REVIEW OF CARBONATE HOSTED LEAD-ZINC (COPPER) DEPOSITS AND THE GEOLOGICAL FACTORS AFFECTING THEIR SHAPE, SIZE AND GRADE

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CONTENTS

Page

1.0 INTRODUCTION 1

2.0 CARBONATE HOSTED LEAD-ZINC-COPPER DEPOSITS 3

- 2.1 Introduction 3
  - 2.1.1 Mississippi Valley Type Deposits 8
  - 2.1.2 Appalachian Type Deposits 10
  - 2.1.3 Alpine Type Deposits 11
  - 2.1.4 Discussion 17
- 2.2 Tectonic Setting 17
  - 2.2.1 Tectonic setting of the Canadian lead-zinc deposits 18
  - 2.2.2 Tectonic setting of the lead-zinc deposits of the United States of America 21
  - 2.2.3 Tectonic setting of the "Alpine" type lead-zinc deposits 24
  - 2.2.4 Tectonic setting of the Irish lead-zinc (copper) deposits 26
  - 2.2.5 Tectonic setting of the carbonate hosted polymetallic deposits in Namibia 29
- 2.3 Basis on which discussion of carbonate hosted lead-zinc deposits will be discussed 31
- 2.4 Deposits associated with reef complexes 32
  - 2.4.1 Deposits in barrier reef complexes 32
  - 2.4.2 Deposits in mudbank complexes 35
  - 2.4.3 Algal reef deposits 37
  - 2.4.4 Back reef deposits 42
- 2.5 Deposits associated with karst features 46
  - 2.5.1 Introduction 46
  - 2.5.2 Solution collapse breccia deposits related to karst topography above 49
  - 2.5.3 Deposits related to collapse structure resulting from thinning of underlying beds by subsurface drainage 49
- 2.6 Deposits not primarily associated with reefs or karsts 50
  - 2.6.1 Deposits located at a facies change 50
  - 2.6.2 Deposits associated with structural and/or sedimentary coincidence 50
- 2.7 Metal transport and deposition 50

Page

3.0 GEOLOGICAL FACTORS AFFECTING THE SHAPE, SIZE AND GRADE OF THE CARBONATE-HOSTED LEAD-ZINC (COPPER) DEPOSITS 52

- 3.1 Introduction 52
- 3.2 Geological factors affecting the shape and size of the ore-bodies 52
  - 3.2.1 Palaeotopographical factor 52
    - (a) Pinchout type 53
    - (b) Algal reef 55
    - (c) Submarine slides 57
  - 3.2.2 Structure 60
    - (a) Faulting, fracturing and jointing 60
      - (i) Vein deposits 60
      - (ii) Bedded deposits 61
      - (iii) Deposits associated with faulting and ridge structures 62
      - (iv) Deposits associated with bar-reef complex and faulting 63
      - (v) Deposits associated with bedding-plane movement 63
      - (vi) Marginal break deposits 64
      - (vii) Deposits associated with tear faulting, fissures and bedding planes 65
      - (viii) Deposits associated with faulting, folding and host rock competency 66
      - (ix) Gash-vein, joint-controlled ore-bodies 66
    - (b) Folding and faulting 68
      - (i) Deposits genetically related to folding and to reverse- and bedding plane faulting; the so called Pitch and Flat deposits 69
      - (ii) Deposits genetically related to folding and tension fractures 72
      - (iii) Deposits genetically related to intense folding 74
  - 3.2.3 Erosion 76
  - 3.2.4 Sedimentology 85
    - (a) Reef complexes 85
    - (b) Disconformaties 88
    - (c) Unconformaties 88
    - (d) Stylolites 88
    - (e) Bedding planes 89

Pages

(f) Impermeable caprock 89

(g) Facies changes 89

3.2.5 Supergene alteration 89

3.3 Geological factors affecting the grade in carbonate hosted lead-zinc (copper) deposits 95

3.3.1 Structure 96

3.3.2 Zoning 96

3.3.3 Ore mineral distribution 100

4.0 IMPLICATIONS FOR EXPLORATION DRILLING AND ORE RESERVE ESTIMATION BASED ON THE GEOLOGICAL FACTORS CONTOLLING THE GEOMETRY AND GRADE OF CARBONATE HOSTED LEAD-ZINC DEPOSITS 103

4.1 Introduction 103

4.2 Exploration drilling 103

4.3 Ore reserve extimation 106

5.0 MINEABILITY AND EXTRACTABILITY OF CARBONATE HOSTED LEAD-ZINC (COPPER) DEPOSITS 112

5.1 Mineability 112

5.2 Extractability of the ore minerals 115

5.2.1 Nature of the ore 115

5.2.2 Quality of the ore 117

SUMMARY AND CONCLUSIONS 118

ACKNOWLEDGEMENTS 120

BIBLIOGRAPHY 121

1.0 INTRODUCTION

For at least two centuries and a corresponding number of generations of geologists and miners there has been active argument concerning the origin of certain types of carbonate hosted mineral deposit. The characterization of the type itself was and still is debatable. Objections have been raised to grouping several examples under one heading because each has its individually distinctive features. This is especially applicable to the carbonate hosted lead-zinc "sedimentary" deposits. The type that will be discussed in the text to follow is composed chiefly of galena, sphalerite, barite and fluorite, with pyrite, marcasite and chalcopyrite as conspicuous accessory ore minerals. Exceptions to this general copper deficient characteristic displayed by the sedimentary carbonate-hosted lead-zinc deposits are the deposits at Tsumeb and Kombat, Namibia. These deposits are hosted by the carbonate sequence of the Otavi Shelf sediments, and copper, in the form of tennantite, chalcopyrite and bornite, is the major ore constituent. Calcite, aragonite, dolomite and quartz are the commonest nonmetallic gangue minerals but siderite and silica may also be present. In contrast with other lead and zinc sulphide (volcanogenic) deposits, those to be considered here seldom carry noteworthy amounts of silver or any other precious metals. Commonly the country rock is a carbonate, limestone or dolomite, but deposits in sandstone, shale and conglomerate are not unknown. Characteristic features are ore bodies that extend parallel or nearly so with the bedding although many such deposits are partly, or completely developed along crosscutting fissures and breccias. Some observers regard these fissure fillings as evidence for a magmatic source of the metals, whereas others regard them as an indication of remobilization of ions, metals or minerals orginally present in low-grade stratiform deposits elsewhere in the stratigraphic succession.

The genesis of these carbonate-hosted "sedimentary" deposits has been extensively debated. The deposits have been regarded as the result of leaching from lean deposits in overlying rocks, with concentration downward in favourable localities: as "lateral secretion" ores gathered from the immediately adjacent rocks; as true sediments; as synsedimentary or diagenetic deposits: as deposits from descending but subsequently re-ascending solutions; as having been precipitated from magnetic solutions; and as sea-floor deposits from thermal springs. In general, one concept or another has prevailed over a shorter or longer period in a given region or country. At present the chief contrasts are between the syngenetic or diagenetic, essentially sedimentary theory of origin and the epigenetic, essentially hypogene interpretation.

The discussion in this dissertation will not revolve around the sources of the metals and reduced sulphur. The dissertation review of the various types of carbonate-hosted lead-zinc (copper) deposits, excluding skarn and replacement types, and will concentrate on the geological factors affecting the geometry and grade of these deposits and the implications for exploration drilling and ore reserve estimation.

2.0 CARBONATE HOSTED LEAD-ZINC-COPPER DEPOSITS

2.1 Introduction

Carbonate hosted lead-zinc (copper) deposits constitute one of the worlds great sources of these two metals. This type of depsit, the principle source of lead and zinc in both the United States and Europe, is represented in the famous Appalachian, Tri-State, southeast Missouri and upper Mississippi Valley districts in the United States, and in the Alpine, Silesian, Central Irish Plain, and Pennine districts of Europe Great Britain. Large deposits also exist in Canada, North Africa and Russia. The more important occurrences are those in North America, Europe, Russia, England and North Africa and these are indicated in figures 1 and 2.

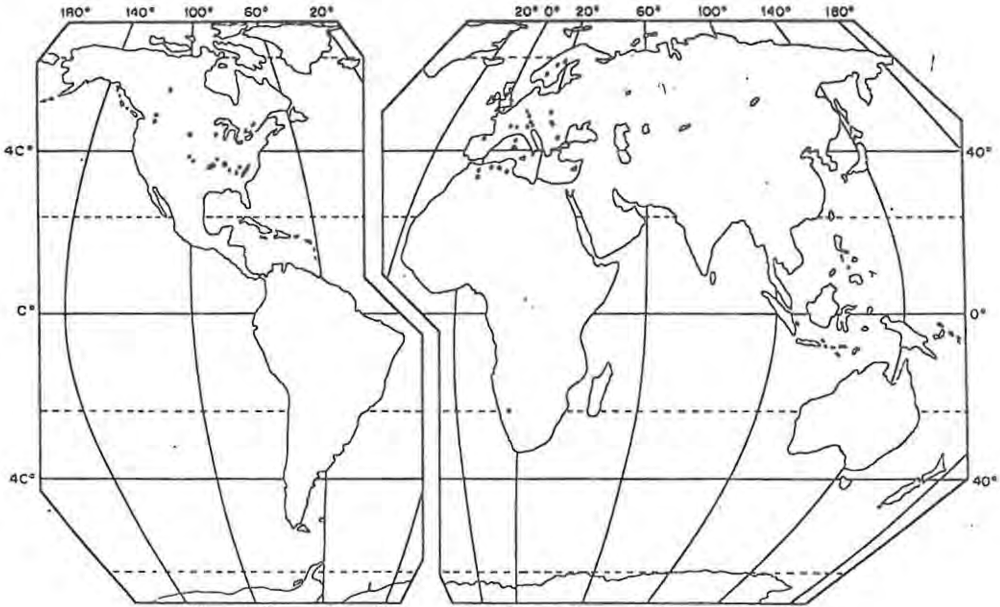


Fig. -1 Distribution of major limestone-type lead-zinc occurrences, and areas of occurrence, throughout the world.

From Stanton, 1972

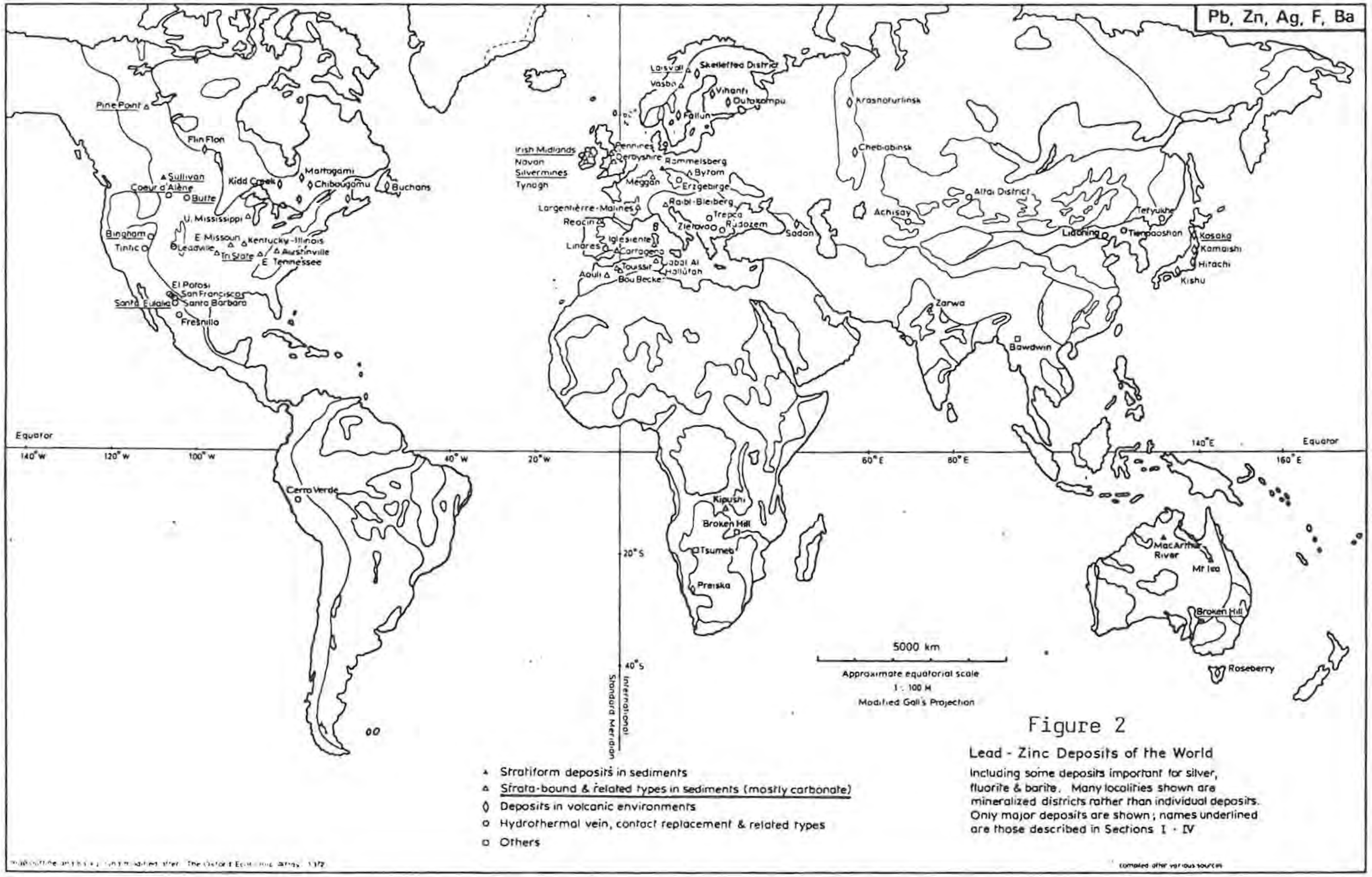


Figure 2

Lead - Zinc Deposits of the World

Including some deposits important for silver, fluorite & barite. Many localities shown are mineralized districts rather than individual deposits. Only major deposits are shown; names underlined are those described in Sections I - IV

From Dixon, 1979

Deposits of this type are known elsewhere, e.g. Australia, but in the present state of exploration (Stanton, 1972) they appear to be small and of a low lead and zinc content.

The principal earlier known areas of occurrence were Europe, particularly the region of the Alps, and a region of the United States roughly within the upper and middle areas of the Mississippi Valley. In consequence this kind of deposit became known as "Alpine-" or "Mississippi Valley-" type mineralization. Lesser used synonyms are, respectively, "Silesian type" and "Tri-State type". An important European area of occurrence is in Silesia (Poland), and in the Mississipi Valley much of the earlier mining was close to the border of Missouri, Kansas and Oklahoma. Other important North American occurrences are in the southern Appalachians, also refereed to as the "Appalachian type", and, particularly, in the Pine Point (Great Slave Lake) are of northern Canada. The principle European occurrences are those of Germany, northern Italy, Yugoslavia, Austria, and southern Poland. Several important occurrences are exploited in Algeria and Tunisia.

In addition to exhibiting quite a wide geological distribution, this type of mineralization shows a fairly wide spread in time. The Precambrian, however, is not prominent. A few deposits occurring in Precambrian rocks are known, e.g. small showings near Mac Arthur River and Dugald River in north Australia are known but deposits of this age are neither abundant nor large (Stanton, 1972). The Proterozoic carbonate sequences of the Transvaal Basin in South Africa are conspicuously devoid of lead-zinc deposits although extensive deposits of fluorite are developed (Martini, 1976). This "absence" of significant lead-zinc mineralization may be more apparent than real since little exploration has been done up until now. The most important known lead-zinc deposits in this Proterozoic age bracket are: the Broken Hill Mine in Zambia (Whyte, 1968), the Nanisivik Mine, Canada (Geldsetzer, 1973), the Balmat Edwards district, U.S.A. (Lea and Dill, 1968), and the unique zinc-oxide deposits of Franklin and Stirling Hill, U.S.A. (Frondel, 1972). Substantial deposits first appear in Lower Palaeozoic sediments, and important occurrences occur in strata from then until at least the end of the Mesozoic era. Some of the more important occurrences and ages of their containing units are: (Stanton, 1972)

Cambrian:	Southeast Missouri, U.S.A.: Norway-Sweden border districts: Sardinia.
Ordovician:	Eastern Tennessee, U.S.A.; Siberian platform deposits, U.S.S.R.
Devonian:	Pine Point, N.W.T., Canada; Silesia (the Silesian-Crocovian deposits extend from Devonian to Jurassic).
Carboniferous:	English Pennines; Ireland; Kazakhstan, U.S.S.R.; Tri-State field, U.S.A.
Permian:	Trentl Valley, Italy.
Triassic:	Eastern Alps; Silesia.
Jurassic:	Silesian-Crocovian province.
Cretaceous:	Northern Algeria and Tunisia.

As a group, carbonate lead-zinc deposits exclude skarns and other replacement deposits, such as the lead-zinc bodies at Bingham, Utah, which would normally be related to nearby intrusions. By far the majority of these deposits occur in dolomite: magnesian limestone and limestone are less common hosts. Frequently the three are present. Although many districts can be shown to be spatially related to large scale sedimentary features such as reefs, facies changes, basin margins, and basin topography, the major factor necessary for development of deposits of this type appears to be the presence of a thick carbonate sequence. Thin carbonate layers in shales seldom contain significant deposits of this type.

Usually the carbonate host rock concerned clearly constitutes part of a reef, i.e. it is biohermal. In some cases it is fore-reef breccia or back reef calcarenite. The deposits thus usually occur along belts conforming to ancient elongated reef complexes or as local groups conforming to more localized irregular reefs and banks. The distribution of such reefs and associated carbonate accumulations is necessarily related to ancient shorelines, bottom topographies, and of course, climate (Sangster, 1976). This given a climate suitable for reef formation, the distribution of the reefs, the potensial host rocks, has been controlled by paleogeography. Formation of carbonate sediments and reefs are enhanced by proper climatic conditions, particularly warm water. A plot of major carbonate hosted lead-zinc deposits on available paleolatitude maps shows a preference of these deposits for low paleolatitudes.

A large proportion of known deposits is found not far from the intersection of major, regional faults with the reef complex concerned e.g. Pine Point (Campbell, 1967). These faults appear to be old features, lineaments, developed in the basement rocks along which movement has continued to occur during and after the deposition of the reef and its associated sediments. Although these major structural features are not always apparent they do appear with conspicuous frequency.

On a smaller scale, the deposits tend to occur in one or a very few units in the local reef-carbonate succession. Within these units they can occur in a variety of situations, e.g. sedimentary features, zones of coincidence of sedimentary and tectonic structures, and in later solution karst openings.

Average ore grades (Sangster, 1976) in the larger districts range between 3 and 10 percent combined lead-zinc with individual ore bodies or zones running sometimes up to 50 percent lead-zinc. Where it is possible to distinguish individual deposits, tonnages range between a few tens of thousands to perhaps 10-20 million tons. Some of the average grade and tonnage data for a few of the better known districts are listed below. (see figure 2 for location).

District	%Pb	%Zn	Tons (Short)
Tri-State, U.S.A.	0.6	2,3	500 m.t.
Eastern Tenn., U.S.A.	-	4	50
Old Lead Belt, U.S.A.	3	-	370
Upper Mississippi Valley, U.S.A.	-	4	50
Pine Point, Canada	3	7	65
Central Irish Plain, Ireland	3	10	115

The Pine Point data include 1,4 m.t. of direct shipping ore at 19,3% Pb and 26,7% Zn. The statistics above do not include those from the

Viburnum Trend which are considered by Wharton (1979) to be at least as good as the Old Lead Belt. The Viburnum trend has become the largest lead-mining area in the world, accounting for over 15% of the total recorded output.

A short review of the terms Mississippi Valley-, Appalachian-, and Alpine Type will now follow in order to provide a standard terminology for the discussions to follow.

2.1.1 Mississippi Valley Type Deposits

As the name implies, classical deposits of this type occur in the drainage basin of the Mississippi Valley of the Central United States. Similar deposits, however, also occur in the Appalachian Valley district, U.S.A. and the Mackenzie Valley (Pine Point) district of Canada (Sangster, 1976).

Callahan (1967) defines Mississippi Valley type base-metal ore deposits as "stratabound in nearly horizontal carbonate rocks lacking congruent tectonic structres which might control their localization." Commonly they are remote from igneous intrusives and through-going plumbing systems which might serve respectively as source and conduit for mineralizing solutions. They are further characterized by an association with dolomite in many instances, but not all e.g. Tynagh (Derry et al., 1965); by relatively simple mineralogy and by textures which indicate the dominant process of mineralization was filling and not replacement. Sulphide and carbonate mineral detritus locally are present in the breccia matrix of some deposits.

Callahan (1967) has proposed a classification of Mississippi Valley "type" deposits according to the features controlling their localization. (figure 3).

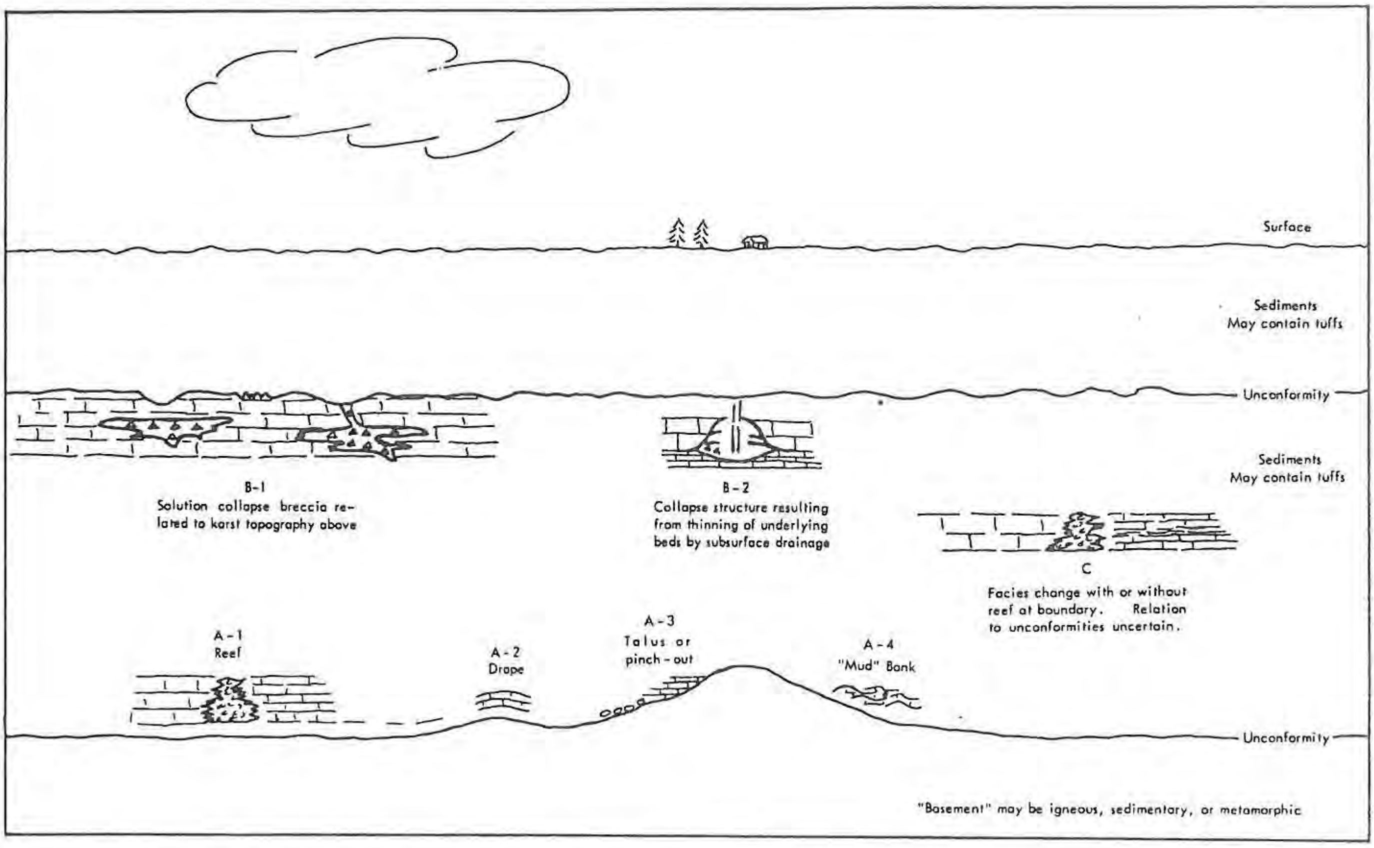


Fig. 3 Idealized vertical section illustrating the range of geological situations in which limestone–lead-zinc deposits are known to occur. (*Fro*
Callahan, Econ. Geol. Monograph no. 3, 1967.)

The important features are as follows:

A. Specific sedimentary environments related to the topographic relief above an uncomformity. These sedimentary environments are reefs and facies changes (A-1), compaction or drape structures (A-2), and in pinch outs, talus or landslide breccias (A-3). In this type of localization the rocks below the unconformity generally are not carbonates.

B. Solution collapse breccias and structures developed below an unconformity. These do not contain stalactites and stalagmites, the characteristic filling of caverns developed in consolidated carbonate rocks. This category is represented by two types viz. (B-1) developed in solution collapse breccia related to a karst topography on the surface of unconformity or in collapse structures (B-2) resulting from the thinning of underlying beds by subsurface drainage system related to the unconformity.

C. At a facies change in the formation or between basins of deposition. These changes are not clearly related to an unconformity.

Examples of deposits and the controls on their localization are listed in Table 1.

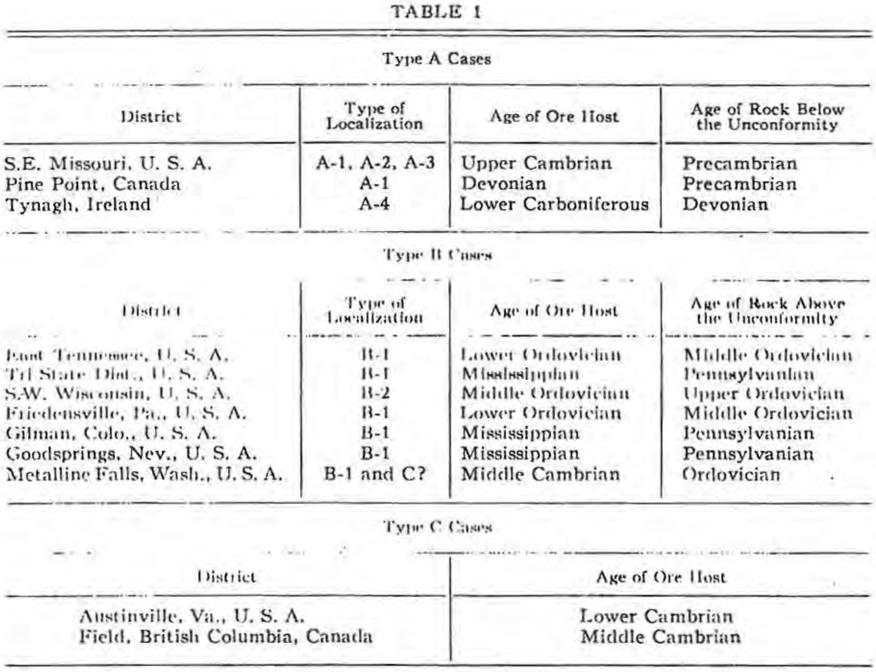


TABLE 1

Type A Cases

District	Type of Localization	Age of Ore Host	Age of Rock Below the Unconformity
S.E. Missouri, U. S. A.	A-1, A-2, A-3	Upper Cambrian	Precambrian
Pine Point, Canada	A-1	Devonian	Precambrian
Tynagh, Ireland	A-4	Lower Carboniferous	Devonian

Type B Cases

District	Type of Localization	Age of Ore Host	Age of Rock Above the Unconformity
East Tennessee, U. S. A.	B-1	Lower Ordovician	Middle Ordovician
Tri State Dist., U. S. A.	B-1	Mississippian	Pennsylvanian
S.W. Wisconsin, U. S. A.	B-2	Middle Ordovician	Upper Ordovician
Friedensville, Pa., U. S. A.	B-1	Lower Ordovician	Middle Ordovician
Gilman, Colo., U. S. A.	B-1	Mississippian	Pennsylvanian
Goodsprings, Nev., U. S. A.	B-1	Mississippian	Pennsylvanian
Metalline Falls, Wash., U. S. A.	B-1 and C?	Middle Cambrian	Ordovician

Type C Cases

District	Age of Ore Host
Austinville, Va., U. S. A.	Lower Cambrian
Field, British Columbia, Canada	Middle Cambrian

From Callahan, 1967

2.1.2 Appalachian Type Deposits

Appalachian type ore deposits are merely folded Mississippi Valley type. This is substantiated by the indifference of these deposits to structural setting, deformation of ore minerals, and parallelism of regional bedding with that of detrital sphalerite and carbonate in the matrix of some solution collapse breccias e.g. the Mascot-Jefferson City Zinc District in East Tennessee (Crawford and Hoagland, 1968). The ore occurs as coatings on breccia fragments and as interbedded detrital sphalerite and carbonate filling the interstices of solution collapse breccias. The bedding of the detrital sphalerite and the carbonate filling is parallel to the bedding of the region indicating that ore deposition preceded folding. Other examples of this type of deposit are present at Friendsville, Pennsylvania (Callahan, 1968) and Austinville, Virginia (Laurence, 1968). Callahan (1977) in his paper on "Some thoughts regarding premises and procedures for prospecting for base metal ores in carbonate rocks in the Northern Cordillers" sites numerous examples that would qualify as Appalachian type deposits. It would therefore eradicate confusion by referring to these deposits merely as deformed "sedimentogenic" (section 2.1.4) carbonate hosted lead-zinc (copper) deposits.

2.1.3 Alpine Type Deposits

The Alpine type lead-zinc ores are named after deposits of the Alpine Mesozoic geosyncline of central Europe, particularly those in the eastern Alps (figure 4) (Maucher and Schneider, 1967). In the

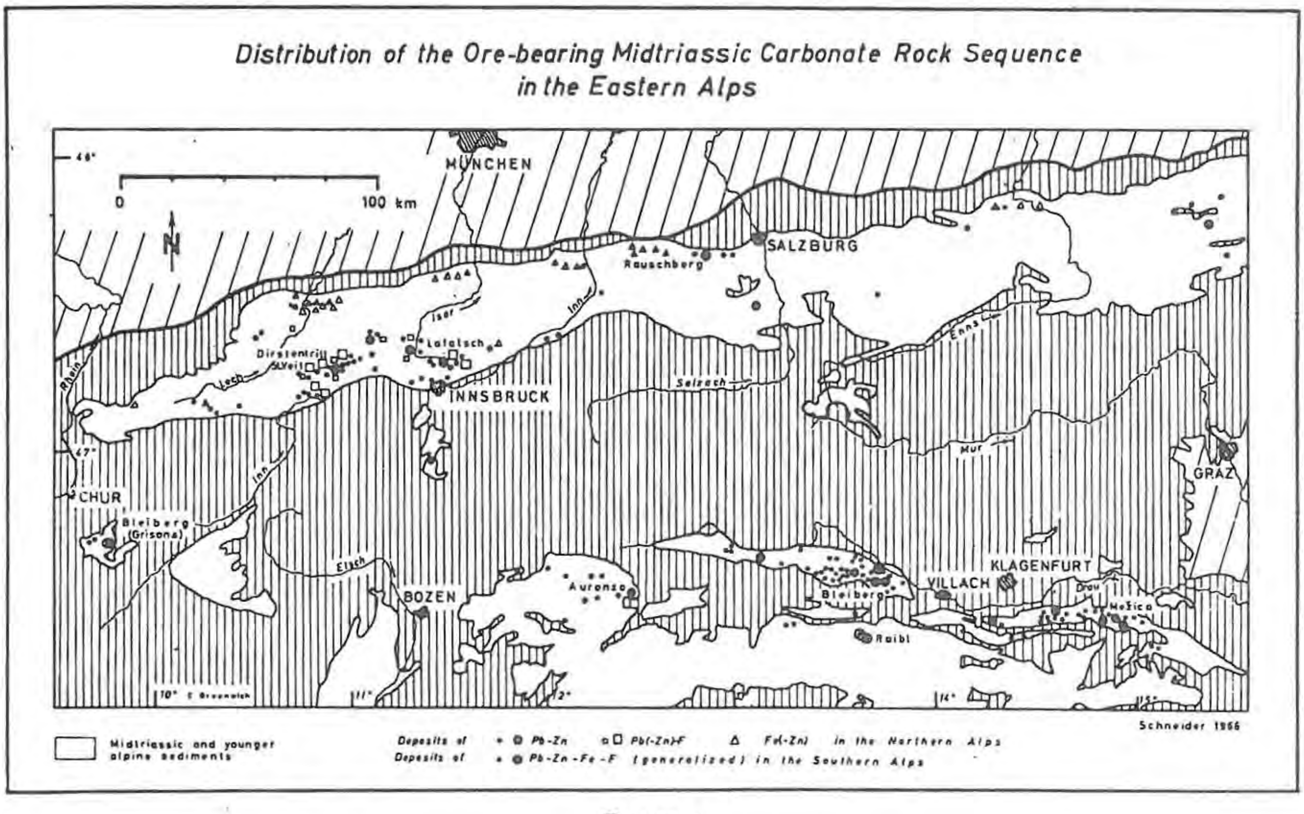

Distribution of the Ore-bearing Midtriassic Carbonate Rock Sequence in the Eastern Alps

FIGURE 4.

From Maucher and Schneider, 1967

discussion on the genesis of the Alpine lead-zinc ores going on for many year, the term Alpine is not used in the geographical but in the geological meaning, concerning rocks and regions of the "Alpine" Mesozoic geosyncline only. In the sequence of the geosynclinal sediments in the eastern Alps, the lead-zinc ores are restricted exclusively to few, relatively thin units of the Middle Triassic Limestone-dolomite complex (figure 5). The ore bearing units are nearly always combined with a "special facies" development of the host rocks. This special facies, indicating a sudden change from quiet water to turbulent water conditions, consists of the combination of the following rock types (Maucher and Schneider, 1967):

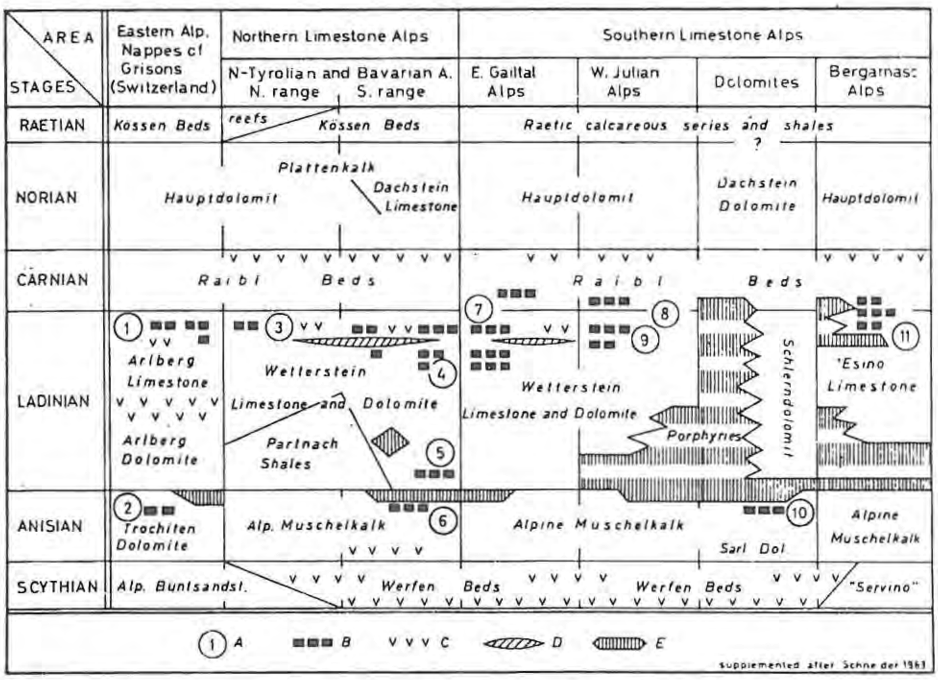


FIG. 5. Ore occurrence, volcanism and their time relation during the Triassic period in the eastern Alpine geosyncline. A: typical deposits of the different areas: 1 = Bleiberg-Ramoz (Grisons, Switzerland); 2 = Silberberg-Davos (Grisons, Switzerland); 3 = Säuling-Füssen (Bavarian Alps, northern border ranges); 4 = Lafatsch-Karwendel (N. Tyrolean Alps, Austria); 5 = Mursee-Mieminger (N. Tryolean Alps, Austria); 6 = St. Veit-Heiterwand (N. Tyrolean Alps, Austria); 7 = Bleiberg-Kreuth (E. Gailtal Alps, Austria); 8 = Cave del Predil, Raibl (Julian Alps, N. Italy); 9 = Mežica, Mies (Karawanken Alps, NW Jugoslavia); 10 = Auronzo (E. Dolomites, N. Italy); 11 = Gorno-Dossena (Bergamasc Alps, N. Italy). B: ore-bearing units. C: weak evaporitic facies (deposition of dolomite and anhydrite, gypsiferous beds). D: indications of volcanism (tuffaceous marls, agglomeratic breccias etc.). E: tuff layers, porphyritic and basaltic eruptions.

From Maucher and Schneider, 1967

(a) Well-bedded pure colomite, passing into rhythmically laminated dolomite-calcilutite.

(b) Laminated bituminous dolomite-calcilutite, passing into bituminous clayey laminae (different types of carbonaceous gyttia).

(c) Greenish beds of marl (tuffaceous marl and bentonite?), occurring often as matrix of sedimentary (agglomeratic) darkish to black, marly limestone breccia.

(d) Fluorite (showing definite sedimentary fabrics), also quartz and barite, with celestite and anhydrite as minor components.

(e) "back reef facies" consisting of composite pisolites, algal pellets, coquina, dolomitic mudstone breccias, biogenetic detritus, different types of calcarenites etc.

(f) Cross-bedding, cut and fill structes, mud cracks, graded bedding, load casts, glide folds, convolute bedding, and all types of resediments of the different types mentioned in (a) to (e), very often similar to turbidites.

Fine grained pyrite, sphalerite and galena with well preserved rhythmic deposition and polar lamination are found in this special facies (especially in type b). The complete Middle Triassic sequence (Anisian, Ladinian plus Carnian) reaches a maximum of more than 2000m, the ore-bearing beds are restricted to:

Upper Anisian - maximum 40m in thickness
Lower Ladinian - maximum 50m in thickness
Upper Ladinian - maximum 200m in thickness

Though confined to some distinct beds and stratiform in part, these deposits generally cannot be called stratiform, since a large part of the ores fills veins, cements breccias or forms massive replacement bodies. But as these transgressive or irregular ores are found only in association with the conformable ones and are always bound with them to the same distinct strata, the Alpine lead-zinc ores, though not stratiform throughout, are, in general, typically strata-bound (Maucher and

Schneider, 1967). As with the Mississippi Valley type, the Alpine deposits also show epigenetic features as outlined above. The main difference however, as pointed out by Schneider (1964, p.73) is that while the ore bodies, "senso stricto", have some epigenetic features, the noneconomic equivalents, i.e. mineralization in "senso lato", are clearly syngenetic or synsedimentary. Implicit in the Schneider-Maucher school of thought is that the epigenetic ore zones merely represent secondary remobilization and concentration of elements originally present in the essentially syngenetic protore. Evidence for this viewpoint is the restriction of the epigenetic ore bodies to narrow stratigraphic zones in the otherwise thick Triassic carbonates. Several Irish deposits e.g. Tynagh (Derry et al., 1965), Mogul (Silvermines) (Graham, 1970) and Navan are mainly conformable with the host rocks except where they are in fault contact with the pre-Carboniferous basement. The essentially stratiform nature of these deposits and their close association with Carboniferous volcanic centres (Morrissey et al., 1971, figure 1) are, in these respects, similar to the Alpine deposits which are also associated with contemporaneous volcanism (Maucher and Schneider, 1967). The main difference between the two districts would appear to be that the Alpine deposits, in their original form, are too low grade to be economic and require post-depositional remobilization and concentration to upgrade the original protores whereas the Irish deposits may simply represent a higher-grade "protore" (Sangster, 1976).

The main difference between Mississippi Valley and Alpine type deposits therefore "require" different genetic models for the two types because of the difference in the time of sulphide deposition relative to host rock in the two types. A model involving emplacement of sulphides into pre-existing traps, whether primary or secondary, may well explain most of the observed features of the Mississippi Valley type of carbonate hosted lead-zinc deposits. It cannot explain the many syn-sedimentary ore textures described by Schneider (1964) and Schulz (1964). For example, in the Alpine type lead-zinc deposits of the Calcareous Alps intercalated laminations of sulphides and clay marls, together with "ore and limemud breccia, figure 6,

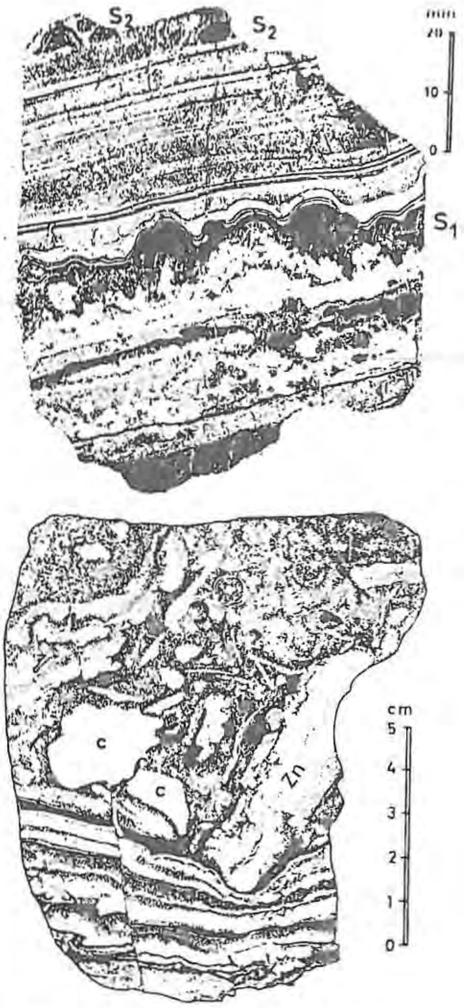


FIG. 6. (Upper). Thin-bedded, partly rhythmic stratiform sphalerite ore with indications of external, mechanical ore resedimentation in Wetterstein limestone. S_1 = geopetally oriented band of schalenblende covered by a fine-grained layer of sphalerite with graded bedding. S_2 = Resedimented, partly overturned fragments of S_1 in two coarser-grained sphalerite laminae. Bleiberg, Rudolf-Schacht, Kärnten (Austria).

FIG. 6. (Lower). Glide breccia ("ore-and-lime-mud breccia") causing load casts on a rhythmic interbedding of bituminous calcilutite (dark) and sphalerite-arenite (light). C = ore-free calcareous mudstone particles, still plastic during resedimentation; Zn = fragment of slightly compacted, extremely fine-grained, banded sphalerite-lime-mudstone. Orientated specimen. Upper Wetterstein limestone, Lafatsch mine; Karwendel Mountains, N Tyrol.

From Schneider, 1964

(Maucher and Schneider, 1967, figures 4 and 5) are presented as textural evidence that mineralization was essentially contemporaneous with the host sediments in contrast to the typical Mississippi Valley deposits. Contemporaneous volcanism is a feature of the Triassic Alpine deposits and the Carboniferous Irish deposits (Schneider, 1964; Schulz, 1964; Morrissey et al., 1971) and may therefore constitute a contemporaneous source of metal-bearing fluids for these deposits as opposed to the relatively later metal-bearing fluids of the typical Mississippi Valley type deposits.

There are relationships between the Alpine ores and palaeogeographical patterns. The mineralization, from the northern limestone Alps, is primarily bound to the reef complexes and restricted to few intercalations in the back reef. (figure 7).

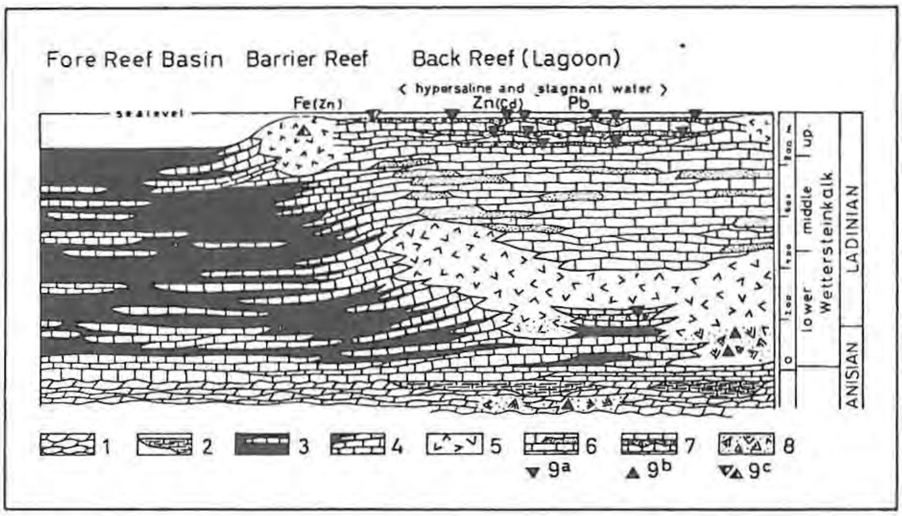


Fig. 7. Diagrammatic view of "Ladinian plateau reef" type of occurrence, in which the sulfides are localized principally in the back-reef facies, and to a lesser extent in limestone of the reef wall. 1 = uppermost "Alpine Muschelkalk": wavy-clumpy, thinly bedded, bituminous limestone with chert nodules; 2 = andesitic green tuffs (ash and crystal tuffs, few lapilli with thin layers of marl and limestone); 3 = "Partnach-shales": marls, shales with lenticles of layered limestone (like 4) (Ladinian basin facies); 4 = "Partnach-limestone": bituminous, marly, layered limestones (Ladinian basin facies); 5–8 = different types of "Wetterstein-limestone" (Ladinian reef facies): 5 = massive limestone and dolomite, partly cavernous with relict patterns of bioherms (often coral colonies); 6 = well-layered gray limestone (mainly calcarenite), with debris and colonies of algae (Dasycladaceae), single algal patch reefs; 7 = predominantly thinly layered limestone, with intercalations of the "special facies" in distinct sequences (back-reef units, tuffaceous marls, slump structures, "ore sediments," etc.); 8 = late, diagenetic alteration of the cavernous reef body by recrystallization of dolomite, quartz, and different Fe dolomites; 9a = Pb–Zn(Fe) sulfide ores with sedimentary fabrics; 9b = Pb–Zn sulfide ores primarily enriched in metasomatic replacement bodies, locally associated with small amounts of Cu–Sb–As minerals; 9c = predominantly Fe dolomite and Fe sulfide ores, with small amounts of ZnS(PbS). (*From Maucher and Schneider, Econ. Geol. Monograph no. 3, 1967.*)

The environment leading to Pb-Zn-sulphide deposition is bound to the Ladinian reef facies. The forereef basins are represented by the argillaceous "Partnach-Schichten" (basinal facies), which contain lead-zinc scattered in uneconomic amounts only. The syn-sedimentary separation and enrichment of lead-zinc (cadmuim) is controlled by hypersaline and (local) weak euxinic conditions restricted to the back-reef facies.

2.1.4 Discussion

Whether they be of the Mississippi Valley or Alpine type, carbonate-hosted lead-zinc deposits appear to owe their origin and distribution to normal sedimentary (and diagenic) processes rather than igneous. The association with reefs, facies changes, hydrocarbons, unconfomities, subsurface brine, etc., are all normal features and products of sedimentary basins and rocks. Even where minor volcanism may be a factor, the distribution of the Alpine ores, for example, is restricted to the back reef carbonate facies implying a sedimentary control. To emphasize the strong sedimentary aspect of these deposits Sangster (1976) proposed the term sedimentogenic to stress the genetic connection between these deposits and sedimentation and/or sedimentary processes. Many other types of sediment-hosted deposits could conceivably be covered by this term but Sangster has found it useful to collectively refer to this class of deposits in the same way as the term volcanogenic is used in a similar sense (Sangster, 1972) for another class.

The different schools of syn- and epigenetic as well as magmatic versus groundwater followers for the origin of carbonate hosted lead-zinc deposits have led Brown, 1970, to tentatively propose a broad class of Mississippi Valley type deposits which might be subdivided into three categories:

(i) Normal type (lead isotopes approximately indicate the age). For instance, the English Pennines.

(ii) B- type (lead isotopes older then deposition). Alpine deposits.

(iii) J- type (lead isotopes suggest future age). Central United States, Sweden, etc.

2.2 Tectonic Setting

Carbonate hosted lead-zinc (copper) deposits are generally hosted in shallow water shelf carbonates that accumulated under stable tectonic sedimentary conditions. These carbonates and their contained mineralization are related to palaeoshorelines. The palaeoshoreline can be developed along the margin between a geosyncline and craton (e.g.

Canadian deposits) or around basement highs within a large basin (e.g. the deposits of the Midcontinent U.S.A.). The tectonic settings of the most important deposits will be dealt with on a geographical bais.

2.2.1 Tectonic setting of the Canadian lead-zinc deposits

The Interior Platform hosts all of the known carbonate hosted lead-zinc deposits of Canada. The Interior Platform is bordered by the Canadian Shield to the east and Cordilleran Orogen to the west. (figures 8 and 9)

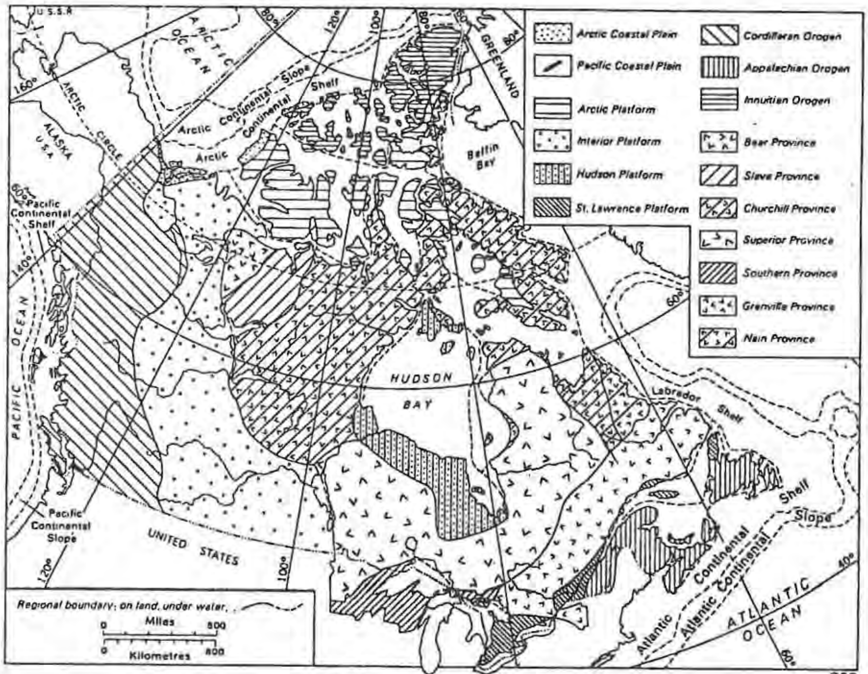


FIGURE 8. Geological regions of Canada.

GSC

From Douglas, 1968

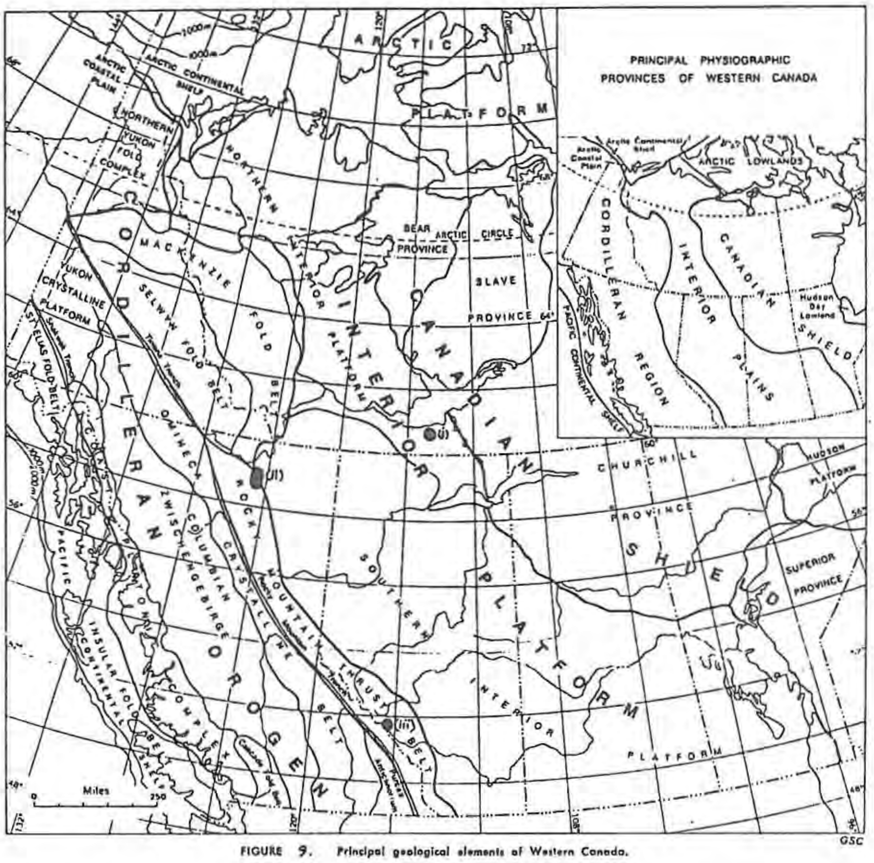


FIGURE 9. Principal geological elements of Western Canada.

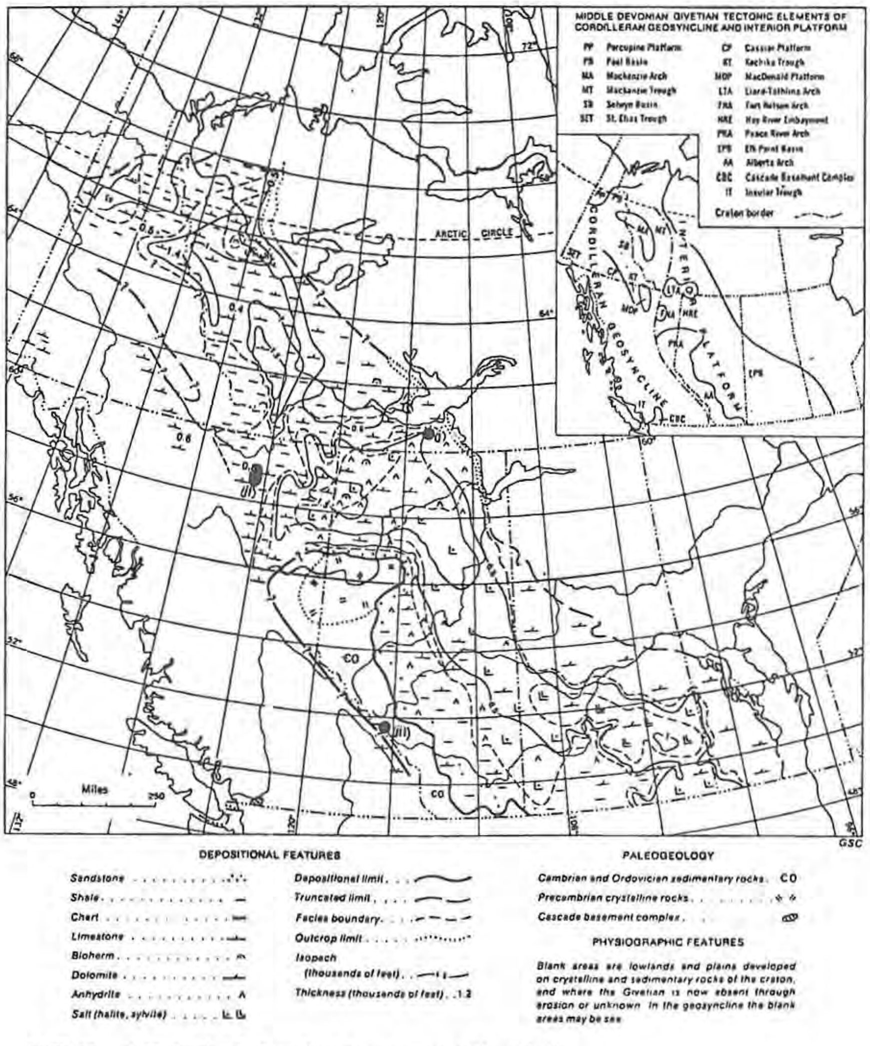


FIGURE 10. Middle Devonian, Givetian, sedimentation and tectonism in Western Canada,

From Douglas et al., 1968

In the "economically" important late Middle Devonian, extensive limestone sheets blanketed the northern craton (figure 10) and adjacent geosyncline, grading northward and westward into thin shale. A continuous bank was formed north of the Peach River landmass over and between the slightly depressed Fort Nelson, Liard, and Tathlina Arches, and probably extended along the west flank of Alberta Arch. Limestone at the front grades northwestward to shale and southeastward to dolomite and evaporites (Elk Point Basin). The front is irregular and flanked by stromatoporoid reefs. The limestone near faults in the basement are recrystallized to coarse vuggy dolomite, locally containing galena and sphalerite. Three economically minerlized areas are known, all associated with the Interior Platform margin. These areas are:

(i) Pine Point. The Pine Point deposits are found on the eastern edge of the Interior Platform (figure 10). This edge is not bordering an orogenic belt thus these deposits have not undergone any large scale tectonic activity. About 40 orebodies have been identified with total reserves of 42,5 million ton grading 7% Zn and 2,6% Pb. The bodies vary in size from 0,1 to 15 million tons.

(ii) Robb Lake area. Numerous sub-economic lead-zinc occurrences were discovered within thrust faulted blocks on the western margin of the Interior Platform in Northeastern British Columbia (figures 9 and 10). One group of showings in which interest remains reasonably high is at Robb Lake itself, where 6,1 million tons of 7,3% combined lead-zinc are present in rocks of Devonian age. The occurrences are located in a narrow belt, 100km long which runs parallel to the Platform edge. A feature of the deposits in northeastern British Columbia that distinguishes them from carbonate hosted deposits in other regions is their regional stratigraphic setting at the distal edge of a miogeoclinal carbonate platform, now strongly folded and faulted as part of the present-day Rocky Mountain Belt (Macqueen and Thompson, 1978).

(iii) Kicking Horst River area. The Kicking Horse and Monarch mines are located on the western edge of the Interior

Platform in a downfaulted block of mid-Cambrian carbonate sediments (figures 9 and 10). The deposits were mined out by 1952 by which time 850,000 tons of ore had been produced grading 7% lead, 10% zinc and 1,2 ounces/ton silver.

2.2.2 Tectonic setting of the lead-zinc deposits of the United States of America

The Mississippi Valley lead-zinc mineral districts of the United States are distributed over the central platform area of the North American craton (figure 11).

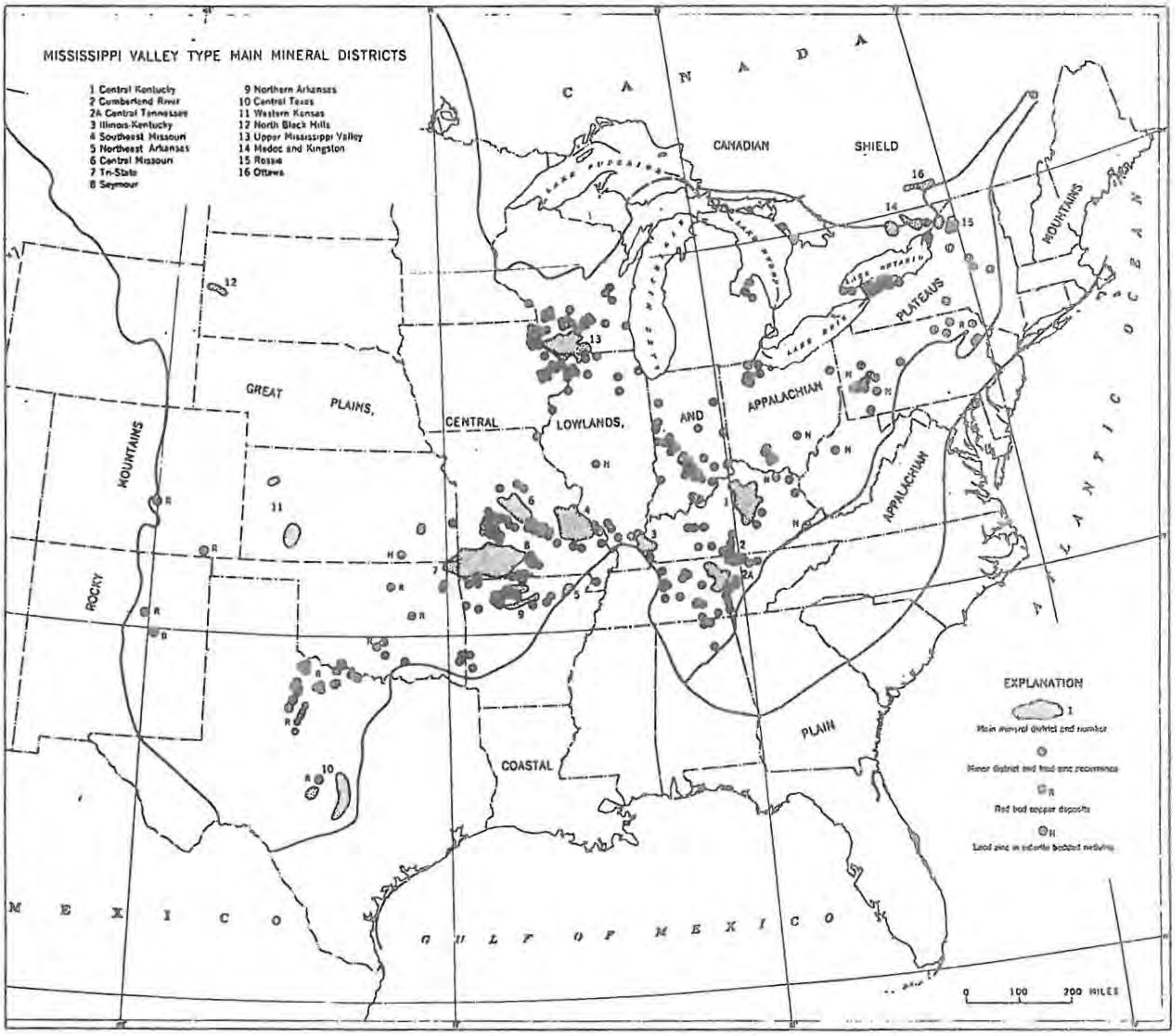


FIG. 11. Map showing the central and eastern United States and the Mississippi Valley-type districts (nos. 1–9, 11–13) and some other closely related districts (nos. 10, 14–16). From Heyl (1967, fig. 2).

The deposits are primarily hosted in carbonate having a wide spectrum of ages ranging from Middle Cambrian to Lower Carboniferous.

The early Palaeozoic platform was mildly deformed by a few poorly defined arches and basins, which during the Ordovician to Devonian times became progrssively more numerous, prominent and complex due to irregular uplift and subsidence (figure 12).

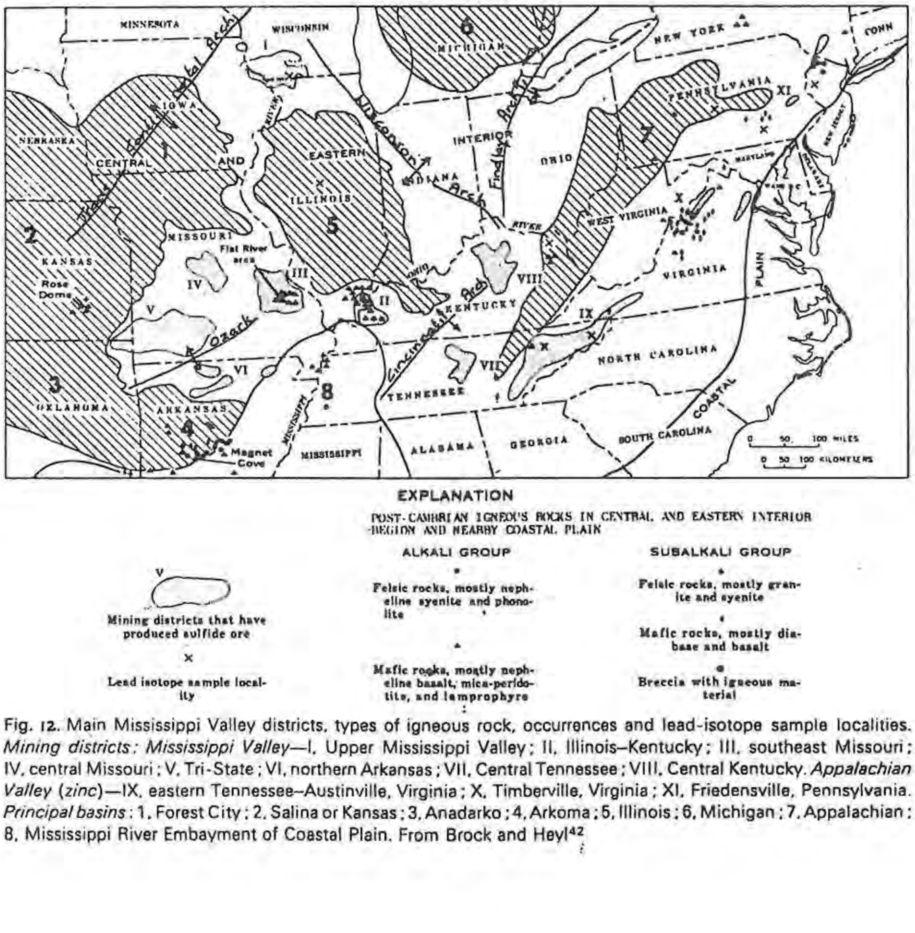


Fig. 12. Main Mississippi Valley districts, types of igneous rock, occurrences and lead-isotope sample localities. *Mining districts: Mississippi Valley*—I, Upper Mississippi Valley; II, Illinois–Kentucky; III, southeast Missouri; IV, central Missouri; V, Tri-State; VI, northern Arkansas; VII, Central Tennessee; VIII, Central Kentucky. *Appalachian Valley* (*zinc*)—IX, eastern Tennessee–Austinville, Virginia; X, Timberville, Virginia; XI, Friedensville, Pennsylvania. *Principal basins*: 1, Forest City; 2, Salina or Kansas; 3, Anadarko; 4, Arkoma; 5, Illinois; 6, Michigan; 7, Appalachian; 8, Mississippi River Embayment of Coastal Plain. From Brock and Heyl[42]

The basins received thick accumulations of sediments while the arches received thinner accumulations and periodically were uplifted and truncated (Snyder, 1968).

During early Cambrian times the seas were confined to the geosynclines at the rim of the continent. Deposition was restricted to the mio- and the eugeosyncline. The sediments consisted of quartz sandstone, in early Cambrian and limestone in middle Cambrian, and shales, graywackes and conglomerates, respectively in the mio- and eugeosyncline. Transgression and regression of the seas onto the cratonic shelf is recorded as having occurred at least four times during the period from Early Cambrian to Permian (figure 13).

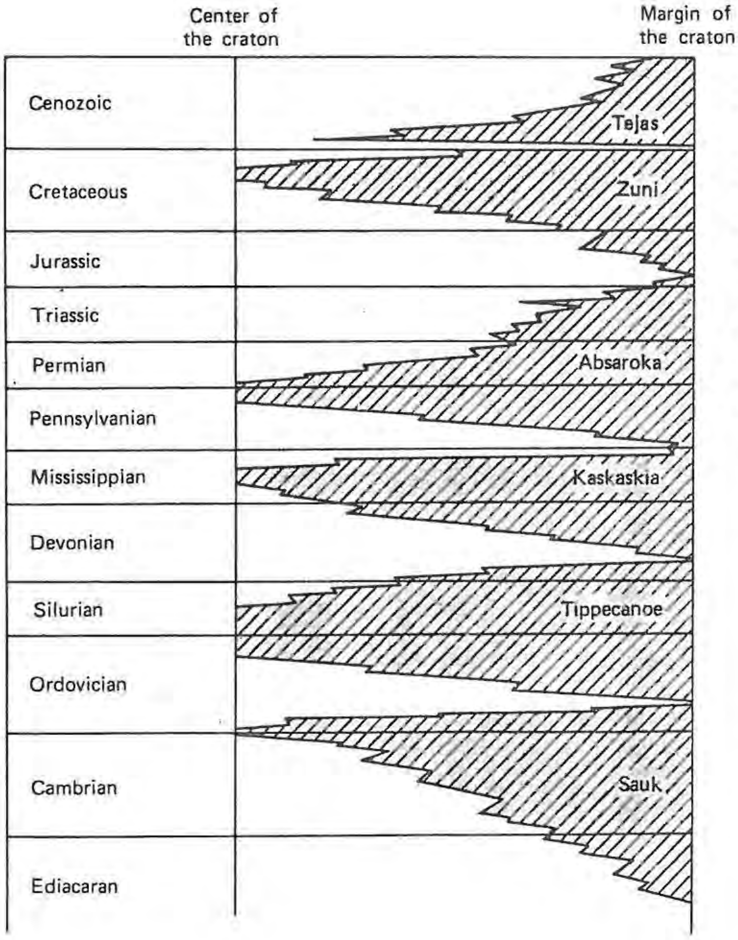


FIGURE 13. **Time relationships of the cratonic sequences of the North American platform. The vertical scale is geological time. The colored areas are the times that are represented by the sedimentary rock record. Note that the sequences are separated by time gaps that lengthen toward the center of the platform. (After L. L. Sloss; courtesy of the Geological Society of America.)**

The sediments are of importance to lead-zinc mineral deposits. The Upper Cambrian units, except for a basal sandstone and shale, are predominantly dolomites. Lower Ordovician formations are chiefly cherty dolomites, Middle and Upper Ordovician units are mainly limestones with minor sandstone shale and evaporites. Silurian lithologies, except for evaporits in subsurface, were thinned or removed by erosion over much of the Midcontinent. The Devonian rocks, where preserved, consists largely of limestone. The Chattonooga shale was deposited over most of the Midcontinent. Widespread submergence in Mississippian (Carboniferous) time led to the deposition of a thick section of fossiliferous, clastic, and cherty limestones (Snyder, 1968).

Dissolution of the Upper Devonian Silurian evaporites by groundwater during periods of regression caused collapse and brecciation of the overlying beds, resulting in the development of karst topography and related features which had a pronounced effect on the localization of lead-zinc ores especially in East Tennassee, Tri-State, Upper Mississippi and Friedenville (Appalachian).

Basement topography was generally very irregular, with subsidiary palaeohighs located on the majore arches. These basement palaeohighs often became the nuclei for low energy platform sedmentation. Stromatolitic growth along the headlands of these positive features led to the formation of organic reefs and associated reef facies depositional enviroments thereby creating potential mineralizing hiatus.

2.2.3 Tectonic setting of the "Alpine" type lead-zinc deposits

The Alpine lead-zinc deposits are hosted by carbonate sequences of the Alpine mesozoic geosyncline of central Europe. The regional tectonic setting of the most important mineralized areas is outlined in table 2 and shown in figure 14. Two groups of zinc-lead deposits in carbonate rocks are recognized, viz.

(i) A group connected with mobile zones or geosynclines. These deposits occur at the end of the magmatic stage of the geotectonic cycle and are connected with the porous carbonate rocks at a certain distance from the magmatic rocks (Galkiewicz, 1967).

TABLE 2

Deposit	Regional-tectonic position	
	Time	Place
High Silesia-Cracow Basin	Geosynclinal stage of the Alpine era	Northern border geosyncline
Northern Limestone Alps	Geosynclinal stage of the Alpine era	Inner north part of geosyncline
Southern Limestone Alps	Geosynclinal stage of the Alpine era	Inner south part of geosyncline
Vratsa Ore District, North Bulgaria	Geosynclinal stage of the Alpine era	Inner part of geosyncline
Hermsdorf-Erzgebirge	Geosynclinal stage, Caledonian era	Border of the geosyncline

From Kautzsch, 1967

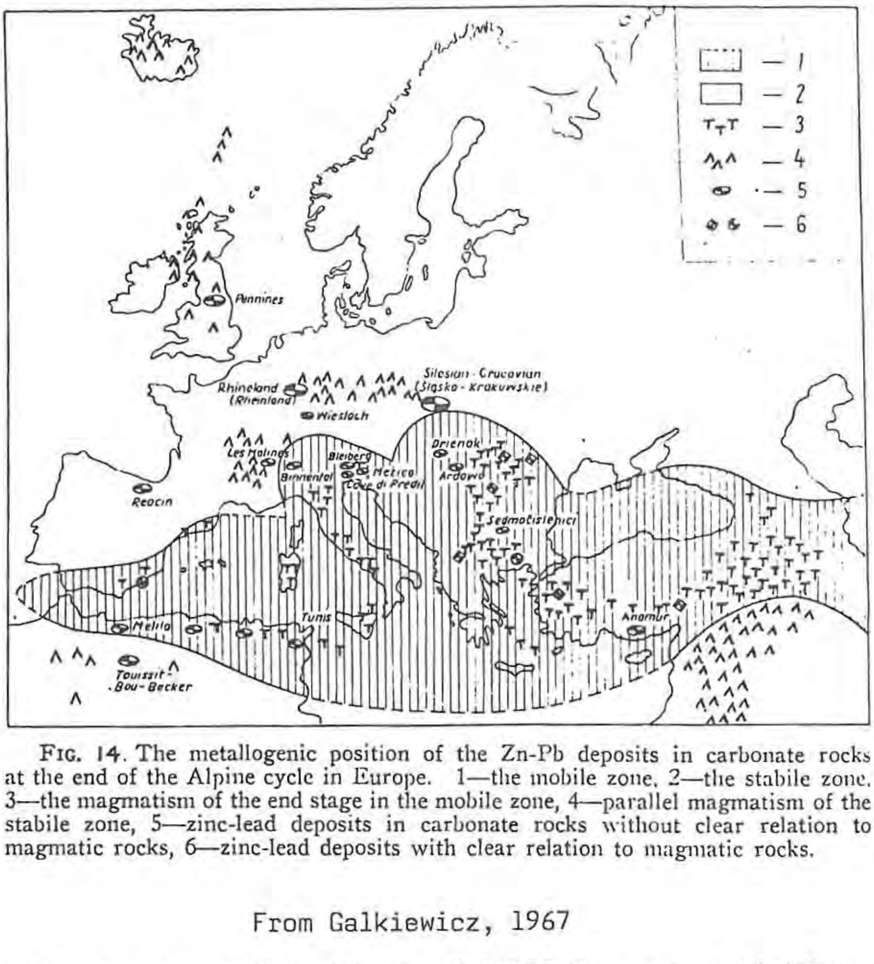


FIG. 14. The metallogenic position of the Zn-Pb deposits in carbonate rocks at the end of the Alpine cycle in Europe. 1—the mobile zone, 2—the stabile zone, 3—the magmatism of the end stage in the mobile zone, 4—parallel magmatism of the stabile zone, 5—zinc-lead deposits in carbonate rocks without clear relation to magmatic rocks, 6—zinc-lead deposits with clear relation to magmatic rocks.

From Galkiewicz, 1967

(ii) A group connected with the "stabile" zones or platforms. These deposits, according to Galkiewicz (1967) occur at the end or at the beginning of the geotectonic cycle and are related to basic-alkaline magma (figure 14). They also occur in the porous carbonate rocks at a certain distance from the magmatic rocks and along lineaments of the earth's crust e.g. the Silesian - Cracovian and Rhineland zinc-lead deposits (figure 15).

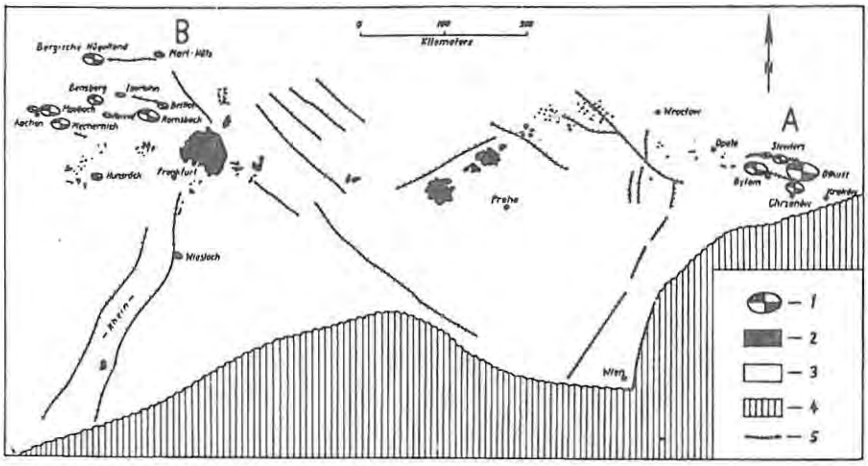


FIG. 15 The scheme of the Silesian-Cracovian and Rhineland deposits. A—the Silesian-Cracovian deposits, B—the Rhineland deposits: 1—zinc-lead deposits in carbonate rocks, 2—Neogene alkaline-basic magmatic rocks, 3—the stabile zone or platform, 4—the Alpine mobile zone or geosyncline, 5—the great fractures, mainly Tertiary.

From Galkiewicz, 1967

The deposits are all stratigraphically connected to a distinct time interval from Upper Ladinian to lower Carnian (figure 5) and palaeogeographically connected to reef complexes (figure 7).

2.2.4 Tectonic setting of the Irish lead-zinc (copper) deposits

Lead-zinc (copper and silver) mineralization occurs in lower Carboniferous carbonate rocks of various sedimentary facies adjacent to east-northeast trending major normal faults at the margins of inliers (figure 16). These inliers are mainly of Devonian (Old Red Sandstone) (Derry et al., 1965) and in some cases also of Silurian age. The Silurian metamorphosed cores acted as palaeohighs during Devonian and Carboniferous sedimentation. Draping of these younger sediments over the paleohighs in Devonian seas are a common feature.

The basal portion of the Lower Carboniferous succession is composed of a number of shaly and sandy units which grade upwards into a thick sequence of dark bioclastic limestones. The bioclastic component consist of crinoid fragments. These lithologies are in turn overlain by and to some extent interfingered with, pale chemically pure limestones of the Waulsortian facies (Lees, 1961) also known as the Reef Limestone or Mudbank Complex. These are overlain by, and pass laterally into, dark compact limestones known collectively as "Calp".

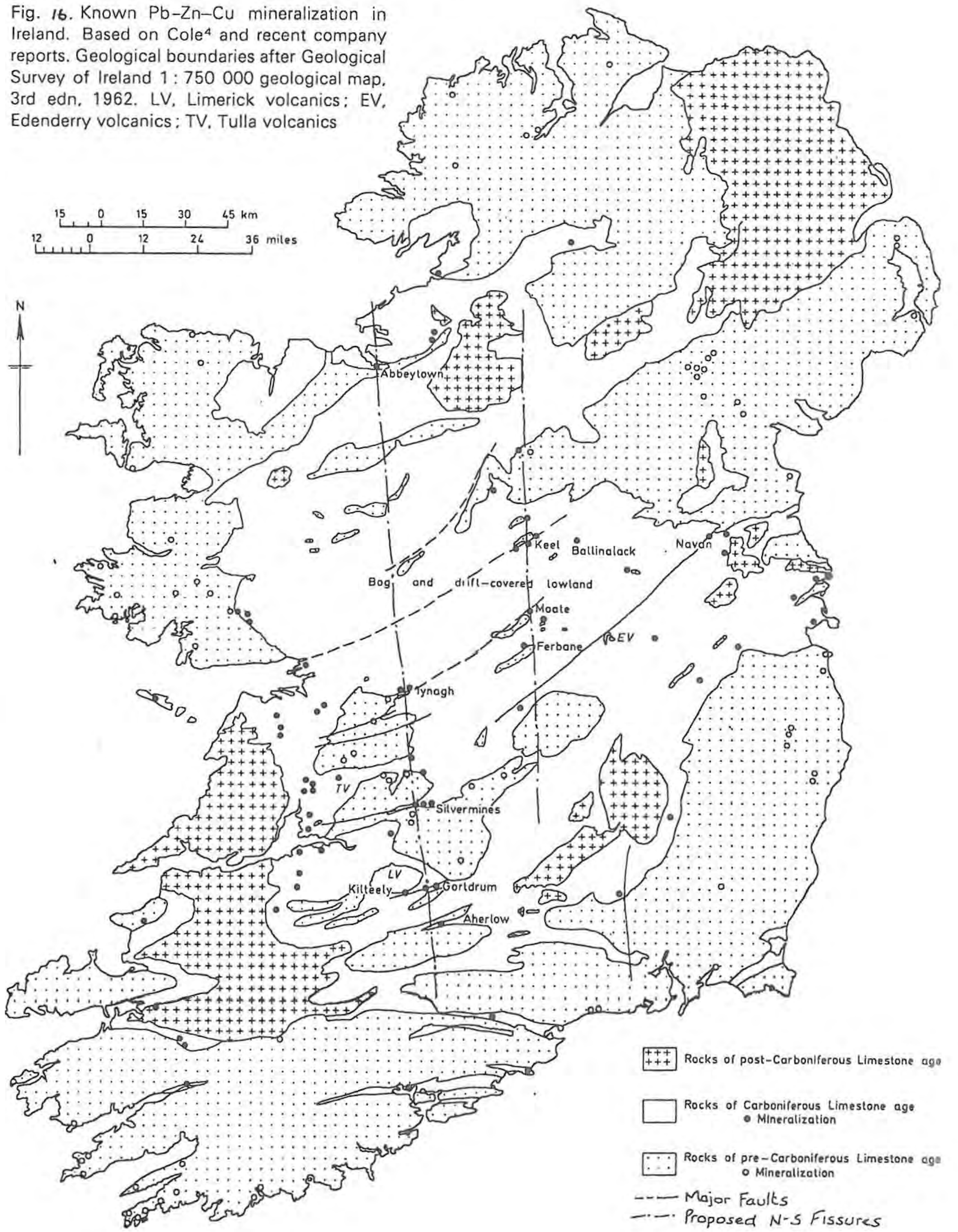


Fig. 16. Known Pb-Zn-Cu mineralization in Ireland. Based on Cole[4] and recent company reports. Geological boundaries after Geological Survey of Ireland 1 : 750 000 geological map, 3rd edn, 1962. LV, Limerick volcanics; EV, Edenderry volcanics; TV, Tulla volcanics

From Morrissey et al., 1971

During Upper Tournaisian and Lower Viaian times (Lower Carboniferous), southern Ireland was occupied by a shallow-water shelf, bounded to the south by the flanks of the Variscan geosyncline and to the north and east by land masses. The Irish deposits are therefore typically shelf deposits at the periphery of a geosyncline. Within the shelf area the Reef Limestone or Waulsortion Complex (Wilson, 1975), separating the lagoon from the southern mudbelt (basin), occupied a position analogous to that of a barrier reef (figure 17) (Derry et al., 1965).

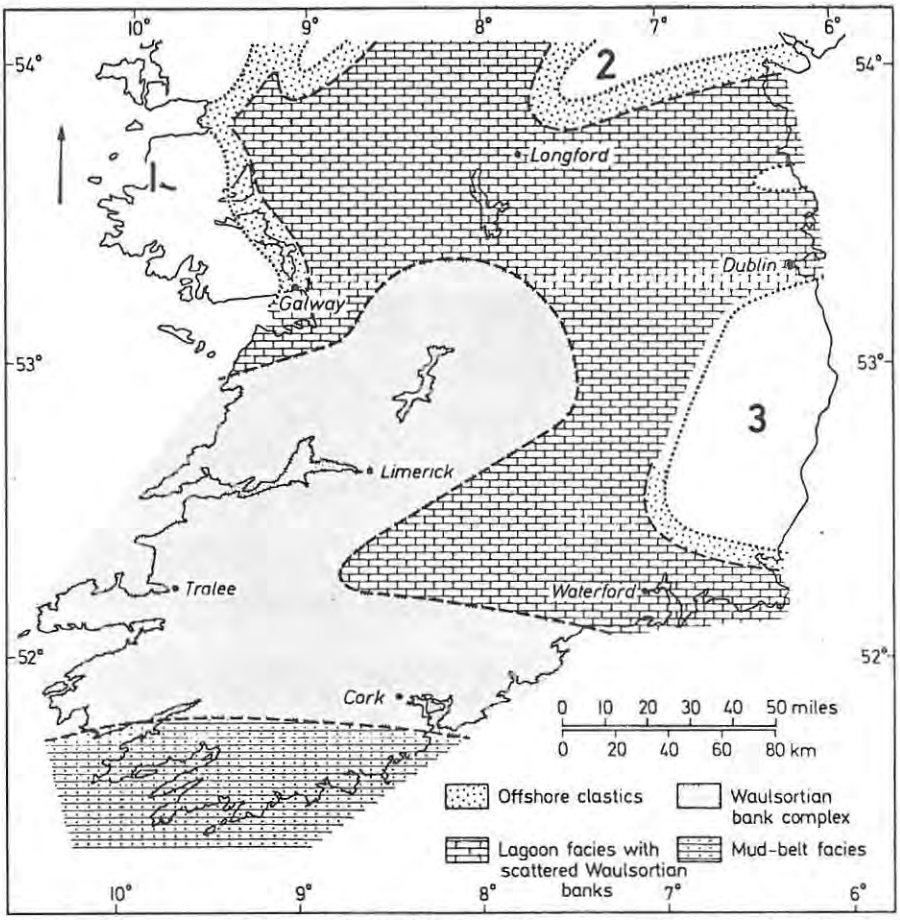


Fig. 17. Paleogeography and lithofacies of the Waulsortian in southern Ireland. From Lees (1961, Fig. 1). The Waulsortian mudbank facies is shown at its maximum extent occupying a wide belt between the basinal mud belt (Culm) and the lagoonal facies. The latter also contains numerous scattered banks which are not indicated. The land masses surrounded by dotted lines are as follows: 1. Galway-Mayo, 2. Longforddown, and 3. Leinster

The numerous occurrences of base-metal sulphide mineralization in Central Ireland relative to their stratigraphic position are outlined in table 3. Most deposits are in Lower Carboniferous limestones, but

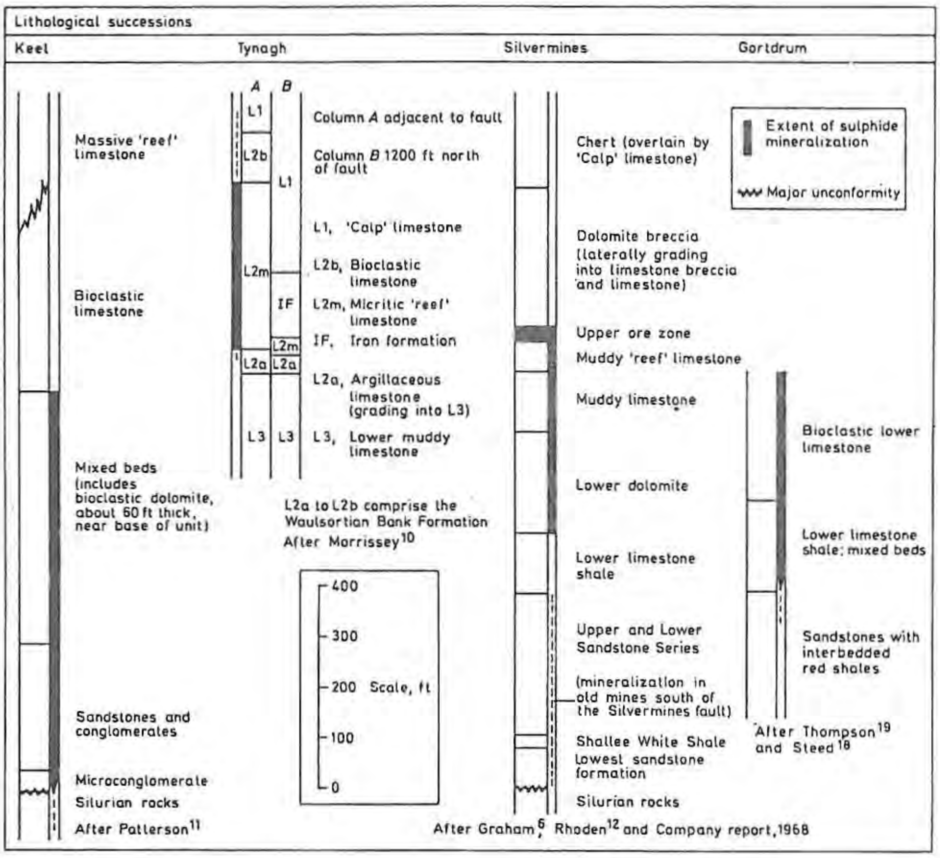


Table 3. Base metal sulphide mineralization relative to their stratigraphic position in Central Ireland. From Morrisey, 1971

host rocks range in age from Ordovician to Upper Carboniferous, and include sandstones, conglomerates and shales as well as various types of limestone (Morrissey, 1971). The five largest deposits are those at: (figure 16).

(i) Tynagh, worked for lead, zinc, copper and silver,
(ii) Gortdrum, worked for copper, silver and mercury,
(iii) Silvermines, worked for lead and zinc,
(iv) Keel, a cadmium-bearing sphalerite deposit and
(v) Navan.

2.2.5 Tectonic setting of the carbonate hosted polymetallic deposits in Namibia.

The lead-zinc and polymetallic carbonate hosted deposits of Namibia are hosted by the Swakop and Otavi Groups of the Central Swakop Shelf and Otavi Shelf. These Shelves form part of the Damara Mobile Belt.

The latter is the most southerly of the great Pan-African belts (Kennedy, 1964) which are defined by late Precambrian sedimentary and volcanic sequences (figure 18). The area between the northern

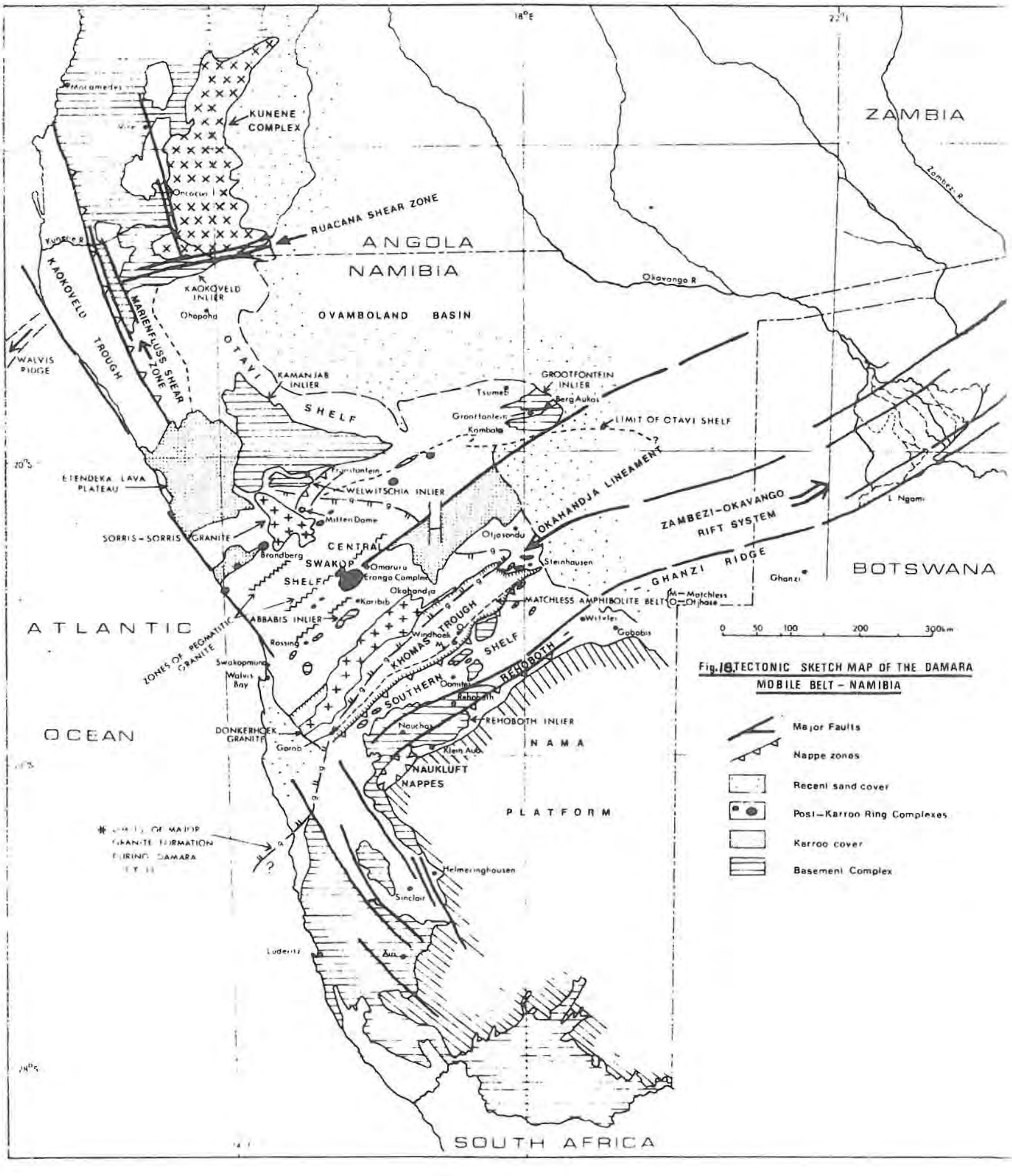


Fig. 18. TECTONIC SKETCH MAP OF THE DAMARA MOBILE BELT - NAMIBIA

From Mason, 1979

margin of the Khomas Trough and the northern limit of the Damara belt was covered by a shallow epicontinental sea which formed the site for the deposition of generally thin, but very extensive shelf carbonate units (Mason, 1979).

The northern part of the shelf was characterized by thick carbonate deposition. These carbonates define the Otavi Shelf Province (figure 18) and attain a maximum thickness of 3000 metres. The dolomites of the Tsumeb Subgroup, which host the Tsumeb and Kombat polymetallic karst deposits, contain oolitic, stromatolitic and cherty units and represent a period of very stable shelf carbonate deposition. The carbonate units of the Otavi Shelf thin towards the southern and western margins. Major unconformities which developed in the Otavi Shelf Sequence played an important role in the genesis of mineralization. The deposits at Berg Aukas, Abenab, Kombat and Tsumeb are genetically associated to karsting during erosional periods.

The Swakop Shelf between the Khomas Trough and Otavi Shelf is characterized by carbonate units and interlayered biotite-quartz schists. These units vary in thickness between 300 and 500 metres and are remarkably persistent and constant over the entire Swakop Shelf area. A persistent prominent marble unit within this sequence contains sulphide rich beds with a strike length of over 100km. Two small lead-zinc deposits, the operational Namib lead mine and the dormant Usakos lead mine, occur within this unit, known as the Karibib Formation.

2.3 Basis on which discussion of carbonate hosted lead-zinc deposits will be based

Basically, a three fold "classification" will be adopted in the discussion on carbonate hosted lead-zinc deposits to follow viz. reef complex deposits, karst deposits and deposits not obviously associated with either reefs or karsts.

Reef complex deposits will include the typical back reef, reef and fore reef types. Karsting and/or structure may contribute to the localization of the ore but the main ore concentrating factor would be the reef facies.

Karst-associated deposits are related directly to erosional surfaces, fissures and joints, and favourable lithologies. Limestones are susceptible to solution and would therefore be liable to the formation of solution collapse breccias. Karsting is a process whereby secondary porosity is created or enhanced in a lithology. Karsting within a biohermal or barrier reef facies will add secondary porosity to an already existing primary porosity and thereby increase the ore volume potential.

The third "unattached" class of carbonate hosted lead-zinc are generally formed by the interaction of favourable lithology and structure i.e. faulting.

A few examples of each "class" of deposit, outlining the characteristic inherent features of that spesific class, will be discussed. Overlapping of classes can and will occur.

2.4. Deposits associated with reef complexes

2.4.1 Deposits in barrier reef complexes

The lead-zinc deposits of the Pine Point area N.W.T., Canada (figure 2) are hosted in a carbonate coral reef complex, the Presqu'ile Barrier Reef, of Middle Devonian age. During sedimentation this barrier separated the marine MacKenzie shale basin to the northwest from the continental Elk Point evaporite basin to the southeast. Towards the end of the Palaeozoic the barrier was deformed and it now plunges gently in the subsurface towards the west. About 40 deposits are hosted in a 33km by 6km belt within the carbonate barrier that is located on the eastern edge of the Canadian Interior Platform (see figures 9, 10 and 19). The ore bodies lie within the Presqu'ile and Pine Point Formations (table 4 and figure 20). Fore reef, reef and back reef facies in these formations are recognizable (Jackson and Folinsbee, 1969) (figure 20). The fore-reef area of the Pine Point Formation is composed of dark brown, bituminous, shaly limestone and dolomite containing Thamnopora and horn corals near the reef, and it is rich in crinoids, brachiopods and tentaculitids further north from the reef. The main reef body is composed of uniform fine to medium crystalline dolomite with idiomorphic to xenomorphic crystals. Relict textures indicate that much of the dolomite originated from fine to medium grained bioclastic debris and some from pelleted logoonal muds. In the back-reef area a considerable amount of the dolomite is finely laminated, suggestive of algal laminations in limestone. Blebs of calcite, pseudomorphous after gypsum occur in the laminated material.

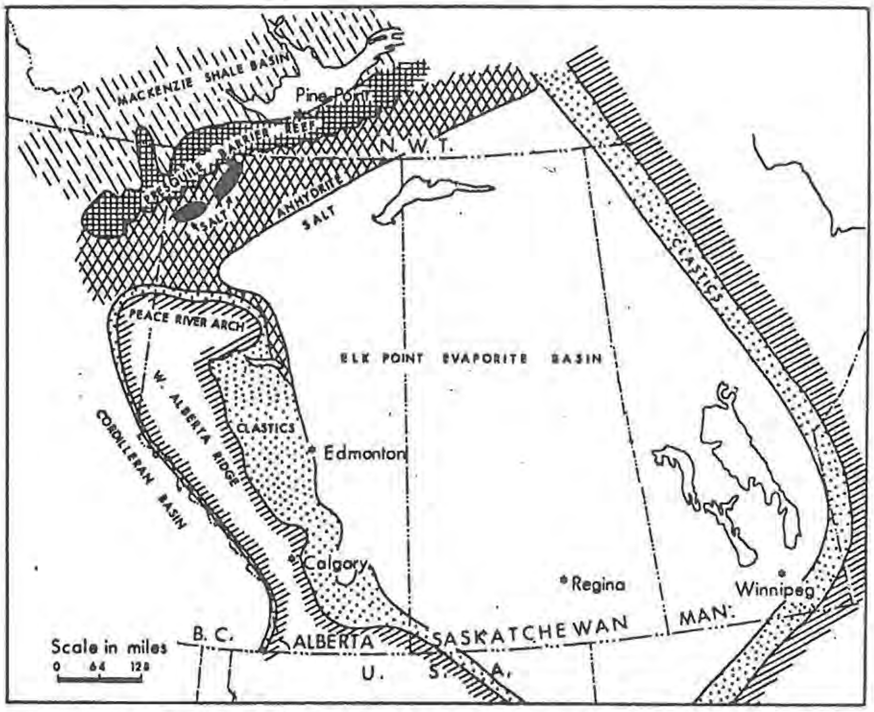


FIG. 19. Location map illustrating the position of Pine Point and the paleogeography of Western Canada during deposition of the Middle Devonian Presqu'ile barrier reef complex (mod. from Grayston, Sherwin and Allan, 1964).

From Jackson and Folinsbee, 1969

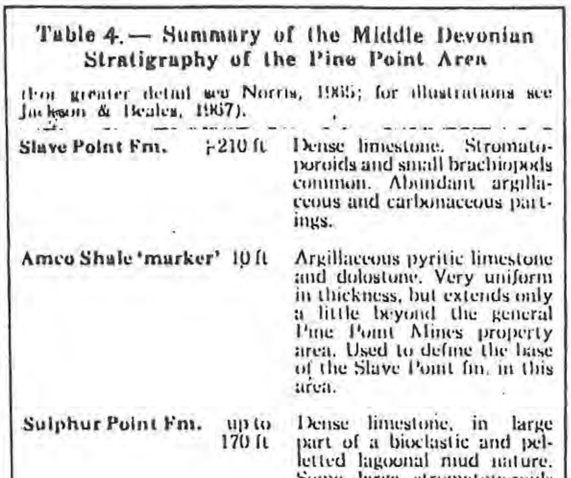


Table 4. — Summary of the Middle Devonian Stratigraphy of the Pine Point Area

(For greater detail see Norris, 1965; for illustrations see Jackson & Beales, 1967).

Slave Point Fm.	±210 ft	Dense limestone. Stromatoporoids and small brachiopods common. Abundant argillaceous and carbonaceous partings.
Amco Shale 'marker'	10 ft	Argillaceous pyritic limestone and dolostone. Very uniform in thickness, but extends only a little beyond the general Pine Point Mines property area. Used to define the base of the Slave Point fm. in this area.
Sulphur Point Fm.	up to 170 ft	Dense limestone, in large part of a bioclastic and pelletted lagoonal mud nature. Some large stromatoporoids and brachiopods. In part laterally equivalent to, and interbedded with, Presqu'ile dolostone.
Watt Mountain 'marker'	±3 ft	Waxy green shale bed usually 2-3 ft thick; sometimes several beds occur, separated by white limestone. Lies 30-50 ft below top of Sulphur Point fm.
Presqu'ile Fm.	up to 200 ft	Coarsely crystalline dolostone with vuggy to cavernous porosity. Sparry dolomite lines most of vugs. Abundant amphiporid remains in places, but other fossils are mainly obliterated by dolomitization. In part, or possibly largely, a diagenetic facies of the Sulphur Point fm. Orebodies occur locally.
Pine Point Fm.	±300 ft	Medium- to coarse-grained, sucrosic to dense, brown dolostone; argillaceous limestone and dolostone. Orebodies occur in upper part.

From Beales and Jackson, 1967

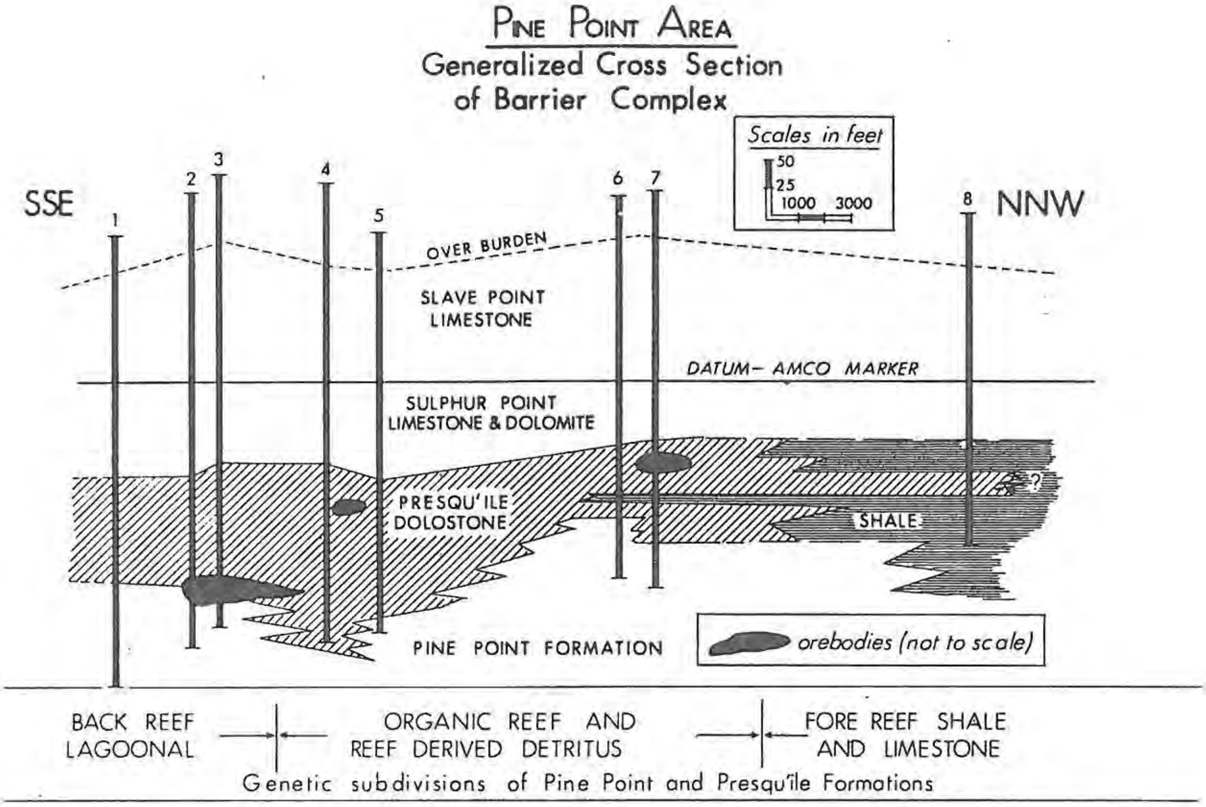


FIG. 20. The ore bodies at Pine Point occur in the Presqu'ile dolostone and at its interface with the Pine Point formation and are controlled in part by the paleoecology of the barrier complex.

From Jackson and Folinsbee, 1969

Several zones of sedimentary breccia occur within the formation in the fore-reef (slump breccia) and back reef area (solution collapse breccia). The top of the Pine Point Formation is characterized by an unconformity consisting of a brecciated dense bluish-gray dolomite horizon. It has resulted from leaching and weathering of the sediment during exposure.

The Pine Point Formation is overlain by the Presqu'ile Formation which is composed of very coarsely crystalline vuggy dolomite. The final geometry of this unit is the result of a combination of primary constructional fabric and a complex sequence of subsequent alterations. Jackson and Folinsbee (1969) state that: "The margins of the resultant characteristic rock are interbedded with, laterally equivalent to and cross cut other formations from the Upper Pine Point to Lower Slave Point". Evaporite solution breccias and lattice work structures developed in the Presqu'ile dolomite played an important role in porosity development.

The ore bodies at Pine Point occur as a series of flat lying elongate lens-shaped bodies. The elongation is parallel to the barrier trend. The margins of the ore bodies are very sharp and no disseminated fringe is developed adjacent to the massive ore even though the wall rock porosity continues. Ore deposition was mainly in open spaces derived from (a) intra- and interskeletal constructional voids, in part from (b) diagenetic changes, and in part from (c) solution of syngenetic evaporites. Colloform and crystalline sphalerite and galena are the only ore minerals. Gangue minerals include marcasite, pyrite, calcite, dolomite and rare pyrrhotite and fluorite.

The reader is also referred to Skall (1975), Beales and Jackson (1966) and 1968), and Campbell (1967) for an indepth discussion on the Pine Point deposits.

2.4.2 Deposits in Mudbank Complexes

The Northgate base metal (lead-zinc) deposit of Tyñagh, County Galway, Ireland (figure 16) is a typical example of a mudbank complex deposit (Derry et al, 1965). This mudbank complex forms part of the Waulsortium facies (figure 17). This facies is composed of massive lime mudstone containing scattered crinoid and bryozoan fragments which forms lens- like buildups and mounds. This distinctive and ubiquitous facies is developed in Lower Carboniferous (Tournaisian - Visean) strata throughout the northern hemisphere (Wilson, 1975). The Waulsortian mounds and lenses appear mainly as a shelf margin facies between geosynclinal basins and shelf deposits which were formed in conditions of open marine circulation (see section 2.2.4).

The Reef limestone of the Waulsortian mudbank complex (facies) is the ore host where it fingers into muddy limestone (figures 21 and 22).

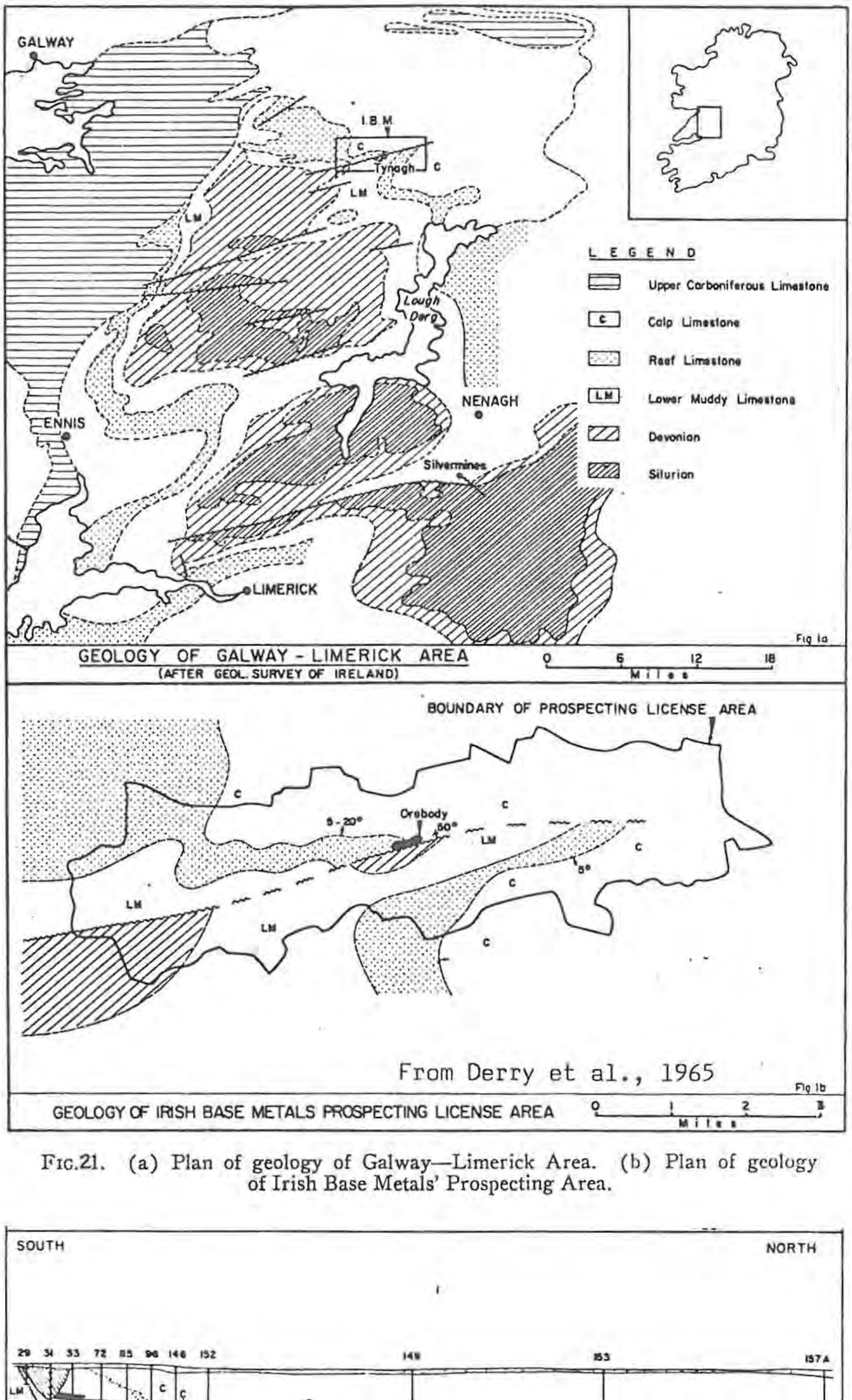


FIG.21. (a) Plan of geology of Galway—Limerick Area. (b) Plan of geology of Irish Base Metals' Prospecting Area.

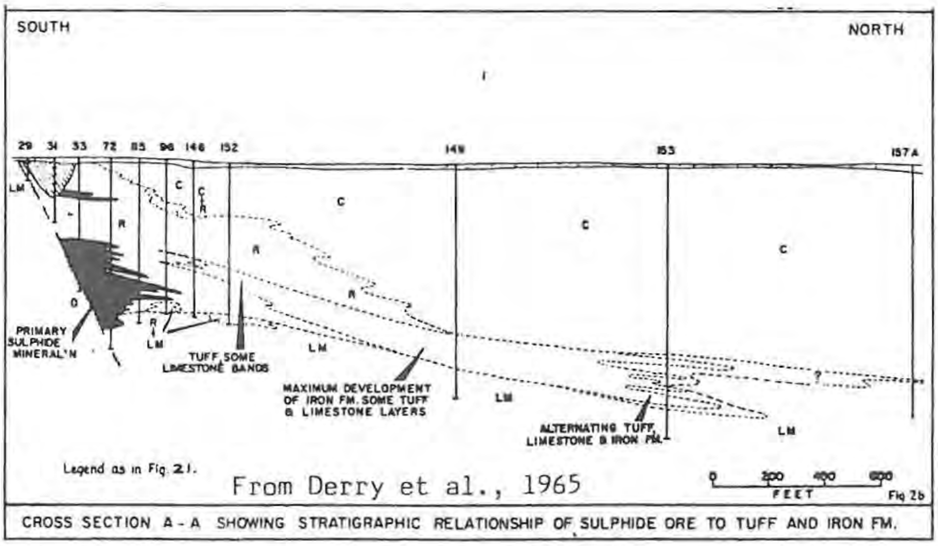


FIG. 22. (a) Plan of secondary ore body at base of overburden. (b) Cross-section AA showing stratigraphic relationship of sulfide ore to tuff and iron formation.

	South	North
Lower Carboniferous	Dark Muddy Limestone (Calp)	
	Reef Limestone	Tuff, iron formation & muddy limestone
	Lower dark shaley limestone	
	Dark shaley limestone with syringopora	
Upper Devonian	Sandstone with shale or mudstone beds.	

Table 5. Stratigraphic succession in the mine area
From Derry et al., 1965

Table 5 outlines the stratigraphic succession in the mine area. The ore body, lying just north of a fault, is in two parts, a boat shaped mass of residual or secondary ore overlying primary sulphide ore. A volcanic ash bed occurs in the muddy limestone at approximately the same stratigraphic horizon as the reef (figure 22). The ash and muddy limestone lithologies are interbeeded with a bed of banded iron formation, the latter and the ash bed pointing to a possible volcanogenic origin of the ore.

The primary sulphides very often have colloform, banded or concentric structures with some masses or veins of coarse sulfides. The average grade of the primary ore is 4,8 percent lead and 4,3 percent zinc. Residual ore is mainly a black mud containing fine sulfides grading 16 percent lead-zinc but sharply defined areas of oxides form about 28 percent of the tonnage. The average grade is about 9,2 percent lead and 7,5 percent zinc. The sulfide-mud ore is believed (Derry et al., 1965) to have resulted from supergene solution of the calcium carbonate from mineralized limestone thereby releasing sulfides and muddy components in some parts, metal oxides in others, to settle or be washed into a deepening, fault controlled gully.

2.4.3 Algal Reef Deposits

Some ore deposits of the Old Lead Belt and Viburnum Trend in Southeast Missouri (figure 12) are localized in an algal reef/bar environment (figure 23) on the northeastern flank of exposed Precambrian of the St. Francois Mountains (figure 24) (Snyder and Gerdemann, 1968). This positive structure in the Old Lead Belt area forms the northeastern part of the Ozark Dome (figure 12).

The Southeast Missouri ore deposits are stratiform in the Upper Cambrian Bonneterre dolomite (figure 25) of the Bonneterre Formation.

This formation has been subdivided into zones numbered from 1 through 19, from the top down. (Snyder and Emery, 1956). Detailed descriptions of the units are given by Ohle and Brown (1954) and Snyder and Odell (1958). The lithologies of the Bonneterre dolomite have been described in terms of four end member components (Snyder and Odell, 1958). These are algal material, sand size grains (carbonate, fossil fragments, quartz), calcareous mud, and argillaceous mud. A given bed may be composed of any one of the components or of any combination, depending on the environment of deposition. The algal reefs grew over calcarenite bars in the dolomite reef facies. In a few places igneous knobs provided the foundation for reef growth. Over the crest of the bar the lower part of the reef is mineralized (figure 26). Internal reef features exerted a strong control over mineralization, so that parts of the reef are mineralized only in the lower 6 metres; parts are mineralized up to 15 metres into the reef. Ore within the reef is variable in grade due to the influence of internal reef features. The reef mass (organic structures with entrapped and interbedded sediment) is roughly comb-shaped in plan (figure 27).

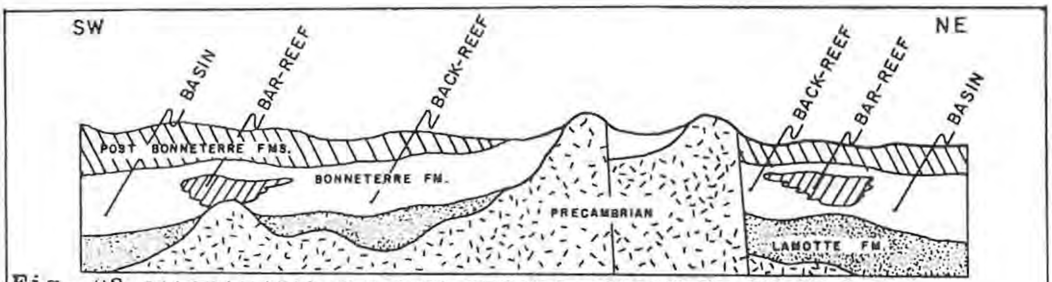
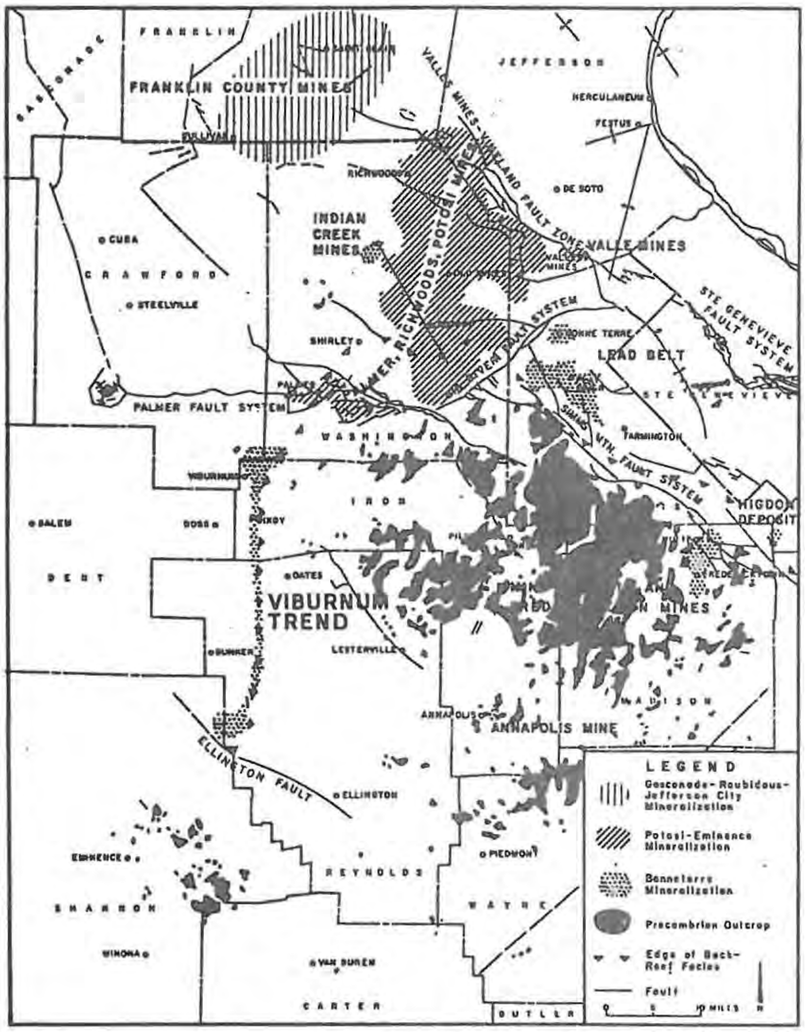


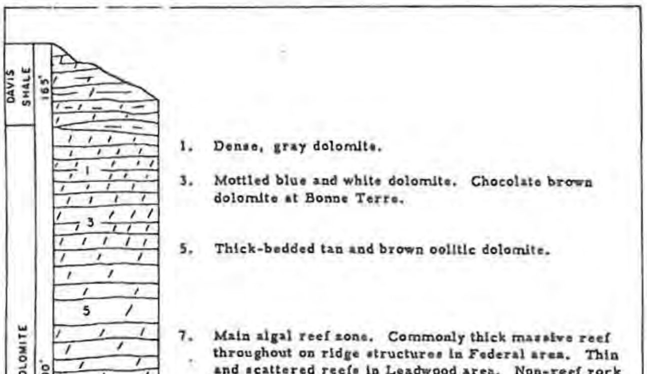
Fig. 23 DIAGRAMATIC GEOLOGIC SECTION—SOUTHWEST-NORTHEAST

From Snyder and Gerdemann, 1968



From Wharton et al., 1975

Figure 24.
Map of Southeast Missouri Lead district.



1. Dense, gray dolomite.

3. Mottled blue and white dolomite. Chocolate brown dolomite at Bonne Terre.

5. Thick-bedded tan and brown oolitic dolomite.

7. Main algal reef zone. Commonly thick massive reef throughout on ridge structures in Federal area. Thin and scattered reefs in Leadwood area. Non-reef rock is generally thin, wavy bedded, fine-grained, gray or tan dolomite. Contains black shale partings and gray spotting.

10. Thick, fine-grained, even-bedded tan dolomite on southwest side of district. Coarse-grained, lenticular tan dolomite over ridge structures. Thin or absent between ridges.

12. Thin, wavy bedded, fine-grained and spotted dolomite, contains black shale partings. Algal beds common at base. Thin over ridges.

15. Light colored, coarsely crystalline. Often glauconitic. Frequently thick over ridges.

16. Brown compact dolomite. Algal mat, sometimes with digitate columns. Usually found at 15/19 contact.

19. Tan or gray sandy dolomite. Thickens to form ridges.

20. Sandstone with occasional siltstone beds. Poorly cemented in upper part. Thin dolomitic beds in upper part. Residual igneous boulders at base.

21. Precambrian, volcanics and granite.

From Snyder and Gerdemann, 1968

FIG. 25 Subdivision of the Bonneterre Formation.

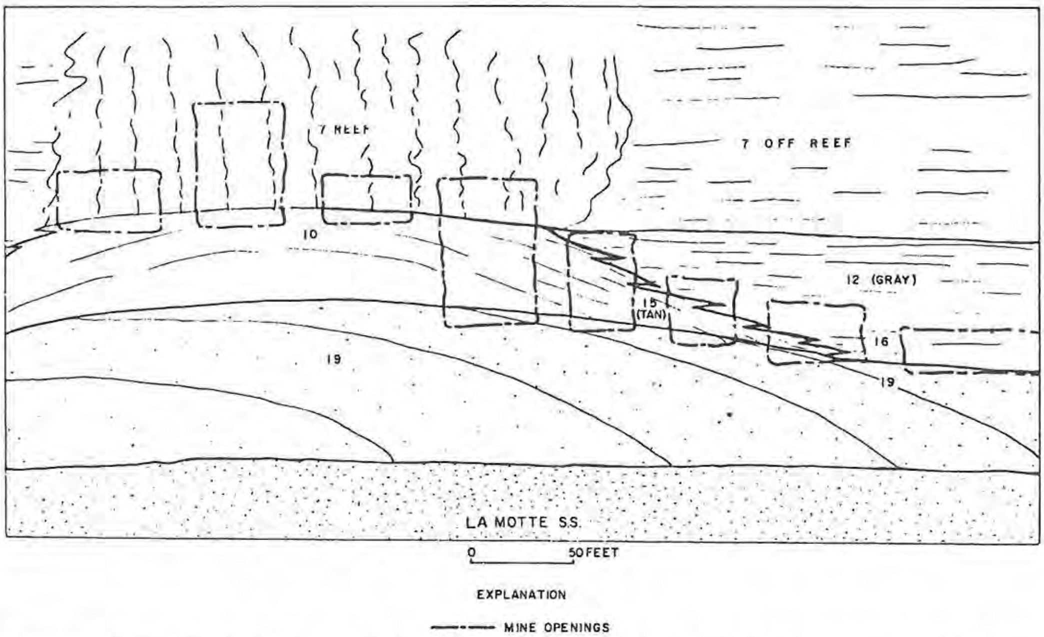


FIG. 26. *Mineralization in Bar-Reef Complex, in Lower Beds on Flank of Structure, and in Reef Over Crest.*

From Snyder and Gerdemann, 1968

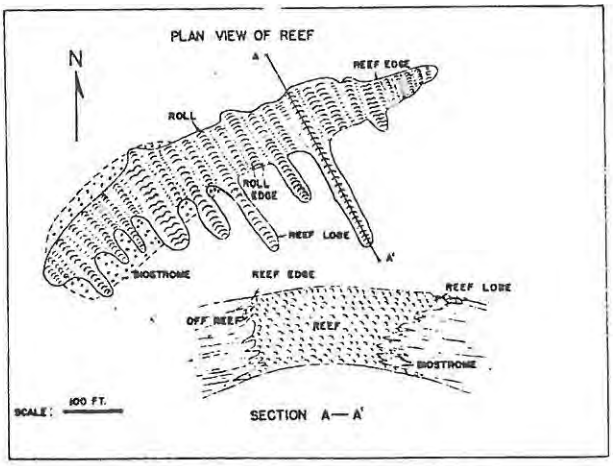
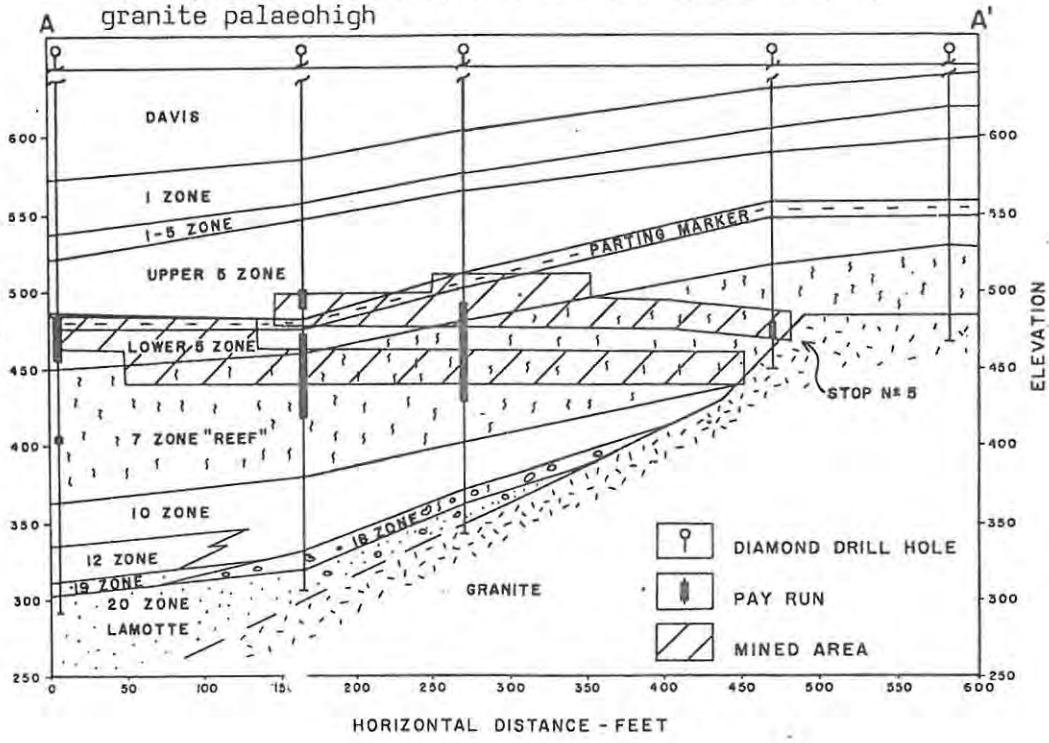


Fig. 27. Plan and section of 7 bed reef.

From Snyder and Emery, 1956

FIGURE 28.

Ore deposition associated with the 7 zone reef on a granite palaeohigh



From Pettus and Rauch, 1979

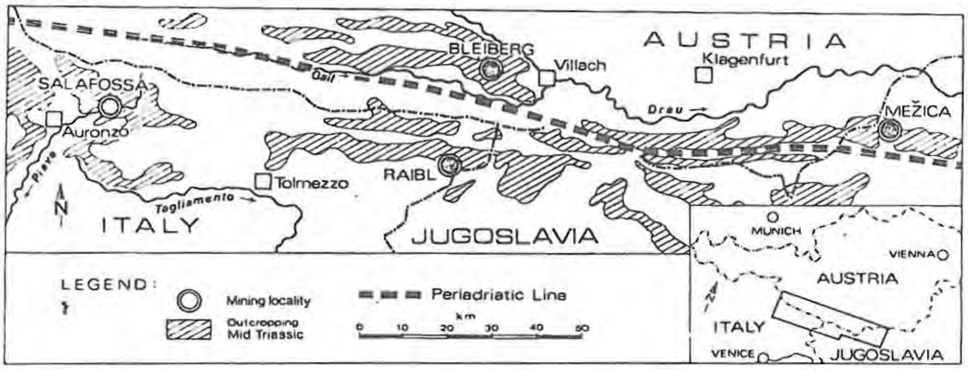


Fig.29.Geotectonic position of the four Pb-Zn deposits within the SE Alpine realm in relation to the Periadriatic Line

From Brigo et al., 1977

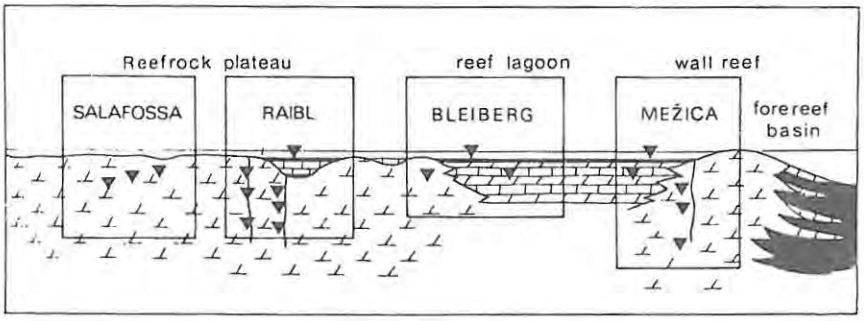


Fig. 30.Schematic reconstruction of the paleogeographic situation of the deposits without stratigraphic relation. (Predominant types of orebodies are indicated)

From Brigo et al., 1977

The ore minerals occur along bedding-plane and growth-line contracts, in fracture zones, and disseminated in the organic carbonates. Vast amounts of reef rock are unmineralized indicating that the ore solutions either carried insufficient concentrations of metals and/or that favourable depositional conditions (hydrogen sulfide) did not prevail throughout the reef. The primary sulfides include galena, sphalerite, chalcopyrite, siegenite, bravoite, pyrite, marcasite, and possibly bornite and millerite.

The 28 Mine in the Viburnum Trend (Pettus and Rauch, 1979) also displays ore deposition associated with the 7 zone reef where the latter was developed on a granite palaeohigh (figure 28).

2.4.4 Back Reef Deposits

The four Mid-Triassic deposits of Bleiberg-Kreuth, Mezica, Raibll, and Salafossa which are classified as the so-called "Alpine lead-zinc type" represent carbonate hosted lead-zinc mineralization in the "back-reef" (figures 29 and 30). The lead-zinc mineralization is stratigraphically connected to a distinct time interval from Upper Ladinian to Lower Carnian (figures 5 and 7). This time interval is represented by the "special facies" (see section 2.1.3).

An east striking fault of regional importance divides the Austroalpine nappes in the north from the South-Alpine block. This dividing fault is referred to as the "Periadratic Line" (Brigo et al., 1977) (figure 29). The present positions of the four deposits under discussion are due to tectonic movements, folding and faulting, which suppose that the deposits were originally at greater distance apart.

The local characteristics of these deposits within the palaeogeographic model of Schneider (1964) (figure 7), and shown in more detail in figure 30, will be discussed.

(i) Bleiberg-Kreuth deposits

The ore-bearing sediments in the Bleiberg-Kreuth Mid-Triassic series belong to four stratigraphic levels (figure 31) within the upper Ladinian and Carnian Groups i.e. Wetterstein dolomite/limestone and overlying Raibl dolomite/calcareous beds respectively. The shallow lagoonal facies of the upper Wetterstein carbonate sequence is characterized principally by intercalations of stromatolites, rhythmites, green marls (tuffites?), black resedimented breccias and calc-arenites.

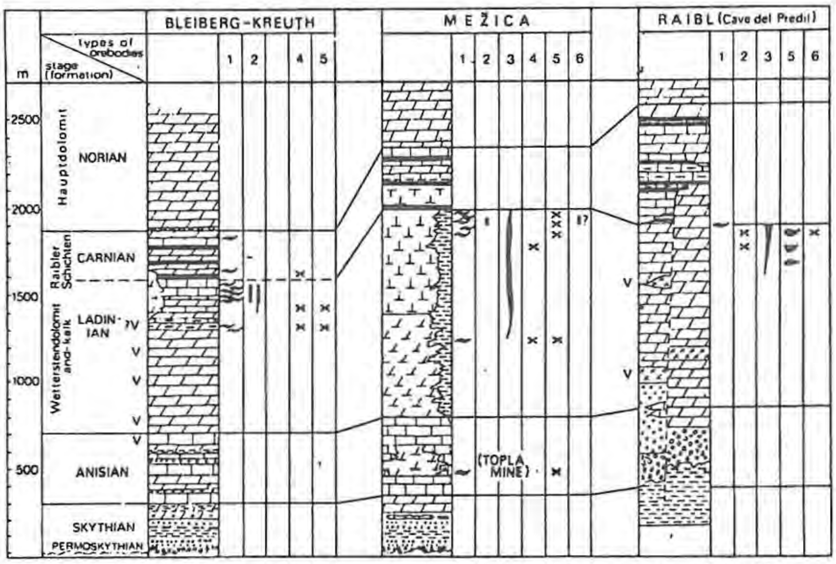


Fig. 31.Stratigraphic record of the facial environments predominating in the host rock sequences of Bleiberg-Kreuth, Mežica, and Raibl in relation to the main genetic types of orebodies. *Explanation: v:* volcanic activity, indicated by extrusions (X), tuffs or tufaceous marls. *Prevailing genetic types of orebodies: 1:* stratiform, mainly sedimentary ores; *2:* strata-bound veins and ore filled fissures; *3:* orebodies linked to disconformable faults of greater range; *4:* orebodies in brecciated parts, networks; *5:* irregular orebodies, oreshoots and stocks; *6:* karstic orebodies

From Brigo et al., 1977

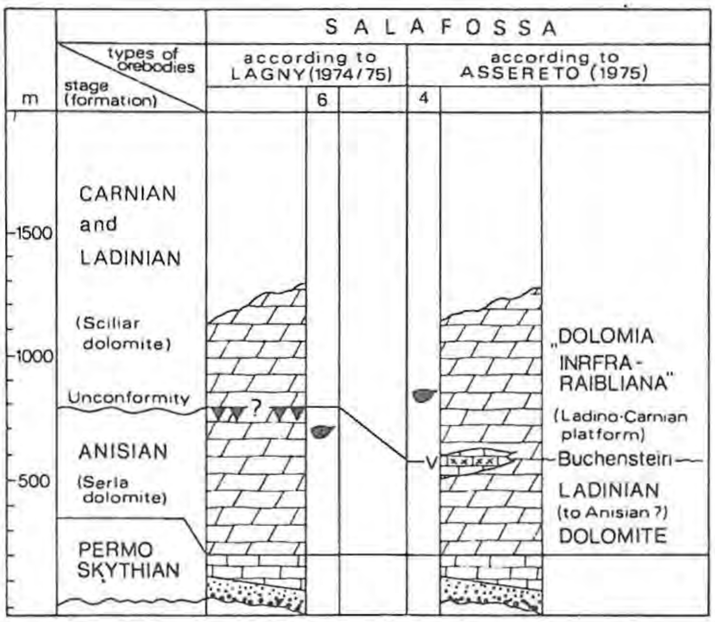


Fig 32.Two different stratigraphic and genetic interpretations of the Salafossa deposit with respect to the facial development of the hostrock sequence.

From Brigo et al., 1977

The economic mineralization is typically stratabound, in the form of conformable layers and discordant veins, and ore-cemented breccias. The lowermost ore-bearing horizon (figure 30) hosts stratiform ore-bodies (100 metres x more than 1 metre thick) interlayered between marly tuffaceous lithologies and locally associated with ore-cemented deformation breccias.

The second ore-bearing horizon comprising the upper 120 metres of the Wetterstein sequence and hosts two types of ore deposits viz.

(a) conformable ore bodies measuring lenghts of several hundred metres, widths of up to 30 metres and thicknesses of several metres, and

(b) veins several hundred metres long and up to 20 metres thick.

The third ore-bearing horizon is located in the Raibl beds some 2 metres below the number 2 Raibl marker (figure 30). The orebodies are conformable, they have subrounded outlines and they measure up to a few hundred metres in diameter and up to 5 metres in thickness.

Mineralization within the Beleiberg-Kreuth mining district is selective i.e. it does not occur at each favourable stratigraphic horizon. The primary mineralizations with similar characteristics in all four ore-bearing horizons are pretectonic and synsedimentary. The main ore minerals are sphalerite, largely of coloform type Schalenblende), galena and marcasite. The gangue minerals include pyrite, melnikovite, fluorite, quartz, barite, calcite and domolmite. The Zn/Pb ratio is 5:1.

(ii) Mezica deposits

The Ladinian sequence in the Mezica region (figure 29), more than 1000 metres thick, consists of three main units, each characterized by differentiated facies development (Brigo et al, 1977), (a) Wetterstein limestone lagoonal facies; (b) Reef limestone, and (c) "Partnachschichten" (basinal facies). The mainly lagoonal economic Wetterstein depositional facies is analogous to that of Bleiberg e.g. recrystallized and dolomitised micrites, intramicrite and intrasparites have abundant intercalations of stromatolites, resedimented breccias, oolitic limestones and green marls indicating very shallow marine sedimentation. Black breccia markers (5 - 15 cm thick) are located at 10 - 15, 15 - 60 metres below the base of the Raibl beds.

The Reef limestone (intrasparites and intramicrites) contains abundant coral reefs with Thecosmilia, Craspedophyllia, Oppelismilia and other sediment-binding organisms. To the (north), the Reef limestone zone grades into basinal marly-clayey sediments.

The Raibl beds conformably overly the Reef limestone. No mineralization is developed in the Raibl limestone sequence.

The Mezica lead-zinc ores occur as stratiform bodies, discordant stocks and veins which are spatially linked to well-defined horizons within the different stratigraphical units (Brigo et al., 1977 p.281). The conformable orebodies are variable in size, shape and form and occupy a stratigraphic thickness of 2 to 4 metres. Unconformable ore is present as (a) strata-bound mineralized veins and fissures; (b) mineralizations linked to faults and fault zones; (c) ore breccias, and (d) mineralizations without any specific spatial connection to strata- or faults.

Ore mineral abundances vary according to mineralization types. Conformable ore consists mainly of lead and zinc sulphides in dolomite gangue with minor amounts of pyrite, marcasite, fluorite, bitumen and some quartz. The unconformable ores consist mainly of lead, zinc and iron sulphides with minor and varying amounts of calcite, barite, fluorite, dolomite and quartz. The average Pb/Zn ratio is 1:1.

(iii) Raibl deposits (figures 30 and 31)

The Anisian-Ladinian sequence in the Raibl area consists of (from bottom upwards): (a) conglomerates and breccias (base of upper Anisian); (b) shales, sandstone and tuffites (upper Anisian); (c) tuffs and ignimbrites (lower Ladinian): (d) dolomite unit more than 1000 metres thick known as the Dolomia Metallifera which is covered by the Carnian units. The entire Triassic sequence underwent the effects of the alpine tectonics.

The Raibl lead-zinc deposit is located within the Dolomia Metallifera. The concentration of the ores took place along the main syngenetic faults striking north-south and to a lesser degree NNW to NW. The vertical distribution of economic ores appears to be limited to the upper Dolomia Mettalifera. The following types of orebodies are recognized in the Raibl deposit: (a) stratiform ores linked to fault zones; (b) stocks (columnar orebodies) roughly parallel to the general bedding strike.

They represent the filling-up of solution cavities and breccia volumes; (c) veins along the main syngenetic faults and lateral fissued zones. A well developed secondary deposit can be divided into an upper oxidized zone (rich in limonite) and a lower zone rich in carbonates (smithsonite).

The main ore minerals are sphalerite (crystal and colloform) and galena (coarse grained).

(iv) Salafossa deposits (figures 30 and 32)

The Salafossa region was palaeogeographically characterized, during the Mid-Triassic, by the continuous development of carbonate platform facies (Brogni, 1977; Lagny, 1975). These are characterized by (figure 32) (a) the Serla Dolomite of lower Anisian age, unconformably overlain by late Anisian marly sediments; (b) the Sciliar Dolomite; (c) the "Infraraibliana" Dolomite of upper Ladinian to Carnian age.

The Salafossa lead-zonc deposit is columnar and elongated parallel to a fault in the Mid-Triassic Serla Dolomite. The orebody consists essentially of a pipe breccia.

The Salafossa deposit exhibits very similar paragenesis when compared with the Raibl deposit. The Pb/Zn ratio is 1:5.

2.5 Deposits associated with karst features

2.5.1 Introduction

Typical karstic topography is developed by chemical erosion of carbonate rocks during subaerial exposure. Three zones can usually be recognized within a mature karst system. These zones were defined by Cvijic (1918) mainly on the basis of the hydronamic properties of the flow of meteoric waters which influence the shape and distribution of caves and related dissolution fissures (figure 33). The development of a dendritic network of solution cavities is governed by both primary and secondary porosity factors. The porous algal laminites and evaporite beds are often preferentially leached while secondary faults and fractures control most of the near surface dissolution and control the major cavern networks. Preferential leaching is also a factor of rock composition. Limestones are much more easily dissolved than dolomites. The flow properties also determine the main characteristics of the internal sedimentation within the karst cavity system (Bernard, 1973) as outlined in the explanation to figure 33. Coarse solution collapse breccias are

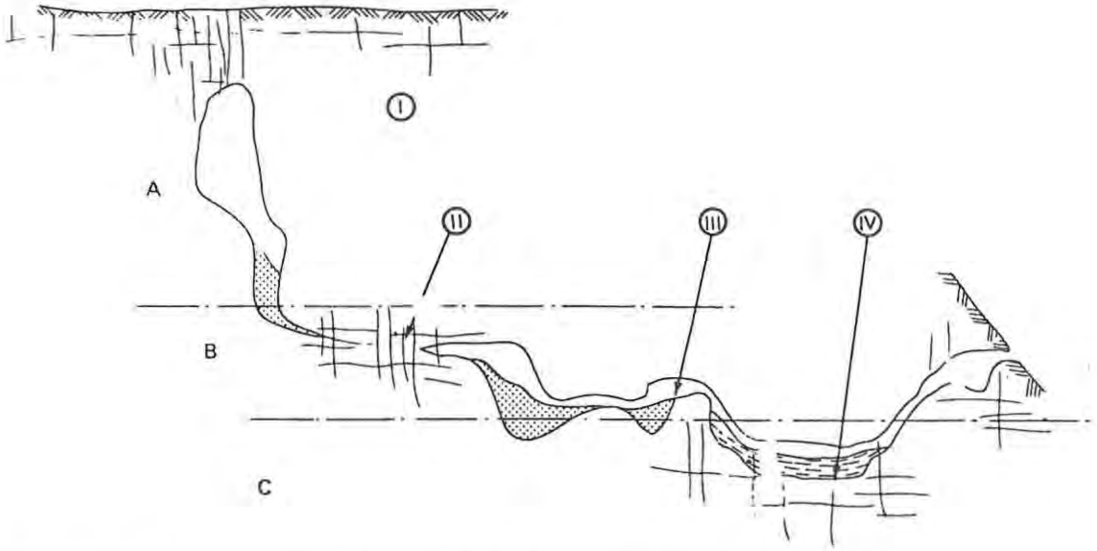


Fig. 33. Simplified section of mature karst system (after J. CVIJIC, 1918)

A - Percolation zone: meteoric waters percolate vertically through carbonate formation, i. e. through fissures which they widen, thus opening caves, sink-holes, gash-veins, etc. Irregular flows, occasionally torrential streams; mechanical erosion largely prevails over chemical leaching. Coarse detrital sedimentation.

B - Permanent circulation zone: water circulation is mostly horizontal when rock jointing allows it; resulting caves exhibit marked lateral extent: galleries. Free or forced flow, always irregular, leads to intense chemical erosion, fine detrital sedimentation.

C - General imbibition zone: comprises the country-rock below the water table. Very slow circulation, if any, i. e. stagnant waters. It is essentially a zone of ultra-detrital and chemical sedimentation.

(Roman numbers within circle refer to chemical composition of corresponding waters, see table I)

From Bernard, 1973

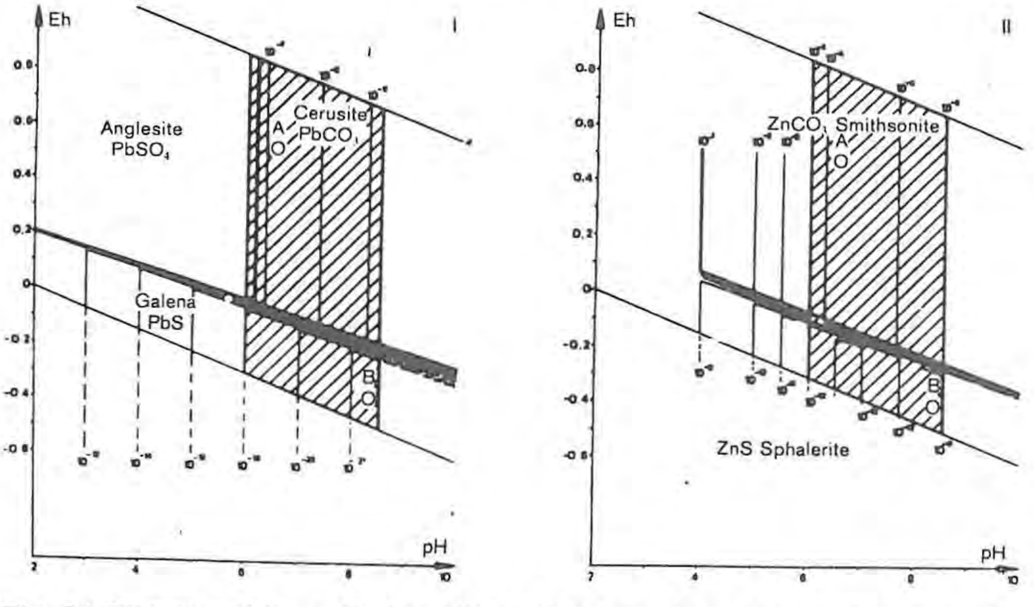


Fig. 34. Diagrams of theoretical stability fields of minerals as functions of pH, Eh and solubility products of various lead (I) and zinc (II) species (after GARRELS, 1953)

formed in the near surface percolation zone where the rate of mechanical collapse exceeds chemical corrosion. Intense chemical erosion occurs with minor fine grained detrital sedimentation in the zone of permanent circulation. In slow circulating zones stagnant conditions can develop which can induce chemical sedimentation in conjunction with ultrafine detrital sedimentation in the Imbibition Zone (Bernard, 1973).

Hydrogen sulphide formation bears very important consequences on the behaviour of base metals in the karst system. Dissolution of evaporite beds can enrich the water in sulphate which can readily be reduced by bacteria, usually in the lower stagnant waters. Should there be significant amounts of metals in the ground waters (brines) sulphides would precipitate. Zinc and minor low concentrations of lead could be transported as bisulphide complexes at the low temperatures (25-50°C) prevailing in these systems.

Zinc sulphide complexes are far more stable than lead complexes and any resultant deposition, either by pH or Eh changes or dilution would result in lead being precipitated first (Garrels, 1953) (figure 34 The deposit that will form is dependent on the concentration of the metals in solution. Earlier precipitated sulphides could further be concentrated into a significant deposit by continual erosion and dissolution. Deposition is controlled by the rising level of the ground water table as the zone of imbibition follows and causes precipitation of sulphides in previously altered solution breccia zones. Lowering of the ground water table (tectonic activity e.g. uplift) would expose the sulphide zone to erosion and oxidation and thereby produce the secondary orebodies so characteristic of many carbonate hosted deposits. The main pH and Eh conditions under which secondary lead and zinc minerals are stable are outlined in figure 34. Such deposits can disply a complex genetic history due to various phases of tectonic activity.

Changes in the chemical activity of surface and ground waters can cause the concentration of metals that form carbonate and oxide minerals in karstic deposits. This depends largely on the source of the metal and also on the stability of the different complexes in the different zones (Dingemans, 1980). Vanadium forms soluble hydroxy and oxy complexes which become destabilized in alkaline conditions and so precipitate as various vanadates in carbonate rocks. The concentration of vanadium in karst breccia fillings within the carbonates of the

Damara Supergroup in Namibia was mainly controlled by the local source of vanadium in the overlying Karoo lavas as well as the development of porous solution breccias in the carbonates.

2.5.2. Solution collapse breccia deposits related to karst topography above

The development of a typical karst system has been discussed in the previous introductionary section. Most of the currently known carbonate-hosted sedimentogenic lead-zinc (copper) deposits are genetically related to karsting. Karsting creates secondary porosity which can then be exploited by mineralizing solutions. These solutions do not necessarily have to be "ore bearing", they could cause dolomitization or precipitate gangue minerals thereby increasing or decreasing porosity respectively.

There are numerous deposits within this "class". These deposits will not be discussed here as reference to many of them will be made when discussing the geological factors that affect their geometry and grade.

The following is a list of the best-known examples of this class:

(a) Central- and East Tennessee (Hoagland, 1976); Laurence, 1971; Le Grand and Stringfield, 1971; Hill and Wedow, 1971; Harris, 1971; Maher, 1971; Hill, Morris and Hagegeorge, 1971; McCormick et al, 1971; Fulweiler and McDougal, 1971; Kyle, 1976).

(b) Tsumeb and Kombat Mines, Namibia (Söhnge, 1961 and Venter, 1980).

(c) Newfoundland (Collins and Smith, 1973).

(d) Baffin Island N.W.T., Canada (Geldsetzer, 1973).

(e) Friedensville Mine, Pennsylvania (Callahan, 1968).

(f) Tri-State, U.S.A. (Brockie et al, 1968; Hagni, 1976).

(g) Sardinia (Padalino et al., 1973).

2.5.3 Deposits related to collapse structure resulting from thinning of underlying beds by subsurface drainage.

This deposit type will be discussed when dealing with section 3.0 so only reference to it will be made here.

(a) Southwest Wisconsin, U.S.A. (Upper Mississippi Valley District) (Heyl, 1968 and Heyl et al., 1959).

2.6 Deposits not primarily associated with reefs or karsts

The primary deposit locating factor, in this class, is not associated with any apparent reef complex. The ore is localized by or in:

(a) facies changes
(b) structural and sedimentary coincidence.

Karsting has exploited these fundemental weaknesses, in some cases, to provide the loci for ore deposition. These deposits will also not be dealt with under this heading but during the discussion on geological factors affecting the shape, size and grade of carbonate hosted lead-zinc (copper deposits).

2.6.1 Deposits located at a facies change

(a) Austinville-Ivanhoe deposits of the southern Appalachians (Hoagland, 1976 p.503).

(b) Rob Lake, northeastern British Columbia (Macqueen and Thompson, 1978).

(c) Yukon, N.W.T., Canada (Smith, 1974).

2.6.2 Deposits associated with structural and/or sedimentary coincidence

(a) "Sedmochiscentse" type in Bulgaria (Minčeva-Stefanova, 1967).

(b) Stratiform deposits of Southern Illinois (Grogan and Bradbury, 1967).

(c) Silesian-Cracovian and Rhineland (Galkiewics, 1967).

(d) Sardinia.

2.7 Metal transport and deposition

Available geological and geochemical data indicate that the solutions that deposited the ores in the main districts were concentrated sodium, calcium, potassium choloride brines at temperatures between 70-160°C generated in adjacent basins. The saline brine solutions mingled with various amounts of other solutions, such as small magmatic fractions in some districts, contributions of potassium and sulphate rich brines from more distant basins in others and local sulphate brines and meteoric waters in still others (Heyl, 1969). There exists a valid reason for invoking a two brine system that carried the metals and sulphur (sulphate) separately. The solubility of base metals in chloride solutions increases with increasing sodium chloride concentration and decreasing pH and only at low pH's of less than 4 can sufficient metal and sulphur be carried by the same brine to form an ore deposit. Such acid solutions would react with the carbonate host rock which would cause precipitation of minute quantities of contained metal. An economic deposit could therefore never be formed. Continual reflux of a metal bearing brine is necessary over long periods of time to form a significant deposit.

Bisulphide transport of lead and zinc is only significant in neutral to alkaline solutions at very low temperatures (Barnes, 1979) of ± 25°C. The chloride complexes of the same metals in slightly acid to neutral solutions, at higher temperatures and in the absence of significant amounts of reduced sulphur are more stable with zinc being almost three times more stable than lead. Copper and silver are also transported as chloride complexes mainly as $CuCl_2^-$ and $CuCl_3^=$. (high sodiumchloride concentrations). Copper complexes are less stable than zinc or lead complexes. Precipitation of these metals would therefore occur in the sequence copper, lead and then zinc. This metal zoning is typical of many sedimentary deposits. Precipitation of these metals from solution can be accomplished by four factors (or combinations thereof):

(a) temperature decrease

(b) pH decrease

(c) dilution

(d) increase reduced sulphur content.

3.0 GEOLOGICAL FACTORS AFFECTING THE SHAPE, SIZE AND GRADE OF THE CARBONATE-HOSTED LEAD-ZINC (COPPER) DEPOSITS

3.1 Introduction

The fundamental prerequisite for ore development in carbonate rocks is effective porosity. Effective porosity is the percentage of connected void space. This is very important in determining whether a host rock is going to be permeable. A rock can be highly porous but impermeable and will therefore be unsuitable for ore development. The host rock must be permeable in order to allow flow of metal-bearing solutions. Porosity can be brought about in many different ways. It can be a primary sedimentary/diagenetic feature of carbonate rocks. Secondary porosity can be superimposed upon the primary porosity by dolomitization and by tectonic disturbance, e.g. folding, faulting, jointing and fracturing. Such features are commonly enhanced by subsequent enlargement through solution activity (karsting). Porosity in limestones is rarely homogeneous and, in consequence, permeability trends will develop. Such trends will, according to Beales and Jackson (1966), not be haphazard and should be geologically predictable. The predictable arrangement of permeability trends in carbonate reservoirs will determine the relative flow of inter- and intraformational fluids. The location and size of the orebodies are determined by the timing, relative movement rates and mixing of these fluids.

The various factors affecting the size, shape and grade of the deposits will be discussed in turn in the discussion to follow. Some overlap will unavoidably occur because ground preparation (porosity) for ore deposition is generally attained by the interaction of various factors.

3.2 Geological factors affecting the shape and size of the orebodies.

3.2.1 Palaeotopographical factor

The palaeotopographical factor affects the shape of the orebodies in that elongation always occurs parallel to the contour of the topographical feature. An example of this occurs at Pine Point, Canada, where the palaeoshoreline controlled the elongation of orebodies in deposits associated with the reef complex. They are elongated parallel to the southwesterly strike direction of the Presqu'ile barrier reef (figure 19) (Jackson and Folinsbee, 1969).

Another example is the Reef Limestone and its contained or deposits, of the Waulsortian mudbank complex at the Northgate base metal deposit (Tynagh) in Ireland. The orebodies are elongated parallel to the Lower Carboniferous shoreline that prevailed to the northeast (figures 17 and 21).

The carbonate-hosted lead deposits of the Missouri area are located on the flank of a circular positive structure of Precambrian age, the northeastern part of the Ozark Dome (figures 12 and 24). The ore is hosted by the Lamotte Sandstone, Bonneterre Dolomite and Davis Shale (figure 25). The Bonneterre Formation is the main ore-bearing host and is composed entirely of dolomite in the mining region. The dolomite forms haloes of uneven size and shape around Precambrian igneous knobs. The palaeotopographic highs also affected sedimentation, giving rise to a different Bonneterre facies on or near the structure. Marine currents, influenced by the larger igneous masses (positive highs), built ridges or splits of clastic carbonate material (Snyder and Gerdemann, 1968). The orebodies associated with the various facies are all elongated parallel to the contours of these topographic features and are therefore linear to arcuate in plan view.

The forms of the orebodies are mainly those of sedimentary depositional structures related to the topographic highs. Many areas show a close fit of ore and sedimentary structure so that in mining, it is essentially the sedimentary structure that is mined. The various types of orebodies are:

(a) Pinchout type

Mineralization is in the 19, 15 and 12 dolomite beds (figure 25) above the Lamotte pinchout line (figure 35). The orebodies partially encircle the buried knob and is narrow (15-50 metres wide). Mineralization comprises disseminated and bedding plane ore. The mineralized thickness varies from approximately 1 metre away from the knob to 15 metres close to the knob. This variation occurs over a distance of 30 metres laterally.

Pinchout deposits are also developed where the knob is high enough to cut out 30 metres or more of the Bonneterre dolomite. In this case

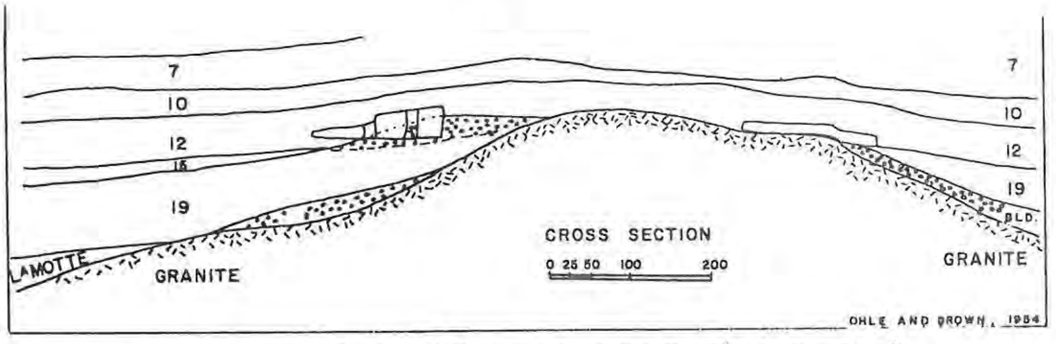


FIG. 35. *Section of Pinchout-Type Ore Body(Doe Run Mine).*

From Snyder and Gerdemann, 1968

a variety of lithologies, including reef, are present, and several levels of ore may occur, viz. sediment/porphyry contact, sandstone/dolomite contact, the 15/19 contact, in the 15 zone, the 12/15 contact, in the 12 zone, and in the 7 zone where algal reef grew against the knob. Exploration is further complicated by the fact that mineralization of economic grade only occurs on the northwest side of the Precambrian knob. Orebodies represent areas where ore solutions spread along bedding planes outward from the knob. Individual orebodies parallel the knob. This is a situation where a combined palaeogeogrphical- and sedimentological (bedding planes) factor determined the shape and size of the orebody.

Another pinchout ore deposit is developed in granite boulder beds on the flank of a granite knob at Hayden Creek, Southeast Missouri (Snyder and Gerdemann, 1968). The mineralization which occurs as replacements of the dolomite matrix and in fractures in boulders, is not evenly distributed as evidenced by the stope outline in figure 36.

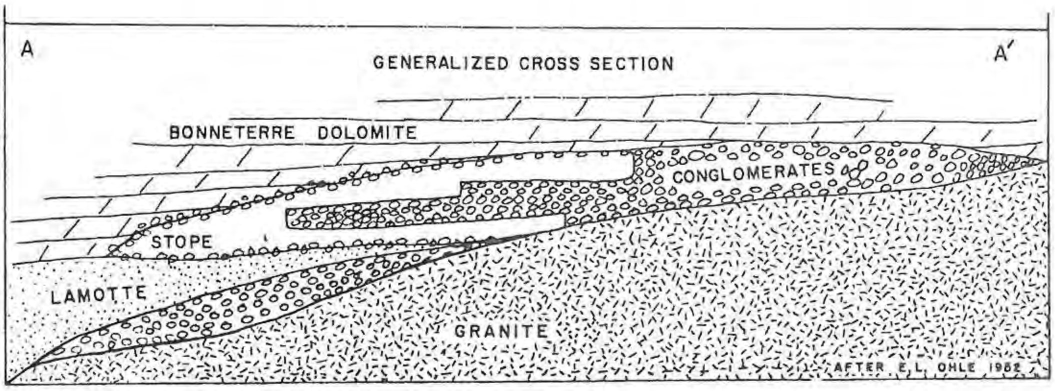


FIG. 36. *Section, Hayden Creek Ore Body.*

From Snyder and Gerdemann, 1968

A large portion of the ore that was mined in the western portion of the Missouri district was associated with ridge structures. The ridge is a bar of coarse-grained sediment that has an anticlinal form. Their lengths vary from 30-1000 metres, relief can be a few metres. Ore may occur on the flank of a ridge related to pinchouts of certain units (figure 37). In some areas, ridges mineralized at the 15/19 or 12/15 contacts contain the only mineralization (figure 37) while in other areas

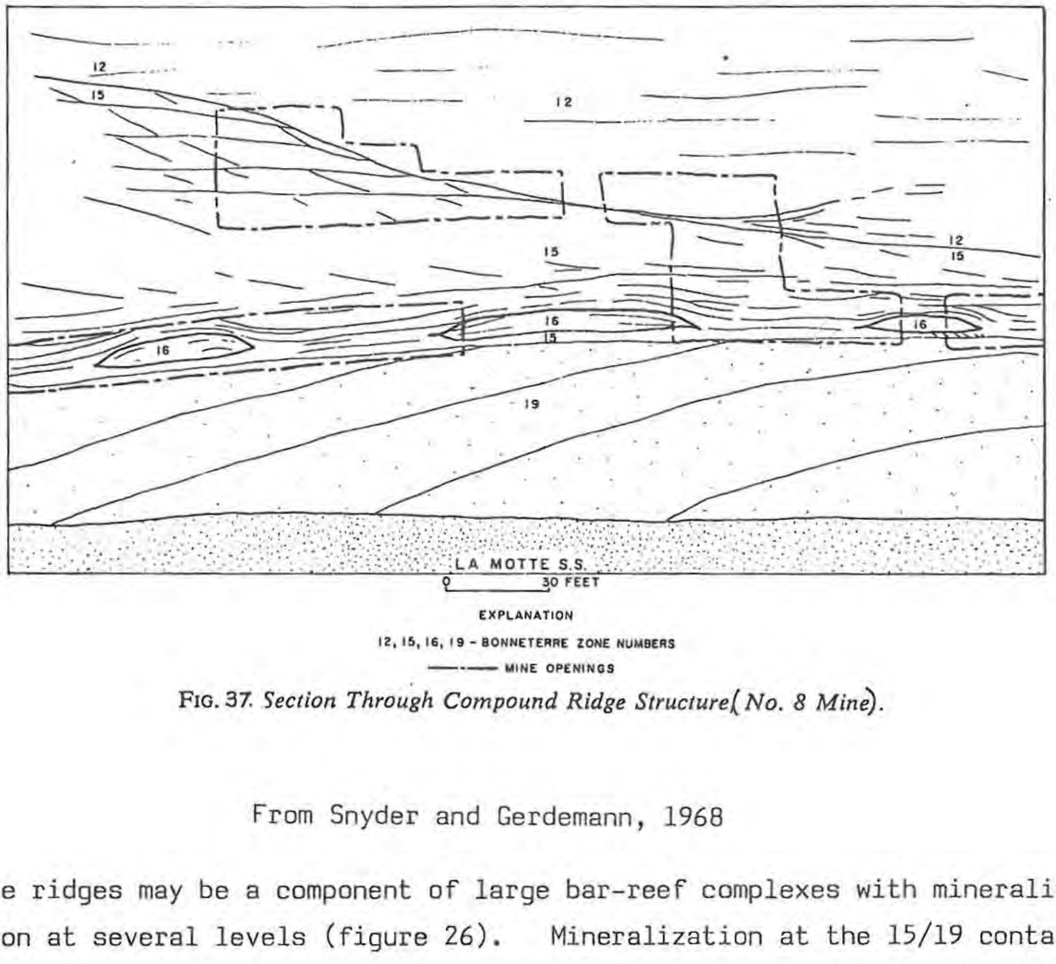


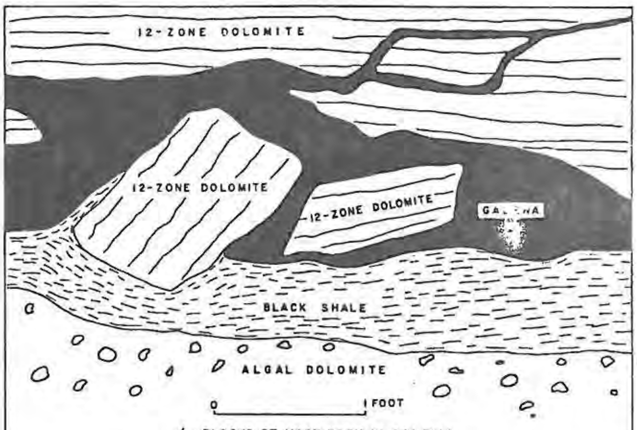
FIG. 37. *Section Through Compound Ridge Structure(No. 8 Mine).*

From Snyder and Gerdemann, 1968

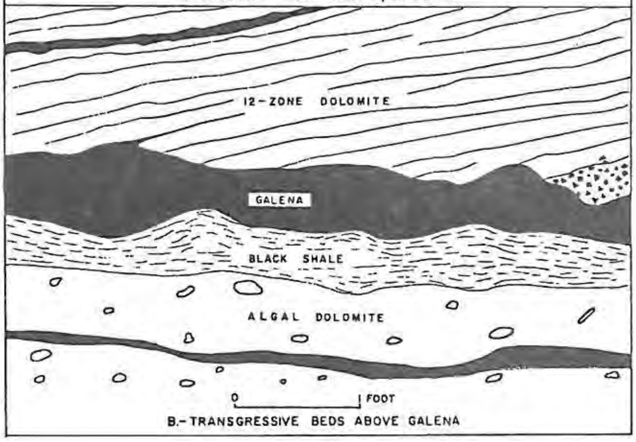
the ridges may be a component of large bar-reef complexes with mineralization at several levels (figure 26). Mineralization at the 15/19 contact is associated with black shale that locally grades into thin lenticular algal mats. The galena commonly is above and within the upper part of black shale. The 12/15 cross-cutting lithologic contact host the mineralization in the upper level structure. Figure 38 illustrates mineralization at lithological contacts on the flank of a ridge structure (Snyder and Gerdemann, 1968; Tarr, 1936).

(b) Algal reef

Positive topographic features such as calcarenite bars and, in a few places, igneous knobs provided the foundation for growth of algal reefs.



A.-BLOCKS OF HOST ROCK IN GALENA



B.-TRANSGRESSIVE BEDS ABOVE GALENA

FIG. 38 *Details of Mineralization.*

From Snyder and Gerdemann, 1968

The strike lengths and widths of reefs are determined by the dimensions of the topographic highs. A typical reef is shown in figure 27 (Snyder and Emery, 1956). The major ore-controlling structure within the reef is the contact between the colonial algal structures and clastic carbonates. The narrow, convex algal zone, usually trending at right angles to the direction of reef elongation, is termed a roll. The contact zone of organic and clastic sediments, containing abundant black shale, invariably is more strongly mineralized than either the organic rock or the clastic carbonate away from the contact. Where rolls are narrow and the better grade zones are closely spaced, the entire reef may be mined; where roll and inter-roll zones are wide, roll edges (figure 39) may be mined as individual orebodies transverse to the main reef trend. The ore minerals occur along bedding-plane and growth-line contacts, in fracture zones, and disseminated in the organic carbonates. This "haphazard" distribution of the mineralization complicates the calculation of an average grade for any such deposit. Vast amounts of reef rock are

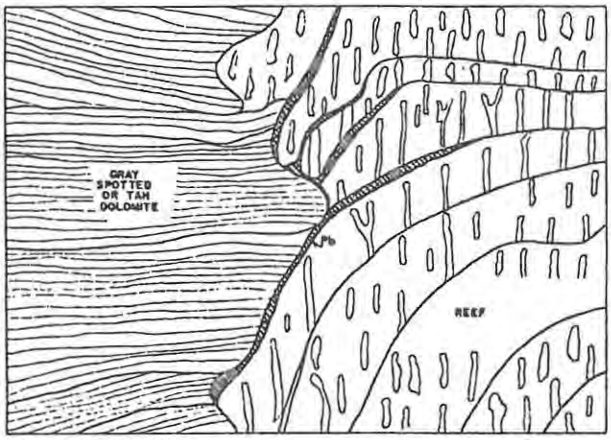


Fig.39.-Roll-edge ore deposit.

From Snyder and Emery, 1956

unmineralized, a factor that influences exploration drilling. Unmineralized drill holes that intersected reef rock are therefore no criteria to terminate a drilling program.

(c) Submarine slides

Breccia bodies are formed by submarine gravity sliding along the margins of sedimentary basins and flanks of calcarenite bars within basins (Snyder and Odell, 1958; Synder and Gerdemann, 1968). Gravity sliding occurred singularly or repeatedly (figure 40). In the latter case the stratigraphically higher slide frequently intersects and truncates a lower one. Continuous ore zones in compound slides have been mined that are up to 2000 metres long and 50 metres high. Individual breccia bodies can be very small (figure 40) but can attain lengths of a thousand metres, widths of 300 metres and thicknesses of up to 25 metres. The orebodies are usually long and narrow and run parallel to a calcarenite bar and are often continuous around the nose of the bar.

The position and trend of each breccia mass is controlled by bank and basin facies relationships at the stratigraphic level of the slide, consequently, successive breccia bodies may vary considerably in lateral position and trend.

Statistics, measured along drill-holes of the sections shown in figure 40, are listed in table 7. This study was done in an attempt to find a practical, workable correlation between breccia thickness

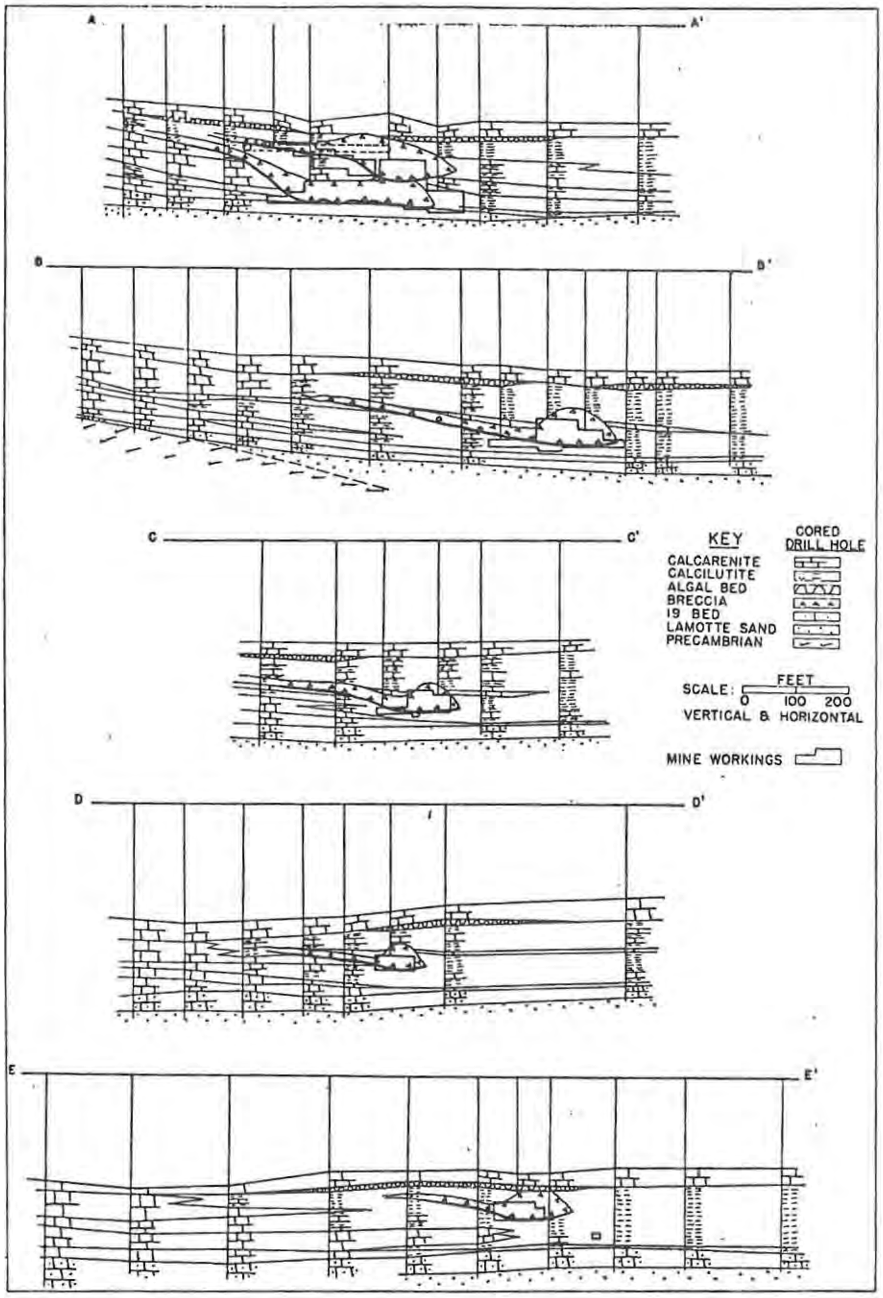


Figure 40. Breccia bodies formed by submarine gravity sliding
From Heyl et al., 1959

and compaction. The latter is directly related to the calculated factors in table 7. It is clear that the correlation is very vague. The section AA' (upper slide) does show a correlation between breccia thickness and thicknesses of bank- and basin sediments. A crude correlation between depth of gouging and thickness of breccia does exist. The breccia thicknesses are roughly double the depth of gouging. These results suggest that estimation of volume of breccia made on the

TABLE 7.—CALCULATED FACTORS OF SLIDE ZONE

Cross-section and breccia zone	Thickness of bank sediments, from top of bed 19 to sediment-water interface (in feet)	Thickness of basin sediments, from top of bed 19 to sediment-water interface* (in feet)	Vertical difference. bank to basin (in feet)	Calculated slope (in per cent)	Depth of gouging (in feet)	Thickness of breccia pile-up (in feet)
AA' (Lower slide)	118	38	80	16.0	38	72
AA' (Upper slide)	136	103	33	7.5	44	86
BB' (Lower slide)	92	58	34	6.8	32	68
CC' (Lower slide)	94	58	36	7.1	32	56
DD' (Lower slide)	88	64	24	7.5	30	52
EE' (Upper slide)	122	92	30	8.8	34	58
Average, All	108	69	39	8.9	35	65
Average, Lower slide	98	54	43	9.3	33	62
Average, Upper slides	129	97	31	8.1	39	72

From Heyl et al., 1959

basis of drill-hole data should be done with caution.

The slides are mineralized only where the breccia mass has intersected one of the major contacts. Mineralization is restricted to the contact and the piled up mass at the basin margin. The sloping updip part of the slide rarely is mineralized. Mineralization continues below the glide plane as contact ore (figure 41).

Mineralization in these breccias consists of galena, sphalerite and iron sulphides. Lead is more abundant than zinc regionally although locally the reverse may apply. Galena occurs as irregular veinlets around breccia blocks, as scattered blebs and small crystals in the breccia matrix, and as irregular massive replacements of the matrix. Distribution of the galena is erratic, although the better grade is concentrated in the zones of chaotic brecciation.

The great variation in orebody sizes, their irregular shapes and grade distribution necessitates close spaced drilling. Thirty-metre drill-hole spacings have been used with success in outlining ore. The irregular mineralization is directly related to the porosity.

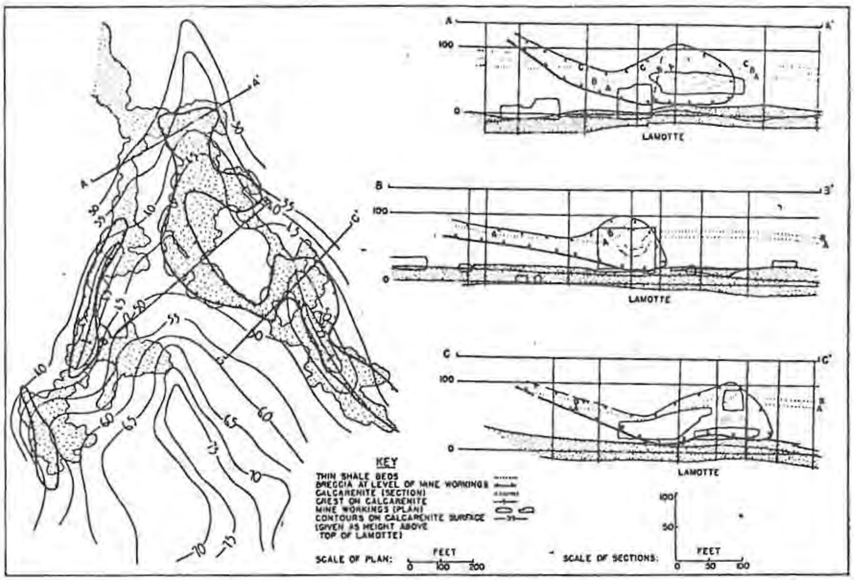


FIGURE 41 – BRECCIA ORE BODIES, SCHULTZ AREA

From Heyl et al., 1959

3.2.2 Structure

Structure plays a very important role in "ground preparation" i.e. creating secondary porosity. These structural elements include folding, faulting, fracturing and jointing. Structure (tectonism) can be constructive in the sense that protore is remobilized and recrystallized in economic concentrations e.g. the Alpine deposits (Schneider, 1964; Schneider and Maucher, 1967). Structure can also be destructive e.g. by dismembering an ore deposit through faulting. Many ore deposits are formed by the coincidense of tectonic, sedimentary and compositional (favourable lithologies) features.

The shape, size and attitude of the orebodies are determined by the geometry and attitude of the fold, fault, fracture, joint etc. as well as the attitude and composition of the host rock being transected.

The various features, structural and sedimentary, influencing the shape and size of the orebodies and that directly determine the distribution of the mineralization within them will be discussed below.

(a) Faulting, fracturing and jointing

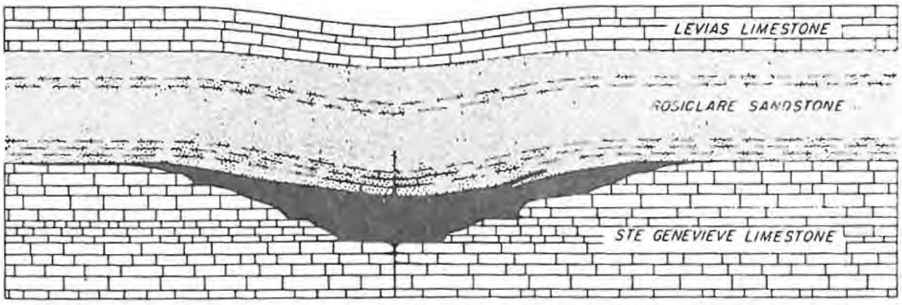
(i) Vein deposits

Faulting can give rise to vein deposits. The veins follow the inclination of the fault or fault zones. In some places the wall rocks of the fault have been only slightly brecciated, and the vein extends from one smooth, well defined wall to the other. In cases where there has been much brecciation along a fault zone, veins may occupy only a part of the zone or may split around large slabs of wall rock and send small branch veinlets out 15-30 metres into the walls. The dip and strike of the vein may change rapidly from place to place. The veins range in width from a fraction of a metre to 15 metres. Pinching and swelling along strike is common. The lengths of main ore veins vary from 60 to 1700 metres (Grogan and Bradbury, 1968). Ore shoots terminate laterally and in depth by lensing out but may be cut off by cross-faults. The mineralization, mainly sphalerite and galena, occurs chiefly as small masses, disseminated grains, and veinlets in the gangue. The distribution of the sulphides is erratic, resulting in a grade variation from zero to several percent over very short distances. Exploration and ore-delineation drilling will have to be very closely spaced because of the pinch and swell effect, the variable attitude of the veins and the erratic mineralization.

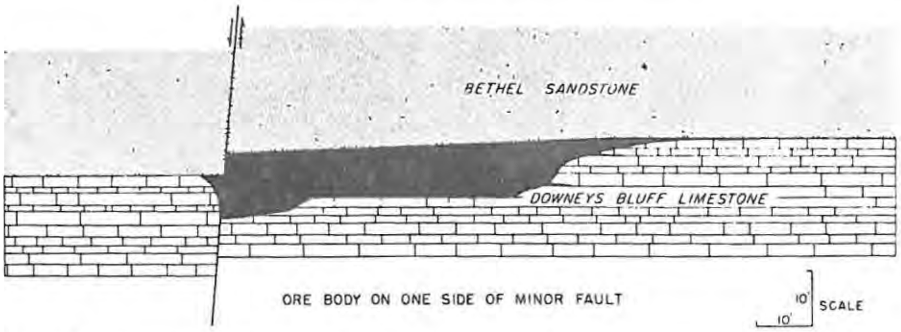
(ii) Bedding replacement deposits develop due to coincidence of faulting and sedimentary features (bedding). The Cave in Rock district in southern Illinois provides a typical example of this type (Grogan and Bradbury, 1967 and 1968) (figure 42). The bedded ore occurs in a limited section of sedimentary carbonate rocks of Mississippian age, closely associated with faults which have very minor displacements but are always clearly related to major faults that evidently served as master conduits.

The bedding-replacement deposits are typically linear in plan (parallel to the fault) and crescentic or wedge-shaped in cross section (figure 42). The wedge shape is controlled by the replacement of limestone along bedding and by the sandstone/limestone contact. The sizes of the ore deposits are controlled by the volume of the ore solutions. Their sizes vary from 70-1000 metres in length, 15-150 metres in width and 2-6 metres in thickness. The ore is thickest along the main fracture and it thins towards the margins.

The main ore minerals are fluorite, sphalerite and galena. Sphaletite and galena are abundant in some deposits but lacking in others. The more common secondary minerals are smithsonite, cerrusite and malachite. The sphalerite is fine grained and iron rich. Galena is



ORE BODY SYMMETRICAL ABOUT CENTRAL FISSURE



ORE BODY ON ONE SIDE OF MINOR FAULT

Fig. 42. Cross section illustrating the occurrence of some limestone-type lead-zinc ores in which particular tectonic and sedimentary features coincide; examples are from the Cave in Rock district, southern Illinois. (*From Grogan and Bradbury, Econ. Geol. Monograph no. 3, 1967.*)

present as coarse-grained crystals. Silicification of the sandstone and limestone is common. The ore is banded, poorly banded and disseminated. The "regularity" of the orebodies and its contained mineralization simplifies drilling and ore reserve estimation.

(iii) Deposits associated with faulting and ridge structures

These deposits were formed where a ridge structure (bar) was intersected by a segment of a fault at a point where displacement on the fault was transformed to the adjacent en enchelon segment (Snyder and Gerdemann, 1968). The area between the segments and for some distance beyond the fault is intensely broken by tear fractures. Within this broken area the height of mining is approximately 15 metres and the width approximately 100 metres, which is about three times as large as mining dimensions outside this zone. The orebody within this structural complex had a cross sectional area of 1300 square metres as opposed to the 160 square metre area in the normal unfaulted sedimentary ridge structure. The grade within the faulted ridge is eight to ten times minimum mine grade.

(iv) Deposits associated with Bar-reef complex and faulting

Horsetailing of a major fault into a braided pattern (Snyder and Gerdemann, 1968) produced a strongly fractured mineralized zone that extends across three parallel bar-reef complexes that normally are separated by 200 to 300 metres of unmineralized sediments (figure 43).

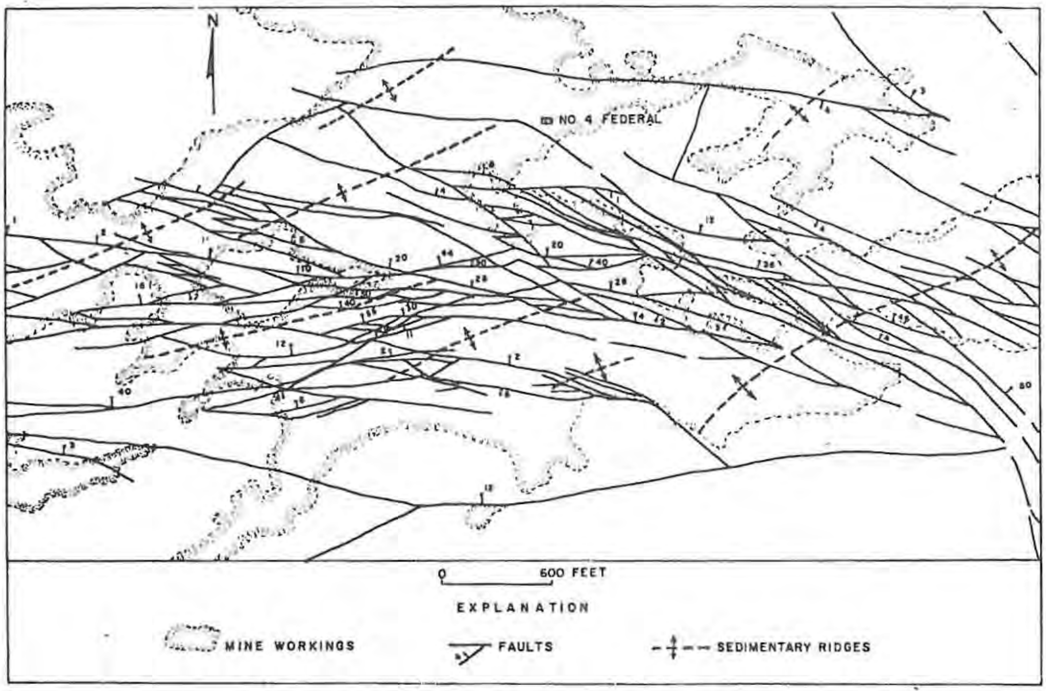


FIG. 43. *Braided Fault Pattern and Mined Areas.*

From Snyder and Gerdemann, 1968

Outside of the fault zone, each of these sedimentary complexes has its normal types of mineralized sedimentary structures. The mineralization extends as a broad rich belt that is a combination of sedimentary and fault trends.

(v) Deposits associated with bedding-plane movement

In the southeast Missouri Lead District three situations exist in which normal bedded carbonates pass into massive structureless rocks (Snyder and Gerdemann, 1968). These are the reef-bedded rock contact, the slide breccia-bedded rock contact, and the boulder-bedded rock contact. In each case, the massive unit contains high-angle fractures dipping towards the bedded rock contact. Snyder and Gerdemann (1968) postulated that slipping along innumerable bedding planes, during genesis, was translated into high-angle fracturing wherever the bedding plane movement was interrupted. In the reef, slide breccia and the boulder bed, the fractures cut across primary features, providing easy access for mineralizing solutions. The result is a greater than usual height of mineralization and a higher grade ore.

The negative effect of this superimposition of fracture mineralization on primary feature mineralization is that grade distribution is even more inhomogenized. Grade calculations during ore reserve estimation would have to be based on very close spaced drilling and large volume sampling in order to obtain a representative grade.

(vi) Marginal break deposits

Marginal break ore zones occur on both sides of a solution collapse breccia (figure 44) (Mouat and Clendenin, 1977). The marginal breaks are fractures developed in response to the solution collapse of the enclosing carbonate units. The collapse was in response to gravity sliding and solution above the Q2/Q3 (figure 44) contact. Extreme porosity was induced in these lower beds by brecciation and the breccia was subsequently mineralized.

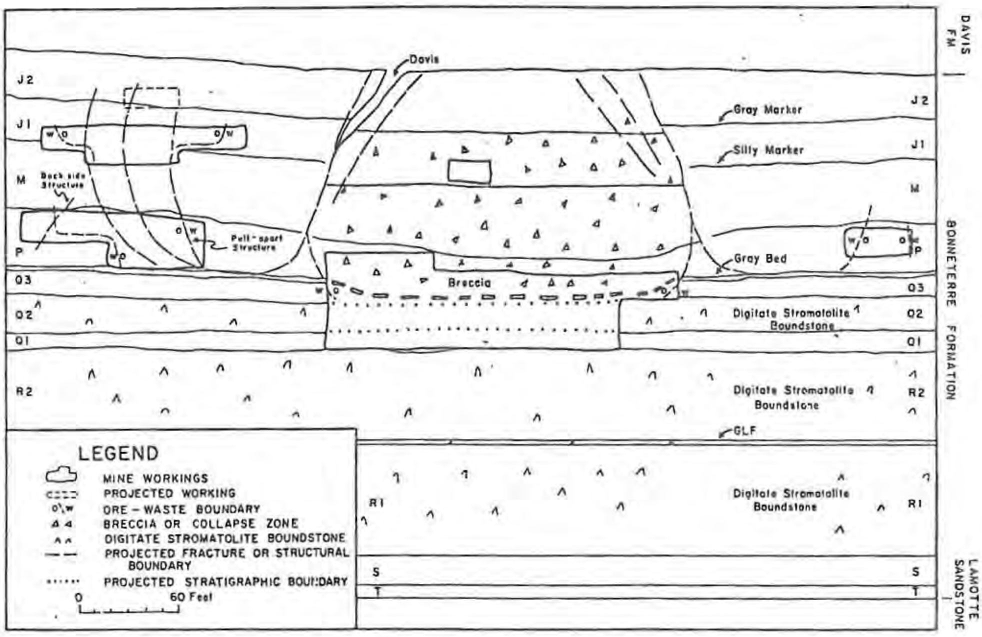


FIG. 44. Schematic cross section of Bonneterre showing some of the mining zones and general relationships of the breccia and marginal breaks.

From Mouat and Clendenin, 1977

The marginal break zones run parallel to the breccia trend and range between 10 and 50 metres wide and are generally separated from the breccia by a barren or weakly mineralized zone. The breaks have a large vertical extent relative to their width. Both solutional and structural features are developed within the marginal breaks. These features commonly intimately modify one another and result in the subtly complex geometry of the zone (Mouat and Clendenin, 1977). The side of the marginal break ore zones closest to the breccia is controlled by pull-apart structures (figure 44), namely faults or joint-like fractures. These structures occasionally have "en echelon" fractures associated with them. Incipient solution collapse is common within the marginal break immediately adjoining the pull-apart structure. A slight downdip roll in the dip of the sediments due to solution collapse produced a reverse fault known as backside structure which is located on the opposite side of the marginal break from the pull-apart structure (figure 44).

Both pull-apart and backside structures acted as feeder channels for the mineralizing solutions. Mineralization spread laterally along bedding planes between the structures. Impermeable units within the bedding caused ponding of the mineralized solutions and widened the mineralized zone significantly.

Mineralization in narrow cross-cutting veinlets and fractures is common below the breccia. This type of mineralization is economically important where the fractures are spaced sufficiently closely to form a stockwork.

The dominant ore minerals are coarse grained galena and finely crystalline sphalerite occurring in a 6:1 ratio. Chalcopyrite is a relatively minor constituent but can occur as discrete bodies.

The limited size of these deposits again necessitates very detailed drilling. The marginal break deposits are not common to all solution-collapse breccias. Drilling is therefore required to at least 70 metres on either side of any solution collapse breccia occurrence at closely spaced intervals (30 metres).

(vii) Deposits associated with tear faulting, fissures and bedding planes

Structural control (of this type) on ore deposition is for example well displayed in the Raibl, Mezica and Bleiberg-Kreuth (Alpine) deposits (Jicha, 1951). The ore occurs in fissures and tear faults, and along bedding planes in areas where there has been bedding-plane movement. The intersections of fractures or faults and planes of movement between beds are particularly favourable for ore deposition. Ore deposits are confined to a chiefly limestone and dolomite horizon, the Wettersteinkalk (figure 31). The structural weaknesess were exploited by solutions, initially causing calcitization and dolomitization and thereby enhancing porosity. Sphalerite, wurtzite, and galena were later deposited in these conditioned areas. The paragenesis of the minerals, the number of solution pulses and the extent of ground preparation by faulting and alteration will determine the shape, size and grade of the deposit. Large areas of "prepared" ground are very often not mineralized, a phenomenon that can be explained, but not predicted, by various factors such as insufficient volume of ore solutions, low metal concentration of solutions, lack of suitable precipitation conditions etc.

Ore deposition related to the interaction of structure and favourable lithology is also well displayed in the Shullsburg area of Wisconsin-Illinois (Reynolds, 1958).

(viii) Deposits associated with faulting, folding and host rock competency.

The interrelationship of faulting and minor folding produced the loci for ore deposition in much of the Austinville-Ivanhoe district, Virginia (Brown and Weinberg, 1968). The complex fault system is best developed in a more competent rock unit. The orebodies are confined to faults and monoclinal terraces. There are locally great enlargements of the ore bodies at the intersections of the strike faults and monoclinal terraces with the cross faults. At these enlargements in some places the orebodies are cross cutting through a vertical section of almost 200 metres. The strikes of the ore, host rocks and many of the faults are parallel. The dip of the faults, and thus also that of the orebodies, varies from very steep in the competent unit to flatter in the less competent unit. This influences drilling and mining methods.

(ix) Gash-vein, joint-controlled orebodies

The gash-vein deposits are very well developed in the Galena

Dolomite of the Upper Mississippi Valley lead-zinc district (Heyl, 1968 and Heyl et al., 1959) (figues 45 & 46). The deposits are within and along long straight vertical joints. The principal minerals in these deposits are galena, pyrite, marcasite, calcite and sphalerite. The vein minerals line the walls of joints forming discontinuous gash-veins. Brecciated and partly dissolved porous zones (openings) in favourable beds along the joints are also filled by vein minerals. Orebodies are spaced irregularly and discontinuously along the lengths of the joints. Pinching and swelling of the gash-vein occurs within the dissolved porous zones ("openings"). Several openings, or lines of openings, may be successively below each other along the same joints in favourable beds (figure 45). The openings may be connected vertically and laterally by thin gash-veins along the joint, but only some of the veins between openings contain mineable ore. The ore openings are extremely variable in size, they vary from 1-6 metres in width, 1-6 metres in length and from a few to more than 150 metres in lenth. The gash-vein deposits occur in single isolated joints or groups of joints. Joints can also intersect one another. Orebodies formed at these intersections, referred to as chimneys, are much bigger than the normal vein type.

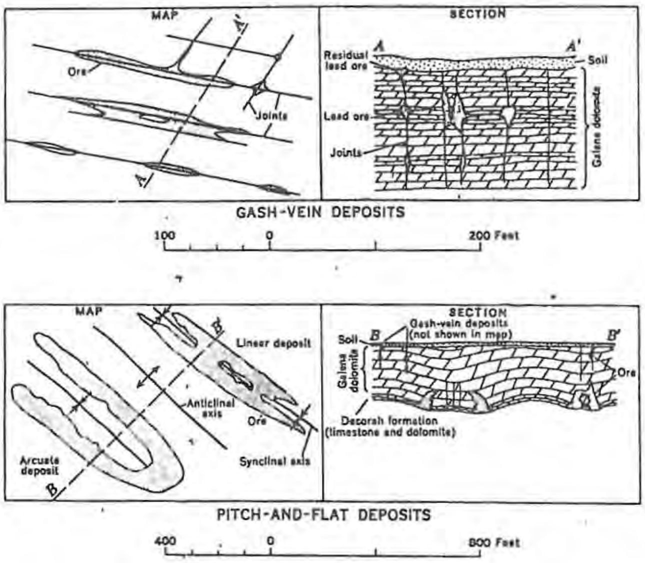
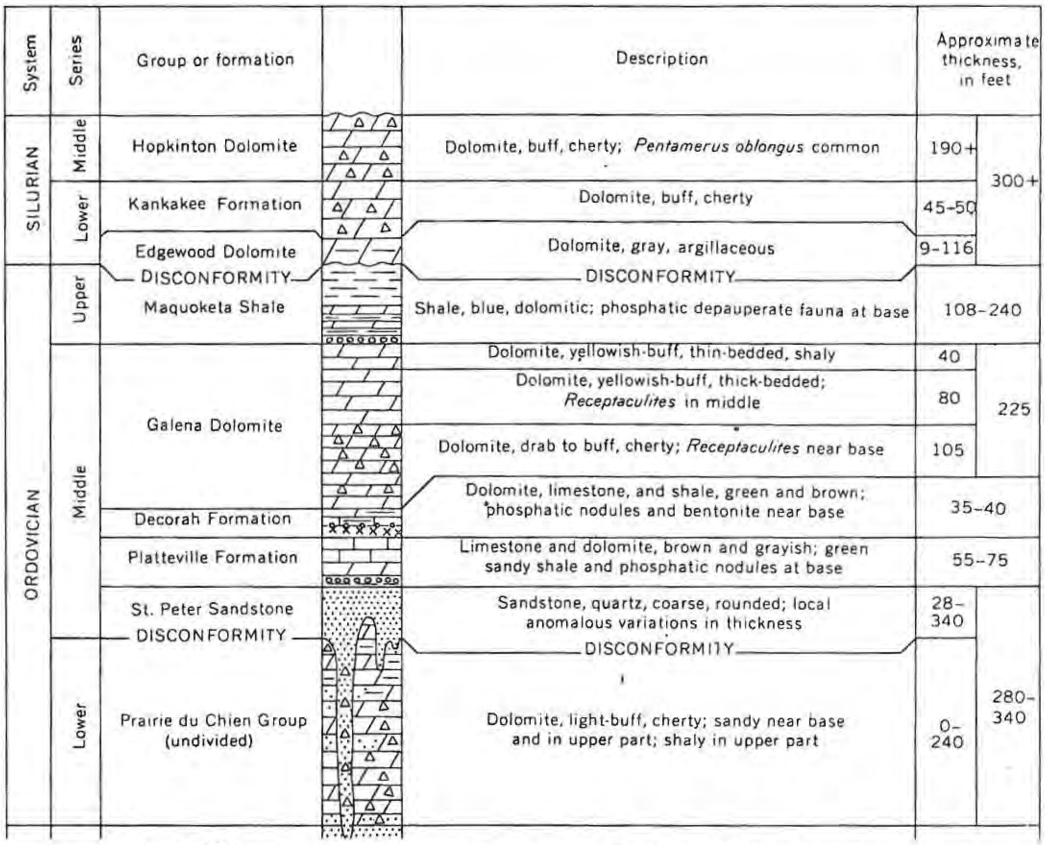


FIG. 45 *Diagrammatic Plans and Sections, showing typical patterns of gash-vein lead deposits and underlying pitch-and-flat deposits of the arcuate and linear types and their stratigraphic positions relative to one another.*

From Heyl, 1968

The main factors controlling the shape and size of these deposits are favourable (to solution) horizon(s), the attitude, interrrelationship



System	Series	Group or formation		Description	Approximate thickness, in feet	
SILURIAN	Middle	Hopkinton Dolomite		Dolomite, buff, cherty; *Pentamerus oblongus* common	190+	300+
	Lower	Kankakee Formation		Dolomite, buff, cherty	45-50	
		Edgewood Dolomite		Dolomite, gray, argillaceous	9-116	
		DISCONFORMITY		DISCONFORMITY		
ORDOVICIAN	Upper	Maquoketa Shale		Shale, blue, dolomitic; phosphatic depauperate fauna at base	108-240	
	Middle	Galena Dolomite		Dolomite, yellowish-buff, thin-bedded, shaly	40	225
				Dolomite, yellowish-buff, thick-bedded; *Receptaculites* in middle	80	
				Dolomite, drab to buff, cherty; *Receptaculites* near base	105	
		Decorah Formation		Dolomite, limestone, and shale, green and brown; phosphatic nodules and bentonite near base	35-40	
		Platteville Formation		Limestone and dolomite, brown and grayish; green sandy shale and phosphatic nodules at base	55-75	
		St. Peter Sandstone		Sandstone, quartz, coarse, rounded; local anomalous variations in thickness	28-340	280-340
		DISCONFORMITY		DISCONFORMITY		
	Lower	Prairie du Chien Group (undivided)		Dolomite, light-buff, cherty; sandy near base and in upper part; shaly in upper part	0-240	

FIG. 46 *Stratigraphic Section of the Upper Mississippi Valley District.*

From Heyl, 1968

and degree of opening of the joints.

The irregularity, both vertically and laterally, in the dimensions of these deposits as well as the pinching and swelling within individual deposits will necessitate a detailed structural map in order to plan exploration drilling, which will have to be very close spaced.

(b) Folding and faulting

Pre-ore folding results in the creation and/or accentuation of loci for ore mineral precipitation. The exact nature of these potensial depositional traps is determined by the intensity of folding, composition of the rock and sedimentary features (bedding thickness etc.).

Post-ore folding determines the location and distribution of the mineralization. The style of folding determines the geometry of the resultant orebodies which in turn influences exploration drilling and ore reserve estimation.

(i) Deposits genetically related to folding, and to reverse- and bedding plane faulting; the so called Pitch and Flat deposits

The primary factors controlling the shape and size of this type of deposit are faulting, folding and solution of favourable lithologies. Pitch-and-flat deposits are veins and replacements in and near reverse and bedding-plane fault zones (pitches and flats respectively) of small displacements controlled by gentle folds and accompanied by some sagging from solution thinning (Heyl, 1968). There are basically three types of ore-body forms viz. arcuate, linear and elliptical (in plan) the forms of which are controlled by their disposition relative to fold closures. The ore-bodies occur more commonly in synclinal closures. Broad blankets of breccia and bedded replacement and bedded vein ores, in part controlled by bedding-plane faults, and by the basal parts of the reserve fault system, are developed below the pitch-and-flat deposits.

The intensity (amplitude) of folding in conjunction with the associated fault determines the shape, size and attitude of the ore-bodies. Three ore-body "types" resulted due to different stages of structural development (Heyl et al., 1959).

The first stage of structural development is characterized by low amplitude (1,5-8 metres) folds where bedding-plane faults are the principle ore loci. Reverse faults are rare and only weakly developed. Solution structures are rare. These ore-bodies have only one main fracture system consisting of a widespread zone of horizontal bedding-plane faults. These faults and associated ore-bodies are very strongly stratigraphically controlled in or near a soft, plastic carbonaceous shale layer (Heyl et al., 1959, p.109). Within the ore-body the main fault planes contain open space filled, horizontal veins of lead-zinc ore that grade into replacement veins towards the edges of the ore-body.

The ore-bodies associated with the second stage of structural development are controlled by a steplike system of almost equally developed bedding-plane and reverse faults (figure 47). The local controlling folds have 6-12 metre amplitudes (Trego mine, Wisconsin; Heyl et al., 1959). Minor drag folding modifies the main structural pattern in places. Solution generally is important in many ore-deposits, owing to numerous access fractures; it tends to accentuate the structure by producing slight slumping owing to thinning and shalification on the calcareous beds.

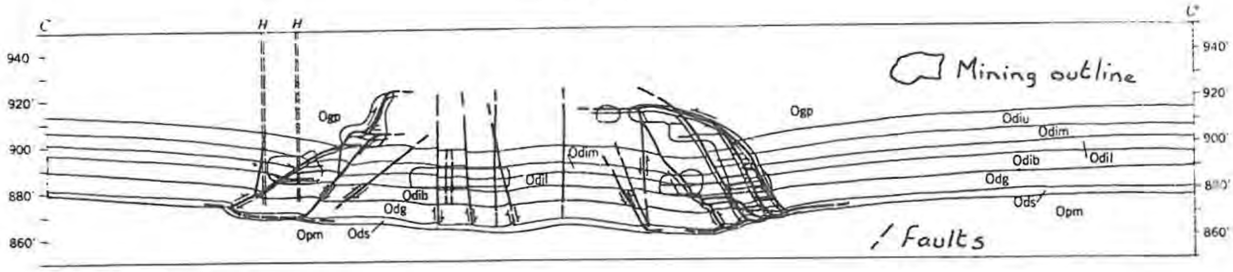


Figure 47. Ore-bodies controlled by a steplike system of almost equally developed bedding-plane and reverse faults

From Heyl, 1959

The ore-bodies associated with the third stage of structural development are commonly controlled by well-defined, smooth-wall reverse faults, which are more prominent than the bedding-plane faults. Steplike fracture patterns are still developed. The local controlling folds have 10-20 metre amplitudes. Solution structures are much more common.

The structures in some of the Upper Mississippi Valley districts (Heyl et al., 1959) are very complex (figure 48). The more complex these structures are the more likely the probability of forming a large ore-body. The structural disturbances created passage ways for ore solution movement and loci for precipitation.

The individual ore-bodies are fairly straight on the flanks of folds but curve at the ends to form crescentic or arcuate "runs" connecting the straight runs on the flanks. The ore-bodies are 12-30 metres wide.

Shear faulting postdating the folding and associated reverse-and bedding-plane faults but still predating ore deposition, had the effect of significantly enlarging the subsequent ore-body by preparing more ground for metal precipitation (figure 49) (Heyl et al., 1959).

Linear ore-bodies are less abundant than arcuate ore-bodies and nearly always flank synclines. These ore-bodies and controlling structures lie transverse to the arcuate ore-bodies. The controlling structures are probably (Heyl et al., 1959) vertical shear joints that the axis of the fold follows. The ore is localized by zones of many bedding-plane faults, reverse faults, fractures and a few normal faults. Solution was an important factor in the development of the structure in these ore-bodies. Solution thinning has accentuated the structures by sagging and slumping.

Cross folding gave rise to several eliptical ore-bodies being formed. These ore-bodies are similar to the arcuate ore-bodies.

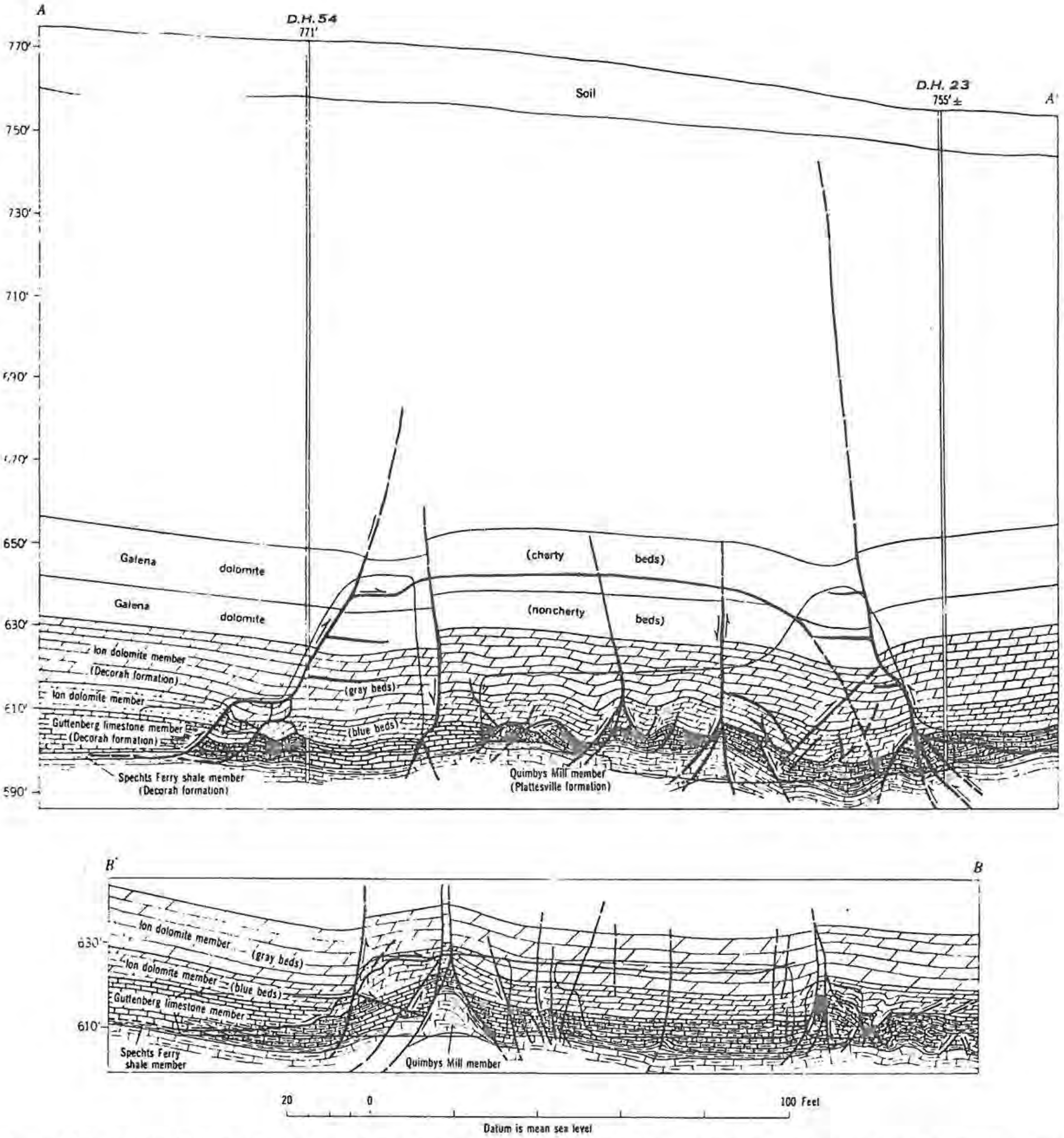


FIGURE 48.—Section C–C' across the central part and section E–E' across the south part of the Graham-Ginte mine. Note the structural complexity and local thinning in the incompetent beds of the lower Decorah (so-called oil rock and clay bed).

From Heyl, 1959

Sphalerite is the main ore mineral, but pyrite and marcasite are abundant and galena is less abundant than sphalerite. The ores form banded veins within faults and fractures and also replace rocks adjacent to the fractures. Most of the ores show crustification in open cavities. The ore-hosting rocks are typically silicified and dolomitized.

Exploration drilling can only be based on a very accurate and detailed structural map. The limited width and the erratic nature of

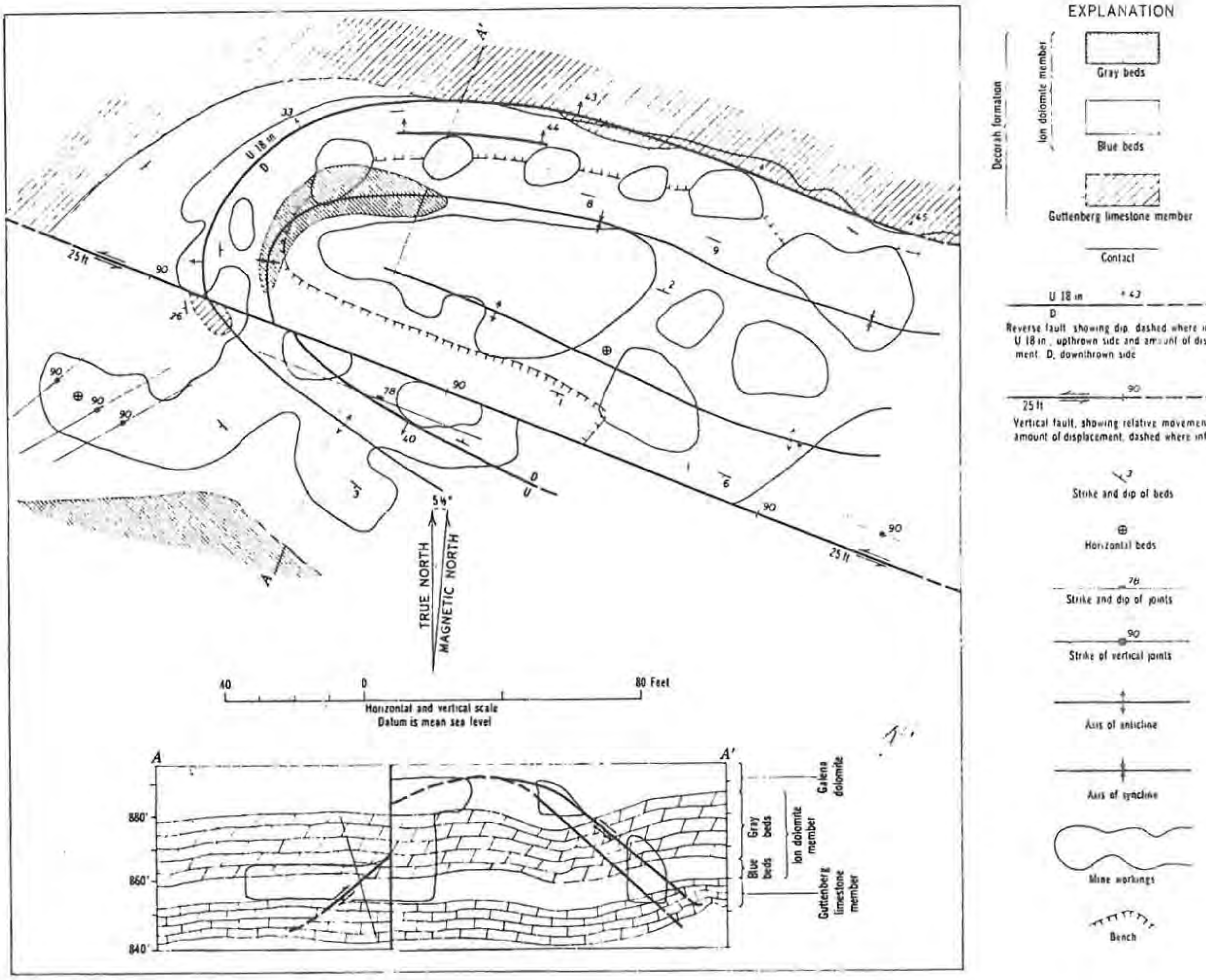


FIGURE 49—Geologic mine map and section showing the shear fault in the west end of the Liberty mine. Note the displaced reve faults that control the ore body.

From Heyl, 1959

the mineralization necessitates close-spaced drilling. Exploration diamond drilling in the Upper Mississippi Valley has been very succesful at 15 metres grid spacing perpendicular to the strike of the ore-bodies.

(ii) Deposits genetically related to folding and tension fractures

Deposits generated by this mechanism are by no means unique. Numerous examples of this type are found associated with the pitch-and-flat deposit types. A typical example of this type, the manto ore-body, is found associated with the Tsumeb polymetallic pipe karst deposit (section 2.2.5). The Tsumeb ore-body is in the form of a steeply plunging pipe which crosscuts several carbonate lithologies of the Tsumeb Sub-Group. The plunge of the pipe, which is approximately perpendicular to bedding in the lower levels and subparallel to bedding in the upper levels, was controlled by the reaction of competent dolomites and incompetent limestones to folding. Bedding slip was more pronounced in limestone lithologies of the upper levels with the result that the body was dragged out along the bedding slips (figure 50). In plan the pipe is

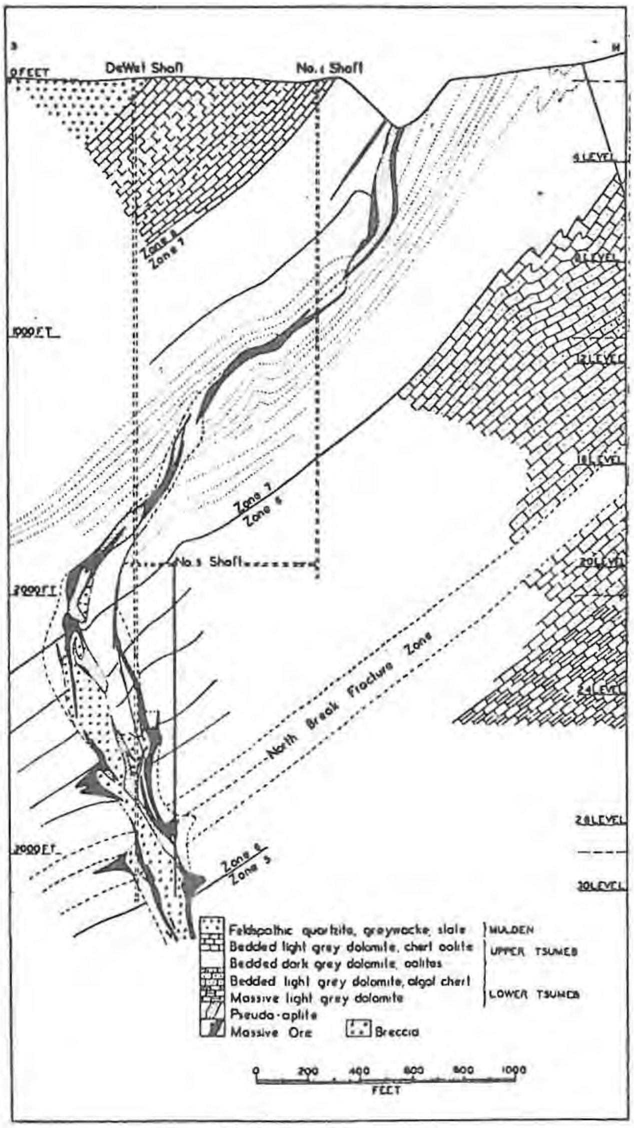


Fig 50—Section through Tsumeb orebody.

From Söhnge, 1961

elliptical in the underformed areas but tabular and lensoid where bedding slip is prevalent. This phenomenan is also reflected in the sulphide ore-bodies. Mineralization is largely restricted to the pipe and is generally concentrated in brecciated zones, marginal arcuate fractures, and areas of intense foliation. Sulphide ore (manto orebodies) extend for up to tens of metres from the pipe margin into the surrounding dolomite between 26 and 30 level. They can have strikes of up to 180 meters (Ainslee, 1980). These mantos, which are exceptionally high grade, have formed by remobilization of sulphides, bornite, chalcocite and galena into tensional fractures during folding. Massive sulphides in the pipe display minor folding and textures indicative of deformation and partial annealing (Hughes, 1979).

(iii) Deposits genetically related to intense folding

Carbonate rocks with contained sulphide mineralization exposed to intense deformation and high-grade metamorphism produce some spectacular fold structures due to the ductility contrast between the carbonate host rock and the sulphide ore horizon. This phenomenon is well displayed by the pyrrhotite-galena-sphalerite ore-deposits at the Namib Lead Mine, Namibia which is hosted by marbles of the Central Swakop Shelf (figure 18). The ore zone has been thickened and extremely boudinaged into steeply plunging cyclindrical pods which developed in the limbs of a large tight fold. The plunge of the ore pods is parallel to the mineral lineation and fold hinges. The ore horizon between the pods has been pinched out. Metamorphism and deformation have caused recrystallization of the ore with a resultant coarse texture that makes the ore very amenable to beneficiation. The limited and variable dimensions of the ore-bodies on surface and underground necessitates exploration diamond drilling based on very detailed geological-, geophysical- and structural maps. Correlation between detailed surface mapping and drilling results is necessary to arrive at a valid tonnage estimate. The tonnage figure may even then be inaccurate due to the down-plunge pinch-and-swell nature of the ore pods.

Appalachian zinc-lead deposits (figure 51) are examples of pre- and synorogenesis (Sangster, 1976). These deposits have been affected by one ore more orogenic events which gave rise to intense asymetrical folding and thrust faulting.

The ore-bodies of the Austinville-Ivanhoe (figure 51) ore zones (Sangster, 1976; Brown and Weinberg, 1968) are fold controlled and pencil shaped with lens-like cross sections. The long dimensions of the ore zones are parallel to the regional Appalachian orogenic trend (N60°E) and have lengths of 2 000 metres or more, widths as great as 120 metres and thickness locally exceeding 30 metres. The mineralization is considered by Brown and Weinberg to have been emplaced during, or subsequent to, the Appalachian orogeny.

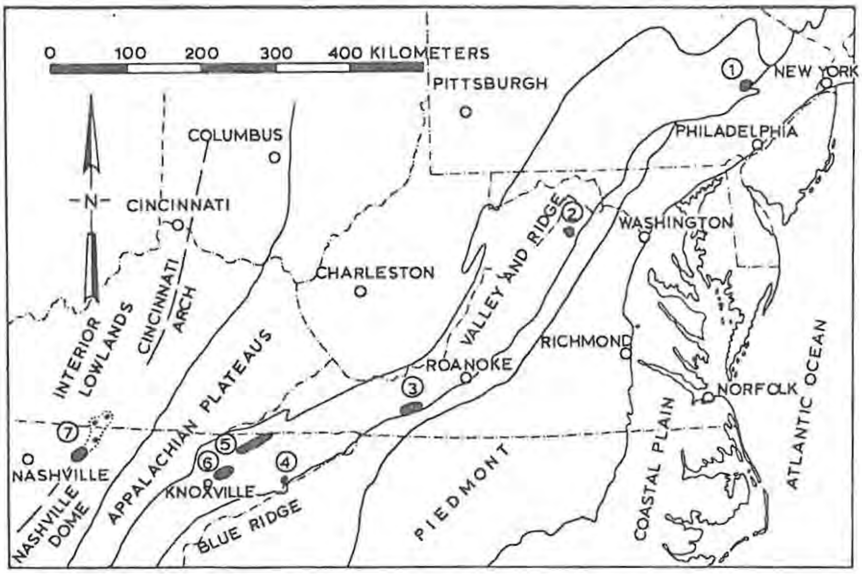
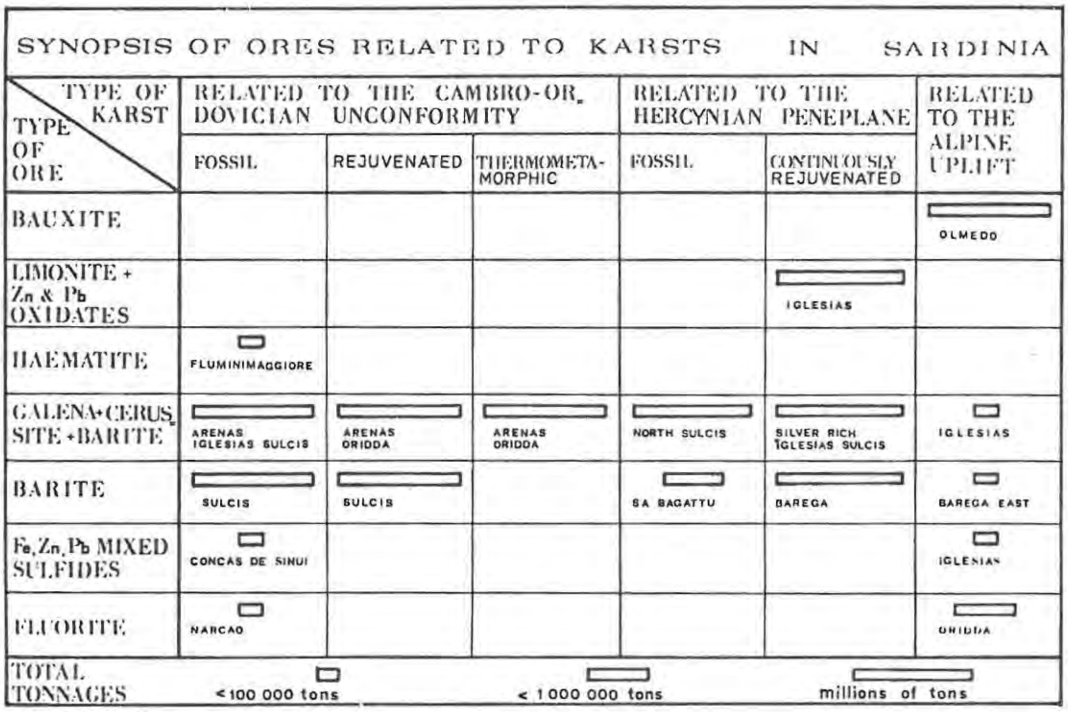


Fig.51.Major Appalachian-type deposits in eastern United States.
1 = Friedensville, Pa.: zinc in Lower Ordovician Beekmantown Formation; *2* = Timberville, Va.: zinc in Lower Ordovician Beekmantown Formation; *3* = Austinville–Ivanhoe, Va.: zinc–lead in Lower Cambrian Shady Formation; *4* = Embreeville, Tenn.: zinc–lead in Lower Cambrian Shady Formation; *5, 6* = east Tennessee districts, Copper Ridge and Mascot–Jefferson City, respectively; *7* = central Tennessee. In these east and central Tennessee districts the zinc ore is in Lower Ordovician Mascot and Kingsport Formations.

From Sangster, 1976

The zinc deposits of the Friedensville Mine (Pennsylvania) are the most strongly deformed of the major Appalachian deposits (Sangster, 1976; Callahan, 1968). The main mineralization is localized in solution collapse breccias which were formed prior to deformation.

The zinc ores in the Northern Arkansas lead and zinc district are localized by tectonic breccias formed by warping or folding and by thrust faulting (Bateman, 1950) (figure 51a). These breccia deposits occur in the Tri-State zinc district and at Mascot, Tennessee (Bateman, 1950). The deformation is observed as fracture cleavage in the beds and flow cleavage in the mineralized interstices of the breccia fragements. The sulphide minerals reacted differently to stresses and strains. The pyrite is usually fractured and crushed; the sphalerite has also been crushed but is generally medium to coarse grained. Callahan (1968) is of the opinion that the deformation merely deformed horizontally disposed ore-bodies and determined their subsequent pattern and attitude of occurence.



SYNOPSIS OF ORES RELATED TO KARSTS IN SARDINIA

TYPE OF KARST / TYPE OF ORE	RELATED TO THE CAMBRO-ORDOVICIAN UNCONFORMITY			RELATED TO THE HERCYNIAN PENEPLANE		RELATED TO THE ALPINE UPLIFT
	FOSSIL	REJUVENATED	THERMOMETAMORPHIC	FOSSIL	CONTINUOUSLY REJUVENATED	
BAUXITE						▬ OLMEDO
LIMONITE + Zn & Pb OXIDATES					▬ IGLESIAS	
HAEMATITE	□ FLUMINIMAGGIORE					
GALENA+CERUSSITE +BARITE	▬ ARENAS IGLESIAS SULCIS	▬ ARENAS ORIDDA	▬ ARENAS ORIDDA	▬ NORTH SULCIS	▬ SILVER RICH IGLESIAS SULCIS	□ IGLESIAS
BARITE	▬ SULCIS	▬ SULCIS		▭ SA BAGATTU	▬ BAREGA	□ BAREGA EAST
Fe,Zn,Pb MIXED SULFIDES	□ CONCAS DE SINUI					□ IGLESIAS
FLUORITE	□ NARCAO					▭ ORIDDA
TOTAL TONNAGES	□ <100 000 tons		▭ < 1 000 000 tons		▬ millions of tons	

Fig. 52.

From Padalino et al., 1973

(a) Large limonite-smithsonite-hemimorphite-cerussite deposits have accumulated as iron caps on top of carbonate hosted stratabound and vein-type lead-zinc-pyrite bodies in the Iglesias area (Padalino et al., 1973).

(b) Barite-galena-cerussite deposits are of two groups. The one group is associated with fossil palaeokarst and the other with rejuvenated palaeokarst (figure 53), stemming from the reworking of the fossil deposit. The fossil palaeokarst deposits are very frequently uneconomic (less than 1,5% lead) whereas rejuvenated deposits derived from them are generally of commercial interest. All these deposits are now almost vertically tilted by intense folding.

(c) Two karstic deposits of pyrite-marcasite-sphalerite-galena are known in the bottom part of karst cavities related to the Cambro-Ordovician unconformity and, some recent crevices in the deepest level of the Iglesias area are partially filled with horizontally stratified earthy deposits of these minerals mixed with fresh black clays and/or reddish cherts. The zinc grade goes up to 12% (Padalino et al., 1973).

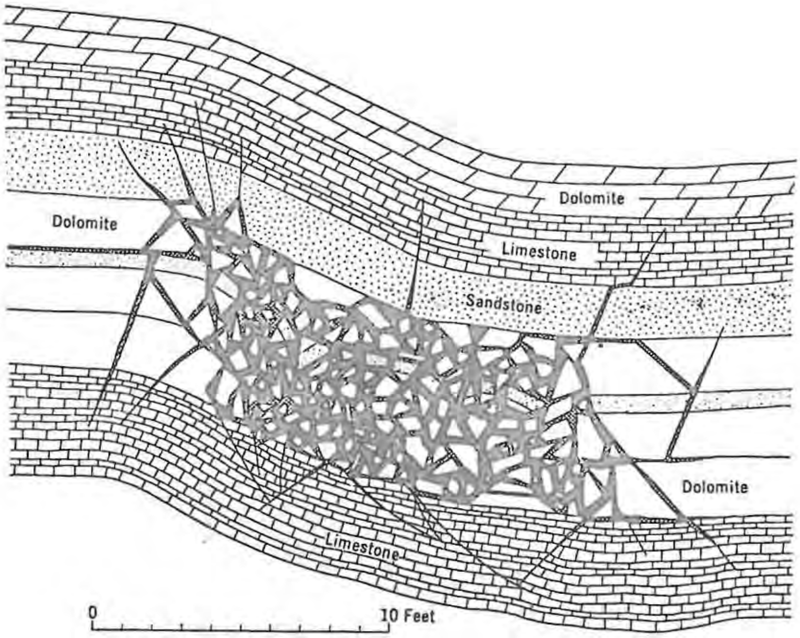


FIG. 51(a). Tectonic breccia formed by shattering of dolomite along axis of bend, forming an "ore run" in northern Arkansas lead and zinc district. (*After McKnight, U. S. Geol. Survey.*)

From Bateman, 1950

3.2.3 Erosion

This section incorporates all the deposits that are genetically associated with an erosion surface. The erosion could have been subareal or subaqueous. The main type of deposit within this category is associated with karst structures (see section 2.5.1). The karst feature could have originated by surface erosion only with the ore being deposited in a typical pinnacle topography e.g. Sardinia (Padalino et al., 1973). The metals are derived by weathering of the host rock and/or by reworking of an existing sulphide deposit e.g. Sardinia (Padalino et al., 1973) and the Northgate base metal deposit at Tynagh in Ireland (Derry et al., 1965; Morrisey et al., 1971).

The geological events that controlled karst development in Sardinia are schematically outlined in figure 52. Karst development took place during three periods of uplift (figure 52). Three types of lead and/or zinc ore-bodies were formed:

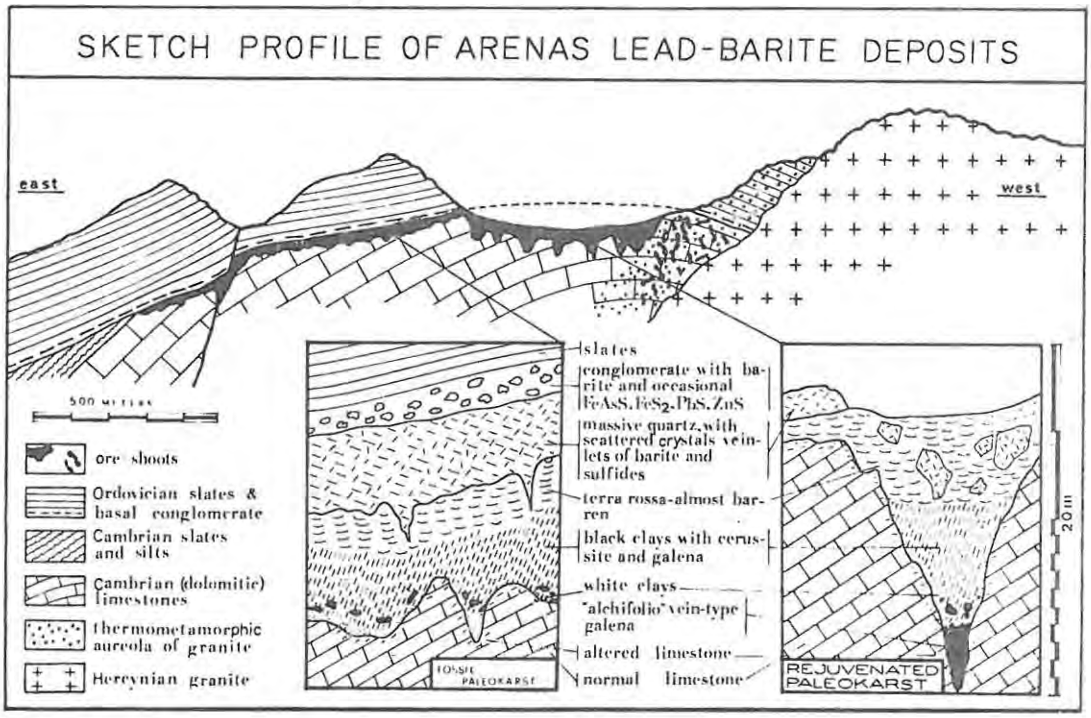


Fig.53.

From Padalino et al., 1973

A very prominent secondary ore-body was developed just above the primary ore-bodies by weathering and erosion of minerlized limestone on its northern flank at the Northgate base metal deposit near Tynagh, Ireland (figure 22) (Derry et al., 1965). These ores are not passively residual as evidenced by the prevalence of rounded grains of both sulphide and oxide metallic minerals. This residual or secondary ore forms a boatshaped mass approximately 700 metres long, 150 metres wide and shelving from both ends to a maximum depth of 80 metres in the middle. The secondary material consists of about 62 percent of black mud containing the detrital lead and/or zinc sulphides and 28 percent containing the lead-zinc oxides. These ore types are not mixed but occur in sharply defined masses (figure 54). This segregation of oxide and sulphide ore is very important because it will influence the tonnage calculation (different S.G.) and extraction process. The 9,2% lead and 7,5% zinc grade of this deposit is about twice that of the primary sulphide ore.

Typical cut-and-fill erosional structures are developed in the upper Wetterstein Limestone of the Ladinian geosyncline of the eastern Alps (Schneider, 1964). The ore mineral content is usually subeconomic.

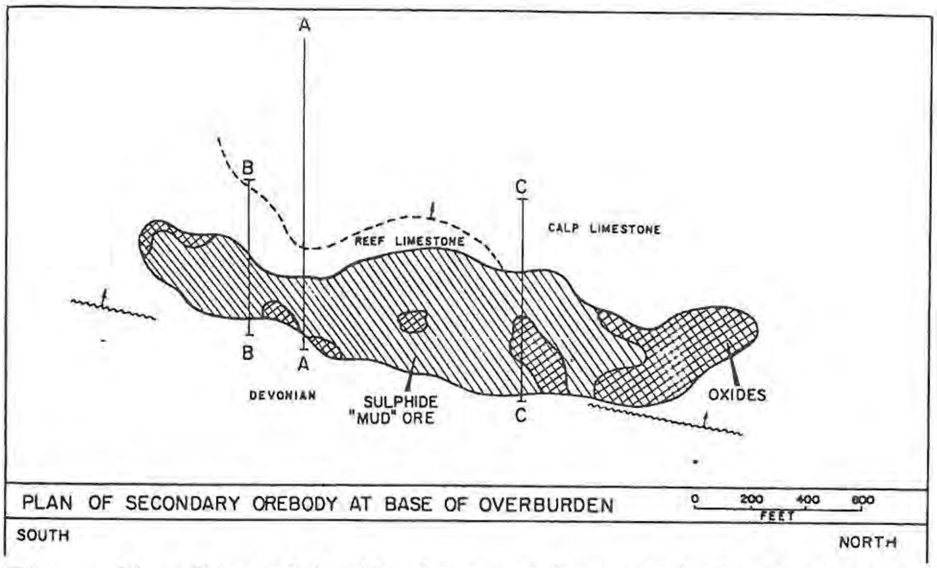


Figure 54. Plan of Northgate secondary ore-body, Tynagh

From Derry et al., 1965

The second type of karst-associated lead-zinc (copper) deposits is related to a palaeoaquifer system where there is a drainage system with an in- and out flow usually transecting a considerable thickness of rock (section 2.5.1). The resultant karst is composed of solution breccia fragments cemented by gangue of various composition. The karst morphology can also develop by solution thinning of underlying lithologies causing collapse of overlying strata (see section 2.5.2. and 2.5.3. for reference to examples).

The exact geometry and size of these karst deposits are not predictable. They form through the interaction of various geological geochemical, structural and hydological factors. A few solution karst breccia types and the factors responsible for their formation will be discussed by means of examples.

Pre-Appalachian orogeny structures, formed by processes of diagenesis involving dehydration and lithification of the sediments and followed by gentle folding and doming with resultant jointing, were exploited by solution and subsequent collapse features in East Tennessee (Crawford and Hoagland, 1968). The Appalachian orogeny was superimposed over the pre-orogeny structures thereby accentuating and modifying the karst features. The major factors controlling ore localization were favourable permeable lithologies localized in the Kingsport limestone-dolomite formation (op cit, p. 254) (figures 55 and 56). Manto ore-bodies are stratiform in their major dimensions and are controlled by a 6 metre limestone bed ("V" bed) between two layers of fine-grained primary dolomite (figure 55).

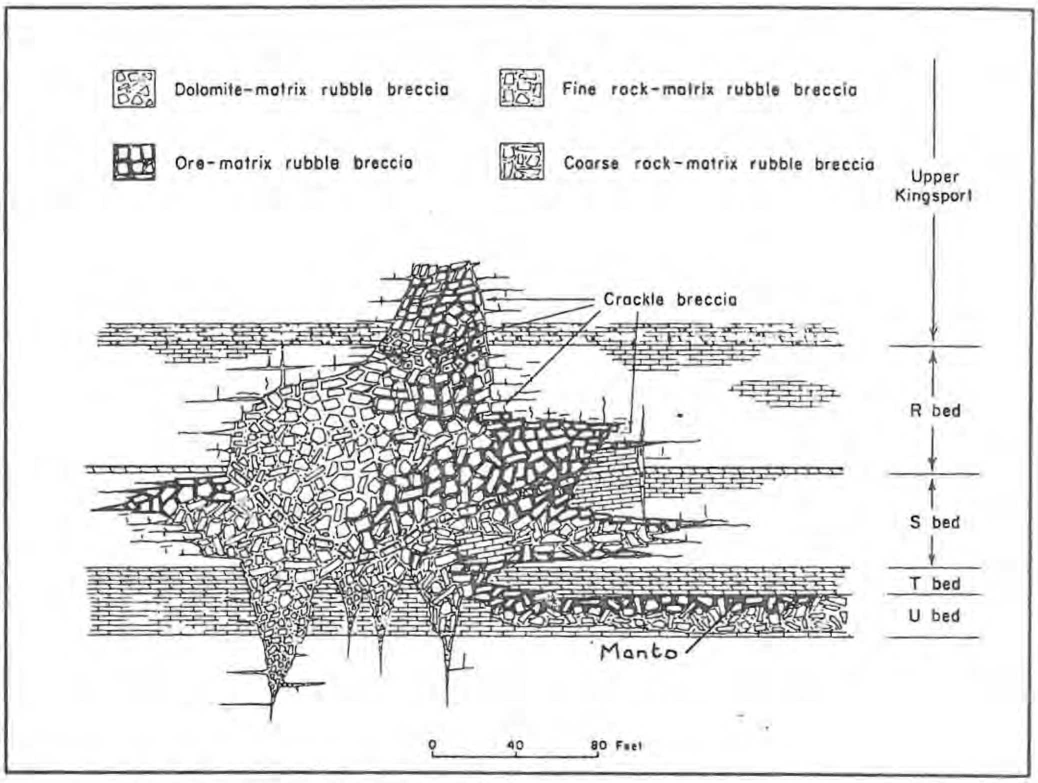


FIG. 55. *Generalized Section through a Portion of the Jefferson City Mine.*

From Crawford and Hoagland, 1968

The ore-bodies above the manto type are irregular and of greater vertical extent. The rock-matrix breccias are of different ages and are of complex shape. Above the stratigraphic horizons of the ore zones, the breccias are sometimes circular or oval in plan and pipe-like in section. In the Kingsport Formation they commonly are rudely tabular linear bodies that extend horizontally for a 1000 metres or more. Adjacent to these. with many irregularities, pipes, offshoots, and spurs, are the structures along which ore zones of great size and length have been localized. The multihistory breccia development is quite clear from figure 55. The very erratic geometry of the mineralized ore zone makes exploration drilling very difficult and expensive.

The mineralization at the Flat Gap Mine, Treadway, Tennessee is localized in breccia bodies formed in the Mascot and Kingsport Formations when the beds were flat lying. Subsequent uplift resulted in the development of an unconformity of regional extent. A palaeoaquifer was developed in limestones of the upper Kingsport Formation. Porous limestones were dissolved by meteoric waters with the result that interbedded

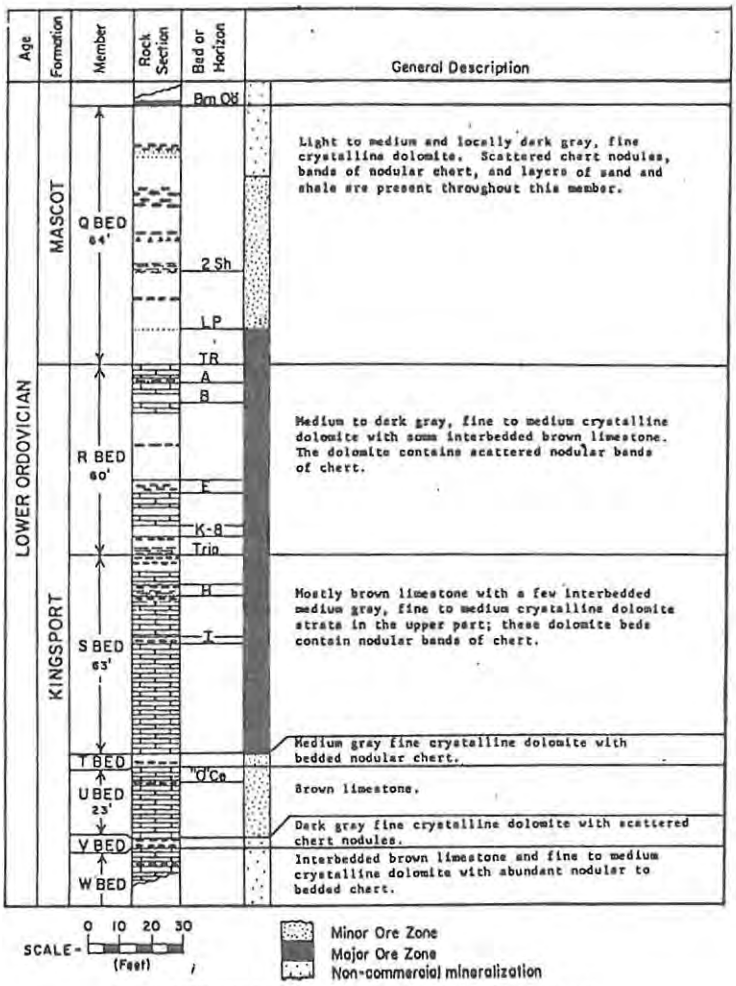


FIG. 56. Stratigraphic details of an unaltered mine section at the Flat Gap mine.

From Hill et al., 1971

and overlying dolomite beds collapsed forming long narrow breccia bodies with a maximum thickness of 60 metres (find rock-matrix breccias) (figure 57). Later solution and collapse resulted from the action of warm metal-bearing solutions giving rise to the ore-matrix breccia (figure 57) (Hill et al., 1966). These breccias represent partly reqorked older fine rock-matrix breccias as well as new breccias along joints essentially normal to the main trend. Both chemical and mechanical erosion of the solution channels resulted in the accumulation of poorly-sorted sediment of dolomitized limestone, fine-grained dolomite, and bleached chert fragments, as well as frequently encountered sand-size accumulations. These debris are referred to as trash zones. Sphalerite mineralization in these zones occurs as breccia fragments and open space filling. Thick ore occurrences, termed "breakthrough-ore-bodies", form where a lap up of ore-matrix breccia occur against older breccias.

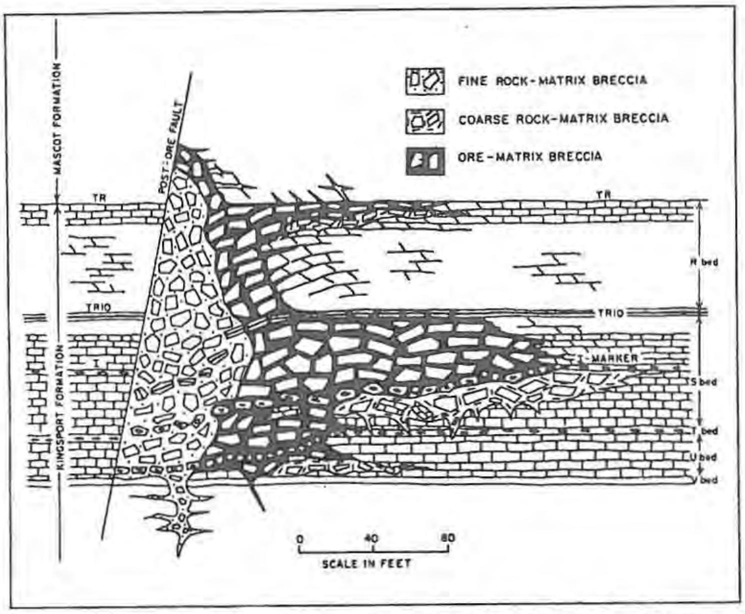


FIG. 57. Cross section of an ore body abutting a fault and showing the general relationships of the several breccia types to unaltered rock. Dissolution and dolomitization of the predominantly limestone section was accompanied by fragmentation and collapse of the overlying dolomite beds. Downward displacement of thin, fine-grained dolomite beds identified as the TRIO, I, and T markers is evident. The fine, rock-matrix breccias are characterized by greatly rotated angular fragments sealed with greenish-gray fine-grained dolomite, by the absence of dolomitized limestone, and by the lack of bleaching. The coarse, rock-matrix breccias commonly are associated pockets of well-sorted carbonate or silica sands, especially in the "trash" zones lying immediately above incised limestone or dolomitized limestone knobs. Crackle breccias were developed along the upper and lateral boundaries of the dissolution zones, forming mosaics in which the separation of fragments and their rotation are minor.

Post-ore faulting has placed unaltered and undisturbed strata in contact with brecciated, dolomitized, and mineralized ground. (After Hill, 1969.)

From Hill, Morris and Hagegeorge, 1971

The breakthrough-ore breccias generally grade laterally into thinner, bedded-type ore-bodies that eventually pinch out into undisturbed wall rock (figure 57).

Two distinctly different types of sphalerite mineralization occur in the Flat Gap ore-body. These are referred to as the galena bearing sphalerite black-ore-bodies and the galena free sphalerite, yellow ore-bodies. It is very important, from a metallurgical point of view, to outline and calculate the tonnage and grade separately for the different ore types.

Post-ore faulting, as with any other deposit, determines the mine planning. Displacement along the faults and damming of possible water behind the fault must be taken into consideration when doing mine planning.

Three geometrically different solution collapse breccias, related to open folding and solution thinning of underlying beds, have also developed in the Kingsport- and Mascot Formations of Tennessee (McCormick et al., 1971):

(a) V-shaped ore structures occur at the crests of gentle anticlinal folds and are greatly elongated in plan, averaging 50 metres in length and 6 metres in width (figure 58). The pre-ore tensional fractures, parallel and perpendicular to bedding acted as channelways for

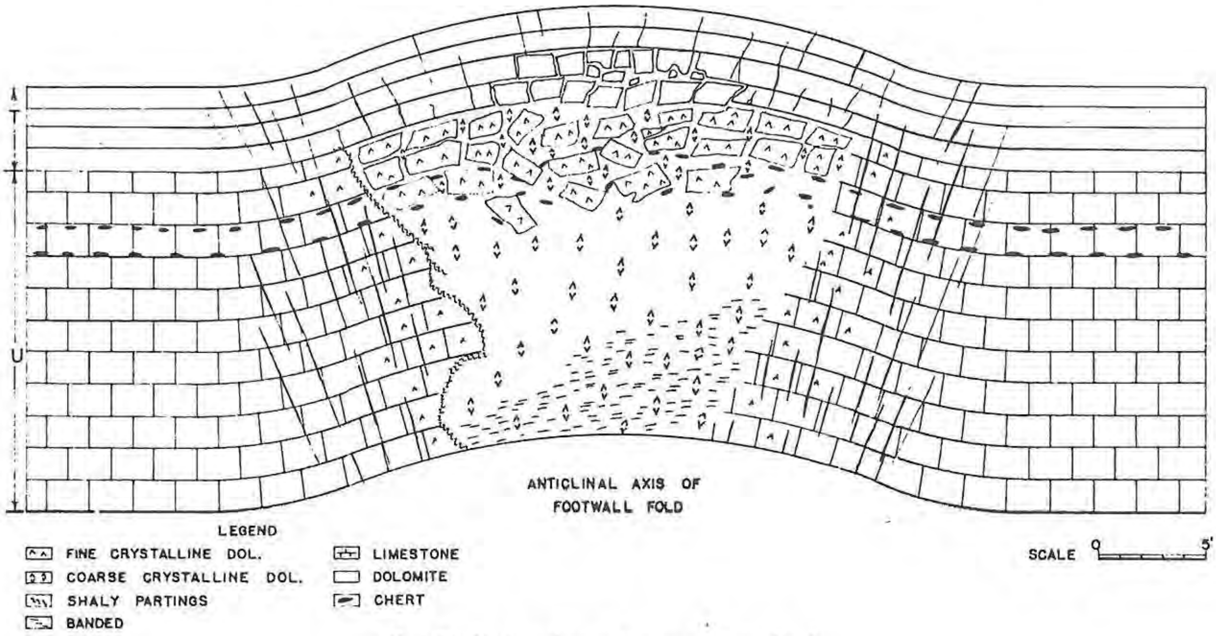


FIG. 58. V-shaped ore structure, generalized.

From McCormick et al., 1971

altering solutions in the limestones. The latter were dolomitized and slightly silicified. Limited solution thinning of the beds just below the impermeable T-bed dolomite (figure 58) caused collapse brecciation. Open spaces as well as some pore space in individual blocks in the breccia body were filled with secondary silica. Some of the silica, dolomite and adjacent limestone were later replaced by sphalerite. Mineralization usually occurs at the top part of the body under the unbroken dolomite cap and along the limestone edges.

(b) High-domal structures (figure 59) are irregular in shape, and may extend as much as 500 metres in length, 300 metres in width, and 50 metres in height. These structures are formed by the extensive solution and alteration of the limestone below the top of the "R" bed (figure 59) which caused the foundering of the interbedded and overlying fine-grained dolomites.

(c) Low-domal structures (figure 60) appears to be related to a lesser original thickness of the S-bed limestone. They have the same

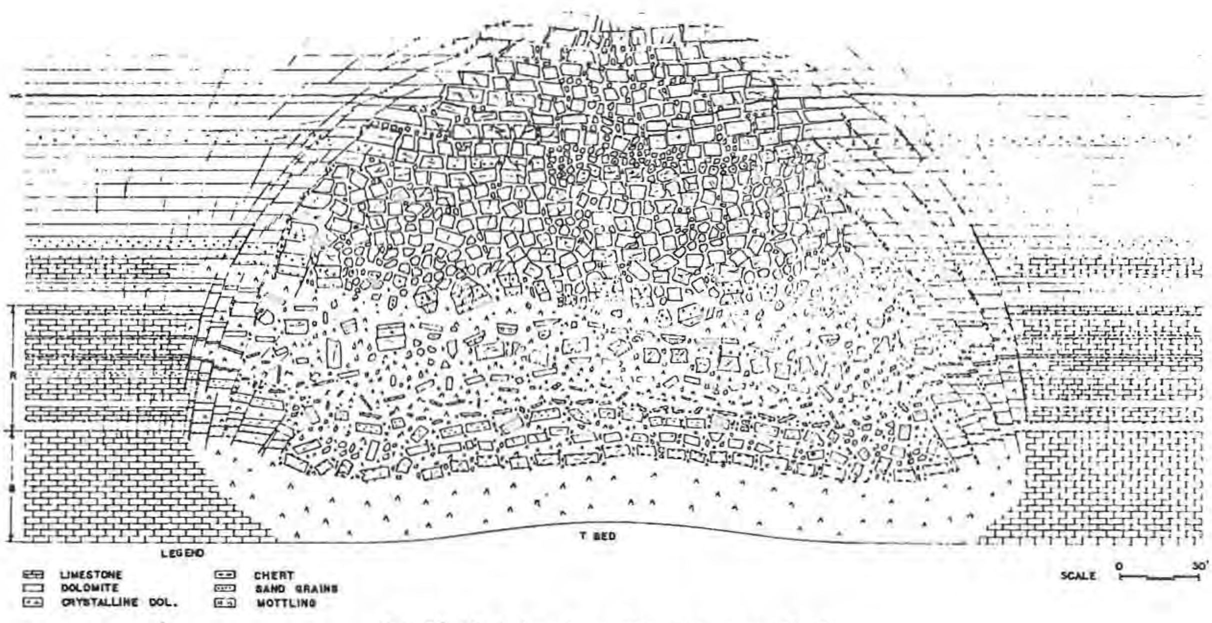


FIG. 59. High-domal ore structure, generalized.

From McCormick et al., 1971

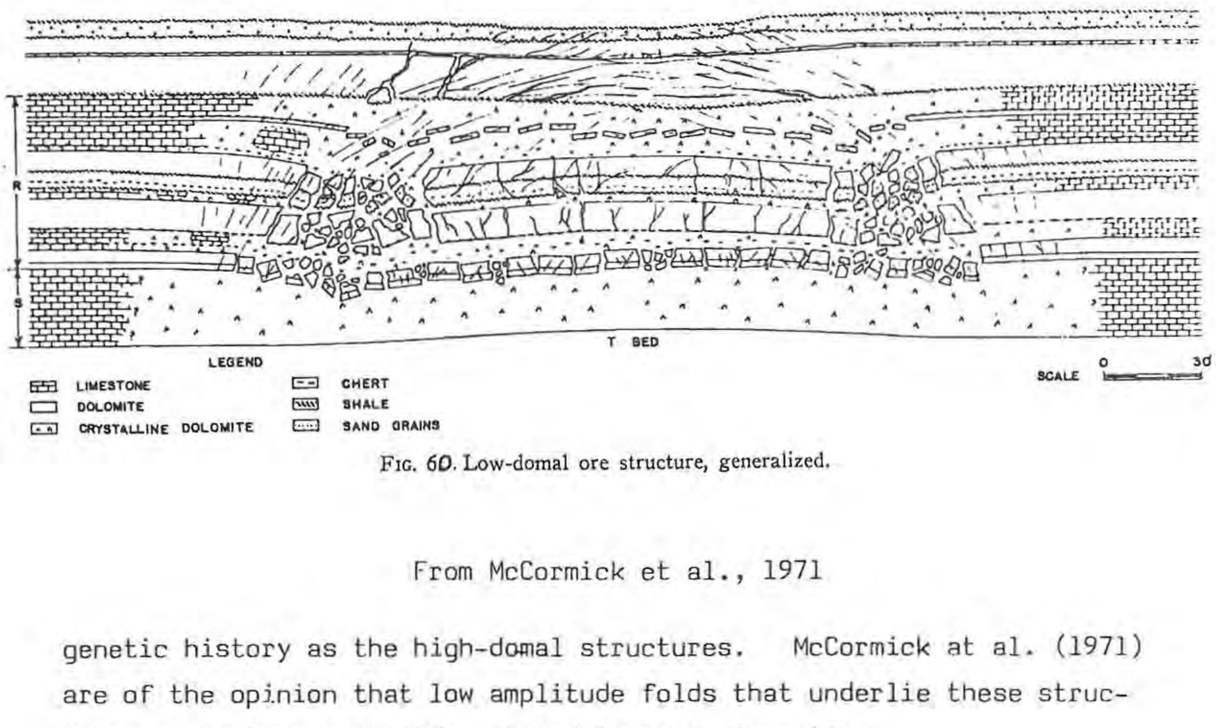


FIG. 60. Low-domal ore structure, generalized.

From McCormick et al., 1971

genetic history as the high-domal structures. McCormick at al. (1971) are of the opinion that low amplitude folds that underlie these structures could be genetically related to their inception.

Ore emplacement took place in open spaces in the breccia, along dilated bedding planes and within fractures. Dolomitization and silicification are the main alteration processes. Ore-bodies are often surrounded by a silica halo. Pyritization occurred in varying degrees.

The variations in the physical appearance of the solution-collapse breccias are directly related to the intensity of solution and alteration. the amount of mineralization was controlled primarily by the porosity and permeability of the material within the structures.

The karstic breccias that have been discussed in the section above differ from the "pipe" karst features, e.g. at Tsumeb in Namibia (Söhnge, 1948; Hughes, 1979) and Broken Hill, Kabwe in Zambia (Kortman, 1972), in that they have a much more extensive lateral- but much more restricted vertical development. The difference in vertical extent is directly related to the thickness of the carbonate sequence and the stratigraphic position of the genetically related unconformity. The carbonate thicknesses hosting the Tsumeb- and Broken Hill deposits are approximately 3000 metres and 1000-2000 metres respectively. Mineralization at Tsumeb has been proved down to a depth of 1700 metres; the maximum depth of mineralization at Broken Hill is 470 metres.

Oxidation of primary sulphides in karst deposits is a characteristic feature. The size and location of the oxidized ore varies considerably. The fluctuation in the watertable level as well as the configuration of the plumbing system determines the sphere of oxidation influence on the primary ore. Oxidation by percolating groundwaters is an active present-day process of karst deposits e.g. Tsumeb and Kombat deposits in Namibia.

3.2.4 Sedimentology

It is eveident from the foregoing discussions, that the shape and size of any sedimentogenic carbonate-hosted lead-zinc (copper) deposit is determined by the combination of its inherent sedimentary and any superimposed secondary (e.g. structure and dolomitization) features. These secondary, induced porosity features have, in most cases, caused the obliteration of the original sedimentary features thereby making them very difficult ot recognize.

(a) Reef Complexes

The main characteristics of a coral-, mudbank and algal reef complex have been discussed under sections 2.4.1, 2.4.2 and 2.4.3 respectively.

A reconstruction of a Devonian Reef-controlled barrier by Beales and Jackson (1968) illustrates the porosity characteristics related to composition (figure 61) of sedimentary facies. The variable nature of

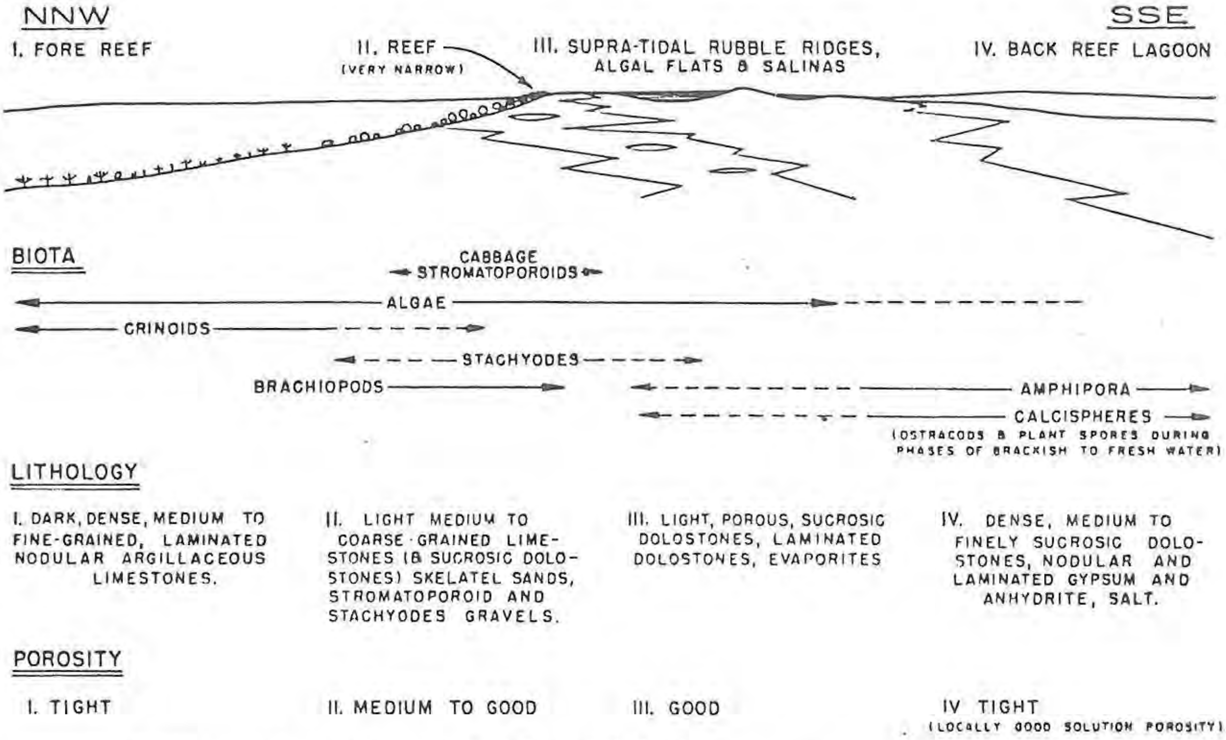


Figure 61.—Reconstruction of a Devonian Reef-Controlled Barrier.
Oriented as a hypothetical NNW-SSE cross section of the Presqu'ile Barrier (not drawn to scale)

From Beales and Jackson, 1968

the porosity in the reef complex at Pine Point (Beales and Jackson, 1966) is shown in figure 62. These features are indicative of the distribution and nature of the mineralization encountered at Pine Point, Canada.

The geometry of the stromatolite reef associated deposits in the Southeast Missouri district, U.S.A. (Larsen, 1977), is determined by the geometry and internal features of the biotic complex. A typical biohermal complex is shown in figure 27. Repetitive biostomal cycles can be developed within a digitate stromatolite facies (figure 63). Grainstone- and packstone deposits fill surge channels and represent the end of a cycle. These are favourable sites for ore deposition e.g. Ozark Mine in the Viburnum Trend (Larsen, 1977). In the Old Lead Belt, the organic accumulations are biohermal in shape and tend to be discrete bodies. The rolls of the bioherms are a characteristic feature not- or poorly developed in biostromes. The areas between rolls are favourable sites for ore deposition. The growth lines of the organic deposits (burrows, coral skeletals etc.) with or without structural aid, increase the porosity, allowing for migration of dolomitizing and mineralizing

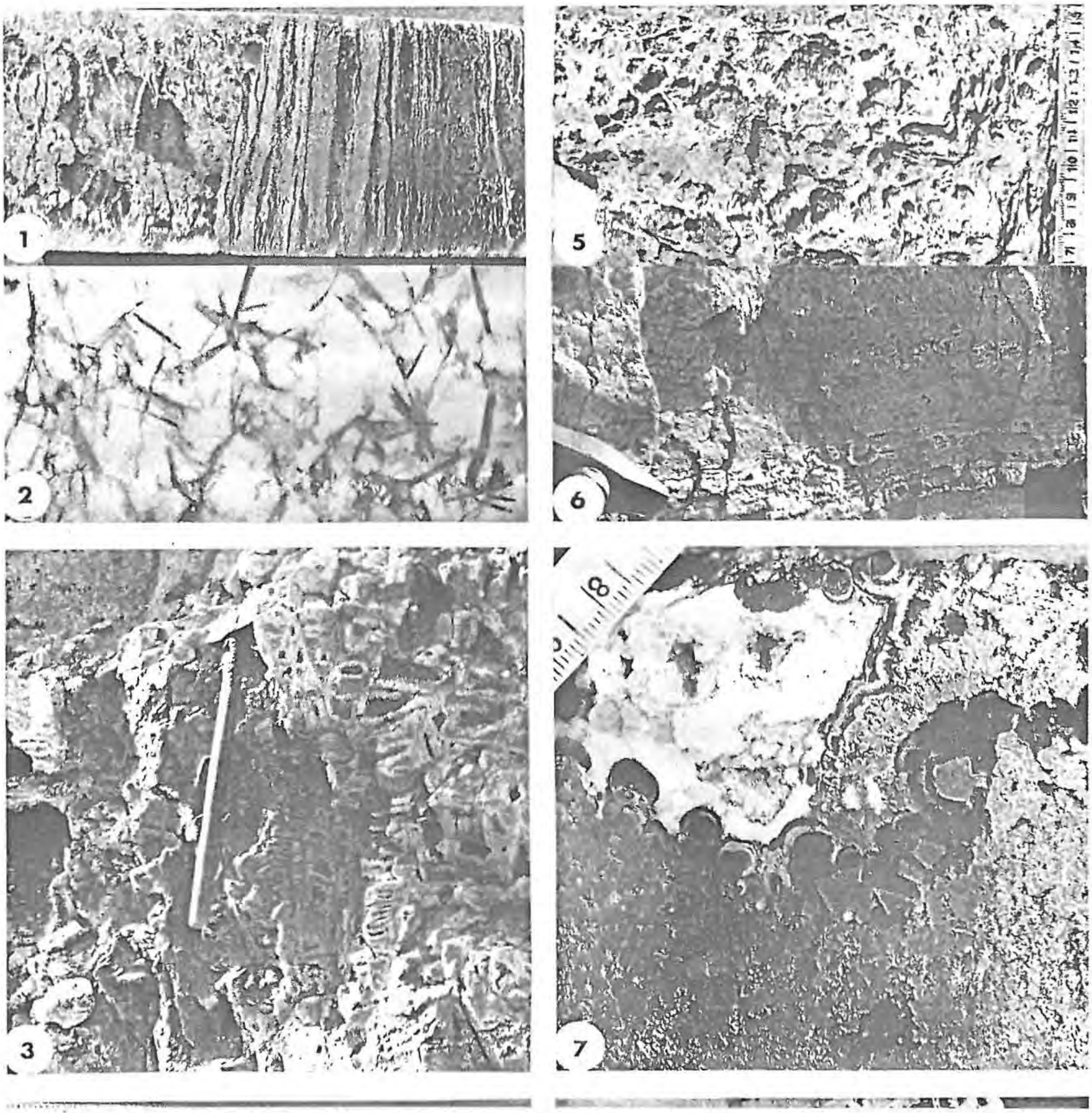


Fig62. (opposite) Porous Presqu'ile dolostone, associated evaporites and mineralization. Both anhydrite an gypsum are commonly encountered in core samples and equivalent moldic porosity occurs in surface sample Common coarse- and fine-solution breccias that have recemented and sealed to varying degrees attest to the forme even more widespread, occurrence of evaporites. Solution of these evaporites provides some of the most permeabl horizons in the Presqu'ile dolostone and such breccia horizons are clearly associated with ore. Much of the massiv ore appears to fill cavernous porosity and is so uniform and high-grade as to be non-photogenic. The examples o mineralization illustrated here are from marginal locations where breccia fragments and vugh fillings are mor apparent. 1, Dolomite–anhydrite laminae and blebs. Such rocks are indicative of back-reef lagoons and isolate pools. Magnification, ×1; 2, coarsely crystalline dolomite mosaic with gypsum-filled anhydrite pseudomorph Moldic porosity (commonly infilled with calcite) from which the gypsum has been dissolved, is widespread i Presqu'ile dolostones. Magnification, ×1; 3, highly porous dolostone, an evaporitic solution breccia with lattice work structure—emphasized by white sparry dolomite rims on brown sucrosic dolomite remnants; 4, detail of sample from the strata shown in 3 in Fig62 showing dolomite spar lining the voids; 5, detail of a sample fron strata shown in 3 in Fig62 showing type of highly porous solution breccia in which white sparry dolomite is lackin Such samples, taken from close to the orebodies, are commonly partly infilled with bitumen; 6, similar dolostone i which the bedded nature of the porosity is readily apparent. Many such porous layers occur adjacent to orebodie yet mineralization is lacking; 7, massive lead–zinc ore with grey massive galena, botryoidal sphalerite and spar calcite cavity filling. Scale in centimetres; 8, mineralized collapse breccia showing brown dolomite fragment cemented by white sparry dolomite, botryoidal sphalerite, minor galena and calcite. Scale in centimetres

From Beales and Jackson, 1966

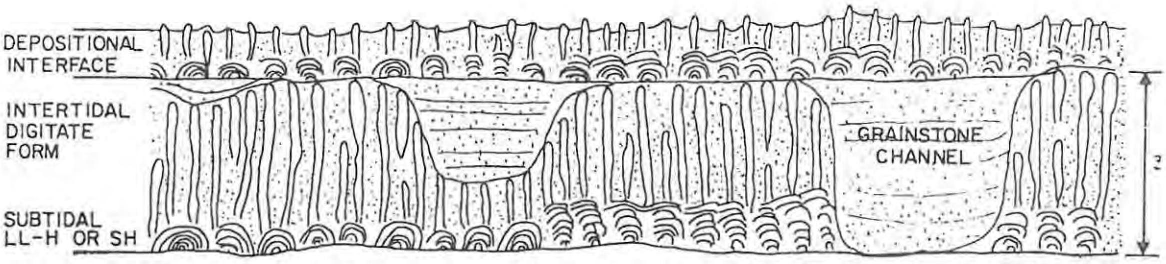


FIG. 63. Biostromal stromatolite cycle.

From Larsen, 1977

fluids. They can also serve as loci for ore deposition. Dolomitization is the main process whereby porosity is increased or induced due to the removal of calcium.

The porosities that can develop in a reef complex are thoroughly explained and exhibited by Larsen (1977) and Lyle (1977).

(b) Disconformities

Minor disconformities within a stratigraphic section are very often the loci of blanket-type mineralization (Snyder and Gerdemann, 1968). The disconformities provide avenues for widespread lateral migration of ore solutions. Mineralization very often becomes ore grade where slight relief on the disconformity simulates a ridge or domal structure.

(c) Uncomformities

Stratabound ores at Mezica (Buhovnik, 1967) are limited to the planes of unconformity which are locally marked by breccia. Duhovnik commented on these breccia ore-bodies as follows "since the ore beds follow unconformities, it is quite understandable that the mechanical properties of the rocks will differ most on these contacts". These contacts would act as weak planes under tectonic processes; most strongly affected by movement, crushed and so best disposed for replacement by ore.

(d) Stylolites

Stylolitic structures in limestones influence ore distribution indirectly in that they act as favourable avenues for the migration of altering solutions. Porosity is thereby increased and favourable sites for ore deposition created e.g. the Mascot-Jefferson City Zinc District in Tennessee (Ohle, 1951).

Stylolites in the Lower Limestone biointrapelsparite beds of the Newfoundland Zinc Mines deposits are ubiquitous though poorly developed.

Solution occurred along these planes and greatly assisted in the formation of the ore-bearing karst features (Collins and Smith, 1973).

(e) Bedding planes

Bedding planes act as zones of weakness in their primary form or during deformation e.g. faulting, folding, karsting, along which altering and mineralizing solutions can migrate. Secondary porosity and permeability is increased and so also the probability of forming an or deposit. Several bedded deposits have been discussed in the previous sections, notably on the solution collapse breccias of Tennessee (Hill et al., 1971; McCormick et al., 1971). Various bedding plane bedded deposits also occur in the Southeast Missouri District (Snyder and Gerdemann, 1968). Figures 64, 65 and 66 are examples of several bedded ore-types in Southeast Missouri (Snyder and Emery, 1956).

(f) Impermeable cap rock

Impermeable lithologies act as barriers to ascending mineralized solutions causing ponding and a subsequent lateral, and to a lesser extent, vertical widening of an ore zone (Mouat and Clendenin, 1977). The ponded solutions exploit bedding planes thereby creating a bedded deposit. The bedded-ore structures at the Jefferson City Mine, Tennessee (Fulweiler and McDougal, 1971) originated in this way.

Permeability studies in the normal course of exploration mapping and drilling would definitely be an advantageous exercise in homing in on potential ore bearing horizons.

(g) Facies changes

The location and geometry of a sedimentary facies interface can also be the location and geometry of an ore deposit by virtue of the difference in composition and/or permeability between units constituting the different facies.

Facies changes are favourable sites for ore deposits to form. Examples are given in section 2.6.1.

3.2.5 Supergene alteration

Supergene alteration is a process that affects both the tonnage and grade of any lead-zinc-copper ore deposit. The alteration also determines

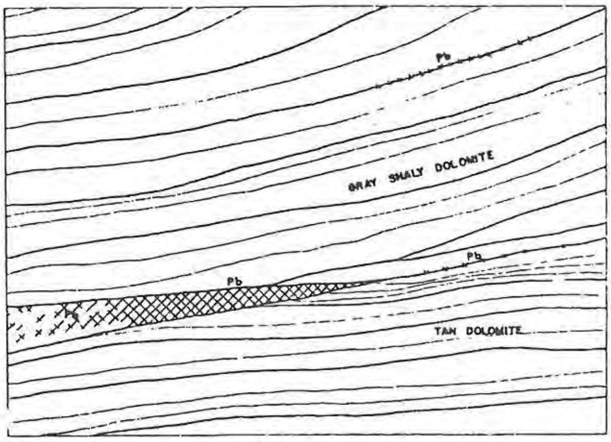


Fig. 64. Bedded ore on flank of structural center.

From Snyder and Gerdemann, 1968

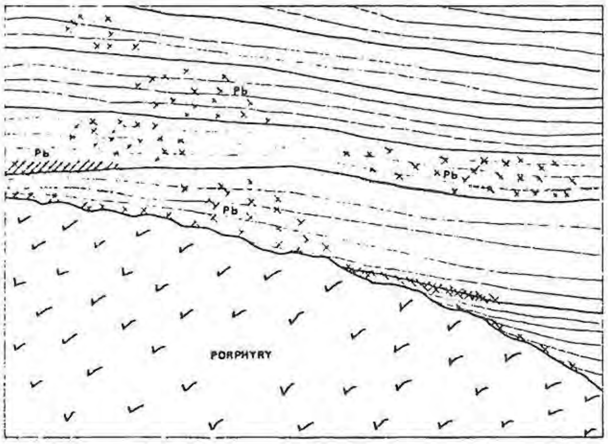


Fig. 65: Bedded and disseminated ore at dolomite/porphyry

From Snyder and Gerdemann, 1968

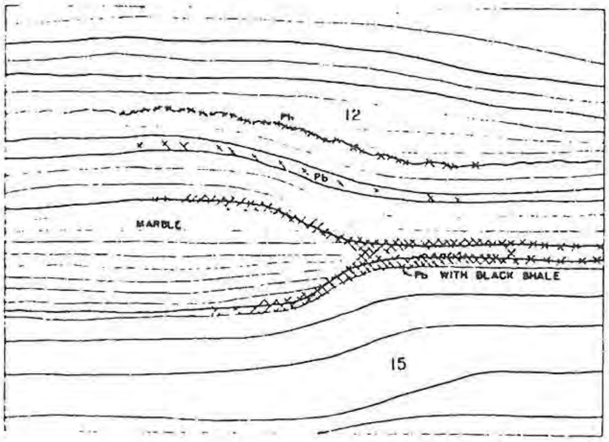


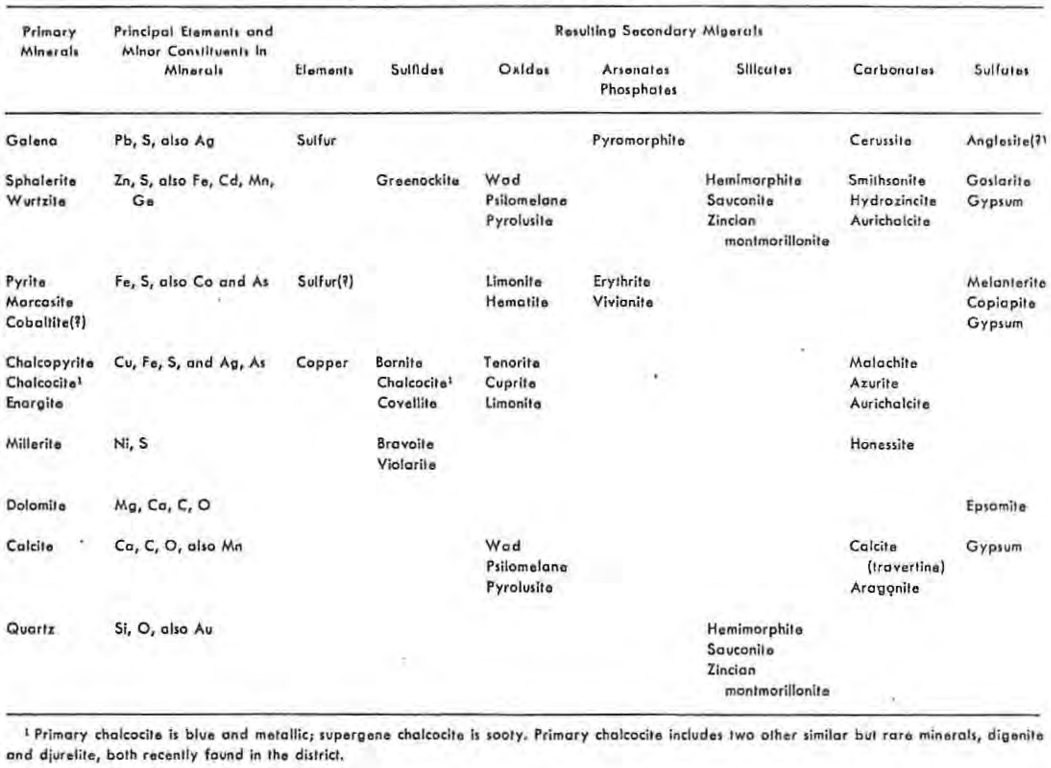
Fig. 66: Bedded ore with *marble* fan.

From Snyder and Gerdemann, 1968

the metallurgical extractive process that will have to be applied in order to recover the optinum quantity of the altered element(s).

Supergene minerals in many districts can occur in three zones. In descending order they are the zone of leaching and oxidation, the zone of enrichment containing secondary oxidized ores and the zone of secondary sulphide enrichment. Table 8 shows the main primary minerals of the carbonate hosted "sedimentogenic" ores, the elements they contain, and the supergene minerals produced from them.

TABLE 8. Minerals Formed by Oxidation and Redeposition



Primary Minerals	Principal Elements and Minor Constituents in Minerals	Resulting Secondary Minerals						
		Elements	Sulfides	Oxides	Arsenates Phosphates	Silicates	Carbonates	Sulfates
Galena	Pb, S, also Ag	Sulfur			Pyromorphite		Cerussite	Anglesite(?)
Sphalerite Wurtzite	Zn, S, also Fe, Cd, Mn, Ge		Greenockite	Wad Psilomelane Pyrolusite		Hemimorphite Sauconite Zincian montmorillonite	Smithsonite Hydrozincite Aurichalcite	Goslarite Gypsum
Pyrite Marcasite Cobaltite(?)	Fe, S, also Co and As	Sulfur(?)		Limonite Hematite	Erythrite Vivianite			Melanterite Copiapite Gypsum
Chalcopyrite Chalcocite[1] Enargite	Cu, Fe, S, and Ag, As	Copper	Bornite Chalcocite[1] Covellite	Tenorite Cuprite Limonite			Malachite Azurite Aurichalcite	
Millerite	Ni, S		Bravoite Violarite				Honessite	
Dolomite	Mg, Ca, C, O							Epsomite
Calcite	Ca, C, O, also Mn			Wad Psilomelane Pyrolusite			Calcite (travertine) Aragonite	Gypsum
Quartz	Si, O, also Au					Hemimorphite Sauconite Zincian montmorillonite		

[1] Primary chalcocite is blue and metallic; supergene chalcocite is sooty. Primary chalcocite includes two other similar but rare minerals, digenite and djurelite, both recently found in the district.

From Heyl, 1968

The zone of leaching and oxidation can be considered as destructive due to the depletion of ore tonnage and grade.

The zone of enrichment containing secondary oxidized ores still represents a deterioration in tonnage. This is brought about by a reduction in specific gravity of the ore minerals. Enrichment can only be brought about by an accumulation of oxide minerals as grade is considerably lowered by alteration.

Grade is considerably increased in the zone of secondary sulphide enrichment. Secondary sulphides are common only in the few copper deposits of which the Tsumeb and Kombat karst deposits in Namibia are the most important examples. No secondary lead and zinc sulphides deposits are known.

The oxidation of the ore minerals is complete in many places but varies from deposit to deposit. Galena remains mostly unoxidized and is generally just coated with lead carbonate (cerussite) and lead sulphate (anglesite). Galena can however be completely leached.

Oxidation is most probably accomplished by sulphuric acid formed from the decomposition of marcasite and pyrite in vadose water. The ferric sulphate from oxidation of the pyrite and marcasite readily attacks the sphalerite to form zinc sulphate and more sulphuric acid. The ferrous and ferric sulphates readily oxidise to ferrous hydoxide. Partial dehydration of the ferrous hydroxide yields limonite (Emmons, 1940, p. 117). The limonite is in two forms, indigenous and transported. The indigenous limonite directly replaces the iron sulphides, forming pseudomorphs, and the transported limonite is deposited in adjacent rocks or further below in the zone of secondary ores. This ferruginization can very often serve as an exploration guide to lead-zinc deposits. The zinc sulphate reacts with the carbonate wall rocks to form zinc carbonate (smithsonite) which is very resistant to further alteration; so much so that it can form placer deposits when eroded. Galena is very immobile in the oxidised zone. All salts of lead are soluable with difficulty, particularly in the slightly basic or nearly neutral meteoric waters of carbonate rocks. Lead carbonate is least soluble, the sulphate somewhat more, and the chloride the most soluable. Galena is attacked by dilute sulphuric acid to a small extent, especially if the sulphuric acid is combined with ferric sulphate. The first change is to anglesite (sulphate) which changes within a short time to cerussite by reaction with the carbonate wall rocks. The cerrusite is formed as coatings which surround and protect the galena, and less commonly as small clear, colourless crystals that coat the surface of galena (Heyl et al., 1959)..

Supergene alteration is almost non-existent in the Canadian and American carbonate hosted lead-zinc deposits. The Southeast Missouri lead- and Upper Mississippi Valley base metal districts are the only really exceptions to this.

Secondary minerals are quite unimportant and uneconomic, except in minor milling losses of oxidized lead, in the Southeast Missouri lead district. The secondary minerals include minor cerussite, anglesite, bornite, chalcocite, covellite and malachite.

The primary lead, zinc, iron and copper sulphide deposits of the Upper Mississippi Valley district are leached and oxidized where they are within 10 to 30 metres of the present land surface (Heyl, 1968). The ore minerals are completely altered in some places except for the insoluable galena which generally only has a veneer of cerussite. Oxidation does occur below the water table along open fractures. Sphalerite has been altered to smithsonite. Residual masses of galena with a carbonate coating are found in large quantities in gossans and in oxidized veins. An upgrading in lead content per volume rock has therefore resulted.

Supergene copper minerals are deposited in and below the zone of leaching, mainly as oxides and carbonates. The copper carbonates were formed by reaction of copper sulphide (produced in primary oxidation) with the carbonate wall rocks before migration occurred to a great extent. This deposition of carbonates probably prevented much supergene sulphide enrichment below the water table even where copper was quite abundant.

Smithsonite increases notably near the fluctuating water table. Where copper is present in the ores, quantities of copper oxides and carbonates are deposited with this smithsonite. Some sphalerite in all stages of oxidation remain. Many of these mixed ores are rich but have remained unmined owing to the difficulties in separating the sphalerite from the smithsonite.

Secondary sulphide enrichment is an unimportant feature of the orebodies. Copper deposits and copper-bearing zinc deposits contain uneconomic chalcocite, bornite and covellite. No lead or zinc supergene sulphides are present in any of the deposits.

A very prominent secondary ore-body, comprising primary and secondary sulphides, was formed by weathering and erosion of minerlized limestone of the Northgate base metal deposit at Tynagh in Ireland (Derry et al., 1965; section 3.2.3).

Oxidized ore constitutes a major proportion of the ore reserves at the Broken Hill Mine in Zambia (Kortman, 1972). The main pipe-like karst ore-bodies have a massive sulphide core consisting of sphalerite, galena and pyrite, surrounded by an oxidized zone containing willemite, smithsonite and cerussite (figure 67). The oxide zone is normally 5-10 metres wide but varies considerably. Where the overall width of the occurrence is less than 20 metres, the ore tends to be completely oxidized. The width of the oxidized envelope generally does not seem to decrease in depth but persist down to the lowest known depth of 470 metres below surface (no. 5/6 ore-body). The oxidized ore is fine-grained and its texture ranges from massive and compact to cavernous and locally open boxwork. The vanadium minerals descloizite, vanadite and mottramite occur in the outermost silicic cavernous shell of the oxide zone. The vanadium content ranges from 1,87% to 2,43% V_2O_5.

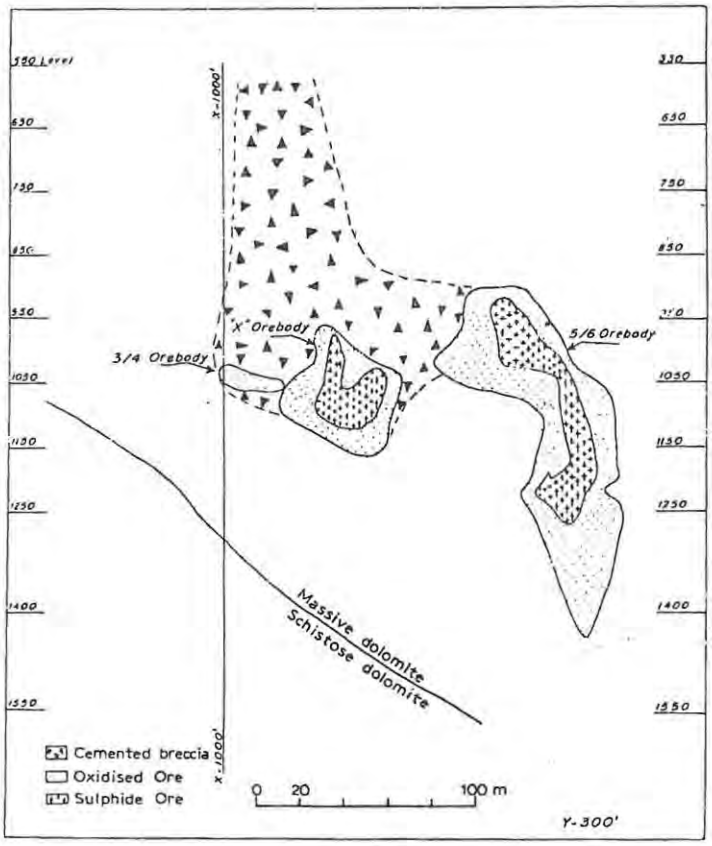


Fig. 67.
Orezones of No. 3/4, "X" and 5/6 orebodies.

From Kortman, 1972

Widespread oxidation of the Tsumeb ore deposit (Söhnge, 1961) reached 300 metres below the surface. A second zone of oxidation commences where the pipe cuts through the North Break Zone and secondary minerals persist to 44 level (figure 50). The ores that were modified are cavernous and more often leached than enriched. The copper and zinc sulphides were redeposited mainly as chalcocite and carbonates, whereas lead, forming relatively insoluble carbonate and sulphate, did not migrate far. The oxidation had the effect of hydrologically separating these metals from the complex primary ore. A partial shell of vanadate and arsenate ore is developed along the north-west periphery of the pipe between 28 and 30 levels.

An economic oxidized ore-body is present at Abenab West on the Otavi Shelf in Namibia (Verwoerd, 1957). The economic ore minerals are descloizite, vanadinite, cerussite, galena and willemite.

The importance of separating the outlining and ore reserve estimation of secondary mineralization from primary mineralization are:

(a) the specific gravity is completely different and this affects the tonnage estimation,

(b) mill head treatment differs, and

(c) mining conditions are different; the oxidized zones are much less stable and more water ridden.

3.3 Geological factors affecting the grade in carbonate hosted lead-zinc (copper) deposits.

The size of carbonate hosted lead-zinc (copper) ore-bodies is directly related to size of entrapping structures in the host. The quantity and distribution of the ore minerals within these entrapping structures determine the grade of that deposit. Distribution of mineralization is in turn determined by the available porosity and the paragenetic sequence(s) of mineralization. The paragenetic sequence of deposition is a function of the stability of the mineral complexes, carried in solution, within the entrapping structures; zonation of ore deposits occurs as a result. The specific minerals (and metals) that are precipitated are a function of solution composition. Various chronological phases or pulses of mineralization can modify and complicate an ore deposit e.g. metal zoning of a younger phase of mineralization superimposed on an older zonation would not necessarily coincide. Metals of the older depositional phase can also be leached and redeposited, thereby causing a redistribution of grade.

There are basically four factors affecting the grade of an ore deposit viz. supergene alteration, structure, zonation and porosity of the host rock. Supergene alteration has been discussed in the previous section and will therefore be omitted under this heading.

3.3.1 Structure

Faulting is a major factor controlling differences in grade of ore and interruptions in the pattern of mineralization within the ore hosting structures (Snyder and Gerdemann, 1968). Figure 68 outlines the distribution and intensity of mineralization related to a fault system (Snyder and Gerdemann, 1968). Figure 68 outlines the distribution and intensity of mineralization related to a fault system (Snyder and Gerdemann, 1968, p. 345). The areas of high mineralization coicide with intensely faulted and fractured areas (also figure 43). The grade in the braided fault pattern in figure 43 is 8-10 times minimum mining grade. The grade also varies on opposite sides of certain faults. The distribution of fault controlled grade is directly dependent on the displacement associated with a particular fault or fault system (Snyder and Gerdemann, 1968; Hill et al., 1971, p. 752; and Derry et al., 1965).

Special notice of the variation of grade due to faulting should be taken when calculating ore reserves. Mining layout will also be affected.

3.3.2 Zoning

Differences in the stabilities of metal carrying complexes result in sequential precipitation of the metals thereby inducing lateral and/or vertical zonation in an ore deposit (section 2.7). The zonation of carbonate-hosted lead-zinc (copper) deposits is, generally speaking, not very well defined. This phenomenon is mainly due to multihistory mineralizing phases associated with one deposit. Timing, in respect to the paragenesis of the ores, plays a very important part in determining whether the receptacle would be mineralized by all of the sulphides or would receive nothing but the very last minerals to deposit (Reynolds, 1958). Every ore-body is unique in this respect and the incipient deposits commonly show a variety of conditions along their strike.

The "normal" predicted sequence of metal deposition i.e. first copper than lead then zinc is not consistently reflected in the various

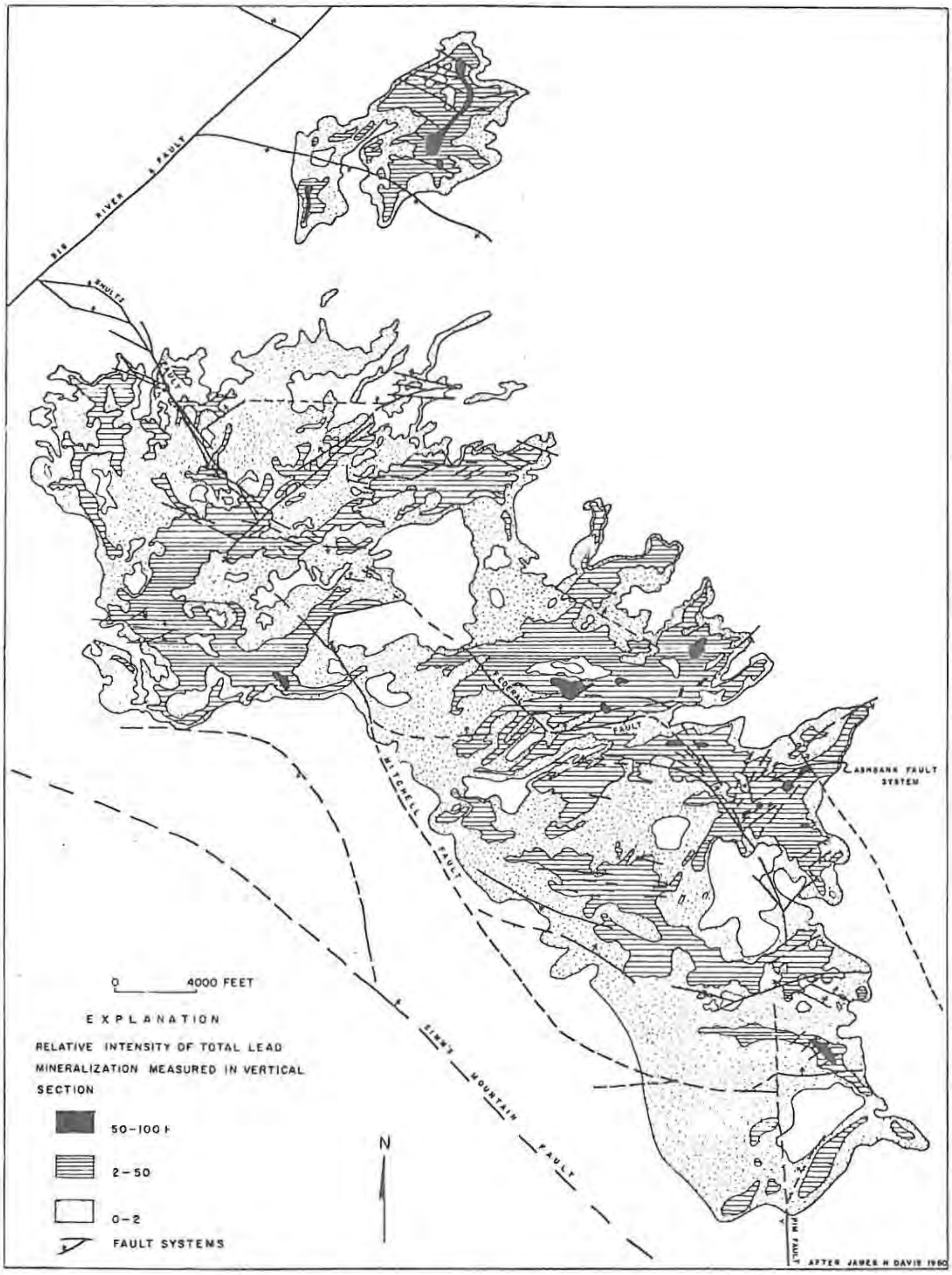


FIG. 68. *Fault System and Intensity of Mineralization.*

From Snyder and Gerdemann, 1968

carbonate-hosted ore-bodies. This irregularity is most probably due to the fact that certain of the metals were just not present in the solution, that the precipitation conditions were such that reverse or complex zoning resulted and/or that more than one mineralizing pulse with different chemistry affected the rocks.

Mineral zoning in the Southeast Missouri district is reflected by early precipitated chalcopyrite in the lower beds followed upwards by sphalerite because Pb and Zn stayed in solution longer to reach the top or upper edge of the ore-body before being precipitated. The sphalerite was restricted to small areas near the extreme upper parts of the ore-bodies (Grundmann Jr., 1977). This normal vertical zoning is supplemented by a lateral zoning of lead-zinc-copper away from the shoreline (St. Francois basement high) indicating that the ore solution flow was from the basin towards the shoreline.

Zoning in the pitch and flat deposits of the Shullsburg area, Upper Mississippi Valley (Reynolds, 1958) is illustrated by initial precipitation of pyrite, marcasite and sphalerite which filled most of the porous spaced created by prior dolomitization of the rock. Galena was deposited later in the paragenetic sequence and occupied the remaining space; predominantly at the edges of the ore-bodies (figure 69). Chalcopyrite-filled galena casts are present in the ore-bodies which indicate that the ore solutions were changing in character and were capable of dissolving early galena (Grundmann Jr., 1977). This change of the character of the ore solution complicates the metal-distribution pattern of an ore-body to such an extent that it becomes impossible to separate the various individual metal-bearing portions of that ore-body under consideration i.e. there is no predictable geological control on the metal distribution. This feature together with the very erratic nature of the mineralization makes ore reserves and grade estimation very unreliable

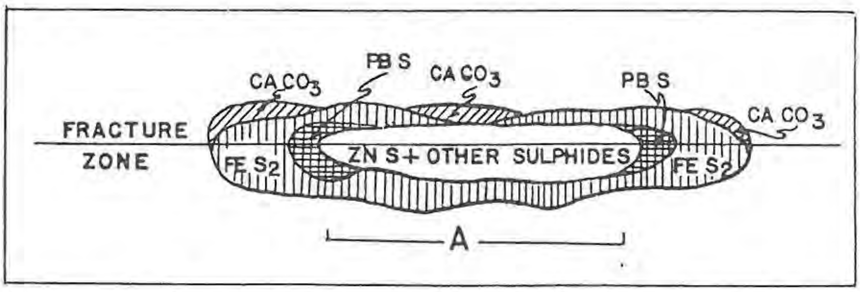


FIG. 69. Plan view of zoning relations in a typical ore deposit.

From Reynolds, 1958

The ore minerals at the Broken Hill Mine, Zambia (Kortman, 1972) consist mainly of sphalerite, galena and pyrite. There is a clear antipathetic relationship between galena and pyrite. The sulphide ore may consist of sphalerite and galena with subordinate pyrite, or of sphalerite and pyrite with subordinate galena, but the combination of galena and pyrite with subordinate sphalerite is absent. Information regarding the spatial relationship of these zones is lacking. It is important to have this information because tonnages and grade will be affected and this in turn would determine the mill capacity, plant design and ultimately, the revenue. This applies to all ore deposits.

The Tsumeb polymetallic karst deposit displays a distinct vertical zoning with lead and zinc content diminishing in depth while copper remains fairly constant (Söhnge, 1961). Generally, lead is more important on the north side and copper on the south side of the pipe.

The breccia ore-bodies of the Viburnum Trend in southeast Missouri, notably the Buick (Rodgers and Davis, 1977) and Magmont Mines (Sweeney et al., 1977) display well developed mineral zoning. A lateral roughly concentric mineral zoning is present at the Magmont Mine. From outside to inside it is marcasite, marcasite galena, and galena-chalcopyrite-sphalerite. The generalized metal zoning of the breccia bodies at the Buick Mine is outlined in figure 70. Along the north-south trend of the Buick ores there are gradual but significant changes in metal ratios (figure 71). North of the shafts, lead content remains relatively constant, while zinc content decreases and copper and cobalt content increase. The breccia ore to the south contains lower amounts of lead and copper, while zinc remains relatively constant. Further south the lead content increases but zinc, copper, and cobalt content decrease. Numerous overgrowths of different sulphide minerals in vugs, leached and etched crystals, pre-breccia ore in a matrix of post breccia ore, and complex zoning of the sulphide minerals point to several mineralizing pulses

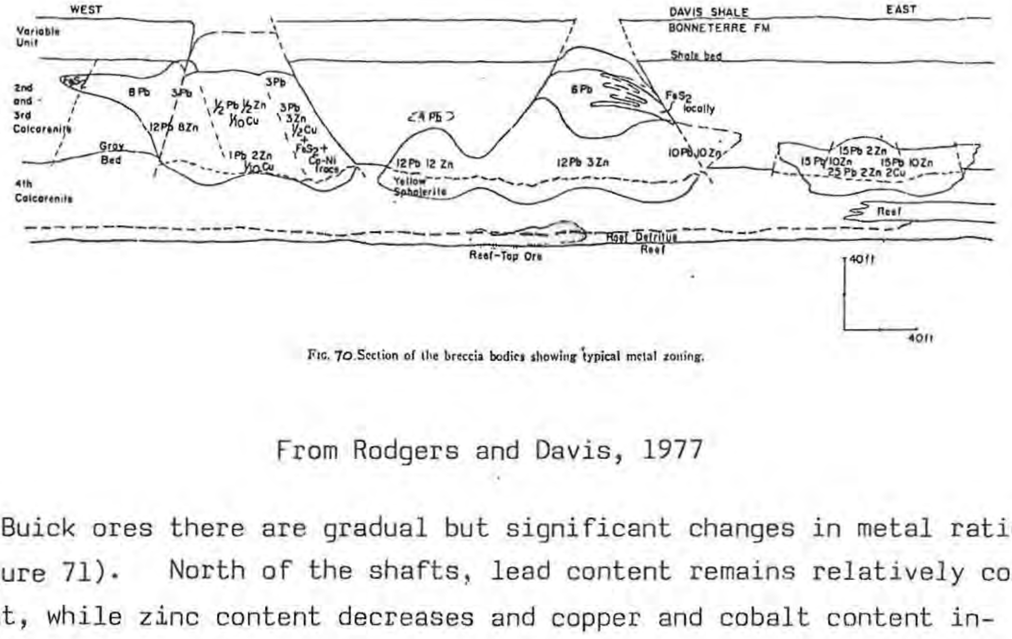


FIG. 70.Section of the breccia bodies showing typical metal zoning.

From Rodgers and Davis, 1977

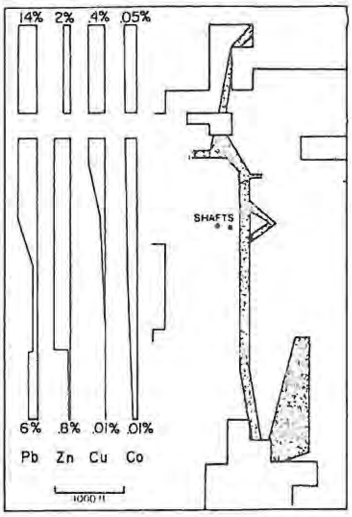


FIG. 71. Buick property map showing the relative metal abundance along the trend of the orebody.

From Rodgers and Davis, 1977

with varying chemical conditions in the mineralizing fluid (Rodgers and Davis, 1977).

Knowledge of the metal zoning in any deposit is critical in order to accurately control grade and in so doing ensuring that the plant's potential is optimally utilized in the long term.

3.3.3 Ore mineral distribution

Ore mineral distribution in any carbonate hosted lead-zinc (copper) deposit is dependent on the available favourable sites for mineral deposition i.e. porosity and the quantity of ore minerals occupying them. Porosity can be pre- and/or syn-mineralization induced, the various factors contributing to it have been discussed.

The majority of ore, in the barrier reef environment of Pine Point, was deposited in open cavities and vugs with some replacement occurring sporadically. The extreme porosity was created by the biota, recurrent dolomitization of the reef and evaporitic brecciation during emergence of reef. The evaporitic solution and brecciation produced box- and lattice-work structures. In general the porosity is moldic and irregular vuggy to cavernous, vugs usually being concentrated into layers accentuating the bedding (figure 62). The texture of the ore minerals is crystalline and colloform (figure 62). The crystalline nature of some of the ore is indicative of saturated slow growth in an open space while the colloform textures point to occasional supersaturation of the ore constituent. Colloform sphalerite very often encloses idomorphic galena. Some ore-bodies consist of massive sulphide pods containing up to 40% combined galena and sphalerite (Jackson and Folinsbee, 1969) but barren pyrite bodies are also present in the Pine Point area. The ore is generally characterized by a very high gangue to ore ratio, especially in breccias. The remainder of the open spaces are filled by gangue, usually dolomite and rarely quartz, calcite, fluorite and barite. The gangue composition varies from deposit to deposit. The ore-bodies are characterized by porosity, the percentage of which varies considerably. Porosity factors are applied to ore reserve estimation calculations by many mining concerns.

Mineralization in the breccia ore-bodies is also characterized by open space filling. Vugs and fractures are filled by the ore metals. Most of the metals however, occur as replacement of the generally coarse grained breccia matrix. The sulphides are frequently found as breccia fragments in the so called trash zones (Hill et al., 1971) which developed at the bottom of the breccia bodies. The better grade mineralization is very often confined to the fault and fractured peripheries of the breccia bodies. Galena in open space fillings is usually coarse grained. It can also be coarse grained as replacement ore of a coarse-grained host. Sphalerite is generally fine grained, both as open space filling and replacement. The grade of breccia ore-bodies is directly influenced by the quantity and size of the barren breccia fragements as well as the gangue and porosity percentage. The distribution of the mineralization throughout the breccia body is erratic and patchy. An extremely high grade patch may be followed in all directions by almost barren rock for decimeters before ore grade is again developed.

Mineralization and wall rock alteration are correlateable on a regional basis. All carbonate hosted lead-zinc deposits are associated with alteration. The latter varies in age from pre- to syn- to post-mineralization and is generally represented by dolomitization, silification and calcitization, alone or in various combinations.

The dolomitization in the southeast Missouri lead district is regarded by Snyder and Gerdemann (1968) as being diagenetic and they could find no evidence to suggest that post-lithification dolomitization occurred or that limestone-dolomite relationships are genetically related to sulphide mineralization.

The full extent of alteration is in many cases not mineralized. A typical example is present at Pine Point, Canada, where the margins of the ore-body are sharp against dolomitized wall rock (Jackson and Folinsbee, 1969).

Alteration is a very useful guide to potential mineralization in any facies environment.

4.0 IMPLICATIONS FOR EXPLORATION DRILLING AND ORE RESERVE ESTIMATION BASED ON THE GEOLOGICAL FACTORS CONTROLLING THE GEOMETRY AND GRADE OF CARBONATE HOSTED LEAD-ZINC DEPOSITS

4.1 Introduction

The section to follow will mainly emphasise the influence that the geological factors have on exploration drilling as applied to ore reserve estimation. Attention will be given to the regional geological implication that will influence exploration drilling as a prelude to ore-outlining drilling.

4.2 Exploration drilling

Exploration drilling for new deposits on a regional scale is mainly influenced by two factors, viz. (i) are the deposits buried and blind and in virgin geological environments in which case exploration for them will be a high-risk venture regardless of premise, and (ii) is there any geological information available regarding the genesis of the sites of known deposits in a particular environment (district). Drilling in the latter case is much simpler and has quite a high degree of control.

The carbonate-hosted drilling targets are characterized by linear elements in an overall pattern appropriate to its palaeophysiographic setting, that is, linear, curved or straight reticulate or dendritic. The individual elements have lengths, thicknesses and widths varying quite considerably. The deposits localized by old shorelines (reef complex associated) as well as the deposits located at facies changes are usually strikingly linear. They may extend for kilometres in a relatively narrow zone; thus they do not have great areal extent. The karst associated deposits are commonly integrated into a dendritic pattern reflecting control by a subsurface drainage system. They have substantial areal extent, up to hundred of square kilometres (Callahan, 1977). Such targets are practically undetectable by remote sensing methods except where they occur at shallow depth and have sufficient density or conductivity contrast with their host to provide gravity or electrical anomalies. It is neither easy to intersect one with a drill hole nor to detect a near miss of mineralization due to the characteristic absence of a substantial halo of ore-associated alteration. Initial search for ore-type environment is done with widely spaced holes in practically horizontal host formations. Drilling in highly deformed strata would require a reliable structural and geological map as planning base. Stratigraphic drilling in the latter area would be very risky. Core logging of the widely spaced stratigraphic/facies drilling must be done in great detail in order to interpret any facies pattern and/or alteration, zonation, mineralization, brecciation and variation in lithological thicknesses that could point to an ore deposit(s). Drilling in all instances should only be done after a thorough study and interpretation of all available relevant geological information had been conducted. The grid spacing for regional drilling would vary according to the geological confidence limit that can be placed on the area of interest e.g. drilling in areas of sound geological information would be relatively close spaced and visa versa. Callahan (1977) and coworkers applied a random walk drilling system (figure 72) in exploring for blind deposits

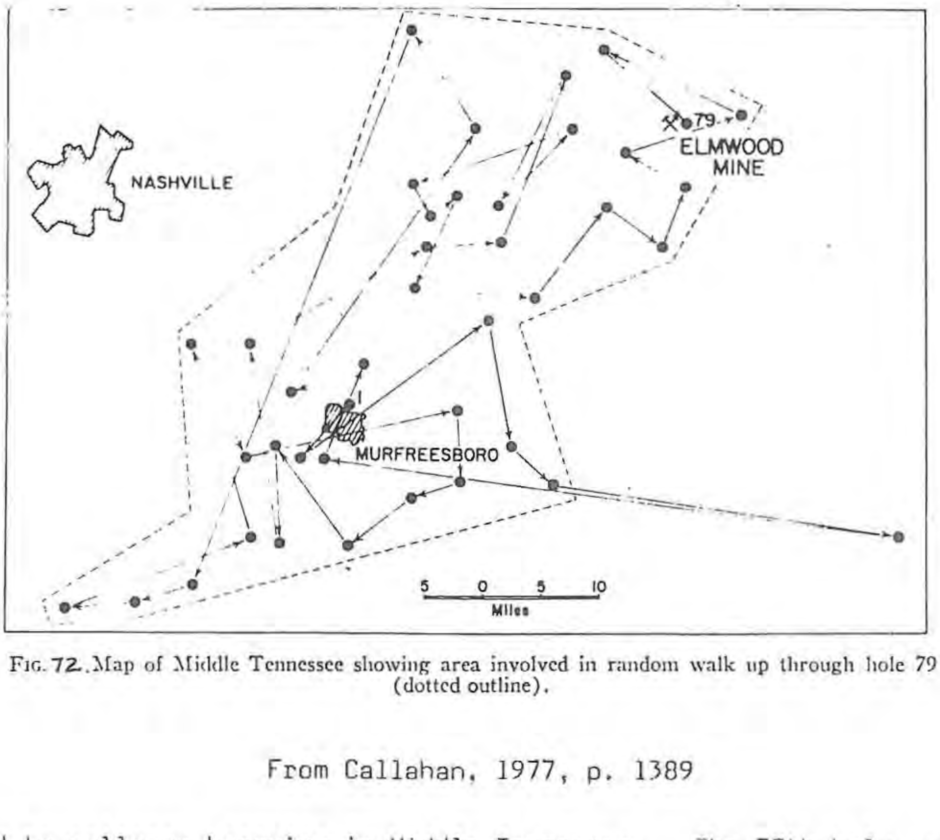


FIG. 72. Map of Middle Tennessee showing area involved in random walk up through hole 79 (dotted outline).

From Callahan, 1977, p. 1389

related to collapse breccias in Middle Tennessee. The 79th hole was the discovery hole of the Elmwood Mine. The drilling grid was then closed in to a 300 meters square grid. Or calculations made from 89 holes on this grid amounted to 50-75 million tons at a grade of 3.5 to 5.2% zinc. Callahan (1977) p. 1390 commented on the spread of the estimate: "although this estimate involves quite a spread, it should be remembered that in a mineralized fossil subsurface drainage system there is no sound basis for delineating the pattern and distribution or ore between holes for the purpose of making a conventional estimate of tonnage and grade. About all that can be said about the deposit is that ore is present at certain points in the area and the pattern of occurrence between can be determined only by mining". The confidence limit in the estimation was increased by sinking a prospect shaft and conducting underground exploration.

Regional exploration drilling for deposits associated with facies changes and reef complexes could be done on a regular square grid because of a much stricter geological control on ore deposition. The initial grid spacing can be anything between 5-10 km, closing in to 1 km spacings in the more favourable areas.

The extreme irregularity in mineralization (grade) both vertically and laterally within an ore-body as well as the discontinuity of mineralixation within a favourable depositional environment, e.g. along a reef or on strike within a slump breccia zone, necessitate close-, but not necessarily regular-spaced drilling to explore for and outline lead-zinc (copper) mineralization.

The most commonly used grid spacing for outlining ore and exploration of continuous ore in a specific environment is 30 metres and less e.g. Tynagh (Derry et al., 1965) (figure 20) Tsumeb, Upper Mississippi Valley (Heyl et al., 1959). The 30 metres parameter is applied to the strike direction of the ore horizon in the Upper Mississippi Valley Lead District (Heyl et al., 1959, plates 1-20). The drilling across strike is very often closed in to 10 metres (op cit). The overall drilling is guided by geology, structure and a lot of geological experience. The latter is a prerequisite in any carbonate hosted environment.

Drilling statistics (regression techniques) have been used by Wedow (1971) to generate models of mineralized solution-collapse structues in East Tennessee that can be used in exploration drilling. Hypothetical cross sections can be synthesized from widely spaced drill-hole data showing mineralized structures of a shape, size and distribution of metal that can be compared to thos diagrammed from actual field relations. From these hypothetical structures the relative position of a particular hole can be approximated within its own structure. The exploration geologist thus have a numerical aid for estimating the amounts of offset needed to penetrate the most favourable part of the mineralized collapse structure with second-stage drill holes.

Ore reserve estimation at Tsumeb is done on underground drill sections spaced 15 metres apart.

Detailed core logging is very important, not only from a geological point of view but also from the mining viewpoint. In the evaluation of ore-bodies, core logs of holes in the ore-body and adjacent holes must be studied for details of lithology of the host rock and of beds above and below the ore. Character of the rock that will form the mine back is noted. Consideration of logs of holes adjacent to the ore-body is necessary to define facies changes, initial dip of beds, and probable width of ore-body. The mineralized portions of the drill core are examined for character and distribution of ore, character of the host rock, extent of post-ore leaching (where applicable), and extent of grinding core. The specific gravity of the ore and the barren host between ore sections are determined for all sampling sections.

It is absolutely essential that the position of all diamond drill holes, both surface and underground, must be accurately determined before the evaluation of any ore-body can be considered to be complete. A slight error in angle or bearing of the hole will make a considerable difference 30 or 50 metres from the collar and may be the difference between cutting the ore-body and missing it. Grade control would also be seriously affected when estimated and mill head grades do not correspond because of faulty surveying.

4.3 Ore reserve estimation

Ore reserves are computed, according to Popoff (1966), to determine the extent of exploration and development; distribution of values; annual output; probable and possible productive life of the mine; method of extraction and plant design; improvements in extraction, treatment, and processing; and requirements for capital, equipment, labour, power and materials. Such computations are used to assist development planning; to determine production costs, efficiency of operations, and mining losses; for quality control; for financing mining venture; for sale, purchase, and consolidation of companies; to determine the production cost per unit of a marketable product; for accounting purposes such as depletion and depreciation; and in some countries for tax purposes. The extreme importance of an accurate and reliable ore reserve estimation can be realized in view of the above mentioned factors.

The most important but also the most difficult part of carbonate hosted lead-zinc ore reserve estimation is the correlation of the generally erratic mineralization from one section to another and from one level to another. An example would be where several zones of good mineralization, separated by zones of weak or no mineralization, is cut by a diamond drill hole. The weak or barren rock could bear good ore (due to the unpredictable erratic mineralization) a metre from the hole and the entire zone may represent minable ore. The drill hole data should be interpretated in light of knowledge of significant geological features characteristic in that area or environment. Such information is obtained b y combining drill information with surface and/or underground mapping. Cross sections, plans, and longitudinal sections are particularly useful.

Past production history of ore at a specific horizon in any area should also be considered. The mere fact that a certain horizon has been a productive one in the area does not mean that every economic hole at that horizon will mine equally well, but, if a certain zone has a poor production, pay holes in that zone should be interpreted with caution.

Mine workings of an area at the same geologic zone as the orebody are an important source of information on mining habit as well as on expected size, grade, and tonnage of ore.

The various factors that have an influence on the shape, size and grade of carbonate hosted ore deposits are almost unique in each individual deposit. Ore reserve estimation would therefore be "adapted" to the individual specific conditions.

The mining method, which is generally controlled by the geology also influences the ore estimation technique e.g. a cut-and-fill method is used to mine the Asis West ore-body which is very irregular and consists of pods and lenses of massive ore in virtually barren dolomite. Five metre ore-outline plans are constructed from drill section which are 15 metres apart. These are used to position the development (Venter, 1980). Ore reserve calculations for longhole open stoping of the Kombat mines, Namibia, are done by blocking out drill sections so that the thicknesses and grade intersected in a particular borehole is carried half-way to the adjacent borehole and 7,5 metres on either side of the section. The volume of each block is calculated and then multiplied by the specific gravity; the latter calculated for each grade by using a Tsumeb Corporation Formula (Söhnge, 1961) which takes into account the extreme specific gravity differences between the metals and barren host rock. The specific gravity factor is combined with each single assay to arrive at a properly weighted average for any group of assays representing a block of Tsumeb-Kombat ores (Söhnge, 1961).

The initial drill-core investigation and interpretation is followed by constructing ore blocks based on geologic inference. The latter include natural boundaries due to structural features (synclines, anticlines, faults, or other dislocations, changes in strike or dip); changes in character of mineralization; thinning out or pitching of oreshoots; zoning; weathering; different physical properties; heterogenous composition, varied alteration; and the presence of detrimental constituents.

Common technologic, physiographic, and economic ground for inference in construction of blocks are topography, thickness of overburden, ratio of overburden to thickness of mineral body, depth, water level, mining methods, processing methods, and cost of extration; also property, section-, and township boundaries (Popoff, 1966).

The structural factor influences ore reserve estimation in that faults, which either increase or decrease the grade on either side of it, will have to be taken as a boundary when blocking out a deposit.

The style of folding is also important in localizing high grade portions of an ore-body e.g. the galena-sphalerite ore at the Namib Lead Mine, Namibia (Ainslee, 1980) is concentrated in elongated steeply plunging boudins representing parasitic folds of a regional refolded structure. Extremely high grade areas are characteristically separated by very low-grade to barren portions.

Supergene altered areas must be blocked out and calculated separately due to the extreme difference in grade and specific gravity.

Zoned ore-bodies must be blocked out in such a way that the individual metal zones are calculated individually as far as practicably possible. This would simplify grade control as well as plant design and feed.

The importance of blocking out and calculating ore reserves for different ore types are illustrated by the following example:

Ore reserve estimation of the Tynagh residual open pit ore-body and stockpiles in Ireland (FitzGerald and Oram, 1969) are done at the end of each year and a long-range mining schedule is drawn up.

Original churn and diamond drilling from surface on a 33 metre (100 foot) pattern indicated two types of reserve-sulphide ore and oxide ore. In the light of operating experience and grade control, it became necessary to utilize the original data, as far as possible, to predict ore types more accurately. The ore was then classified into treatment types, and this is done according to the concentrates which may be produced from them. With these data, and other information from pit geological mapping and advance grade control drilling, a set of bench plans is compiled to show the bench outline and primary and secondary ore structures, with tonnages and grade calculated on a block basis. The drill-hole at each corner of each block contributed to the block result according to its total sample length and tonnage factor. The volume, mean density and weight of ore, and of waste where it occurred above or below ore, were computed in addition to the weighted average of ore grades.

The size of the blocks depends on the density of drilling; in this case 8 metres (25 foot). The boundaries of the blocks are determined by ore type contacts or by the perpendiculars at mid-points between holes where adjacent holes are in the same ore type. Thus the geometrical and geological concepts of block configuration are combined to give the most accurate picture possible. Reserve tonnages are then summarized bench by bench and a total reserve by ore type is calculated. Ore stockpiles are included.

The use of polygons in blocking out ore blocks seems to be the most widely used method in the very irregularly shaped and mineralized carbonate hosted ore deposits of Joplin and Wisconson (Upper Mississippi Valley) in 1920 (Harding 1920). This method is at present being applied at the Buick Mine in the Viburnum Trend (Shealy, 1980 pers. com.). The peripheries of the ore deposits are taken on the last hole that intersected ore. Interpretation of ore extensions beyond these holes can only be done by means of a very thorough knowledge of the mineralized structure. The ploygon method can only be successfully applied if polygonal plans are constructed every few metres below surface. The extremely variable grade and specific gravity of the ore could then be depicted.

The Tsumeb ore deposit is divided into trapezian blocks on section. The trapezians are created by intersecting bore holes and ore-body peripheries (Söhnge, 1966). The influence of each section is 15 metres laterally.

The actual calculation of tonnages and grade must incorporate the variable spesific gravity problem encountered in polymetallic deposits. This can be done by applying the specific gravity factor as calculated by the Tsumeb Corporation (Söhnge, 1966). The specific gravity factor eliminates, to a large extent, the dilution that was caused by the barren host rock and the variation in metal specific gravities. A dilution factor of 10% was previously applied to the calculations at the Tsumeb Mine (Söhnge, 1966).

Several corrections are applied to block volumes depending on the character of the ore. Deductions have to be made if the ore is accompanied by a lot of low specific gravity waste e.g. breccia bodies; only massive ore are excluded. Deductions are also made if the ore is well oxidized and vuggy; volumes are cut by up to 10%.

The accuracy of the results increases with the number of blocks and the density of the grid of workings and drill holes. Most ore reserve calculations are updated on a three monthly basis due to additional information gained by mining and/or drilling.

Ore reserve calculations of selected stopes of the massive subhorizontal lead-zinc deposit at the Mogul Mine, Silvermines, Ireland (Filion, 1976 and geology by Morrissey et al., 1971) were done by three methods and the results compared. Computations were done by means of a geostatistical approach, a standard polygonal method and a classical statistical method. The classical statistical method proved to be sufficiently adequate and less time consuming than the standard polygonal method. The hand calculated geostatistical results showed very little precision as to the grade around the mean and may be used for grade control in specific blocks of ore (Filion, 1976).

Universal Kriging for ore reserve estimation has been applied to the Navan lead-zinc deposit (Dagbert and David, 1976). Dagbert and David came to the conclusion that less time consuming simpler methods of estimation or geostatistical inference could produce the same results. The kriging method does allow the quantification of the amount of confidence that can be attached to the estimation. The principles of the method insure that the error of estimate is the minimal that can be expected taking the available information into account.

5.0 MINEABILITY AND EXTRACTABILITY OF CARBONATE HOSTED LEAD-ZINC (COPPER) DEPOSITS

5.1 Mineability

Ore-bodies in any area or district have to be evaluated as a development risk by both the exploration geologist and the mine geologist. The geologists therefore must have a basic knowledge of the various mining methods that can be applied in exploiting deposits of various attitudes, shapes, continuities and regularities. The information gained from mapping and from drill logs provides the basis for evaluation. This evaluation has been discussed under section 4.3.

Ore-bodies can be rated according to decreasing mining probability on a scale developed to meet individual requirements. Number one on the scale will be a certain economically viable proposition; the last one on the scale will be unproductive. Most of the items on the scale involve little subjective judgement. The requirements of return relative to development cost embraces those intangibles gained from study of drill core and first hand knowledge of the area and is carefully weighed for each ore-body.

Classification of ore-bodies by geological features, although necessary in interpretation, is of little direct value to operators. It is more useful to classify according to mining habit. By mining habit is meant those characteristics of an ore-body, particularly size, shape, and nature of the mining floor, that determine the development and mining procedure necessary for most complete and economical extraction of the ore. Variations in mining habit, for example, of Lead Belt ore-bodies in southeast Missouri (Snyder and Emery, 1956) are due to minor, but usually predictable, features of the host rock. Mining habit is not related to any stratigraphic zoning although zones show a disposition toward one or toward a limited number of mining habits. The major zone contacts at all horizons may be similar in habit. If of sufficient size and tenor, an ore-body within a reef complex may have the same mining habit as a bedded deposit.

Mining habit must be related to the basic methods and equipment used in a district. Methods that influence classification of ore-bodies include haulage gradient and minimum operating width.

Figure 73 outlines the classification of ore-bodies in southeast Missouri (Snyder and Emery, 1956).

The type 1 ore-body has a floor which slopes less than 6% and has a minimum width of 30 metres. This width is chosen because this is the minimum dimension at which any angle of approach will allow complete reversal of track within the ore-body. With less width certain angles of approach necessitate redevelopment, leaving some ore, or taking low grade rock. Ore-bodies falling within this group include most of those on the main stratigraphic contacts.

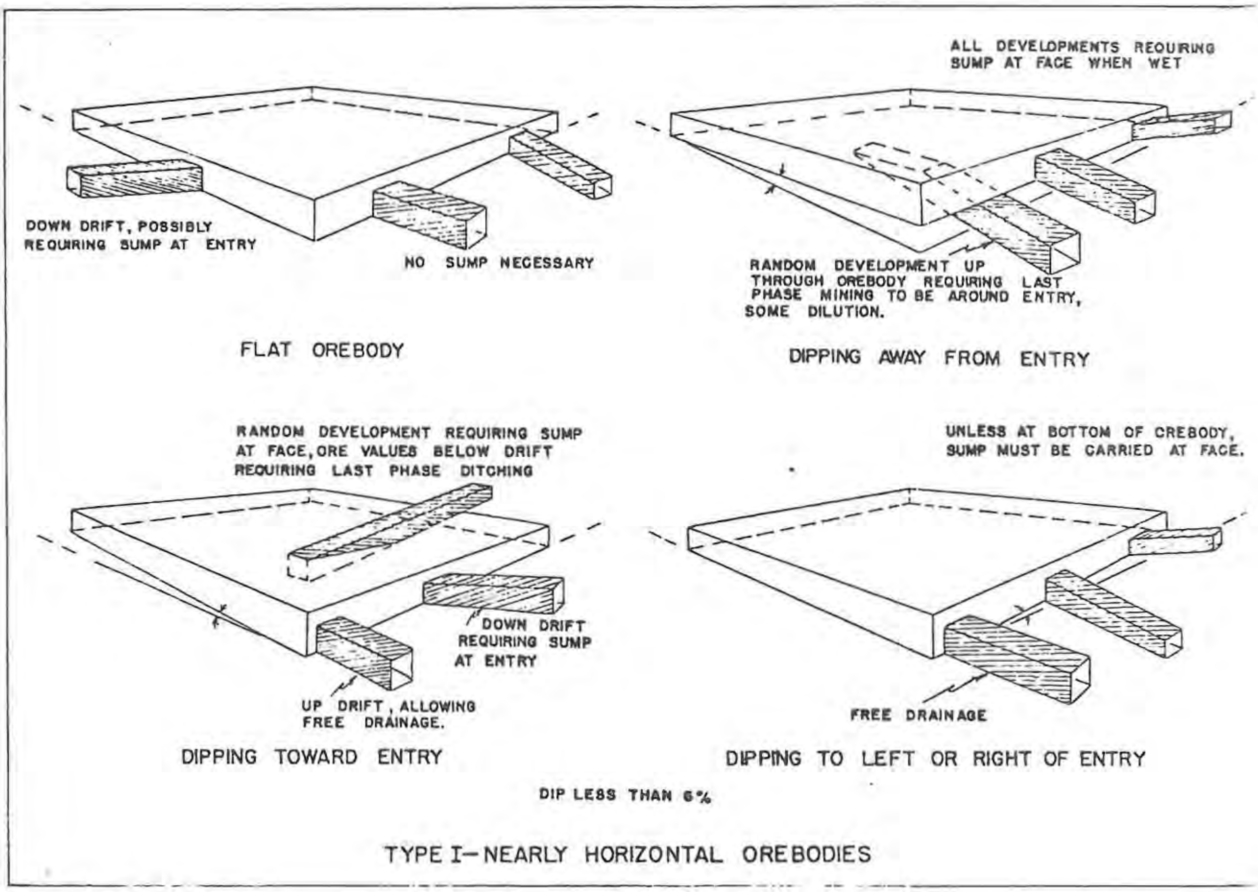
The approach of an ore-body from the best possible position, even if it requires additional development is worthwhile in order to secure better mining conditions and lower mining cost.

The type II ore-body has a floor that slopes less than 6% and has one lateral dimension less than 30 metres but more than 6 metres. The ore-body is wide enough for trackless haulage. With the use of track, preferred mode of development is to make entry relative to shape and trend of ore-body as shown in figure 73.

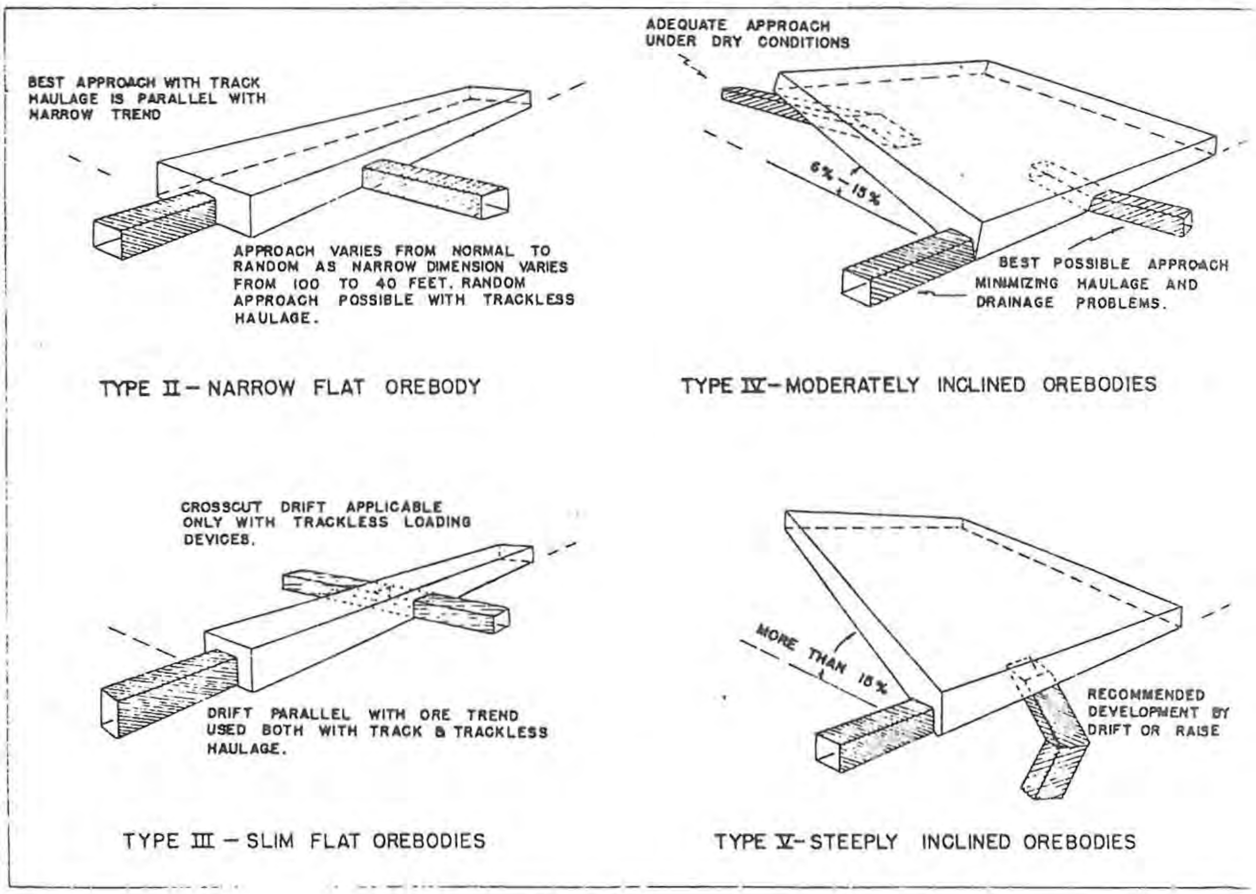
The type III ore-body has a floor that slopes less than 6% and has one lateral dimension less than 6 metres. These ore-bodies are not mined as the ore zone is too narrow to carry a heading. The most common occurrence is within the reef complex where individual roll-edges may be too widely separated to mine two or more as a single heading.

The type IV ore-body has a floor sloping more than 6% but less than 15%. As the ore-body is too stepply inclined for track haulage, width is not a factor. Ore-bodies of this type occur as bedded deposits at all stratigraphic zones. In those stopes which have been developed for track haulage mining is done in parallel benches resulting in considerable dilution of ore and multiple development to stay with the dip of the mineralization. Development or ore at the level indicated by the drillhole usually does not provide an entry favourable for mining. Attention must be given to slope of floor and trend of ore-body prior to development.

The type V ore-body has a floor sloping more than 15%; width is not a factor. Ore-bodies of this type are not common. They are found along the flanks of the structural centres and on porphyry knobs.



↑ Fig. 73.—Recommended development for type I orebody. ↓ Fig. 73.—Recommended development for types of orebodies.



From Snyder and Emery, 1956

Mining of the open space and fracture filling sphalerite ore-bodies, ranging in thickness from 3 to 46 metres and dipping from flat to 20°, in East Tennessee (Dunaway, 1977), is done by random room and pillar method modified by shrinkage and bench stoping.

The exploitation of breccia associated ore deposits poses a much more difficult problem than the more stratiform deposits. The irregular distribution of the mineralization as well as the irregular shape of the ore-bodies both vertically and laterally necessitates the application of more than one mining method.

The contacts of the ore-bodies with wall rock are generally sharp and assay contacts are a rarity.

The hangingwall conditions, or also known as the mine back, are an important factor to consider when planning mine development. The hangingwall conditions are determined by weathering, faulting and fracturing as well as the composition of lithology. A good example of a lithological control on mine back stability is at Kombat, Namibia, where a dolomite-phyllite contact composes the hanging of the karst-associated deposits.

Close co-operation between the geology- and mining departments is necessary for the most economical exploitation of an ore deposit. This can be achieved through periodic visits to active stopes with operating staff. The geologist must become familiar with the problems that face the mining department in their efforts to maintain grade and tonnage and to control mining costs. Such contacts cement relations between geological and operating staffs and develop a co-operative approach to mutual problems. Operating staff is also acquainted with major relevant aspects of geology of the mine. The main zone constacts, recognition of rock type in each zone, important types of structures that control ore trends and recognition of displacement on faults represent useful information to the operator.

5.2 Extractability of the ore minerals.

5.2.1 Nature of the ore

Primary sulphides of carbonate hosted ore deposits occur mainly as open -space filling and/or replacement of a suitable host. The economic concentrations of these sulphides are considered to be epigenetic, and this together with the low temperature deposition and generally unmetamorphosed character of these ores generally results in simple ore- and ore/gangue relationships.

The ores show several varieties of texture dependent upon the process of deposition, structural control, and wall rock alteration (Heyl, 1968):

(a) veins with comb structures or colloform bands with symmetrical or asymmetrical banding,

(b) solid veins of one or more minerals,

(c) individual well-formed crystals impregnating host rock without notable replacement of the rock grains,

(d) individual euhedral crystals that replaced the host rock,

(e) coarse and fine crystals lining open cavities,

(f) reniform, colloform, nodular, and stalactitic masses,

(g) replacement of fossils,

(h) pseudomorphic replacement of earlier formed minerals, and

(i) massive replacement of host rock by more than one mineral.

The granularity of these ores varies from very coarse grained (decimeters) to fine grained (less than 2 mm) but very rarely microscopic. The simple grain-boundary relationships and the relatively coarse-grained nature of the ore minerals and gangue facilitate their liberation during metallurgical extraction processes.

The polymetallic ores of the Tsumeb deposit in Namibia (Söhnge, 1961) are more complex. Compact intergrowths of galena, sphalerite and copper minerals are typical but pose no serious problem in extraction.

Minor economic constituents of the carbonate hosted lead-zinc and copper minerals are mainly silver, cadmium, germanite and renierite.

The silver occurs as substitutions in the galena and sphalerite lattices.

Cadmium is present in the sphalerite lattice to values of up to 2% e.g. Tsumeb.

Germanite and renierite form occasional local stringers in dolomite wall rock and rare veins in high-grade copper ore at Tsumeb. They are economically important because of their widespread presence as microscopic intergrowths in the copper ores. The ore will have to be crushed to a very small size in order to liberate these intergrowths; the result of which could be loss of primary sulphides due to sliming.

The silver and cadmium are recovered during the smelting process.

The recovery of the metals from the secondary ores is relatively simple because the metals have already been liberated from the sulphide and gangue constituents. Oxide minerals do pose a problem in the chemical extraction of sulphides e.g. a cerussite coating on the galena prevents reaction of chemicals with the lead and a major loss could occur. This coating can however be removed by acid but its presence must be known.

5.2.2 Quality of the ore

The quality of the carbonate hosted ores is generally high. The main detrimental impurities are iron and arsenic.

Galena is very pure; the only "impurity" is silver that is incorporated in its lattice.

The quality of sphalerite is measured by its iron content. The iron contents vary from 0,3% to 3,75%; the latter is exceptional. The high iron content sphalerite is characteristically darker in colour and the lower iron content sphalerite is more yellowish. The two types of sphalerite very often occur in one deposit and are related to two different periods of mineralization.

Arsenic usually occurs in iron sulphides and arsenic sulphides can reach concentrations of up to 3% in marcasite (Galkiewicz, 1967).

The main copper minerals are chalcopyrite, bornite, chalcocite, tennantite and enargite.

Tennantite is the most persistent copper mineral in the Tsumeb deposit and locally contains up to 8% zinc. The other copper minerals are devoid of any impurities.

SUMMARY AND CONCLUSIONS

Carbonate hosted lead-zinc (copper) deposits owe their origin and distribution to normal sedimentary and diagenetic processes rather than igneous processes. Available geological and geochemical data indicate that the solutions that deposited the ores were low temperature concentrated sodium-calcium-potassium chloride brines. The source of the metals of most deposits are still controversial. The "Alpine- type" deposits have in many cases some igneous intrusion associated with them although not directly. The Northgate base metal deposit in Ireland has a very strong volcanogenic overtone.

The lack of any significant detail genetic classification of these "sedimentogenic" deposits is due to the fact that almost each one is unique in its own right. The only unquestionable characteristic that is common to all these deposits is the fact that they are associated with shallow water platform carbonates. Palaeoshorelines and palaeohighs with superimposed tectonic features control the location and geometry of carbonate hosted deposits.

The shape, size and distribution of grade of these deposits are primarily governed by primary and/or secondary porosity and permeability. The very irregular and mostly unpredictable distribution of mineralization complicates exploration drilling and ore reserve estimation. Very expensive close-spaced drilling is required to arrive at a dependable tonnage and grade estimation. In reality these figures are only proved (or modified) by actual mining. Regular re-evaluation of tonnage and grade is essential in order to maintain a fairly accurate grade control. The extremely erratic lateral and vertical distribution of mineralization in any one deposit has resulted in many companies abandoning actual sampling of the deposit as a means of grade control. Grade control is carried out by underground observations of the mineralization using nomographs.

The application of statistical and geostatistical methods to try and predict variability of grade in any one deposit has to date not proved to be very successful. The use of variograms, provided samples are sufficiently big and densely spaced, could, to some extent, predict variability.

The building up of a universally applicable, standardized carbonate hosted "type" model(s) is just not possible. A thorough geological knowledge of a deposit is a prerequisite to the economic exploitation of that deposit.

The continued existence of carbonate hosted lead-zinc-copper exploration and exploitation as an investment alternative is dependent on the geological, mining and mineral economic expertise of the company concerned.

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