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# A PENNINE MODEL FOR THE DIAGENETIC ORIGIN OF BASE - METAL ORE DEPOSITS IN BRITAIN

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Abstract: A resume of the main developments in ore genesis theory, from Agricola to Lindgren, is followed by a summary of the Pennine orefield research and review papers published since the 1930's. A sedimentary-diagenetic model for the Pennine orefields is described which relates the fluid mobilisation and eventual orebody emplacement to *tectonic* activity. A comparison of the Mississippi Valley type criteria with the characteristics of the Pennine ores highlights systematic differences, and a new, Pennine *type of* classification is proposed. The characteristics of the other British lead-zinc orefields are then compared with the Pennine *type* criteria and it is suggested that the British orefields exemplify the complete range of generic types (from porphyritic to sedimentary) but that within each type local conditions during orefield development may give rise to wide differences in eventual orebody characteristics.

Over the years there has been some variation in the names given, and the boundaries applied, to the Pennine orefields. In this paper the terms 'Northern, Central, Southern Pennine orefields' refer to the commercially mineralised areas associated with the Alston Block, the Askrigg Block and the Derbyshire Dome, respectively. The ore deposits of Staffordshire and Cheshire have been excluded from the Southern Pennine classification because of the relative lack of relevant literature.

Although igneous-hydrothermal theories of the origin of metallic and gangue mineral ore deposits had reached a peak of development and acceptance by the early 20th Century, 'modern' ideas involving sedimentary and diagenetic processes have been current for a long time. During the past forty or so years the availability of advanced technology, the development and refinement of sophisticated geophysical and geochemical techniques, and the accelerating rate of oil-funded sedimentological research have been parallelled by a change away from a concensus based on magmatic activity towards one based on the environments at the margins of sedimentary basins.

In Britain, the change in perception has concentrated on the Mississippi Valley ore deposit classification. This had been developed to define the geochemical and structural parameters of a particular type of low temperature sulphide ore deposit that has been identified in several parts of the world. By reference to the Pennine research and review papers published since K.C. Dunham's "The genesis of the North Pennine ore deposits", and to the more recent refinements in the Mississippi Valley literature, the present paper suggests that the three main Pennine orefields exemplify a distinctive type of ore deposit which, though similar to the Mississippi Valley type, is intrinsically different.

## THE HISTORICAL BACKGROUND

The following resume is based on Dunham (1934, 1948, 1970), Park and MacDiarmid (1964) and Stanton (1972).

Agricola (1546, 1556) recognised that orebodies were emplaced in older rocks by circulating currents of various origins, also that the shape and orientation of the emplacement was controlled by the structure of the host rock. Descartes (1644) considered that most ores were additions from a sub-crustal shell of heavy material that were sometimes expelled in exhalations, and Steno (1669) wrote that ores were a product of the condensation of vapours which ascended from the deep through open fissures in the crust. Henkel (1725) and Zimmerman (1746) both applied the term 'hydrothermal solutions' to Steno's vapours, and further hypothesied that these solutions should contain material dissolved from the country rock through which they had ascended, Delius (1773) developed the idea that once emplaced, ore deposits undergo superficial alteration by atmospheric agents to produce a zone of secondary mineralization above a zone of supergene enrichment, while Charpentier (1778) and Gerhardt (1791) produced a theory of lateral secretion, with the minerals comprising an orebody being leached from the adjacent wall-rock by meteoric water.

Hutton (1788) and Werner (1791) initiated what has since been termed the Plutonist/Neptunist schism; Hutton held that ore deposits were derived from deep molten magmas (Plutonism), and had been transported to the depositional site in ascending fluids; Werner maintained that mineral veins originated as chemical precipitates in structural cracks that developed on the floors of primeval oceans (Neptunism).

De Beaumont (1850) developed the idea that hydrothermal solutions, resulting from magmatic separation, reacted with the country rock in the contact zone of an igneous intrusion to produce replacement ores; Sandberger (1882) suggested the lateral secretion of metallic elements from the country rock by circulating groundwater, and Posepny (1893) considered that deep circulating meteoric water was the mobilising agent. In a series of writings between 1907 and 1935, Lindgren developed a hierarchy of genetically separate mineralizing mechanisms which, whilst allowing for syngenetic and diagenetic modes, placed the main emphasis on igneous-hydrothermal activity. Dunham (1970) pointed out the irony that the dominance of the magmatic concept thus reached its culminations "precisely at the time when the petroleum industry was providing the first knowledge of the chemical nature of the deep formation waters in sedimentary rocks".

## THE PENNINES IN RELATION TO MISSISSIPPI VALLEY - TYPE ORE DEPOSITS

Dunham (1948) proposed a magmatic source for the Northern Pennine orefield, with most of the minerals emanating from two centres beneath Upper Weardale, but with some minerals derived metasomatically from the wall-rocks. For the Southern Pennines, Wedd and Drabble (1908), Shirley and Horsfield (1945) and Traill (1939) proposed that the mineralisation was by hydrothermal solutions rising from the later stages of igneous activity beneath the Derbyshire Dome. Maps of the gangue mineral zones by Dunham (1952a) and Mueller (1954) showed concentric patterns in the North Pennines suggesting that the fluids cooled as they moved outwards from two emanitive centres. For the Southern Pennines Dunham and Mueller separately noted lateral patterns, suggesting a westwards flow and cooling sequence. Dunham and Stubblefield (1944) reported a crude zonal pattern at Greenhow in the Central Pennines and surmised that the fluids had been forced into the primary depositional sites under considerable pressure.

Bott and Masson-Smith (1953) using gravity data, postulated an acid igneous intrusion vertically beneath the mineralization centres described by Dunham. Later, in 1957, they defined the Weardale intrusion as a potassic-rich alkali granite with five culminations. From the close coincidence of the granite with the mineralization, and variations in coal rank data from the granite flanks, they firmly dated the intrusion as contemporaneous with the mineralization, and therefore Hercynian.

Syngenetic deposition, contemporary with the enclosing limestone, was proposed as an alternative to classical plutonism by Knight (1957). He thought the ores subsequently migrated when the emplacement temperature rose because of increasingly overlying sediments, metamorphism, or igneous activity.

The first modern model for Central Pennine ore genesis was put forward by Dunham (1959), who concluded that the most likely derivation for the mineralizing fluids was in the addition of juvenile waters to the mixed ground and connate water circulation following activation by Hercynian movements. He estimated that unenriched connate and subvadose groundwater could not produce sufficient mineral content to deposit the known tonnage of ore (Dunham, 1943), and the absence of any regional metamorphism during the Carboniferous precluded the addition of metamorphic water. Bott (1961) interpreted aeromagnetic data to suggest that the Askrigg Block basement could be either a thick lava pile or a metamorphic belt. He also suggested that the Central Pennine orefield might not be directly related genetically to the basement.

Ford (1961), after a comprehensive review tentatively suggested granitic sources for the Southern Pennine mineral solutions "near or under the eastern margins of Derbyshire."

In a preliminary note on the Rookhope borehole findings, Dunham et al. (1961) reported a tentative pre-Carboniferous dating of the Weardale granite, stating that the mineral vein source must be deeper than the drill had reached. They suggested that five geophysically defined cupolas (one of which was beneath Rookhope) had funnelled the mineralizing fluids into the Carboniferous strata. Dodson and Moorbath (1961) dated the Weardale granite radiometrically at 326 ± 6 Ma and concluded that the mineralization was not related to the granite. Fitch and Miller (1965) also dated the Weardale granite radiometrically, defining an initial intrusion at 425 - 400 Ma, a further intrusion at 392 ± 6 Ma and subsequent metasomatism between 356 ± 6 Ma and 255 ± 12 Ma. Dunham et al. (1965) mentioned finding strongly metasomatic mineralization in three limestone horizons of the Rookhope boring. Mineralization was reported as continuing deep into the granite, but none was found in the immediate vicinity. K-Ar and Rb-Sr methods both gave the granite dates of 362 ± 6 Ma. Mineral veins in the vicinity and in the granite were dated, respectively, 175-150 Ma and 174 Ma.

Sawkins (1966), using fluid inclusion data, showed that the Northern Pennine fluorite had been deposited at temperatures between 200°C and 100°C by fluids with Na:K ratios ranging between 6.8 and 12.4. The barite had been deposited between 130° and less than 50°C, the fluid Na:K ratio ranging between 15.3 and 46. The fluids were seemingly derived by mixing juvenile with connate waters having a high Ba content. He proposed a barite concentration mechanism to the east of the Alston Block, whereby sulphate was reduced by bacterial action to sulphide in the low Eh conditions of the Durham coal measures. At a symposium organised by the Institute of Mining and Metallurgy, Solomon (1966) described an alternative Ba concentration mechanism, suggesting that the enrichment zone alongside the mineral veins was indicative of the barite being transported by the mineralizing fluids. Additionally, the barite concentrically zoned with the other minerals around the cupolas indicated a common magmatic source.

Davidson's (1966) fluid inclusion data were mainly American, but he suggested that the telethermal lead-zinc ores were deposited by interstratal brines derived diagenetically from evaporites, with the brines concentrating metals from sediments through which they had migrated. Davidson argued that because the fluid entrapment temperatures precluded sea floor syngenetic processes, and the salinities were higher than for normal connate or magmatic waters, the likely sources of the mineralizing fluids were brines and connate waters obtained from evaporites by diagenesis and/or leaching. The metals were transported by early diagenetic brines and precipitated only when mixed with later diagnetic brines charged with sulphate and bacteriogenic sulphide. Applying this model to the Northern Pennines, the barium would have been derived diagenetically from the overlying (and now eroded) Zechstein strata. By analogy with field evidence from Derbyshire, fluorite could also be derived from the evaporite beds. The lead could be concentrated initially within lagoonal carbonate deposits by calcareous and other algae with a large propensity for extracting lead. With a concentration of only 1 ppm in the interstratal fluids, 1000 ft of strata could yield 2000 tonnes per square mile; equivalent to 4 million tonnes from the limestones of the Northern Pennine orefield. (Dunham, 1943, had estimated that the total tonnage extracted from the Northern Pennines was 3 M tonnes). From coal rank data Davidson suggested that the immediately post-Carboniferous geothermal gradient was 21°C per 1000 ft, and that the function of the Weardale granite was merely the provision of a local geothermal and structural high.

Dunham (1966) countered Davidson (1966), suggesting that the Zechstein had been insulated from the mineralized sediments by impervious shales, whilst the evaporite sequences were separated from them by a barrier reef. From Northern Pennine fluid inclusion data the sediments would have needed burial to 15 km. Davidson cited coal rank data to support a mineralizing groundwater depth between 1000 ft and 8000 ft, and showed from a typical evaporite basin/back reef sequence that the Northern Pennine orefield lay where the chlorides from an evaporite basin would have mixed with the sulphate and sulphide-rich water from back reef sediments.

Beales and Jackson (1966) described the Pine Point orefield in Western Canada, and then defined the stratigraphic, structural, geochemical and mineralogical parameters of Mississippi Valley type ore deposits by means of five criteria:

Host rock - dolomite, limestone, cherty dolomite or cherty limestone.

Porosity - considerable.

Regional structure - sedimentary basin margin, little tectonic deformation, absence of apparent igneous activity.

Mineralization - by cavity filling and wall-rock replacement; an up-dip migration pattern, specific horizons mineralised but not whole rock units.

Mineralogy - simple, low precious metal content.

In their theory Mississippi Valley type deposits occur in carbonate rocks because their well-developed permeability provides easy fluid migration routes (plumbing). During late stages of shale sequence compaction the expelled connate waters were likely to be hypersaline, carrying metals as soluble chloride complexes. Water rich in $H_2S$ would also escape concurrently with the brines through the same plumbing, though not necessarily by the same routes. The metals would be precipitated as sulphides where the basinal brines subsequently mixed with the carbonate formation waters which, by analogy with experience with petroleum bearing strata, would contain $H_2S$ rich 'sour gas'.

In discussing Derbyshire, King (1966) concluded that the rakes were plutonic-hydrothermal in origin, pipes were neo-Neptunist, whilst scrins could have originated by either mode.

In 1966 the Yorkshire Geological Society held a symposium on the Sub-Carboniferous Basement in Northern England, published late in 1967. Bott (1967) synthesised all the geophysical evidence to show that whilst the Alston Block and the central part of the Askrigg Block were underlain by Devonian granites, the southern half of the Askrigg Block was resting, at a shallow depth, on a metamorphic basement. Summarising the post Carboniferous fault trends and movements, ascribing the latter to upper-mantle flow, the paper concluded that the primary mineralizing fluids had welled-up through the granites of both blocks. Kent (1967) suggested that the North East Midlands were underlain by a sub-Carboniferous basement block, trending NW-SE and terminating northwards at Woodale. Dunham (1967) argued that the thermal zoning indicated hot solutions. Commenting on Sawkins' (1966) data, which showed that the solutions could not have originated as sea water or entirely as connate water, he concluded that there was no alternative to rising hydrothermal water, with deep-seated magmatism beneath Alston, Askrigg and North Derbyshire either emitting potassic brines containing complex solutes of fluorite, lead, zince, barite, or stimulating the circulation of such brines.

Downing (1967) established the presence of sulphate-rich groundwater in the sub-surface Carboniferous Limestone beneath Nottinghamshire. At the 1967 Inter-University Geological congress (published 1969) Ford postulated for the Southern Pennines a hydrothermal fluid source buried east of Derbyshire. The Carboniferous sediments in the North Sea Basin were thought to be a possible source, but with reservations about the burial depth and temperature gradients. The alternation of wrench-faulting and mineralization was held to imply Triassic tectonic activity. The Southern Pennine orefield was dated as late Triassic to early Permian, and significantly later than the Northern Pennine orefield. Ineson (1967) described metasomatic alteration in the Northern Pennines, noting that it was restricted to a narrow zone around the veins.

White (1968) discussed the criteria for the generation of Mississippi Valley type base metal ores. His conclusions, based on a comparative study of five, widely-spaced, deposits, were that:

1. deposition was a complex process involving two or more fluid sources.

2. metal-bearing fluids were sulphide-poor and highly saline (Na, Ca)Cl brines which could be formed either magmatically, or from connate waters, or by membrane concentration of dilute meteoric water,
3. the metals in these brines were transported in chloride complexes which were stable under low-sulphur conditions,
4. the sulphur necessary to initiate metal precipitation could be derived by a variety of geochemical processes,
5. the brine densities were typically higher than those of waters of near-surface origin.

Llewellyn and Stabbins (1968) interpreted the Hathern Anhydrites as evidence of sabkha deposits on early Carboniferous mud-flats along the flanks of the Derbyshire Dome, suggesting that Lower Carboniferous source brines migrated thence upwards and laterally. The widespread occurrence of oil and other hydrocarbon deposits in the East Midlands Carboniferous Limestone strata suggested that the Lower Carboniferous sediments acted as hydrocarbon reservoirs until earth movements and erosion permitted their escape. Dunham et al. (1968) concluded from argon isotope data that the Northern Pennines underwent repeated pulses of mineralization between 284 Ma and 170 Ma, further concluding that episodic hydrothermal action may have been widespread throughout Britain. Ineson (1969) examined wall-rock alteration in the Northern and Southern Pennines and concluded that, chemically, the mineralising solutions were of different compositions. Based on zirconium aureole widths, he suggested that the ores were magmatic. Ineson and Al-Kufaishi (1970) observed that the Southern Pennine mineralization was multi-phase and predominantly the filling of sub-vertical fissures, with some horizontal, silicified and dolomitized lodes underlying shales. Associated earth movements were initially late Hercynian, with post-Triassic dilation and lateral movement. Pyrite formations were suggested as the result of sulphurous leaching of the shales by downward percolating and laterally migrating connate water.

In 1970 the Institute of Mining and Metallurgy held a symposium on the derivation of Mississippi Valley type ore deposits. Beales and Onasick (1970) compared single fluid transportation systems with two fluid systems and concluded that a two fluid model met the thermodynamic and hydrodynamic requirements better. They also defined the stratigraphic criteria for classifying Mississippi Valley type ore deposits:

1. stratiform epigenetic deposit in a carbonate host rock but with little or no host rock solution by the mineralizing fluid,
2. situated on sedimentary basin flanks and associated with structural 'highs',
3. anomalous lead and sulphur isotope values, suggesting a sedimentary origin,
4. igneous or metamorphic activity normally absent.

Bush (1970) discussed the chemistry, origin and role of the inclusion brines found in Mississippi Valley type deposits. He suggested that marine derived brines from sabkha sediments provided the closest chemical correlation with leaching and transportation of base metals by early diagenetic brines. In the later stages of diagenesis the increased temperature and pressure would enable the exothermic reduction of anhydrite by hydrocarbons to produce both heat and $H_2S$. Dozy (1970) described a geological model for the ore deposition in which fluids produced by basinal sediment compaction and diagenesis escaped along sedimentary aquifers. If trapped by local structures fluid pressure could rise above hydrostatic pressure. Tectonic disturbances could release the pent-up fluids up-dip away from the basin, and if the fluid pressure was approaching lithostatic pressure, strata displacement could occur. If the rising fluids mingled with sulphur-rich fluids, minerals could be deposited. In 1970 Dunham concluded that "it is apparent that multiple hydotheses 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 pre-requisite; the water may originate in the ocean or as meteoric water ... the deep sedimentary basins and their margins should receive more attention from the ore geologists".

Hirst (1971) described a diagenetic mechanism for leaching Co, Ni, Cu and Pb from sediments by formation waters and compared data from modern, Liassic and Carboniferous sediments. He suggested a progressive decrease in the cobalt and nickel content with age. Solomon et al. (1971) compared sulphur and oxygen isotope ratios of Northern Pennine barite with world-wide data for evaporitic sulphates, and conjectured that the sulphate originated in Lower Carboniferous connate waters which percolated downwards to be heated above 200°C, and mingled with hypersaline, metal-rich brines rising through the granite plutons beneath Tynehead and Upper Weardale into the Carboniferous sediments where they mingled with cool, sulphate-rich connate waters. Solomon et al. (1972) later revised their model taking the Carboniferous sea water as the origin for the sulphur. Subsequently Shearman (1972) on the basis of crystal chemistry, suggested that the base metals may have been similarly derived.

Mitchell and Krouse (1971) analysed lead isotope data from the Central Pennines, showing the presence of anomalous 'J-type' lead. They proposed two alternative models; mineralising fluids of deep origin, released during the Variscan cycle through associated fracture zones; or mineralization related to the rheomorphism of the lower crust, with extraction during the Variscan cycle.

Stevenson et al. (1971) argued that the thermally determined mineral zones of Wedd and Drabble (1908), Dunham (1952a) and Mueller (1954) are only of general validity, noting that there are many anomalies and reversals and that the fluorite extends west of Mueller's limit. Ineson and Mitchell (1972) radiometrically examined lavas and tuffs from sites adjacent to several Derbyshire mineral deposits, concluding that mineralization was active in several phases, namely at 270 Ma, 235 Ma and then continuously until 180 Ma. Ineson et al. (1972) examined a barite-galena deposit in the Upper Permian Magnesian Limestone. From the similarity in mineral assemblage to that of the outer zone of the Southern Pennines, they deduced a genetic connection with the main orefield, with a fault-controlled up-welling solution comprising mixed juvenile fluids and connate waters from the sedimentary basin to the east. Pering (1972) established that the North Derbyshire hydrocarbon deposits were generically associated with organic material in the overlying shales as well as with petroleum deposits in the East Midlands. Ixer's (1972) evidence from Masson Hill, Matlock, confirmed the presence of two types of mineralization: metasomatic replacement and the in-filling of voids and pre-mineralization solution cavities. He also suggested that leaching from the volcanic and igneous rocks could not have supplied the bulk of the minerals. Isotope analyses indicated that the sulphur was not magmatically derived. The ubiquitous occurrence of bravoite $(Fe,Co,Ni)S_2$, in low concentrations throughout Derbyshire was also suggested. Ixer (1974) refined parts of his 1972 paper to conclude that bravoite is a characteristic accessory of primary low temperature mineralization.

In a preliminary report on the Eyam borehole, Dunham (1973) described a Tournaisian sabkha sequence, comparing it with the sub-Carboniferous Hathern anhydrites and, by reference to the sulphate-rich groundwaters of the East Midlands, suggested that the Southern Pennine mineralization may be linked with the presence of anhydrites at depth throughout much of the area. Reference was also made to the similarity between the sulphur isotope values for the Hathern anhydrites and the Northern Pennine barite deposits.

Firman and Bagshaw (1973) showed that the gangue mineral distribution zones of Dunham (1952a) and Mueller (1954) were neither coincident with each other, nor reliable in reflecting the in situ variations in mineral grade. They also showed, citing their own observations and those of Ineson and Al-Kufaishi (1970) that because of the superimposition of later mineralization phases on earlier ones, the 'normal' fluorite-barite-calcite sequence was unreliable, and may be isochronous rather than isothermal. Later Firman and Bagshaw (1974) showed that in many cases the mineralizing fluids apparently migrated down-dip through the more porous and cavernous local strata. They also suggested that faults, as well as providing migration channels, sometimes acted as hydrological barriers.

Ford (1976) again reviewed Southern Pennine ore genesis. In his model the ore materials are derived by slow diffusion through the Carboniferous Limestone from the strata in the North Sea Basin. Sulphurous hydrocarbons, disseminated pyrite in the dark basinal limestones, and bacterial reduction of the anhydrite series beneath the South Derbyshire limestones are tentatively adduced as sulphur sources. The peripherally scattered ore occurrences, such as at Alderley Edge in Cheshire and Whitwell and Bulwell in the East Midlands, are evidence that the de-mineralized waters escaped either to the surface as hot springs, or into the Triassic groundwater circulation. This model is consonant with the Mississippi Valley criteria: deposition in carbonate rock, an argillaceous cap rock structure, filled fissure deposits, and pre-mineralization karst features.

White (1974) reviewed the world-wide geochemical, isotopic and physical data from forty low temperature hydrothermal orefields. His conclusion was that no single model adequately explains all, or even most, metalliferous ore deposits. Individual constituents (metals, chlorides, sulphur, etc.) may or may not be derived from the same source as the dominant water. Igneous intrusions may or may not provide the driving energy and/or any of the constituents. A two-fluid model was felt to provide a closer fit to more of the known data than does a single fluid model, but this was not generally accepted. Anderson (1975) and Beales (1975) independently reviewed the geochemical criteria for the precipitation of Mississippi Valley type ores. According to Anderson, the solubility of galena in near-boiling NaCl brines is such that acidic conditions would be necessary for sulphides to be carried in the same solution. Calcite and dolomite are not stable in acid brine but for chalcopyrite to be stable, the brine should be quite acidic and highly reduced. Thus the low acidity of formation waters requires a separate supply of sulphur for metals to be precipitated. Mississippi Valley type orebodies represented sites where basinal brine metals and limestone sulphides coexisted over a long time. Beales supported Anderson's advocacy of a two fluid model adding that Mississippi Valley type ores were characterized by a lack of concurrent host rock solution. The corollary making pH criteria into a main prerequisite by adding that this type of ore emplacement is characterised by a lack of concurrent host rock solution. The corollary was also argued; that host rock solution characterised superficially simiar, but fundamentally different ore precipitation mechanisms, based on different pH parameters.

For ore genesis in the North Pennines Ineson (1976) combined the models of Sawkins (1966) and Solomon et al. (1971) to produce one in which upward migrating juvenile waters combined with hypersaline connate brines to leach the granitic basement. Near the surface these mixed brines mingled with downward percolating meteoric waters, eventually depositing lead, zinc and fluorite immediately above the granite cupolas. At the same time barium-rich connate waters from the adjacent sedimentary basins (the North and Irish Seas) migrated up-dip to deposit an outer ring of barite. For the Central Pennines Ineson cited Bott (1967) to show that there is no coaxial coincidence of fluorite and granite (as in the Northern Pennines), referring to Mitchell and Krouse (1971) who proposed that the mineralizaing fluids were either of deep origin or associated with crustal rheomorphism.

Evans and Maroof (1976) extended the work of Turner and Le Bas on the basement rocks of Central and Northern England to suggest the presence of a Caledonian igneous belt extending North-West from the London Brabant Massif "in a zone parallel to and underneath the Derbyshire Orefield". The absence of negative Bouguer *anomalies* was ascribed to the low contrast between the densities of the enveloping country rocks (typically ranging from 2450 $kg.m^{-3}$ to 2700 $kg.m^{-3}$) and that of the Mountsorrel granodiorite (2650 $kg.m^{-3}$). The patterns of magnetic anomaly data were adduced to support the suggestion that the hypothetical intrusion was similar in composition to the Mountsorrel granodiorite. By analogy with the Northern Pennine orefield model of Bott (1967), Evans and Maroof suggested that the East Midlands basement intrusions funnelled mineralizing solutions into the anticlinal traps of the Derbyshire Dome, and whilst not categorically claiming an upper mantle/lower crust origin, state that "the mantle must be seriously considered as a possible source".

Using oxygen, carbon and sulphur isotope data derived from the Southern Pennines galena, barite and fluorite deposits, Robinson and Ineson (1976) suggested connate water as the sulphur source for the barite, but postulated an interaction between light biogenic and heavy, deep seated, sources of sulphur for the galena. The oxygen isotope data is used as evidence of two fluids, one ultimately meteoric. Carbon isotope values indicated derivation from marine limestones without fractionation. Worley (1976) argued from evidence in the Blende Mine, Bakewell, that low pH, hot, saline brines dissolved the country rock before the arrival of the mineral bearing fluids. Evidence from thin sections indicated that bitumens were present; derived either by diagenesis or from trapped, migrating, hydrocarbon fluids.

Firman (1977), discussing the propagation modes of the Derbyshire rakes, and their association with mineralization; concluding that they had been initiated as short, primary, wrench faults and were subsequently extended along a series of secondary faults. The morphology of the secondary faults was almost invariably that of high shear stresses, without either compressive or tensional stresses. The mineralization was shown to be related to the dilation and re-opening of both types of fault.

A recent study by Ixer (in press) draws together evidence from throughout the Pennines of the ubiquitous occurrence of bravoite and other heavy metal disulphides in low concentrations and as trace minerals in fluorite crystal fluid inclusions.

## A TECTONIC PERSPECTIVE

Worley and Ford (1977) refined Ford's earlier model (1976), defining Mississippi Valley type orefields simply as "dominated by lead and zinc ores, with or without accompanying baryte, fluorite and calcite, in a host rock of limestone or dolomite, remote from any potential parent igneous rock mass". Using this definition they classified the Pennines, Halkyn-Minera and Mendips Hills orefields as the type examples in Britain. Their genetic model comprised five main elements: mineral and sulphur sources; diagenetic, migration and precipitation mechanims. They enlarged the current sedimentary process models by the inclusion of Hercynian sub-crustal activity as the source of the initial, mobilizing heat source. They also invoked sabkha-like conditions during the Dinantian marine cycles as a possible, *in situ*, sulphur source.

This review leads the writer to propose a model that differs from that described by Worley and Ford, on three points:

1. Although the limestone strata in the Southern North Sea Basin could have provided sufficient quantities of lead, zinc, barite, fluorite (etc.), the losses inherent in the system due to erosion and diffusion into areas unsuitable for ore deposition will have been considerable. It is therefore suggested that enhancement of the indigenous mineral content of the limestone sediments took place, with metals leached from the overlying shales by downward migrating (Na, K) brines originating in the Permian evaporites. The mechanism of fluid migration by dense brines downwards through Carboniferous shales has been described by Beales and Jackson (1966) for the Pine Point orefield in Western Canada.
2. Evidence in the literature suggests that there were considerable quantities of strategically placed sulphates from which the necessary sulphide-rich fluids could have been derived; Lower Carboniferous sabkhas at the centre of the Derbyshire Dome (Dunham, 1973), sub-Carboniferous sabkhas flanking the Derbyshire Dome (Llewellyn and Stabbins, 1968) and adjacent to the Northern Pennines (Bush, 1970), sulphate-rich groundwaters in the East Midlands (Downing, 1967) and to the east of the Alston Block (Davidson, 1966). Additionally, biogenic $H_2S$ could have been derived from organic matter in the limestone sediments either directly via normal decay processes, or indirectly by metamorphosis into paraffinic hydrocarbons which then reduced the available sulphates. The problem of maintaining separation between the sulphide-rich and the metal-bearing fluids may also have been exaggerated, given the considerable

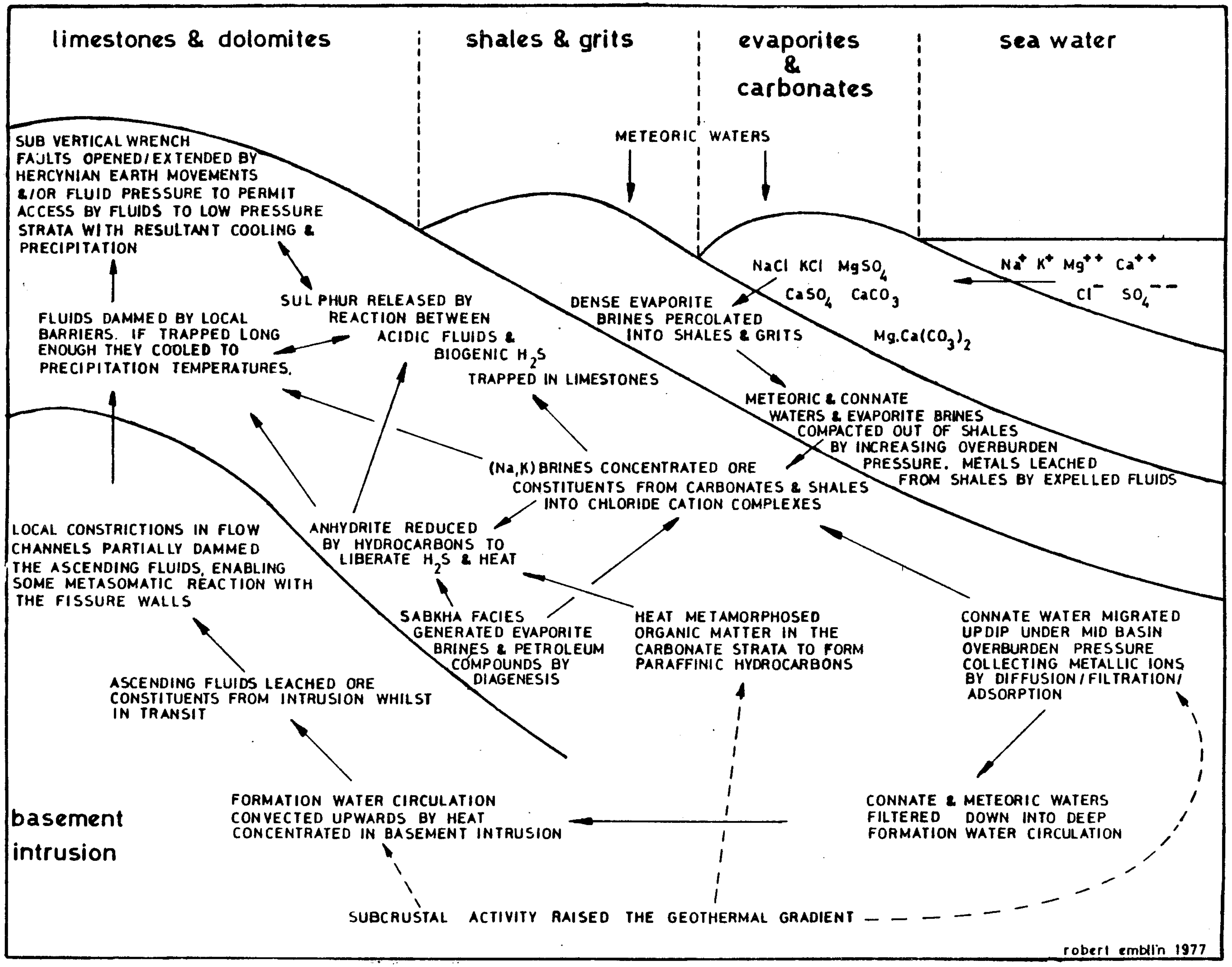


Fig. 1. Pennine type ore genesis model.

variations with time in the temperatures and pressures (and hence solubility products) present across the model as well as the wide variety of routes available to fluids migrating along a broad front through strata several thousand feet thick.

3. Throughout the period relevant to the Pennine mineralization (i.e. from mid-Carboniferous to early Jurassic) several phases of tectonic activity affected the Pennines and the North Sea basin; shock movements due directly to the Variscan orogeny (Trotter, 1967), and crustal warping that may be ascribed to upper mantle flow (Leeder, 1974; Kent, 1975; Pegrum et al., 1975). As well as causing the abnormally high geothermal gradient that mobilized the various diagenetic processes within the model, these phases of tectonic activity also generated the wrench fault initiation/propagation/dilation cycles which enabled the sequential damming and releasing of mineralizing fluids into the Derbyshire rakes (described by Firman, 1977). No similar studies seem to have been made in the other Pennine orefields; but in the light of Dozy's 1970 hydrogeological model, and from the evidence of high-pressure mineralizing fluids in the Northern Pennines (Dunham, 1934) and the Central Pennines (Dunham and Stubblefield, 1944), the extension of Firman's approach throughout the Pennines could provide a basis for a working hypothesis.

The modified model thus defines the genesis of the Pennine orefields in terms of regional stratigraphy and tectonic activity as shown in Fig. 1.

Worley and Ford, in common with many authors since the mid-1960's, describe the Pennine ore deposits as Mississippi Valley type - but is such a description really valid? A U.N.-sponsored symposium in 1966 on the genesis of stratiform lead, zinc, fluorite, barite deposits in carbonates drew together the threads of research to set a coherent framework for the classification of the so-called Mississippi Valley type ores (Brown, 1967). Although no single, simple, genetic model was established, the general consensus closely followed the criteria of Beales and Jackson (1966). Later geochemical studies have refined the criteria into those of Beales and Onasick (1970). In trying to define the genetic model(s) which could produce such deposits White (1968) maintained a catholic approach; allowing any number of fluid sources, any combination of up to eight sulphide concentration mechanisms, any degree of magmatic influence, etc. Whilst this provides the criteria for the systematic investigation of low temperature, base metal sulphide, ore deposits, it is too loosely drawn to serve as a classification system. Later White (1974) accepted that there are low temperature sulphide ore types other than, though similar to, the Mississippi Valley type. Beales and various other authors have consistently argued the importance of geochemical criteria, and since 1970 have treated the absence of concurrent wall-rock solution, and evidence of separate metal bearing and sulphide rich solutions, as *sine qua non* for the Mississippi Valley classification. Throughout, all the theoretical studies of the type have stressed the importance of structural criteria in defining the type as stratiform. Thus the essential differences between the conditions of the Pennine ore deposits and the Mississippi Valley type criteria are:

a. The essential influence of successive phases of tectonic activity. In contrast the absence of tectonic activity was one of the original Mississippi Valley criteria.

b. The ubiquitous presence of metasomatic mineralization throughout the Pennines. The absence of concurrent wall-rock solution is geochemically essential in the Mississippi Valley classification.

c. Most Pennine orebodies are discordant but by definition those of the Mississippi Valley type are stratiform.

The evidence from the Pennine orebodies leads to the following empirical criteria for classification as Pennine-type:

a. Ore deposition is on the flanks of a structural high in brittle, porous and mainly carbonate strata which exhibit a well-developed plumbing system and which dip without serious discontinuity into a sedimentary basin.

b. Evaporites may be below and/or within, as well as above, the carbonate and shale strata in the stratigraphic sequence at the basin margin.

c. Mineralization is in different horizons, but does not occupy whole rock units.

d. The content of precious metals is low (Ag:Pb ratio $\leqslant$ 200 ppm by weight averaged over the orefield) with primary mineral assemblages of lead and zinc sulphides with fluorite, barite, calcite, baritocalcite and aragonite as variables, heavy metal disulphides ubiquitous in low concentrations and as trace minerals in fluid inclusions.

e. Mineralization is multi-phase in sub-vertical fault fissures and/or beneath impermeable horizons.

When these criteria are applied to the epigenetic mineral deposits of Britain (Dunham, 1952b), they show a continuous spectrum, ranging from complete agreement (Halkyn-Minera and Mendips Hills) to almost complete disagreement (Cornwall, South Devon, Harlech, Parys Mountain and Cumbria). Of the orefields with an intermediate response, North Devon and South Wales have many similarities with the Pennines; but less with West Shropshire, Leadhills-Gasswater and the Ochils. All these fields are shown in Fig. 2.

It may be significant that, although the absence of a genetic magmatic association was deliberately excluded from the Pennine criteria, the orefields that fitted the criteria least were those British deposits with the most directly genetic magmatic associations. The greatest discrepancy was in the exotic mineral content. The averaged Ag:Pb ratios for each orefield were $\geqslant$ 750 ppm by weight. Gold has been mined in some of the fields in commercial quantities and has been found in trace quantities in others. As Dunham (1952b) specifically highlights, all of these fields contain arsenopyrite, a mineral that is wholly absent from the Pennines, North-East Wales and Mendips Hills orefields.

The patterns of coincidence and discrepancy shown up by this comparison suggest two possible hypotheses:

i. If the common characteristics of the Cornwall, South Devon, Harlech, Parys Mountain and Cumbria orefields may be considered as a function of their magmatic associations, the absence of these same characteristics from the Pennine orefields may indicate a wholly non-magmatic genesis. This would reduce the function of the Pennine basement intrusions solely to that of structural support with local geothermal high points. These form convection current channels to funnel the geothermal heat, and some of the deeper circulating formation water, up into the lower levels of the Carboniferous strata where the outrush of hot fluids modulated the up-dip flow of directly migrating meteoric and connate fluids. Thus, to the criteria that had been defined for the Pennine-type ore classification may be added:

f. The absence of a directly genetic magmatic association.

ii. The incremental variation in the discrepancies between the model criteria and the parameters of the non-conforming orefields, and the similarities between the model criteria and those of the Mississippi Valley classification, reinforces White's suggestion (1968) that there was a broad spectrum of possible mechanisms for the supply of each of the essential factors for the deposition of an orebody. His suggestion included a continuous spectrum of orebody types: ranging from the wholly magmatic, to the totally sedimentary-diagenetic. The characteristics of any one orebody depend on the particular combination of genetic factors. In Britain, this range could be exemplified by the porphyritic deposits of Harlech and the sedimentary-diagenetic rakes of Derbyshire.

The operation of such a range of genetic mechanisms may be masked by variations in local conditions which moderated the development of some of the constituent processes. Unfortunately the issue is confounded by insufficient or non-coherent data. In the Southern Pennines this is exemplified by the differences between rakes, pipes and scrins and by the non-coherence of data regarding wall-rock replacement and the different mineralization pulses, and by the proximity of Ecton and Alderley Edge to the main Southern Pennine orefield. Ford (1976) suggested that

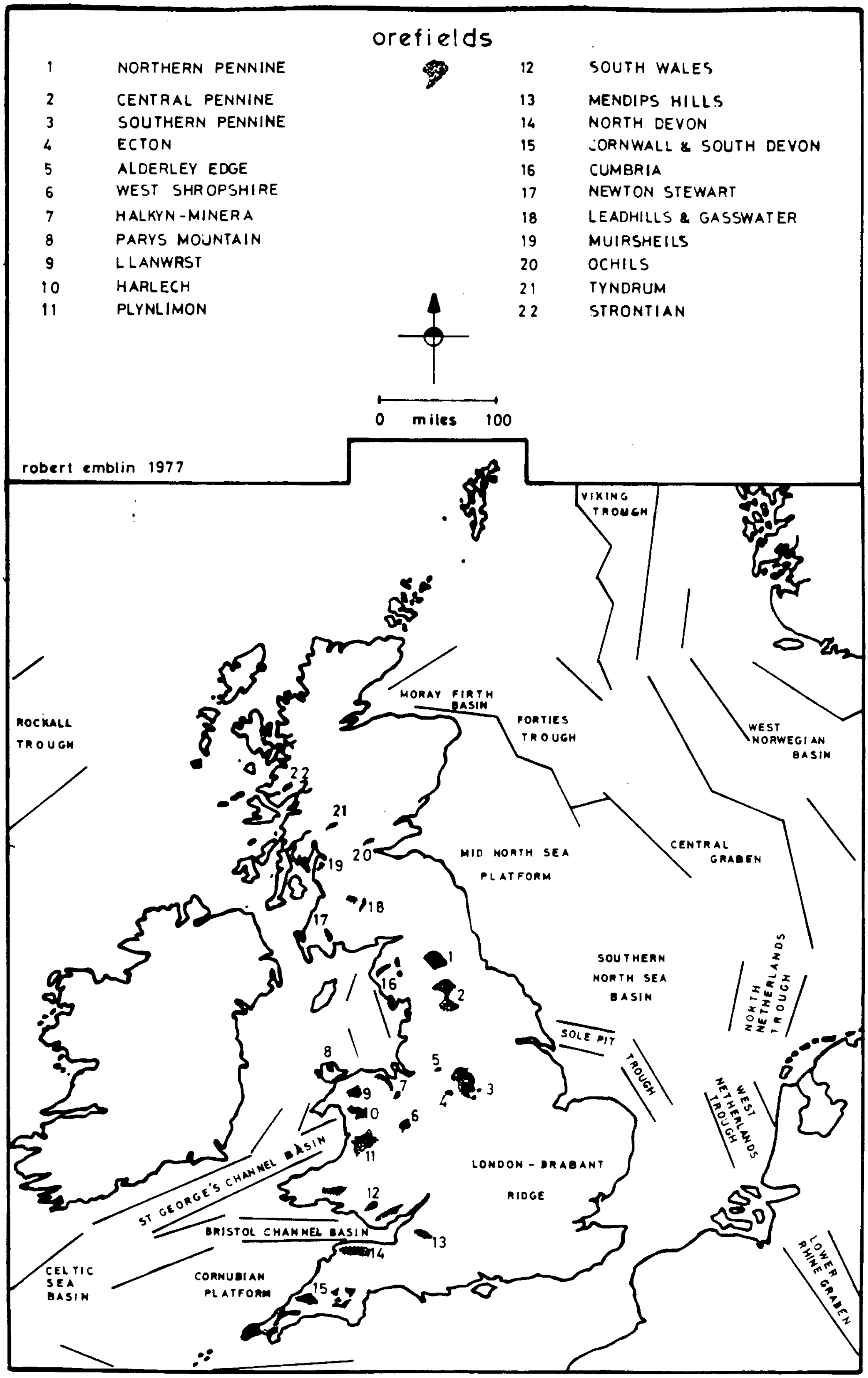


Fig. 2. The geographic and tectonic environment of the British orefields. (after Dunham 1952; Kent 1975 and Pegrum etal. 1975).

Alderley Edge and Ecton were mineralized by the overflow from mineralizing fluids in the Derbyshire Dome and the Cheshire Basin. Be that as it may; in the absence of geo-technical data such as stable isotope ratios, fluid inclusion freezing and homogenisation temperatures, etc., an agnostic position would seem to be justified. There is lack of data concerning the significant differences in mineralization dates of the Southern and the other two Pennines orefields, and on the ubiquitous presence of hydrocarbons in the Southern Pennines and the East Midlands. The literature suggests relative lack of these in the Northern and Central Pennines. There is also the uncertainty regarding the significance of the gangue mineral distribution zones: are they isothermal, isochronous, or merely illusory?

It would be arrogant to assume that the current acceptance of marine sediments as the prime source of the Pennine ore minerals has established beyond dispute the genetic connection. The acceptance of the validity of any model of ore genesis depends on an assessment of a balance of probabilities. In 1963 Sir Kingsley Dunham opened a lecture to the Society of Economic Geology with the comment "I imagine that not many members of my audience take sedimentary syngenesis very seriously". In 1977, referring in this Bulletin to igneous-hydrothermal theories of Pennine ore genesis, N.E. Worley and Dr. Ford wrote "few geologists would subscribe to such ideas today". *O tempora, o mores!*

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