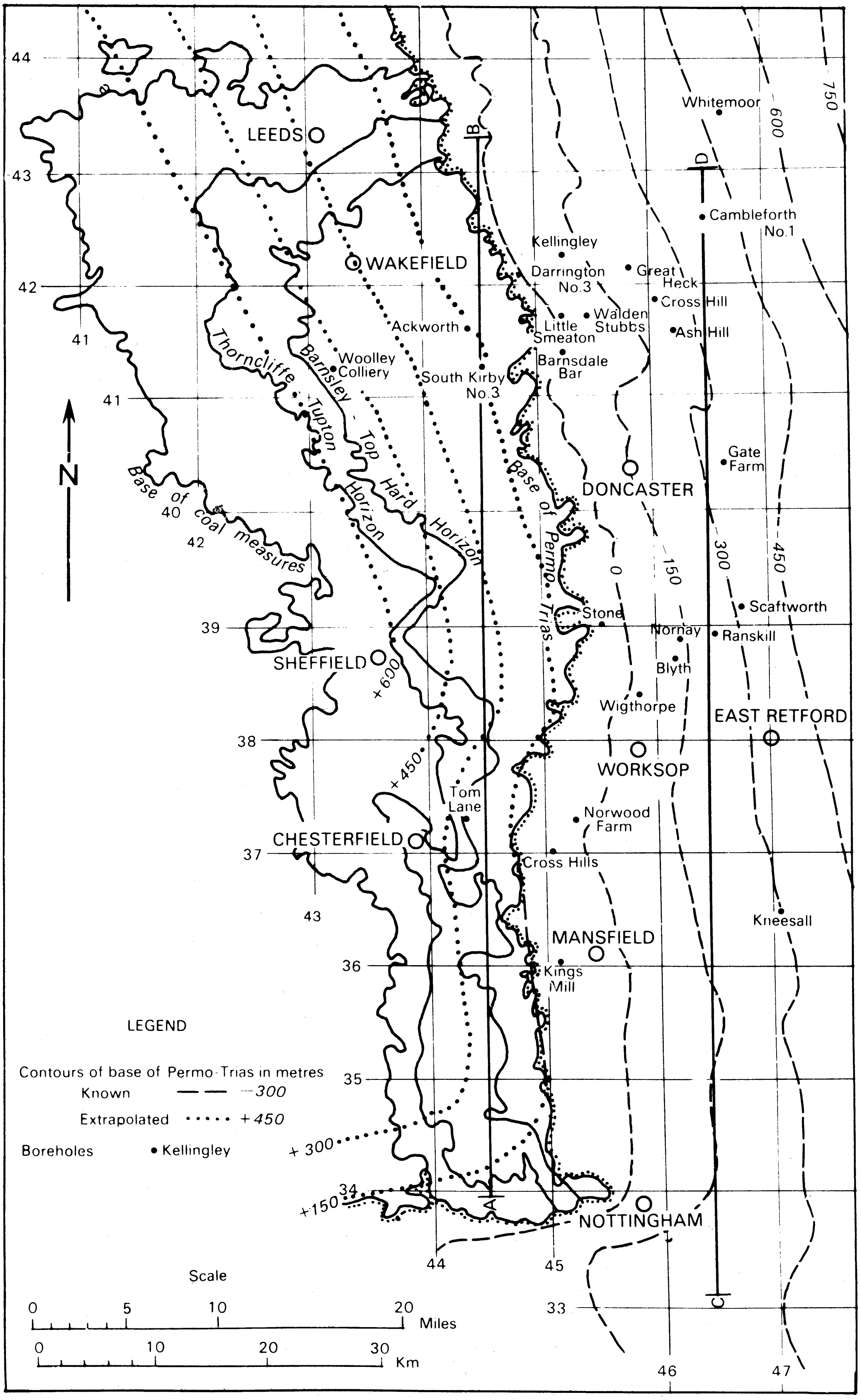
Introduction

The coalfield in Nottinghamshire and Yorkshire, with a minor part in Derbyshire (text-fig. 1), contains relatively low rank coals; almost all are high-volatile bituminous, but some are non-agglomerating. The coals were the subject of an overall study of the relation of rank to structure by Mott (1945), in an attempt to predict the ranks of coal in areas then unworked. After the 1939-45 war, an extensive boring programme was undertaken and mining extended towards the east. In conjunction with these developments great numbers of coal analyses have been made by the National Coal Board. The Board has published maps showing the ranks of coal in several seams, using their own rank classification.

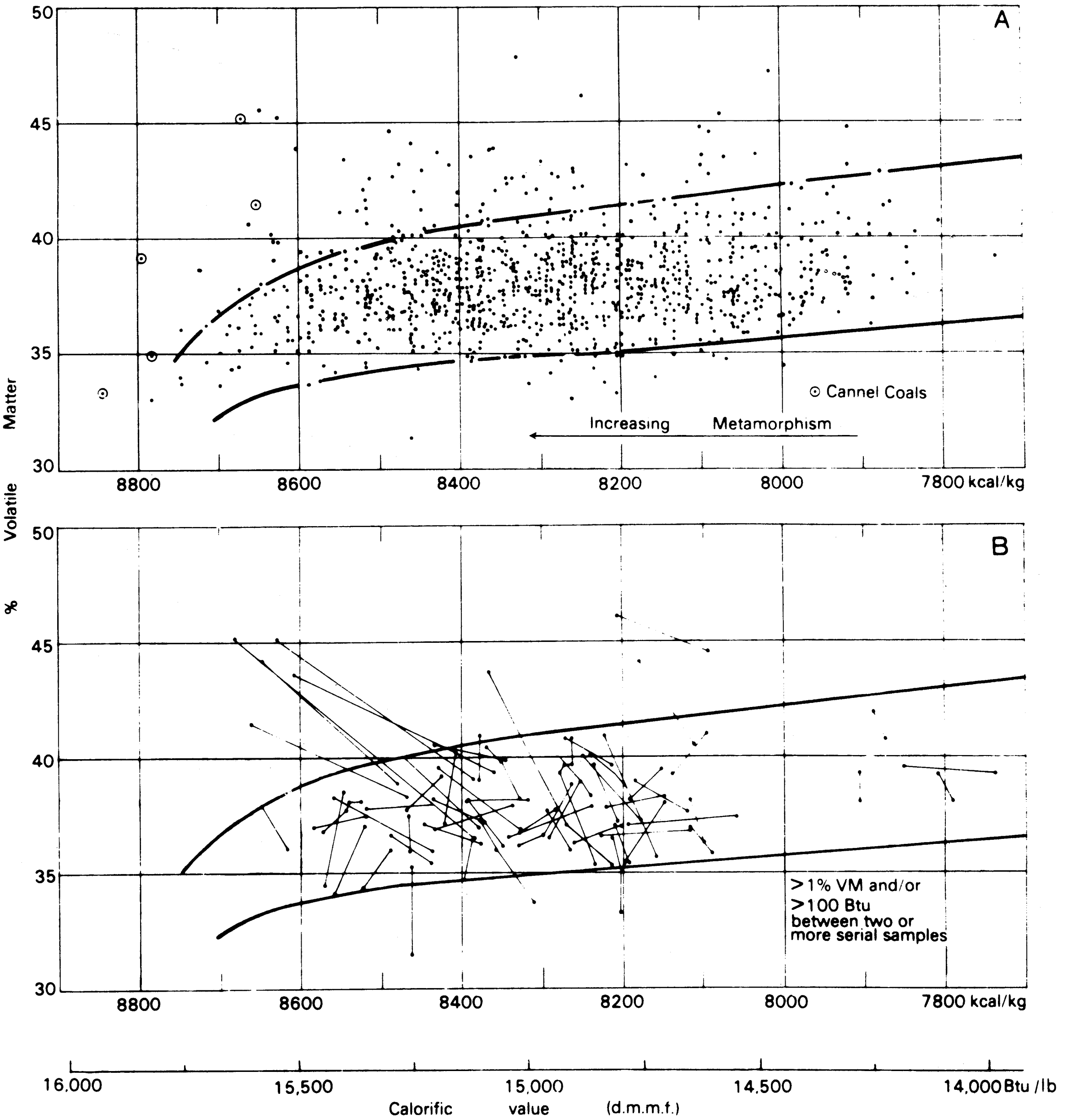
All the coals in the coalfield have over 32 per cent volatile matter, and for such coals the classification depends for its major groups on 'Gray-King coke types'. The maps indicate that systematic changes of rank take place over the coalfield, but no recent study has been made of the relationship of these changes to the geology.

For a geological study of rank changes, some parameter or parameters of rank that change progressively with increasing metamorphism need to be chosen. The National Coal Board classification is designed for the coal user and its groups and classes are not suitable for a geological study. The analytical parameter of coal rank most commonly used in Britain is the volatile content, which is successful for coals of medium volatile bituminous and higher ranks, for example in studies of coal rank in the South Wales Coalfield (e.g. Jones, 1951). As indicated by Trotter (1952, 1954), however, volatile content is of no

Mercian Geol. Vol. 6. No. 1.
1976. pp. 1-24, 14 text-figs.

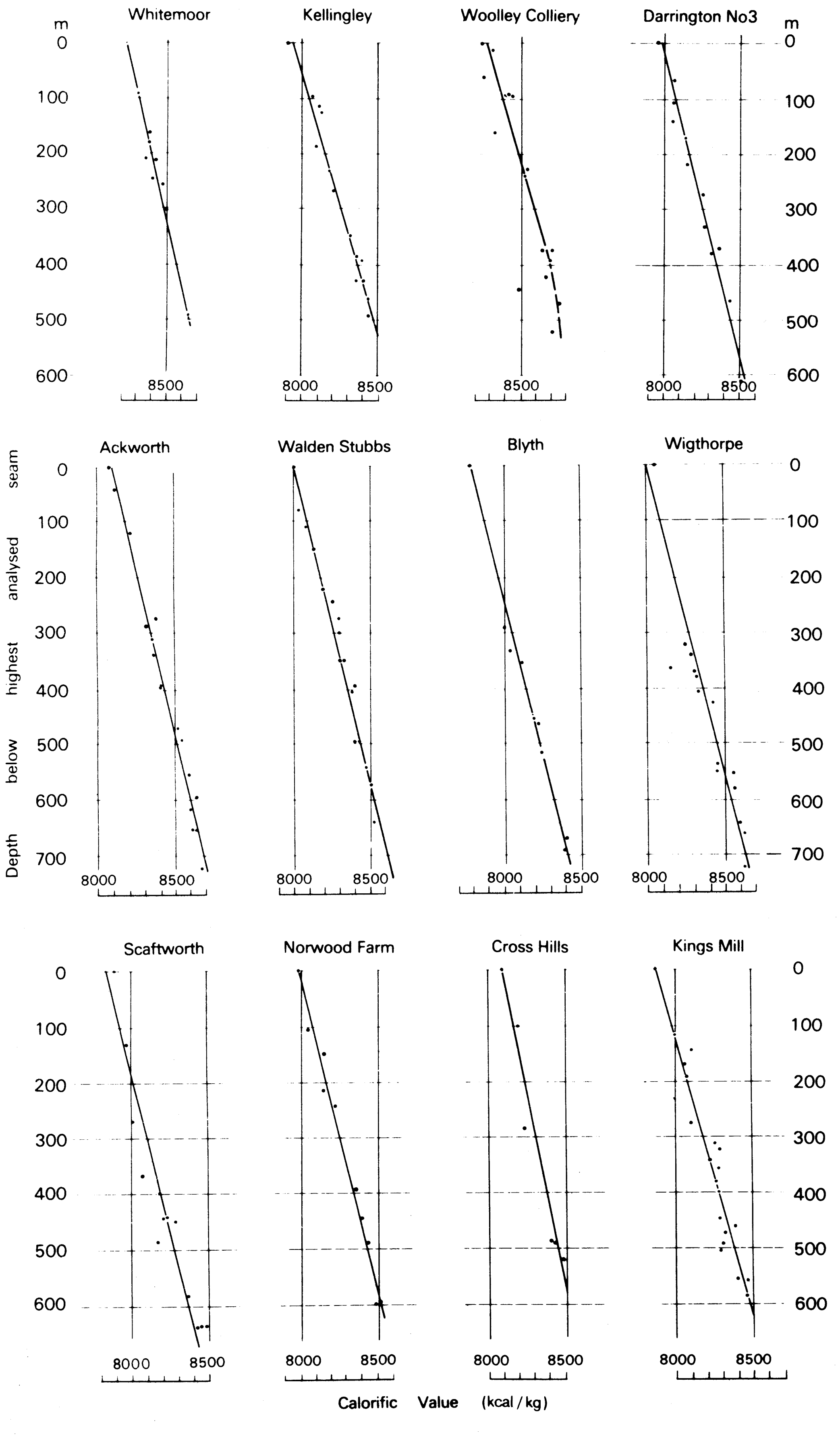


Text-fig. 1. Nottinghamshire-Yorkshire Coalfield, showing principal boreholes discussed in the text, cross-section limes and structure contours on the base of the Permo-Trias.



Text-fig. 2*A* Nottinghamshire-Yorkshire coals, showing inferred coal band on axes of calorific value and volatile matter.

2*B*. Effects of type variations on analysis, as indicated by serial samples (samples from one seam at one place).



Text-fig. 3. Relation of calorific value to depth in selected boreholes.

value at lower ranks, as in the Nottinghamshire-Yorkshire Coalfield. This is because, for low-rank coals, the differences in volatile content that result from original differences of coal type are commonly greater than those found over the vertical thickness of Coal Measures or over many km. laterally.

For the low-rank coals, the analytical parameters that change most rapidly are the carbon content of the ultimate analysis, the calorific value and the moisture content. The far greater number of determinations of calorific value makes this parameter preferable to the carbon content. The dependence of moisture determinations on the temperature and relative humidity at the time of analysis makes the common determinations of moisture in air-dried coal difficult to use, but if sufficient values of equilibrium moisture content at 96% R. H. (relative humidity) and 30°C are available, these provide important rank data.

The coal analyses were made at the laboratories of the National Coal Board. Calorific values were calculated to the dry mineral-matter-free basis, allowing the most accurate comparison that can be made.

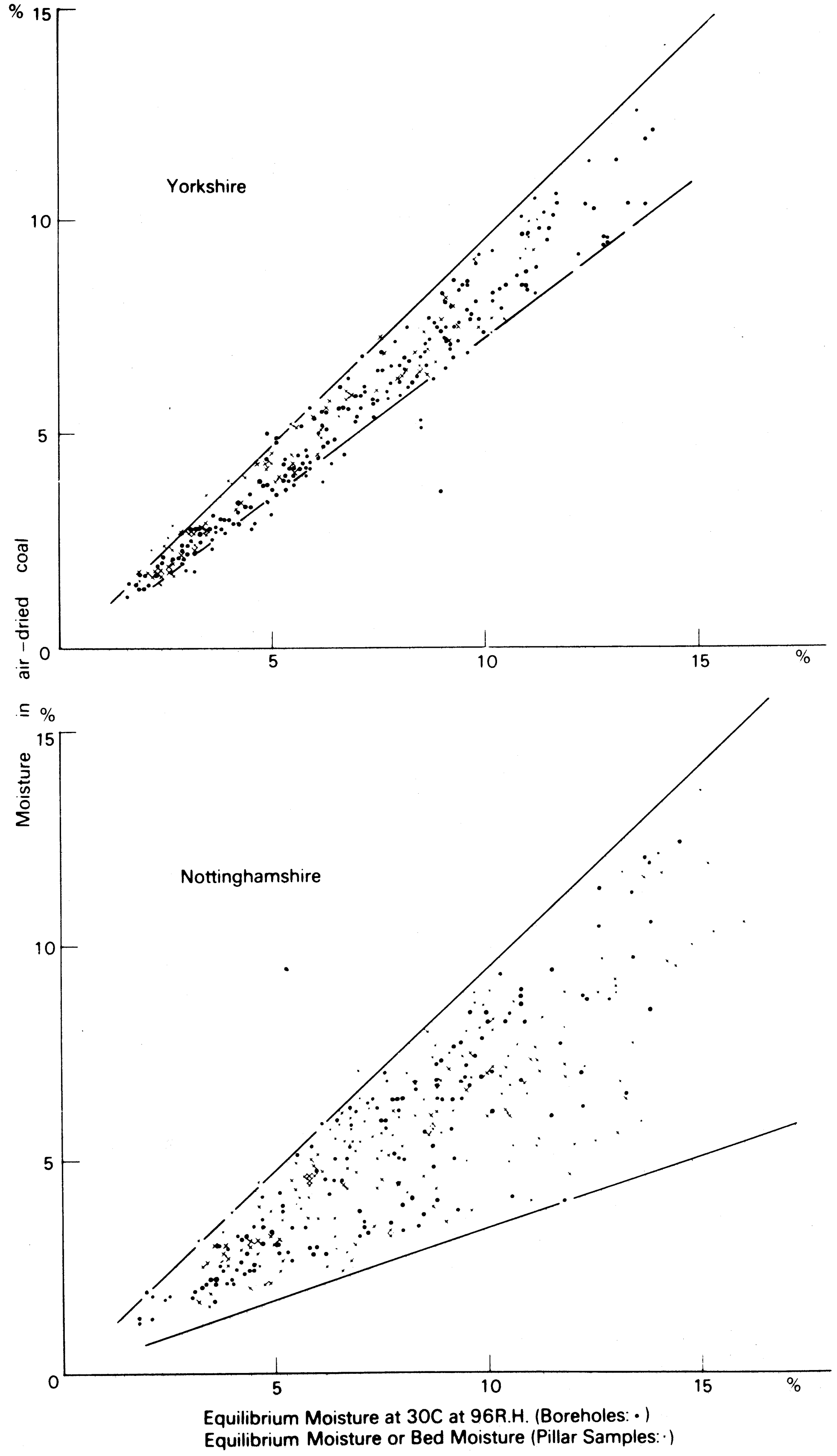
Calorific value as a parameter of rank for high-volatile bituminous coals

The calorific values (dry mineral-matter-free basis) of the majority of Nottinghamshire-Yorkshire coals lie between 8820 kcal/kg and 7890 kcal/kg; few exceed 8700 kcal/kg. The Pie Rough borehole (Millott *et al.*, 1946) in Staffordshire penetrated coals with almost this whole range of calorific values, which increased linearly with increasing depth up to a maximum of 8620 kcal/kg, and thereafter increased at a diminishing rate. Comparable linear increases might be expected in Nottinghamshire-Yorkshire, but with many fewer analyses from individual boreholes, and with shorter vertical sequences, there is a significant likelihood of the relationship being obscured by one or two analyses of coals of unusual type. Accordingly it is desirable to avoid the use of analyses of coals of unusual type, especially cannel coals. This can be done by rejecting those analyses that lie outside the coal band - the band within which fall nearly all the coal analyses made plotted on a chart that uses axes of volatile matter and calorific value. Text-fig. 2A presents such a chart with the plotted positions of coals from over 100 boreholes, and the adopted coal band, within which fall over 85 per cent of analyses, is marked.

Cannel coals have both higher volatile contents and calorific values than normal coals from the same locality and of the same rank, and fall well above the coal band. The other coals falling above the coal band are almost all from minor seams - for example several samples from the Two Foot, Meltonfield and Shafton Seams from Yorkshire and the Norton and Alton from Nottinghamshire; it is interesting that these particular seams are close to marine beds.

Serial samples from the same seam at the same locality, if differing significantly in volatile content and/or calorific value, provide information on the effects of differences of coal type (text-fig. 2B) Higher volatile contents accompany higher calorific values for cannel coals, but no clear relationship shows for pairs of coals both of which are *within* the coal band. For coals within the coal band, 40 pairs of serial samples had average differences of 51 kcal/kg and 98 per cent of these pairs had differences of 110 kcal/kg or less. For seams less than 15 m apart, and hence almost negligibly different in rank, 96 pairs of seams had average differences of 50 kcal/kg, and 75 per cent of these pairs had differences of 110 kcal/kg or less. The average increase of calorific value with depth in boreholes is roughly 850 kcal/kg/1,000 m, so that rank differences in drillholes may be expected to show within a depth of 150 m, corresponding to an increase of calorific value of about 120 kcal/kg.

Text-fig. 3 shows calorific values in 12 of the deeper boreholes in the coalfield. These have been selected as the deepest from as many different 10 km grid squares as possible, with a minimum depth between the highest and lowest seams (whose analyses plot within the



Text-fig. 4. **Relation of equilibrium moisture to moisture in air-dried coals.**

coal band) of 460 m. A linear increase of calorific value with depth is shown by all the boreholes, except for Woolley Colliery where the calorific value reaches over 8620 kcal/kg. This exception is to be expected, by analogy with the Pie Rough borehole, and from knowledge that the metamorphic progression in coal is tending to take it to a maximum calorific value.

Text-fig. 3 clearly illustrates the usefulness of calorific value as a measure of increasing metamorphism of coals through the greater part of the high volatile bituminous range (and it is similarly useful at lower ranks). Among the bore-holes listed in text-fig. 3 the rate of change of calorific value with depth varies substantially from 700 kcal/kg/1000 m at Cross Hills (Derbyshire) to 950 kcal/kg/1000 m at Kellingley; the significance of difference of gradient is discussed later.

Moisture content as a parameter of rank for high-volatile bituminous coals

Besides the routine determinations of moisture in air-dried coal (for which conditions of air-drying have not been standardized), there have been many determinations of equilibrium moisture at 30°C and 96% R. H.

Text-fig. 4 shows the relationship between equilibrium and air-dried moisture contents for coals from boreholes and pillar sections in Nottinghamshire and in Yorkshire; coals from the two parts of the coalfield are analysed at different laboratories. Clearly the Yorkshire samples have been air-dried under a limited range of conditions. Those from Nottinghamshire, however, show such variations in the losses on air-drying that the conditions of relative humidity, in particular, must have varied widely. For Yorkshire coals an approximation to equilibrium moisture can be obtained by multiplying the air-dried moisture by 1.2, but substantial errors could be introduced by using this factor, particularly for individual analyses. No such procedure is valid for the Nottinghamshire coals.

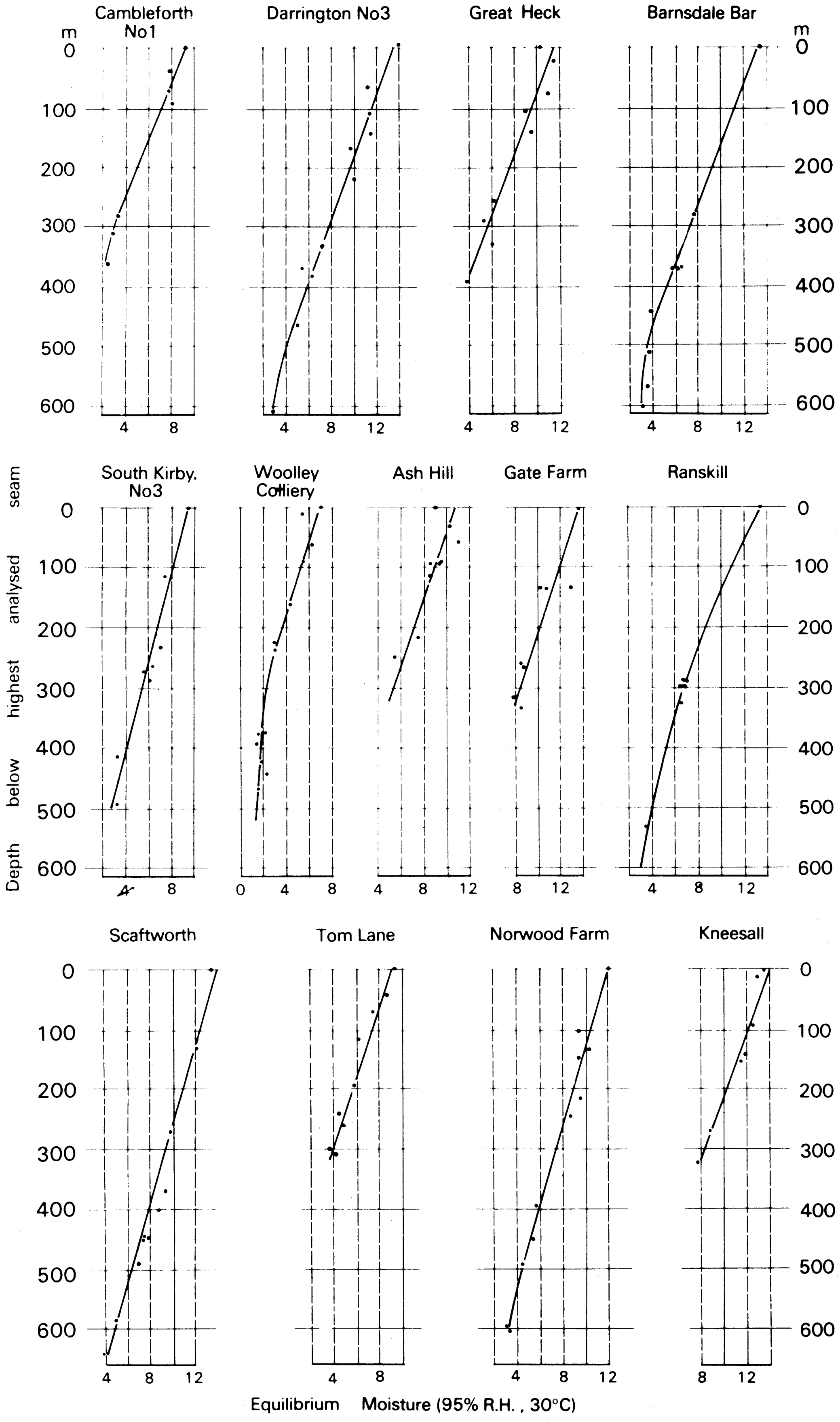
The moisture content of the coal in the ground - the bed moisture - is closely similar to the equilibrium moisture, and for carefully sampled seam sections, the moisture "as received" at the laboratory should not differ greatly from the bed moisture.

Moisture contents vary with coal type (Suggate, 1959) and in the following study only coals plotting within the coal band have been used.

Text -fig. 5 shows 13 of the deeper boreholes for which equilibrium moisture contents have been determined, selected as representative of each 10 km grid square for which such boreholes are available. It is clear that in general the moisture content diminishes progressively with depth, so that it is a suitable parameter of rank. In these boreholes the rate of change of moisture content with depth is substantially linear with depth down to about 4 per cent but with further increase of depth the rate decreases. The rate also differs from borehole to borehole for similar ranges of moisture content; for example there is roughly a 15 per cent difference in the rate from the Norwood Farm borehole to the Darrington No. 3 borehole. Differences of rate are discussed later.

Lateral rank variation

For rank studies it is necessary to select horizons that can be confidently traced throughout the coalfield, and that are sufficiently widely mined to provide a good distribution of analyses. Seam correlations are not incontestable, but provided that correlated horizons are not more than about 15 m in error, no significant errors in interpretation will be introduced. The highest horizon chosen within the Coal Measures sequence, is, the Barnsley and Top Hard Seams, including the Warren House Seam; and the lowest, is the Thorncliffe Seam, locally Middleton Main of Yorkshire, together with the Tupton Seam of Nottinghamshire. The Thorncliffe Seam is close to the horizon of the Tupton Seam, even if it is not precisely its lateral equivalent.



Text-fig. 5. **Relation of equilibrium moisture to depth in selected boreholes.**

The Barnsley-Top Hard horizon is well represented by analyses of pillar sections and drillhole samples, except in the Barnsley area which was mainly worked out many years ago. The stratigraphically lower Thorncliffe-Tupton horizon covers a larger area and it too, is well represented by samples, except in the deep basin south of Doncaster. For both horizons, many more calorific values are available than are equilibrium moisture contents. Mott (1945) also studied the Barnsley-Top Hard horizon, but his choice of a lower horizon was the Silkstone Coal, lower in the sequence than the Thorncliffe-Tupton but less well represented in the post-war coal analyses.

Variations in calorific value and equilibrium moisture content for the two horizons are shown in text-figs 6 to 9. In these plans, the lines of equal calorific value and of equal moisture content have been drawn from the values at the sample positions without regard to structure. It will be shown later, however, that values can be expected to change significantly across the larger faults, and to vary systematically in relation to the folds. In general the accuracy of the lines, whose details are dependent on the minor but significant variations resulting from differences of coal type as well as limits of accuracy of the analyses, is not sufficient to warrant the complex adjustments that might be reasonably inferred from the relations of rank to structure.

The development of the structure of the coalfield

The structural development took place in two main stages: folding and faulting before deposition of Permian rocks, and a regional eastward tilt with minor faulting after the completion of Mesozoic deposition. Wills (1956) suggested that the first period of deformation may have been episodic, with deposition continuing in developing synclinal areas while anticlines were rising, but there is little evidence for this. The Permian rocks east of the exposed coalfield, and Triassic strata to the south, lie on a peneplain (Wills, 1956) that provides an excellent reference surface by which to judge the preceding deformation, and Fearnsides (1916), Mott (1945) and Kent (1966) have illustrated the structure of the Barnsley-Top Hard seam as it was before the regional tilt of the Permian and younger rocks was superimposed. Kent (1966) used the extensive modern data for the east of the coalfield and although he extended the structure contours over the Nottinghamshire-Derbyshire part of the exposed coalfield, he did not do so over the Yorkshire part, perhaps because it would have required greater extrapolation of the structure of the Permian rocks. This had been done, however, by Fearnsides (1916) and Mott (1945), who relied on the known structural simplicity of the Permian strata above the concealed coalfield.

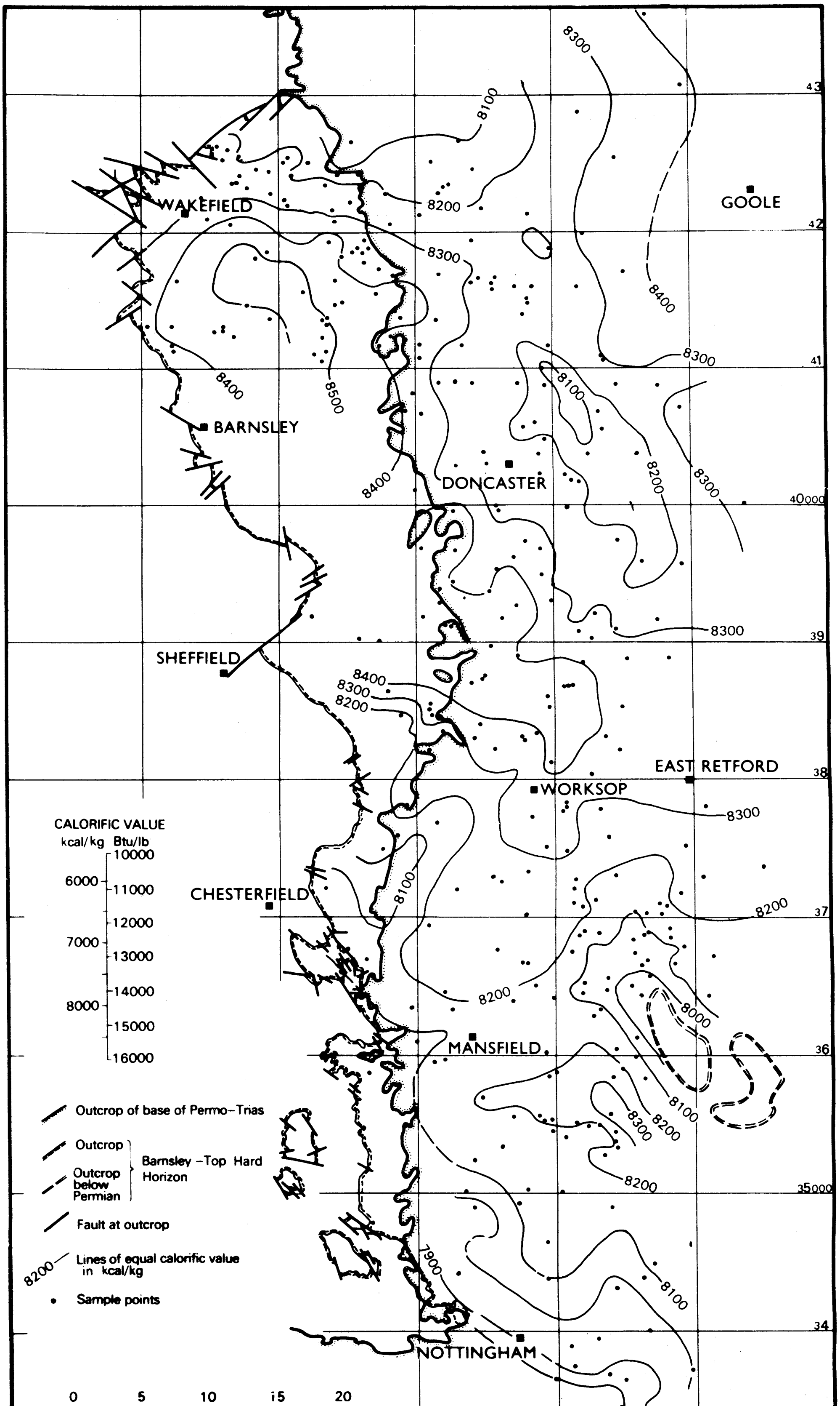
Text-fig. 10, which is a map of the pre-Permian structure of the lower, and hence more extensive, Thorncliffe-Tupton horizon, has been compiled mainly from National Coal Board records, Geological Survey memoirs and Kent's (1966) map. Also used were the extrapolated contours on the base of the Permian shown in text-fig. 1.

The structure of the coalfield is clearly complex, despite generally low dips, and although analysis of the pattern of deformation is not relevant here, it may be noted that a series of synclinal basins separated by faulted anticlines extends centrally through the coalfield, flanked to east and west by regional "highs".

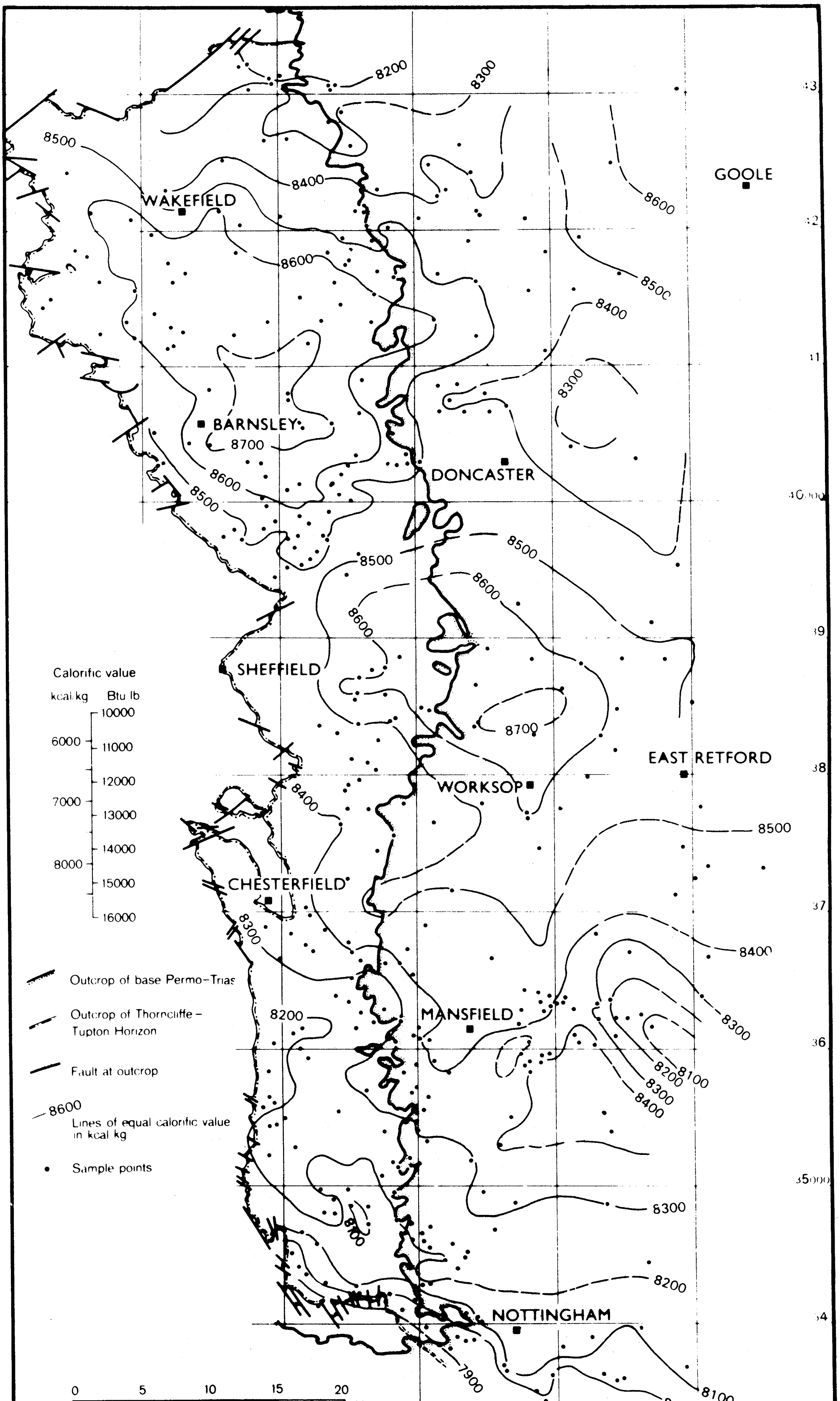
Besides the regional eastward tilting of the Permian and younger rocks, there was minor faulting, rarely reaching 30 m in throw and mainly rejuvenation of older faults, extending into the younger cover. The age of this deformation is probably Tertiary.

The range of ranks

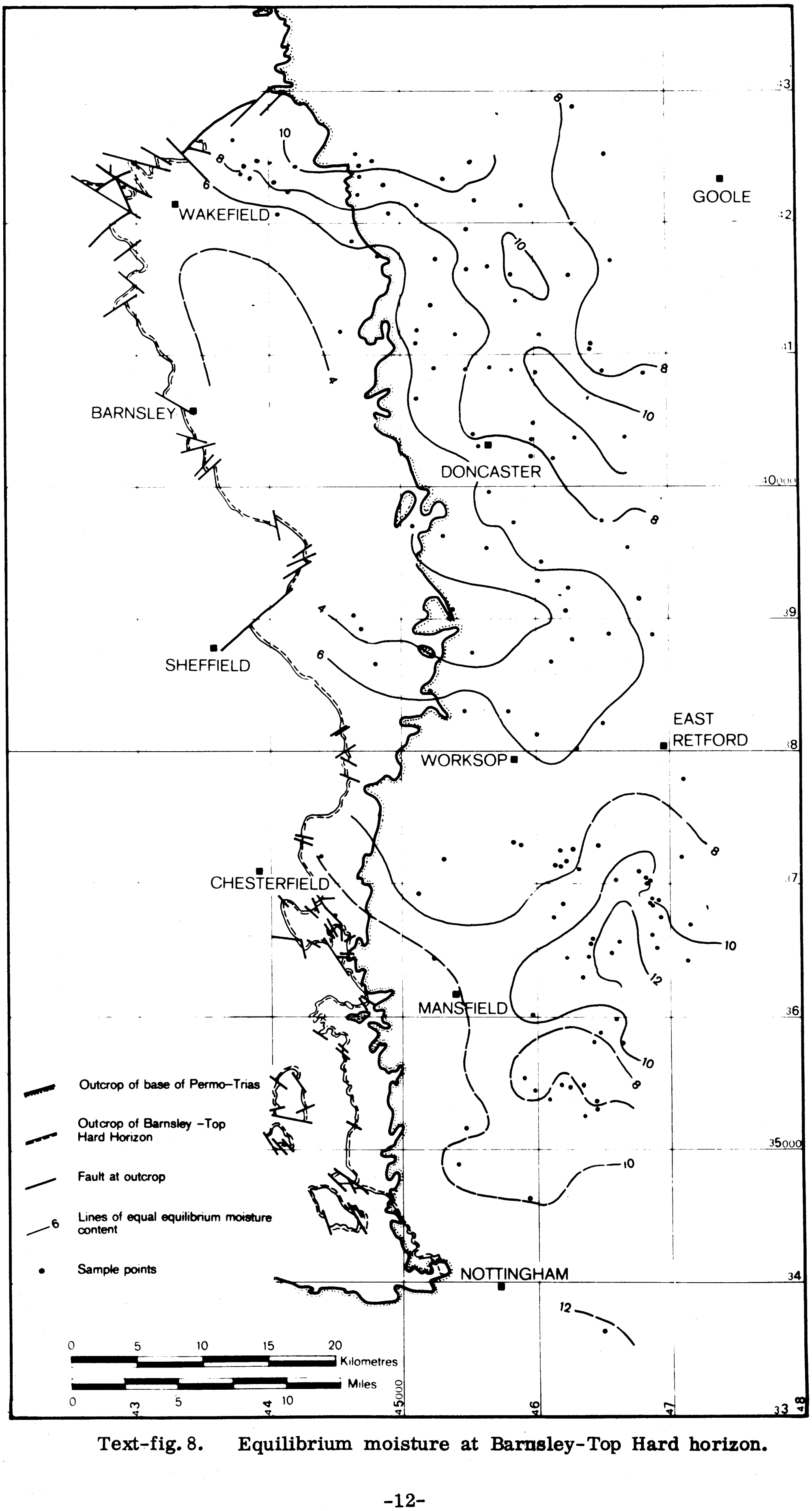
The lowest rank coals are close beneath the Permian or Triassic unconformity in the south of the coalfield. These have calorific values of 7800 kcal/kg on the dry mineral-matter-free basis, equilibrium moisture contents of 15 per cent, and are on the borderline between non-agglomerating and agglomerating; they are, accordingly, lowest-rank bituminous coals.



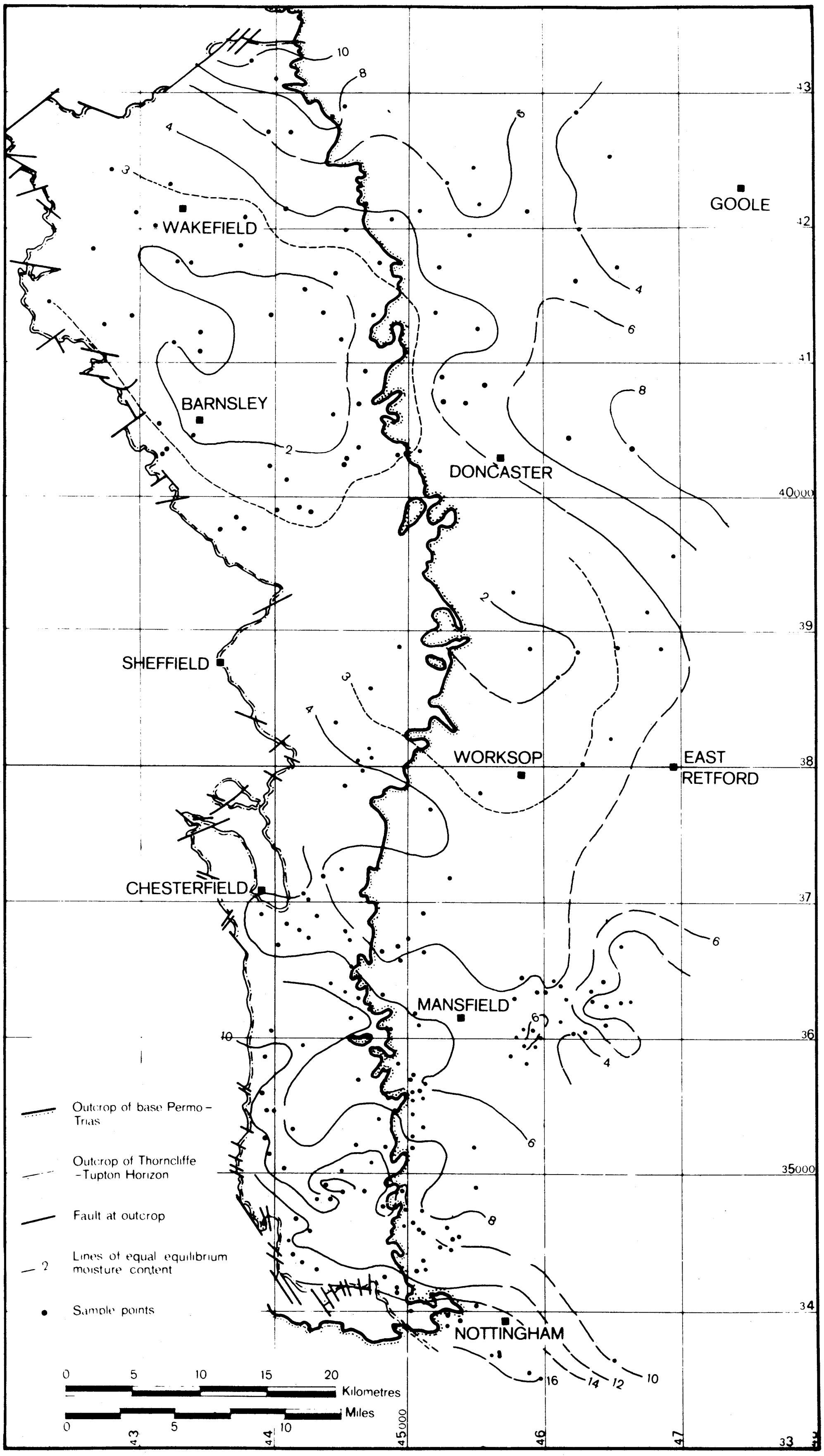
Text-fig. 6. Calorific value at Barnsley - Top Hard horizon.



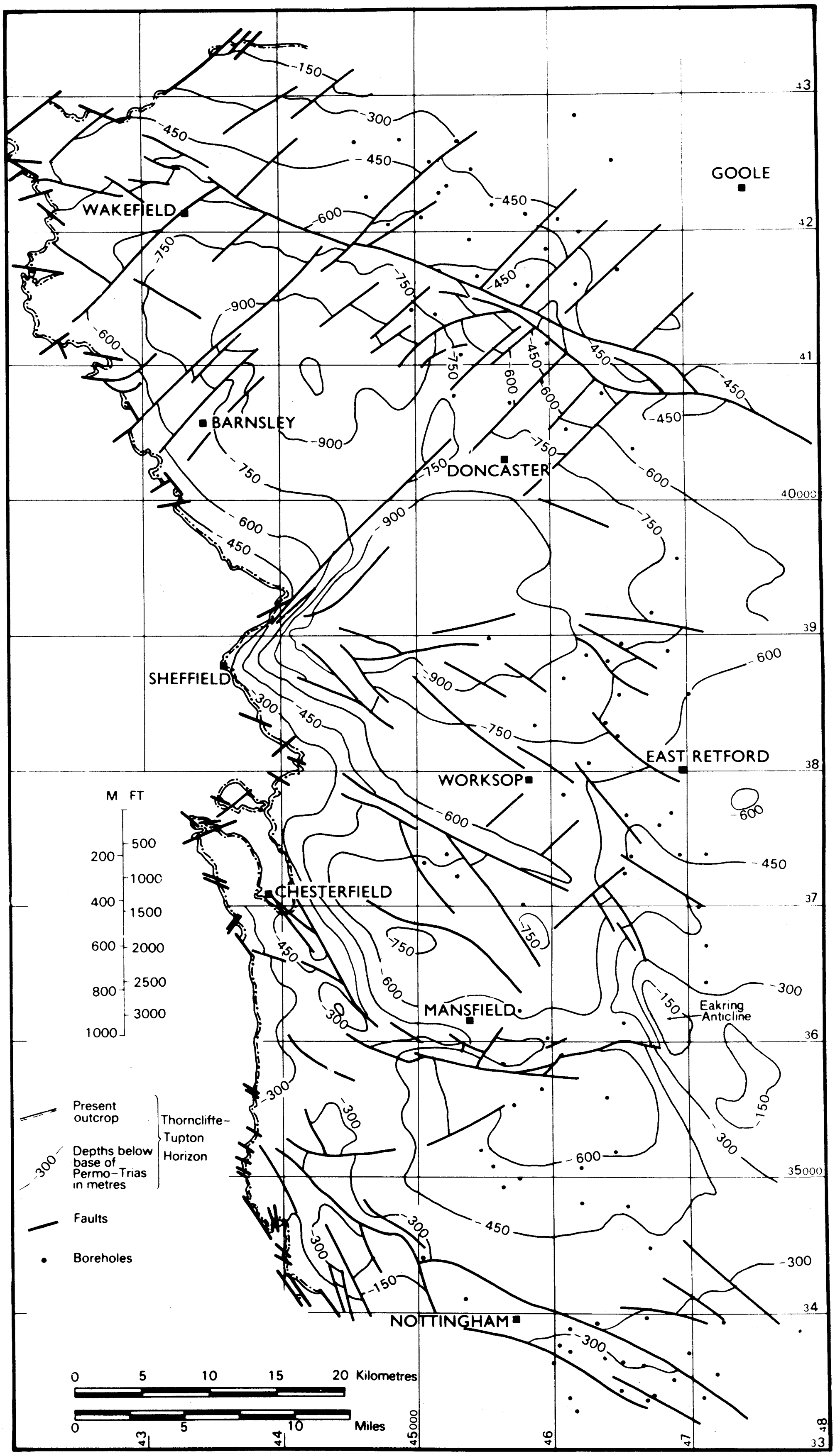
Text-fig. 7. Calorific value at Thorncliffe-Tupton horizon.



Text-fig. 8. Equilibrium moisture at Barnsley-Top Hard horizon.



Text-fig. 9. Equilibrium moisture at Thorncliffe-Tupton horizon.



Text-fig. 10. Pre-Permian structure of the Thorncliffe-Tupton horizon.

The highest-rank coals are in the deep basin north-east of Barnsley. These have calorific values of 8700 kcal/kg, equilibrium moisture contents of 1.7 to 1.9 per cent, volatile contents of 33 to 34 per cents and are very strongly caking; accordingly they are high-volatile bituminous coals, almost reaching to medium-volatile bituminous.

The range of rank is attained in roughly 900 m and nowhere in the coalfield is there any particular small thickness over which the rank range is covered. This range is only part of the range from peat through lignite, sub-bituminous, bituminous to anthracite, and as there is nothing exceptional in the relation of rank to depth, presumably the Coal Measures were formerly - or are now - in sequence with rocks above and below in which lower and higher rank coals would have formed if seams had been present.

The causes of the rank variations

The general patterns of variation shown in text-figs 6 to 9 are similar and systematic, and any geological explanation of the rank variation must be consistent both with these lateral rank variations and with the vertical rank variations shown in boreholes (text-figs 3 and 5). The principal geological explanations of rank variations in coalfields are variations in depth of burial, in tectonic pressure and heat, or in magmatic heat. There is no reason to suppose a magmatic source of heat in the Nottinghamshire-Yorkshire coalfield, and this explanation is not considered further.

Assessment of the tectonic hypothesis for this coalfield is relatively easy because the structure of the Coal Measures and, above of the unconformity, of the Permo-Triassic rocks, is well known.

Assessment of the depth of burial hypothesis, however, is hampered by the extensive erosion that took place (i) after the end of Coal Measures deposition and before the deposition of the basal Permo-Triassic beds and (ii) after the end of Mesozoic sedimentation.

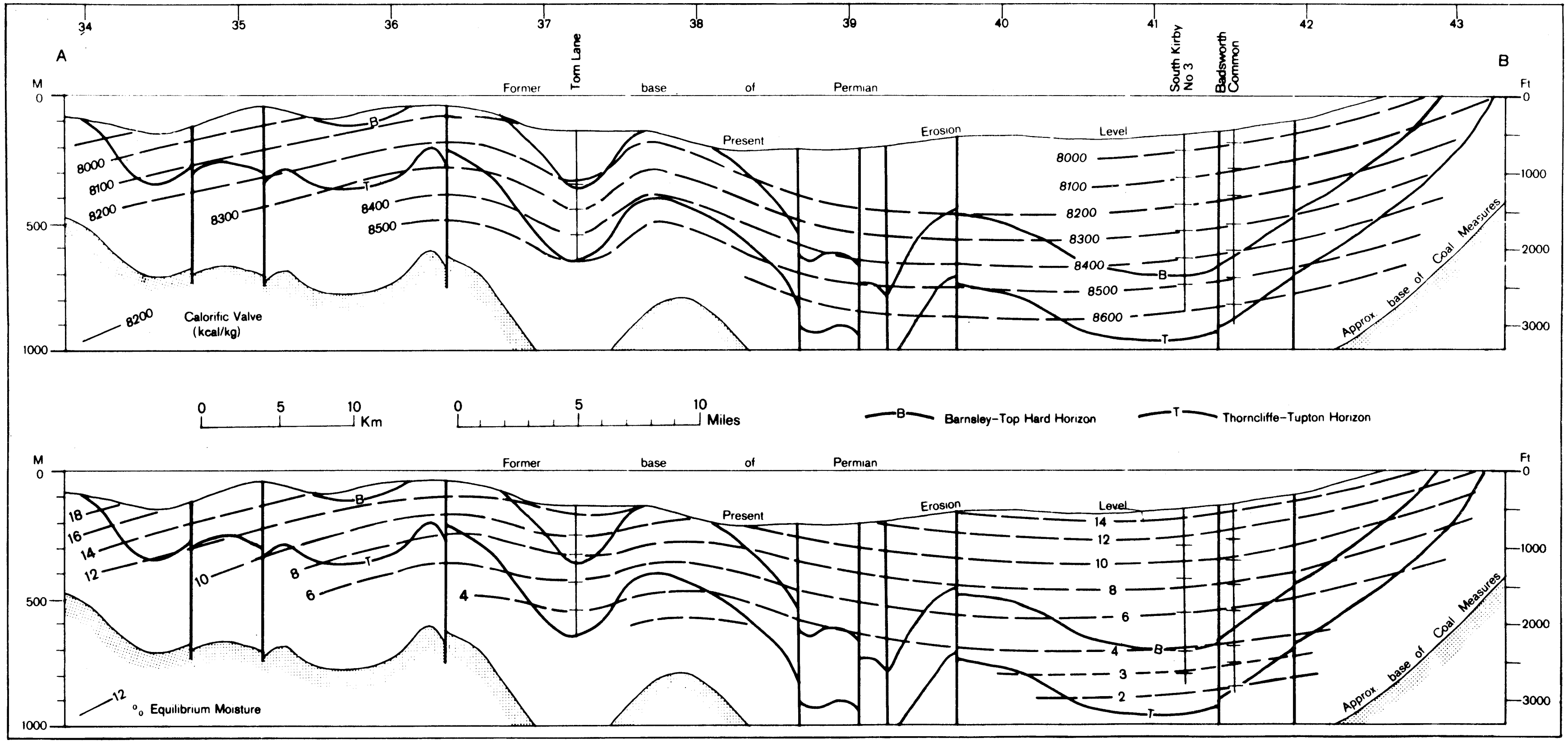
(a) Structure and Coal Rank

Comparison of the pre-Permian structure (text-fig. 10) with the lateral variations of rank at individual seam horizons, judged by calorific value and moisture contents (text-figs. 6 - 9), indicates a general similarity of pattern, the seams being of higher rank in synclines than in the anticlines. As was recognized by Mott (1945), the similarity is far greater than can be found by comparing the rank pattern with the present-day structure, which includes the effect of the Tertiary-imposed eastward tilt; for example, the north-west elongation of the highest-rank coal zone in the Wakefield area, and the south-eastward closure, north-east of Workshop, of the higher-rank coal zone that lies south of Doncaster, are not matched by the present-day structure. Steeper, smaller structures such as the Eakring anticline, which show well on pre-Permian and present day structure maps (cf. also those of Kent, 1966 and of Edwards 1967), clearly show the related rank patterns.

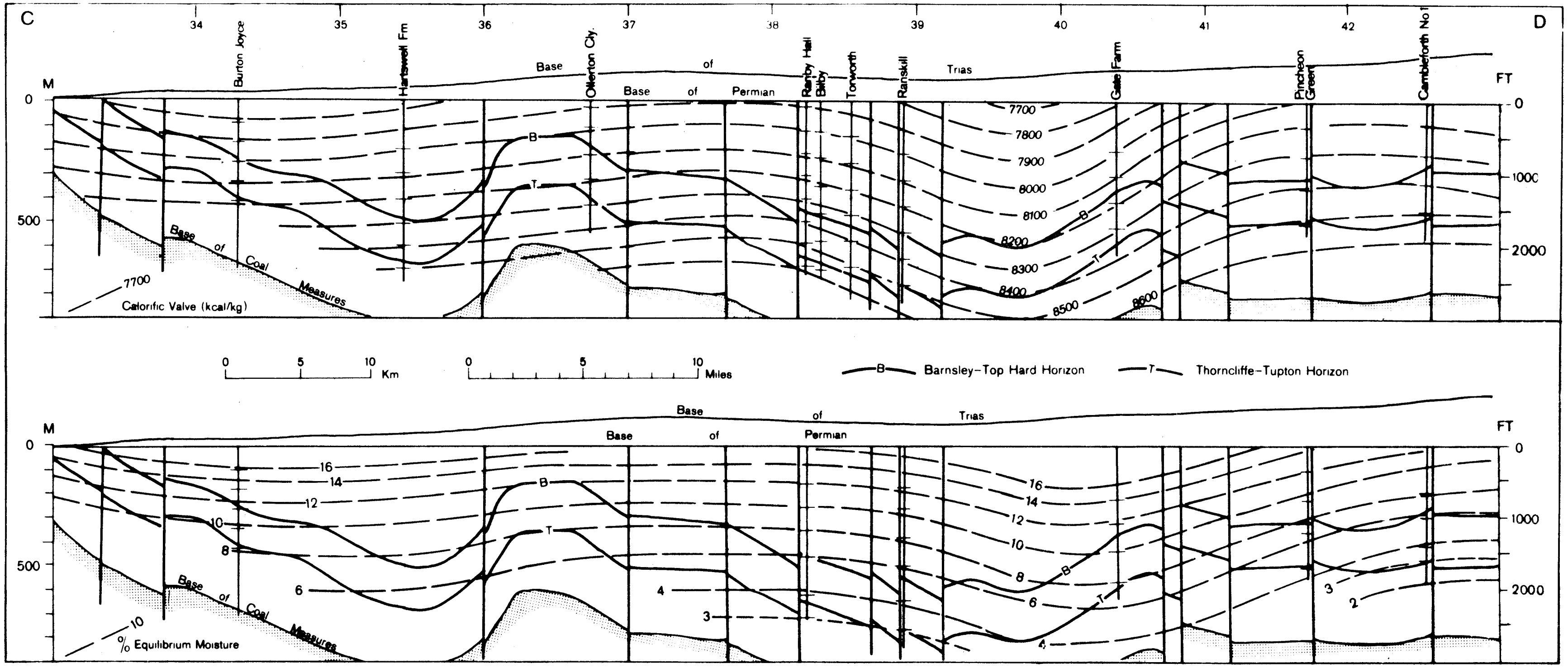
Text-figs. 11 and 12 are longitudinal cross-sections that illustrate in detail the relations of calorific value and moisture to the pre-Permian structure.

Text-fig. 1 gives the cross-section lines and also the known and inferred contours on the base of the Permo-Trias, which is used as the datum horizon. In the cross-sections, all faults are drawn vertical; all are steep, and because of the vertical exaggeration (X15) they would appear close to vertical. The actual detail of the faulting does not affect the discussions of coal ranks.

The cross-sections have been constructed from text-figs 6 - 10 together with the data from boreholes close to the cross-section lines. These boreholes have been projected at right-angles to those lines to provide control of variations in relation to the base of the Permian.



Text-fig. 11. Cross-sections relating structure, calorific value and equilibrium moisture to the base of the Permo-Trias; for position of cross-section A-B, along grid line 44500, see text-figs. 1 and 13.



Text-fig. 12. Cross-sections relating structure, calorific value and equilibrium moisture to the base of the Permo-Trias; for position of cross-section C-D, along grid line 46500, see text-figs. 1 and 13.

The following inferences can be drawn from text-figs 6 - 12:

(1) The rank increases with depth below the base of the Permian, and as shown in the cross-sections, the lines of equal calorific value and moisture do not follow the folds of the strata but clearly cross the structures.

(2) At any particular depth below the base of the Permian the rank tends to be less in the main synclines than in the anticlines. These fluctuations of rank are, however, not exactly coincident with the folds, and their amplitudes are much less than those of the folds. Minor details of the structures do not affect the major rank variations.

(3) Faults do not interfere with the pattern of rank variation; this would be best demonstrated from boreholes, but few have passed through faults with large enough displacement to show whether the rank/depth is disrupted. The Little Smeaton borehole, 15 km north-north-west of Doncaster, did, however, penetrate a normal fault with 75 m throw in the Coal Measures (less than 3 m throw in the overlying Permian) and the uniform rates of both the increase of calorific value with depth and of the decrease of equilibrium moisture with depth are not interrupted. Nor is there the least hint that the faulting has affected the rank itself.

Thus the rank was apparently superimposed on the Coal Measures after at least some of the folding and faulting, so that tectonism can be discounted as a cause of the rank variations.

(b) Depth of burial and coal rank

The clear increase of rank with depth throughout the coalfield points to the probability that the original total depth of burial was the prime factor in determining the rank. That depth is not known because of erosion of former cover, and two possibilities for the time of attainment of rank need to be considered: (i) after completion of Carboniferous sedimentation, and (ii) after completion of Mesozoic sedimentation.

Critical to choosing between these alternatives is the likely former thickness of deposits representing lower ranks. Coals begin as peats with calorific values (dry basis) of about 5500 kcal/kg and moisture contents of about 80 per cent. The change to a coal of about 7800 kcal/kg and about 15 per cent moisture, as in seams close beneath the Permian, represents a change roughly twice as great as the further change to about 8700 kcal/kg and about 1.8 per cent moisture that has taken place over a depth of about 900 m within the coalfield. Thus the former cover above the Coal Measures was probably about 1800 m. a not exceptional thickness for sediments in regions including only lignite and sub-bituminous coal. If the thickness had been significantly less, the depth/rank gradient in eroded deposits above the present top of the Coal Measures must have been radically different from that within the Coal Measures. Such a change in the depth/rank gradient would imply a change in temperature or pressure conditions. As the pressure will not have changed suddenly, it would be necessary to postulate a rapid change in geothermal gradient.

Accordingly the basic consideration in judging the time of development of the coal ranks, whether the cover was pre-Permian or post-Permian, is that the cover must have been of the order of 1800 m thick unless the geothermal gradient in the eroded strata was much higher than in the existing Carboniferous. If the eroded strata was itself Carboniferous, no major change in geothermal gradient is likely.

If the rank was attained prior to the Permian, the following sequence seems the most probable, to account for the partial reflection of the broader structures in the rank pattern. First, there must have developed during the late Carboniferous a new pattern of sedimentation unrelated to the previous south-eastward thinning but related to the broad folding now seen in the Coal Measures. This would have resulted in a structure-related pattern of ranks in any one seam. But unless the geothermal gradient differed from anticlines to synclines, equal rank surfaces will have remained parallel to the final depositional surface, thus not reflecting the structure. Accordingly further folding, during pre-Permian uplift and erosion and after the ranks had been imprinted on the Coal Measures, would seem probable. In so far as the coal ranks would have been attained during an early stage of folding - even though at the same time as sediments were still accumulating everywhere - the rank development might be regarded as synorogenic.

Mott (1945) rejected any effect of Permian and younger rocks and welcomed contributions to the discussion (published with his paper) by Fearnsides, Wandless and Hickling, who individually all accepted that the coal rank resulted from the pre-Permian depth of burial. Only in Millott's discussion of the paper was the view expressed that the rank variation might be related to "*maximum*, rather than to pre-Permian, depth of burial". Hicks expressed difficulty in accepting the need, implied by Mott, for the total thickness of the supposed denuded Carboniferous rocks to be the same over the whole coalfield.

The necessary thick (c. 1800 m) late Carboniferous sediments are indeed unlikely to have been present, in view of the incoming of red measures and an unconformity within the youngest preserved Carboniferous strata (Edwards, 1967). Wills (1956) inferred that only thin deposits accumulated in local subsiding areas. Accordingly an alternative explanation for the rank pattern needs to be considered.

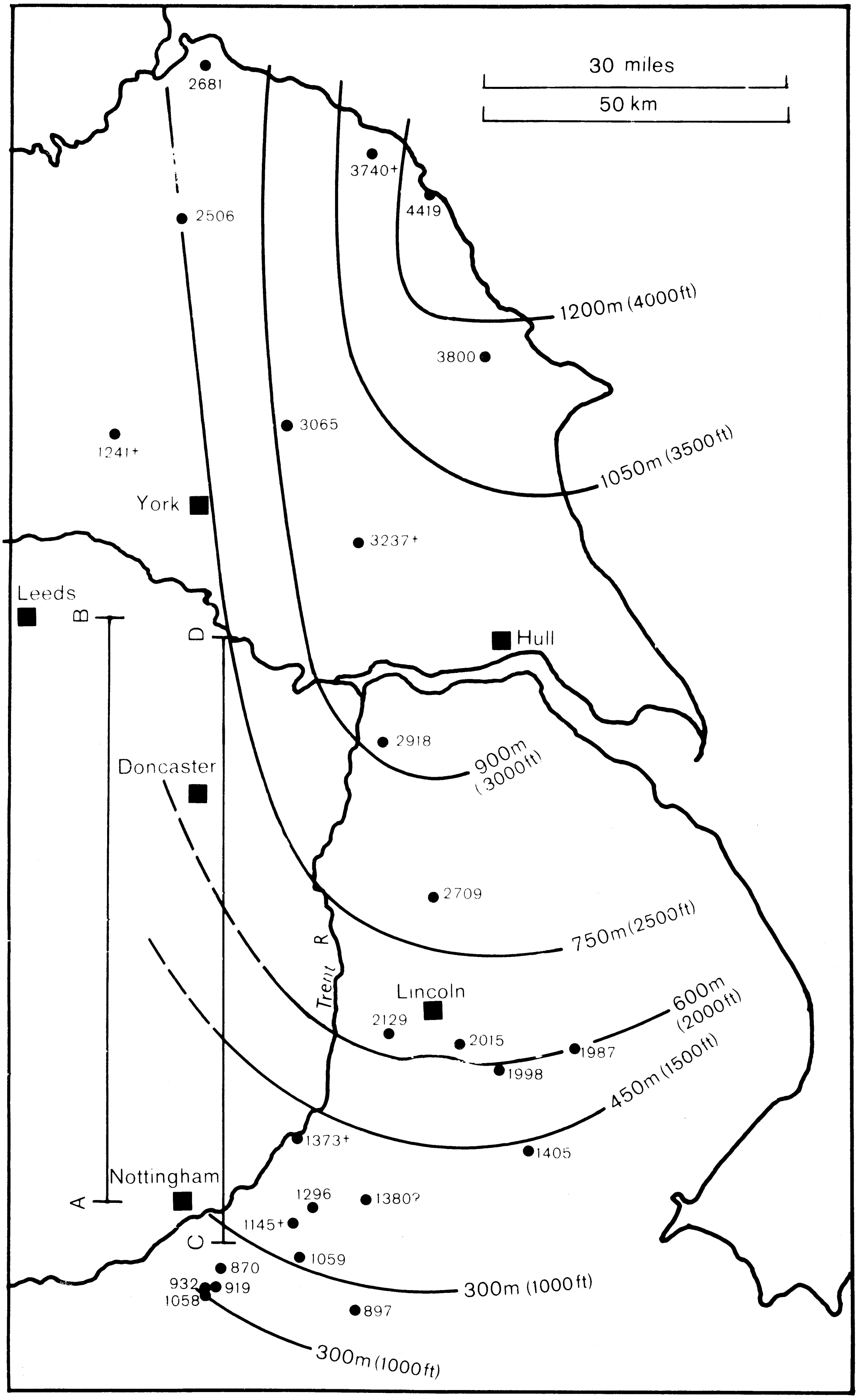
If the coal ranks were attained under conditions of maximum cover at the conclusion of Permian-Mesozoic sedimentation, this cover could have been substantially less than the suggested 1800 m because a rapid change in geothermal gradient at the unconformity at the base of the Permian is quite possible. On the other hand, it seems unnecessary to postulate such a change because such a thickness of cover may well have been deposited, although erosion prevents an accurate estimate of its total thickness. In a series of paleogeographic reconstructions, Wills (1951) inferred deposition over the coalfield from Permian to Upper Cretaceous (Senonian), but interrupted from the late Jurassic to the Lower Cretaceous (Neocomian). Some indication of the pattern of thickness variation of Permian, Bunter and Keuper sediments can be gained from oil exploration (text-fig. 13) with thicknesses within the coalfield ranging from 300 m in the south to 750 m in the north. The thickness from the base of the Keuper to the top of the Oxford Clay in the Stixwould bore east of Lincoln is 446 m (Lees and Taitt, 1945), and a comparable thickness may well have formerly overlain at least the northern part of the coalfield. A further unknown thickness, possibly of Upper Jurassic and more probably of Cretaceous, must be added to provide some estimate of the former total cover over the field; Wills (1956) suggested "at least another 1500 to 2000 ft" (450 to 600 m) for this additional thickness. The total could well have reached or exceeded 1800 m; the variations in thickness within the coalfield area cannot, however, be inferred.

Thus the coal ranks are considered to have been attained under a cover of Permian and Mesozoic sediments, as foreseen by Wills (1956, p. 117) who stated"... we must not neglect this additional thickness of Mesozoic cover when considering the conditions of temperature and pressure to which the coals in the Coal Belt have at some time been subjected." Nevertheless, it leaves unexplained the slight reflection of broad structure of the Coal Measures seen in the coal rank pattern. This is discussed below, after consideration of some details of the variations in rank.

The detailed variations in rank

(a) Differences in the rate of change with depth of calorific value and moisture

The differences in depth/calorific value gradients are substantial. Deeper boreholes with adequate numbers of analyses have a range from 600 kcal/1000 m at the Stone borehole to 950 kcal/kg/1000 m at the Kellingley borehole. The Stone borehole, and also that at Cross Hills (Derbyshire) (700 kcal/kg/1000 m) are close to the centres of synclinal basins. The Kellingley borehole, and also the Darrington No. 3 borehole (900 kcal/kg/1000 m), are on the flank of a major structure. A particularly high value of 1000 kcal/kg/1000 m is found for the Ash Hill borehole, which provides a well-controlled sequence over a depth of 350 m, and the



Text-fig. 13. Isopachs of Permian-Bunter-Keuper strata, based on boreholes mainly for oil exploration. Data from Lees and Taitt (1946), Fowler (1944), Edwards (1951), Falcon and Kent (1960) and Brunstrom (1962). A-B and C-D are the lines of cross-sections illustrated in text-figs. 11 and 12.

nearby Cross Hill (Yorkshire) borehole gives 950 kcal/kg/1000 m. These boreholes are close to the anticlinal crest 12 km north of Doncaster. On another anticlinal structure, west of Mansfield, the Kings Mill borehole gives a relatively high value of 920 kcal/kg/1000 m.

The smaller number of boreholes with determinations of equilibrium moisture contents prevents as close a comparison of structural position with depth/moisture gradients. Of the boreholes discussed in the previous paragraph, the Cross Hills (Derbyshire) and Darrington No.3 boreholes, with contrasting depth/calorific value gradients, show comparable contrasts in depth/moisture gradients. Where the ranges of moisture contents in these boreholes coincide - from 10.5 per cent to 3.0 per cent - the depth for this decrease is 590 m at Cross Hills (Derbyshire) and 460 m at Darrington No.3. The Ash Hill borehole has a gradient similar to that at Darrington No.3.

Thus the Cross Hills (Derbyshire) borehole - synclinal - contrasts with the Darrington No.3 - flank - and Ash Hill - anticlinal - boreholes in both calorific value and moisture gradients, a greater depth being needed at Cross Hills than at Darrington No.3 and Ash Hill in order to produce the same amount of change. This appears to confirm that the variations in rate are significant. The relation of the variations to structure seems probable rather than certain.

At the Eakring anticline, the western flank of which is crossed by cross-section C-D (text-fig. 12, near the Ollerton Colliery borehole), the calorific value gradient is about 1000 kcal/kg/1000 m, a high value, but the moisture gradient is about average.

(b) Variations in moisture/calorific value relations

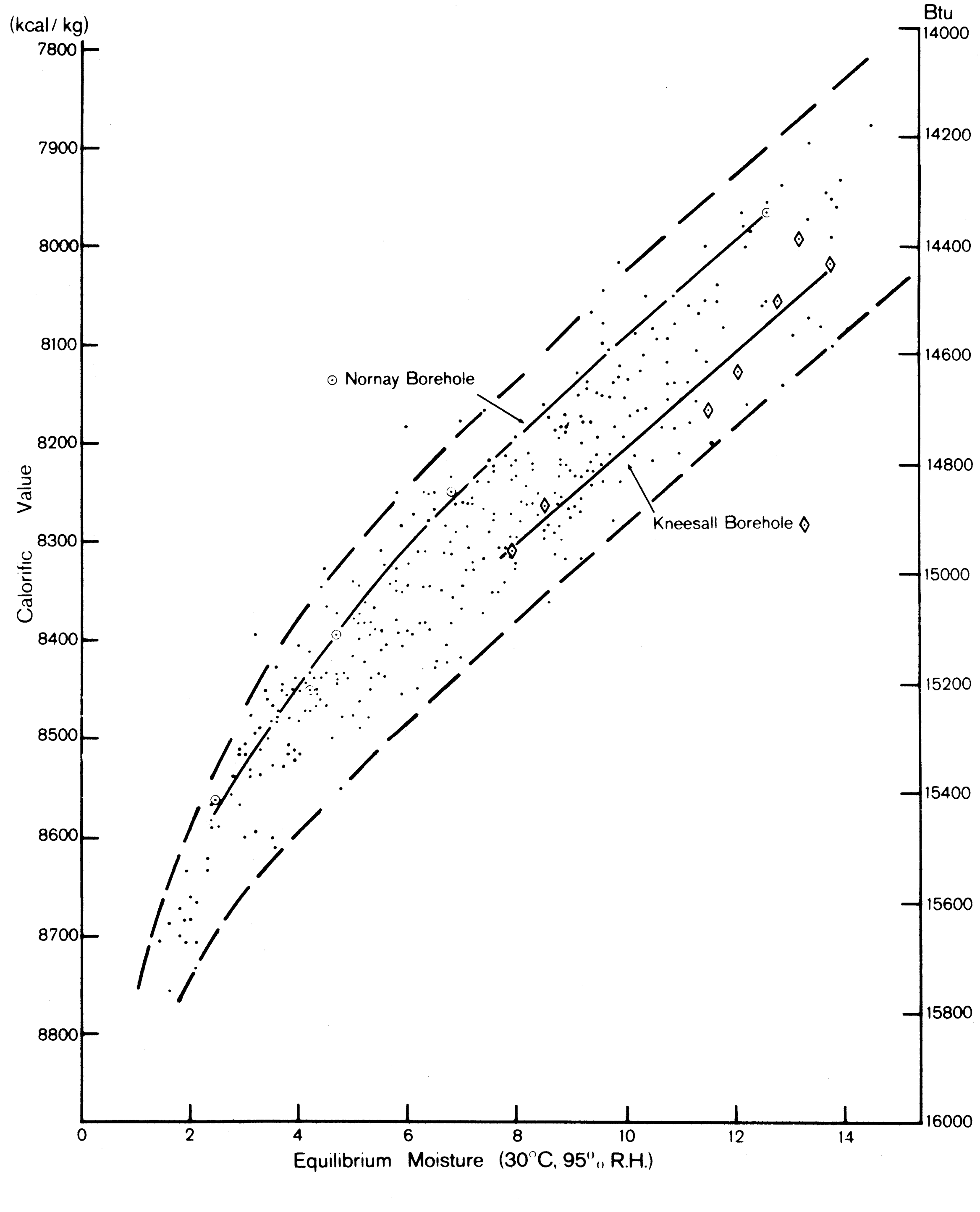
The progressive downward increase in calorific value and decrease in moisture have generally similar patterns over the coalfield, as indicated by text-figs. 11 and 12, but in detail the moisture content for any particular calorific value is not constant and text-fig. 14 illustrates the range of moisture/calorific value relations. Minor variations in coal type would account for some of the range, but not the extreme variation of nearly 2:1 in moisture content at any particular calorific value. The differences are probably related to varying pressure/temperature relations in the coalfield at the time of attainment of rank, as the moisture content is more influenced by pressure and the calorific value by temperature.

There is indecisive evidence suggestive of lower moisture contents for particular calorific values in synclinal areas than in anticlinal areas. Thus the moisture/calorific value relation (text-fig. 14) in the Nornay borehole near the bottom of a synclinal basin is markedly different from that in the Kneesall borehole on an anticlinal flank where individual horizons are 500 m closer to the base of the Permian. Where cross-section C-D (text-fig. 12) crosses the more northerly syncline (at grid line 395000 N), the moisture content at 8500 kcal/kg is about 3.5 per cent, whereas it is about 5 per cent on the anticline 10 km to the north. A comparable though rather less marked variation is found at the syncline (grid line 372000 N) penetrated by the Tom Lane borehole (cross-section A-B, text-fig. 11).

Such variations as these are not unexpected in folded and faulted Coal Measures subjected to a more or less uniform superincumbent load of Permian and Mesozoic sediments. During increasing burial the expulsion of moisture may well have been influenced by the relative ease of its movement through the Coal Measures, and the resultant variations could well have guided to some extent the detailed pattern of geothermal temperatures. The general pattern of moisture/calorific value relations, inferred to imply higher temperatures in anticlinal areas, is held to account for the partial reflection of broad Coal Measures structure, seen in the rank pattern.

(c) Variations of calorific value and moisture at base-Permian

Text-figs 11 and 12 indicate that at the base of the Permian calorific values are lower and moisture contents higher in the south than in the north, although the difference is almost



Text-fig. 14. Relation of calorific value to equilibrium moisture.

overshadowed by local variations. The difference in calorific value is about 400 kcal/kg along cross-section A-B, and about 300 kcal/kg along cross-section C-D. The moisture content diminishes from an estimated 22 per cent to 12 per cent along A-B and from about 16 per cent to about 12 per cent along C-D. These values represent the equivalent of roughly 400 m difference of depth of burial along A-B and between 300 and 200 m difference along C-D, which are substantial in relation to an original total Permian and Mesozoic cover of the order of 1800 m. They imply a general southward thinning of this cover. This is implied in text-fig. 13, which, however, gives no hint of a lesser decrease along C-D. The variations related to structure make comparisons between A-B and C-D rather uncertain, but the southward rank decrease seems rather less than might be expected from regional differences in Permian-Bunter and Keuper thicknesses. It is perhaps pertinent that the variations of the Keuper are slight compared with those of Permian and Bunter, and the change may have heralded a different pattern of variation in the later Mesozoic. It is the total variation from Permian to late Mesozoic that is likely to have been significant in controlling the rank at the base of the Permian.

(d) "Rank" of coal

Throughout this paper, the term "rank" has been used in a general sense, to imply approximate degrees of diagenesis (metamorphism). Both calorific value and equilibrium moisture content are equally useful to indicate general rank, but the range of variation between these two parameters has been shown to be such as to preclude the use of either the one or the other as a prime indicator of rank. The coals in the Nottingham-Yorkshire Coalfield are almost all high-volatile bituminous coals, in that they coke and have more than 29 per cent volatile matter (dry basis). Within this general rank description it would be desirable to describe the coals by the independent - or at least partially independent - parameters of calorific value (dry mineral-matter-free basis) and equilibrium (or bed) moisture content. Only by so doing can close comparison be made of coals developed under a range of independent - or at least partially independent - temperature and pressure conditions.

Acknowledgements

Every assistance was given by G. Armstrong, formerly Chief Geologist, and other members of staff of the National Coal Board, including R. E. Elliott and E. Skipsey of the East Midlands Division and R. F. Goosens, E. Bradburn and Mrs. J. Jones of the North Eastern Division. This study would have been impossible without the structural and analytical information provided. Much of it was carried out in 1969 at the Department of Geology, University of Nottingham, while on leave from the New Zealand Geological Survey.

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