THE EAST MIDLANDS AULACOGEN OF CALEDONIAN AGE

by

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Summary

It is suggested that a late Precambrian to Lower Palaeozoic aulacogen is present in the basement of much of eastern England. In this structure Pre-Cambrian, Cambrian, Ordovician and Silurian rocks of geosynclinal-type were laid down. It is suggested that the supposed westerly trending ridge of Pre-Cambrian rocks stretching from the Wash to the Melton Mowbray-Market Harborough area represents Lower Palaeozoic extrusive and intrusive rocks belonging to the East Midlands aulacogen which is here described.

Evidence is presented for the widespread occurrence of deformed Lower Palaeozoic rocks in this aulacogen including hitherto unpublished data for the presence of such rocks in the general area between Charnwood Forest and Nuneaton. The rocks in the trough suffered at least two phases of folding, one late Pre-Cambrian and one late Caledonian. The former was about north-west to south-east and the latter about westerly axes, with the accompanying development of a penetrative cleavage which affects both the Pre-Cambrian of Charnwood Forest and the Cambrian and Ordovician. Radiometric dating and field evidence suggest that this cleavage is Caledonian in age.

Subduction occurred beneath the aulacogen over a long period giving rise to a widespread suite of plutonic and volcanic rocks in both the Pre-Cambrian and the Lower Palaeozoic. The available data suggests a north-easterly dipping subduction zone.

Introduction

There are many intriguing and unanswered questions concerning the Pre-Cambrian and Lower Palaeozoic history of the East Midlands. Some of these have already been discussed (Evans, 1963, 1968, Evans and Maroof 1976, Le Bas 1968, 1972) and the suggestion put foward that an important igneous-tectonic north-westerly trending Caledonian province is present beneath the East Midlands. Most of the evidence comes from the exposed Pre-Cambrian and Lower Palaeozoic rocks of Charnwood Forest and the Nuneaton area, boreholes and geophysical data. The Cambrian and Ordovician of Nuneaton have for long been interpreted as representing shelf sedimentation laid down on a stable Pre-Cambrian craton flanking the Anglo-Welsh Lower Palaeozoic mobile belt (Owen 1976). A question which must, however, be considered is whether another mobile belt of the same age is present underlying much of England to the east of Nuneaton. Just such a possibility was put forward by Turner in 1949 in a brilliantly deductive paper in which he suggested that the Anglo-Welsh Caledonides form an arc, convex northwards, which surrounds the Midland Massif and passes south-eastwards into central Europe. Turner considered the folding of these Lower Palaeozoic rocks to be Hercynian in age and their south-western margin to lie just east of the Pre-Cambrian Charnian rocks of Charnwood Forest. Wills (1951) proposed a similar hypothesis but invoked a Caledonian age for the folding. Recently Dewey and Kidd (1974) suggested that the Leicestershire area may represent a late Pre-cambrian aulacogen. Such a structure is a large, long-lived, fault-bounded trench which intersects the Caledonian geosyncline at a high angle and extends into the neighbouring craton, (text-fig. 3), p. 37, (Smith, 1976). The trench becomes filled with sediments and volcanics. Despite the work of the above mentioned and other authors,

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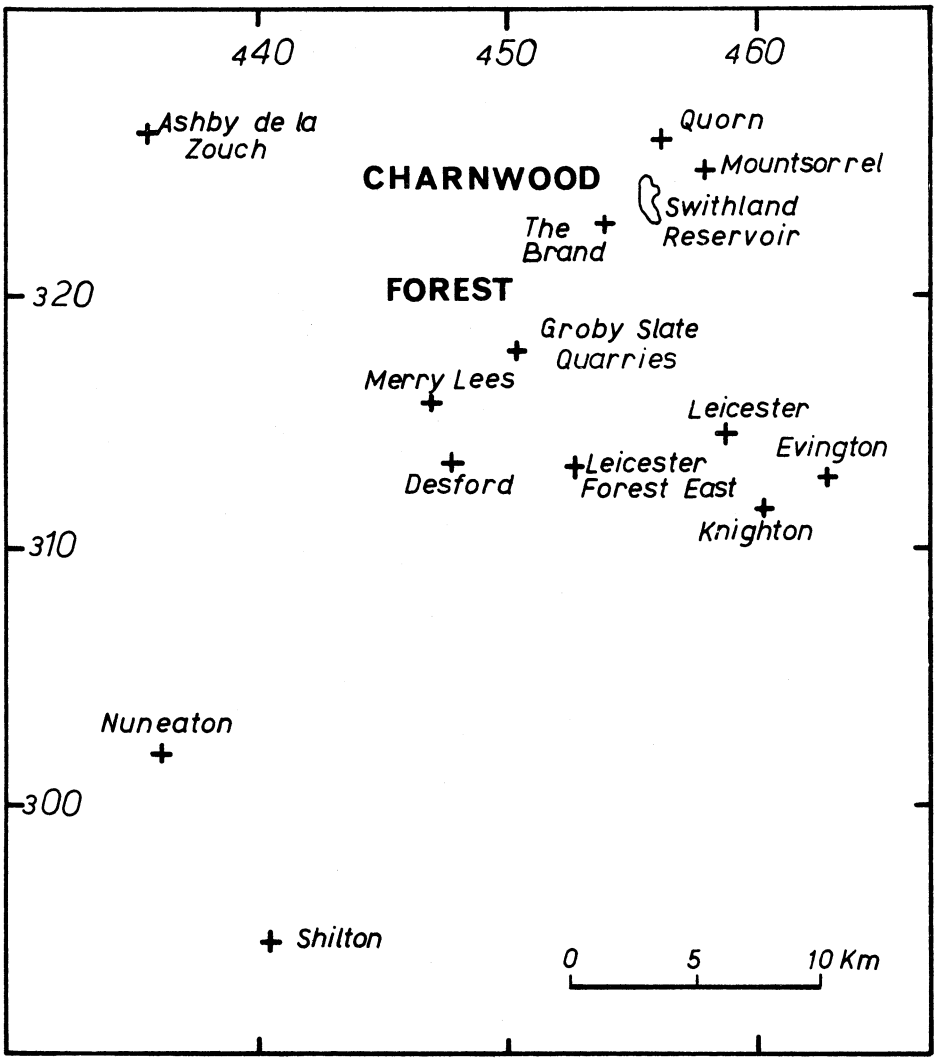
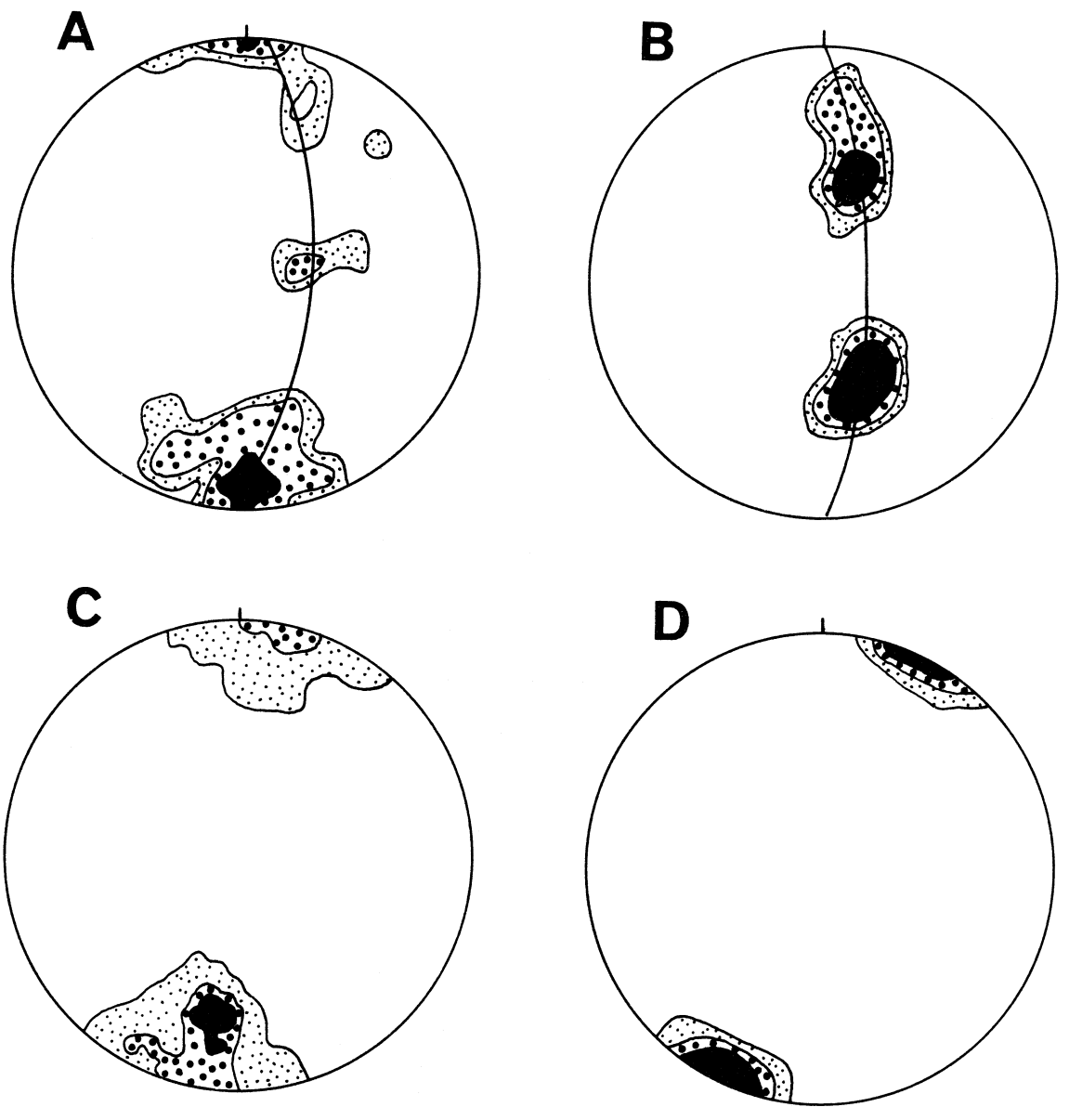
1979, pp. 31-42, 4 text-figs.



Text-fig. 1. Locality map showing the position of Charnwood Forest and other nearby places mentioned in the text.



Text-fig. 2. Stereograms of: A - 78 poles to bedding for the Ordovician of the Merry Lees Drifts; B - 68 poles to bedding for the Cambrian of Swithland Reservoir (contours for A and B at 3, 4 and 10 per cent of one per cent areas); C - 500 poles to cleavage for the Charnian of Charnwood Forest (contours at 2,8 and 12 per cent); D - 100 poles to cleavage for the Cambrian at Swithland Reservoir (contours at 4, 12 and 20 per cent). All data projected on the lower hemisphere of a Lambert equal-area net.

the general tendency in most stratigraphical reconstructions is to treat the whole of the English Midlands as a stable Pre-Cambrian cratonic block which carries only a thin veneer of Lower Palaeozoic sediment (Read and Watson 1975, Owen 1976, Lovell 1977).

In this paper further evidence for the existence of a Lower Palaeozoic mobile belt underlying much of the East Midlands is put forward. It is postulated that the south-western margin of this belt may be close to Nuneaton and that the Pre-Cambrian of Charnwood Forest was considerably deformed during the Caledonian orogeny. It is further postulated that this orogeny was responsible for the principal cleavage in the Charnian Supergroup and the folding and cleavage in the adjacent Palaeozoic rocks.

Folding in the Charnian and Lower Palaeozoic rocks

The notion that the Charnoid trend is north-westerly was challenged by Evans (1963) who pointed out that although the major anticline followed this trend over much of Charnwood Forest it is flexed round to an easterly trend in the south-east of the Forest, whilst the cleavage is generally oblique to the fold and, over the Forest as a whole, has an average strike of 280°. A model was proposed in which it was suggested that the folding and oblique cleavage, though broadly non-parallel, were coeval and probably Pre-Cambrian in age. Later data suggested that this hypothesis must be abandoned and that the Charnian rocks have suffered at least two important phases of deformation (Evans *et al.* 1968).

Minor folds in the Charnian

A number of minor folds are present and these have wavelengths ranging from 0.3 - 1.6 km. Some of these trend parallel to the major anticline and possess a similar plunge. Another group have horizontal or subhorizontal axes which trend obliquely across the main fold with a trend concentrated about 280°. They are concentric folds with north-south slickensides developed on those bedding surfaces which accommodated much of the bedding slip. Localities of many of these folds are given in Evans (1963).

Minor folds in the Lower Palaeozoic

The only extensive exposures of unequivocal Lower Palaeozoic rocks east of the Nuneaton area were those exposed in the Merry Lees Drift (text-fig. 1) near Desford. (Butterley and Mitchell 1945). These rocks lie beneath the Trias and fossil evidence indicates a Tremadoc age. Butterley and Mitchell recorded dips approaching the vertical with a westerly strike. Le Bas (1972) noted the presence of a weak cleavage.

Recently structural mapping of these rocks has revealed the presence of minor folding and a stereogram of poles to bedding is given in text-fig. 2. This indicates a plunge of about 22° in a direction 275° essentially parallel to the second group of minor folds in the Charnian and with a very different plunge from that of the probably late Precambrian folding.

On the east side of Charnwood Forest, but not in contact with the Charnian rocks, the Caledonian Mountsorrel igneous complex crops out. Associated with it are a number of small outcrops of pelitic hornfelses. Some of these appear to be rafts within the granodiorite. On the south-western shore of Swithland Reservoir (text-fig. 1), however, low grade hornfelses, about half a kilometre from the contact, are well exposed in and around a small hill. Le Bas (1972) has made out a good case for regarding these as hornfelsed Cambrian rocks. Bedding is clearly visible and this has been folded into an upright syncline with a vertical axial surface. The axis plunges at about 16° in a direction 269° (text-fig. 2). This is about 45° anticlockwise to the principal axial trend in the nearby Charnian rocks. The joint controlled shapes of the xenoliths in the Mountsorrel complex indicate that it is probably a permitted intrusion emplaced by stoping, in which case it is unlikely that this fold has been tilted by the intrusion.

It can hardly be a coincidence that the folds at Merry Lees and Swithland Reservoir have similar trends which are parallel to the second group of folds in the Charnian rocks.

The conclusion is drawn that all these folds are probably Lower or mid-Palaeozoic in age.

Cleavage in the Charnian and Lower Palaeozoic rocks

The presence of cleavage in the Ordovician rocks of the Merry Lees Drifts was noted by Le Bas (1972). Unfortunately this was not detected underground, but only in thin sections. A weak cleavage is also present in the Ordovician rocks intersected by the Evington and Knighton boreholes in Leicester City, specimens of which can be seen in the Leicester Museum. Relict cleavage is readily apparent in the hornfelses at Swithland Reservoir. Here it has an average trend of 296° (text-fig. 2) essentially parallel to that in the nearest outcrops of Charnian rocks, but oblique to the minor fold described above.

It must be borne in mind, however, that although the average cleavage trend in the Charnian rocks is 280° (text-fig. 2) it does show some variety in its trend and intensity. It actually follows a somewhat sinuous course across the Forest from approximately westerly in the south to more north-westerly in the centre and west-north-westerly in the north-west (Evans 1963).

Recently boreholes by the Institute of Geological Sciences and National Coal Board have penetrated Upper Cambrian (not Tremadoc) rocks between Charnwood Forest and Nuneaton (details in press). These are at Rotherwood (SK345155) just south of Ashby-de-la-Zouch, Dadlington (SP 399991) 7. 5 km north-east of Nuneaton and Leicester Forest East (SK 525029) 6. 5 km west-south-west of Leicester (text-fig. 1). The rocks are dominantly well cleaved slates and the bedding frequently shows high dips. These discoveries together with the evidence from the Merry Lees Drifts and the Leicester boreholes indicate the presence of considerably deformed and folded Cambrian and Ordovician sediments *to the west* of Charnwood Forest. To these may probably be added the non-fossiliferous slates of the Lindridge borehole near Desford.

In the broad region of basement rocks running north-westwards beneath the Mesozoic rocks from near Dover through the Home Counties, Bedfordshire, Northamptonshire, Leicestershire, Nottinghamshire and the adjoining areas there is now abundant evidence of the development of Cambrian to Silurian rocks (Le Bas 1972). Cleavage has been reported as being present in some of these and there is an extensive development of calc-alkaline intrusions (Le Bas 1972; Evans and Maroof 1976).

A number of authors (e. g. Kent 1968; Le Bas 1972) have postulated the presence of a westerly to west-south-westerly trending ridge of Pre-Cambrian rocks which cuts across this Palaeozoic belt. The area of the ridge includes Melton Mowbray, where a recent National Coal Board borehole has proved the presence of granite which probably represents part of the Mountsorrel batholith (Evans and Maroof 1976), and the Thorpe-by-Water borehole near Uppingham from which Bath (*vide* Richardson and Oxburgh 1978) obtained an Ordovician Rb-Sr whole rock isochron. Speculation that this ridge was Pre-Cambrian was quite reasonably based in part on the presence of volcanics in the Glinton, North Creake and Orton boreholes which were compared with the Pre-Cambrian volcanics of the Charnian Supergroup. Evans (1964), however, considered that the Orton rock was not directly comparable with any Charnian volcanics. It is suggested by the present writer that these may be volcanic equivalents of the extensive Caledonian plutonic intrusions of this belt and that the existence of this E.-W. Pre-Cambrian ridge must be in some doubt.

Kent (1968) has noted the geosynclinal nature of the Lower Palaeozoics intersected by boreholes at Twyford and Calvert (Bucks.) and Huntingdon. These show high dips but no metamorphic features have been reported. He considered that the basement rocks further north encountered in deep boreholes might be Pre-Cambrian or Lower Palaeozoic. These include sheared (cleaved?) mudstone at Eakring (Notts.), vertical and steeply dipping quartzites at Nocton, Bardney and Stixwould (Lincs.), purple phyllites at Foston (Lincs.), phyllitic shales at Sproxton (Leices.) and schistose rocks at Dukes Wood (Notts.). In view of the above evidence the probabilities now favour the interpretation of these rocks as being

Lower Palaeozoic in age particularly in view of the fact that cleaved Arenig or Llanvirn pelites were found in the Eyam (Derbys.) borehole (Dunham, 1973). This implies the presence of mildly metamorphosed and considerably deformed and cleaved rocks of this age in this region.

Further west in Derbyshire the Woo Dale borehole near Buxton penetrated altered lavas and pyroclastics which lie north-west of the Lower Palaeozoic area between Nuneaton and Charnwood Forest (Cope, 1973). These rocks have been shown from their micro-fauna to be Ordovician (Downie pers. comm.).

Age of the cleavage

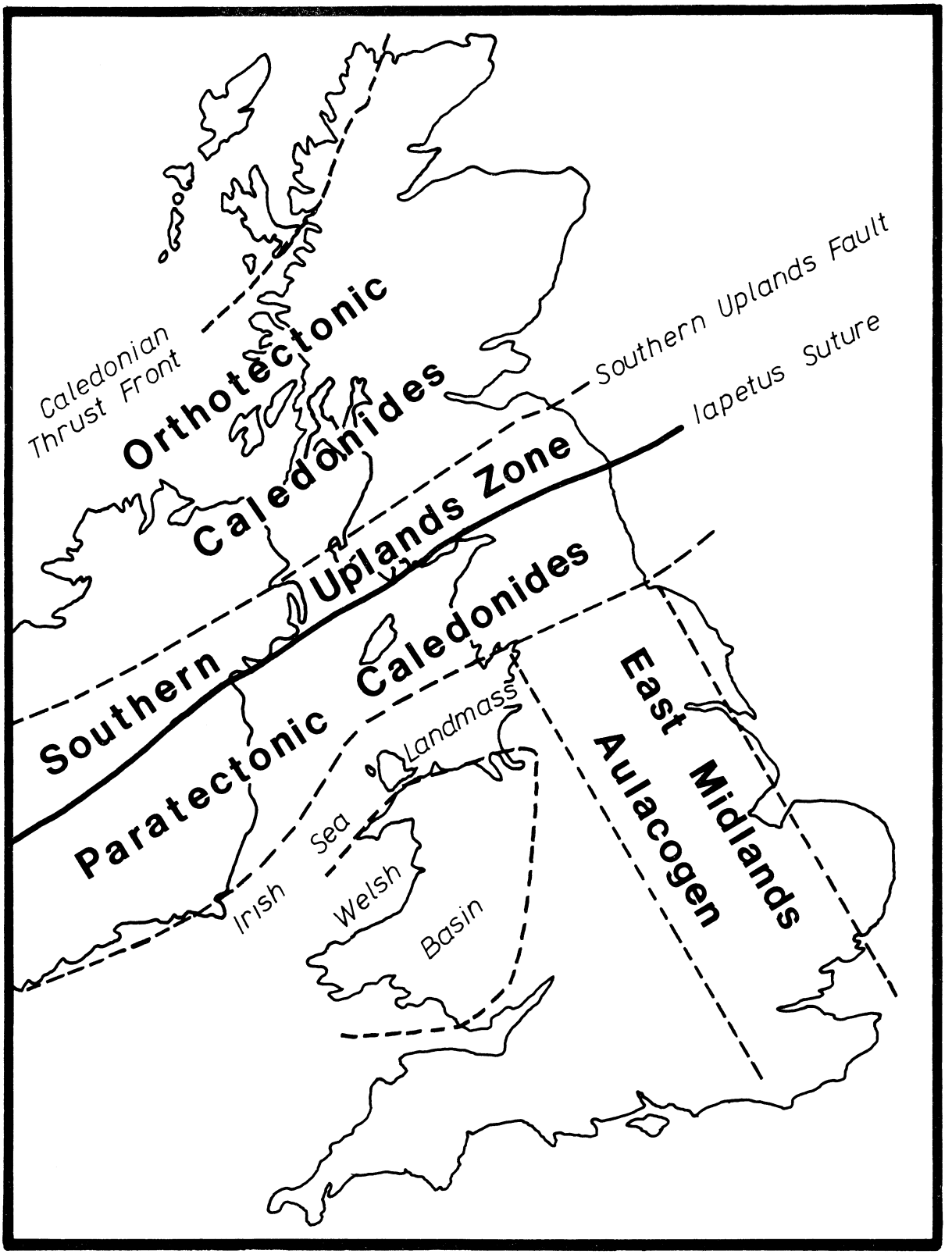
Cleavage has now been reported from Cambrian and Ordovian rocks over an extensive part of the Midlands. Its orientation has only been measured at Mountsorrel, where it is clearly parallel with that in the nearby Charnian rocks suggesting a Palaeozoic age for the latter cleavage. This possibility is supported by the parallelism of the Charnian cleavage with the second group of minor folds which are colinear with those in the Palaeozoic rocks.

An important point of evidence is the development of a rude cleavage in the Lubcloud dyke (SK478164). This rock, which intrudes the Charnian, is petrographically similar to the Mountsorrel granodiorite and most previous workers have considered that it is of the same age and derived from the same magma. Meneisy and Miller (1963) obtained a K-Ar age of 374±13 Ma on a sample of biotite from the dyke. This compares closely with the K-Ar age of 403±18 Ma Miller and Padmore (1961) obtained for the Mountsorrel granodiorite. This evidence can be interpreted as showing that the main Charnian cleavage was developed after the intrusion of the Lubcloud dyke and is therefore probably a Caledonian feature, a conclusion which was reached by Jones (1927) who noted its parallelism with shear zones in the Mountsorrel granodiorite.

In order to test the above hypothesis samples of Charnian Swithland Slate from the Brand (SK 538137) and the Groby Slate Quarries (SK 508082) (text-fig. 1) were kindly analysed by Dr. D.C. Rex at Leeds University. These gave K-Ar whole rock ages of 417±16 Ma and 398±16 Ma respectively, ($\lambda\beta = 4.962 \times 10^{-10}\ y^{-1}$, $\lambda_\epsilon = 0.581 \times 10^{-10}\ y^{-1}$, $^{40}K = 0.01167$ atom %). A sample of well cleaved Upper Cambrian from the Rotherwood borehole gave 477±19. The ages for the Charnian material taken on their own would merely indicate a minimum age for the formation of the cleavage, (Dodson and Rex, 1971). However, taken in conjunction with the structural and stratigraphical evidence they strongly support a Caledonian age for the impression of the cleavage. The older date for the Upper Cambrian sample may well be due to the fact that this sample is not as well recrystallized as the Charnian samples, it probably contains some non-recrystallized detrital 2M muscovite and it would not meet all the criteria listed by Dodson and Rex (1971). It is possible that this Cambrian rock sample was at a higher structural level than the Charnian samples when the cleavage was formed. The results obtained from the Swithland Slate are in close agreement with the date of 413±19 Ma which Meneisy and Miller (1963) obtained on tuffs from Beacon Hill a date which they considered might be that of the formation of the cleavage.

Regional Implications

There seems to be little doubt in view of the evidence cited above that an important Caledonian mobile belt exists beneath the East Midlands. Turner (1949) considered that this was a continuation of the exposed Anglo-Welsh Caledonian geosyncline which he termed the Central European Branch. Le Bas (1972) also strongly argued the case for a development of thick geosynclinal Lower Palaeozoic rocks in this belt and he emphasized the important development of a calcalkaline intrusive suite typical of orogenic belts. Evans and Maroof (1976) demonstrated that these intrusions are of batholithic dimensions and because of the common development of magnetite they can be outlined by following the magnetic anomalies they produce. The data put forward in this paper shows that these Lower Palaeozoic rocks and the Pre-Cambrian basement (in the form of the Charnian rocks) underwent an important and widespread Caledonian deformation.



Text-fig. 3. Position of the East Midlands aulacogen relative to the Caledonide orogenic belt based in part on the reconstruction in Phillips *et al.* (1976).

In considering the regional picture there appear to be a number of possibilities. First is that put forward by Turner and by Le Bas, second is an extension of the hypothesis of Dewey and Kidd (1974) that we are dealing with the development of an aulacogen and third that the Anglo-Welsh geosyncline is much wider than was previously thought and that the south-eastern front lies much further to the south-east than has previously been considered to be the case.

In examining these possibilities it is important to elucidate the principal lithological and tectonic trends. Unfortunately these are not unequivocal. In the Nuneaton area the lithological trends of the Cambrian are north-westerly (Allen, 1968) and the palaeocurrent direction in the Upper Cambrian was north-easterly (Rushton, 1974), perhaps indicating marginal flow into a NW trending trough. The dip is south westwards, but as there is little discordance between the Cambrian and the Coal Measures this is probably a Hercynian effect. Minor folds in the Pre-Cambrian tuffs after elimination of the Hercynian tilt have a south-easterly plunge like the major Charnian fold.

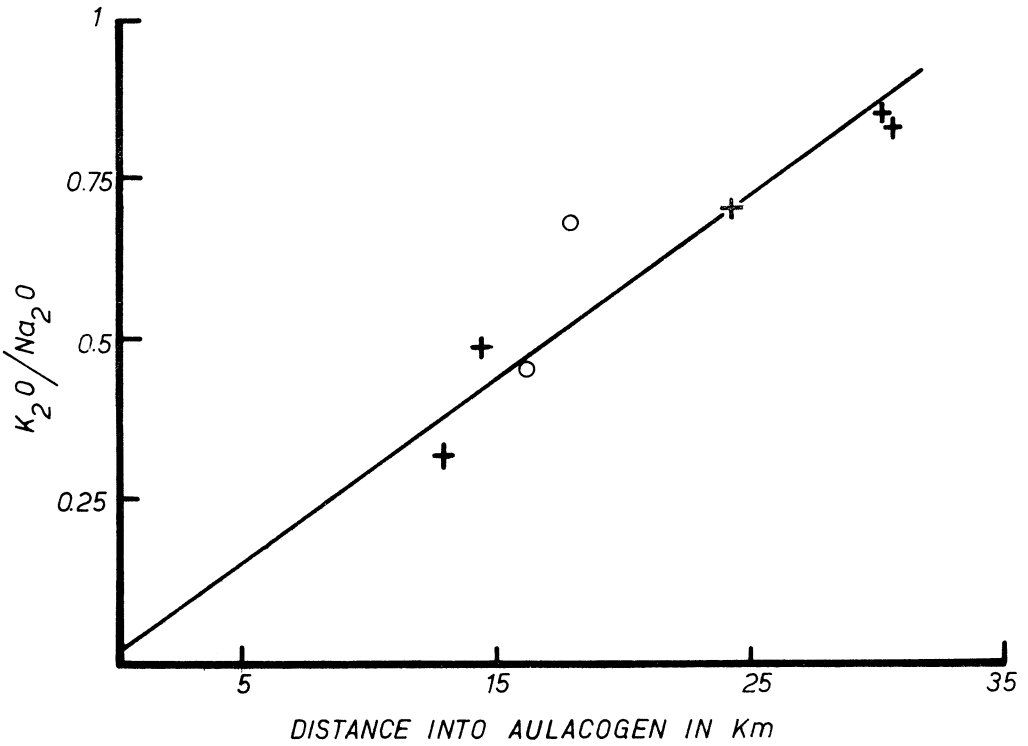
In the Charnwood Forest area and its environs the Charnian has an older north-westerly lithological and tectonic trend with a superposed westerly trend, the latter, as has been shown above, is a Caledonian effect. Le Bas (1972) considered that the surrounding Caledonian region had a west-north-westerly trend. The belt of positive magnetic anomalies which reflect the outline of the principal Caledonian intrusions (Evans and Maroof 1976) has a clearly defined north-westerly trend. Detailed examination of the individual anomalies, however, indicates a subsidiary 260° - 290° trend. Since large orogenic intrusions normally follow the principal tectonic trend it is considered that the bulk of the present evidence indicates that this is north-westerly and that the westerly trending second phase of folding and the cleavage of the Charnwood Forest area follow a less important late stage tectonic trend. This westerly trend is of course well known in central and north-east Wales (Bassett 1955; Shackleton 1954) and northern England (Moseley 1972). It seems therefore that the dominant trend is perpendicular to that of the Anglo-Welsh geosyncline and the third possibility can be ruled out, leaving a choice between deposition along a geosynclinal plate margin or in an aulacogen.

On the whole the second possibility seems more likely in the light of present plate tectonic theory. A well documented example is that of the Athapuscow aulacogen in the NW Canadian shield (Hoffman 1973). This contains sediments over 11 km thick in a trough which reaches 70 km in width where it joins the Coronation Gulf geosyncline and which narrows to less than 20 km some 200 km into the adjacent foreland. These dimensions are comparable with those with which we are dealing in the East Midlands. Volcanism is, however, dominantly basaltic but late stage tonalitic and granodioritic intrusions are present. Deformation is only by open folding and faulting and no regional metamorphism or penetrative deformation has been reported. On the other hand the Mount Isa geosyncline now regarded as an aulacogen contains strongly folded geosynclinal-type sediments with both basic and acid volcanics (Heidecker 1976; Windley 1977). The Southern Alberta aulacogen (Burke and Dewey 1973) contains dioritic intrusions some of which are granophyric like the Charnian and Nuneaton diorites. Aulacogens may be as wide as 160 km (Keweenawan trough, Windley 1977) and their calc-alkaline igneous rocks are presumably related to subduction zones as has been suggested for the Lower Benue trough where the sediments were deformed during the closure of the aulacogen (Burke and Dewey 1973). It is proposed that the mobile belt discussed in this paper be called the East Midlands aulacogen (text-fig. 3).

Polarity of the subduction zone

Igneous activity occurred throughout the known existence of the aulacogen from at least 684 ± 29 Ma to 433 ± 17 Ma (Meneisy and Miller 1963; Cribb 1975) and, if the Northern Diorites of the Charnian be included, as late as 311 ± 92 Ma. Exposures of hypabyssal and plutonic rocks across the aulacogen are not common. Of those which do crop out, most belong to the diorite-tonalite clan with a fairly restricted variation in silica content and this permits an *approximate* estimate of the trend of the K_2O/Na_2O ratio across the south-western part of the aulacogen modifying the method of Hatherton and Dickinson (1969). $^{87}Sr/^{86}Sr$ ratios for these rocks from Charnwood Forest and the surrounding area suggest a subduction zone

origin (Cribb 1975). Data for these rock-types falling close to a line running from Shilton (SP 405845) to Quorn (SK 562164) have been taken from Le Bas (1968 and 1972) and Thorpe (1974) and plotted on text-fig. 4. The data fall close to a straight line indicating what appears to be a significant increase in the K_2O/Na_2O ratio in a north-easterly direction. This suggests that the calc-alkaline intrusions were generated along a north-eastward dipping subduction zone. Partial closure of the aulacogen related to this subduction was probably responsible for the earlier north-westerly trending folds. The cause of the later westerly trending structures is less certain. They could have been formed by north-south stresses generated by dextral movement of the sides of the aulacogen.



Text-fig. 4. Plot of the K_2O/Na_2O ratio in diorites (crosses) and tonalites (circles) along a north-easterly line across the south-western portion of the East Midlands aulacogen.

Conclusions

1. Deformed Lower Palaeozoic rocks of geosynclinal aspect and thickness are widespread in the basement of the East Midlands.

2. A stable Pre-Cambrian Midland massif in Lower Palaeozoic times was much smaller than is envisaged in most stratigraphical reconstructions of the area.

3. The supposed presence of a westerly trending ridge of Pre-Cambrian rocks cutting across the Lower Palaeozoic rocks from the Wash to the Melton Mowbray - Market Harborough area is questioned.

4. A north-westerly trending aulacogen ran through the area between Nuneaton and the east coast during late Pre-Cambrian and Lower Palaeozoic times. The Pre-Cambrian Charnian rocks and a geosynclinal suite of Cambrian, Ordovician and Silurian rocks were laid down in the structure, here called the East Midlands Aulacogen (text-fig. 3).

5. Deposits in the aulacogen underwent at least two periods of deformation. The first was responsible for the north-westerly folding in the Charnian. The second gave rise to westerly trending folds and cleavage which affect the Pre-Cambrian, Cambrian and Ordovician. The second deformation probably occurred about the end of Lower Palaeozoic time.

6. Subduction took place beneath this aulacogen over a long period and the available data suggests a north-easterly dipping subduction zone. Melting along this subduction zone gave rise to a suite of calc-alkaline intrusions some of which are of batholithic dimensions. Deformation related to this subduction was responsible for the north-westerly folding in the Charnian. The compression which gave rise to the later structures could have been generated by dextral movement of the sides of the aulacogen.

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