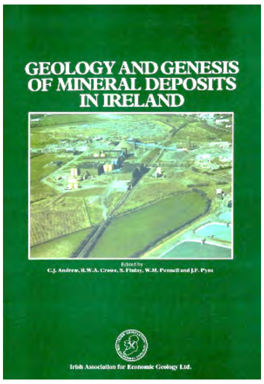

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Localization and source of Mississippi Valley-type zinc deposits in Tennessee, USA and comparisons with Lower Carboniferous rocks in Ireland.

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Localization and source of Mississippi Valley-type zinc deposits in Tennessee, USA, and comparisons with Lower Carboniferous rocks of Ireland.

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Abstract

Palaeozoic shelf-carbonate rocks in both Tennessee and Ireland occur within the Alleghenian-Hercynian orogenic belt and its foreland area. In Tennessee, Lower Ordovician carbonate rocks contain large epigenetic Mississippi Valley-type zinc deposits that are, in part or all, of late Palaeozoic age. The stratigraphic and structural features that localized these zinc deposits, and the rocks that were the probable source of the ore fluids, appear to have counterparts in Lower Carboniferous and perhaps in Upper Devonian rocks in Ireland.

Mineralization in the Tennessee deposits occurred principally by open-space filling in dissolution collapse-breccia and caverns comprising an extensive subsurface palaeoaquifer system that formed beneath a regional palaeokarst surface of Early Ordovician age. In eastern Ireland, Wales, and England, palaeokarst surfaces of Visean (late Early Carboniferous) age occur along the northern margin of the Welsh (Leinster) Massif. Consequently, regional palaeoaquifer systems with caverns and collapse breccia might be present in Ireland along the flanks of the Leinster Massif, or near any other block periodically emergent in the Lower Carboniferous, and might, therefore, host zinc deposits similar to those in Tennessee.

A wide variety of porous and permeable primary depositional textures and structures in the carbonate host rocks of Mississippi Valley-type ore deposits are mineralized. Tidal-channel grainstone, breccia, and other detrital dolostone units occurring between columnar stromatolites and in stromatolite biostromes host some deposits in Tennessee. Many of these textures and structures are known in Lower Carboniferous carbonate rocks of Ireland, and are potential sites for localization of ore bodies. Incompletely filled stromatactis cavities in the extensive Waulsortian carbonate mudbank complex of Ireland are one important example.

Broad, gently dipping (2 to 5 degrees) structural highs control the distribution of ore within porous and permeable stratigraphic zones in central Tennessee. Ore bodies are confined to the flanks and crests of these highs. Northeast-trending Hercynian anticlines, and uplifts like the Leinster Massif, also could have localized ore bodies in Ireland.

The Tennessee zinc deposits may have been deposited from pulses of ore fluids expelled from ruptured geopressurized zones in the numerous shale beds of the Appalachian Basin during basin subsidence and compaction, and during faulting, all of which accompanied basin development and tectonism during the Taconic, Acadian, and Alleghenian orogenies. Possible source rocks for Mississippi Valley-type ore fluids occur also in Ireland. The Cornwall-Rhenish Basin, represented by over 9 500m of principally Upper Devonian and Lower Carboniferous clastic rocks in the Munster and South Munster Basins of southern Ireland, possesses characteristics favourable for the formation of Mississippi Valley-type ore deposits during episodic expulsion of ore fluids from geopressurized zones in the Basin. The timing of Basin development was such that the peak rate of fluid expulsion probably occurred in the Late Carboniferous, roughly coincident with the Hercynian orogeny.

Source rocks and environments for deposition of Mississippi Valley-type zinc-lead deposits apparently existed in Upper Devonian and Lower Carboniferous rocks in Ireland at a time when development of sedimentary basins and regional Hercynian tectonism were capable of generating and mobilizing ore-bearing fluids of this type. Consequently, Mississippi Valley-type deposits may occur in the Lower Carboniferous carbonate rocks of Ireland.

Introduction

Structural and stratigraphic features that localize epigenetic Mississippi Valley-type zinc ore bodies in Tennessee have analogues in Lower Carboniferous rocks of Ireland. Stratigraphic controls of ore deposition include porous and permeable zones related to development of palaeokarst systems, and to primary carbonate depositional features. Structural controls include folds and local structural highs of debatable origin. Major sedimentary basins are potential sourcs of metals and ore fluids in both areas. Consequently, Ireland has the potential for discovery of Mississippi Valley-type deposits separate and distinct from the sediment-hosted exhalative massive sulphide zinc-lead deposits that presently dominate exploration strategies.

Palaeozoic shelf-carbonate rocks in Tennessee and Ireland occupy part of the Alleghenian-Hercynian orogenic belt and its foreland area (Fig. 1). Major Mississippi Valley-type zinc districts occur in upper Lower Ordovician carbonate rocks of the Upper Cambrian-Lower Ordovician Knox Group in Central and East Tennessee. The deposits in East Tennessee occur in the overthrust belt of the orogen, and the deposits in Central Tennessee occur in the foreland area on the crest of the Nashville Dome (Fig. 2).

Mississippi Valley-type deposits in Tennessee supply about 40% of US zinc production. Nearly all of the production in the Central Tennessee district is from the Elmwood and adjacent Gordonsville deposits. Underground mining began in these deposits in 1975, and through 1985 they have produced 10Mt of ore containing about 3.45% Zn. Current production is about 6 000t/day of ore, averaging about 3.5% Zn, with cadmium and germanium as byproducts. The ore contains approximately 0.1% Pb, which is not recovered. Ultimately, the Central Tennessee district is expected to produce over 500Mt of ore containing about 3% Zn. Underground mining in the Mascot-Jefferson City and Copper Ridge districts in East Tennessee has produced approximately 250Mt of ore averaging about 3% Zn since 1912, with estimated remaining reserves and paramarginal resources of nearly the same tonnage and grade (F. D. Rasnick, oral communication, 1986). Mines in East Tennessee currently are producing about 13 500t/day of ore containing about 2.75-3.0% Zn (F. D. Rasnick, oral communication, 1986). Stone aggregate and agricultural lime are important coproducts in both districts, adding about 25-30% to the value of the ore in Central Tennessee, and about 50% in East Tennessee.

Geological features that localize ore in the two Tennessee districts are similar in many respects, particularly in the localization of ore in palaeokarst systems. However, the deposits in Central Tennessee are relatively undeformed, and, therefore, are preferred examples with which to illustrate these features.

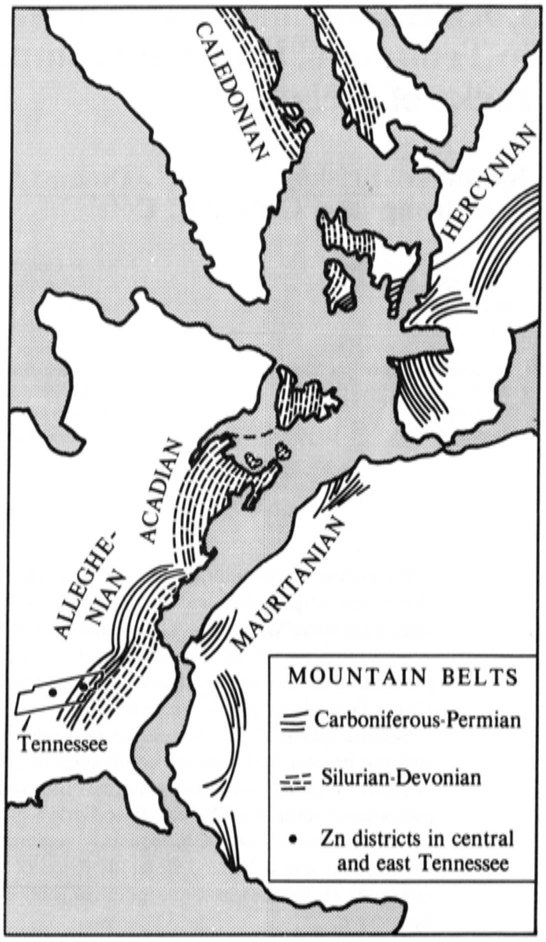


Figure 1. Diagram showing Palaeozoic fold belts in the North Atlantic region. Late Palaeozoic continental reconstruction, but without the effects of transform faulting. After Stearn et al. (1979).

Central Tennessee District

Major sphalerite deposits of the Central Tennessee zinc district occur in the northeastern part of the Central Basin, and in adjacent parts of the Eastern and Western Highland Rim physiographic provinces of north-central Tennessee and south-central Kentucky (Fig. 2). The geology of zinc deposits in the district has been described recently by Hoagland (1976), Kyle (1976), and Gaylord and Briskey (1983). The deposits are localized in late Lower Ordovician carbonate rocks of the Upper Cambrian-Lower Ordovician Knox Group along the crest of the Nashville Dome (Fig. 2). This Dome is a southern extension of the Cincinnati Arch, a broad NE-trending regional uplift with gentle dips of only a few metres per kilometre. The crestal area of the Dome is roughly defined by the outcrop area of Ordovician rocks in central Tennessee (Fig. 3). The Dome plunges gently northeastwards, and dips in the Elmwood-Gordonsville area are towards the NE at about six metres per kilometre.

Discovery

Main (1976), Callahan (1977), and White (1979) have documented the discovery of the Central Tennessee district. The district was found as the result of an exploration programme begun in 1963 by the New Jersey Zinc Company, and initially centred near the apex of the Nashville Dome about 56km SW of the Elmwood mine. This area was selected for the following reasons:

(1) Oil-well borings had previously discovered small amounts of sphalerite in Lower Ordovician carbonate rocks of the upper Knox Group, the main ore host in the East Tennessee zinc districts;

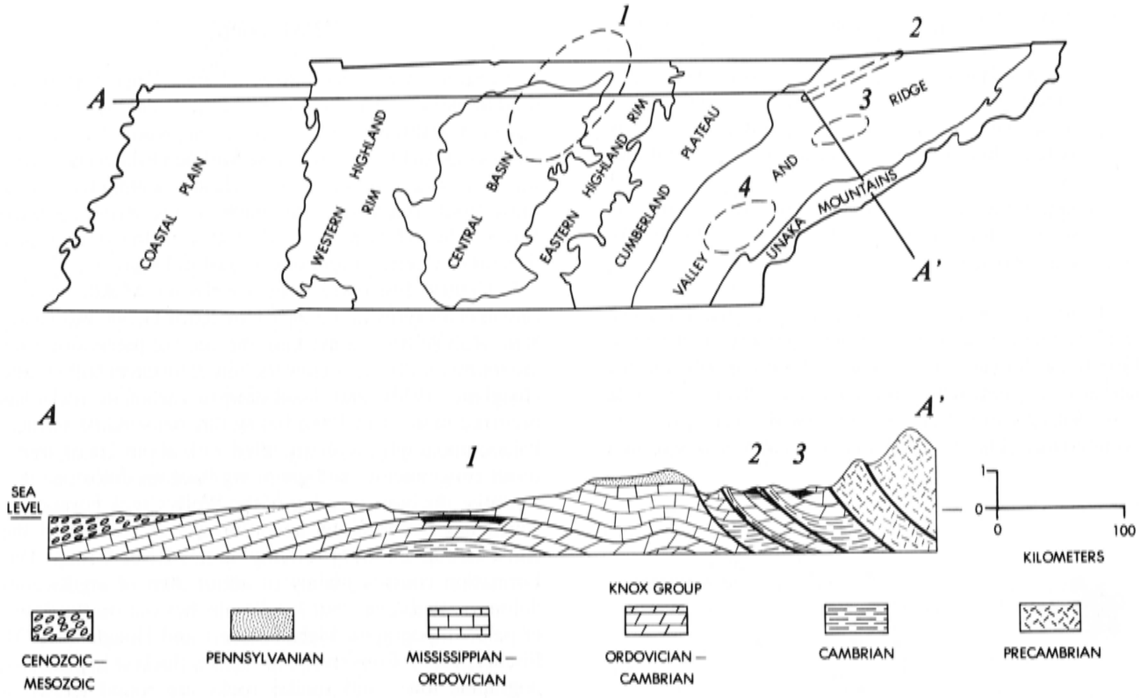


Figure 2. Location of carbonate-hosted zinc districts (solid black on cross section) in the Knox Group with respect to major physiographic provinces and geological structures in Tennessee. The Central Tennessee district (1) occurs in the subsurface in gently warped strata along the axis of the Nashville Dome. The Copper Ridge (2), Mascot-Jefferson City (3), and Sweetwater zinc-barite-fluorite (4) districts are exposed in belts of imbricate thrust faults in East Tennessee. After Kyle (1976).

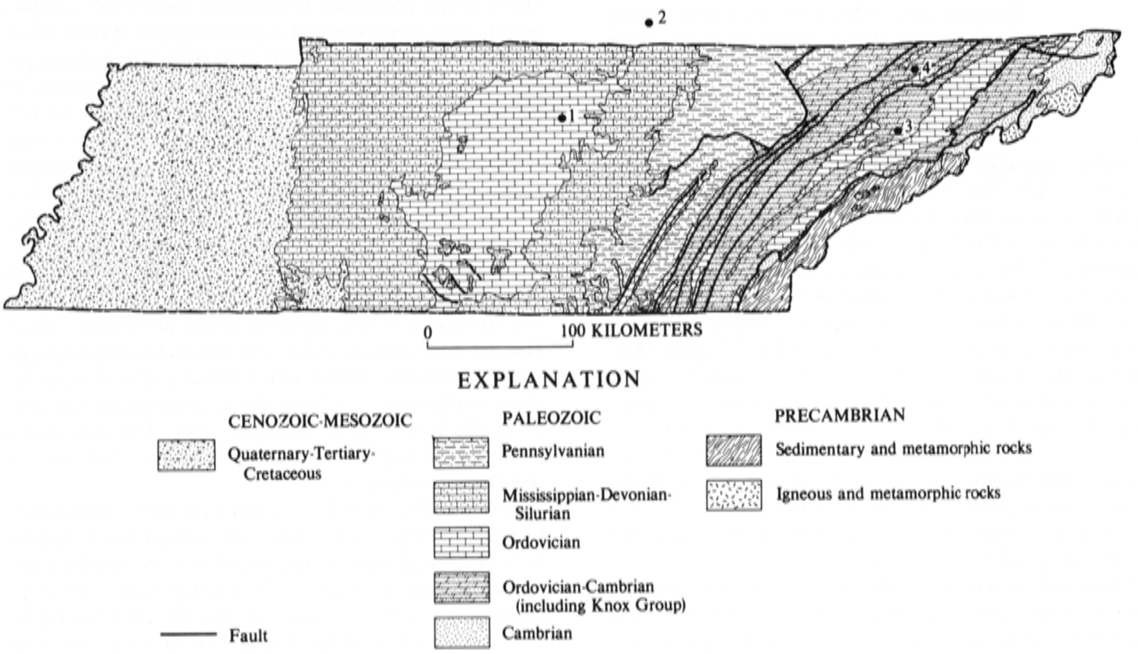


Figure 3. Generalized geological map of the state of Tennessee. Most of the NE-trending faults shown are thrust faults that dip to the SE. Numbered locations are: 1, Elmwood-Gordonsville zinc mines; 2, Burkesville zinc deposit, Kentucky; 3, central part of the Mascot-Jefferson City zinc district; 4, central part of the Copper Ridge zinc district. The crestal area of the Nashville Dome is roughly defined by the outcrop area of Ordovician rocks in Central Tennessee. Adapted from Leimer and Helton (1983).

(2) Although rocks of the upper Knox Group that host the deposits in East Tennessee do not crop out in Central Tennessee, they occur within 600m of the surface over an 18 000km^2 area along the crest of the Dome, thus providing a large target zone accessible by drilling and underground mining operations; and

(3) Sphalerite, galena, barite, and fluorite occur in fissure veins at the surface, mainly in Middle Ordovician limestone.

The first hole was drilled in May 1964, adjacent to an oil test hole that had encountered minor sphalerite in the Knox Group. Additional holes were drilled at randomly selected sites in a "random walk" along the crest of the Dome, using 8 to 10km spacing subject to modification as geological data accumulated (Fig. 4). Drill-hole spacing was based on a similar, simulated programme in the Tri-State zinc-lead district in SW Missouri. The first drill hole confirmed the presence of favourable host rocks of the upper Knox Group, and drill holes 2 and 3 penetrated breccia and secondary dolomite similar to that associated with zinc ores in East Tennessee. Early drill holes encountered minor sphalerite, but the first ore-grade intersection was in hole 79, which penetrated 1.5m of 16.5% Zn at 421.8m in February 1967. While the regional drilling programme continued elsewhere, additional drilling in the vicinity of hole 79 eventually delineated the Elmwood orebody, which was reported to contain between 45 and 70Mt of 3.5 to 5.2% Zn (Engineering and Mining Journal, 1978; White, 1979). These figures were preliminary "geologic reserves", and have been revised downwards to reflect more closely mining and economic conditions.

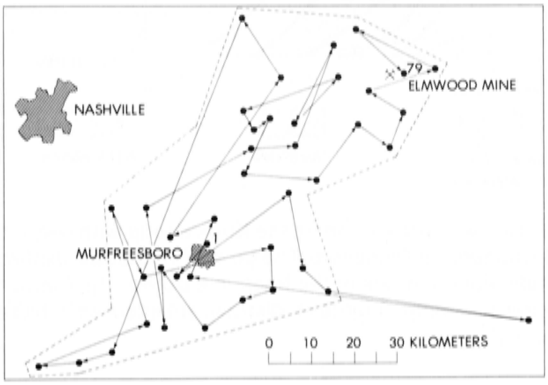


Figure 4. Map of Central Tennessee showing pattern of random drilling leading to the first ore-grade intersection in hole 79, and in turn to the discovery of the Elmwood and nearby Gordonsville mines. More than one hole was drilled at some sites. After Callahan (1977).

Following the announcement of the Elmwood discovery, many mining and oil companies rushed to the Central Tennessee area, and between 10 and 20 zinc deposits with commercial potential were subsequently discovered. Many of these new deposits probably each contain between 10 and 30Mt of mineralized rock with 3 to 4% Zn. In addition, large deposits of dominantly barite and/or fluorite commonly were encountered during exploration, and it is likely that some of these deposits will be exploited in the future.

Host rocks

A regionally extensive erosional unconformity separates predominantly shallow-water marine dolostone of the Upper Cambrian-Lower Ordovician Knox Group and equivalent rocks from overlying Middle Ordovician deeper water marine limestone and clastic sedimentary rock throughout Tennessee and much of the eastern United States. This relationship is illustrated in the stratigraphic column of Central Tennessee shown in Figure 5.

In Central Tennessee, relief on the pre-Middle Ordovician unconformity at the top of the Knox Group was nearly 38m. Rubble breccia marking the sites of palaeosinkholes are found locally just below the unconformity (Gilbert and Hoagland, 1970), and dissolution of carbonate rocks has occurred more than 500m below this palaeokarst surface. Palaeotopographic lows are filled with about 2m of arenaceous conglomerate and green argillaceous dolostone that comprise the basal member of the Wells Creek Formation, which lies between the unconformity at the top of the Knox Group and the overlying Stones River Group. This Formation consists mainly of about 30m of argillaceous dolomitic limestone, but locally pinches out on the flanks of palaeotopographic highs (Gilbert and Hoagland, 1970; Fischer, 1977). Conversely, the unit is thickest in palaeotopographic lows, and similar rocks are found locally in fissures as much as 45m below the unconformity (Gilbert and Hoagland, 1970). Furthermore, green shaly dolostone, apparently derived from Wells Creek sedimentation, occurs as cavern fillings in the Gordonsville and Elmwood mines, about 60m and 110m, respectively, below the palaeosurface.

Most of the ore in the Central Tennessee zinc district occurs in, or immediately above, altered limestone interbeds in the lower and middle members of the Mascot Dolomite, the uppermost formation of the Knox Group. Ore is found principally in extensive dissolution collapse-breccia and caverns within a palaeoaquifer system developed mainly in the soluble limestone beds. This palaeoaquifer is related to Early Ordovician karst development on the regional unconformity at the top of the Knox Group. Additional amounts of ore are present in similar palaeoaquifers in altered limestone of the underlying Kingsport Formation. The Kingsport Formation is the principal host for zinc ores in East Tennessee. At Burkesville, Kentucky, in the north part of the Central Tennessee district (see Fig. 3), some zinc deposits occur in breccias developed in detrital dolostone formed in tidal channels between columnar stromatolites and in stromatolite biostromes, which also are mineralized locally. This mineralized stromatolite zone is named the Burkesville C-level, and is at about the same stratigraphic position as the K-ds sandstone bed (Fig. 5) in the Elmwood-Gordonsville area. The generalized stratigraphic disposition of ore in Central Tennessee is portrayed in Figure 5.

Both the Mascot Dolomite and Kingsport Formation in Central Tennessee are dominantly composed of shallow-water marine dolostone and limestone that display widespread supratidal, tidalite, and evaporite facies. The dolostone is a product of early diagenesis, and has crystal sizes generally less than 0.25mm. The limestone is chiefly pelmicrite containing a few gastropods and fragments of ostracods, trilobites, brachiopods, and pelmatozoans (Kyle, 1976).

The stratigraphy of the upper 38m of the Kingsport Formation in the Central Tennessee zinc district has been summarized by Fischer (1977). Where it is not altered,

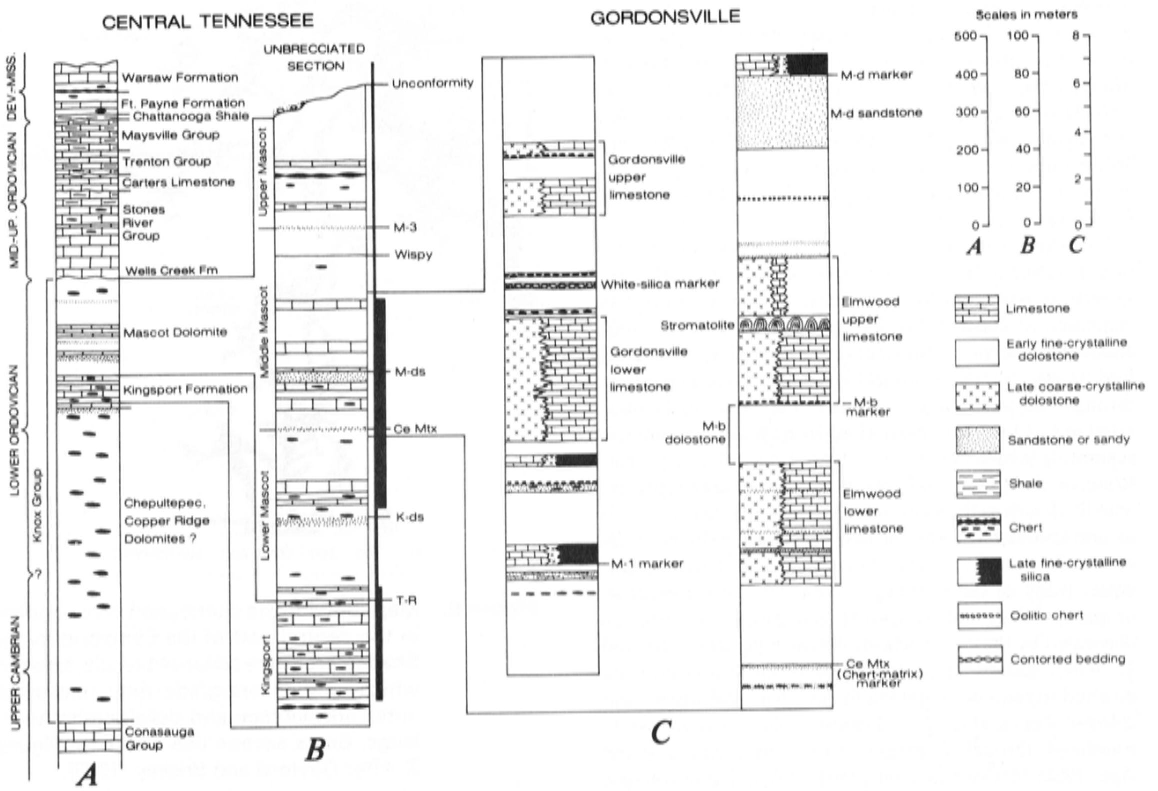


Figure 5. Generalized stratigraphic sections of Central Tennessee and the Gordonsville mine. Black bar beside column B shows the stratigraphic disposition and relative abundance of ore. The M-3, wispy, M-ds, Ce Mtx, K-ds, T-R, White-silica, M-1, M-d, and M-b are local marker horizons used for stratigraphic correlation in the mines. The Central Tennessee section is slightly modified from Kyle (1976); the Gordonsville section is after Gaylord and Briskey (1983).

the Formation consists mainly of brown dense massively bedded limestone with interbeds of light-olive-grey to brownish-grey finely crystalline dolostone. Other sedimentary lithologies include zones containing (i) blue to light-blue nodular, ribbon, and oolitic chert, (ii) thin beds to laminations of isolated, rounded, sand-sized grains of quartz, and (iii) bedding plane partings of thin green shale.

The Mascot Dolomite is composed of light-olive to olive-grey finely crystalline dolostone containing between 10 and 15% unaltered and altered limestone as sporadic interbeds typically from 1 to 5m thick. As in the Kingsport Formation, the Mascot Dolomite has numerous intervals containing chert, quartz sand, and shale partings like those described above. The Mascot Dolomite contains two major sandstone interbeds, the K-ds and M-ds sandstones, which each attain maximum thicknesses of about 5m in the district, but which are only about 3m thick at the mines. Both sandstones are composed of rounded grains of quartz with siliceous or calcareous cement, and locally grade into sandy dolostone. Stagg and Fischer (1970) subdivided the Mascot Dolomite into lower, middle, and upper members, with bases at the T-R, Ce Mtx (Chert Matrix), and M-3 markers, respectively. The Mascot Dolomite is approximately 210m thick in the Elmwood-Gordonsville area.

In the Elmwood-Gordonsville area, the middle member of the Mascot Dolomite is the principal ore host. In this area, the middle Mascot Dolomite consists of light-grey to brown finely crystalline dolostone interbedded with about 20% limestone that is variably dolomitized and silicified (Fig. 5). Many of the dolostone beds display bluish-grey speckled mottling, which reflects the irregular distribution of finely divided iron sulphides, presumably early diagenetic pyrite and/or marcasite. In and near altered mineralized areas, these sulphides commonly are remobilized to form parallel bands or concentric zones, also called "reaction rims." Concentric zones are most abundant in breccia clasts. Some dolostone is mottled with patches of more coarsely crystalline white calcite or dolomite. Intervals containing chert, rounded quartz sand grains, and green shaly partings typical of the Mascot Dolomite are also common in the mine area. Ore is localized chiefly in dissolution collapse-breccia and caverns, mainly in the Elmwood upper and lower limestones at the Elmwood mine, and in the Gordonsville upper and lower limestones at the Gordonsville mine (Fig. 5, column C).

Stratigraphic controls of ore deposition

Dissolution collapse-breccia and caverns

Mineralization in both Central and East Tennessee occurred principally by filling of open spaces in dissolution collapse breccia, and, in Central Tennessee, also by filling of caverns. Breccia and caverns both formed in palaeoaquifers related to palaeokarst development on and below the regional unconformity at the top of the Knox Group. Most of the breccia formed resulted from the dissolution and dolomitization of the soluble limestone, followed by collapse of overlying, relatively insoluble dolostone beds. Consequently, breccia is most common along limestone-dolostone contacts. Formation of this dissolution collapse-breccia is well known from descriptions of the East Tennessee zinc districts and surrounding areas (Wedow and Marie, 1964; Callahan, 1964 and 1968; Wedow, 1965 and 1971; Hoagland et al., 1965; Crawford and Hoagland, 1968; Hoagland, 1967; Harris, 1969 and 1971; Hill, 1969; and McCormick et al., 1971). The distribution of collapse breccia in the Mascot Dolomite in the Elmwood mine is illustrated in Figures 6 and 7.

Limestone dissolution and accompanying dolomitization, potentially leading to collapse of roof and wall rocks to form dissolution collapse breccia, can be visualized as beginning as illustrated in Figure 8. This Figure is a schematic cross section representing any of the linear mineralized breccia trends shown in Figure 6. Lateral movement through the palaeoaquifer of meteoric water undersaturated in $CaCO_3$, channelled along irregularities in contacts separating primary dolostone above from underlying limestone, or along faults or joints cutting such contacts, preferentially dissolves the more soluble limestone, leaving voids or unconsolidated sediment into which the overlying beds eventually founder. Where dissolution ceased prior to collapse, many of the resulting caverns later became filled, or partly filled, with sphalerite and gangue minerals as illustrated by the cross sections shown in Figures 9, 10, and 11. Where dissolution continued, downwardly and inwardly directed stresses developed in the overlying dolostone, and collapse began (Fig. 12). Typically, these stresses were translated through a pressure-arch configuration (Coal Age, 1966; McCormick et al., 1971), which led to collapse through development of *en echelon* tangential fractures in the wall rocks (Figs. 13 and 14). Incipient development of a pressure arch is reflected in the arcuate fracture pattern of the crackle breccia zone shown in Figure 9. Crackle breccia occurs in dilatant zones in the roofs of collapse breccia, and is characterized by only minor clast dislocation and rotation. The *en echelon* tangential fractures, like those along the walls of the breccia in Figure 13, commonly exhibit reverse offset (Fig. 14), a consequence of brittle failure in a pressure-arch strain field. When collapse extends upward through the overlying dolostone into limestone above, the resulting breccia is termed a break-through breccia. Breccia zones shown in Figure 7 in the Elmwood limestones are examples, as is the huge breccia mass penetrated by DDH 34 (see Fig. 7 also). This large breccia mass apparently formed by dissolution of thick limestone beds in the underlying Kingsport Formation, and is host to the 34 Orebody containing nearly 1.5Mt of ore. In plan view, dissolution collapse breccia systems commonly have the form of an interconnected, rectilinear to irregular coalescing net (e.g. Fig. 6), which may reflect regional joint and fault patterns, and the attitude of bedding. Ore and gangue minerals typically are concentrated in openings along the tops and sides of the breccia.

In the Central Tennessee district, collapse breccia consists of early and late varieties related to overlying palaeokarst surfaces, but mainly to the palaeokarst surface on the unconformity at the top of the Mascot Dolomite. However, some of the late varieties, at least in part, penetrate, and, therefore, post-date this unconformity (Hoagland, 1973, 1976; Winslow and Hill, 1973; Kyle, 1976; Gaylord and Briskey, 1983). Early and late breccias also occur in East Tennessee, and are similar in composition to those in Central Tennessee. The breccia descriptions that follow are principally from the Elmwood-Gordonsville area.

Early breccia consists of fragments of finely crystalline dolostone, coarsely cyrstalline dolostone, and chert. These

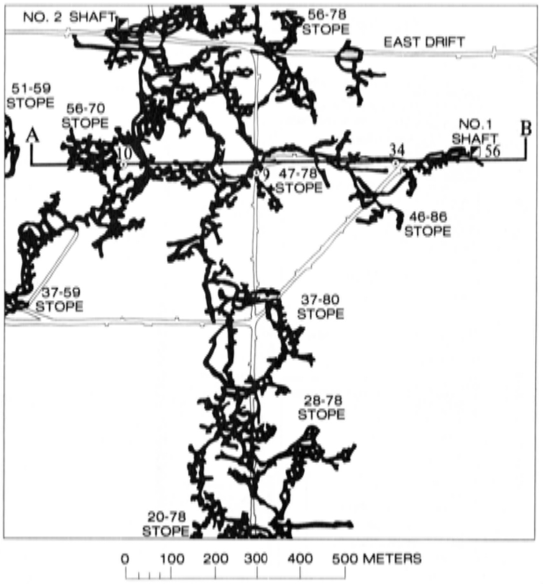


Figure 6. Map showing the distribution of ore bodies in the central part of the Elmwood mine. Shaded areas are collapse breccia, most of which contain ore-grade zinc; unshaded areas are haulage and development workings. Cross section line A-B is for Figure 7. After Gaylord and Briskey (1983).

fragments are in a matrix of finely crystalline dolostone, chert, quartz sand grains, and argillaceous material, which represent the insoluble residue resulting from dissolution of limestone and dolomitic limestone. This early breccia, designated "fine rock-matrix breccia", is not abundant in the mine, but is more common outside mineralized areas. Fine rock-matrix breccia is largely unmineralized except along late cross-cutting fractures, and typically has masses of late coarse rock-matrix breccia (described below) along its margins.

Late breccia, in contrast, is host to most sphalerite and many gangue minerals, and generally has two types of matrix (Figs. 7 and 13). The lower parts of late breccia masses commonly consist of blocks of finely to coarsely crystalline dolostone, and an insoluble residue ("trash zone") of chert fragments, argillaceous material, quartz sand, and silt, all in a matrix of medium to coarsely crystalline dolomite rhombs. This type of breccia is called "coarse rock-matrix breccia." In the upper part and along the sides of some late breccia, the matrix is composed of white calcite, locally with subordinate sphalerite, galena, fluorite, barite, and small amounts of marcasite, pyrite, quartz, and white dolomite. This breccia is called "mineral-matrix breccia," and contains most of the ore (see Figs. 7 and 13). Where late breccia formed marginal to masses of early breccia, it is apparently the result of reactivation of the early breccia. Locally, late breccia containing sphalerite extends across the Knox unconformity, rising at least 15m into overlying Middle Ordovician carbonate rocks (Gaylord and Briskey, 1983). The parts of collapse breccia that cross this unconformity probably formed during Middle Ordovician and/or later reactivation of the palaeoaquifers. Numerous unconformities in the overlying Middle Ordovician sequence, and a major unconformity separating Upper Ordovician rocks from the overlying Upper Devonian Chattanooga Shale (Fig. 5), reflect periods of regional uplift

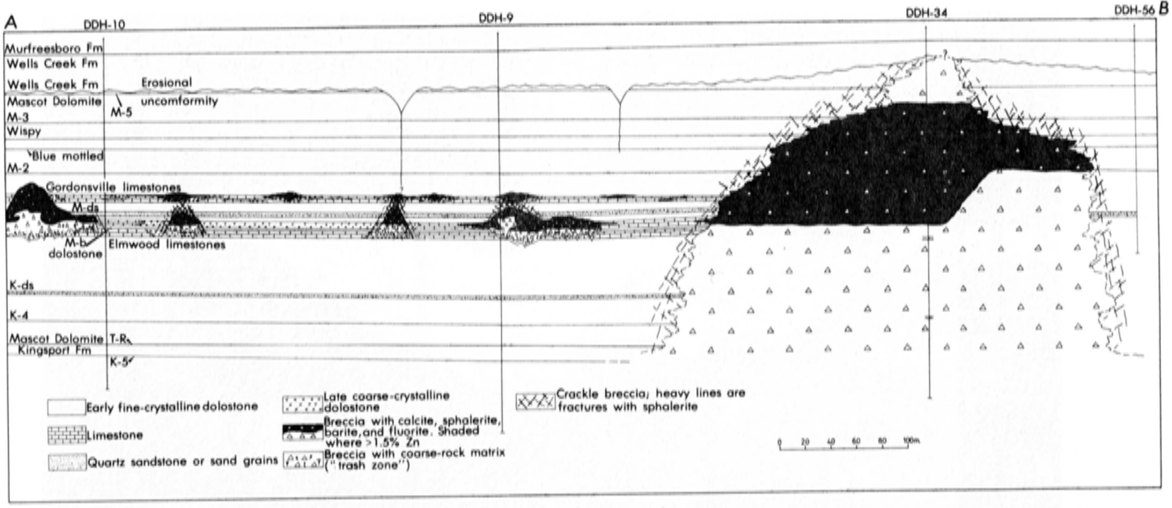


Figure 7. W to E cross section showing the development of mineralized dissolution collapse breccias in the Elmwood mine. Vertical and horizontal scales are equivalent. The line of cross section is shown in Figure 6 and 20. The sink holes shown on the unconformity at the top of the Mascot Dolomite are schematic representations. After Gaylord and Briskey (1983).

that could have provided recharge areas for reactivation of the extensive Knox palaeoaquifer system.

Joints in the Knox Group were an important control for channelling groundwater in the palaeoaquifer system. Ore-bearing breccia masses generally trend about N65°E and N25°W in the Elmwood mine (Fig. 6), coincident with the dominant trends of joints in the Mascot Dolomite, which are about N60°E and N25°W. Ore-bearing breccia masses in the Gordonsville mine are less systematic, but generally trend northerly to northeasterly. Joints in the Knox Group were developed as a consequence of gentle folding that accompanied emergence(s) of the Knox Group, principally at the end of Early Ordovician time, and are generally more numerous at the crests and noses of palaeostructural highs (described below). The joints permitted penetration or movement of meteoric water at least to the depths of the collapse breccia zones. Joints in the overlying Middle Ordovician limestone trend N60°E and N25°W (Fischer, 1977); they are discordant with joints in the Knox Group, and presumably formed during later episodes of deformation and probably emergence.

Primary carbonate depositional features

In contrast to the deposits that occur in porosity resulting from dissolution of limestone in the palaeokarst environment, some zinc deposits in the Central Tennessee district occupy porosity related to "primary" carbonate depositional features in early diagenetic dolostone. At Burkesville, Kentucky, in the northern part of the district (Fig. 3), sphalerite deposits are localized in porous detrital dolostone formed principally in tidal channels between columnar stromatolites, and in stromatolite biostromes (bioherms?) composed of coalescing columnar stromatolites (Figs. 15-18). Dolomite grainstone deposited in the tidal channels contains abundant bedded chert, chert breccia,

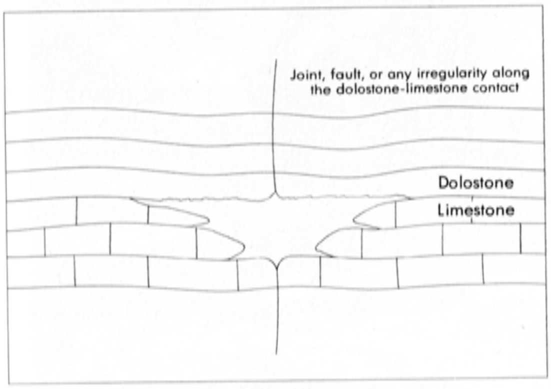


Figure 8. Schematic illustration of initial limestone dissolution beneath contact with early fine-crystalline dolostone, leading to collapse of roof and wall rocks to form dissolution collapse breccia like that portrayed in Figures 7 and 13. After Gaylord and Briskey (1983).

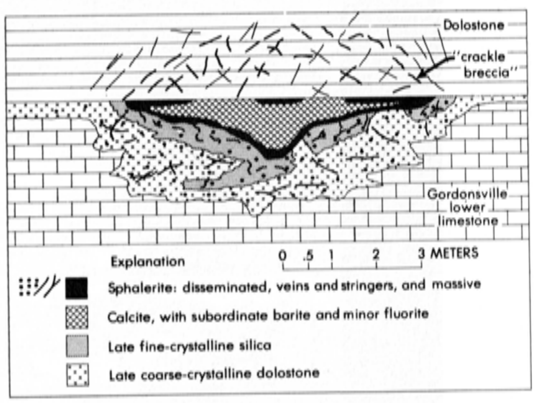


Figure 9. Cross section through part of the Gordonsville 67 stope #2, showing a dissolution cavern filled with ore and gangue minerals, and showing dolomitized and silicified wall rocks, and incipient collapse fractures and crackle breccia in the roof. After Gaylord and Briskey (1983).

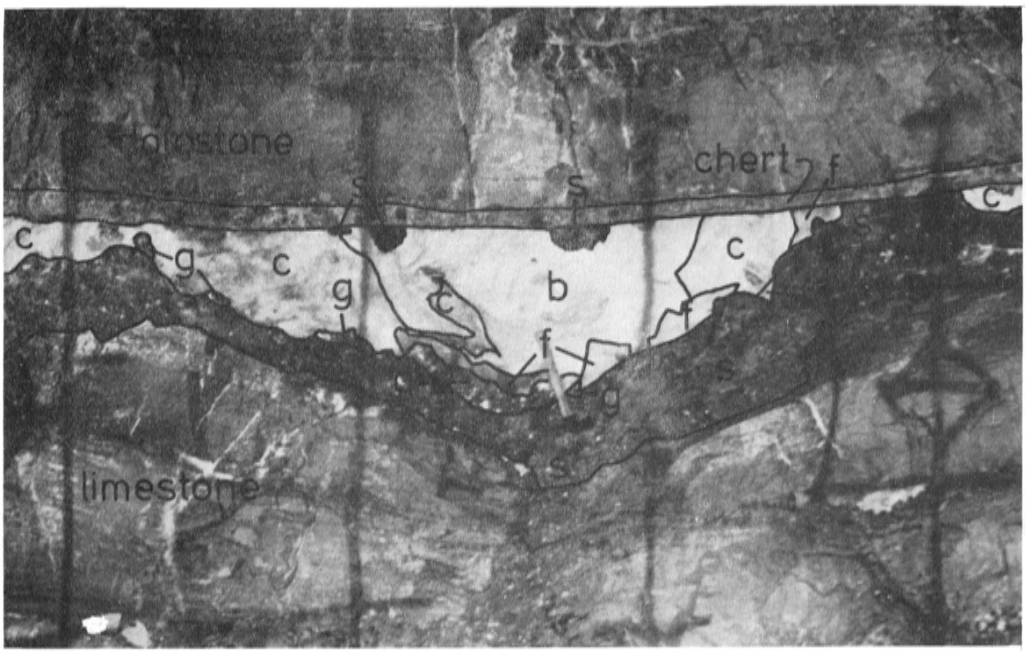


Figure 10. Photograph of dissolution cavern filled with ore and gangue minerals from the Gordonsville mine, stope 03S #4. The minerals are, from oldest to youngest; s, sphalerite; g, galena; f, fluorite; b, barite; and c, calcite. Hanging-wall is dolostone with a bed of chert at its base, and with mineralized incipient collapse fractures above the filled cavern. The footwall is dissolved and thinned, partly dolomitized limestone with disseminated sphalerite, and with wispy discontinuous partings of green argillaceous material that locally cut across bedding and represent the insoluble residue left from dissolution of the limestone.

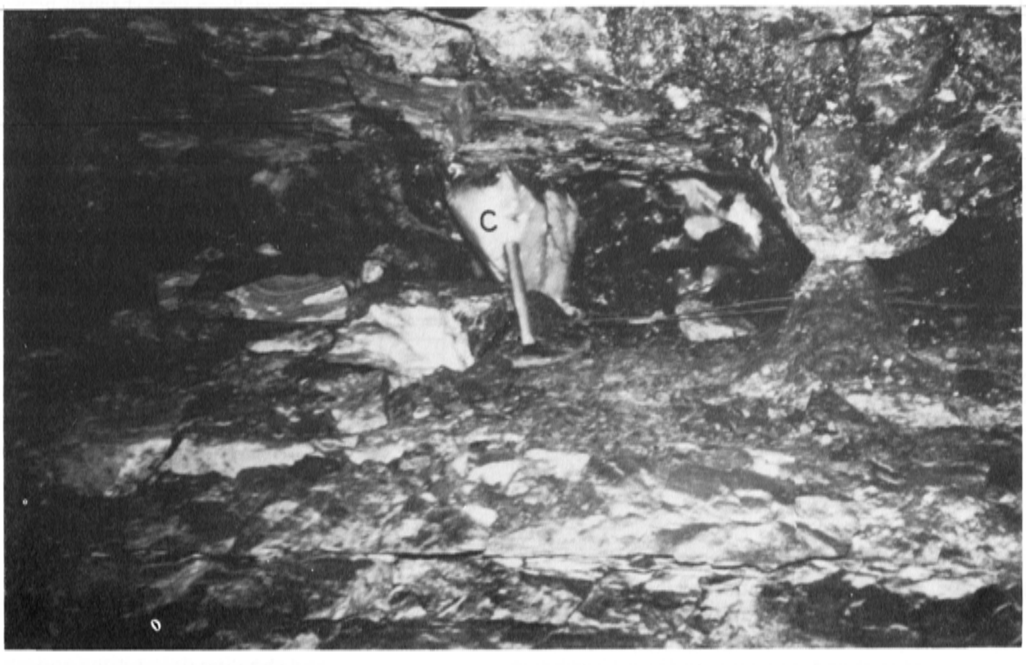


Figure 11. Photograph of dissolution cavern encrusted with euhedral crystals of sphalerite and calcite. Sphalerite shows as black clusters on the sides of the cavern. Calcite (c) forms white scalenohedrons.

Figure 12. Photograph showing partial collapse of hanging-wall dolostone above a dissolution-collapse breccia in the Elmwood mine, stope 15-78 #3. Open spaces in breccia, gash veins, and bedding partings are filled with calcite (white) and sphalerite (s; dark grey).

and dolostone clasts. These rocks are referred to collectively as the Burkesville C-level, and occur at about the same stratigraphic level in the lower Mascot Dolomite as does the K-ds marker in the Elmwood-Gordonsville area (see Fig. 5).

Dolostone of the C-level is part of a 50m thick cyclic sequence of upward-shoaling dolostone lithofacies formed by early diagenetic dolomitization of lime mud deposited in three principal carbonate depositional environments described by Craig (1982). These environments consist of: (1) an algal-rich sabkha-beach environment; (2) a "restricted shallow subtidal to low intertidal pan with hypersaline ponds" (Craig, 1982, p. v); and (3) an algal-rich subtidal environment of near normal salinity with large columnar stromatolities 1.5 to 2.0m high. Supratidal, intertidal, and subtidal rocks of the C-level are shown schematically in Figure 16. Primary porosity includes fenestral, interparticle, burrow, and algal growth-framework varieties. Secondary porosity includes breccia, fracture, intercrystalline, channel, vuggy, and shrinkage porosity. Although most interparticle porosity was destroyed by dolomitization, intercrystalline porosity resulted from growth of coarsely crystalline zoned dolomite rhombs during dolomitization of supratidal sediments. Extensive chertification and epigenetic silicification in and around the stromatolites both destroyed and preserved early porosity. Sphalerite occupies both primary and secondary porosity, especially in the tidal-channel dolostones.

Mounds and beds of stromatolites in various parts of the world typically have zones of high primary porosity. Tidal channels, and fissures caused by slumping, commonly cut stromatolite mounds, and are filled with coarse bioclasts composed of echinoderms, brachiopods, and trilobites, and with lithoclasts that are usually composed of pebble conglomerate of reworked, desiccated tidal-flat sediment (Wilson, 1975). Some stromatolites are separated by channels filled with cross-bedded and mega-rippled coarse-grained sand and conglomerate composed of stromatolite fragments and clasts of oolitic grainstone (James, 1983). Stromatolites and tidal channel deposits forming today in Shark Bay, Australia (e.g. James, 1983; Shinn, 1983), appear to be modern analogues of those at Burkesville.

In addition to the mineralized tidal-channel granstone at Burkesville, some sphalerite also is localized by what appear to be slump breccias like those shown on the left side of the lower cross section in Figure 15. The scarp that bounds this breccia shows normal rather than the reverse displacement typical of the margins of collapse breccia. Sphalerite also has been localized by what may be cut-and-fill structures such as those illustrated on the left side of the upper cross section in Figure 15. Consequently, sphalerite is localized between, adjacent to, and above the tops of individual stromatolite columns (Fig. 16-18). Minor sphalerite also was deposited within the stromatolite columns. These columns commonly occur in clusters that are from 30m to 40m wide where intersected by underground exploration drifts (Fig. 15). Sphalerite is concentrated at the edges and immediately above these clusters. Similar ore controls are known in SE Missouri where lead-zinc ore in dolostone also is commonly localized at the contact between stromatolite "reefs" and the grainstone of adjacent channel-fill deposits (e.g. Snyder and Gerdemann, 1968; Grundmann, 1977).

The Burkesville deposit also contains mineralized collapse breccia. The Elmwood and Gordonsville upper and lower limestones, and limestone in the underlying Kingsport Formation, are all completely dolomitized in the Burkesville area, yet contain abundant dissolution collapse breccia. Consequently, and because early diagenetic ("primary") dolostone apparently resisted dissolution relative

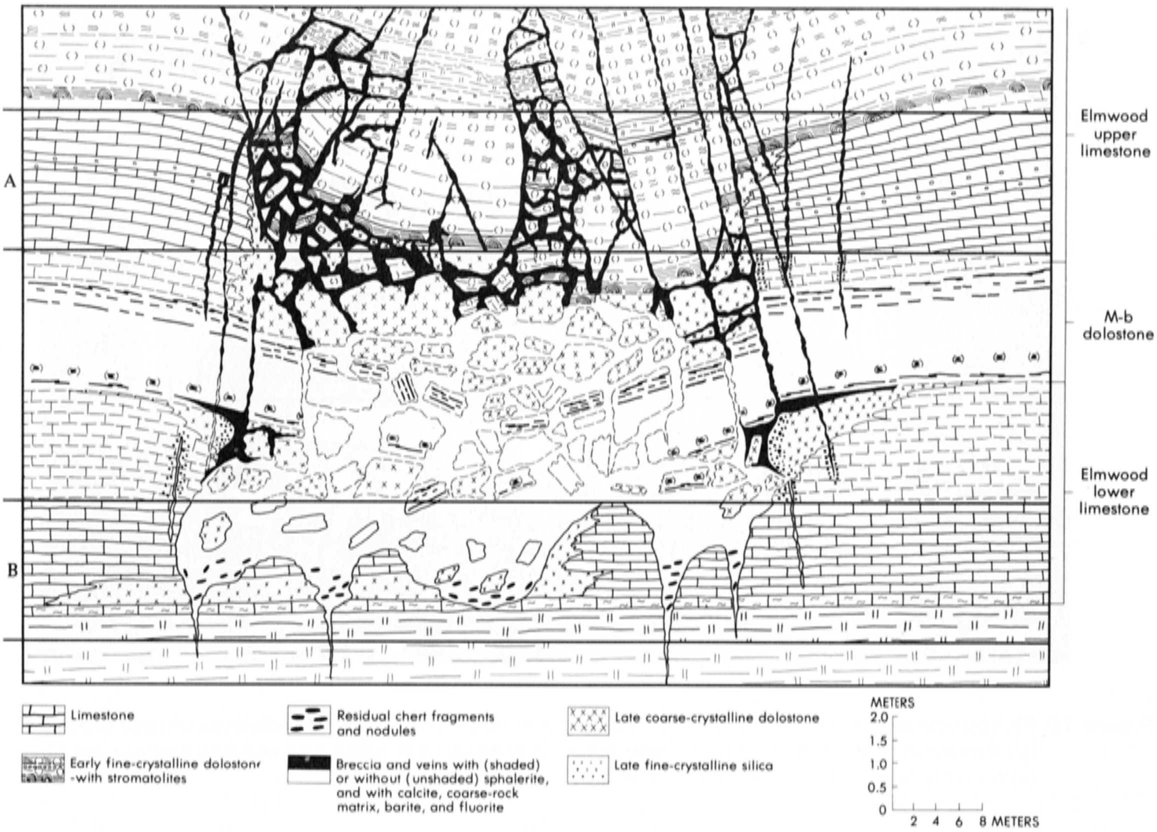


Figure 13. Cross section of a mineralized collapse breccia in the 37-80 stope of the Elmwood mine. Areas A and B were exposed in underground workings that were accessible during mapping; intervening areas are extrapolated. Stope location shown in Figure 6 and 20. After Gaylord and Briskey (1983).

Figure 14. Photograph of the edge of a mineralized collapse breccia from the Gordonsville mine. Sphalerite (dark grey) fills open spaces between fragments of early fine-crystalline dolostone (light grey) derived from the hanging-wall of the breccia. Mottled beds in the lower left and upper right corners are equivalent units separated by reverse fault displacement along the side of the collapse breccia. The zone of displacement is occupied by mineralized breccia that dips from the upper left, down to the lower right.

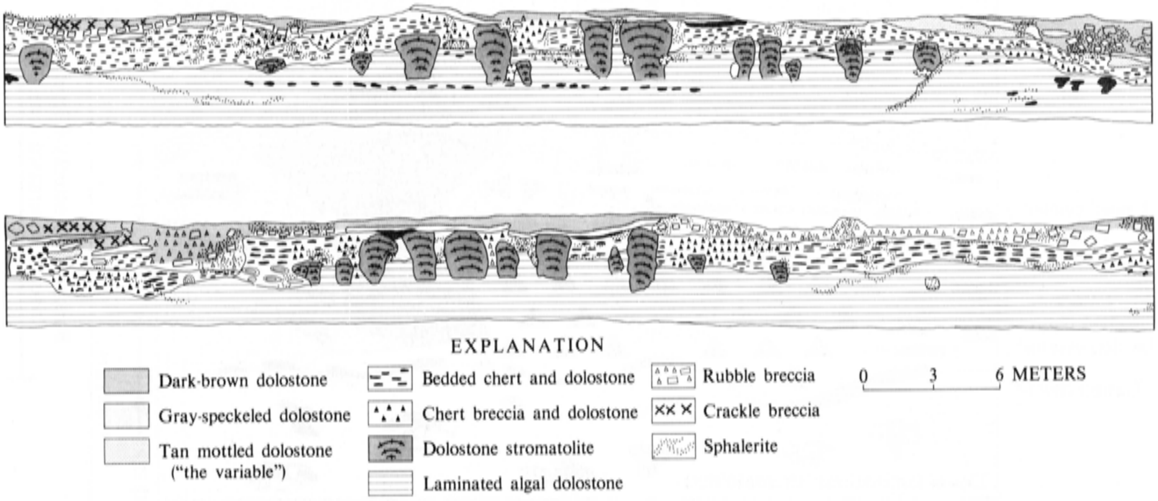


Figure 15. Cross section in exploration drift showing the distribution of sphalerite, breccia, and columnar stromatolites in the rocks of the Burkesville C-level. Irregularly-shaped patches of solid black are zones of silicification. The two cross sections represent opposing sides of the drift. Mapping by P. R. Dingess.

to limestone, dolomitization of these limestones probably occurred during or after dissolution of the limestone, and after subsequent collapse in the palaeoaquifer zone. This pervasive epigenetic dolomitization event is perhaps reflected in the presence of dolomite rather than calcite as the principal gangue mineral, as compared to the predominance of calcite in the Elmwood-Gordonsville area. Collapse brecciation in the Kingsport Formation has contributed to the brecciation of the overlying Burkesville C-level, and it is commonly difficult to separate this type of breccia from that which may have resulted from sedimentary processes. Much of the rubble and crackle breccia, some of the chert breccia, and most of the mineralized fractures in the C-level (Fig. 15) appear to be the result of incipient collapse above large breccia bodies and depressions in the underlying Kingsport Formation. Chertification and silicification in the Burkesville C-level enhanced the brittleness of the host rocks, and probably contributed to breccia development during collapse. Dissolution of evaporite minerals may have contributed to collapse in a small way, and, consequently, may have been a minor ore control.

Structural controls of ore deposition

Broad, gently dipping (2-5°) local structural highs along the crest of the Nashville Dome control the distribution of ore within porous and permeable stratigraphic zones in Central Tennessee. Ore bodies are confined to the flanks and crests of these highs. Palaeostructural highs and present structural highs both are spatially related to ore. Locally, on these highs, some ore also is associated with small structural depressions that resulted from collapse accompanying dissolution of limestone.

The potential importance of relations between pre-Middle Ordovician palaeostructure and the distribution of ore was recognized early in the exploration and development of the Central Tennessee district by the New Jersey Zinc Company, and was emphasized recently by Gaylord and Briskey (1983) and by Braun (1983). Figures 19 and 21 portray the palaeostructural configuration of the upper Knox Group in the Elmwood-Gordonsville area at the beginning of the Middle Ordovician marine transgression. Post-Knox Group deformation, which is largely late Palaeozoic in age, was eliminated from these Figures by creating a reference datum 500 feet below the top of the Middle Ordovician Wells Creek Formation. Contours in Figure 19 represent distances in feet from this reference datum to the overlying M-3 marker, which is the top of the middle member of the Mascot Dolomite. Consequently, large contour values represent palaeostructural highs in the upper Knox Group. Figures 19 and 21 show that the Elmwood, Gordonsville, and South Carthage deposits occur along the flanks or crests of broad gentle palaeostructural highs having dips generally less than 1.5 degrees, although dips as steep as 5 degrees occur locally across small depressions like that in the NE corner of the area. The origin of the palaeostructural highs and lows is conjectural, but might be attributable, in part, to gentle deformation, to dissolution of thick limestone beds in the underlying Kingsport Formation, to the presence of limestone mounds formed in the shallow Knox Group seas, and/or to differential compaction. The concentration of joints on the noses and crests of the highs implies that deformation was perhaps most important. Palaeostructure is not obviously related to dissolution of limestone in the Mascot Dolomite.

Present structure in the upper Knox Group in the Elmwood-Gordonsville area is depicted in Figures 20 and 21. Much of this structure is probably the result of foreland deformation associated with the late Palaeozoic Alleghenian orogeny. Present structure essentially duplicates the relations elucidated by the preceding palaeostructure maps. Moreover, the main ore deposits are similarly located on the flanks and crests of present structural highs. There is a rough correlation between the locations of broad structural highs shown on both present structure and palaeostructure maps. However, present highs are better defined and more intricate, and have more relief, than do the palaeohighs. Dips of present structural highs and lows are greater, generally between 2 and 5 degrees. It appears that post-Knox Group deformation along the crest of the Nashville Dome has, in places, emphasized and steepened the subdued pre-existing palaeostructures. In other places, however, palaeostructure and present structure may diverge greatly. Structural data have not yet been released for the Burkesville area, or for deposits in East Tennessee.

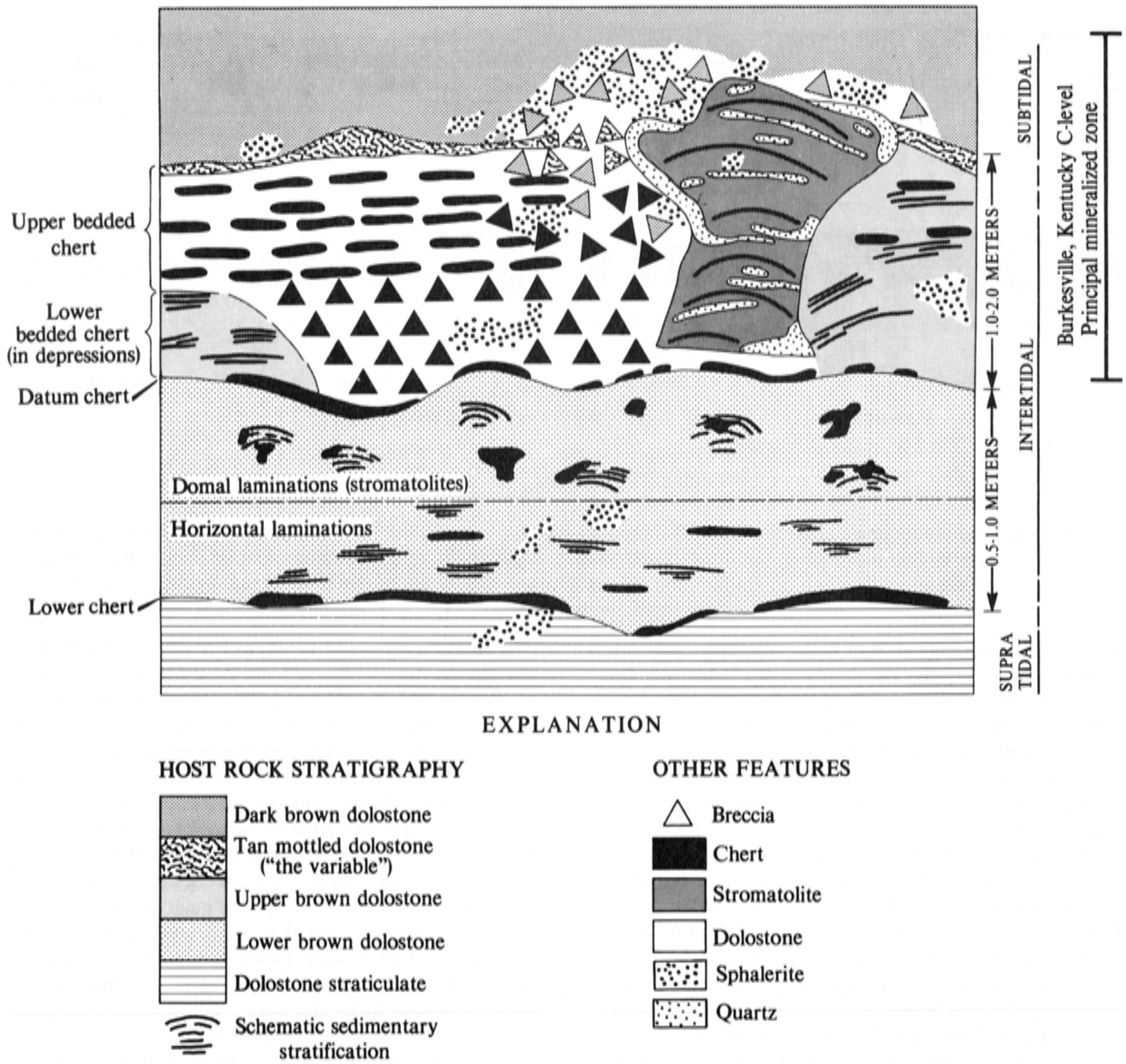


Figure 16. Detailed schematic diagram showing distribution of breccia, chert, columnar stromatolites, sphalerite, and quartz in the supratidal, intertidal, and subtidal host-rock dolostones of the Burkesville C-level. Dolostone units appear to be mostly of early diagenetic origin.

Epigenetic alteration of limestone

Throughout much of the Central Tennessee district, limestone beds in the upper Knox Group have undergone late-stage partial to complete replacement by medium- to extremely coarse-crystalline (0.25-5mm) dolomite, and by microcrystalline to cryptocrystalline quartz that resembles chert. These alteration products are shown as "late coarse-crystalline dolostone" and "late fine-crystalline silica," respectively, on the accompanying illustrations. These dolomitized and silicified rocks are distinguishable from primary dolostone and chert that formed during early diagenesis. The stratigraphic distribution of late-stage dolomitized and silicified limestone in the Elmwood-Gordonsville area is portrayed in Figure 5. Figures 7 and 9 to 14 illustrate the spatial distribution of primary dolostone (early fine-crystalline), unaltered and altered limestone, dissolution structures, and ore. As shown in these Figures, altered areas are particularly well developed where porosity and permeability were enhanced by dissolution of limestone in the Knox Group palaeoaquifer system. Furthermore, the close spatial relation of dolomitized and silicified limestone with dissolution structures including collapse-breccia and caverns, suggests that these rocks resulted from epigenetic alteration that apparently began after initial development of dissolution openings in limestone.

Epigenetic dolomitization of limestone in the Knox Group was a regional process that occurred within the Knox palaeoaquifer system, and, on a smaller scale, is closely associated with individual dissolution structures. In the Elmwood-Gordonsville area, coarsely crystalline dolomite forms prominent selvages around dissolution collapse-breccia and caverns, and selectively replaced intervening limestone beds (Figs. 7, 9, 10 and 13). The dolomite selvages are commonly less than 2m wide, but locally extend tens of metres from some dissolution structures. Epigenetic dolomitization may have alternated with periods of limestone dissolution, but was probably in large part later. Dolomitization preceded the introduction of ore and increased the porosity and permeability of the dense lime-

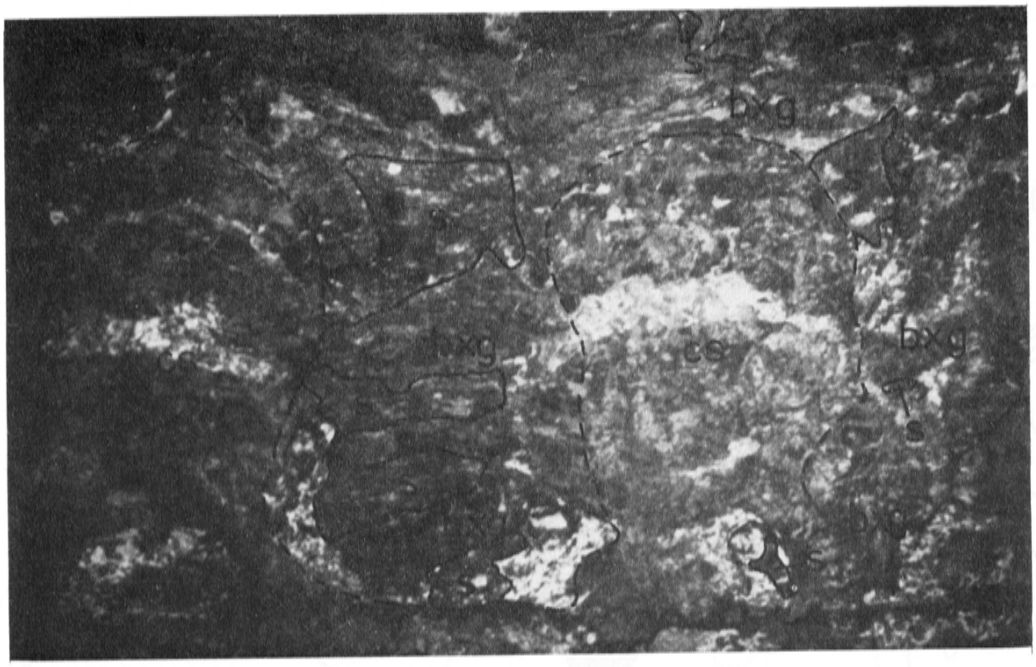


Figure 17. Photograph showing the distribution of sphalerite (s), quartz (white), and columnar stromatolites (cs) in the breccia and grainstone (bxg) of the Burkesville C-level (exploration drift NW 32). In the outlined areas, sphalerite forms most of the matrix around clasts and grains of dolostone and chert. The two white patches of quartz that are convex upward are silicified domal laminations in two columnar stromatolites; the white patch in the bottom centre of the photograph is convex downward, and results from silicification of grainstone and breccia near the base of an intertidal channel between the two columnar stromatolites. Sphalerite occurs mainly in the breccia and grainstone around the stromatolites. The columnar stromatolites are about 1.5m high.

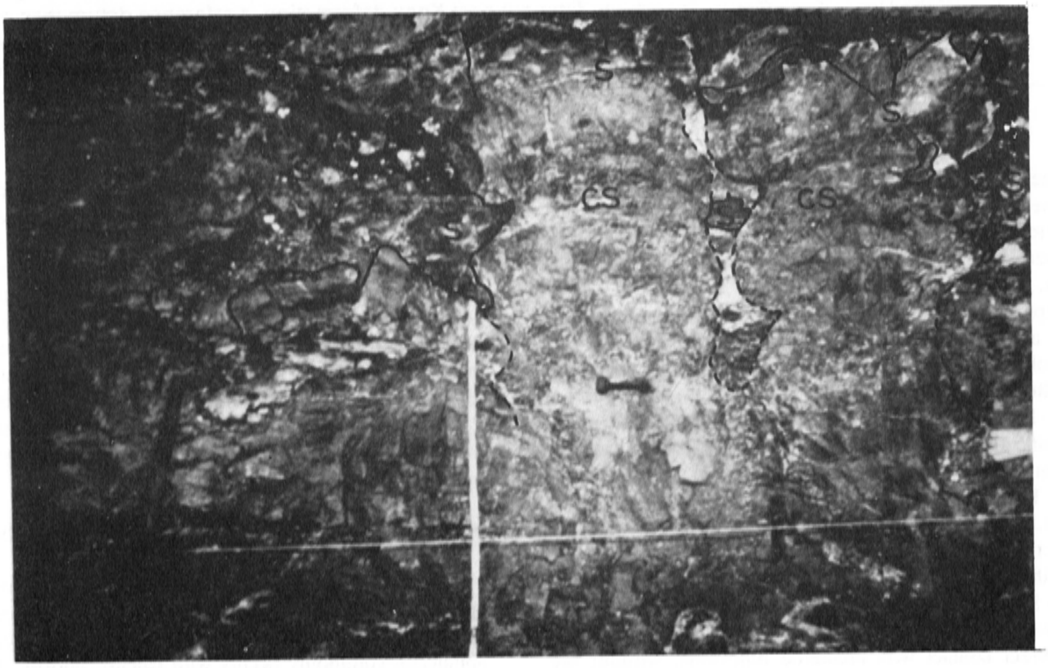


Figure 18. Photograph showing the distribution of sphalerite (s) in dolostone and chert breccias adjacent to two columnar stromatolites (cs) in the Burkesville C-level (exploration drift NW 59). In the outlined areas, sphalerite forms most of the matrix around clasts of dolostone and chert. Subordinate amounts of sphalerite also occur between the stromatolite columns, and in voids in domal laminations near the tops of the columns. The columnar stromatolites are about 1.5m high.

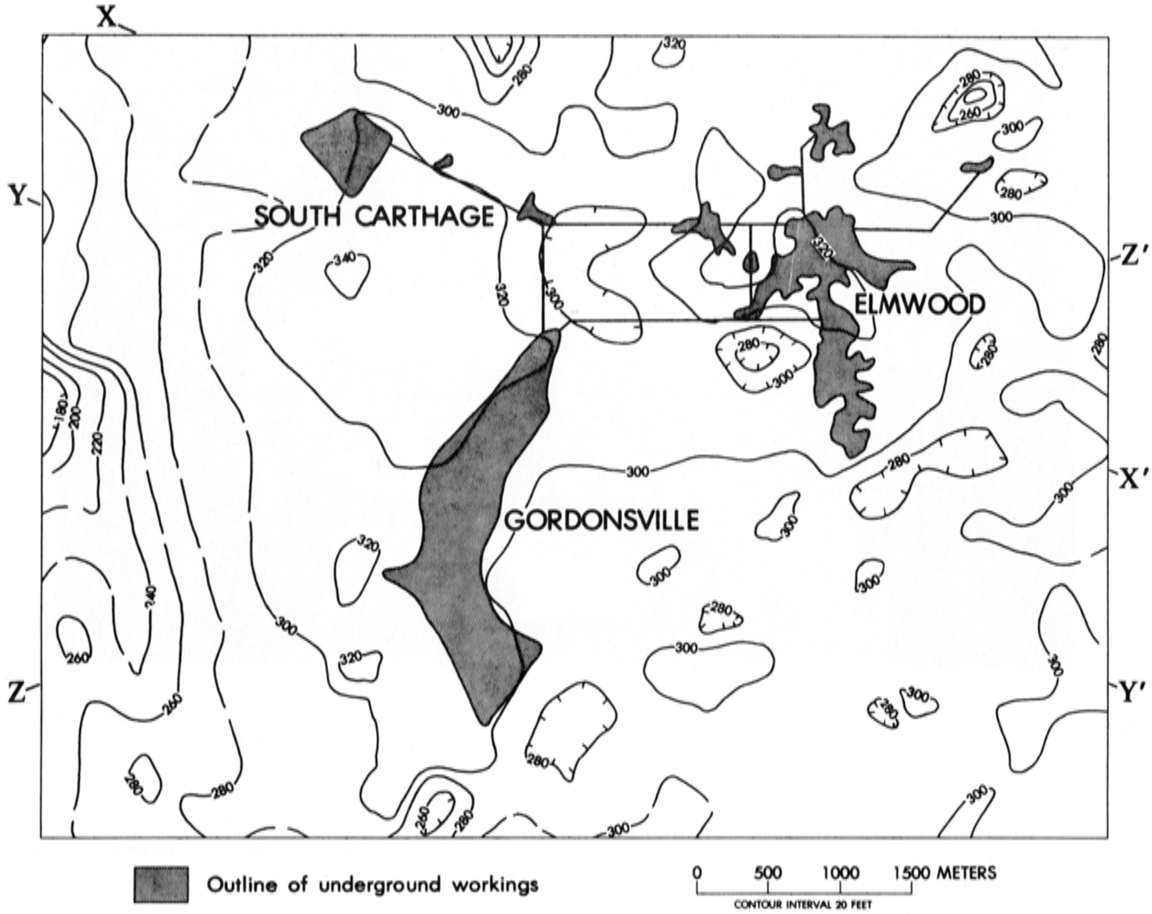


Figure 19. Map of the Elmwood-Gordonsville area illustrating the pre-Middle Ordovician structural configuration of the Upper Knox Group. In order to filter out post-Knox deformation, a reference datum was created 500 feet below the top of the Wells Creek Formation. Contours represent distances in feet from the reference datum to the overlying M-3 marker, which is the top of the middle Mascot Dolomite. Consequently, large contour values represent palaeostructural highs in the upper Knox Group. Control points for the map are drill holes spaced on about 300m centres. After Gaylord and Briskey (1983).

stone, typically forming a vuggy coarse-crystalline dolostone. Disseminated sphalerite was deposited in these intercrystalline vugs. Volume reductions attendant on dolomitization may have contributed to collapse and brecciation.

Epigenetic silicification of Knox Group limestone also was a regional process, and is also closely associated with dissolution structures on a small scale. Silicified limestone in the Elmwood-Gordonsville area is shown in Figures 9 and 13, and is most common in the Gordonsville mine. Silicification typically formed selvages of jasperoid up to 15cm wide adjacent to collapse fractures in limestone (e.g. Fig. 13). In addition, completely silicified selvages as much as 0.5m wide are common along the limestone walls of caverns and collapse-breccia (Figs. 9 and 13), and partly silicified selvages may extend two metres or more beyond this. Silicified zones following bedding in the limestone may be traced for many metres. Silicified limestone is commonly in direct contact with unaltered limestone, without the intervening zone of coarsely crystalline dolostone shown in Figure 9. Silicification preceded the main stage of ore deposition.

In the East Tennessee zinc districts, dolomitization and silicification similar to that described above are the principal types of alteration observed.

In the Burkesville C-level, early diagenetic silicification formed abundant chert by replacement of limestone along zones of primary porosity, concurrently with the early diagenetic dolomitization event that formed the primary dolostone host rocks (Craig, 1982). However, later epigenetic silicification of the dolostone also occurred, and deposited quartz in primary pore spaces and replaced evaporite minerals. Quartz-lined vugs are particularly abundant in the stromatolites of the C-level (Fig. 16). Pervasive silicification increased the brittleness of the rocks in the C-level, which promoted fracturing and brecciation, and, therefore, sphalerite deposition also.

Mineralogy, distribution, and age of ore bodies

Coarsely crystalline, dark-reddish-brown, low-iron sphalerite is the principal ore mineral in the Central Tennessee district. In the Elmwood-Gordonsville area, this sphalerite commonly occurs with calcite, fluorite, barite, yellowish-brown sphalerite, galena, and minor drusy dolomite and quartz. However, in the C-level at Burkesville, quartz and dolomite are the principal gangue minerals, and calcite, fluorite, and barite are absent or rare. Dolomitization and silicification of the host rocks are widespread, as described above. Other minerals occurring in minor to trace

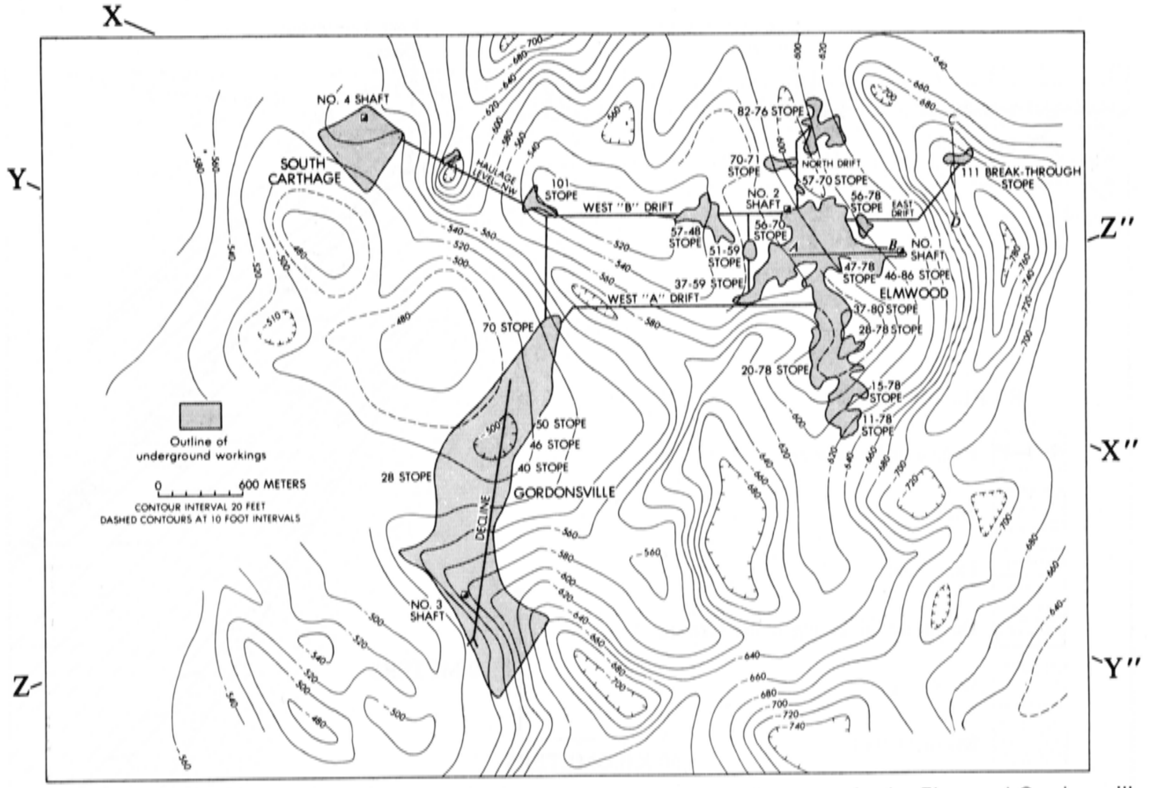
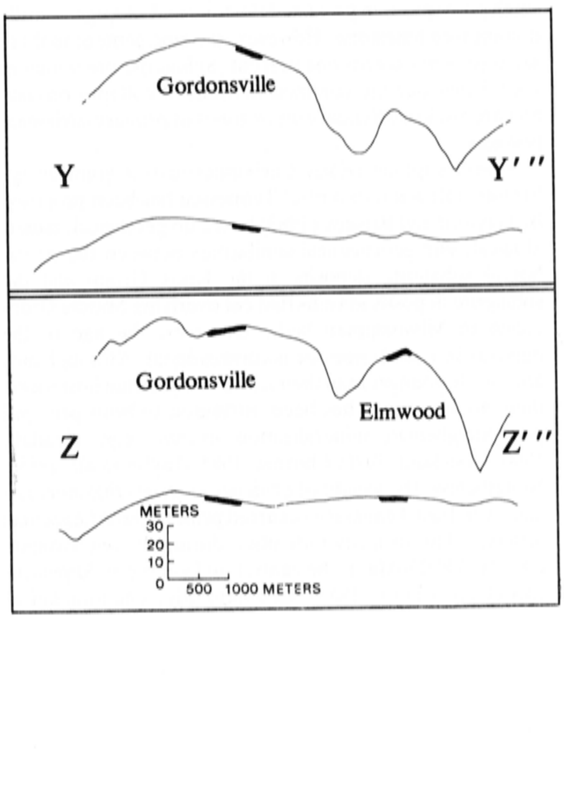


Figure 20. Structure contour map of the top of the Gordonsville lower limestone in the Elmwood-Gordonsville area. Contours are elevations in feet, all are below sea level (minus elevations). Control points for the map are drill holes spaced on about 300m centres. Cross section C-D is not shown in this paper. After Gaylord and Briskey (1983).

amounts in the district include marcasite/pyrite, celestite, gypsum, and enargite. Minor bituminous material and liquid hydrocarbons occur locally in sphalerite, fluorite, and calcite, and as coatings on rocks and minerals near the tops of collapse-breccia and caverns. The paragenetic sequence of ore and gangue minerals in the Elmwood-Gordonsville area has been outlined by Gaylord and Briskey (1983). Deposition was mainly by open-space filling of caverns, fractures, and of interclast cavities in breccia. Caverns commonly contain subhedral to euhedral crystals of ore and gangue minerals that attain lengths of several tens of centimetres to nearly a metre locally. The mineralogical composition of zinc ores in the East Tennessee districts differs from that in Central Tennessee in several



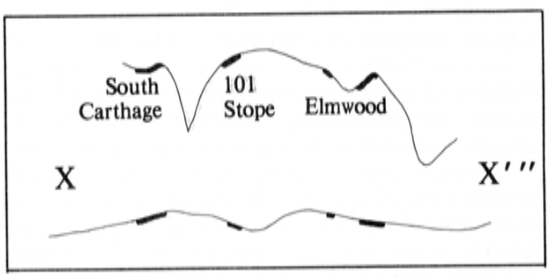


Figure 21. Structure (upper) and palaeostructure (lower) profiles in each of three cross sections through the Elmwood-Gordonsville area. Single-prime cross sections are from the palaeostructure map in Figure 19; double-prime cross sections are from the structure map in Figure 20. Black bars illustrate the distribution of mine workings (zinc ore bodies) projected to each structural surface. Vertical exaggeration is 30. Lines of cross section are shown on Figures 19 and 20.

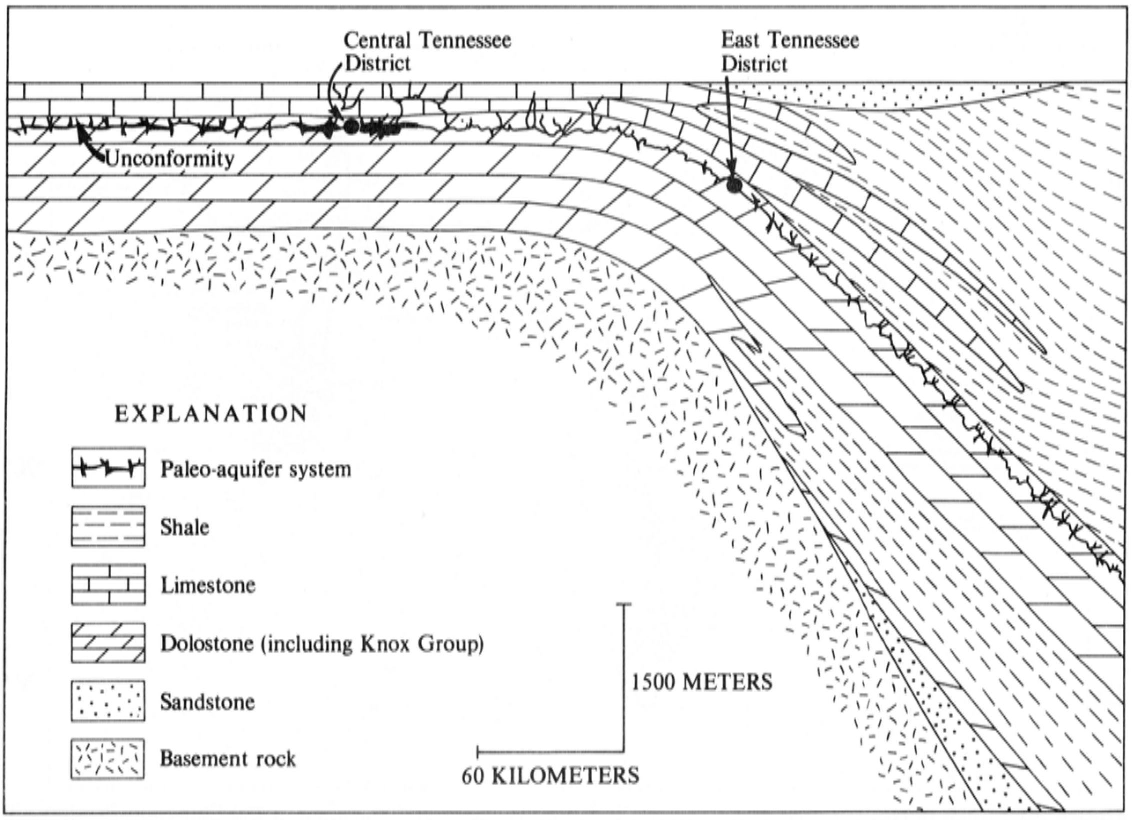


Figure 22. Diagrammatic reconstruction in cross section of pre-Mississippian (pre-Lower Carboniferous) Appalachian clastic basin and carbonate shelf. Looking northeasterly today. The subsurface palaeoaquifer in the Lower Ordovician Knox Group palaeokarst system is also shown. The locations of the East and Central Tennessee zinc districts along the carbonate shelf are approximate inasmuch as their original positions are obscured by faulting and folding during the Taconic, Acadian, and Alleghenian orogenies. Modified and simplified from Hoagland (1976).

respects, including, (1) dolomite rather than calcite is the predominant gangue mineral, (2) barite, fluorite, galena, and organic matter are much less common and are more sporadically distributed, (3) few open spaces remain and large euhedral crystals are absent, (4) sphalerite replaces limestone locally, and (5) small amounts of haematite, gypsum, anhydrite, and chalcopyrite are present.

The distribution of zinc ores in the Central and East Tennessee districts reflects the distribution of zones of high porosity and permeability. Deposition of sphalerite and associated minerals in the upper Knox Group of Central Tennessee occurred principally in caverns and in the upper dilatant parts of masses of dissolution collapse breccia that formed in and above limestone beds. However, some deposits are in zones of primary porosity in dolostone. Sphalerite mineralization took place after cessation of nearly all dissolution, collapse, and alteration. Rare occurrences of brecciated sphalerite are present in reactivated parts of the palaeoaquifer system, and in areas where masses of this mineral were deposited on the ceilings of caverns, and later fell under their own weight to the floor of the cavern. Although most ore is associated with dissolved, brecciated, and altered rock, extensive areas of such rock do not contain ore. There is no obvious correlation between the occurrence of sphalerite and that of altered areas and gangue minerals. However, there is a tendency for large concentrations of barite and fluorite to be deposited outside of, and commonly above, areas containing major accumulations of sphalerite. Where these three minerals do occur together, sphalerite is always earlier in the depositional sequence. These relations may reflect spatial and temporal variations in the redox conditions of the ore fluids. Widespread regional deposition of minor sphalerite occurred in small pore spaces in primary dolostone and in epigenetically dolomitized limestone. However, the zinc content in these areas seldom exceeds one percent. Sphalerite ore bodies in East Tennessee are confined to areas of collapse breccia, and are not known in caverns or zones of primary carbonate porosity.

A Mississippian (Early Carboniferous) or younger age for mineralization in central Tennessee has been proposed by Gaylord and Briskey (1983) based on geological, mineralogical, and geochemical similarities between the stratabound sphalerite deposits in the Knox Group and the sphalerite deposits in veins that cut overlying Middle Ordovician to Mississippian beds. However, the age of the deposits in East Tennessee is controversial. Although they are clearly younger than their Lower Ordovician host rocks, their minimum age has been attributed to both pre- and post-Alleghenian mineralization events (e.g. Kendall, 1960; Hoagland, 1976; Churnet, 1985; Taylor et al., 1985). Nonetheless, the weight of evidence suggests that mineralization in East Tennessee occurred prior to the Alleghenian orogeny. This orogeny took place during the approximate interval 330-230Ma in the central and southern Appalachians (Glover et al., 1983). Consequently, zinc mineraliza-

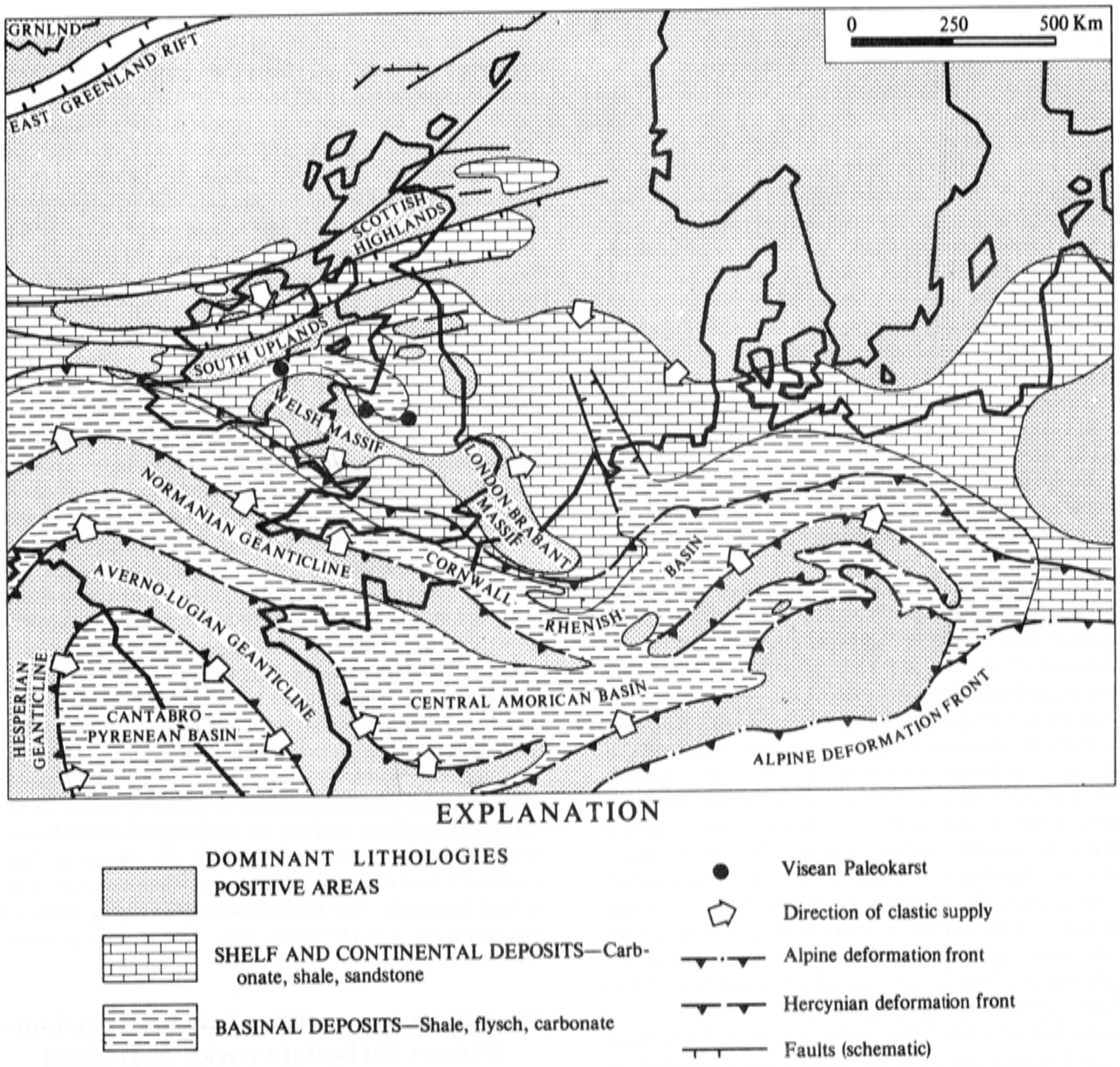


Figure 23. Map of the Early Carboniferous palaeogeography of NW Europe. Heavy lines indicate the present coasts of NW Europe. Simplified from Ziegler (1981).

tion in East Tennessee could be as young as about 330Ma, approximately equivalent to late Early Mississippian to early Late Mississippian, and also to the Early Carboniferous.

Basinal source of ore fluids

The formation of Mississippi Valley-type zinc-lead deposits is commonly attributed to deposition by the actions of metalliferous pore-fluid brines expelled from thickening, subsiding and compacting sedimentary basins. These brines, at least in part, must have migrated downwards to warmer parts of the basin, then laterally along basal aquifers and/or along structures that cross bedding, eventually reaching near-surface sites where precipitation of ore minerals occurred as a consequence of pH change, cooling, dilution, sulfate reduction, and/or mixing with solutions containing sulphide sulphur. This basinal brine model, originally proposed by Noble (1963), was modified and expanded by others including Beales and Jackson (1966), Jackson and Beales (1967), and Beales and Onasick (1970), and was recently reviewed by Anderson and Macqueen (1982). Some investigators (e.g. Dozy, 1970; Sharp, 1978; Cathles and Smith, 1983) have proposed that pulses of rapidly moving metalliferous brines were expelled during episodic rupture of geopressurized zones.

Calculations by Cathles and Smith (1983) reveal that extremely high flow rates are necessary to account for the conditions of deposition in the deposits. They calculate that fluid flow rates of 300 to 5000 times those resulting from steady state subsidence, compaction, and dewatering of a basin are required to transport hydrothermal fluids from near the bottom of a basin to within about 1km of the surface and yet retain sufficient heat to account for temperatures indicated by fluid inclusions in the deposits. They attribute these high flow rates to episodic fluid pulses generated by cyclic pressurization and rupture of geopressurized zones in impermeable shale beds during basin subsidence and compaction. Pressurization resulting from compaction during basin subsidence would eventually exceed that of the lithostatic load, causing rupture and expulsion of pore fluids, followed by a reduction of pressure to hydrostatic values. This process would repeat many time as subsidence and compaction continued. Cathles and Smith (1983) calculated that approximately 50 fluid pulses would result over about a 30 to 50 Ma period as the strata subside through the 3-5km depth necessary to generate temperatures in the range of Mississippi Valley-type mineralization. However, the actual duration of ore deposition (fluid pulses) was probably only a few thousandths of this period. The amount of a basin's fluid necessary to form Mississippi Valley-type deposits is small. Cathles and Smith (1983) estimated that for the Illinois Basin (USA), which contains more than $3.8 \times 10^5 km^3$ of sedimentary rock with greater than 20% shale, a porosity decrease of 0.26% could provide the necessary ore fluids. Rupture of geopressurized zones might also result from faulting during regional tectonism. Sharp (1978) proposed that late Palaeozoic faulting of geopressurized zones that formed during rapid deposition of over 10km of Mississippian and Pennsylvanian (Carboniferous) flysch in the Ouachita Basin (USA) released hot pressurized ore fluids along faults and stratabound aquifers to deposit the lead-zinc ore bodies of northern Arkansas and SE Missouri.

The Appalachian Basin has been proposed as the source of ore fluids that formed Mississippi Valley-type zinc deposits in East and Central Tennessee (e.g. Hoagland, 1971, 1976; Gaylord and Briskey, 1983; Cathles and Smith, 1983). This basin contains more than $2.15 \times 10^6 km^3$ of sedimentary rock composed of about 35% shale (Colton, 1970), including more than $1.5 \times 10^5 km^3$ of Middle Ordovician Taconic flysch from 2.4km to 4.9km thick (Hoagland, 1976) deposited unconformably on the palaeokarst surface at the top of the Knox Group in East Tennessee (Fig. 22). Pulses of ore fluids may have been expelled from ruptured geopressurized zones in the numerous shale beds during basin subsidence and compaction, or during faulting. Major periods of clastic sedimentation in the Appalachian Basin occurred during the Taconic, Acadian, and Alleghenian orogenies, but major faulting was principally an Alleghenian event. Consequently, the apparent pre-Alleghenian age of the deposits in East Tennessee suggests that they may have been associated with Taconic, Acadian, or perhaps the earliest part of the Alleghenian event, whereas the Early Mississippian or later age of mineralization in Central Tennessee is more easily attributed to the main Alleghenian event. Evidence of regional mobilization and migration of brines during at least part of the Alleghenian orogeny was recently presented by Hearn and Sutter (1985). They provided geological, geochronological, and geochemical data indicating that widespread authigenic potassium feldspar in Cambrian and Ordovician carbonate rocks of the Appalachian Mountains formed by reactions between connate brines and siliciclastic debris at elevated temperatures (less than 250°C) in the Late Pennsylvanian to Early Permian, during the middle part of Alleghenian compression, folding, and faulting. Consequently, pulses of ore fluids expelled at various times from the Appalachian Basin during parts of the Taconic, Acadian, and/or Alleghenian orogenies could have migrated along stratabound aquifers and /or along faults to the Basin margin where they would have entered the Knox Group palaeokarst system, and hence could have moved laterally and upwards along this palaeoaquifer to near-surface sites of ore deposition in the dissolution collapse-breccia and caverns in East and Central Tennessee.

Zinc ore in Central Tennessee was deposited where the ore fluids rose into the broad crestal area of the Nashville Dome and coincidently into local structural highs. In these areas, sphalerite was precipitated in caverns and collapse breccia, particularly in open spaces at the tops of the larger breccia masses, and in the primary porosity of detrital dolostone deposited in tidal channels between columnar stromatolites and stromatolite biostromes. If the ore fluids carried metals and sulphide sulphur together in solution as suggested by Sverjensky (1981, 1984), sphalerite may have been deposited during pH change, cooling, and/or dilution of the fluids with near-surface waters along the slightly elevated structural highs. Alternatively, the localization of ore in structural highs may reflect the accumulation of hydrocarbons in the highs. Four episodes of hydrocarbon deposition were recorded by Gaylord and Briskey (1983) in the Elmwood-Gordonsville area, and the first of these was coincident with deposition of main-stage sphalerite. Hydrocarbons are also present in sphalerite from the East Tennessee zinc districts (Craig et al., 1983). If the ore fluids carried sulphate or partly oxidized sulphur species (Spirakis, 1983) rather than sulphide sulphur, the two former sulphur compounds could have been reduced to sulphide by mixing with hydrocarbons, which would cause precipitation of sulphide minerals. Alternatively, oxidized sulphur compounds may have been transported in relatively unmetalliferous fluids, and, on arrival in the structural highs, could have been reduced to hydrogen sulphide (including bisulphide) by hydrocarbons. Hydrogen sulphide trapped in the structural highs could then have mixed with introduced metalliferous brines and caused precipitation of sulphide minerals. Hydrogen sulphide is frequently encountered during mining and exploration drilling in Central Tennessee. Sulphur may have been derived from sulphate and sulphide minerals in sedimentary rocks of the Appalachian Basin, or from sulphate minerals in supratidal and high intertidal lithofacies of the carbonate host rocks. Zinc and small amounts of lead were probably derived from metalliferous clastic rocks in the deeper parts of the Basin. Other potential sources for some of the metals are the carbonate host rocks, including regionally altered and dissolved limestone, and soluble evaporite-bearing facies of the dolostone (e.g. Davidson, 1966; Thiede and Cameron, 1978).

Comparisons with Lower Carboniferous carbonate rocks of Ireland

The regional geological setting and plate-tectonic evolution of NW Europe has been aptly summarized by Ziegler (1981). During the late Silurian Caledonian orogeny, the Laurentian-Greenland plate was sutured to the Fennoscandian-Russian plate along the Arctic-North Atlantic Caledonides. this compressional event was succeeded by a tensional tectonic regime that formed a complex intracontinental geosynclinal-geanticlinal rift system in NW Europe during the Devonian and Early Carboniferous. Lower Carboniferous basin, shelf, and continental depositional environments, and positive areas, resulting from this system are shown in Figure 23, and are similar to those existing during much of the Devonian. The Cornwall-Rhenish Basin, which also included southern Ireland, began to subside rapidly in the Early Devonian, and to receive basinal deep-water shales in its axial part. Subsidence and clastic sedimentation in this Basin continued during the Devonian and Early Carboniferous, and continental deposits and platform carbonate rocks accumulated on the northern shelf of the Basin. Onset of the Hercynian orogeny in the Early Carboniferous ended the tensional episode, and the Basins developed the configuration of foredeeps asymmetric to the south. Progressive northwards advance of the Hercynian deformation front generated marine flysch sequences that buried the carbonate shelf, and were succeeded by shallow-water marine to continental molasse deposits, and, in turn, by Upper Carboniferous coal measures that are as much as 3.5km thick locally.

The stratigraphic and structural setting, and genesis, of Irish base metal deposits, particularly those in the Lower Carboniferous, have been reviewed by numerous investigators, including Morrissey et al. (1971), MacDermot and Sevastopulo (1972), Williams and McArdle (1978), Sevastopulo (1979), and Phillips and Sevastopulo (this vol.). However, to our knowledge, none have focussed on the potential for occurrence of Mississippi Valley-type deposits. Any detailed analysis of the potential of formations and structures in Ireland to generate or host ore deposits of this type must be conducted by those more experienced with the geology of Ireland than we are. Nonetheless, we have attempted below to make some generalizations and to speculate about the possible generation and localization of such deposits in Ireland.

Potential basinal source of ore fluids

Thick sequences of fine-grained clastic rocks in the Cornwall-Rhenish Basin are potential sources of ore fluids like those that formed the large Mississippi Valley-type zinc districts in Central and East Tennessee. The northern side of the Cornwall-Rhenish Basin in southern Ireland is represented by the Munster Basin and by its successor the South Munster Basin, both of which have been described by Naylor et al. (1980), Sevastopulo (1981a), and Holland (1981). Sedimentation in the Cornwall-Rhenish Basin began with deposition of deep-water shales along its axial area in the Early Devonian. Subsequently, the Munster Basin received more than 6.5km of dominantly fine-grained clastic sediment, mainly Upper Devonian non-marine sandstone, siltstone, mudstone, and conglomerate of the Old Red Sandstone. These rocks are conformably overlain principally by more than 3km (G.D. Sevastopulo, oral communication, 1984) of Upper Devonian and Lower Carboniferous shallow-water marine mudstone, shale, limestone, sandstone, and siltstone that were deposited in the South Munster Basin during a generally south to north marine transgression (Fig. 24). The southern extent of the South Munster Basin is unknown, but a well drilled 170km off the southern coast of Ireland intercepted Lower Carboniferous (Courceyan) platform carbonate rocks (Sevastopulo, 1982).

Cathles and Smith (1983) identified characteristics of a basin favourable for the formation of Mississippi Valley-type deposits by episodic expulsion of ore fluids from geopressurized zones in the basin. These characteristics include the following:

1. The basin should contain abundant rocks with very low permeability, such as shale, in which geopressurized zones can form. For example, a permeability of less than or equal to about 0.005mD is required when sedimentation rates are approximately 25 metres per million years.
2. These low-permeability rocks are most likely to develop geopressurized zones if they have the complex internal sedimentary structures associated with thick, areally restricted, poddy and discontinuous beds typical of rapid deposition. Areally extensive, continuous thin beds resulting from slower more uniform sedimentation are less favourable.
3. The basin must be wide enough to generate abundant fluid from extensive geopressurized zones, and it must subside to depths of 3km or more in order to generate observed fluid-inclusion temperatures.
4. The aquifer(s) that channel the ore fluids should be thin and highly permeable to minimize cooling *en route*.
5. A relatively stable basin margin is required in order to channel multiple pulses of ore fluids to the same near-surface depositional site, which must also remain relatively stable.
6. Steep basin sides will reduce the amount of cooling *en route* by minimizing the length of an aquifer that must be traversed by the ore fluids in order to reach the surface. For comparison, the margins of basins associated with Mississippi Valley-type deposits in the US have slopes generally less than 1% (0.6 degrees).
7. The basin should have structures to focus the flow of ore fluids into or along restricted portions of the basin margin and aquifers; such focussed flow would increase the effectiveness of small fluid pulses, and favour formation of larger and higher-grade deposits.

The Cornwall-Rhenish Basin possesses a number of these favourable characteristics, as determined from the geological summaries of the Munster and South Munster Basins by Naylor et al. (1980), Sevastopulo (1981 a and b), Holland (1981), and Ziegler (1981). For example, mudstone and shale, which might have developed geopressurized zones, are common in the Munster and South Munster Basins; such rocks apparently include units of the Upper Silurian to Lower Devonian Dingle Group, the Castlehaven, Sherkin, and Lower Slate-Valentia Slate Formations in the Devonian Old Red Sandstone, the Upper Devonian Old Head Sandstone Formation, the Lower Carboniferous Kinsale and Courtmacsherry Formations, as well as other stratigraphically equivalent rocks. These units are among those deposited in alluvial and fluvial environments, including alluvial coastal plains and pro-delta slope transitions, and, in part, in Carboniferous fore-deep basins. Consequently, some of these units may be expected to display complex internal structures, which favour development of geopressurized zones. The Cornwall-Rhenish Basin may have been approximately 150km wide (Fig. 23), about one third the width of basins associated with Mississippi Valley-type zinc-lead deposits in the United States. However, the combined thickness of sedimentary rocks in the Munster and South Munster Basins exceeds 9km, compared to an average thickness of only about 6.5km in the basins of the United States. The nature of the aquifers that might have channelled ore fluids from deep within the Munster and South Munster Basins to near-surface sites of ore deposition along the Basin margin are speculative. Portential aquifers include some combination of: (1) permeable beds such as sandstones, particularly those deposited along the Basin margin or near impermeable beds that might generate geopressurized zones; (2) palaeokarst aquifers in carbonate rocks (discussed below); and (3) Hercynian faults, including N-, NE-, and NW -striking high-angle faults, and perhaps some southwardly dipping thrust faults.

The northern margins of the Munster and South Munster Basins may have been sufficiently stable periodically to permit the arrival of multiple pulses of ore fluids at the same depositional site(s). On a continental scale, the area north of the northern hinge lines of these Basins appears to

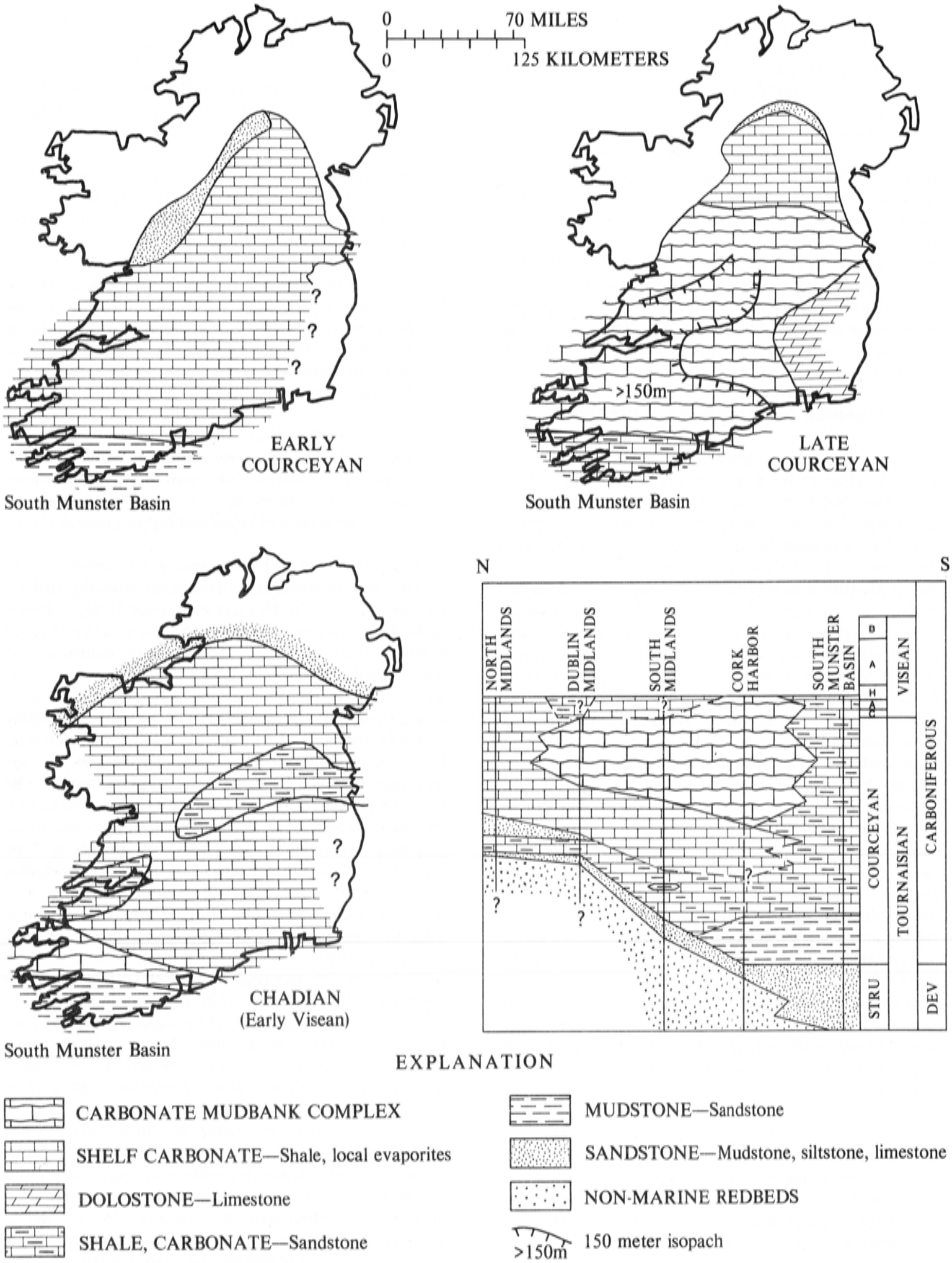


Figure 24. Map of Ireland showing stages in the Lower Carboniferous marine transgression. Modified and simplified from Naylor et al. (1980) and Sevastopulo (1981a). No scale was given for the cross section in Naylor et al. (1980). The South Munster Basin, shown here, was preceded by the Upper Devonian Munster Basin, whose hinge line was parallel to, and about 30km north of, the hinge line of the South Munster Basin.

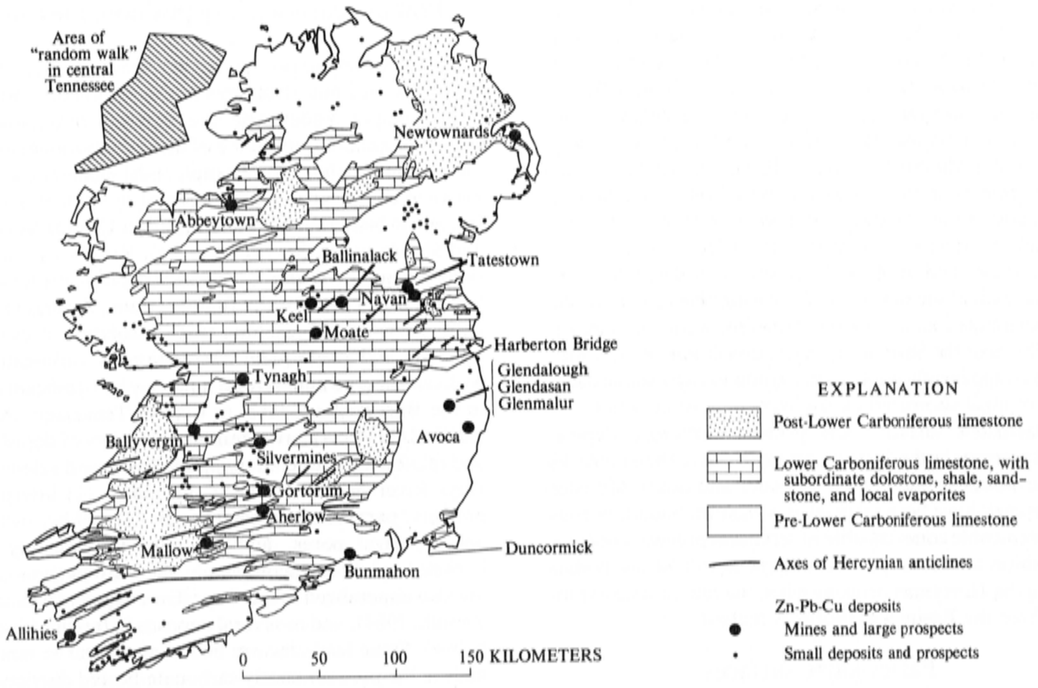


Figure 25. Generalized geological map of Ireland showing distribution of Lower Carboniferous rocks, Zn-Pb-Cu deposits, and axes of Hercynian anticlines. The area of the "random-walk" exploration drilling programme conducted in central Tennessee is shown to scale for comparison. Simplified from Morrissey et al. (1971), Naylor et al. (1980), Sevastopulo (1981b), and the Geological Map of Ireland (1979).

have been relatively stable since the end of the Caledonian orogeny. The northern hinge line of the South Munster Basin is shown in Figure 24; the northern hinge line of the Munster Basin is approximately parallel and about 30km farther north. During the Devonian and Carboniferous, most of this northern area consisted of positive land masses and continental shelf, but with some NE-trending horsts and grabens. The locations and activity of these fault blocks may have disrupted and/or complicated the flow paths of ore-bearing fluids locally. By the Early Permian, all of Ireland had become part of the Irish Massif, which persists today. The northern margin of the Munster Basin is steep (Holland, 1981), which would minimize the distance that ore fluids had to travel. Isopach maps of the Devonian Old Red Sandstone suggest that the Basin margin slopes from 4 to 17% (2-10 degrees), and, therefore, is much steeper than are the basins in the United States.

Structures that could have focussed the flow of ore fluids expelled from the Munster and South Munster Basins include: (1) NE-trending anticlines, (2) N-, NE-, and NW-striking high-angle faults, and (3) southerly-dipping thrust faults. These structures formed mainly during the Hercynian orogeny, and could have promoted rupture of geopressurized zones and expulsion of ore-bearing brines from the Basins in to platform rocks along the northern margins of the Basins where Mississippi Valley-type ore bodies could then have been deposited..

Cathles and Smith (1983) estimated that basins associated with Mississippi Valley-type ore deposits must be at least 10Ma old to attain basal temperatures greater than 100°C. Basins of this age expel fluids at a rate that is about 86% of the peak expulsion rate, which occurs after about 40Ma, and then decreases to roughly 58% after 80Ma. This timing suggests that the peak of fluid expulsion from the Munster and South Munster Basins was probably in the Late Carboniferous, roughly coincident with the early stages of the Hercynian orogeny. Mobilization of metalliferous brines in Ireland during the Hercynian orogeny would coincide approximately with the Alleghenian mobilization believed responsible for the formation of some Mississippi Valley-type deposits in the eastern United States.

Garvin and Freeze (1984) proposed that Mississippi Valley-type deposits were formed by a gravity-driven fluid-flow groundwater system that formed when the uplifted central part of a compacted sedimentary basin became topographically higher than its margins. However, the nature of the Late Carboniferous Hercynian upland area appears to be too poorly known to evaluate adequately the ore-forming potential of this model in Ireland.

Potential stratigraphic controls for ore deposition

Three stages of the Early Carboniferous marine transgression in Ireland are depicted in Figure 24, and have been summarized by MacDermot and Sevastopulo (1972), Naylor et al. (1980), and Sevastopulo (1981a). Deposition of shelf-carbonate rocks began in the early Courceyan Stage, and was accompanied by deposition of mainly mudstone in the South Munster Basin, and by chiefly sandstone along the northern shoreline. By the late Courceyan, a Waulsortian-type carbonate mudbank complex had spread across the shelf, and the Navan-Shannon Trough began to develop. This Trough is approximately defined by the 150m isopach, and served as the depositional basin for the large stratiform sediment-hosted exhalative massive sulphide zinc-lead deposits like those at Silvermines and Navan (e.g. Boyce et al., 1983; Taylor, 1984; Ashton et al., this vol.;

Andrew, this vol.). Dolostone predominated on the flanks of the Leinster Massif, which is the western extension of the Welsh Massif in Ireland (Fig. 23). Deposition of carbonate rocks encroached on the South Munster Basin. During the Chadian Stage, the carbonate mudbank complex receded basinwards, deposition of carbonate rocks decreased in the South Munster Basin, and shale became more common in the Shannon-Navan Trough. The Lower Carboniferous shelf-carbonate rocks of Ireland are principally limestone with subordinate but locally abundant dolostone, shale, and evaporite deposits. Subtidal, intertidal, and supratidal environments, including those that favour that accumulation of evaporite minerals, were widespread. Locally, near the Shannon Estuary, dissolution of evaporite deposits apparently caused brecciation of carbonate rocks. Beds of algal stromatolites also were deposited locally.

Palaeokarst surfaces, and primary carbonate depositional features in the Lower Carboniferous carbonate rocks on the northern shelf of the Munster and South Munster Basins may have been associated with stratabound, porous and permeable zones capable of serving as potential sites for deposition of Mississippi Valley-type zinc-lead ore bodies during the Hercynian orogeny when the rate of fluid expulsion from the Basins was probably highest.

Palaeokarst surfaces

Visean (late Early Carboniferous) palaeokarst surfaces occur in shelf-carbonate rocks along the edge of the Welsh Massif (Fig. 23). Walkden (1974) described multiple subaerial palaeokarst surfaces that formed penecontemporaneously with Asbian and Brigantian Stage shelf limestone of the Derbyshire block in central England. Somerville (1979 a and b) investigated palaeokarst surfaces associated with cyclic emergence of shelf-carbonate rocks in northern Wales during the Asbian and Brigantian Stages, and correlated these events with similar ones in Derbyshire and Yorkshire. Moreover, he found that the boundary between these two stages in northern Wales is marked by features indicating a prolonged emergence and by distinctive changes in fauna and lithology. The North Wales and Derbyshire areas were probably part of the same shallow-water shelf environment along the edge of the Welsh Massif. Cyclic emergence and development of these palaeokarst surfaces were probably related, in part, to periodic uplift of the Massif. In Ireland, at the beginning of the Visean, uplift and faulting created local unconformities and carbonate conglomerate (MacDermot and Sevastopulo, 1972). Near Loughshinny, for example, on the coast north of Dublin, the nonmarine Lane Conglomerate was deposited on karstified Chadian limestone along the edge of the Leinster Massif (Welsh Massif) (Naylor et al., 1980; Sevastopulo, 1981a). Other palaeokarst surfaces of Visean age occur in Belgium (e.g. Lees and Conil, 1980) near the London-Brabant Massif, which is the eastern continuation of the Welsh Massif. It is possible that emergent palaeokarst surfaces along the Welsh Massif acted as recharge areas for subsurface palaeoaquifers. These palaeoaquifers may have extended a considerable distance from the edge of the Massif. For example, more than 300km separate the most distant recharge and discharge areas of the modern limestone aquifer in Florida and southern Georgia, USA. Consequently, regional palaeoaquifer systems with caverns and collapse breccia could occur in Ireland along the flanks of the Leinster Massif, or near any other block periodically emergent in the Early Carboniferous, and might, therefore, host zinc deposits similar to those in Tennessee.

Primary carbonate depositional textures

A wide variety of porous and permeable primary depositional textures and structures in the carbonate host rocks of Mississippi Valley-type ore deposits throughout the world are mineralized. Some of these depositional features are identified below. For example, tidal-channel grainstone between columnar stromatolites and in stromatolite biostromes or bioherms are mineralized in Central Tennessee and SE Missouri (described earlier). Porous algal laminations in supratidal and intertidal lithofacies preferentially localize ore in parts of the Bleiberg mine, Austria (Hagenguth, 1984). Voids resulting from dissolution of evaporite minerals and consequent brecciation of carbonate host rocks can also be mineralized, and may be significant locally in the Burkesville C-level in Central Tennessee. Akande and Zentilli (1984) have identified a variety of depositional and related textures containing sphalerite and galena in the Gays River deposit, Canada, including, (1) interparticle porosity, particularly in algal bands, (2) moldic, sheltered, and fenestral pores, and (3) porosity occurring in or between stylolites. Incompletely filled stromatactis cavities are also mineralized in the Gays River deposit (Akande and Zentilli, 1984), and in several deposits in Ireland (discussed below). Some lead-zinc ore bodies also occur in sandstone beds in the predominantly carbonate-hosted districts in SE Missouri. However, such ore bodies are most common in exclusively sandstone-hosted districts such as Laisvall (Sweden), Largentière (France), and Yava (Canada) (Bjørlykke and Sangster, 1981). All of these sedimentary environments are represented in the Lower Carboniferous rocks of Ireland, and most were identified earlier in this paper; some might host Mississippi Valley-type zinc-lead deposits.

The Waulsortian-type carbonate mudbank complex that spread over much of southern and central Ireland during the late Courceyan was recently described by Sevastopulo (1982), and is a potential host rock for Mississippi Valley-type deposits. The complex is more than 1km thick locally. Principal lithologies include coalescing mound- and sheet-like build-ups of lime mudstone, wackestone, and packstone. These rocks commonly contain primary cavities, including stromatactis, which are filled with internal sediment and with fibrous and sparry carbonate cements. The complex is host to an abundant fossil assemblage including numerous brachiopods, bryozoans, and molluscs. The enigmatic stromatactis cavities that characterize many carbonate mudbank complexes in Ireland and elsewhere were traditionally attributed to the actions of organisms. However, Bathurst (1982) recently presented evidence indicating that they are a result of episodic submarine lithification of carbonate muds in bioherms. Lithification formed successive crusts between which cavities were eroded and then filled with spar calcite and geopetal sediment. This porosity was augmented by bioturbation, differential compaction, or shearing during burial, which collectively broke and rotated the crusts.

The Irish Waulsortian complex probably retained at least some porosity, even after compaction and cessation of its development (Sevastopulo, 1979). By comparison, porosity and permeability in Waulsortian-type carbonate mounds in the Lower Mississippian Fort Payne Formation in NE Tennessee are sufficient to have allowed production of over 5.5 million bbl of oil through 1980, and were well described by MacQuown and Perkins (1982). Both primary and secondary porosity are important in the Fort Payne mounds. Primary porosity includes stromatactis cavities in mud-supported microfacies, but, in associated grainstone microfacies, the porosity results from submarine cementation on bryozoan fragments. Major secondary porosity consists of vuggy, moldic, and minor intercrystalline porosity in grainstones and some packstones that were altered by progressive solution diagenesis by connate or meteoric ground water. Minor secondary porosity includes vuggy and moldic porosity in the mud-supported mound facies. Carbonaceous material is also present in Waulsortian-type mounds in Europe (MacQuown and Perkins, 1982). In Ireland, MacDermot and Sevastopulo (1972) speculated that black lustrous hydrocarbons occurring in large vugs and fissures in the Waulsortian complex, or in dolomitized zones, might be related to base-metal mineralization, presumably by reducing sulphate or partly oxidized sulphur species to sulphide sulphur. In addition to hydrocarbons, the Irish complex also contains low-grade zinc and lead deposits formed by open-space filling and minor replacement (Boyce et al., 1983). Stromatactis cavitis are weakly mineralized in some of the sedimentary exhalative deposits (Boyce et al., 1983), and in the Ballinalack zinc-lead deposit (Jones and Brand, this vol.). Consequently, porosity, permeability, and perhaps hydrocarbons in the Irish Waulsortian complex might also have localized zinc-lead deposits of the Mississippi Valley-type.

Potential structural controls of ore deposition

A variety of structures could have channelled ore fluids and localized Mississippi Valley-type ore bodies in Ireland. Hercynian N-, NE-, and NW-trending high-angle faults, and southerly dipping thrust faults, might have served as aquifers and focussing structures for ore fluids expelled from the Munster and South Munster Basins (Cornwall-Rhenish Basin) as described earlier. NE-trending anticlines of Hercynian age (Fig. 25) are also proposed as potential focussing structures for ore fluids. These NE-trending anticlines, and uplifts such as the Leinster (Welsh) Massif, might have localized ore deposits by providing areas for entrapment and/or mixing of surface waters, hydrocarbons, sulphur-bearing fluids, and/or metalliferous brines, as described for the zinc deposits localized along the crest of the Nashville Dome in Central Tennessee. Moreover, several uplifts were active in Ireland during the Late Devonian and Early Carboniferous (e.g. Naylor et al., 1980; Holland, 1981; Sevastopulo, 1981 a and b; Ziegler, 1981). These uplifts also might have contributed to other conditions favourable for the localization of ore, including, (1) sedimentary pinch-outs like those that localize lead-zinc ore along the flanks of Precambrian basement highs in SE Missouri, (2) karstic recharge areas, and (3) restricted shallow-water environments favouring deposition of dolostone. Where dolostone is interbedded with limestone, dissolution collapse breccia is more likely to form because of the differing solubilities of the two rocks in a karst system. Furthermore, dolostone typically has higher porosity and permeability than does limestone, and is more likely to contain soluble sulphur as evaporite minerals. Finally, areas along the crests and flanks of large uplifts and anticlines should be examined for the presence of local structural highs like those that host zinc ore bodies in the Elmwood-Gordonsville area of Central Tennessee.

Summary and conclusions

Palaeozoic shelf carbonate rocks capable of hosting epigenetic Mississippi Valley-type zinc-lead deposits in Tennessee and Ireland occur within the Alleghenian-Hercynian orogenic belt and its foreland area. Potential source rocks for such deposits occur nearby in basins that were marginal to the carbonate platforms, and are now part of the orogenic belt.

Large zinc deposits in Tennessee consist chiefly of open-space fillings of low-iron dark-reddish-brown sphalerite (Central Tennessee) and pale yellow sphalerite (East Tennessee), with various amounts of dolomite, calcite, quartz, fluorite, barite, pyrite/marcasite, galena, bituminous matter, haematite, celestite, gypsum, anhydrite, chalcopyrite, and enargite, roughly in order of decreasing abundance. Dolomitization and silicification of host rocks are widespread. The deposits may have precipitated from pulses of ore fluids expelled from ruptured geopressurized zones in the numerous shale beds of the Appalachian Basin during basin subsidence and compaction, and/or during faulting, all of which accompanied basin development and tectonism during the Taconic, Acadian, and Alleghenian orogenies. Deposition of zinc ore in Central Tennessee probably occurred during the Alleghenian (Hercynian) event. Ore bodies were localized where these ore fluids rose into the broad crestal area of the Nashville Dome, and coincidently into local structural highs, there precipitating sphalerite in palaeokarst dissolution collapse-breccia and caverns, and in the primary porosity of detrital dolostone deposited in tidal channels between columnar stromatolites and in stromatolite biostromes. Structural highs apparently localized ore bodies by providing areas for entrapment and/or mixing of surface waters, hydrocarbons, sulphur-bearing fluids, and/or metalliferous brines. Zinc ore bodies in East Tennessee also occur in collapse breccia, and probably have a similar origin.

Potential source rocks for Mississippi Valley-type ore fluids occur in Ireland. The Cornwall-Rhenish Basin, represented by over 9.5km of principally Upper Devonian and Lower Carboniferous clastic rocks in the Munster and South Munster Basins of southern Ireland, appears to possess characteristics favourable for the formation of Mississippi Valley-type ore deposits from ore fluids expelled periodically from geopressurized zones in the basin. These characteristics include, (1) presence of thick accumulations of mudstone and shale, (2) deposition of some of these rocks in sedimentary environments favourable for development of complex internal structures, which can promote development of geopressurized zones, (3) occurrence of potential aquifers, including permeable sandstone beds, palaeokarst systems, and Hercynian faults, (4) a stable and steep northern basin margin, and (5) structures capable of focussing the flow of ore-bearing fluids expelled from the basin, and including Hercynian faults and anticlines. The timing of basin development was such that the peak rate of fluid expulsion probably occurred in the Late Carboniferous, roughly coincident with the Hercynian orogeny.

Stratabound, porous and permeable zones capable of hosting ore deposits of the Mississippi Valley-type could be associated with Visean palaeokarst surfaces and with primary carbonate depositional textures and structures in the Lower Carboniferous carbonate rocks of Ireland. Potentially favourable host carbonate textures and structures include, (1) tidal-channel grainstone, (2) algal laminations in stromatolite beds, (3) breccia resulting from dissolution of evaporite minerals, (4) interparticle porosity, (5) moldic, sheltered, and fenestral pores, (6) porosity occurring in or between stylolites, and (7) incompletely filled stromatactis cavities and other porosity in the Waulsortian carbonate mudbank complex. Some ore deposits also might be localized in porous and permeable sandstone beds. The porosity and permeability in some parts of the extensive Waulsortian complex in Ireland are potentially high. Moreover, hydrocarbons occur locally in this complex, and in some areas it contains small low grade zinc-lead deposits formed by open-space filling and minor replacement. Consequently, the Irish Waulsortian could have localized ore deposits of the Mississippi Valley-type.

NE-trending Hercynian anticlines, and uplifts such as the Leinster (Welsh) Massif, could have localized Mississippi Valley-type deposits by providing areas for entrapment and/or mixing of ore-forming fluids in stratabound zones of high porosity and permeability as proposed in Tennessee. Moreover, the uplifts may have contributed to other conditions favourable for the localization of these deposits, including sedimentary pinch-outs, karstic recharge areas, and deposition of interbedded limestone and dolostone.

Two epigenetic carbonate-hosted zinc-lead deposits in Ireland that appear to have some of the geological characteristics of Mississippi Valley-type deposits are those at Harberton Bridge (Holdstock, 1982; Emo, this vol.) and Duncormick (Carter and Wilbur, 1982, this vol.), both of which are located along the edge of the Leinster Massif (Fig. 25). These two deposits occur in breccia associated with dolostone and/or dolomitized limestone. Brecciation at Duncormick is attributed to processes related to "cave formation" or to "solution of an evaporite horizon" (Carter and Wilbur, 1982, this vol.). At Harberton Bridge (Holdstock, 1982), extensive collapse breccia occurs in Visean carbonate rocks, and, in many respects, closely resembles the palaeokarst collapse breccia in Tennessee. However, the presence of corroded breccia fragments, the occurrence of brecciated mineralized rock, and the close proximity of sulphides to faults apparently persuaded Holdstock (1982) to invoke a model of "hydrothermal karst or solution" in an acid hydrothermal system. Nonetheless, his descriptions are not incompatible with original formation of the collapse breccia in a Visean palaeokarst system, subsequently modified by reaction with the ore fluids, or with closely related fluids. Breccia and sulphide minerals at Harberton Bridge are concentrated in argillaceous bioclastic limestone immediately below the basal contact of the Waulsortian limestone. This preferential localization might reflect a relatively higher solubility for the argillaceous bioclastic limestone. Such a difference in solubility would probably be more pronounced in a meteoric groundwater system than in an acid hydrothermal system.

In conclusion, source rocks and environments for deposition of Mississippi Valley-type zinc-lead deposits apparently existed in Upper Devonian and Lower Carboniferous rocks of Ireland at a time when development of sedimentary basins and regional Hercynian tectonism were capable of generating and mobilizing ore-bearing fluids of this type. Consequently, Mississippi Valley-type deposits may occur in the Lower Carboniferous carbonate rocks of Ireland. Discovery of ore bodies will probably require some version of the random drilling technique that was successfully applied in Central Tennessee. The area of this "random walk" is shown on Figure 25, in comparison to the relatively much larger outcrop area of Lower Carboniferous carbonate rocks in Ireland. Detailed studies capable of predicting the occurrence and distribution of stratabound porous and permeable zones, and of structural and stratigraphic traps, should provide more specific drilling targets, thereby reducing the large number of holes required for a major discovery.

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