THE SOUTH PENNINE OREFIELD:

ITS GENETIC THEORIES AND EASTWARD EXTENSION

by

P.R. Ineson and T.D. Ford

Summary

Genetic theories regarding the origin of the Pb-Zn-Ba-F mineralisation of the South Pennines generally invoke the leaching of at least some of the metals and anions by hypersaline brines from strata in adjacent sedimentary basins. The ores are emplaced in structural culminations (apparently controlled by basement tectonics) the basins adjacent to which expelled large quantities of deep formation waters. Depositional models are based on direct evidence from mineral occurrences in the exposed orefield and exploration boreholes in the concealed extension eastwards.

Genetical implications result from geophysical surveys of the surrounding basins, analyses of groundwaters, heat flow, isotopic studies, geochronology, trace element geochemistry, mineral zonation and fluid inclusion research, all seen in the context of the stratigraphical and structural setting of the South Pennines and surrounding areas.

Collation of all the available information leads to the conclusions that mineral fluids migrated from the east though the exact source(s) remain uncertain, and that deposits probably occur at depth beneath the Upper Carboniferous and younger strata of the East Midlands.

Introduction

Comprehensive research on mineral zonation, structural and stratigraphical studies, fluid inclusion geothermometry, hydrogeochemistry, geophysical surveys, wallrock alteration, trace element geochemistry, isotopic analyses and geochronology has provided the evidence upon which the genetic models for the occurrence and migration of the ores and minerals located in the South Pennine (or Derbyshire) orefield, have been based.

The work has indicated that the South Pennine Orefield is the most complex of the three Pennine orefields. Unlike the Alston and Askrigg Orefields, the mineral zonation in the South Pennines is not concentric but aligned in a north-south direction on the eastern margin of the

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pp. 285-303, 1 text-fig., 1 table.

Carboniferous Limestone massif. The fluid inclusion data has not yet delineated any significant 'hot spots'. Geophysical evidence has not defined more precise 'basement models'. Isotopic studies have indicated a high degree of intermixing of the ore fluids. The overall concensus of opinion, albeit based on incomplete evidence, was that the most probable source for the ore minerals or fluids was from the east with expulsion of formation waters from deep sedimentary basins.

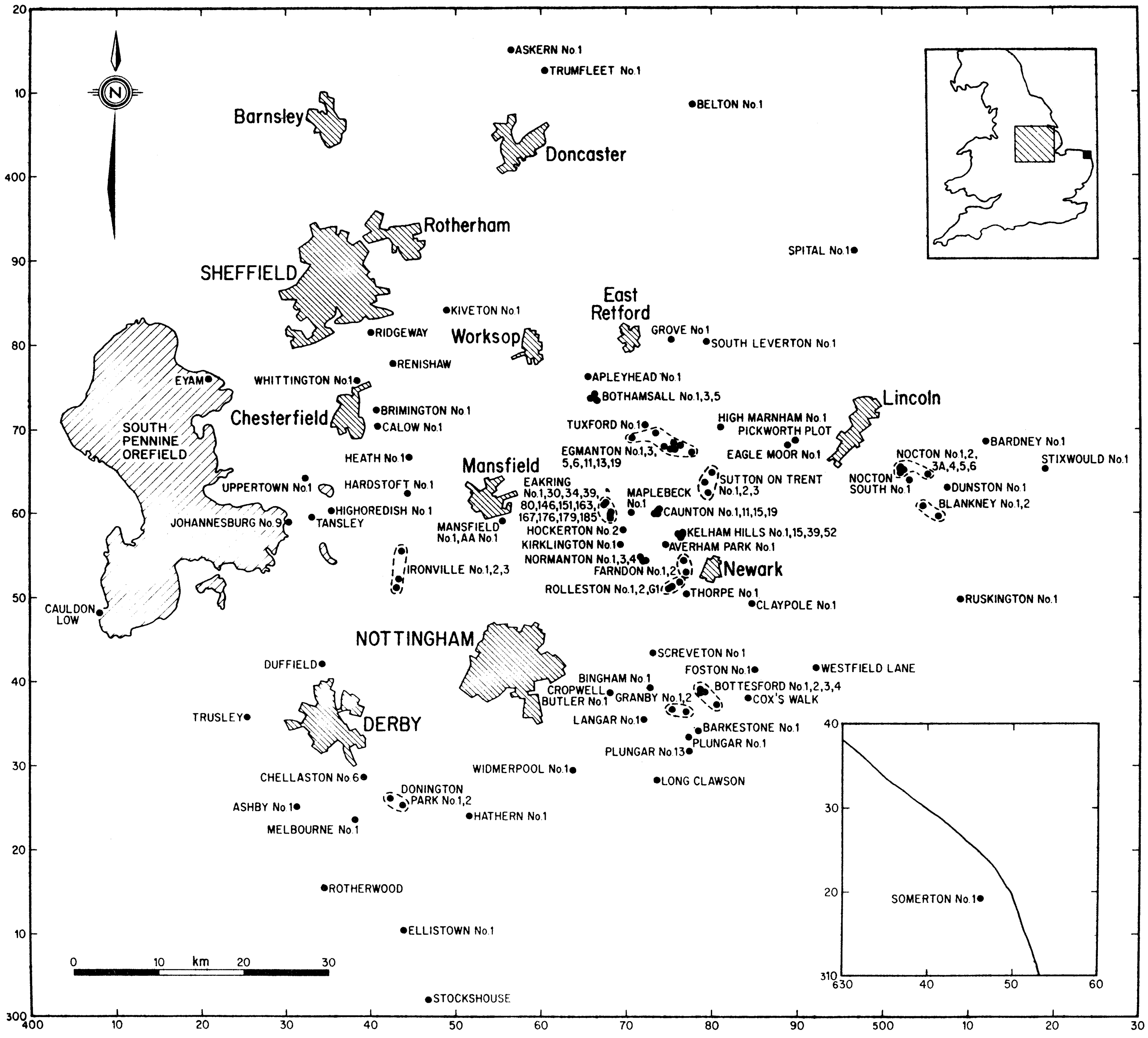
A study of areas peripheral to the South Pennine Orefield, has provided new evidence in support of this genetic hypothesis, which has not been available elsewhere in the Pennines. This is due to geological exploration for fossil fuels in the East Midlands, the initial results of which have been presented by Lees & Kent (1960) and Kent (1966, 1967, 1968). More than a hundred deep boreholes (see table 1, p. 296-297, and text-fig. 1) combined with geophysical surveys have indicated Carboniferous and pre-Carboniferous structures, and several boreholes have penetrated into the Precambrian or Lower Palaeozoic basement. In the search for oil, discoveries have been made of base metal mineralization in Dinantian limestones. The authors herein show that not only were the small oilfields located over basement highs, but demonstrate that the base metal mineralisation may likewise be located on the flanks and above such structures.

The Genetic Models

In describing the distribution of fluorite, Wedd & Drabble (1908) advocated the lateral up-dip movement from the east of the mineralising fluids within the strata between the impermeable layers of lavas, tuffs, etc. Schnellmann & Willson (1947) suggested that the main feeders were concentrated along the eastern margin of the exposed limestone, whilst Dunham (1952), drawing an analogy with the Northern Pennines, stated that the fluorite zone lay nearest to the source of the fluids, which he then envisaged to be of granitic nature. Following Dunham's lead, Ford (1961) similarly suggested a granitic source for the South Pennine mineral solutions "near or under the eastern margins of Derbyshire".

At that time, what appeared to be a most controversial hypothesis was proposed by Davidson (1966) who suggested that the ores were deposited by interstratal brines, derived diagenetically from evaporites, leaching and concentrating the metals from the sediments through which they migrated. Precipitation occurred when the fluids mixed with later diagenetic brines enriched with sulphate and bacteriogenic sulphide. This hypothesis was countered by Dunham (1966) who suggested that the evaporitic source - the Upper Permian Zechstein dolomites and evaporites - had been insulated from the mineralised sediments by impervious Upper Carboniferous shales. If the preliminary fluid inclusion data were to be believed it implied burial of the source sediments to a depth of some 15 km. As Dunham noted, arguments for or against the direct genetic connection with evaporitic sequences were equivocal, but he did accept that the evaporites could provide additional chlorine and/or potassium in the brines, as noted by fluid inclusion studies. Substantiating evidence was subsequently provided by Downing (1967) who reported that the Na and Ca chlorides predominate in the down-dip groundwaters of the Carboniferous Limestone in east Derbyshire and adjoining counties. He also noted that a belt of sulphate-rich groundwaters appeared to coincide with a depression in the sub-Carboniferous floor. This latter statement, although at the time being of relatively minor significance, was to provide evidence for theories then in the initial stages of formulation.

Although the Pennine Orefields have been cited (Ford, 1976) as an example of 'Mississippi Valley type' mineralisation, and models for these types of deposits (Beales & Jackson, 1966; White, 1968; Dozy, 1970; Beales & Onasick, 1970) may be used in more generalised genetic models even this approach has been questioned by Worley & Ford (1977) and Emblin (1978). These last two compilations must therefore be viewed in the light of Dunham's (1966) suggestion that the derivation of some of the ore minerals may have been by the lateral secretion of elements from micas in the basement. At approximately the same time King (1966) concluded that while the rakes in Derbyshire were of a plutonic-hydrothermal origin, some pipe deposits were neo-Neptunist, and other ore-bodies may have had a varied origin.



Text-fig. 1: Geographical location of boreholes in the East Midlands which have penetrated the Carboniferous (Dinantian) Limestone or basement formations.

In reviewing the mining potential of the South Pennines, Ford & Ineson (1971) concluded that future exploration and development should investigate faults and anticlinal structures in the Carboniferous Limestone beneath the Upper Carboniferous cover east of the orefield. This suggestion was based on Dean's (1961) description of stratiform deposits in the Permian Magnesian Limestone of Nottinghamshire, and King's (1966) diagnosis of episyngenetic deposits, as well as the report of a near-surface barite-galena vein in the Upper Magnesian Limestone (Ineson *et al.*, 1972). In this paper it was suggested that the genesis of the Permo-Triassic deposits and those in the Carboniferous Limestone were closely related in that they may be fault-controlled with the intermixing of juvenile and connate waters from the deep sedimentary basins beneath the general area of the East Midlands. As the mineral assemblage in the Permo-Trias is similar to that of the outer (calcite) zone in the South Pennine Orefield, these occurrences may be classed as leakage deposits overlying a steeply dipping eastern extension of the orefield.

In order to investigate the stratigraphical succession and prove the true nature of the basement beneath the South Pennine Orefield, the Institute of Geological Sciences sank a deep borehole near Eyam (see table 1). The preliminary results were reported by Dunham (1973) who described equivalents of the exposed Viséan succession resting on a previously unrecognised and unexpectedly thick Tournaisian limestone sequence with basal anhydrites; he suggested that the mineralisation might be concentrated on the flanks of basement highs in proximity to basins from which large quantities of deep formation waters were expelled.

In 1976, Ford reviewed the ore genesis of the South Pennine Orefield and argued that the ore fluids were derived from strata beneath the North Sea basin and the fluids slowly diffused through the Carboniferous Limestone towards the basin margin in the Pennines. The sulphurous hydrocarbons (Mueller, 1954b; Pering, 1973), disseminated pyrite and the basinal limestones together with the bacterial reduction of the Tournaisian anhydrite sequences (see Dunham, 1973) were all invoked as possible sources for sulphur. Since the anhydrites are still in place, they could only have been a minor source of sulphate fluids, though it was thought possible that the limestone formation waters could have been sulphate-rich if evaporite interludes in sedimentation had only approached, but not reached, the concentrations necessary for sulphate precipitation. The isolated mineral occurrences peripheral to the South Pennines were considered (Ford & King, 1968) to represent partially depleted mineralizing solutions leaking to the surface as hot springs or into the Triassic groundwater circulatory system.

Evans & Maroof (1976), using an analogy with Bott's interpretation of basement structures, suggested that the East Midlands basement intrusions may have directed mineralising solutions into the anticlinal areas. They also stated that the mantle must be considered seriously as a possible source rock.

As fluid intrusion studies had provided useful evidence in the Alston Block, so it was argued should similar studies on the Derbyshire material (i.e. fluorite). Results reported by Smith (1973), Ford (1976) and Rogers (1977) provided only an outline picture and additional work on *in situ* material is being undertaken at present.

In an attempt to clarify the origin, intermixing and depositional history of the ore fluids, the analysis of sulphur, oxygen and carbon isotopes was undertaken by Robinson & Ineson (1979) in the South Pennines who reported that analyses of barite, calcite, galena and sphalerite showed unique trends and reflected a high degree of mixing of fluids and components from many different sources. Barite results, for example, were explained by the partial mixing of fresh-water sulphate and connate sea-water sulphate. The reduced sulphur may have had a dual source, one part being derived from biogenic sulphur in the limestone kerogens (light sulphur) and the other source (heavy sulphur) resulting from the reduction of connate sea-water sulphate. The deposits fitted a pattern of brines, of either sabkha or connate origin that were interpreted as being derived from the east. As they moved into the limestones and encountered initially reducing fluids, they gave rise to the precipitation of sulphides.

In a Yorkshire Geological Society symposium on the sub-Carboniferous basement in Northern England, Bott (1967) described the configuration of the underlying Devonian granites beneath the Alston and Askrigg Blocks as well as concluding that the primary mineralising fluids had risen through the granites. Kent (1967) implied that the NE Midlands were underlain by a NW-SE basement block and hinted that this may have genetic conotations, whilst Dunham (1967) stated that the solutions could not have a total primary connate origin and concluded that there was, at the time, no alternative but to propose rising hydrothermal waters with deep-seated magmatism beneath the Pennines emitting potassic brines with metals, or that the magmatism had stimulated the circulation of such solvents.

In reviewing the possible modes of mineralisation by deep formation waters, Dunham (1970) commented that large scale sedimentary basins "may prove to be the sources of some classes of epigenetic ore deposits". He also summarised the various research aspects needed to substantiate additional conclusions, and fortuitously Dunham's contribution was followed by Bush (1970) who suggested that chloride-rich brines derived from sabkha sediments might play an important role in ore formation. Although Bush quoted evidence and examples from the Trucial Coast of the Persian Gulf, he could well have chosen the Hathern Anhydrites, as Llewellyn and Stabbins (1968, 1970) did, to illustrate his theory. The latter authors suggested a link between the epigenetic mineralisation of the East Midlands and saline waters derived from anhydrite sequences.

The application of K-Ar isotopic geochronology as well as paragenetic studies on the ores, enabled Ineson & Mitchell (1972) and Ineson & Al-Kufaishi (1970) to conclude that the mineralisation was episodic and spanned a time interval from the Upper Carboniferous to the Jurassic, they were also able to recognise multi-phase injections of the same mineral suite. Dunham in 1970 stated that "it is apparent that multiple hypotheses leading to similar end products are no more avoidable here than elsewhere in geology: the intervention of igneous activity may or may not be a prerequisite; the water may originate in the ocean or as meteoric waters .... the deep sedimentary basins and their margins should receive more attention from the ore geologists".

Although the initial work on model lead isotopic ages (Moorbath, 1962) had reviewed the age of United Kingdom galenas, Mitchell & Krouse (1971), working in the Askrigg Block, reported anomalous J-type lead. The results were in keeping with models that either indicated mineral fluids of a deep-seated origin, released through fracturing during the Armorican orogeny, or that mineralisation may have been related to rheomorphism of the lower crust and leaching during those movements. A similar study on the South Pennines by Coomer & Ford (1975) also reported J-type leads emplaced in Carboniferous and Triassic strata.

One of the main differences between the South and North Pennine Orefields is that the former appears not be be underlain by granites, although Le Bas (1972) proposed that granites of a similar density to basement sediments may occur further east beneath the East Midlands. The available evidence (e.g. White, 1948, and the Institute of Geological Sciences, aeromagnetic map, 1965) enabled Evans & Maroof (1976) to suggest that competent basement rocks fractured and produced channelways for uprising solutions which, on reaching the overlying limestones, precipitated the metals and gave rise to mineralisation.

This could, in part, explain the absence of a concentric thermal zonal arrangement of the minerals. The orefield does display a mineral zonation though Stevenson & Gaunt (1971) commented that the zones of Wedd & Drabble (1908), Dunham (1952) and Mueller (1951 and 1954a) are only of general validity, as many anomalies and reversals in the zonation pattern are apparent. A survey of the distribution of non-metallic gangue minerals by Firman & Bagshaw (1974) demonstrated that, whilst stratigraphical, lithological and structural controls on deposition were important, episodic emplacement was fundamental in explaining mineral zonation. They agreed that the main supply of mineralising fluids was up the crests of plunging folds or along faults but suggested that locally the fluids migrated down-dip through more porous and cavernous strata, particularly if the faults threw impervious rocks against pervious, so creating hydrological barriers.

One of the more recent reviews of the literature has been by Emblin (1978) who proposed a compound sedimentary-diagenetic model for the Pennine Orefields in which fluid mobilisation and eventual orebody emplacement was ascribed to tectonic activity.

The majority of the authors who have theorised on the origin of the South Pennine Orefield have advocated, albeit with minor or major variations, transport from the east towards the west. The field evidence as well as the applied studies (e.g. isotopic and fluid inclusion data) would give credance to this general pattern of movement. Nevertheless, there is a strong possibility that the ores on the western flank, especially the copper ores at Ecton and Mixon in Staffordshire, may have originated from fluids migrating from west to east, i.e. out of the Cheshire basin, some of which leaked up faults to give the copper deposits in the Triassic sandstones of Alderley Edge (Carlon, 1979). Indeed Mueller (1954), Schnellmann (1955), Firman & Bagshaw (1974) suggested this while Robinson & Ineson (1979) provided isotopic evidence that a proportion of the mineralisation could only have been derived from the west. However, in the light of all the evidence it must be concluded that at present a major proportion of the mineralising fluids, emanated from a source, or sources, in the east.

Smith's (1974) work on the trace elements in Pennine fluorites showed the paucity of yttrium together with the comparative lack of fluorescence and indicated a major difference between the deposits in the south and the north. Furthermore, Russell (1976, 1978) related the ore deposits to plate tectonic models and alkali magmatism; however, at present there is no evidence to support or refute this hypothesis.

South Pennine Orefield - concealed extensions

Direct evidence

The most commonly quoted example of mineralisation beneath the East Midlands is the calcite-fluorite-barite veins intersected by the Eakring (Duke's Wood) No. 146 Borehole, (see table 1, text-fig. 1). This borehole and others sunk for oil exploration (Lees & Taitt, 1946) encountered mineralized ground characterized by the presence of silicification, brecciation and dolomitization of the Dinantian limestones. Other boreholes described by Gifford (1923), Boulton (1934), Lees & Tait (1946), Mitchell & Stubblefield (1948), Eden *et al.*, (1957), Falcon & Kent (1960), Ramsbottom *et al.* (1962), Kent (1966/67), Smith *et al.* (1967), Edwards (1967), Smith *et al.* (1973), Dunham (1973), Institute of Geological Sciences (1978), Frost & Smart (1979), B.P. & Conoco (pers. comm.) have continued to provide corroboratory evidence that: (a) veins, stratified or stratabound, and disseminated base metal mineralisation with the attendant gangue minerals and metasomatic alteration products, occur widely under the East Midlands; (b) saline waters are circulating in the strata; (c) gypsum or anhydrite-rich beds, etc. are locally present in Carboniferous strata; (d) flanking the South Pennines, deep Carboniferous sedimentary basins occur and (e) associated structural highs related to the basement appear to be the most favourable sites for the location of the base metals. Indeed, in the discussion of Schnellmann's paper (1955), it was even recorded that a 1 in 4, 914 m long cross-measure drift from Bilsthorpe Colliery, in the adjacent downwarp, could well have explored or even exploited the ground intersected by Eakring's No. 146 Borehole, beneath the oil-bearing Upper Carboniferous.

Using the data presented in text-fig. 1 and table 1 it is clearly possible to argue a case for the South Pennine Orefield being only the exposed part of a much larger mineral field, the majority of which is concealed beneath the East Midlands. The evidence is entirely from boreholes which have been sited on or close to structural highs determined by geophysical surveys, published summaries of which have been included in Lees & Taitt (1946), and Kent (1966 and 1967). These structures are the result of several phases of folding so that it should be possible to extract a regional slope of the top of the Carboniferous Limestone by a computer analysis of the heights of that formation in the boreholes (text-fig. 2). However, if one does the comparable exercise of regenerating a contour plot of the present topography from the collar heights of the boreholes it bears little resemblance to the observed topography, so that considerable caution should be used in interpreting the Carboniferous Limestone surface. After all, few boreholes are sunk in structural lows. Geophysical evidence for the form of the sub-Carboniferous basement is less accurate than could be desired, though it must be expected that the features of the basement will follow the pattern proved elsewhere in the world where both limestone sedimentation and structural configuration reflect basement culminations and depressions (e.g. Heyl, 1967; Ohle, 1967).

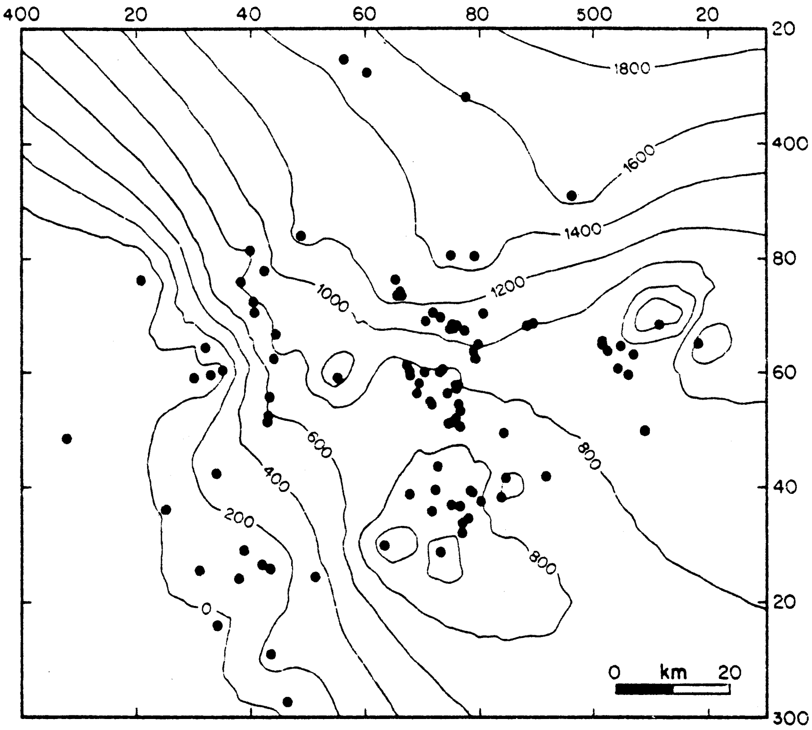
Indirect evidence

Considering the number of boreholes centred on or in the flanks of domal structures in the East Midlands (see table 1) it may be fortuitous that they have intersected mineralisation. A borehole located only a few metres either side of a deposit can visually fail to indicate that occurrence, though analyses indicate metasomatic alteration. Silicification and dolomitisation have been considered to indicate 'low temperature metasomatism by hydrothermal fluids' (see Frost & Smart, 1979, p. 12) but these conclusions cannot always be attributed to the proximity of mineralisation, and should not be taken as such when observed in borehole logs (see table 1). Furthermore thermal waters do not prove the presence of magmatic or other deep-seated fluids, for Edmunds' results (1971) showed that the geochemical analyses of such waters in Derbyshire are indicative of deeply circulating local meteoric waters.

The results of Downing (1967) and Downing & Howitt (1969) are more informative with respect to the potential 'carrying capacity' and when combined with the publications of Llewellyn & Stabbin (1968) on the presence of potential source rocks for the alkali chlorides, and Lees & Taitt (1946) and Kent's (1966, 1967) structural information, they support Dunham's (1973) proposal for derivation from the flanks of basement highs and deposition in domal areas (Shirley & Horsfield, 1945; Shirley, 1959, p. 420).

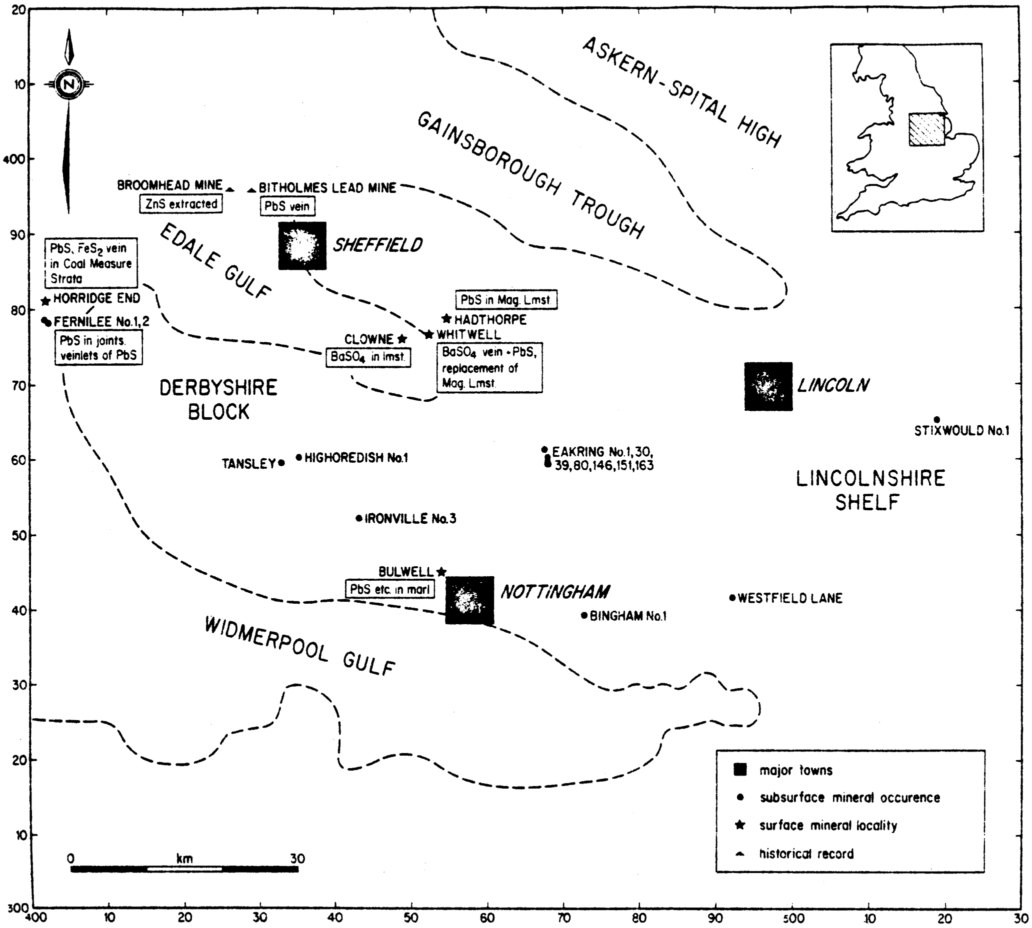
Ford (1976) proposed that a possible derivation of the metals was from the North Sea basin. This hypothesis, as Robinson & Ineson (1979) indicated, required a transport flow over a distance of at least 160 km. They noted the presence of the Gainsborough, Edale and Widmerpool Gulfs separating a Lincolnshire shelf area and the Askern-Spital high (Kent, 1966, 1967) and suggested that the gulfs may have acted as barriers to the westerly migration of the magnitude by Ford, and hence the basinal sediments in the gulfs could then have been the sources of the metals (see text-fig. 3). However, recent information supplied by Conoco does tentatively support Ford, in that the Somerton Borehole on the Norfolk coast (see table 1) encountered mineralised ground in the Carboniferous Limestone at a depth of over 1000 m.

Kent (1966 and pers. comm.) noted a westward pre-Permian stratigraphical gradient (i.e. rate of increase of thickness as measured in the Coal Measures, probably also present in the Carboniferous Limestone) into the Pennine sedimentary basin. Thus, during Carboniferous times migration of fluids would have been eastwards towards the basin margin, though doubtless meeting greater quantities of fluids migrating westwards out of the North Sea basin somewhere under the East Midlands or near the coast. By the end of the Carboniferous the structural uplift of the Pennines reversed the gradient and from Permian times onwards long distance fluid migration from east to west could much more easily have been established. The effects of the Gainsborough, Edale and Widmerpool Gulfs and any eastwards extensions would be to provide local sources of fluids during the Carboniferous, while the intervening highs provided traps then and later. Kent believes that the relative richness of hydrocarbons at Eakring and Gainsborough in part relates to eastwards migration out of the Pennine basin, perhaps guided by the arrangement of gulfs and platforms. The reversal of gradient at the end of the Carboniferous caused by the Armorican movements offers a possible explanation for the dual source for mineralising fluids proposed on isotopic arguments by Robinson & Ineson (1980), and for the major episodes of emplacement deduced from K-Ar dates by Ineson & Mitchell (1972). Broadly a late Carboniferous episode could have been derived largely from the Pennine basin, with some mixing of North Sea fluids, while later episodes were dominated by North Sea fluids mixed with residual Pennine fluids. If paragenetic studies could show which parts of the exposed mineral field were of late Carboniferous age and which were later, a much stronger case could be put forward for this hypothesis, but too little paragenetic research has been carried out so far.



Text-fig. 2: Computer generated contour plot of the top of the Carboniferous Limestone (depths below O. D. in metres).

● Boreholes used in computer program.



Text-fig. 3: East Midlands Carboniferous blocks and gulfs, after Howitt & Brunstrom (1966) with the addition of mineral localities both at surface and in boreholes.

Fluid inclusion studies might demonstrate a thermal gradient if they could be related to the episodes of mineralisation. However, the results from Eakring (Rogers, 1977) indicate a homogenisation temperature range of 86-98° C. (mean 92.4° C.) and when compared with the results for the South Pennine Orefield (range 92-154° C, + 11° C. as a pressure correction) neither area is shown to have an anomalously high formational temperature and no gradient can be demonstrated in either direction.

An easterly heat-flow gradient was noted in the Eakring area as early as 1951 (Bullard & Niblett, 1951) though this area lies in the middle of the high heat-flow belt demonstrated more recently by Brown *et al.* (1980). They showed that there was a broad northwest to southeast high heat-flow belt across the Pennines, with the South Pennine Orefield on its western margin. Brown *et al.* argued that this belt is possibly due to heat-generating radioactive minerals in concealed Caledonian granites and that such a heat-flow gradient falling from east to west has existed since emplacement of the granites. Such a gradient supports the concept of westwards movement of ore-fluids into the exposed orefield but Brown *et al.* suggest the granites may lie beneath highs in eastern and northeastern England, possibly enhancing the dual source effect of the basins in the Carboniferous and the barrier effect later.

Iron sulphides and organic compounds (kerogens and other hydrocarbons) are usually concentrated in black shales deposited under euxininc conditions and, as Dunham (1961) indicated "... while a concentration of trace amounts of other metals may have been achieved in ancient black muds, high concentration of such metals as copper, zinc and lead was only produced where very special local circumstances prevailed. The special circumstance favoured in this paper is the operation of submarine springs, releasing juvenile or hydrothermal fluids into a stagnant environment ...". A subsequent publication by Hirst & Dunham (1963) on the Permian Marl Slate in southeast Durham, proposed that the origin of Zr, Sr, Rb, Mo, Co, Ni and Mn ± Cu in the Marl Slate may have been the result of normal weathering. The source for the enhanced Pb, Zn and Ba ± Cu may be due to (a) the weathering of exposed mineral veins from the Alston area, (b) post-consolidation via hydrothermal solutions, or (c) by introduction via submarine springs into the lagoon. They favoured the last hypothesis.

Recent work by Spears & Amin (1981) on the marine and non-marine Namurian black shales from the Tansley Borehole (see table 1) has provided direct evidence that at least during or subsequent to the diagenesis of the Namurian, the marine black shales have accumulated enhanced quantities of Pb, Cu, V and Ni with respect to the non-marine shales. Interpreting these results in the light of Hirst & Dunham's findings it may be argued that enhancement of V, Ni + Cu may be the result of surface weathering, but not Pb. Spears & Amin report an average content in the non-marine shales of 37 ± 16 ppm Pb, whilst the marine shales have 155 ± 44 ppm Pb indicating a 319% increase between these horizons. When these figures are compared with average (median of the medians of 20 sets) world black shales (Vine & Tourtelot, 1970; Holland, 1979) which contain 20 ppm, the marine shales in the Tansley Borehole are significantly anomalous (90th percentile for the 20 sets = 70 ppm).

Spears & Amin (1981) relate these enrichments to reactions involving organic matter and oxyhydroxide material in environments in which salinity and slow rate of sedimentation were important factors. However, they state that the results cannot be related directly to seawater concentrations as often has been the case for black shales. The origin of these extremely low concentrations is unknown but may be related to diagenetic processes.

The sporadic mineral deposits in the Permo-Triassic of eastern England may be related to mineralisation. Possibly one of the most well known deposits in the galena-wulfenite-uraniferous-asphaltite horizon in the Magnesian Limestone of Nottinghamshire (Deans, 1961), although other deposits, either vein, stratabound/stratified, replacement or discrete masses have been recorded by King (1966), Ford & King (1968), Ineson *et al.* (1972), Taylor & Holdsworth (1973), Hirst & Smith (1974) and Carlon (1979). These deposits may be classed as 'leakage deposits' whose migratory channelways were faults connecting with the underlying Carboniferous strata, and the subsequent deposition in the next overlying suitable host rock - the Magnesian Limestone or higher porous sandstones. However, Deans stated that they may have resulted from re-deposition of syngenetic ores precipitated in certain phases of Zechstein sedimentation and remobilised during the complex dolomitisation process. Hirst & Smith (1974) showed that barite mineralisation to the east of the Alston Block corresponds closely to structurally positive features and the precipitation of the barite is attributable to the mixing of $BaCl_2$-bearing brines, derived from the Coal Measures, with SO_4^{2-}-bearing brines from the Permian. By contrast they were unable to deduce an origin for the attendant fluorite except to state that it appeared to be unrelated to the economically exploitable deposits in the Alston Block.

The data presented in the text-fig. 1 and table 1 include all the non-confidential records of boreholes which have reached the Carboniferous Limestone, but few of these have recorded mineralisation, perhaps because at the time of drilling it was of little interest to the oil companies. In the future, however, it would help to substantiate the hypothesis presented herein of a concealed ore-field if all boreholes could have any attendant mineralisation recorded. Furthermore, the cores could be studied for trace-element chemistry of the ore minerals and their associates. Whilst the Namurian and Westphalian are known to contain non-economic quantities of the ore minerals, and some trace element studies have been conducted, no systematic survey of these formations has been conducted from a ore-genesis concept point of view. Senior Geologists of the National Coal Board have commented "it is mainly the lithological units we are primarily interested in and, consequently we do not give an 'in depth' description of any mineralisation that occurs". However, there are records of mineralised faults as well as discrete sporadic occurrences but no true metalliferous deposits. For example, in the Roall borehole, southwest of Selby it was noted "joint with small displacement and calcite mineralisation, dip 45°". Mr. R.W. Vernon related "we find sporadic traces of barytes, and calcite with pyrite in Permian Limestone and Coal Measures adjacent to and in fault zones. Very rarely do we see traces of galena". Likewise, Mr. D.E. Raisbeck stated "We have a record, and a sample exists at the colliery, of a small trace of galena on a fault plane in the Elmton Trough fault at Cresswell Colliery, Nottinghamshire. The depth would be approximately 540 m, below O.D. in the Three-quarter Seam. There is a record of barytes and galena at a depth of 213 m (some 9 m above the Wales coal) in Buskeyfield Lane, National Coal Board borehole (E.456, 171 m, N.371, 988 m)".

A visit to almost any colliery in the Pennines will produce reports of 'brass' (= pyrite) and lead (presumably galena) etc. having been found in the workings. Some of this is probably diagenetic but without a systematic survey both in the field and geochemically, the significance of the Upper Carboniferous both as a depositional site and as a potential source of ore-fluids must remain unknown.

Conclusions

The genesis of the South Pennine Orefield is related to the up-dip migration in a westerly direction of thermally elevated metal-leaching hypersaline brines at least since the end of the Carboniferous. Emplacement in the ground beneath Lincolnshire, Nottinghamshire, East Derbyshire and possibly north Leicestershire and North Norfolk has been on the fold culminations and on their flanks, within the most favourable host rock - the Carboniferous Limestone. These anticlinal structures may tentatively be related to similar but as yet unproved culminations in the pre-Carboniferous basement.

The mineral fluids in which meteoric and connate waters pre-dominate over juvenile waters have been expelled during Upper Carboniferous to Lower Jurassic times and in fact may still be being released from deep sedimentary basins to the east beneath the North Sea. Minor and more localised components may have been provided by the sedimentary downwarps of the Carboniferous Pennine basin, and the gulfs indenting the Lincolnshire shelf.

Of an unknown initial composition, the fluids later became hypersaline in composition. The depth of initial mobilisation depended on the contemporary geothermal gradient, possibly affected by magmatic influences, but it was more than adequate to elevate these fluids to the depositional temperatures now recorded in the orefield, even allowing for some heat-loss during migration.

TABLE 1

Borehole Information on the Dinantian Limestones to East of the South Pennine Orefield

Borehole Name and Number		Source of Information	Locality (National Grid Reference) * Computer Generated	Collar or KB Height (m)	Dinantian Limestone Depth to: Top (m)	Dinantian Limestone Depth to: Base (m)	Total Depth of Borehole (m)	Dinantian Zone	Mineralisation and Other Details	Overlain by:	Underlain by:
Apleyhead	No.1	J	SK 65510.76310	43.89	1399.03		1467.00	D,P?	Calcite Veins	Namurian (E_1)	?
Ashby	G1	D,O,P	SK 31340.25240	59.40	·284.07		285.90	C_2S_1,D_1-P_{1a}		Namurian	?
Askern	No.1	F	*SE 56526.15027	7.62	1452.98		1467.00			Namurian	?
Averham Park	G1	C,F	SK 74505,56305	48.77	800.10		805.89		Strong Brecciation	Namurian	?
Bardney	No.1	G,O,P	TF 11915.68617	5.79	5.72	1851.05	1897.99		Dolomitisation	Namurian	Cambrian ?
Barkestone	No.1	C	*SK 78348.34261	60.05	944.27		1005.84			Namurian	?
Belton	No.1	F,O,P	SE 77730.08450	4.72	1610.87		1663.90			Namurian	?
Bingham	No.1	O,P	SK 72520.39350	26.59	873.86		1814.7		Galena,calcite veins.	Namurian	?
Blankney	No.1	C	*TF 06398.59698	28.35	907.99		940.31		Oil in Limestone	Namurian	?
Blankney	No.2	C	*TF 04565.60854	38.40	932.69		936.96			Namurian	?
Bothamsall	No.1	I,P	SK 65860.73675	35.74	1367.64		1427.68	D_2,P_2?	Pyrite,bituminous	Namurian	?
Bothamsall	No.3	J	SK 66320.74210	34.44	1342.64		1432.56	D_2,P_2	Pyrite in limestone	Namurian	?
Bothamsall	No.5	I,P	SK 66595.73440	37.72	1365.20		1388.97		Pyrite in limestone	Namurian	?
Bottesford	No.1	C	*SK 79095.38853	30.78	975.36		988.47			Namurian	?
Bottesford	No.2	C	*SK 80437.37401	40.54	963.17		973.23			Namurian	?
Bottesford	No.3	C	*SK 78610.39194	28.04	990.90		994.26			Namurian	?
Bottesford	No.4	F,P	*SK 78581.38804	31.69	983.28		995.48			Namurian	?
Brimington		H	SK 40720.72310	135.94	915.92		1231.39		Anhydrite and Toadstones	Namurian	?
Cauldon Low		L,P	SK 08040.48220	335.00	000.00		535.37	C_1,C_2?	Dolomitisation	Namurian	?
Calow	No.1	H	SK 40860.70410	128.01	830.27		1132.94	$D,D_2?,P_2$	Cherts, toadstones, tuffs, etc.	Namurian (E_1)	?
Caunton	No.1	I,P	SK 73790.60570	39.32	787.91		818.69	Viséan?	Brecciated limestones	Namurian	?
Caunton	No.11	I,P	SK 73520.60310	30.18	758.34		768.71			Namurian	?
Caunton	No.15	I,P	SK 73600.60000	33.83	753.77		768.10			Namurian	?
Caunton	No.19	I,P	SK 73250.60000	51.21	791.87		794.92			Namurian	?
Chellaston	No.6	D,O,P	SK 39220.28710	42.10	117.35		151.79	P_1		Namurian	?
Claypole	No.1	C	SK 84501.49332	17.68	621.18		669.34			Namurian	?
Cox's Walk		R	SK 84115.38077	56.00	499.70	566.20	800.60	Asbian/Holkerian	Dolomite	Namurian	Charnian(Maplewell Series)
Cropwell Butler	No.1	O,P	SK 68135.38695	63.66	962.25		980.54			Namurian	?
Donington Park	No.1	D,O	SK 42330.26240	70.10	76.40		93.40	P_1		Widmerpool Formation	?
Donington Park	No.3	D,O	SK 43760.25450	85.30	55.90		84.10			Namurian	?
Duffield		M	SK 34280.42170	61.57	417.88		1052.47	P_1,P_2	Faults, tuffs, dolerite sills	Namurian (E_{1a})	?
Dunston	No.1	C	*TF 07399.63124	12.50	1290.52		1299.97	D_2	Penecontemporaneous brecciation	Namurian	?
Eagle Moor	No.1	F	*SK 88747.68203	31.69	1029.00		1041.81	D_1		Namurian	?
Eakring	No.1	I	SK 67600.61330	90.83	805.59		819.91		Veins + cav. $CaF_2,ZnS,PbS,BaSO_4$	Namurian	?
Eakring	No.30	I,P	SK 68170.60210	118.26	812.90		824.48		Pyrite and phosphate nodules	Namurian	?
Eakring	No.34	I,P	SK 68050.59870	116.13	786.38		803.45			Namurian	
Eakring	No.39	I,P	SK 68200.59620	103.02	787.60		800.05		Silicified + veins of $CaF_2,BaSO_4$	Namurian	?
Eakring	No.80	I,P	SK 68050.59380	99.36	784.86		803.76	P?	Veins of $CaCO_3,SiO_2,BaSO_4,CaF_2$	Namurian	?
Eakring	No.146	I,P	SK 68075.59450	104.24	778.76	2209.80	2278.68	Brigantian/Courceyan	Veins-$CaF_2,BaSO_4,CaCO_3,ZnS,SiO_2$+ elaterite	Namurian cemented by CaF_2, SiO_2	Cambrian
Eakring	No.151	I,P	SK 68170.59370	101. 0	797.97		813.82	P?	Veins-$PbS,ZnS,CaF_2,BaSO_4$ + hatchettite		
Eakring	No.163	I,P	SK 68030.59740	103.63	785.47		800.10		Veins-$CaCO_3$ and pyrite	Namurian	?
Eakring	No.167	I,P	SK 68180.59730	107.89	794.00		805.59		Quartz Grit, $CaCO_3$ veins,	Namurian	?
Eakring	No.176	I,P	SK 67970.59560	94.79	763.22		786.38		Quartz grit, siliceous limestone	Namurian	?
Eakring	No.179	I,P	SK 67490.61220	98.45	801.01		817.47		Brecciated limestone	Namurian	?
Eakring	No.185	I,P	SK 68080.59530	104.54	783.64		807.72		Quartzitic	Namurian	?
Egmanton	No.1	I,F	SK 75510.68420	34.44	∿1146.96		1205.18	Visean(P_2?)		Namurian	?
Egmanton	No.3	I	SK 77570.67330	21.34	∿1103.07		1121.36			Namurian	?
Egmanton	No.5	I,P	SK 76260.68130	31.54	1133.86		1143.00			Namurian	?
Egmanton	No.6	I,P	SK 70670.69000	24.76	1164.03		1173.78		Bitumen in limestone	Namurian	?
Egmanton	No.11	I,P	SK 75120.67700	44.89	1143.91		1156.72			Namurian	?
Egmanton	No.13	I,P	SK 73410.69600	30.05	1216.76		1225.30			Namurian	?
Egmanton	No.19	I,P	SK 75590.67610	23.32	1115.57		1122.88			Namurian	?
Ellistown		D,B	SK 43900.10560	170.69	467.87		494.08		Dolomitic, 'quartz dust', dolomite vein, iron pyrite and chert	Namurian	?
Eyam		K	SK 20960.76030	230.12	000.00	1803.25	1851.05	C_1,C_2-S_1,S_2,D_1,D_2	Dolomitic,anhydrite,tuff,lava + bitumen	N/A	Llanvirn
Farndon	No.1	F	SK 76613.54453	12.80	777.85		804.06			Namurian	?
Farndon	No.2	F	SK 76914.53117	13.41	771.75		775.72			Namurian	?
Foston	No.1	C	SK 84894.41470	28.35	466.34	614.17	782.28	S_2,D_2		Permian	Charnian ?
Granby	No.1	F	*SK 75316.36836	38.10	904.65		939.09			Namurian	?
Granby	No.2	F	*SK 76890.36533	31.39	905.86		909.22			Namurian	?
Grove	No.1	J	SK 75230.80700	68.27	1551.43		1573.07	P_2?		Namurian (E_1)	?
Hardstoft	No.1	H	SK 44340.62380	192.02	937.87		997.31				

										Namurian	?
Hathern	No.1	F	*SK 51594.24149	49.07	387.71		634.59	C_1-C_2?	Anhydrite beds, veins	Namurian	?
Heath		H	SK 44520.66740	157.28	1194.82		1221.94		Pyrite	Namurian	?
High Marnham		I,P	SK 80930.70285	10.36	1143.00		1158.24			Namurian	?
Highoredish		H	SK 35410.60320	184.40	85.65		157.89	D_2,P	Chert, olivine-basalts,CaF_2+ ZnS vein at 116.4m.	Namurian (E_1)	?
Hockerton	No.2	F,I	*SK 69583.58081	75.59	∿852.83		899.16			Namurian	?
Ironville	No.1	M	SK 43070.51300	102.11	620.27		1114.04	D_1,D_2,P_2	Chert, dolomite, pyrite quartz + dolerites/tuffs	Namurian	?
Ironville	No.2	A,H,M	SK 43620.55620	150.57	923.24		1221.03	D_1,D_2,P_2	Chert, tuffs, agglomerates, toadstone	Namurian	?
Ironville	No.3	F,H,M	SK 43250.52320	124.05	∿680.62		835.76	D_1?,P_2	CaF_2 veins	Namurian	?
Johannesburg	No.9	H	SK 30370.59010	205.74	115.21		165.51	D_2,P_2	Chert, pseudobreccias, lava	Namurian	?
Kelham Hills	No.1	I,P	SK 75940.57620	52.45	∿735.18		767.94			Namurian	?
Kelham Hills	No.15	I,P	SK 76480.57800	41.45	692.81		699.21			Namurian	?
Kelham Hills	No.39	I,P	SK 76290.57230	42.67	690.68		704.09			Namurian	?
Kelham Hills	No.52	I,P	SK 76500.57580	56.39	732.43		736.09			Namurian	?
Kirklington	No.1	I,F	*SK 69290.56300	29.87	∿840.64		852.22			Namurian	?
Kiveton	No.1	E	SK 48940.84120	100.89	1386.84		1415.49		Fractures, FeS,$CaCO_3$, silicified	Namurian	?
Langar	No.1	F	*SK 71988.35577	31.70	946.10		986.33			Namurian	?
Long Clawson		O	SK 73500.28410	54.25	1331.98		1434.08		Igneous horizons	Namurian	?
Mansfield (BP)	No.1	F,I	*SK 55500.59055	134.11	∿1325.88		1368.55		Spicular chert, bituminous	Namurian	?
Mansfield (AA)		I,P	SK 55500.59100	132.45	∿1330.45		1374.34		Cherty Limestone	Namurian	?
Maplebeck	No.1	I,P	*SK 70529.60101	83.21	∿916.53		928.73			Namurian	?
Melbourne(High Wood)	B	P	SK 38200.23740	89.30	163.22		168.95			Namurian	?
Nocton	No.1	C	*TF 05106.64661	28.04	914.40	1173.79	1181.71	C_1,S_2?		Namurian	Cambrian ?
Nocton	No.2	C,P	TF 02079.65257	54.86	954.63		957.38	D_1?	Dinantian oil producer	Namurian	?
Nocton	No.3A	C	TF 01956.65517	56.08	957.68		972.31			Namurian	?
Nocton	No.4	C	TF 01867.65349	57.61	964.08		967.43			Namurian	?
Nocton	No.5	C	TF 02233.65264	54.56	957.07		967.74			Namurian	?
Nocton	No.6	F	*TF 01913.64864	57.61	960.12		990.60	S_2?		Westphalian	Lower Visean
Nocton South	No.1	C	*TF 02956.63956	50.29	935.43		940.92			Namurian	?
Normanton	No.1	C	*SK 71942.54384	30.78	847.34		850.09			Namurian	?
Normanton	No.3	I,P	SK 71610.54850	49.68	∿882.40		903.73			Namurian	?
Normanton	No.4	F	*SK 72189.54431	23 47	793.39		871.42			Namurian	?
Pickworth Plot		R	SK 89597.68678	31.80	1018.50		1077.66		Stylolitic	Westphalian	?
Plungar	No.1	F	*SK 77206.33479	64.92	935.13		944.27	D_1?		Namurian	?
Plungar	No.13	O,P	SK 77260.31940	65.23	929.03		935.74			Namurian	?
Renishaw		A,E	SK 42650.77830	90.53	1249.68		1290.83		Silicified sandstone,limestone + chert	Namurian	?
Ridgeway		A,E	SK 40060.81520	155.14	877.82		913.18			Namurian	?
Rolleston	No.1	C	*SK 76122.51905	15.24	685.19		725.42			Namurian	?
Rolleston	No.2	C	*SK 74912.51132	16.76	717.80		722.07			Namurian	?
Rolleston	G2	C	*SK 75300.51348	14.33	655.93		666.90			Namurian	?
Rotherwood		L	SK 34580.15587	109.50	61.49	173.90	199.00	D_2	Dolomitic, pseudobreccias	Namurian	Post Middle Cambrian
Ruskington	No.1	F	*TF 09207.49746	10.97	1000.49		1002.49	D_1		Namurian	?
Screveton	No.1	F	*SK 73075.43483	25.91	1053.69		1103.68			Namurian	?
Somerton	No.1	N	*TG 46164.19349	00.00	1040.28	1365.81	1396.56	S,D and Thick P	Veins and geodes. PbS,FeS,$CaCO_3$	Namurian	Silurian ?
South Leverton	No.1	J	SK 79330.80400	11.28	∿1514.86		1562.10	D?,P?	Dolomitisation	Namurian (E_1)	?
Spital	No.1	C	*SK 96531.91143	44.81	1698.65		1705.05	D_2?		Namurian	?
Stixwould	No.1	C,G	*TF 18846.65308	8.23	1386.84	1441.70	1454.20	C (part of)	Signs of hydrothermal alteration in basement	Namurian	Pre-Cambrian/Cambrian
Stockshouse Farm		D,O,P	SK 46800.02120	121.92	143.86	152.09	152.09	P		Namurian	?
Sutton-on-Trent	No.1	C	SK 79490.62490	11.28	999.44		1004.32			Namurian	?
Sutton-on-Trent	No.2	C	SK 79950.64950	10.67	1025.65		1028.70			Namurian	?
Sutton-on-Trent	No.3	F	*SK 79130.63775	12.19	1008.28		1026.26			Namurian	?
Tansley		H	SK 33130.59600	201.78	307.24		348.08		Base metals concentrated in black shales	Namurian (E_1)	?
Thorpe	No.1	F	*SK 76922.50530	14.63	683.67		691.90			Namurian	?
Trumfleet	No.1	F	*SE 60510.12588	8.23	1524.30		1580.08			Namurian	?
Trusley		M	SK 25480.35880	79.25	101.50		154.53	D_1(at base)	Gypsum, veinlets and faults	Triassic	?
Tuxford	No.1	F	*SK 72180.70500	78.18	1281.38		1294.18			Namurian	?
Uppertown		H	SK 32370.64250	211.83	160.63		176.78			Namurian (E_1)	?
Westfield Lane		R	SK 91990.41721	44.87	643.00		679.60	Brigantian -late Asbian.	Dolomite, some galena and pyrite	Namurian	?
Whittington	No.1	E,F	SK 38430.75790	141.43	1003.10		1026.87		Silicification	Namurian	?
Widmerpool	No.1	F	*SK 63657.29583	81.08	1325.88		1890.98	L.Carb. Shales		Namurian	Lower Carboniferous Shale

A - Giffard (1923); B - Boulton (1934); C - Lees and Tait (1946); D - Mitchell and Stubblefield (1948);
E - Eden et al. (1957); F - Falcon and Kent (1960); G - Kent (1967); H - Smith et al. (1967);
I - Edwards (1967); J - Smith et al. (1973); K - Dunham (1973); L - Institute of Geological Sciences (1978);
M - Frost and Smart (1979); N - Conoco (pers.comm.); O - Institute of Geological Sciences (pers. comm.),
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Although the deposition of the bulk of the base metals and gangue minerals has been confined to calcareous environments, in which local aquicludes may have acted as temporary cap-rocks (Firman & Bagshaw, 1974; Walters & Ineson, 1981) the more mobile phases appear to have 'leaked' or migrated into the overlying Upper Carboniferous, Permian and Triassic sediments. In these horizons, their passage has been facilitated by major faults, often reactivated, as at Whitwell. Deposition, principally confined to barite-calcite + galena, is vein-like with subordinate replacement flats or wholesale metasomatic alteration of suitably porous units, e.g. oolitic Magnesian Limestone. In such circumstances, leakage deposition is proposed. Considering the palaeogeographical conditions of this epoch, it may well be that episyngenetic or syngenetic (stratabound-stratified) deposits have also resulted on a local scale. Isotopic evidence supports a multi-component model with intermixing at high structural and stratigraphical levels. The scattered occurrences in the Upper Carboniferous and Permo-Trias may well indicate a transitional environment between the thermal zoning at depth and escape at the surface into the Triassic groundwaters.

A contour plot of data from boreholes in the East Midlands supports the hypothesis of the mineral field extending in depth beneath the younger strata of the East Midlands, probably as far as the coast.

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P.R. Ineson, B.Sc., Ph.D.,
C.Eng., M.I.M.M., F.G.S.
Department of Geology,
University of Shefield

T.D. Ford, B.Sc., Ph.D., F.G.S.
Department of Geology,
University of Leicester

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