# ORIGIN
# *of the*
# PEAK DISTRICT OREFIELD

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THE SOUTH PENNINE OREFIELD consists of hydrothermal vein and stratiform deposits containing fluorite, baryte, calcite, galena and sphalerite that occupy Upper Dinatian limestones in Derbyshire (Fig. 1). Mineralization has resulted from a unique interaction between stress history, basement structure and basin development in the Upper Palaeozoic rocks of the East Midlands.

The formation of the South Pennine Orefield can best be explained by considering three main elements:

- preparation of the host-rock;
- source and migration of the orefluid/s;
- emplacement of the mineral bodies.

These processes involve aspects of sediment deposition, structural evolution, diagenesis, fluid flow and wallrock interactions that have led to the creation of a favourable environment for deposition of significant quantities of hydrothermal minerals. These are discussed below.

## STRUCTURAL EVOLUTION OF THE EAST MIDLANDS DURING THE PALAEOZOIC

The South Pennine Orefield lies at the NW end of a belt of Palaeozoic rocks that extends from Germany, through Holland and the Southern North Sea and into the East Midlands (see Ziegler, 1990). The Devonian, Carboniferous and Permian rocks in this belt are dominated by NW-SE faults that originate from underlying Lower Palaeozoic basement. This structural grain developed in the late Silurian/early Devonian when a small piece of continental crust, known as Eastern Avalonia, docked with the Caledonian mountain belt along the SW edge of present-day Scandinavia (Pharaoh *et al*, 1987; Woodcock *et al*, 1988).

Eastern Avalonia is now known as the Midlands Micro-Craton (Fig. 1; Pharaoh *et al*, 1987). It underlies most of Central England and is bordered by the Church-Stretton fault lineament along its NW margin and by the Variscan front to the south. In the Midlands the NE edge of the Micro-Craton runs from north of Stafford, through Nuneaton, Northampton, Luton and NE London, to Ashford in Kent. Folded and faulted Lower Palaeozoic rocks surround the Micro-Craton. The Micro-Craton has remained relatively high since the Silurian, forming St. George's Land during the Upper Palaeozoic and the English part of the London-Brabant Massif during the Mesozoic and Cenozoic.

NW-SE compressional structures in the basement on the NE side of the Midlands Micro-Craton were reactivated as extensional faults during rifting in the late Devonian/early Carboniferous (Quirk, 1987a). A set of NW-SE oriented half-grabens known as the Widmerpool Gulf, Edale Gulf and Gainsborough Trough developed during the Dinantian (Fig. 1). Shallow-water carbonates were deposited on the up-tilted, south-western end of the Edale Gulf half-graben, in a region known as the North Derbyshire Shelf (Fig. 2). Evaporites are present in the lower part of the section (Dunham, 1973).

The Dinantian strata on the North Derbyshire Shelf exhibit major variations in thickness (600-1900m) as a result of:

- pre-existing variations in topographic elevation of the basement;
- active growth faulting during deposition.

The direction of extension during Dinantian rifting was predominantly NE-SW (Fig. 3A) leading to the formation of long NW-SE oriented joints in the Derbyshire limestones (Quirk, 1987*a*). Widespread basaltic volcanism also occurred owing to upwelling of the asthenosphere (Fig. 2; MacDonald *et al*, 1983; Walkden, 1977; Quirk, 1987*a*).

Rifting ceased towards the end of the Dinantian. A phase of uplift occurred on the North Derbyshire Shelf in the earliest Namurian, associated with an anticlockwise rotation of the stress field (Figs. 3B and 3C; Quirk, 1986; Quirk, 1987*a*, *b*). Major ENE-WSW dextral wrench faults became active at this time (Fig. 3B). These fractures now host the largest mineral veins exposed on the North Derbyshire Shelf.

After the early Namurian the East Midlands area began to sag owing to post-rift cooling and contraction of the lithosphere and asthenosphere (Quirk, 1987*a*). The direction

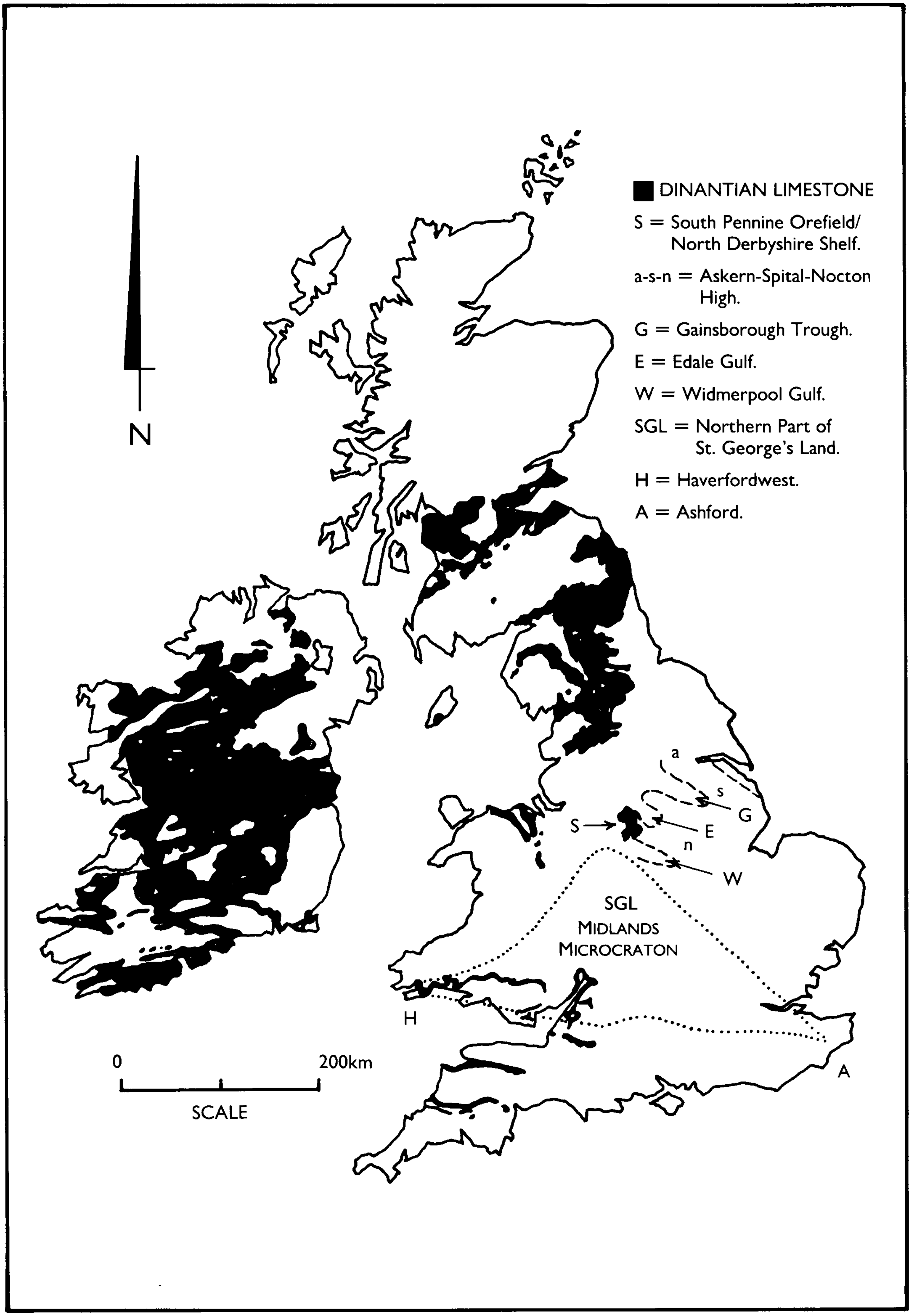


*Figure 1* Location of the South Pennine Orefield/North Derbyshire Shelf relative to the Midlands Microcraton and other areas of Dinantian limestone in the British Isles (after Downing and Gray, 1986; Lovell, 1977; Strank 1987).

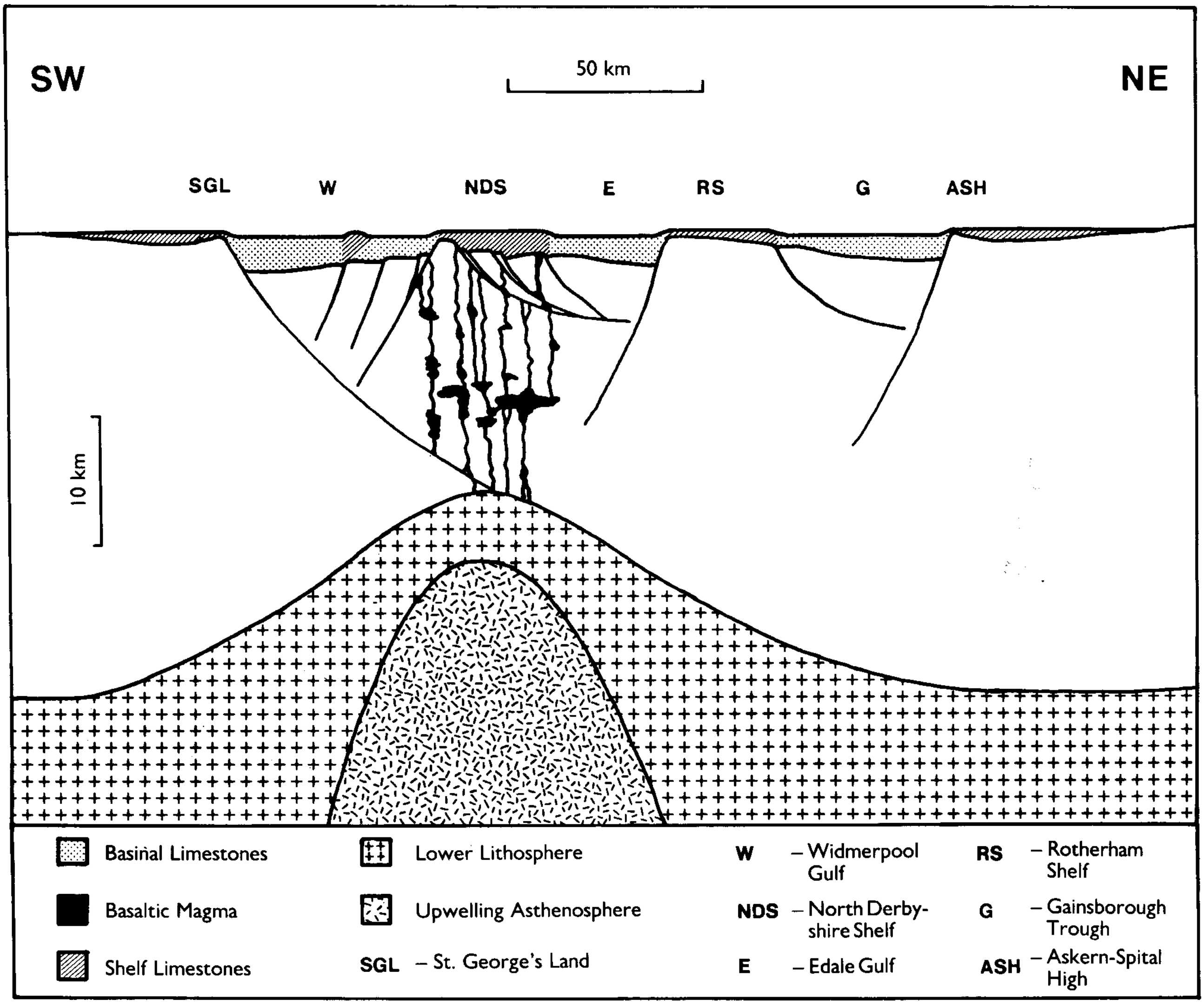


*Figure 2* Conceptual cross-section through the lithosphere and upper asthenosphere of the East Midlands Basin during the Upper Dinantian.

of minimum principal stress during thermal subsidence was NW-SE (Fig. 3D). Small NE-SW joints developed in the Derbyshire limestones in response to this stress. Initially the new basin was starved of sediment and relatively deep marine conditions prevailed during the Lower Namurian. However, during the Upper Namurian, deltas, advancing mostly from the north, rapidly filled in the basin and thus, in the Westphalian, continental conditions were established. By the end of the Westphalian the North Derbyshire Shelf was buried beneath approximately 2km of Upper Carboniferous sediment. Red beds were deposited at this time in the SW part of the East Midlands Basin.

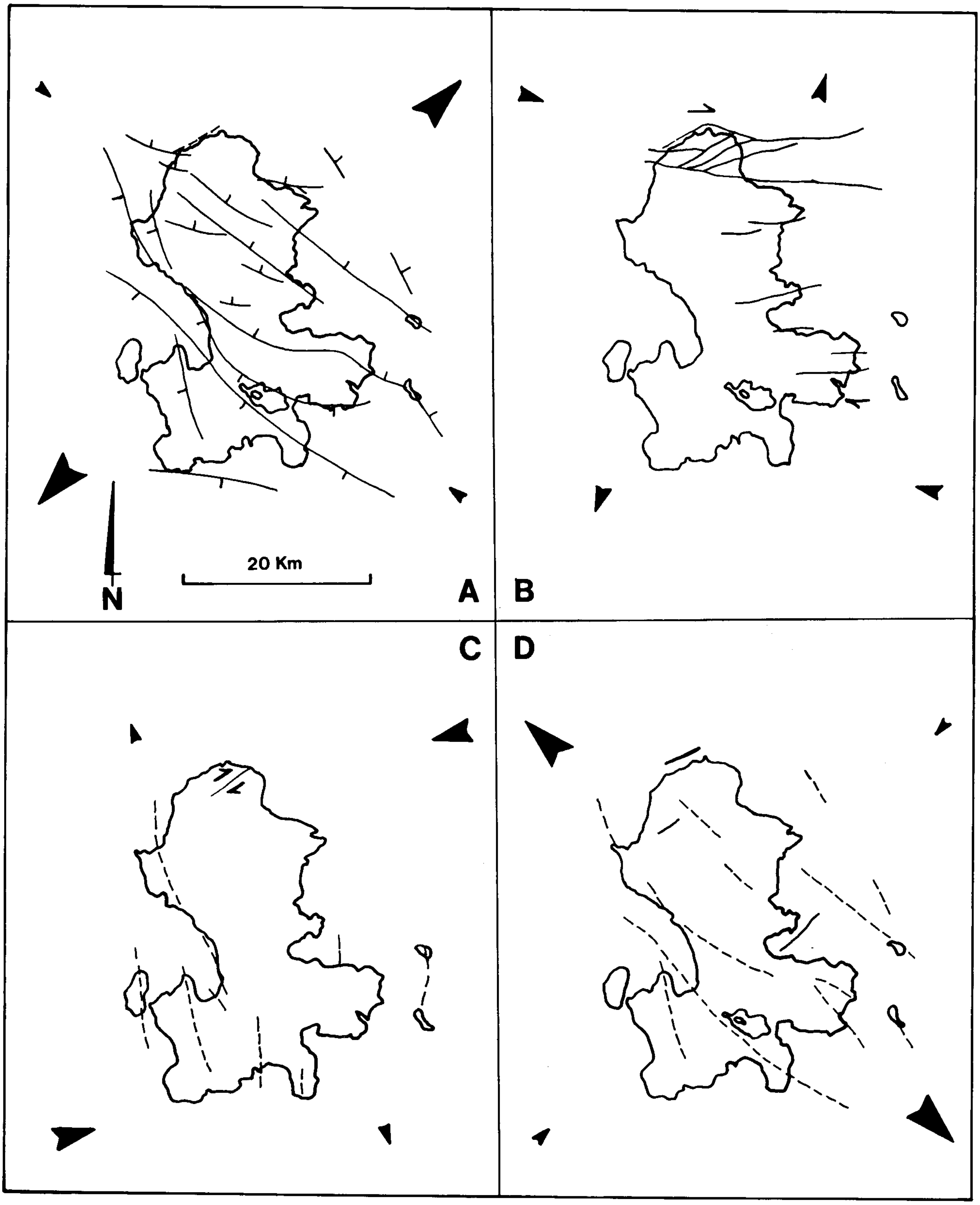
During its burial in the Upper Carboniferous, the North Derbyshire Shelf remained slightly protruding into overlying marine shales of Namurian age. In places the upper part of the limestone became dolomitized by porefluids, most probably originating from overlying Namurian shale (Quirk, 1987*a*). Previously it was thought that dolomitization was caused by saline groundwaters during the Permian. However, both the chronology and petrography of the dolomite suggest that it was actually formed by diagenetic processes associated with deep burial.

During the Stephanian (late Carboniferous), the East Midlands Basin began to tilt about a NW-SE axis (Quirk, 1987*a*). Thus the Widmerpool Gulf continued to subside but towards the Askern-Spital-Nocton High uplift occurred. By late Stephanian – early Autunian times most of Northern Europe was affected by high heat flows and crustal extension. Most of this extension was N-S in orientation. Inversion (or uplift of the basin) over the whole East Midlands area began to occur towards the end of this period. This can be explained as owing to doming of the lithosphere above upwelling asthenosphere. A similar pattern of extension and uplift preceded formation of the Southern Permian Basin in the North Sea where it is known as the Saalian rifting event (Quirk, 1993). In contrast to the North Sea, the North Derbyshire area did not subside significantly after the Autunian. Inversion was greatest in the area of the North Derbyshire Shelf. However, a thin cover of Namurian shale remained in place above the limestone until relatively recently.

# DESCRIPTION OF ORE-BODIES

## INTRODUCTION

Mineral deposits in the South Pennine Orefield have been deposited in dilatant fractures, dissolution cavities and zones of metasomatic replacement (Fig. 6; Quirk, 1987*a*). The host-rock consists almost exclusively of shallow water carbonates of Asbian-Brigantian (late Dinantian) age. The



primary mineralization comprises only fluorite, baryte, calcite, galena and sphalerite. Iron sulphides, such as pyrite, chalcopyrite and bravoite, are found in microscopic amounts within the main minerals. Nearly all other mineral types described from the South Pennine Orefield are secondary in origin, having resulted from oxidation of the primary minerals.

The Ecton copper deposit occurs in basinal limestones to the SW of the North Derbyshire Shelf. Although it shows some similarities to the South Pennine Orefield it appears to have been formed separately and hence is not included in this discussion.

*Figure 3* Basement lineaments active during the Carboniferous in North Derbyshire relative to the outline of presently exposed Dinantian limestone. Solid straight line = strike-slip and extensional fractures (including dolerite dykes); hatched straight line = folds and reverse faults.

(A) Dinantian: NE-SW extension causes growth faults to develop above NW-SE trending basement fractures;

(B) end Dinantian: stress field rotates anticlockwise leading to the development of dextral wrench faults;

(C) early Namurian: stress field continues to rotate associated with uplift and erosion and the development of NNW-SSE trending faults;

(D) middle Namurian-Stephanian: minimum principal stress during thermal subsidence was NW-SE in direction thus allowing NW-SE reverse faults and some NE-SW growth faults and dolerite dykes to develop.

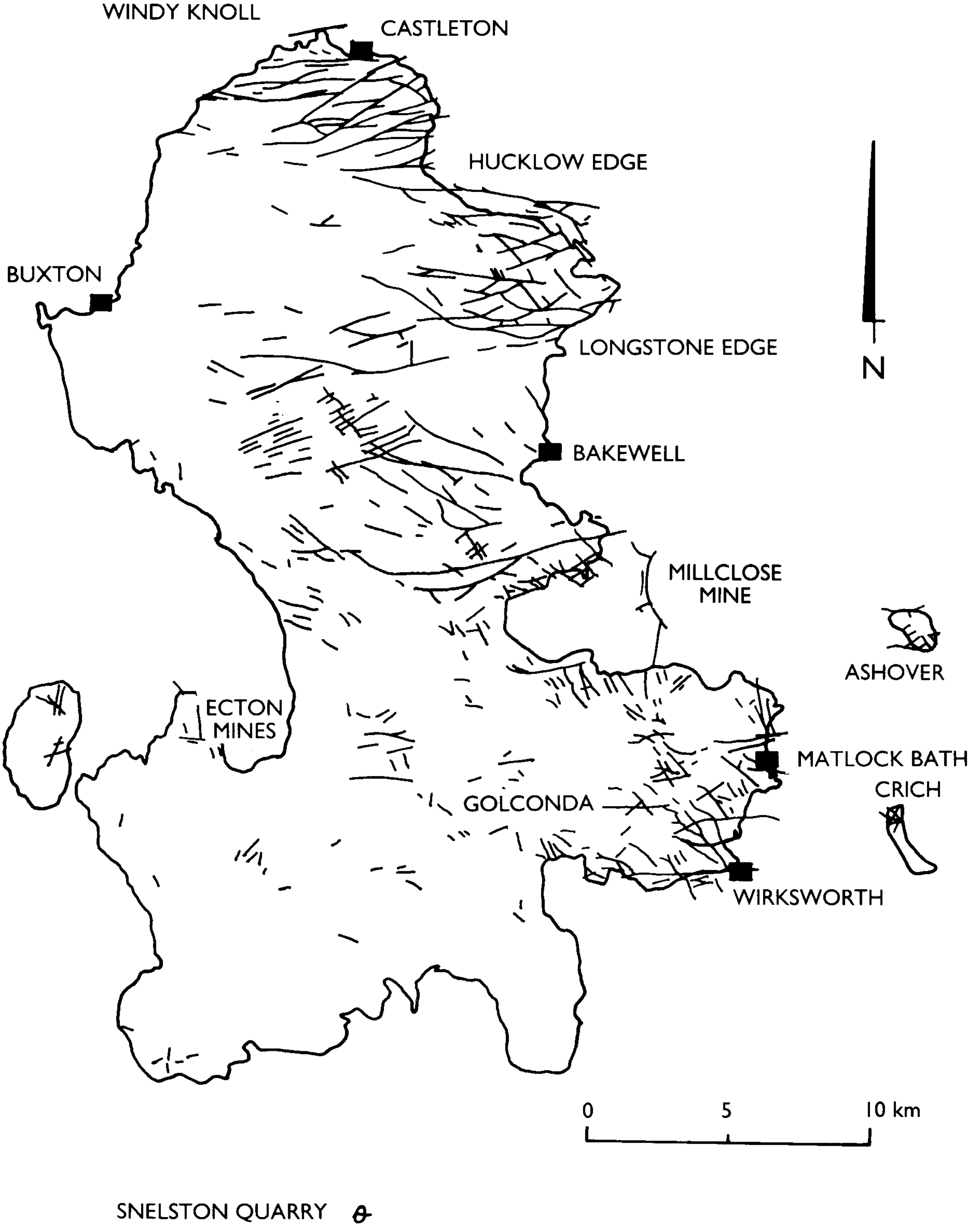


*Figure 4* Major ore veins present in the South Pennine Orefield identified mostly from old lead mining activity visible on aerial photographs and sub-surface mapping. All the veins marked occur in Dinantian limestone although some of these were mined beneath Namurian shales on the eastern side of the orefield. The veins occupy NW-SE, ENE-WSW and NE-SW fractures formed earlier in the Carboniferous under different stress regimes (as shown in Fig. 3) and which were reopened during mineralisation as a result of N-S extension.

## CRYSTAL MORPHOLOGY

Fluorite in the South Pennine Orefield tends to occur as well-formed cubic crystals that typically range in size from less than 1mm to several centimetres. Fine grained fluorite is usually metasomatic in origin.

Most of the baryte in the South Pennine Orefield occurs in a colloform variety known as cawk. This consists of a mass of extremely fine grained crystals which appear to have precipitated rapidly. Metasomatic baryte is rare.

Calcite cyrstals occur in three main varieties:

- the most common variety has a columnar texture and consists of a mass of parallel crystals that have grown simultaneously, at right angles to the wall of a vein or cavity;
- large blocky crystals of scalenohedral calcite occur in the centre of many of the larger veins and stratiform orebodies and represent the latest mineralizing event in the South Pennine Orefield;
- recrystallized limestone wallrock is a metasomatic version of calcite.

Galena and sphalerite occur mostly as sub-euhedral coarse grained crystals within either baryte or fluorite. Sphalerite is also sometimes found within calcite.

## PARAGENESIS

Despite the low diversity in primary minerals present in the South Pennine Orefield, individual ore deposits exhibit a highly complex and variable paragenetic sequence (Quirk, 1987*b*). This makes correlating specific mineralizing events over distances of greater than a few hundred metres almost impossible. Thus the South Pennine Orefield has not been subjected to regional fluorite- or galena-forming episodes; the type of mineralization owes its origin much more to the local conditions during orefluid migration.

Dilation, dissolution and metasomatism are often recorded within a single mineral deposit (Fig. 6; Quirk, 1987*b*). The main types of mineral bodies can be simply classified by the degree to which each of these three processes was important during their formation.

Fig. 6 shows how the author has classified the mineral deposits of the South Pennine Orefield. A *rake* of earlier nomenclature is equivalent to an **asymmetric vein** and a *scrin* is a **joint vein**.

Only one form of mineralization in the South Pennine Orefield cannot easily be attributed to dilation, dissolution or metasomatism, namely **net veins** (Fig. 6). Net veins consist of areas of brecciated wallrock that are completely cemented by sparry minerals. They mostly developed during early mineralization probably by an explosive process such as hydraulic fracturing, tectonism or solution collapse, or a combination of these processes.

## DILATION

NW-SE, ENE-WSW and NE-SW fractures were formed in the limestones of the North Derbyshire Shelf during basin evolution in the Upper Carboniferous (Quirk, 1987*a*). These fractures were subject to dilation as a result of N-S extension at the time of mineralization. Dilation created space for the growth of crustiform mineral layers. During vein formation, open fractures often became totally cemented. Where such a vein was subject to renewed dilation, this typically occurred along the wall, rather than in the centre of the vein, and was usually followed by another phase of crystal growth. In this way an asymmetric ("rake") vein was built up (Fig. 6). Most of the major ENE-WSW veins in the South Pennine Orefield are of this type. Symmetric veins are more typical of fractures that were enlarged by hydrothermal dissolution prior to crystal growth (Fig. 5).

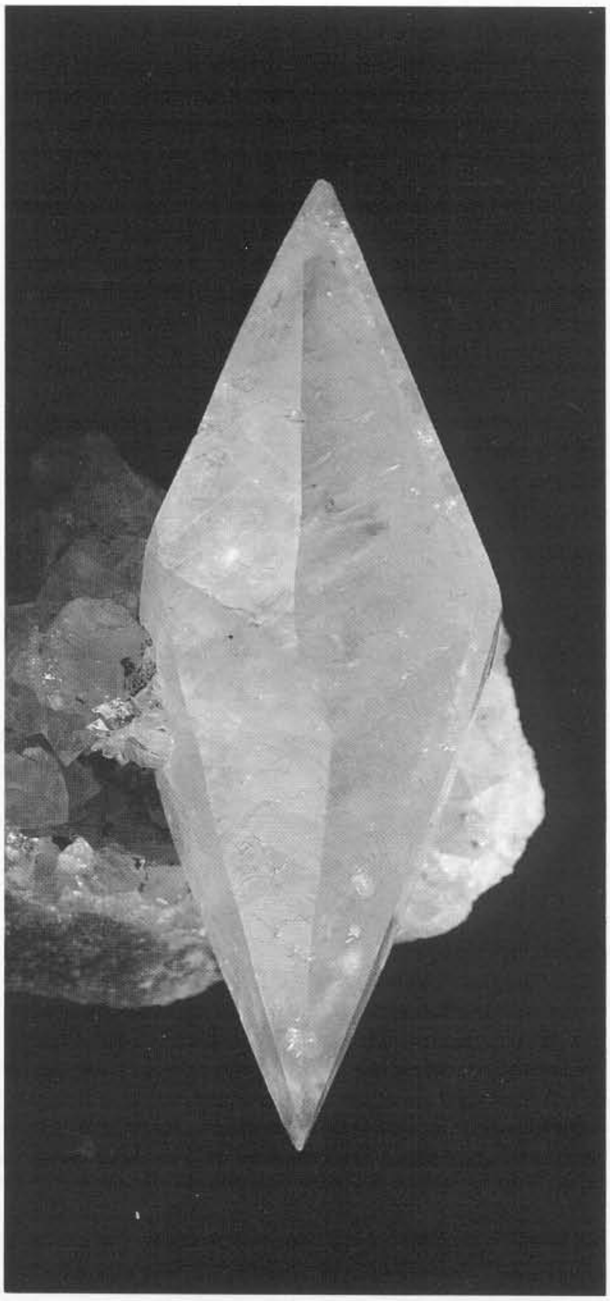


*Figure 5* CALCITE, 4cm scalenohedron from Fall Hill Quarry, Ashover. Specimen: G. Batey. Photo: David Green.

Veins consisting of only two inwardly facing mineral layers are known as **joint veins** (Fig. 6). Joint veins record a single episode of opening and crystal growth.

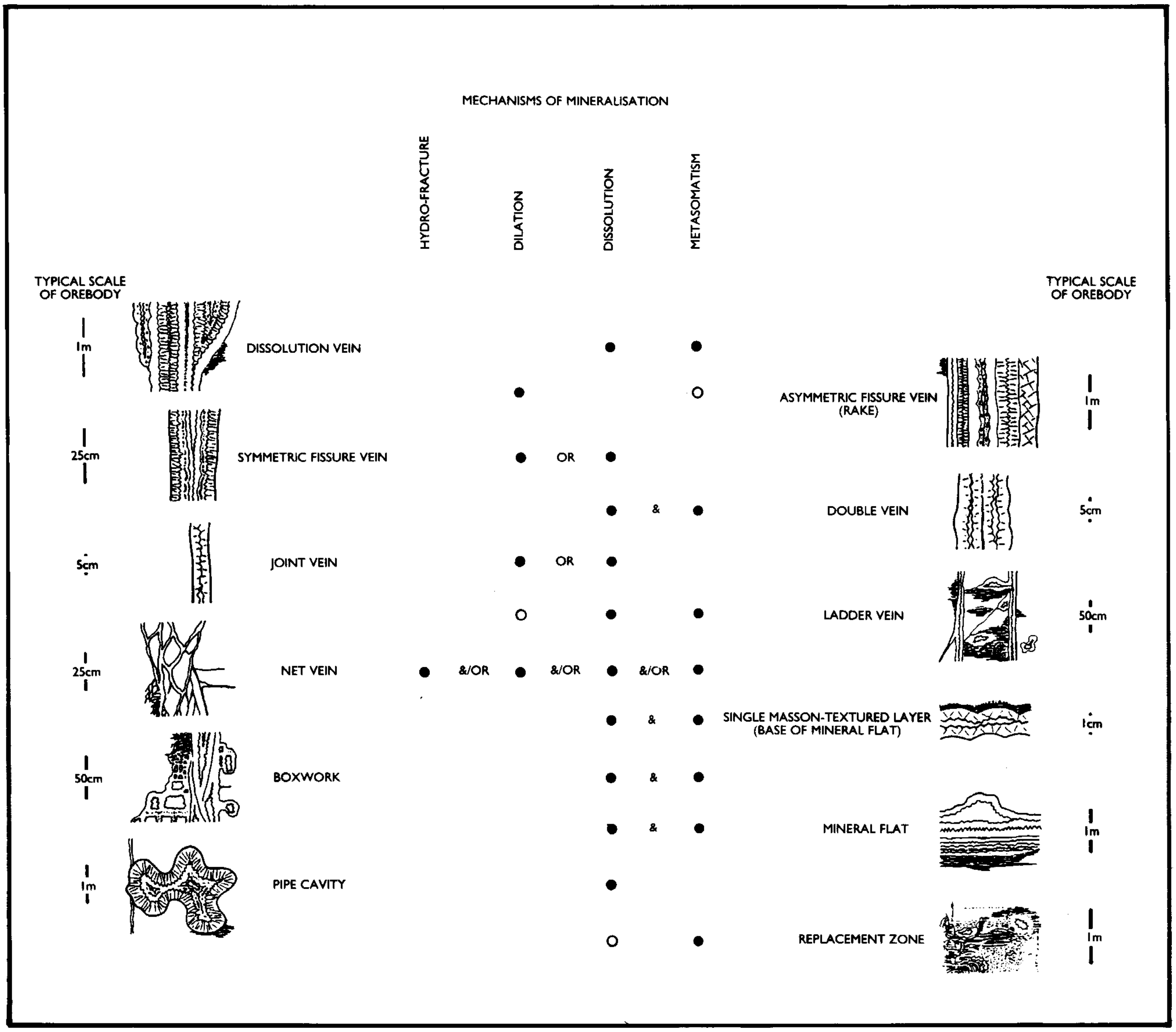


*Figure 6* Types of primary orebodies in the South Pennine Orefield and their mode of emplacement.
● = involved in formation of orebody; ○ = sometimes involved in formation of orebody.

## METASOMATISM AND DISSOLUTION

Metasomatic replacement involves simultaneous removal of the host-rock and growth of a new mineral. Crystals formed by metasomatism are typically euhedral and show no preferred direction of growth. However, in terms of mass balance there is little overall difference between metasomatic replacement of wall-rock and hydrothermal dissolution of wall-rock followed by cementation of the cavities. Only the timing and geochemical evolution of the orefluid is different. A metasomatic orefluid is both aggressive to host-rock and oversaturated in the appropriate mineral. A cavity-forming orefluid is predominantly aggressive. A crystallising orefluid is predominantly oversaturated or may consist of metasomatic orefluid that has not come in contact with unaltered host-rock.

In the South Pennine Orefield fluorite-lined dissolution cavities are always associated with metasomatic replacement and vice versa (Fig. 6). During mineralization the limestone host-rock was a source of calcium and hydroxide ($OH^-$) ions and the orefluid provided fluoride and hydrogen ($H^+$) ions. Fluorite becomes relatively insoluble in calcium-rich alkaline fluids. Thus dissolution of limestone would quickly lead to precipitation of fluorite because of:

- an increase in the concentration of $[Ca^{2+}]\ [F^-]^2$
- an increase in pH

The timing of wall-rock removal relative to fluorite precipitation determined whether metasomatic fluorite or fluorite-lined cavities are more important in any particular deposit.

**Ladder veins** consist of joint veins separated by wall-rock that has been significantly altered by processes of metasomatic replacement and hydrothermal dissolution (Fig. 5).

Some fractures that did not dilate during mineralization have nonetheless suffered metasomatism of the wall-rock immediately adjacent to the fracture. These are known as **replacement veins. Double veins** have developed where dissolution of the wall-rock occurred on either side of an early replacement vein, followed by crustiform mineral growth on the walls of both cavities (Fig. 6). **Boxwork textures** consist of a criss-crossing network of replacement veins and crystal-lined dissolution cavities (Fig. 6).

**Pipes** are pre-existing cavities that became lined with concentric crystal layers during mineralization (Fig. 6). In contrast, **flats** (Fig. 6) developed as a result of hydrothermal dissolution at the boundary between strata of differing permeabilities, the foot-wall being less permeable than the hanging-wall.

Flats usually record several discrete episodes of dissolution and mineral growth, where each new layer has developed on top of the previous layer. In more detail, the oldest layers at the base of a mineral flat are usually the thinnest. They typically have a scalloped appearance (convex-upwards) and are fringed, top and bottom, by a thin layer of metasomatic fluorite (and sometimes galena). The following layer developed on top of the upper fringe of metasomatic fluorite. Each layer in a mineral flat records, therefore, a period of dissolution followed by wall-rock replacement and crustiform mineral growth. These are known individually as Masson-textured layers (Fig. 6) since they were first recognised by the author in Masson Cavern in Matlock Bath (Quirk, 1987*b*). As well as forming the component layers of most mineral flats they sometimes occur as single horizons. They differ from dissolution and double veins in that Masson-textured layers are stratiform and asymmetric whereas dissolution and double veins are vertical or sub-vertical and symmetric in appearance (Fig. 6).

### GEOPETAL STRUCTURES

The effects of gravity during mineralization are commonly seen in the South Pennine Orefield. Broken layers of baryte that have fallen off the roof of a pipe cavity or flat are often found cemented by later minerals. Galena is more common on the floor and sides of a cavity than on the roof. Within some of the larger mineral veins fine-grained fluorite or galena crystals occur only on the upper sides of larger crystals and layers of sedimented crystals are found in some flats.

## MAIN CHARACTERISTICS OF THE SOUTH PENNINE OREFIELD

In the interests of space the main points that are relevant to ideas on the formation of the South Pennine Orefield are listed below. The reader is referred to Qurik (1987*a*) for discussion of or reinterpretation of the original data.

1. the mineral deposits of the South Pennine Orefield consist of only fluorite, baryte, calcite, galena, and sphalerite plus minor amounts of other sulphides (mostly iron) and bitumen;
2. approximately 20 million tonnes of fluorite (Atkinson, 1983), 20 million tonnes of baryte, 4 million tonnes of galena (from Ford & Rieuwerts, 1978) and 1 million tonnes of sphalerite are calculated to have been present in the South Pennine Orefield prior to mining;
3. no equivalent mineralization occurs in strata overlying or adjacent to the mineralized Asbian-Brigantian carbonates of the South Pennine Orefield;
4. ore deposits are largely confined to the NE side of the now exposed North Derbyshire Shelf (eg. Dunham 1952);
5. economic mineralization dies out with increasing depth from the top of the Asbian-Brigantian carbonates (eg. Wedd & Drabble, 1908) and individual ore deposits tend to taper downwards (eg. Quirk, 1987*b*);
6. flats are often found at the base of porous dolomitized zones close to the top of the Dinantian sequence or above impermeable volcanic layers (Shirley, 1950; Ford & King, 1965; Quirk, 1987*a*; Quirk 1987*b*);
7. mineral veins occupy pre-existing ENE-WSW, NW-SE and NE-SW vertical fractures that opened contemporaneously during N-S extension.

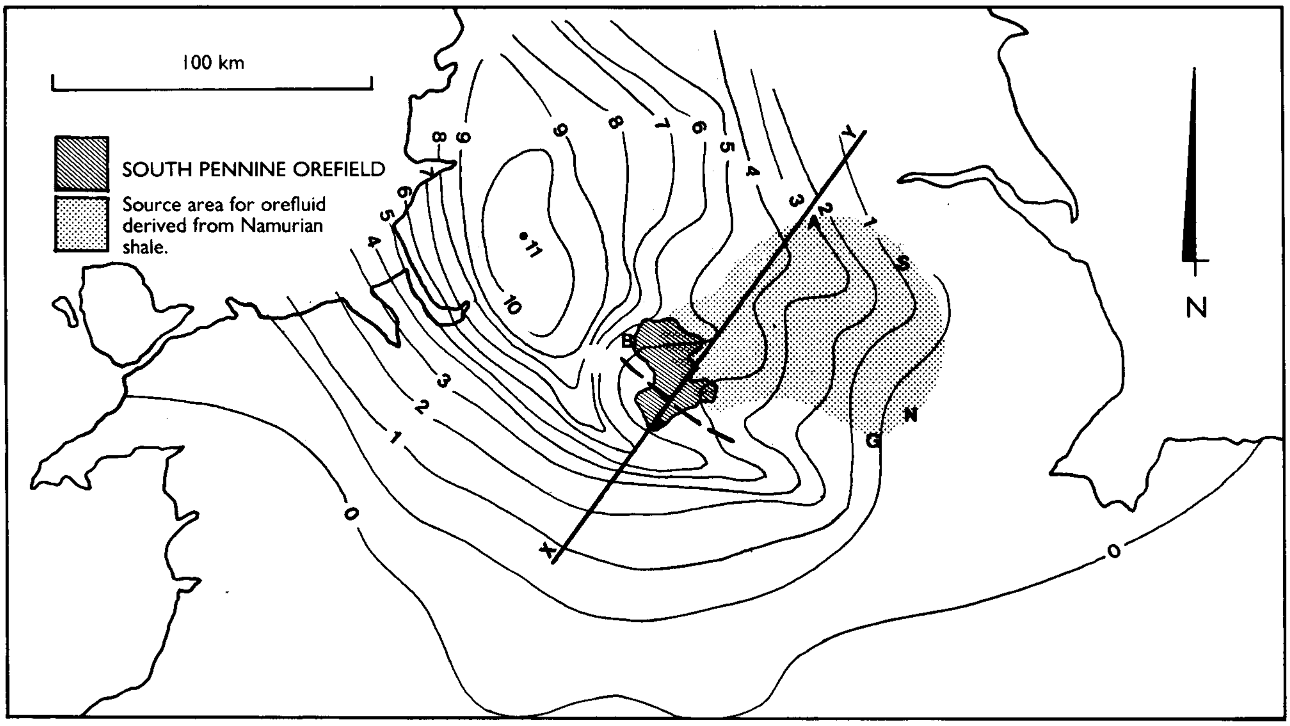


*Figure 7* Approximate isopachs (in thousands of feet) for the Upper Carboniferous in central England, achieved by adding previous estimates of Namurian and Westphalian thicknesses by Ramsbottom (1969) and Calver (1969). X-Y is the line of section shown in Fig. 7. Dashed line represents a possible compactional fault on the NE side of the Widmerpool Gulf.
B= Buxton; A = Askern; S = Spital; N = Nocton; G = Grantham.

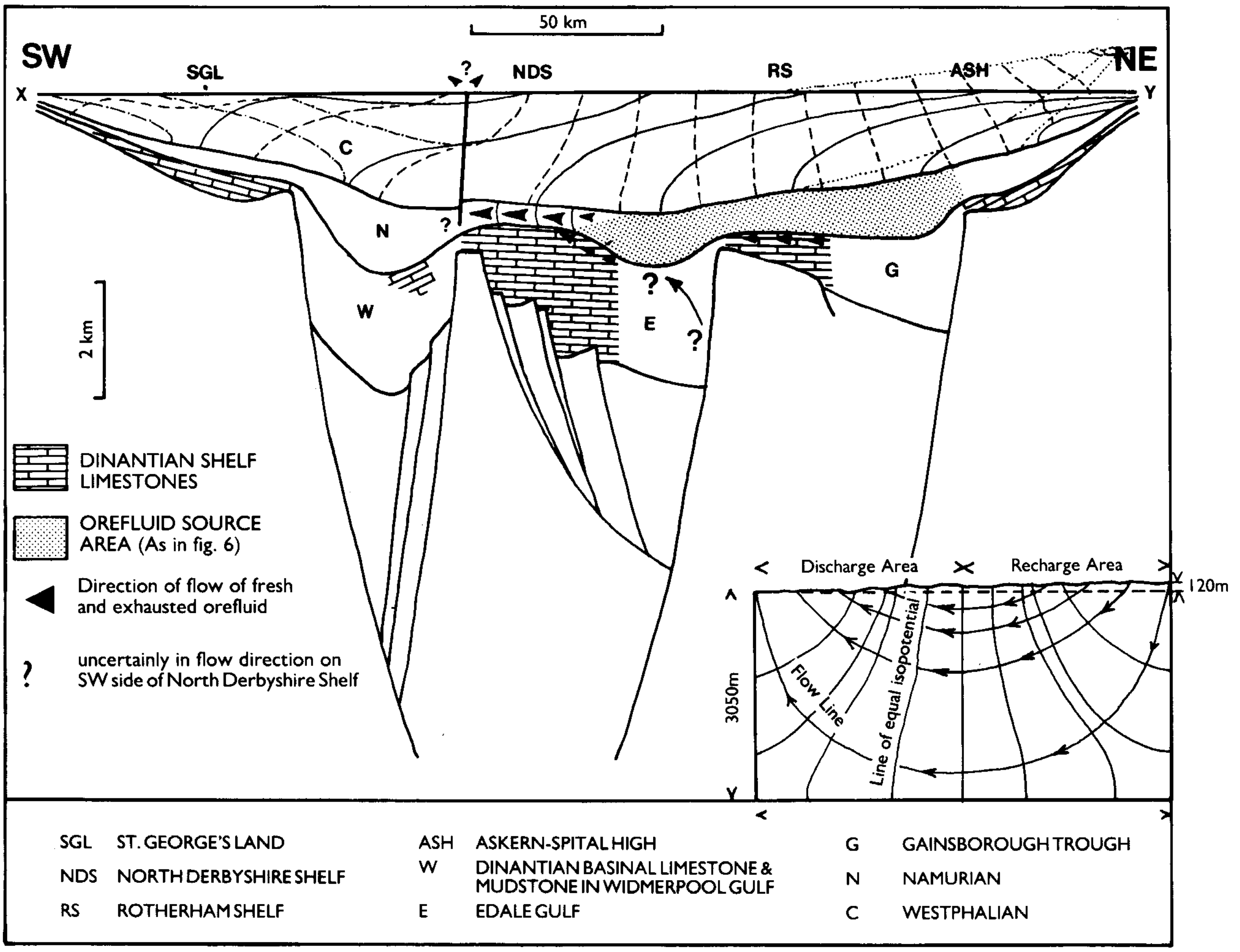


*Figure 8* Schematic cross-section of the East Midlands Basin at the end of the Stephanian when N-S extension began. Curved solid lines (NE side) = lines of hydraulic isopotential (decreasing downdip) for a low relief basin; curved solid lines (SW side) = lines of hydraulic isopotential for a low relief basin assuming that water flows up along the margin of St. George's Land; curved dashed lines (NE side) = lines of hydraulic isopotential for basin with uplifted NE margin; curved dashed lines (SW side) = lines of hydraulic isopotential assuming that water flows up along the margin of St. George's Land; curved dot-dashed lines = lines of hydraulic isopotential on SW side of basin if a compactional fault is present along NE side of the Widmerpool Gulf along which fluids can ascend. The inset shows a model of gravity-induced cross-formational flow in a tilted homogeneous drainage basin showing patterns of fluid potential and water flow (after Toth, 1978). The lines of hydraulic isopotential are similar to the hatched lines in the main diagram, although on a much smaller scale.

8. paragenetic sequences within the ore deposits of the South Pennine Orefield are highly complex and variable although the mechanisms of mineral emplacement are everywhere similar;

9. the orefluid was reactive to limestone;

10. droplets of hydrocarbons are sometimes found within mineral deposits of the South Pennine Orefield, some of which are geochemically similar to Namurian-sourced oil (P. Kelly and V. Garner, *pers. comm.*);

11. Namurian shales on the NE side of the North Derbyshire Shelf became briefly mature for oil only at the end of the Carboniferous (Quirk, 1987*a*);

12. the oldest and thus most reliable K-Ar date obtained from mineralized claystones in the South Pennine Orefield is 289± 6 million years (from Ineson & Mitchell, 1973);

13. almost constant fluid inclusion homogenization temperatures of 84°C are recorded in fluorite from the South Pennine Orefield (Atkinson, 1983) which are equivalent to natural geothermal conditions of approximately 130°C at a depth of 2km if a pressure correction is used (from Potter, 1977);

14. two main types of fluid inclusions, one containing more sodium chloride and the other containing more calcium chloride, have been described in fluorite from the South Pennine Orefield (Atkinson, 1983) although some mixing of these fluids has occurred;

15. rare earth elements from fluorite in the South Pennine Orefield have signatures typical of both Namurian shale and Dinantian limestone (from Atkinson, 1983);

16. strontium isotopic ratios from fluorite in the South Pennine Orefield ($^{87}Sr/^{86}Sr$ of 0.7082-0.7101) are typical for Namurian shale approximately 295 million years ago (from Shepherd *et al*, 1982; Atkinson 1983);

17. strontium isotopic ratios from calcite in the South Pennine Orefield are similar to those of fluorite and are not equilibriated with the host-rock suggesting that orefluid did not reside long in the host rock (from Atkinson, 1983);

18. oxygen and carbon isotopes from calcite from the South Pennine Orefield ( $^{13}C_{PDB}$ of +0.6-+3.9‰; $^{18}O_{SMOW}$ of +19.0-+27.0‰) are the same as the carbonate host-rock (Robinson and Ineson, 1979);

19. sulphur and oxygen isotopes in baryte from the South Pennine Orefield ( $^{34}S_{CDT}$ of +4-+23‰; $^{18}O_{SMOW}$ of +9.0-+26‰) are indicative of a Dinantian source for the sulphate (from Robinson & Ineson, 1979; Quirk, 1987*a*);

20. sulphur isotopes from galena from the South Pennine Orefield ( $^{34}S_{CDT}$ of -23-+7‰ are similar to total sulphur within Namurian shale (from Robinson & Ineson, 1979; Quirk, 1987*a*);

21. the unusual uniformity of lead isotope ratios in galena from the South Pennine Orefield ($^{206}Pb/^{204}Pb$ of 18.45 +/- 0.02; $^{208}Pb/^{204}Pb$ of 15.62 +/- 0.01; $^{208}Pb/^{204}Pb$ of 38.32 +/- 0.03) indicate that orefluid migrated only a short distance, over a relatively short period of time from a uranium-enriched source rock such as shale (from Coomer & Ford, 1975);

22. lead isotopes of galena from the South Pennine Orefield most closely match those calculated for Namurian shale during the Upper Carboniferous (from Coomer & Ford, 1975; H. Mills, *pers. comm.*);

23. the basal Namurian shales overlying and adjacent to the mineralised Asbian-Brigantian carbonates of the South Pennine Orefield have unusually high concentrations of fluorine (eg. 730+/-113 ppm), barium (eg. 355+/-298 ppm), lead (eg. 67+/-53 ppm), zinc (eg. 164+/-326 ppm) and uranium (Spears & Amin, 1981; Harrison *et al*, 1982; K. Ball, *pers. comm.*);

24. the present day groundwaters emerging from the basal Namurian shales overlying and adjacent to the North Derbyshire Shelf are acidic and rich in metal ions relative to groundwater from the limestone (Edmunds, 1971);

Much of the evidence above suggests that the South Pennine Orefield was formed during the late Stephanian/early Autunian, approximately 290 million years ago, when the North Derbyshire Shelf was at maximum burial. Orefluid was sourced from Namurian shale, along the NE side of the North Derbyshire Shelf, and flowed through Dinantian limestone where this was relatively permeable, particularly in fractured and dolomitized zones. Precipitation of ore minerals was due to wall-rock and porefluid interactions. However, in order to refine these conclusions, a genetic model has been developed for the South Pennine Orefield

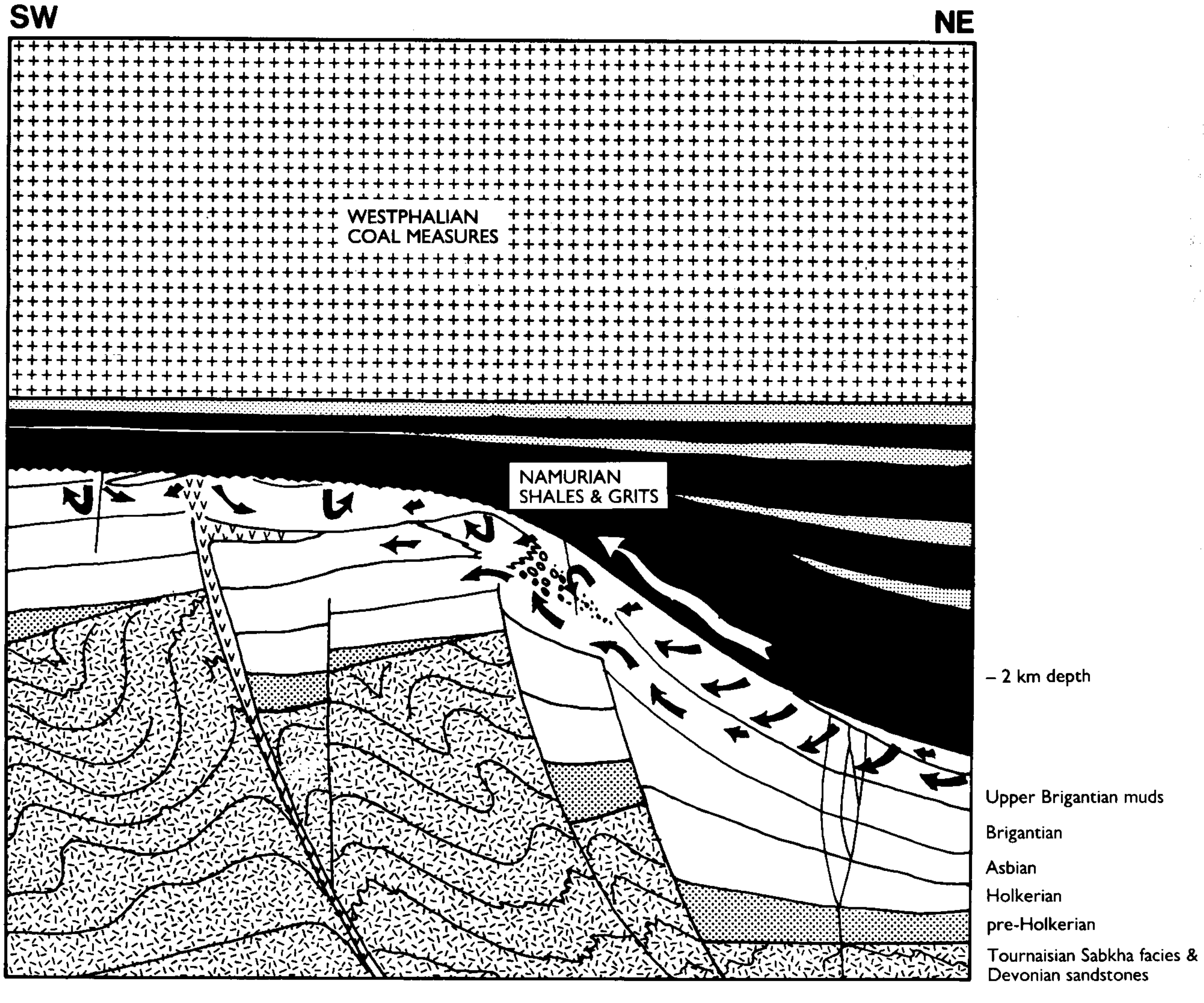


*Figure 9* Model for the formation of the South Pennine Orefield during end Stephanian/early Autunian times. The arrows indicate schematically the direction of flow of low pH, F-Ba-Pb-Zn-S-enriched orefluid derived from Namurian shales where it entered dilatant fractures and porous zones in the upper part of the North Derbyshire Shelf.

by Quirk (1987*a*) to explain the current geological, geochemical and geophysical data. This model is briefly described below. Other ideas on the origin of the South Pennine Orefield are reviewed by Emblin (1978), Ineson & Ford (1982), Dunham (1983) & Ridge (1984).

## FORMATION OF THE SOUTH PENNINE OREFIELD

During the late Stephanian/early Autunian, at the end of the Carboniferous, all of Europe, north of the Variscan mountains, experienced N-S extension associated with high heat flow. The top of the North Derbyshire Shelf was at this time buried at a depth of approximately 2km (Fig. 6). NW-SE and NE-SW joints and ENE-WSW wrench faults already present in the limestone began to dilate as a result of this N-S extension. The East Midlands Basin itself began to invert at its NE end whilst continuing to subside at its SW end, thus creating a hydraulic gradient (Quirk, 1987*a*). Meteoric water began to flow in a SW direction from the Askern-Spital-Nocton High and through the tilted Carboniferous strata of the East Midlands Basin (Fig. 7). This process is known as hydrodynamic or gravity-induced flow (Toth, 1978; Garven & Freeze, 1984a; Garven & Freeze, 1984b; Garven, 1985).

The rate of flow of water through the East Midlands Basin during the late Stephanian/early Autunian was probably in the order of 1m per year (Quirk, 1987*a*). With increasing depth the water became considerably modified by diagenetic interactions so that a highly saline (NaCl) porefluid was formed. The temperature of the porefluid was controlled by the geothermal gradient of the East Midlands Basin which is estimated to have been 50-60°C per kilometre during this time. At a depth of 2km in the North Derbyshire area this porefluid was migrating through shales in the lower part of the Namurian section (Fig. 7). These shales, which are marine in origin, have unusually high concentrations of fluorine, barium, lead and zinc and the porefluid was consequently enriched in these components as well as hydrogen and sulphide ions. These ore components were carried in solution as aqueous complexes due to the high salinity and low pH of the fluid, thus forming orefluid. This flowed into dilatant limestone on the NE side of the North Derbyshire Shelf where it protruded into the overlying Namurian strata (Fig. 8).

The orefluid was calcium-poor, of low pH and relatively highly concentrated in reduced sulphur. Therefore it was reactive with both the limestone and the CaCl, sulphate-enriched porefluid already present in the North Derbyshire Shelf. As a result of this interaction an increase in pH, calcium concentration and sulphate concentration occurred within the orefluid and led to precipitation of fluorite (eg. 20mg per litre orefluid), baryte (eg. 40mg per litre orefluid), galena (eg. 20mg per litre orefluid) and sphalerite.

The spent orefluid continued to flow towards the SW side of the East Midlands Basin eventually to emerge as artesian springs in the vicinity of the Widmerpool Gulf (Fig. 7).

It is calculated that 2000km$^3$ of water flowed through the North Derbyshire Shelf over a period of some 0.7 million years to form the South Pennine Orefield. 50ppm fluorine, 60ppm barium, 20ppm lead, 5ppm sphalerite and <25ppm sulphur were removed from approximately 500km$^3$ of basal Namurian source rock during this time.

## CONCLUSIONS

There is a unique origin for the South Pennine Orefield. Mineralization occurred during the late Stephanian/early Autunian at a depth of burial of 2km. Orefluid was derived from meteoric water that migrated from the Askern-Spital-Nocton High. This became enriched in fluorine, barium, lead, zinc, reduced sulphur and hydrogen ions where it moved through Namurian shale in the deeper part of the East Midland Basin. This fluid entered permeable Dinantian carbonates on the NE side of the North Derbyshire Shelf. Fluorite, baryte, galena, sphalerite and calcite were precipitated following a relative increase in pH, calcium and sulphate concentrations in the orefluid on entering the limestone.

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