

CLASSIFICATION OF THE SOUTH PENNINE OREFIELD

by

Mohammed A. Mostaghel

Summary

The general characteristics of mineralisation in the South Pennine Orefield are compared with the common characteristics of Mississippi Valley-type ore deposits and it is concluded that the South Pennine Orefield should be considered to be an example of Mississippi Valley-type ore mineralisation. A comparative study of the South Pennine Orefield with two other major carbonate-hosted lead-zinc districts, namely, the English Northern Pennines and Central Ireland, has shown that, despite some similarities, they belong to three different classes of ore deposits.

Introduction

Since the first discovery of carbonate-hosted lead-zinc deposits in the Mississippi Valley region of the United States, the term "Mississippi Valley-type" ore deposits has been applied, in a general sense, to those base metal sulphide deposits formed in unmetamorphosed sedimentary carbonates. Over the years the genesis and the characteristics that differentiate the Mississippi Valley-type ore deposits as a group have been controversial. Although the current opinion on the genesis of these deposits is that, in most cases, the ore bodies are sedimentary and diagenetic in origin, there is still some confusion concerning the characteristics which have provided the basis for the classification of Mississippi Valley-type ore deposits. In this context the South Pennine Orefield is not an exception.

Although Ford (1976), Worley and Ford (1977) and Worley (1978) have "simply" cited the South Pennine Orefield as an example of Mississippi Valley-type ore deposits in the British Isles, Emblin (1978) has argued that there are three "essential differences between the conditions of the Pennine ore deposits and the Mississippi Valley type criteria". According to Emblin (1978), the three differences 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 mineralisation 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".

Because of these differences, Emblin (1978) proposed a new class of ore deposits, termed "Pennine-type", to characterise the ore deposits in the orefields of the Northern Pennines (Alston and Askrigg Blocks) and South Pennines (Derbyshire Dome). As discussed below, the nature and genesis of ore mineralisation in the Northern Pennine Orefield is different from that of the South Pennine Orefield and, although the two orefields show some similarities, in the author's opinion they belong to two different groups of ore deposits. Moreover, two important references defining the characteristics of Mississippi Valley-type ore deposits (Ohle, 1959; Brown, 1970) are at variance with the criteria proposed by Emblin (1978). The pioneer work of Ohle (1959), which summarised and reviewed the information available in 1957 on the geology of Mississippi Valley-type ore deposits in the United States and other countries was the first attempt to determine the common characteristics of these deposits. In 1970, Brown published a review and sequel to the Behre Symposium, held in New York in March, 1966, on the problems of the origin of Mississippi Valley-type ore deposits, in which he pointed out their distinctive

Mercian Geologist, vol. 10, no. 1,
1985, pp. 27-38.

characteristics in the central United States and discussed the different North American and European schools of thought concerning the origin of these deposits. These two publications, in the opinion of the author, indicate that the three differences cited by Emblin (1978) as a means of separating the Pennine orefields from Mississippi Valley-type ore deposits, can be regarded as either falling within the Mississippi Valley-type category or as relatively minor differences which may be found within ore bodies of almost any other category of ore deposit (White, 1968).

Some of the Mississippi Valley-type ore mineralisation has been found in the carbonates of foreland fold and thrust belts and in areas that have been strongly affected by orogenies (Anderson and Macqueen, 1982; Ohle, 1959). The influence of tectonic and structural activities on the deposition of sulphides in sedimentary rocks can be summarised as: (a) raising the geothermal gradient of the region; (b) orogenies providing additional forces for migration of the mineralising fluids, especially during the later phases of fluid migration (Mostaghel, 1983a); (c) faults providing channel-ways for migrating fluids which may be responsible for reopening, by hydraulic fracturing, pre-existing faults (Firman, 1977); and (d) folding providing positive structures which are favourable reservoirs for ore mineralisation (Mostaghel, 1984a). These factors do not affect or change the processes of ore deposition other than facilitating the process of ore fluid migration.

The presence of replacement mineralisation is not uncommon in Mississippi Valley-type ore deposits. Ohle (1959) pointed out that "most of the tonnage of Mississippi Valley type ore has come from bedded replacement deposits and in these the ore of each district shows great selectivity for certain favourable beds". The replacement of the limestone host rock by ore minerals, and especially by fluorite, has been documented in many Mississippi Valley-type orefields, for example in the southern Illinois area of the United States (Ohle, 1959).

It has been estimated that approximately 75 percent of the mineralisation in the South Pennine Orefield is in the form of discordant deposits and only 25 percent is stratiform (Mostaghel, 1984a). Although most of the Mississippi Valley-type ore deposits are stratiform or strata-bound, some of the ore bodies of this group are discordant. In a review of the common characteristics of the lead-zinc districts in the central United States, Brown (1970) stated that "the ores ... occur mainly in certain preferred horizons or strata and are sufficiently conformable to bedding that they usually, though not always, may be described as stratiform or strata-bound" but "in Kentucky-Illinois the deposits are chiefly fissure veins". Ohle (1959) also gave examples of discordant deposits in the ore bodies which are classified as Mississippi Valley-type. Thus the author disagrees with Emblin's (1978) suggestion that the South Pennine Orefield differs significantly from Mississippi Valley-type ore deposits.

In a recent review of ore genesis in the English Pennines, Dunham (1983) suggested that the orefields of the South and Northern Pennine, Illinois-Kentucky, central Kentucky and Sweetwater should be recognised as a fluoritic subtype of the Mississippi Valley-type ore deposits on account of their distinguishing characteristics which include the presence of extensive fluorite mineralisation and association with deep-going fracture systems. As discussed below, the present author is of the opinion that, despite their general similarities, the genesis of ore mineralisation in the South Pennine Orefield is not entirely similar to that of the Northern Pennine orefield and the two orefields should not be classified into one subtype or one class of ore deposit. Although extensive fluorite mineralisation took place in the Pennine orefields, not all the deposits contain fluorite (Mostaghel, 1983b) and, in fact, the base metal sulphides have some preference for association with calcite throughout the South Pennine orefield (Mostaghel, 1984b). The subdivision of Mississippi Valley-type ore deposits on the basis of the presence or amount of a particular mineral would result in not only having a large number of subtypes but also in dividing the ore bodies of a single orefield into different subtypes with, presumably, a common origin.

To discuss the classification of the South Pennine Orefield, a review of general characteristics of Mississippi Valley-type ore deposits and the South Pennine Orefield is presented in this paper, together with a comparative study of carbonate-hosted lead-zinc deposits in the Pennine orefields and central Ireland.

Common characteristics of Mississippi Valley-type ore deposits

As stated by Brown (1970), "although no precise definition of a Mississippi Valley-type ore deposit exists, the term embraces a large number of common characteristics" and, as noted by Ohle (1959), "although not all of the ores from the different districts exhibit all of the characteristics, there are present invariably enough of the typical features so that most geologists quickly identify each area as a representative of the Mississippi Valley type". Several authors have attempted to identify the most common characteristics of these ore deposits. The contribution of Ohle (1959) has been updated by White (1968), Brown (1970), Heyl *et al.* (1974) and most recently, by Anderson and Macqueen (1982). Gustafson and Williams (1981) and BJORLYKKE and SANGSTER (1981) also discussed the broader relationships between the different types of ore deposits hosted by sedimentary rocks. The following are characteristic of Mississippi Valley-type ore deposits:

1. According to Ohle (1959), “the one universal and fundamental characteristic shown by all of these deposits is a lack of nearby bodies of igneous rocks that are obvious or even likely sources of the ore solutions” and “this characteristic of Mississippi Valley type ore, of course, is the one that has confounded the hydrothermal school”. Furthermore, Ohle (1959) stated that “most of the districts have no evidence whatever of igneous activity that is younger than the ore host rock”. Brown (1970) also pointed out that “igneous activity is minor or lacking in most mineralized areas and, even where present, has little or no obvious connection with mineralization”.
2. “Most rocks are not metamorphosed regionally and the deposits show no signs of having undergone any important physical alteration since deposition except for weathering on outcrop” (Brown, 1970). Anderson and Macqueen (1982) also pointed out that the host rocks of Mississippi Valley-type ore deposits are unmetamorphosed.
3. “Most deposits occur in carbonate rocks, with a strong bias toward dolomites” (Anderson and Macqueen, 1982). Minor mineralisation may take place in associated sandstones (Brown, 1970).
4. Although the ores are mainly stratiform or strata-bound, “a smaller but still important production has come from veins such as those in Central Kentucky and Tennessee, in England and in the Illinois-Kentucky fluorspar district” (Ohle, 1959).
5. “Individual deposits, similar to one another in their occurrence, tend to occur in districts which may be distributed over hundreds of square kilometres” and “this argues against strictly local sources for metals and sulphur” (Anderson and Macqueen, 1982).
6. “Deposits occur in most sedimentary basins in all parts of the world” and, “host rocks range in age from Proterozoic to Cretaceous, although many fewer deposits are known in the Proterozoic, Jurassic and Cretaceous than in the Cambro-Ordovician and Carboniferous” (Anderson and Macqueen, 1982).
7. “Deposits tend to be found at or near the edges of basins as presently preserved, or on arches between basins” (Anderson and Macqueen, 1982). “There is a definite tendency for the ore to occur in structurally positive areas” such as knob structures, folds, domes and the sedimentary depositional arches (Ohle, 1959).
8. The ore deposits “may occur in relatively undisturbed platformal carbonates, or within foreland fold and thrust belts” (Anderson and Macqueen, 1982). Ohle (1959) stated that the ore deposits of Mississippi Valley-type are mostly located in passive structural regions, and these regions “have not undergone strong mountain building activity since the ore-bearing beds were deposited”. However, “this is not to imply ... that none of the districts lie in areas that have been affected by orogeny” (Ohle, 1959).
9. As noted by Anderson and Macqueen (1982), “some deposits appear to be strongly controlled by unconformity-associated features such as paleokarst terrane” (e.g., East Tennessee, U.S.A.; Pine Point, Canada), and “some deposits tend to be localized along facies fronts between platformal carbonates and basinal shales” (e.g. Robb Lake, Canada).
10. “Although early workers commonly suggested that deposits were located within carbonate reef masses, subsequent work on many deposits demonstrates that actual reef-hosted deposits are minor” (Anderson and Macqueen, 1982).
11. There is evidence of ore mineralisation in solution and collapse structures (sink holes, collapsed caves) in a number of Mississippi Valley-type ore deposits (Ohle, 1959).
12. In some deposits “stratigraphic evidence suggests that mineralization took place at relatively shallow depths” (Anderson and Macqueen, 1982).
13. There is very little variation in the mineralogy of Mississippi Valley-type ore deposits, with galena and/or sphalerite as the principal sulphide and pyrite, marcasite and chalcopyrite as the accessory metalliferous minerals (Ohle, 1959; Brown, 1970; Anderson and Macqueen, 1982). Dolomite, calcite, fluorite and baryte are present in varying proportions. As noted by Anderson and Macqueen (1982), “commonly, galena is low in silver, and sphalerite is low in iron” in the Mississippi Valley-type ore deposits. Sphalerite occasionally shows colour banding which is “indicative of minor compositional variation” (Brown, 1970).
14. “Coarse crystallinity of sphalerite, galena and fluorite, especially in the usually abundant cavities, is characteristic” (Brown, 1970).

15. "The ores are relatively lean in precious metals, but high in various trace elements (Cu, Cd, Ge, Ga, Co, Ni, Hg, etc.) which differ in different deposits" (Brown, 1970).
16. "Studies of fluid inclusions within coarsely crystalline [fluorite,] sphalerite, barite and carbonates have established two important facts: (a) mineralization temperatures on average ranged from 80°C to 200°C, and (b) ore-bearing fluids were highly saline Na-Ca-Cl brines" (Anderson and Macqueen, 1982). These brines "are similar to but five to ten times as concentrated as sea water" (Brown, 1970).
17. "Organic materials in the form of kerogen or bitumen in the host rocks and/or petroleum in fluid inclusions is very commonly observed" in the Mississippi Valley-type ore deposits (Anderson and Macqueen, 1982). "The association between 'oil and ore' is so complete that ... it was inevitable that oil was involved as one of the ore-forming fluids" in formation of Mississippi Valley-type ore deposits (Dunsmore and Shearman, 1977).
18. Sulphur isotope studies of galena and sphalerite "show that sulphur is generally heavy and with fairly wide ranging values" which "establishes a crustal, ultimately sea-water origin involving sulphate-reduction at some time in the genetic story" (Anderson and Macqueen, 1982).
19. "Lead isotopes can also show a considerable range in any one district, and are commonly highly radiogenic, yielding future ages (negative model ages)" (Anderson and Macqueen, 1982).
20. "Open space, developed by a variety of mechanisms in carbonate rocks ... seems to be a prime requisite for the development of an economic deposit" (Anderson and Macqueen, 1982).

General characteristics of ore mineralisation in the South Pennine Orefield

The general characteristics of the ore deposits in the South Pennine Orefield are briefly discussed here employing the same order as is used in the preceding section for the Mississippi Valley-type ore deposits.

1. The igneous rocks in the South Pennine Orefield include basaltic lava flows, tuff and ash horizons, vents and occasional sills and dykes. Some thirty lava and tuff horizons are recognised in the orefield (Walters and Ineson, 1980) though many have no surface exposure. The volcanic activity occurred in the Lower Carboniferous prior to ore mineralisation. Although it was a long held general belief that ore minerals were rare within igneous rocks of the orefield, Walters and Ineson (1980) have compiled a list of localities in the orefield where ore is found in lava and tuff horizons.
2. The host rocks are not metamorphosed and the ore deposits have not undergone any important physical alteration other than weathering which has resulted in formation of secondary minerals (Mostaghel, 1984a).
3. The ore deposits are largely hosted by limestone. Some mineralisation is also found in dolomitised limestones and dolomites, especially in the southeast part of the orefield where the porosity of dolomites has been an important factor in controlling mineralisation, and a little in overlying Upper Carboniferous shales and sandstones.
4. Although the ores are strata-bound, only 25 percent are stratiform and the remaining 75 percent are discordant vein deposits (Mostaghel, 1984a).
5. The South Pennine Orefield occupies an area of about 900 Km² of exposed Lower Carboniferous limestones (Rogers, 1977). There is also evidence of ore mineralisation in the concealed eastward extension of the orefield (Ineson and Ford, 1982).
6. The age of the host rocks is Lower Carboniferous (Dinantian) which is divided into Courceyan, Chadian, Arundian, Holkerian, Asbian and Brigantian stages. The first three stages are known largely from deep boreholes whereas the other three stages are widespread at outcrop surfaces (Worley, 1978).
7. The South Pennine Orefield is located on a structural high between the North Sea Basin to the east and the Cheshire-Irish Sea Basin to the west.

8. The limestone host rocks were deposited in an active structural region on a pre-Carboniferous basement thought to have a graben structure in which the central block of the basement is downthrown relative to the northern and southern blocks (Maroof, 1976). The structure of this basement beneath the orefield has affected the structure of the overlying rocks. The predominant structural element of the orefield is the Derbyshire Dome with the Dinantian limestones as its core. The dome is an asymmetrical anticline with a flat north-south culmination toward its western margin. Superimposed on this structure are folds and faults within the limestones and the younger rocks. Folding developed during sedimentation of the limestones and resulted in the development of lagoonal and reef environments on the anticlines and basinal environments in the synclines (Ford, 1977). The earliest faults were initiated during the Dinantian and some illustrate subsequent reactivation during mineralisation. The main structural features of the orefield were produced during the Hercynian Orogeny in Permian times. A further period of structural deformation affected the orefield and the surrounding areas during the Alpine Orogeny in the Miocene resulting in renewed faulting and gentle folding (Frost and Smart, 1979).
9. The orefield is located below an erosion surface which was produced in late Dinantian or early Namurian prior to Upper Carboniferous sedimentation.
10. The reef-hosted deposits in the South Pennine Orefield form a minor proportion of the total ore mineralisation in the orefield.
11. A number of deposits in the orefield are found in solution and collapse structures.
12. Mineralisation in the South Pennine Orefield occurred at relatively shallow depths within the crust (Mostaghel, 1984a).
13. The principal sulphide mineral is galena which usually constitutes, with sphalerite and pyrite, less than 10 percent of the minerals present in most ore bodies. More than 90 percent of the deposits contain varying proportions of calcite, fluorite and baryte.
14. A number of minerals, especially calcite, fluorite and galena, show coarse crystallinity in some areas of the orefield.
15. The galenas from the orefield are low in silver (less than 10 ppm on average) and sphalerites are iron-poor with less than 0.7 mole percent of FeS₂ (Mostaghel, 1984a).
16. The ore fluid depositional temperature is estimated to have been between 50°C and 150°C and the ore fluids are thought to be concentrated saline brine dominated by Na, Ca and Cl (Atkinson *et al.*, 1982; Rogers, 1977).
17. Hydrocarbons are present in the form of asphalts, bitumen, pitch, or thick, heavy, unconsolidated oil and occasionally as bitumens in fluid inclusions of fluorite (Atkinson, *et al.*, 1982). These hydrocarbons are sometimes localised in the limestones to form a bitumen deposit but often disseminated through the pore spaces of the limestones either as a matrix component or as the bonding material (Mostaghel, 1984a). The presence of bitumen and asphalt traces in or near the ore bodies is common and many oil "shows" have been encountered in nearby colliery workings in addition to commercial oil and gas discoveries on both at the top of the Lower Carboniferous limestones and in the overlying Upper Carboniferous sediments, in te areas surrounding the orefield (Frost and Smart, 1979). The association between mineralisation and hydrocarbon generation leads to the conclusion that "oil" was involved in the ore forming process (Mostaghel, 1984a).
18. Robinson and Ineson (1979) found that galenas from the orefield have sulphur isotope composition of -23.2 to 6.6‰ whereas the analysed sphalerite and baryte samples show a spread of -16.0 to -9.5‰ and +4.4 to 22.6‰, respectively.
19. A study of lead isotope ratios in galenas from the orefield by Coomer and Ford (1975) has shown that the lead in these galenas is anomalous J-type and yields negative ages, though the ratios do not show a particularly wide spread.
20. Mineralisation in the South Pennine Orefield occurred in the open spaces in the Limestones; indeed a distribution map of the discordant (vein) deposits of the orefield is almost identical to a structural map of the faults. The ore fluids were apparently responsible for reopening, by hydraulic fracturing, pre-existing primary and secondary wrench faults. (Firman, 1977). The precipitation of ore minerals from these

solutions in faults and fractures resulted in formation of discordant deposits (rakes and scrins) which form a substantial part of the mineralisation.

Classification

The similarities between the general characteristics of the Mississippi Valley-type ore deposits and the ore deposits in the South Pennine Orefield are apparent when the preceding two sections are compared. Therefore, the inevitable conclusion is that the South Pennine Orefield belongs to the Mississippi Valley-type class of ore deposits. However, there are differences amongst the various types of ore deposits which may owe their genesis in some way to connate (formation) waters. Table 1 summarises the results of a comparison between the general characteristics of ore mineralisation in the South Pennine Orefield with those of carbonate-hosted lead-zinc deposits in the Northern Pennines and the Tournaisian of Central Ireland.

Although there are some common characteristics between the style and environment of mineralisation in the three orefields listed in Table 1, the deposits in these districts belong, in the writer's opinion, to three different groups. The South Pennine Orefield represents a group of ore deposits which were probably formed by refluxing connate brines during the diagenesis of the enclosing host rocks. The ore minerals of these deposits were precipitated from Na-Ca-Cl fluids at temperatures which were attained likely by deep sedimentary burial and were lower than those present during formation of the other two groups discussed here. The lead in galenas from these deposits has a range of isotopic compositions and, in most cases, is found to be enriched in the radiogenic isotopes.

The Tournaisian-hosted ore deposits in Ireland are considered by some authors to be carbonate-hosted submarine exhalative lead-zinc deposits (e.g., Large, 1981; Badham, 1981; Russell *et al.*, 1981). Badham (1981) stated that formation waters are "either dispersed or form ... secondary Pb-Zn deposits" in carbonate rocks; but "in areas of higher than normal heat flow and active tectonism such fluids may be expelled from the sedimentary column, particularly up faults" and "if this occurs beneath the sea into a euxinic environment, sulphide [minerals] may be precipitated". According to Badham (1981), "if expulsion continues for some time and if the sedimentation rate is low, considerable volumes of sulphide [minerals] may accumulate". Russell *et al.* (1981) pointed out that this group of ore deposits "formed in local basins on the sea floor as a result of protracted hydrothermal activity accompanying continental rifting". As in the case of Mississippi Valley-type ore deposits, formation (connate) waters and episodic basin dewatering are involved in formation of submarine exhalative lead-zinc deposits (Cathles and Smith, 1983; Sawkins, 1984). However, sea water and downward penetrating convection cells are also involved in the genesis of the sediment-hosted exhalative ore deposits according to Russell *et al.* (1981). As pointed out by Large (1981), Mississippi Valley-type ore deposits "generally lack many of the internal characteristics of the sediment-hosted, submarine exhalative sulphides—no stratiform mineralisation [stratification in the ore bodies], little or no copper mineralisation, no distinctive metal zonation sequences, no hydrothermal alteration, as well as non-conformable (anomalous) and generally inhomogeneous Pb-isotope characteristics". Fluorite is considered to be rare in submarine exhalative mineralisation (Large, 1981). As noted by Sawkins (1984), in a general sense, the sediment-hosted exhalative lead-zinc deposits and Mississippi Valley-type ore deposits "can be viewed as end-member variants of the same general episodic sediment dewatering process, the former related mainly to rift basins, the latter to epicratonic basins". Therefore, although there are some similarities between the ore mineralisation in the South Pennine orefield and the Tournaisian of Ireland (Table 1), it is concluded that they belong to two different groups of ore deposits, the former is a Mississippi Valley-type ore deposit, the latter a submarine exhalative deposit.

In the author's opinion the Northern Pennine Orefield occupies an intermediate position between the Mississippi Valley-type ore deposits and the submarine exhalative ore bodies. The ore deposits of this area are believed to have been formed by interplay of connate waters, derived from the sediments in the adjacent sedimentary basins, and hydrothermal solutions rising through the Weardale Granite buried beneath the orefield (e.g., Sawkins, 1966; Ineson, 1976). The minerals in the Northern Pennine Orefield were precipitated from relatively potassium-rich Na-Ca-Cl brines at temperatures higher than those found in the Mississippi Valley-type ore deposits. The northern half of the orefield (Alston Block) exhibits an areal concentric zonation of fluorite surrounded by an outer zone of baryte and calcite (Ineson, 1976). This part of the orefield is also "vertically zoned with quartz-chalcopyrite-pyrrhotite at depth passing upwards to galena-sphalerite, fluorite-baryte and finally baryte" (Ineson, 1976). The zonation is believed to be related to the dual origin of the orefield (Ineson, 1976). As mentioned in the introduction, there are major differences between the two Pennine orefields. The most important of these dissimilarities are the following (*cf.*, Dunham, 1983, for more detail):

1. Sphalerites in the North Pennine Orefield, and especially in the Alston Block, are rich in iron because of the higher formation temperature for mineral deposition in this orefield (Vaughan and Ixer, 1980) and leaching of the Whin Sill.

2. The mean Ag content of galenas is 150 ppm in Alston Block, 40 ppm in Askrigg Block and less than 10 ppm in the South Pennine Orefield (Dunham, 1983; Mostaghel, 1984a).
3. The Pb isotopes in galenas are inhomogeneous and anomalous (J-type) in the South Pennine Orefield whereas they are conformable and homogeneous in the Northern Pennine Orefield (Coomer and Ford, 1975; Dunham, 1983). Some Pb isotopes in galenas from the Askrigg Block are inhomogeneous and give negative model ages (Dunham, 1983).
4. The ore fluids had different chemistry in the Pennine orefields. As noted by Rogers (1977), the mineralisation in the South Pennine Orefield “may represent the end member in a range of increasing temperature and potassium levels when compared to the mineralization of the Askrigg Block, which occupies the intermediate position, and of the Alston Block, with a strong enrichment of potassium”.
5. As noted by Atkinson *et al.* (1982), there is a marked increase in the mean homogenisation temperature of fluid inclusions in fluorite crystals from the South Pennine Orefield (low), the Askrigg Block (intermediate) and the Alston Block (high). There are also a number of hot spots within the fluorite zone in the Alston Block (Dunham, 1983; Atkinson *et al.*, 1982).
6. The zonation of the non-metallic minerals is well defined in the Northern Pennine Orefield (Dunham, 1983). In the South Pennine Orefield, although most of the fluorite deposits are found near the eastern margin of the orefield they overlap and interdigitate with baryte and calcite deposits both of which have very irregular distribution patterns (Mostaghel, 1983b).
7. Metasomatism is a common phenomenon in the Northern Pennine Orefield, especially in strata adjacent to the veins and in quartz-dolerite sills and dykes (Ineson, 1976).
8. Unlike the South Pennine Orefield, diagenetic structures (solution collapse breccias and zones of secondary porosity) are unimportant as host structures in the Northern Pennine Orefield (Ineson, 1976).
9. Frequently dolomite, ankerite and quartz minerals are found, as principal minerals, within the ore deposits of the Northern Pennine Orefield indicating the presence of significant Mg and Si in the ore fluids responsible for some deposition in this orefield. The veins of the Alston Block contain between 8 to 25 percent quartz (Ineson, 1976) whereas this mineral is generally rare in the ore deposits of the South Pennine Orefield.
10. Both witherite and ankerite occur in the Northern Pennine Orefield, especially in the Alston Block, but are absent from the South Pennine Orefield.
11. Smith (1974) has demonstrated that the yttrium content of fluorite is greatest in the Northern Pennine Orefield.
12. Fluorite is fluorescent in the North Pennine Orefield whereas, with minor exception, there is a general lack of fluorescence in the minerals of the South Pennine Orefield which may be attributable to the lack of rare earth elements, in these minerals.
13. The characteristics of the ore mineralisation of the southern half (Askrigg Block) of the Northern Pennine Orefield may be considered to have an intermediate style of ore mineralisation, with the other Pennine orefields as the two end-members.

Conclusions

1. The characteristics of ore mineralisation in the South Pennine Orefield are typical of Mississippi Valley-type ore deposits.
2. The present author is of the opinion that, despite some similarities, the ore deposits of the South Pennine Orefield and the Tournaisian of Ireland belong to two distinct classes of ore deposit, the former is a Mississippi Valley-type deposit, the latter a submarine exhalative deposit. An intermediate position between these two classes of ore deposit is occupied by the Northern Pennine Orefield which is thought to have a dual origin.

3. The mineralisation in the southern half of the Northern Pennine Orefield has characteristics between those of the South Pennine Orefield and the northern half of the Northern Pennine orfield.

Acknowledgments

This paper is a by-product of a Ph.D. research project on the ore mineralisation in the South Pennine Orefield. I am greatly indebted to Dr. T.D. Ford, University of Leicester, who supervised the original work and commented on the manuscript. Thanks are also due to my wife, Elisabeth, for preparation of the table and the manuscript. The author remains solely responsible for the views expressed here.

References

- Anderson, G.M. and Macqueen, R.W., 1982. Ore deposits models-6. Mississippi Valley-type lead zinc deposits. *Geoscience Canada*, 9, 108-117.
- Atkinson, P., Moore, J. McM. and Evans, A.M., 1982. The Pennine orfields of England with special reference to recent structural and fluid inclusion investigations. *Bull. Bur. Rech. geol. min. Paris*, 2, 149-156.
- Badham, J.P.N., 1981. Shale-hosted Pb-Zn deposits: products of exhalation of formation waters? *Trans. Instn. Min. Metall.* (Sect. B: Appl. Earth Sci.), 90, B70-B76.
- Bishara, W.W., 1966. *Studies on trace and minor elements in sphalerite and galena from the northern Pennine Orefield*. Ph.D. thesis, Univ. of Leeds, 113 pp.
- Bjorlykke, A. and Sangster, D.F., 1981. An overview of sandstone lead deposits and their relationship to red-bed copper and carbonate-hosted lead-zinc deposits. In B.J. Skinner (ed.), *Economic Geology Seventy-Fifth Anniversary Volume*, 179-213.
- Boast, A.M., Coleman, M.L. and Halls, C., 1981. Textural and stable isotopic evidence for the genesis of the Tynagh base metal deposit, Ireland. *Econ. Geol.*, 27-55.
- Boast, A.M., Swainbank, I.G., Coleman, M.L. and Halls, C., 1981. Lead isotopic variation in the Tynagh, Silvermines and Navan base-metal deposits, Ireland. *Trans. Instn. Min. Metall.* (Sect. B: Appl. Earth Sci.), 90, B115-B119.
- Brown, J.S., 1970. Mississippi Valley type lead-zinc ores. *Mineral. Deposita*, 5, 103-119.
- Cathles, L.M. and Smith, A.T., 1983. Thermal constraints on the formation of Mississippi Valley-type lead-zinc deposits and their implications for episodic basin dewatering and deposit genesis. *Econ. Geol.*, 78, 983-1002.
- Coomer, P.G. and Ford, T.D., 1975. Lead and sulphur isotope ratios of some galena specimens from the south Pennines and north Midlands. *Mercian Geol.*, 5, 291-304.
- Coomer, P.G. and Robinson, B.W., 1976. Sulphur and sulphate-oxygen isotopes and the origin of the Silvermines deposits, Ireland. *Mineral. Deposita*, 11, 155-169.
- Deeny, D.E., 1981. An Irish Carboniferous metallogenetic model. *Trans. Instn. Min. Metall.* (Sect. B: Appl. Earth Sci.), 90, B183-B185.
- Dunham, K.C., 1983. Ore genesis in the English Pennines: a fluoritic subtype. In *Proc. Int. Conf. on Mississippi valley type lead-zinc deposits*, 1983, Rolla, Univ. of Missouri, 86-112.
- Dunham, D.C., Dunham, A.C., Hodge, B.L. and Johnson, G.A.L., 1965. Granite beneath Viséan sediments with mineralization at Rookhope, northern Pennines. *Q. J. geol. Soc. Lond.*, 121, 383-417.
- Dunsmore, H.E. and Shearman, D.J., 1977. Mississippi Valley-type lead-zinc orebodies: a sedimentary and diagenetic origin. In P. Garrard (ed.) *Proc. Forum on oil and ore in sediments*, Imperial College London, 189-201.
- Emblin, R., 1978, A Pennine Model for the diagenetic origin of bas-metal ore deposits in Britain. *Bull. Peak Dist. Mines Hist. Soc.*, 7, 5-20.
- Firman, R.J., 1977. Derbyshire wrenches and ores—a study of the rakes' progress by secondary faulting. *Mercian Geol.*, 6, 81-96.
- Ford, T.D., 1976. Mississippi-Valley type ore deposits in Britain. *25th Int. Geol. Cong.*, Sydney, Australia, Abstracts, 1, 161-162.
- Ford, T.D. (ed.), 1977. *Limestone and caves of the Peak District*. Geo Abstracts Ltd., Norwich, 469 pp.
- Frost, D.V., and Smart, J.G.O., 1979. Geology of the country north of Derby (explanation of geological sheet 125). *Mem. Geol. Surv. G.B.*
- Gustafson, L.B. and Williams, N., 1981. Sediment-hosted stratiform deposits of copper, lead and zinc. In B.J. Skinner (ed.), *Economic Geology Seventy-Fifth Anniversary Volume*, 139-178.

- Heyl, A.V., Landis, G.P. and Zartman, R.E., 1974. Isotopic evidence for the origin of Mississippi Valley-type mineral deposits: a review. *Econ. Geol.*, 69, 992-1006.
- Ineson, P.R., 1976. Ores of the Northern Pennines, the Lake District and North Wales. In K.H. Wolf (ed.), *Handbook of strata-bound and stratiform ore deposits*. Elsevier, Amsterdam, 5, 198-230.
- Ineson, P.R., and Ford, T.D., 1982. The south Pennine orefield: its genetic theories and eastward extension. *Mercian Geol.*, 8, 285-303.
- Large, D.E., 1981. Sediment-hosted submarine exhalative lead-zinc deposits—a review of their geological characteristics and genesis. In K.H. Wolf (ed.), *Handbook of strata-bound and stratiform ore deposits*. Elsevier, Amsterdam, 9, 469-507.
- Larter, R.C.L., Boyce, A.J. and Russell, M.J., 1981. Hydrothermal pyrite chimneys from the Ballynoe baryte deposit, Silvermines, County Tipperary, Ireland. *Mineral. Deposita*, 16, 309-317.
- Maroof, S.I., 1976. The structure of the concealed pre-Carboniferous basement of the Derbyshire Dome from gravity data. *Proc. Yorks. geol. Soc.* 41, 59-69.
- Morrissey, C.J., Davis, G.R. and Steed, G.M., 1971. Mineralization in the lower Carboniferous of central Ireland. *Trans. Instn. Min. Metall.* (Sect. B: Appl. Earth Sci.), 80 B174-B185.
- Mostaghel, M.A., 1983a. Genesis of disseminated sulphide assemblages in Niagara Peninsula, Canada. *Geol. Rundsch.*, 72, 353-375.
- Mostaghel, M.A., 1983b. Evolution of the south Pennine orefield: I. regional distribution of major non-metallic minerals. *Bull. Peak Dist. Mines Hist. Soc.*, 8, 369-372.
- Mostaghel, M.A., 1984a. *Trace elements in sulphide minerals and their genesis in the south Pennine orefield*. Ph.D. thesis, Univ. of Leicester, 547 pp.
- Mostaghel, M.A., 1984b. Evolution of the south Pennine orefield: II. mineral associations. *Bull. Peak Dist. Mines Hist. Soc.*, 9, 101-107.
- Ohle, E.L., 1959. Some considerations in determining the origin of ore deposits of the Mississippi Valley type. *Econ. Geol.*, 54, 769-789.
- Riedel, D., 1980. Ore structures and genesis of the lead-zinc-deposit Tynagh, Ireland. *Geol. Rundsch.*, 69, 361-383.
- Robinson, B.W. and Ineson, P.R., 1979. Sulphur, oxygen and carbon isotope investigations of lead-zinc-barite-fluorite-calcite mineralization, Derbyshire, England. *Trans. Instn. Min. Metall.* (Sect. B: Appl. Earth Sci.), 88, B107-B117.
- Rogers, P.J., 1977. Fluid inclusion studies in fluorite from the Derbyshire orefield. *Trans. Instn. Min. Metall.* (Sect. B: Appl. Earth Sci.), 86, B127-B132.
- Rogers, P.J., 1978. Fluid inclusion studies on fluorite from the Askrigg Block. *Trans. Instn. Min. Metall.* (Sect. B: Appl. Earth Sci.), 87, B125-B131.
- Russell, M.J., 1978. Downward-excavating hydrothermal cells and Irish-type ore deposits: importance of an underlying thick Caledonian prism. *Trans. Instn. Min. Metall.* (Sect. B: Appl. Earth Sci.), 87, B168-B171.
- Russell, M.J., Solomon, M. and Walshe, J.L., 1981. The genesis of sediment-hosted, exhalative zinc + lead deposits. *Mineral. Deposita*, 16, 113-127.
- Sawkins, F.J., 1966. Ore genesis in the North Pennine orefield, in the light of fluid inclusion studies. *Econ. Geol.*, 61, 385-401.
- Sawkins, F.J. 1984. Ore genesis by episodic dewatering of sedimentary basins: application to giant Proterozoic lead-zinc deposits. *Geology*, 12, 451-454.
- Sheridan, D.J.R., 1977. The hydrocarbons and mineralisation proved in the Carboniferous strata of deep boreholes in Ireland. In P. Garrard (ed.), *Proc. Forum in oil and ore in sediments*. Imperial College, London, pp. 113-137.
- Solomon, M., Rafter, T.A. and Dunham, D.C., 1971. Sulphur and oxygen isotope studies in the northern Pennines in relation to ore genesis. *Trans. Instn. Min. Metall.* (Sect. B: Appl. Earth Sci.), 80, B259-B275.
- Smith, F.W., 1974. *Factors governing the development of fluor spar orebodies in the North Pennine Orefield*. Ph.D. thesis, University of Durham.
- Vaughan, D.J. and Ixer, R.A., 1980. Studies of sulphide mineralogy of north Pennine ores and its contribution to genetic models. *Trans. Instn. Min. Metall.* (Sect. B: Appl. Earth Sci.), 89, B99-B109.
- Walters, S.G. and Ineson, P.R., 1980. Mineralisation within the igneous rocks of the south Pennine orefield. *Bull. Peak Dist. Mines Hist. Soc.*, 7, 315-325.
- Watling, R.J., 1976. Trace element distribution in primary sulphide minerals from the Kell Prospect, County Longford. *R. Ir. Acad., Proc.*, 76, Sect. B, 242-261.
- White, D.E., 1968. Environments of generation of some base-metal ore deposits. *Econ. Geol.*, 63, 301-335.

Worley, N.E., 1978. *Stratigraphical control of mineralisation in the Peak district of Derbyshire*. Ph.D. thesis, Univ. of Leicester, 263 pp.

Worley, N.E. and Ford, T.D., 1977. Mississippi Valley type orefields in Britain. *Bull. Peak Dist. Mines Hist. Socl.*, 6, 201-208.

M.A. Mostaghel, B.Sc., M.Sc., Ph.D.,
25 8112 36 Avenue, N.W.,
Calgary, Alberta, T3B 3P3,
Canada.

Table 1 Comparison of the general characteristics of the Pennine orefields with the Tournaisian-hosted deposits of Ireland.

<i>Table 1 (part 1)</i>	<i>South Pennine Orefield, U.K.¹</i>	<i>Northern Pennine Orefield, U.K.²</i>	<i>Tournaisian-Hosted Pb-Zn Deposits, Ireland³</i>
I. Host rock character			
A. Mainly Carbonate rocks	***	***	***
B. Favourable stratigraphic horizons for ore precipitation	***	***	***
C. Presence of igneous rocks and tuff horizons	***	***	*
D. Unconformities	***	***	***
II. Post-depositional modification			
A. Dolomitisation	**	***	***
B. Re-crystallisation	***	***	***
C. Silicification	**	***	*
D. Karstification and cavity development	***	***	***
E. Local metasomatism	**	***	
III. Regional mineralisation controls			
A. Orefields located near sedimentary basins	***	***	***
B. Ore deposits localised by major structural features	***	***	***
C. Ore deposits located near facies boundaries of sedimentary or diagenetic origin	**	**	**
IV. Local mineralisation controls			
A. Sedimentary structures (reefs, bars, slump breccias, local facies, pinch-outs and lateral or vertical facies changes) were important in ore localisation	**	**	***
B. Tectonic structures (folding, faulting and fracturing) were important controls of ore mineralisation	***	***	**
C. Diagenetic structures (solution collapse breccias and zones of secondary porosity) are important ore hosts in some deposits	***	*	***
V. Ore character			
A. Coarse and well-developed crystals of ore and gangue minerals	***	***	**
B. Disseminated and/or replacement deposits	**	**	***
C. Most deposits in the orefields contain less than 10% sulphide	***	***	***
D. Main character of the ore deposits			
strata-bound	***	***	***
stratiform	**	*	***
E. Main morphology of the ore deposits			
vein (large vertical and lateral dimensions)	***	***	*
tabular (large lateral relative to vertical dimensions)	**	**	***

<i>Table 1 (part 2)</i>	<i>South Pennine Orefield, U.K.¹</i>	<i>Northern Pennine Orefield, U.K.²</i>	<i>Tournaisian-Hosted Pb-Zn Deposits, Ireland³</i>
VI. Ore mineralogy and paragenesis			
A. Sulphide minerals			
galena	***	***	**
sphalerite	**	**	***
B. Non-metallic minerals			
baryte	***	***	***
fluorite	***	***	
quartz (silica)	*	***	***
dolomite	**	***	***
calcite	***	**	***
witherite		**	
ankerite		**	
C. Ore deposits have simple mineralogy	***	*** ⁴	***
D. Local and/or regional zonation of minerals or metals	**	***	***
E. Repetitive deposition of minerals	***	***	***
F. Simple regional paragenesis	***	*** ⁴	***
VII. Chemical constituents of the ore			
A. Major elements			
Pb, Zn, Fe, Ca, S, C and O	***	***	***
Cu	**	***	***
Mg	**	***	***
Si	**	***	***
Ba	***	***	***
F	***	***	
B. Reported minor and trace elements in galena ⁵			
Ag and Sb	***	***	*** ⁶
Zn, Cu and Fe	***		
Bi and Ca	***		
C. Reported minor and trace elements in sphalerite ⁵			
Fe	***	***	*** ⁶
Pb, Cu and Cd	***	***	***
Mn		***	***
Ag, Ge, Ga, In and Co		***	***
Ca and Sb	***	***	***
Bi	***		
Si and Hg		***	***
Ni, Ti, Ba and Mg			***
VIII. Isotopic composition of the ore			
A. Wide range in lead isotope composition of galena			***
B. Radiogenic lead isotopes enrichment (J- type)	***	**	
C. Wide range in sulphur isotope composition of sulphides	***	***	***

<i>Table 1 (part 3)</i>	<i>South Pennine Orefield, U.K.¹</i>	<i>Northern Pennine Orefield, U.K.²</i>	<i>Tournaisian-Hosted Pb-Zn Deposits, Ireland³</i>
IX. Mineralising fluid character			
A. Concentrated saline brine dominated by:			
Na, Ca and Cl	***		***
Na, Ca, K and Cl		***	
B. Homogenisation temperatures of fluid inclusions			
50 – 150°C	***		
50 – more than 150°C		***	***
C. Density greater than normal water	***	***	***
X. Postulated genesis			
A. Sedimentary-diagenetic origin	***		
B. Dual origin: ore mineralisation by juvenile hydrothermal solutions and connate water		***	
C. Polygenetic; mainly submarine exhalative			***

Table 1—Key and footnotes

- *** commonly present
- ** occasionally, or in part, present
- * rare
- ¹ after Mostaghel (1984a)
- ² after Dunham *et al.* (1965), Sawkins (1966), Bishara (1966), Solomon *et al.* (1971), Ineson (1976), Rogers (1978), and Vaughan and Ixer (1980)
- ³ after Morrissey *et al.* (1971), Coomer and Robinson (1976), Watling (1976), Sheridan (1977), Russell (1978), Riedel (1980), Deeny (1981), Larter *et al.* (1981), Badham, (1981), Large (1981), Boast *et al.* (1981) and Boast, Coleman and Halls (1981)
- ⁴ According to Vaughan and Ixer (1980), the southern half of the Northern Pennine Orefield (the Askrigg Block) has a simple and uniform mineralogy and paragenesis whereas the northern half (the Alston Block) exhibits a more complex and varied mineralogy and paragenesis.
- ⁵ The galena and sphalerite samples from the orefields were not analysed for all the elements listed.
- ⁶ Data for minor and trace elements in galena and sphalerite are for the Keel deposit only.