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Comparison of the Cracow-Silesian Mississippi Valley-type district, southern Poland, with Mississippi Valley-type districts in North America

by

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Abstract

Preliminary results of field observations, geological, geochemical, and sulfur isotope studies of the Cracow-Silesian Mississippi Valley-type district, southern Poland, provide new constraints on the genesis of ore deposition. These results together with previous studies provide a basis for comparing the Cracow-Silesian ore district with deposits of the Mississippi Valley-type in North America.

The major controls on ore deposition in the Cracow-Silesian district appear to be a combination of dolomite to limestone transition, shale edges, faults, and pre-ore karst breccias. Evidence suggests that the ore-bearing dolomite was formed prior to sulfide minerals and unrelated to the deposition of sulfides. The important breccias that host much of the ore in the district are believed to be pre-ore karst features which were later enlarged, replaced, and altered by sulfide deposition. Many ore textures, including breccia-hosted ore, can be interpreted as products of fabric-conservative sulfide replacement. Hydrothermal brecciation is common in the district but less important than sulfide replacement of pre-ore breccia. Faults played a critical role as ground preparation to produce enhanced fracture-controlled permeability for stratigraphic fluid flow and pathways for ascent of ore fluids.

Fluid inclusion studies show that the ore fluid was highly saline, with final melting temperatures between -13.9 to -29.4° C corresponding to 19 to significantly greater than 23 wt. % NaCl equivalent salinity. Homogenization temperatures are from 45 to 140° C. Fluid inclusion gas analysis shows that the dominant gas is CO_2 with lesser amounts of H_2S and CH_4. The total gases in the fluid inclusions are less than 1.5 mole %. Gas compositions of the fluid inclusions appear to contain two distinct compositions, one containing CO_2+CH_4 and the other containing CO_2+H_2S. Highly

variable salinity together with apparent bimodal fluid inclusion gas compositions are consistent with fluid mixing as an ore depositional process.

Lead isotopes suggest a crustal source with a homogenous lead isotopic composition. In addition, homogenous lead isotopes in the district require ore deposition to be a short-lived event, rather than multiple, extended process. Although the model-lead age for the ore is Triassic, the presence of ore minerals in Upper Jurassic rocks and in faults that displace Upper Jurassic rocks, requires ore deposition to be post-Upper Jurassic in age. Sulfur isotopes have the widest range of those reported from Mississippi Valley-type lead-zinc districts and they suggest multiple sources for the sulfur. In addition, certain galena samples from the Cracow-Silesian district contain the the lightest sulfur isotopes (-18.6 $d^{34}S$.) reported for any MVT district.

The Cracow-Silesian ores contain a wide variety of trace and minor elements. Compared to other Mississippi Valley-type districts, sphalerite from the Cracow-Silesian district contain the widest range in Fe, Cd, and the second widest range in Ag concentrations.

The features of the Cracow-Silesian district are remarkably consistent with the characteristics of Mississippi Valley-type districts throughout North America. However, each district has its own set of characteristics that sets it apart from other districts. Compared to North American Mississippi Valley-type districts, the Cracow-Silesian district shares many features with Pine Point, northern Arkansas, Tri-State, and Polaris districts.

Introduction

The Polish Geological Institute and the United States Geological Survey are conducting geological and geochemical studies of the Mississippi Valley-type (MVT) ore deposits in the Cracow-Silesian (C-S) zinc-lead district in Upper Silesia, southern Poland. Other scientists participating in this study are M. Szuwarzynski (Trzebionka mine), A. Kozlowski (University of Warsaw), D. Symons (University of Windsor, Canada), and D. Sangster (Geological Survey of Canada). These studies are intended to provide new information on the genesis of the ore and controls on the distribution of ore deposits for this important ore district.

This paper resents preliminary interpretations of field observations on possible geologic controls on C-S ore deposits, their ore and mineral textures, and briefly discusses new geochemical data. In addition, important features observed for the C-S district are compared to North American MVT deposits. This paper is not intended to be a comprehensive genetic or exploration model for the C-S district nor is it intended to provide a thorough discussion of implications of the new data presented. This paper should be considered a "descriptive progress report" on our investigations in the C-S district because many geochemical, isotopic, and fluid inclusion data are unavailable at the time this paper was prepared. Nevertheless, the new observations and data presented on the C-S district provides an opportunity to reexamine existing concepts on the genesis of the ore deposits and suggests new constraints on the the process of ore emplacement. The information presented may provide incentives for additional research that needs to be conducted as well as stimulating "cross-fertilization" of observations between North American MVT districts and the C-S district.

Description of Mississippi Valley-type deposits

The following is a summary of the important features of world MVT deposits described by Leach and Sangster (in press). Leach and Sangster (in press) described lead-zinc deposits of Mississippi Valley-type (MVT) as a varied family of epigenetic ores precipitated from dense basinal brines at temperatures ranging between 75 and 200°C, typically in platform carbonate sequences. The great diversity of geological and geochemical characteristics between MVT districts has hindered development of a unifying descriptive or genetic model for these seemingly simple deposits. Recent advances in understanding large-scale fluid-flow in the crust, coupled with new geochemical and geological studies of MVT districts, have established that most MVT ore districts are the product of regional or sub-continental scale hydrological processes. Therefore, diversity among MVT districts is expected because of the wide range in fluid composition, geological and geochemical conditions, fluid pathways, and precipitation mechanisms possible at the scale of MVT fluid migration. Other than the general definition of MVT deposits given by Leach and Sangster (in press), a single descriptive or genetic model for all MVT deposits is an unreasonable expectation (Sangster, 1983).

MVT deposits are found throughout the world (Fig.1) but the largest, and most intensely studied, occur in North America where the deposit-type was first recognized more than 50 years ago (Bastin, 1939). MVT deposits owe their commonly accepted name to the fact that several classic districts are located in the drainage basin of the Mississippi River in central U.S.A. Outside of North America, important MVT districts include Cracow-Silesian in Poland, the Alpine district of Austria-Yugoslavia-Italy, and lately, the Lennard Shelf area of Western Australia has emerged as a new, potentially significant, MVT district (Fig.1).

Lead and zinc are the most common commodities recovered from MVT lead-zinc deposits, although the relative proportions of these elements vary widely between districts. In some areas, silver is an important by-product, but generally it is negligible. Cadmium, germanium, barite, and fluorite are recovered in some districts as minor by-products. In the southeast Missouri and, to a lesser extent, the Upper Mississippi Valley districts, Cu, Ni, and Co are diagnostic accessory elements.

The most important characteristics of MVT lead-zinc deposits presented by Leach and Sangster (in press) are:

1) they occur principally in dolostone, rarely in limestone or sandstone;
2) ore is epigenetic and stratabound;
3) they are not associated with igneous activity;
4) they commonly occur at shallow depths at flanks of basins;
5) they occur in platform carbonate sequences, located either in relatively undeformed rocks bordering foredeeps or in foreland thrust belts;
6) they typically occur in districts which cover hundreds of square kilometers, and a number of districts may even form metallogenic provinces;
7) they form districts that are localized by geologic features that permit upward migration of the ore fluids; examples are breccias, depositional margins of shale units (shale edges), facies tracts, faults, and basement highs;
8) the temperatures of ore deposition are low (75 to 200°C), but typically higher than can be accounted for by local basement-controlled thermal gradients; ores were typically deposited by fluids that were at or close to thermal equilibrium with the host rocks;
9) they are mineralogically simple, with dominant minerals being sphalerite, galena, pyrite, marcasite, dolomite, calcite, and quartz;
10) associated alteration consists mainly of dolomitization, brecciation, host-rock dissolution, and dissolution/crystallization of feldspar and clay;
11) there is always evidence of dissolution of carbonate host rocks, expressed as slumping, collapse, brecciation, or some combination of these;
12) the ore fluids were dense basinal brines, typically containing 10 to 30 wt.% salts;

13) their isotopic compositions indicate crustal sources for both metal and reduced sulphur; and
14) the sulphide textures are extremely varied, and the ores range from coarsely crystalline to fine-grained, massive to disseminated.

Geology of the Cracow-Silesian MVT district

The following is a brief description of the regional geology of the C-S district, largely summarized from Wodzicki (1987). Ore deposits in the district are hosted mainly in the Muschelkalk Formation (Middle Triassic) in the Silesia-Cracow monocline in southern Poland. The Silesia-Cracow monocline contains Triassic, Jurassic, and Cretaceous rocks that dip gently to the northeast. Sulfide deposits largely of sphalerite, galena and iron sulfides are typically stratabound and tabular in form and show a close spatial relationship to karsts and faults. Most of the ore occurs as replacement of a variety of rock fabrics and as open space produced during replacement and dissolution of the host rock during sulfide deposition. Economic deposits are contained within an extensively dolomitized part of the Muschelkalk referred to as the ore-bearing dolomite (Bogacz et al., 1972). However, the ore-bearing dolomite is considerably more extensive than the known ore deposits and mineralization is present in rocks that range in age from Devonian to Upper Jurassic and possibly Tertiary.

The C-S district is located at the boundary between the Caledonide Cracow-Myszkow structural zone, the Varisican Upper Silesian coal basin and the Carpathian foredeep produced during Alpine orogenic phases in the Cretaceous to Tertiary periods (Fig. 2). The Cracow-Myszkow structural zone may represent a large crustal boundary or flaw that has been a locus for deformation in both the Caledonian and Variscan orogenies and was tectonically reactivated during Alpine deformation. The Cracow-Myszkow zone is a positive structural element in the pre-Mesozoic basement in which the southern portion coincides with a deep lineament indicated by gravity anomalies (Sass-Gustkiewicz et al. 1982). Illustrated in Fig. 2 is the generalized pre-Cretaceous geology of the area and in Fig.3 is a idealized geologic cross-section.

In the central and eastern eastern part of the district, the Precambrian crystalline basement is unconformably overlain by at least 11.5 km of Cambrian through Silurian sedimentary sequence dominated by flysch. These sediments were intensely folded along a NNW axes (Ekiert, 1971) and metamorphosed during the Caledonian orogeny. This Caledonian basement is overlain by Lower Devonian sandstones and carbonates and Middle Visean (Carboniferous) carbonates.

In the Upper Silesian coal basin, the Precambrian crystalline basement is overlain by 400 m of Cambrian and Lower Devonian sandstones, up to 1.5 km of Middle Devonian sandstones and Visean carbonates, and 1.5 km of Visean flysch-like shales, and up to 8 km of Carboniferous coal-bearing molasse (Wodzicki, 1987). During the Variscan orogeny, the western part of the Silesian basin was intensely deformed and cut by NNW-striking thrust faults whereas the eastern part of the basin was cut by WNW-striking normal faults. In the C-S district, Permian terrestrial sediments were deposited along a WNW-striking tectonic depression, which is connected to the central Permian basin in Poland.

At the close of the Paleozoic, appreciable relief existed in the Variscan basement. During the Triassic, marine trangression produced a large shallow carbonate platform in which existed "islands" of the Paleozoic basement. The Mesozoic and younger stratigraphic sequence is shown in Fig.4. After deposition of Muschelkalk, a disconformity developed and was followed by deposition of non-marine shales of the Keuper Formation. During Early to Middle Jurassic, the region remained above sea level. In Cretaceous through Miocene, the area was affected by Alpine tectonics that produced uplift, erosion with periods of marine transgression, and widespread faulting; the most intense Alpine faulting occurred at the end of the Cretaceous, Early Tertiary, and during the Miocene. Approximately 20 km south of the C-S district are the most inboard Carpathian thrusts of Miocene age. The proximity of a orogenic foredeep to the C-S district has important implications for possible migration of MVT ore fluids (e.g., Bethke and Marshak, 1990; Garven, 1985).

Time of mineralization

At present, the best constraints on the time of mineralization are field observations on the distribution of sulfides with respect to host rocks and time of faulting relative to ore emplacement. The arguments presented here are based on the premise that paragenetic stages of mineral deposition in the district, regardless of host rock or geographic location, represents a specific time of sulfide deposition. This premise is supported by the observation that the same mineral paragenesis is present throughout the district and in occurrences in rocks from Devonian to Upper Jurassic (Haranczyk, 1979; 1984; Gorecka et al., 1992; this study). In addition, mineralization at the Klucze deposit cuts faults that displace Upper Jurassic rocks. Therefore, the age of mineralization must be younger than Upper Jurassic (Gorecka, 1991). Although it could be argued that mineralization in Upper Jurassic rocks is a younger mineralizing event superimposed on an older episode of mineralization. However, other evidence supports a discrete episode of mineralization. Lead isotopes in the district are remarkably homogenous, consistent with a relatively short-lived mineralizing event rather than several episodes on ore formation (Church and Vaughn, 1992). Fluid inclusion studies show a distinct decrease in fluid inclusion homogenization temperatures with decreasing depth (Kozlowski, 1991), consistent with a discrete period of mineralization rather than superimposed and unrelated mineralizing events.

Although it is clear that mineralization is younger than Upper Jurassic, it is unclear how young ore deposition may be. It is possible that the age of mineralization is Cretaceous or Tertiary. This is suggested by the observation that the normal faults that are important ore-controlling structures in the Klucze and Trzebionka deposits appear to be related to reactivation of NW-trending basement faults with EW-trending faults (Kibitlewski, personal communication, 1992). These EW-trending faults have a similar trend with with structural features in the Carpathian orogenic belt of Cretaceous to Miocene age. (Kibitlewski, personal communication, 1992). Although this potentially important observation needs more clarification, it is reasonable to suspect that Alpine compression may have played a role in the important fault-controlled mineralization in the district. Other evidence consistent with post-Jurassic mineralization are the presence of sulfide minerals and barite in post-Jurassic faults (Haranczyk et al., 1968) and along Cretaceous or even Tertiary fractures (Haranczyk,1979). Bogacz et al. (1970) and Panek and Szuwarzynski (1975) report weathered clastic fragments of galena in pre-Miocene sinkholes, suggesting a pre-Miocene age for mineralization. However, the genetic relationship of these minerals occurrences to the C-S district ores is unclear.

Source and migration of the ore fluids

The source of the ore fluids is speculative at best. Pelissoner (1986) and Rozkowski et al. (1979) suggested that fluid flow was artesian in nature. Rozkowski et al. (1979) specifically implicated uplift of the pre-Carpathians as the recharge area for the C-S ore fluids. Wodzicki (1987) suggested episodic release of thermal waters derived from diagenesis of sediments in the Carboniferous coal basin. Recent work (Gorecka et al. (1992) suggested seismic pumping from tectonically active faults within the Paleozoic basement as source for the ore fluids.

If an analogy is made with North American MVT districts where fluid flow for MVT deposits have been linked to fluid migration away from orogenic belts (e.g., Bethke and Marshak, 1990; Leach and Sangster, in press), a possible control on fluid migration for the C-S district may be the Alpine orogeny in the Carpathians. If this is true for the C-S district, a likely time for fluid migration would be in the Late Cretaceous or Tertiary, coinciding with intense Alpine deformation in the Carpathians.

District ore controls

Shown in Table 1 are various ore controls recognized for world MVT deposits (Leach and Sangster, in press). Each can be viewed as some fundamental control on ore fluid transmissivity, either at the district or mine scale, that allows the focusing of fluid flow and creates the opportunity for depositional processes to occur. All ore controlling features typically have their unmineralized counterpart in each district, suggesting that several controls must have been important in localizing ore. In the C-S district, ore may have been controlled by the combined effects of limestone to dolostone transition, shale edge, karst breccias, and faults on the migration of the ore fluids.

Shale edges

In some North American MVT districts, shales and shaley carbonates acting as aquitards within a stratigraphic sequence, may have provided an important control on the migration of ore fluids. The relationship between a shale edge and localization of MVT deposits in the Tri-State district is shown by the occurrence of ore only beyond the subcrop edge of the Chattanooga and Northview shales, both of which stratigraphically underlie the main ore-bearing carbonate units in the district (Siebenthal, 1916; Brockie et al., 1968,). Palmer and Hayes (1989) extended this concept to other Ozark MVT districts and found similar relationships. Possibly shale edges allowed the ascent of the regional brines into overlying rocks and the subsequent cooling, fluid mixing, and wall rock alteration to produce ore.

It is possible that shales in the Carboniferous Silesian coal basin may have played a similar role in the C-S district. As noted by previous workers (e.g., Rozkowski et al., 1979; Wodzicki, 1987) the C-S district is located near the edge of the Carboniferous coal basin which contains a significant thickness of shales and coals. Triassic rocks in the southwestern part of the district overlie the Carboniferous coal deposits. It is possible that regional migration of ore forming fluids through the Carboniferous basin (Rozkowski et al., 1979; Wodzicki, 1987) was confined by shale aquitards. Ore forming fluids may have ascended into platform carbonates at the edge of the shales and coals or where the aquitards were breached by faults.

Ore-Bearing dolostone

C-S economic MVT deposits (Fig. 2) are hosted in what is referred to as the "ore-bearing dolomite" (Bogacz et al., 1972). Ore-bearing dolomite is contained within the Lower Muschelkalk Formation and occurs as extensive replacements of limestone and early diagenetic dolostone (Bogacz et al., 1972). Contacts between the ore-bearing dolostone with rocks of different depositional environments are often sharp and discordant. Ore-bearing dolomite was formed after the deposition of the Muschelkalk but before Jurassic sedimentation (Petrascheck, 1918). During Early Jurassic, it was exposed to weathering and karstification (Sass-Gustkiewicz et al. (1982). Entrenched in the literature is the concept that the ore-bearing dolostone is genetically and temporally related to the emplacement of MVT sulfide minerals (e.g., Haranczyk, 1970; Bogacz et al., 1972; Bogacz et al., 1973; Sass-Gustkiewicz et al., 1982). However, Haranczyk (1970) and Mochnacka and Sass-Gustkiewicz (1981) restrict the formation of the ore-bearing dolomite to the formation of paragentically early disseminated sulfides and not main-stage ore. The concept of genetically relating formation of ore-bearing dolomite to sulfide deposition is apparently based upon the following points: (1) The ore-bearing dolostone is epigenetic and discordant with younger limestones and "diagenetic dolostone" (as used by Bogacz et al., 1972); (2) The ore-bearing dolostone is host for economic ore deposits and often contains disseminated sulfides, and in places, contains anomalous zinc and iron as carbonate phases; (3) Minor disseminated sulfides are common in the ore-bearing dolostone and the size of the sulfide crystals are similar to the carbonate grains (Mochnacka and Sass-Gustkiewicz, 1978).

The evidence presented for the coeval precipitation of sulfides and dolomitization do not provide conclusive evidence that ore-bearing dolomitization of the Muschelkalk Formation was coeval with either disseminated sulfides or main-stage ore. There is evidence that the ore-bearing dolomite formed prior to deposition of sulfides, including disseminated sulfides, and probably was unrelated to the process of sulfide deposition. The evidence includes the following: (1) Paragenetic studies presented in this paper do not show coeval deposition of dolomite and sulfides. The sulfide-rich zones as well as the disseminated sulfides replace ore-bearing dolomite; (2) Age of sulfide mineralization (discussed later in more detail) must be younger than Jurassic (Gorecka et al., 1991) and possibly as young as Tertiary (Haranczyk, 1979), whereas the age of ore-bearing dolomite is older than deposition of the Late Triassic Keuper Formation (Ekiert, 1959; Lipiarski, 1971). (3) The ore-bearing dolomite is displaced by faults that localized ore in some deposits. Both the ore-controlling faults and the ore-bearing dolomite are cut by the ore bodies (Gorecka et al., 1991). Therefore, the ore-bearing dolostone predates ore and faulting. (4) Although ore-bearing dolomite occurs over a wide area (Fig 2), sulfide minerals are not consistently associated with ore-bearing dolomite. Rather, sulfide minerals and ore deposits are only locally present within the regional ore-bearing dolomite (Pawlowska and Szuwarzynski, 1979, p. 22). (5) Sulfide deposition occurred throughout a large stratigraphic section in the C-S district without dolomitization or recrystalization of the host carbonates (Gorecka et al., 1991). Goercka (1991) also shows that within the Muschelkalk Formation, sulfide mineralization is present without ore-bearing dolomite.

Although field evidence shows that the regional ore-bearing dolomite is older than sulfide mineralization, there is evidence to suggests that the parts of the ore-bearing dolomite were altered by a component of the fluids responsible for the C-S deposits. Most of the ore-bearing dolomite is fine to medium grained but there are parts of the ore-bearing dolomite which appear as coarse grained (~ 1 mm) sparry dolomite. Preliminary carbon and oxygen isotope analysis of these sparry dolomites are lighter than the common fined grained ore-bearing dolomite, suggesting recrystallization by hot fluids. Hydrothermally altered pre-ore dolostone and limestone are commonly found as halos and stratigraphically controlled zones spatially associated with ore emplacement in many North America MVT deposits. Typically the hydrothermal dolomitization occurs as a coarse-grained mosaic of dolomite crystals enclosing ore and breccia zones. Examples include the "coarse recrystalline" dolomite in the East Tennessee deposits (McCormick et al., 1971) and the "gray coarse-grained" dolomite in alteration halos about the Tri-State deposits (McKnight and Fischer, 1970). In southeast Missouri, pre-ore dolomite in the basal Bonneterre Formation that overlies the sandstone aquifer for the southeast Missouri lead-districts, has been recrystallized by the ore fluid. This recrystallized Bonneterre dolomite contains anomalous concentrations of Pb, Zn, Cd, and Mn as carbonate-bound metals (Viets et al., 1983). Therefore, the evidence suggests that the term ore-bearing dolomite, as used in the C-S district, includes (1) regional, diagenetic (epigenetic) dolomite that replaced limestones and early diagenetic dolomites and (2) sparry dolomite that resulted from local recrystallization of the host-rock by metalliferous brines.

Ore-bearing dolomite may represent a favorable host rock for MVT mineralization because of higher transmissivity to fluid flow relative to limestone portions of the Muschelkalk Formation. The ore-bearing dolomite contains more fractures than other parts of the Muschelkalk Formation which may be related to its apparently higher susceptibility to brittle fracture (Sass-Gustkiewicz et al., 1982). This also was documented in the Trzebionka mine (Pawlowska and Szuwarzynski, 1979). Higher fracture density in the ore-bearing dolomite relative to limestone would result in higher permeability and intraformational flow of the ore fluids, thereby accounting for the selective emplacement of ore in ore-bearing dolostone. In addition, Gruszczyk (1967) noted that the C-S ore deposits are located within dolostones but near the transition of limestone to dolostone (Fig. 5). This spatial relationship between a limestone to dolostone transition and the occurrence of MVT ore deposits is important for some North American MVT deposits. For example in the Ozark region, central United States, the Viburnum Trend and Old Lead Belt are located near a transition of limestone to dolostone in the Bonneterre Formation where the dolostone is clearly pre-ore. The ore fluid for southeast Missouri migrated largely through the basal sandstone aquifer below the Bonneterre Formation. Palmer and Hayes (1989) suggested that the limestones behaved like an aquitard., in a similar manner as shales. Therefore, at the transition of limestone to dolostone in the Bonneterre Formation, the ore fluid had an opportunity to ascend and deposit ore by cooling or fluid mixing. It is possible that the area of ore-bearing dolostone shown in Fig.2 and Fig. 5, may have been a "dolostone window" within the Muschelkalk limestones that allowed fluid mixing to precipitate sulfides in the C-S district.

Fault controlled ores

Faulting has been shown to be a critical control on ore deposition in the C-S district. For example, at the Trzebionka mine, Gorecka et al., (1991) demonstrated that there is a direct relationship of ore with faults and small folds and deformation related to basement dip-slip movements. Much of the ore at

Trzebionka is hosted by tectonic breccias and open space created by normal faulting. Similar relations (Fig. 6) are found at the Klucze deposit (Gorecka , 1991) and for ore hosted in the Roethian dolomites (Lower Triassic) in the Boleslaw mine (Niec, 1980). At the Klucze deposit, ore also occurs in faults within the Devonian carbonates (Gorecka, 1991). These observations suggest that faulting played an important role in preparing the rocks for introduction of the ore fluids and probably provided a pathway for the ascent of fluids into the Muschelkalk where intraformational fluid flow allowed fluid mixing to produced stratabound replacement ores.

Faults and fractures are common in many North American MVT districts and are important local ore controls. In the Upper Mississippi Valley district, faults and fractures provided pathways for the upward migration of ore fluids (Heyl et al., 1959). In other districts, such as the Viburnum Trend (e.g. Evans, 1977) and Old Lead Belt (Snyder and Gerdemann, 1968), faulting provided important ground preparation and enhanced permeabilities for fluid migration through development of fault breccias and dilational fractures. Faults and fractures are also believed to have allowed ascent of ore fluids into pre-existing karst breccias in the Tri-State district (McKnight and Fischer (1970) and in the northern Arkansas district (Plumlee et al., in press).

Karst-Hosted Ores

The term "karst" is used in this paper in a broad context to indicate dissolution cavities and the resultant products of the chemical disaggregation of carbonate rocks. Breccias within collapsed karst cavities are the most common host for MVT deposits throughout the world. Karst breccias may take a variety of forms. The most common are high domal breccias (e.g., East Tennessee district; McCormick et al., 1971), low domal breccias (e. g., Central Tennessee; Gaylord and Briskey, 1983), vertical pipes or prismatic breccias (e.g., Pine Point; Rhodes et al., 1984), and bedded breccias (e. g. Tri-State district; McKnight and Fischer (1970). Excellent discussions of MVT ores in karst breccias are given by Ohle (1985) and Sangster (1988).

Breccias in MVT deposits have several types of internal features that are common to most districts (e.g., Sangster,1988); these features include crackle breccias, rock-matrix breccias, ore-matrix breccias, and internal sediments (Fig. 7). *Crackle breccias* consist of highly-fractured carbonate rock, typically located in the upper part of the ore zone and above the main collapse breccia body. Crackle breccias form as fractures or bedding plane separation of the host rock that results from the dissolution and collapse of underlying carbonate rocks. *Rock-matrix breccias* are composed of fragments or clasts of carbonate host rock within a clastic matrix of finer grained carbonate rock fragments. *Ore-matrix breccias* are characterized by carbonate rock fragments cemented by ore and gangue dolomite. Ore-matrix breccias differ from rock-matrix breccias in that the fine-rock matrix has been removed and the voids between clasts are filled with ore and gangue minerals. *Internal sediments* are stratified fine sand and finer sized carbonate fragments together with insoluble residues produced from the dissolution and disaggregation of the host rock.

Although there is general agreement that karst breccias hosting MVT ores were produced by dissolution-induced collapse of the host rocks, there is less agreement on the nature of the fluids that dissolved the host rock and the timing of brecciation relative to ore deposition. Fluids that created the dissolution collapse breccias are believed to be either meteoric or hydrothermal in origin. The strongest evidence for a meteoric origin for pre-ore breccias is the near universal presence of unconformities above the breccias. For example, an interdisciplinary conference on the East Tennessee district concluded that ore emplacement was controlled in part by pre-ore karst breccias related to the Middle Ordovician Knox-Beekmantown unconformity (discussed in Economic Geology, v. 66, no., 5, 1977). Similarly, other Appalachian MVT deposits are related to the extensive Middle Ordovician unconformities (Callahan, 1967). The only North American MVT district that lacks a well defined unconformity near the ore is the southeast Missouri lead district (Viburnum Trend and Old Lead Belt). However, there are pre-ore karst breccias in the Viburnum Trend and in the host rocks outside the known limits of the district. Some of of these pre-ore karst breccias are unmineralized whereas others contain some of the richest ore in the district.

Dissolution of carbonate rocks can also be accomplished by acidic hydrothermal fluids unrelated to sulfide mineralization to yield hydrothermal karsts an associated breccias and internal sediments that are identical to meteoric karsts. However, hydrothermal karsts lack the close spatial relation to unconformities. Hydrothermal karsts have been described mostly in eastern Europe and the former Soviet Union (Jakucs, 1977; Muller and Savary, 1977; Dublanskyi, 1980).

The development of karst breccias hosting most MVT deposits is more likely due the action of meteoric water although a hydrothermal origin is certainly possible. An important as well as controversial question is what is the timing of the development of karst breccias relative to emplacement of the ore deposit? In North America, it is clear that karsts breccias were present before ore deposition. This evidence includes the following: (1) Most MVT districts with karsts breccias are located beneath a major erosional unconformity, thereby implicating meteoric fluids in the development of the karst breccias; (2) In MVT districts where karst breccias are important hosts for ore, there are karst breccias both in the ore deposit and in equivalent but unmineralized host rocks outside of the deposits. This suggests that there was a preexisting karst system independent of the deposition of sulfides. Sulfide deposition was localized within certain breccia bodies because of other features such as faults that focused fluid flow into selective breccia bodies; (3) MVT mineralization in breccias preserve the pre-ore breccia fabric. As discussed below, most ore emplacement into breccias is largely one of selective replacement of fine-rock matrix. In most cases, this replacement involves dissolution of the fine-rock matrix followed by open-space filling by sulfide and gangue dolomite; (4) In MVT deposits, ore and gangue dolomite have replaced a variety of sedimentary fabrics in and outside of the karst breccias bodies and in some deposits (e.g. northern Arkansas), fault breccias are replaced. Although karst breccias are the favorite hosts for MVT deposition, ore deposition has occurred in a variety of features without dissolution and collapse of the host rock; (5) The preference for MVT ore deposition in pre-existing karst breccias is probably related to focused and cross-stratigraphic flow of the ore fluids permitted by karst breccias which allows for fluid mixing and other process of sulfide deposition (Plumlee et al., in press). Thus, MVT ore deposition in karst breccias are not a coincidental superposition of two different and genetically unrelated events, rather, karst breccias are important controls on ore fluid migration which localized many MVT deposits.

Hydrothermal MVT brecciation

Field examination shows that pre-ore karst breccias are the most common hosts for MVT deposits in North America and that mineralized breccia bodies have preserved most of the original fabric of the pre-ore karst breccia. Nevertheless, there is clear evidence that some dissolution and collapse of the carbonate host rock occurred during sulfide deposition in many MVT deposits. Unequivocal evidence for coeval dissolution and brecciation of the carbonate host rock during sulfide emplacement is the presence of "detrital" sulfide clasts (e.g., Kendall, 1960; Rhodes et al., 1984; Randell and Anderson, 1990) produced from dissolution of previously deposited sulfide ore. In these examples, previously deposited sulfide minerals have been broken and moved from their original position, frequently forming a "sulfide concentrate" within ore cavities. Commonly, sulfide clasts are cemented with younger sulfides. Another example of hydrothermal dissolution coeval with sulfide emplacement are sulfide-rich layers in graded bedding within internal sediments (Kendall, 1960). In central Tennessee (Gaylord and Briskey, 1983) and Pine Point (Rhodes et al., 1984), pre-ore karsts breccias have been enlarged by later dissolution, presumably during ore deposition, to the extent that they pierced the overlying unconformity.

Commonly, areas where hydrothermal brecciation occurred during sulfide deposition are places where there is abundant marcasite and pyrite. Perhaps the best examples of detrital sulfides in North American MVT deposits are the Polaris mine and Pine Point district, where there are abundant iron sulfides. The presence of abundant marcasite is indicative of low pH (< 4-5; Stanton and Goldhaber, 1991; Goldhaber and Stanton, 1987; Murowchick and Barnes, 1986), consistent with ore-stage carbonate dissolution. Deposition of iron sulfides is a highly effective acid generation process that could produce localized host-rock dissolution.

The examples given for hydrothermal dissolution and brecciation occuring during sulfide deposition are of minor importance when compared to the abundant evidence for extensive pre-ore dissolution and collapse breccias in North American MVT deposits. Although many North American MVT deposits have clear evidence for limited dissolution and brecciation of the carbonate host rocks during sulfide deposition, field evidence suggests that hydrothermal brecciation is commonly superimposed on pre-existing meteoric breccias (Leach, 1988; Qing, 1991).

Karst breccias in the C-S district

In the C-S district, karst breccias are important hosts for a significant part of the ore. These karst breccias are widely thought to have been produced entirely by the ore fluids and that ore deposition, dissolution, and brecciation were essentially simultaneous (Bogacz et al.,1970; Bogacz et al., 1973; Sass-Gustkiewicz, 1975a; Sass-Gustkiewicz, 1975b; Dzulynski and Sass-Gustkiewicz, 1985). Field observations are consistent in part with the previous studies and indicate that a significant amount of dissolution and brecciation did occur during ore deposition. However, field observations in the C-S and North American MVT deposits suggest an alternative interpretation for the origin of the C-S karst ore breccias. The field observations suggests that ore-bearing karst breccias in the C-S district are the result of superposition of ore-stage dissolution, hydrothermal brecciation, and replacement of preexisting karst breccias by the ore-forming fluids. Many ore textures presented as support for ore-stage hydrothermal brecciation (Bogacz et al.,1970; Bogacz et al., 1973; Sass-Gustkiewicz, 1975a; Sass-Gustkiewicz, 1975b; Dzulynski and Sass-Gustkiewicz, 1985) can be interpreted as dominantly replacement textures that mimic the pre-ore breccias (fabric-conservative replacement). Karst breccias are just one of several rock textures that have been selectively mineralized and replaced by the ore fluid. (This process of fabric-conservative replacement of pre-ore breccias and internal sediments is discussed in more detail below.) Fabric-conservative replacement has not only affected the pre-ore breccias but has also mimicked primary sedimentary fabric of the host rock (Bogacz,et al., 1973). In fault brecciated rocks in the Trzebionka mine, the fine-rock fragments within fault breccias have also been selectively replaced by sulfides to make a ore-matrix breccia. This observation shows that sulfide replacement of pre-existing breccias, whether they are breccias formed from faulting or dissolution, yields an ore-matrix breccia. Therefore, brecciation and sulfide deposition are not necessarily linked to the same event.

As in North American MVT deposits, there are many karst breccias in the C-S mines that are either devoid of sulfide minerals or weakly mineralized, supporting the conclusion that dissolution and brecciation of the host carbonates often occurred without associated sulfides. In weakly mineralized karst breccias, sulfides are clearly selectively replacing fine-rock matrix. This is consistent with the conclusion that karst breccias were formed prior to sulfide mineralization.

Consistent with other MVT districts with important pre-ore karsts breccias, important unconformities overlie the C-S ore-bearing formations. Karst development in the Muschelkalk carbonates could be related to development of the disconformity at top of the Muschelkalk and prior to deposition of the overlying Keuper and Rhaetian sediments. Also, as pointed out by Sass-Gustkiewicz et al. (1982), the Triassic carbonates were exposed to intensive karstification in Early Jurassic. Karsts could also have developed in Middle Jurassic when the C-S region was again exposed to erosion. These periods of erosion correspond to episodes of minor folding and uplift related to Early Cimmerian, Late Cimmerian, and Laramian tectonic phases of the Alpine orogeny (Wodzicki, 1987). If meteoric fluids were responsible for the pre-ore karst breccias in the C-S district, there were sufficient opportunities for karst development after deposition of the Muschelkalk Formation.

Although the field evidence suggests that karsts breccias were present prior to introduction of ore-forming fluids in the C-S district, there is also evidence that some hydrothermal brecciation occurred during ore formation. In fact, some of the best hydrothermal, ore-stage brecciation observed in MVT deposits occur in the iron sulfide-rich ore bodies in the Pomorzany and Olkusz mines. Ore-stage hydrothermal brecciation is described in more detail in the next section.

Ore Textures

Most MVT ores are described as open space filling of fractures, breccias, solution-collapse features, or a variety of vuggy pore spaces (Leach and Sangster, in press). In many deposits, sulfides fill primary porosity cavities such as fossil molds or voids between carbonate grains. Ore and gangue minerals in MVT deposits commonly appear as open space filling of voids created by dissolution of the host carbonate during sulfide emplacement. The process of dissolution of host rock followed by open space filling appears to be broadly coeval in most deposits. The result of this process produces an ore texture where the original fabric of the rock is often preserved but the ore and gangue minerals appear as euhedral crystals that apparently grew in open space. A typical example of this linked-process of dissolution-open space filling is the ore-matrix breccias discussed below.

Replacement of the carbonate host rocks is nearly complete in some deposits as in the massive sulphide zones at Nanisivik and Polaris deposits in the Canadian Arctic. In other deposits, replacement has been remarkably selective, and sulfides have replaced stylolitic seams, thin organic-rich layers, and a variety of primary sedimentary fabrics (Fig. 8A). This highly selective replacement mimics original rock fabric and grain size and once led to much debate about whether or not MVT ores were epigenetic (Bastin, 1939; Ohle and Brown, 1954; Bogacz et al., 1973).

At the Daniels Harbour mine, Newfoundland, Canada, sparry dolomite formed by selective replacement of dolomitized, bioturbated limestones (Lane, 1984) and produced a breccia-like fabric, termed pseudobreccia (Fig. 8B). A particularly common MVT fabric is zebra texture (Park and Cannon, 1934) in which ore and gangue minerals selectively replaced original rock fabrics or by open space filling of dilational partings along bedding planes due to faulting or solution collapse (Fig. 8C). In these examples of selective replacement textures, MVT minerals commonly appear as open space filling within voids created by selective dissolution of some aspect of the original rock fabric. This "fabric conservative" process of selective dissolution followed by open space filling appears to be broadly coeval or at least closely related in time.

An interesting feature observed in solution-collapse breccias in the northern Arkansas and Tri-State districts, central U.S., is the selective replacement of fine-rock matrix in a pre-ore karst breccia by sphalerite and gangue minerals (Figs. 8D, 9A, and 9B. This process can account for the ore-matrix breccias in the Tennessee MVT deposits (Kyle, 1983) and northern Arkansas (Figs. 9A and 9B). In the ore-matrix breccias, fine-rock matrix has been selectively removed and sphalerite and gangue dolomite commonly appear as open space filling supporting apparently unaltered breccia clasts. The density of breccia clasts in the ore-matrix breccia is comparable to the density of breccia clasts in unmineralized rock-matrix breccia, suggesting that dissolution of the rock-matrix was broadly coeval with open space filling. The fabric conservative replacement process described above has led to much debate on the relative importance of open space filling versus replacement and has probably contributed to the debate on the origin of ore-bearing breccias in the C-S and other MVT districts.

Replacement ores in the C-S District: Minor disseminated sphalerite and occasionally iron sulfides define broad low-grade zones about the more intensely mineralized ore bodies. It is uncertain how far these low grade replacement zones may extend from known limits of the ore bodies. However, trace sulfides were observed in apparently unmineralized rocks hundreds of meters to several kilometers from highly mineralized ore zones. Typically, the disseminated sulfide minerals have replaced carbonate grains and filled intergranular porosity.

Sulfide replacement of host rock in which the original rock fabric is preserved is characteristic of MVT districts throughout North America and is well developed in the S-C district. Spectacular sulfide replacement of the ore-bearing dolostone accounts for much of the ore produced from the Trzebionka mine. Similar but economically less important replacement ore also occurs at the Olkusz and Pomorzany mines (Mochnacka and Sass-Gustkiewicz, 1981). Replacement ore bodies in the Trzebionka mine, described in detail by Bogacz et al. (1973), typically appear as tabular but stratabound replacement zones several meters thick with ore textures that mimic the original stratification of the ore-bearing dolostone. The rich tabular replacement ores may have been localized by faults and pre-existing solution collapse breccias that allowed introduction of the ore fluids into permeable zones in the ore-bearing dolostone. The contact of these replacement zones with the ore-bearing dolostone can be rather sharp but more commonly form a broad transition zone into weakly mineralized dolostone. Shown in Fig. 9C is an example of the high-grade replacement ore from the Trzebionka mine that shows the relic sedimentary fabric of the ore-bearing dolostone. The ore appears as bands of fine-grained replacement sphalerite with interlayered open-space filling of banded sphalerite. The voids that are filled with banded sphalerite in the replacement ore can be traced to dark-wavey sedimentary laminae in unmineralized ore-bearing dolostone. This replacement ore texture, shown in Fig. 9C, consists of open-space fill together with replacement sphalerite, and indicate sulfide replacement and dolomite dissolution were broadly coeval.

Replacement of Pre-Ore Karsts: Pre-ore karst breccias appear to have been an important control on many high-grade ore bodies in the C-S district. Sulfide replacement together with hydrothermal dissolution of the breccias is one of the most common and important processes of ore formation in the the C-S ore deposits, particularly in the Pomorzany and Olkusz mines. As discussed previously, the greater the content of iron sulfides in the ore assemblage, the more hydrothermal brecciation present in the ore zone.

A continuum of sulfide replacement of the pre-ore breccias was observed in the C-S district, varying from unmineralized breccias to breccias that have been completely replaced. Shown in Fig. 9D is the edge of a small karst breccia from the Trzebionka mine containing minor sphalerite and lesser amounts of galena, and iron sulfides preferentially replacing fine-rock matrix. This is shown in greater detail in Fig. 10A; at the right of the specimen, the fine rock matrix has been partially dissolved and replaced by sulfide ore whereas to the left, fine-rock matrix is devoid of sulfides. In Fig. 10B, sulfides have completely replaced the fine rock matrix; the result is a ore-matrix breccia reminiscent of breccia ore in the Tennessee and northern Arkansas districts (Figs. 9A and 9B). In most North American MVT breccia ore bodies, breccia clasts have generally been only slightly altered. However, in the C-S deposits, breccia clasts commonly show a reaction rim of replacement sulfides (Fig. 10C) whereas other clasts have been completely replaced by sulfides. In ore bodies with abundant iron sulfides, the clasts are significantly corroded or completely dissolved.

Sulfide replacement of pre-ore karst breccias yield mineralized breccias that can be interpreted to have been produced largely through hydrothermal dissolution of the host rock during ore deposition (hydrothermal breccias). Field observations in the C-S district suggest that most of the ore-bearing collapse breccias were originally pre-ore karst breccias that have been replaced to varying degrees by sulfides. Much of this replacement is a process of dissolution of the rock matrix together with open space filling of sulfides in newly created voids. In most cases, the fine-rock matrix was selectively replaced by sulfides, preserving the original pre-ore karst fabric and leaving clasts intact.

Hydrothermal Breccias: As discussed previously, there is abundant evidence in some ore bodies for dissolution and hydrothermal brecciation during sulfide precipitation. Commonly, pre-ore breccia bodies containing abundant iron sulfides (e.g., Pomorzany and Olkusz mines) have been enlarged by dissolution accompanying sulfide emplacement. In these ore bodies, breccia fragments are significantly corroded and in some cases, completely dissolved. Much of the ore in these areas occurs as open-space filling of voids created during dissolution of the pre-ore breccia. Previously deposited sulfides are corroded, rotated, and transported as sulfide clasts and may be cemented by paragentically younger sulfides (Fig. 10D). In some ore cavities, sulfide clasts constitute essentially pure sulfide residues produced from dissolution of the host rock. In North America, hydrothermal breccia textures and detrital sulfides (Fig. 11A) are well developed at Pine Point (Rhodes et al., 1984), Polaris mine (Randell and Anderson, 1990), and in some locations in the the Viburnum Trend.

Open Space Filling: In addition to filling a variety of open spaces formed during replacement and hydrothermal dissolution, sulfides were deposited in faults, fractures, and dilations along bedding planes. At the Trzebionka mine and Klucze deposit where faults have played an important role in localizing ore (Gorecka, 1991), joints, fractures, crackle breccias, and bedding plane dilations have been sites of open space filling by sulfides.

Mineral Textures

Ore minerals from the C-S deposits have a variety of textures and forms that indicate rhythmic and rapid deposition from supersaturated fluids. Most ores are highly banded both in hand specimen and under the microscope. Sphalerite (Fig. 11B) typically occurs as colloform (brunchite) or dark banded sphalerite (schalenblende). A minor amount of sphalerite occurs as small crystals (granular sphalerite; Fig. 11C) usually early in the mineral paragenesis. An unusual form of sphalerite occurs in the Pomorzany mine as "brunchite mud" consisting of unconsolidated micron size sphalerite in ore cavities. Banded sphalerite typically appears as radial masses of sphalerite crystals (Fig. 11D) with highly developed microbanding (Fig. 12A). In fluorescence illumination under the microscope, organic matter is commonly concentrated along most microbands in both colloform and banded sphalerite (Fig. 12B). Particularly indicative of rapid precipitation is dendritic galena (Fig. 12C) which is commonly associated with colloform sphalerite and is particularly well developed in the Pomorzany and Olkusz mines. Iron sulfides typically appear as bands of botryoidal marcasite and pyrite.

Sulfides also form a variety of "dripstones-like" or "speleothem" stalactites (Fig. 12D), stalagmites, curtains, and drapestones (Bogacz et al., 1970; Sass-Gustkiewicz, 1985; Sobczynski and Szuwarzynski, 1975; Motyka and Szuwarzynski, 1989) Typically these features are composed of marcasite but in the Trzebionka mine, the dripstone-like forms are also composed of sphalerite and occasionally galena. Motyka and Szuwarzynski (1989) describe these drip-stone like features as usually forming "stalactites" on the top of cavities and open spaces; stalagmites are less abundant and similar forms of sulfide pipes occur on the sides of cavities. In cross section, these forms have a radial texture of crystals with a central open tube. The origin of these features have been ascribed to growth in gas filled cavities (Motyka and Szuwarzynski, 1989) and to formation in vadose conditions in hydrothermal karst cavities (Bogacz et al., 1970; Sass-Gustkiewicz, 1985) or as remobilized sulfide ore (Sobczynski and Szuwarzynski, 1975). Similar features are observed in the Viburnum Trend , Pine Point, and central Missouri districts.

Fluid Inclusion Studies

Previous fluid inclusion studies on sphalerite from the C-S district have shown that the C-S ores were deposited by saline fluids at temperatures between 87 and 132°C (Karwowski et al., 1979; Kozlowski et al., 1980; Kozlowski, 1991). Descriptions of the fluid inclusions in sphalerite from the C-S district is presented in (Karwowski et al., 1979 and Kozlowski et al., 1980). Recent fluid inclusion studies by Kozlowski (1991) on samples of sphalerite from 9 boreholes in the district show a distinct trend of increasing homogenization temperatures with depth. Kozlowski (1991) indicates the apparent thermal gradient for all boreholes is similar and ranges from 6 to 10°C/100m and further suggests this apparent gradient indicates the ascending nature of the ore fluids. The spatial thermal gradient observed for the C-S district is rare in MVT deposits (Leach and Sangster, in press) and has been demonstrated only at the Nanisivik mine in Canada (Olson, 1984). The observed thermal gradient in the C-S district is consistent with the important control of normal faults on the localization of ore (Goercka, 1991).

In order to better determine the salinity and density of the C-S ore fluids, freezing point depression and homogenization temperatures were determined on fluid inclusions in samples of granular sphalerite from several locations in the district (Fig. 13). Most of these inclusions have significantly lower homogenization temperatures than have been previously reported. The homogenization temperatures are mainly between 45 and 65° C but range up to 139° C. The low temperatures observed in this study are remarkably low even for MVT deposits. The distribution of low temperatures in this study may reflect a "sampling bias" because only large inclusions (10 to 50 micrometer) in relatively clear granular sphalerite were selected for study in order to provide clarity in observing final ice melting temperatures. Previous studies (Karwowski et al., 1979; Kozlowski et al., 1980; Kozlowski, 1991) reported homogenization temperatures on fluid inclusions typically 3 to 4 micrometers in size. Although a sampling bias is likely, the data (Fig. 13) do provide some indication of the salinity of the ore fluids. As shown in Fig. 13, fluid inclusions with low homogenization temperatures (< 75°C) show a wide range in final ice melting temperatures, from -13.9° to -29.4°C, corresponding to 17.7°to greater than 23.3 equivalent wt. % NaCl. The higher temperature inclusions (>75°C) appear to be less saline than the lower temperature inclusions. Final ice melting temperatures are -15 to -24.3°C, corresponding to 18.6 to > 23.2 equivalent wt % NaCl. The fluids in the inclusions contain appreciable divalent salts in addition to NaCl, indicated by final melting temperatures below NaCl saturation (23.18 wt %; Bodnar, 1992) and first melting temperatures less than 35° C. These results are consistent with analysis of water leachate from inclusions (Karwowski et al., 1979) that indicate the fluids were of the Cl-HCO_3-Na-K-Ca type.

Composition of the gases in fluid inclusions in samples of sphalerite and galena from the C-S district was determined by quadrupole mass spectrometry using the procedures by Landis and Hofstra (1991). The analyzed gases are released by thermal decrepitation of large fluid inclusions (>10 micrometer) and from sets of fluid inclusions opened by cracks developed during heating. The fluid inclusions typically contain less than 1-1.5 mole % gases;

CO_2 is the major gas, and there are lesser amounts of CH_4, H_2S, N_2, and short-chain hydrocarbons. As shown in Fig. 14, the fluid inclusion gases appear to contain two end member composition, CO_2-CH_4 and CO_2-H_2S bearing fluid inclusions as well as fluid inclusions with intermediate compositions. It is not possible to determine if the intermediate gas compositions represents individual fluid inclusions containing a mixture of the end member gas compositions or sets of fluid inclusions containing both possible end members compositions. Nevertheless, the data suggest that two distinct fluid inclusion gas compositions were present during ore deposition. These observations are consistent with ore precipitation produced by fluid mixing.

Paragenesis

The depositional sequence of epigenetic hydrothermal minerals was determined based on a study of several 100 samples available from mines and drill locations in the C-S district. The district paragenesis outlined in Fig. 15 differs from the paragenesis developed for the Oklusz mine by Sass-Gustkiewicz (1975a) in that it does not differentiate metasomatic ore and ore filling opens space. In addition, the paragenesis presented here notes stages of hydrothermal brecciation but does not recognize correlations between brecciation and specific stages of mineral deposition. The mineral sequences described in Fig. 15 are based strictly on superposition and although limited by the number of samples examined the overall paragenesis observed is similar to the unpublished paragenesis developed by Dr. Ewa Gorecka of the Polish Geological Institute.

The general mineral deposition succession in the district begins with hydrothermal dolomite, followed by pyrite and/or marcasite, sphalerite, galena, pyrite and/or marcasite, calcite, and barite. When observed, hydrothermal dolomite is always earliest with no later deposition. Pyrite and/or marcasite precede sphalerite and galena deposition, may be deposited during main ore stages, and after sphalerite and galena. Sphalerite is initially deposited in a granular form. Later sphalerite is deposited as banded crustifications of either microcrystalline tan sphalerite, and/or a dark fine or dark fibrous sphalerite with some wurtzite. The dark banded texture is usually the last major deposition of sphalerite with only minor amounts of sphalerite deposited with late pyrite and/or marcasite. Galena deposition accompanies banded zinc sulfide deposition and also some of the granular sphalerite. In practically all cases sphalerite deposition commenced before galena deposition. The last minerals deposited were calcite and barite which occasionally were followed by fine pyrite and rarely by a late sphalerite with a fine granular texture.

When compared to the mineral succession of other major MVT districts of the world; Tri-State (Hagni and Grawe, 1964), Viburnum Trend (Heyl, 1983), Upper Mississippi Valley (McLimans, 1975), East Tennessee (McCormick et al, 1971) in the U.S. and Pine Point (Krebs and McQueen, 1984), Polaris (Randell and Anderson, 1990) and Nanisivik (Olson, 1984) in Canada, the C-S district shares many similarities. The general sequence of iron sulfides, sphalerite, galena, iron sulfides, calcite (±) barite, is shared by all these districts except Nanisivik which was deposited at significantly higher temperatures than the other deposits. In the Viburnum Trend, Tri-State, and East Tennessee districts, quartz, jasperoid, and hydrothermal dolomite proceeded early iron sulfides and were also deposited in small amounts through the paragenesis. In the Upper Mississippi Valley district, quartz and dolomite were only deposited before early iron sulfides, while Pine Point and Polaris deposits lack quartz but have hydrothermal dolomite deposited through the paragenesis. In the C-S deposits, hydrothermal dolomite was deposited only before early iron sulfides and no quartz was deposited, although minor silicification of some host rocks has been observed.

Compared to the other major deposits, C-S has very little silicification and is thus similar to Pine Point and Polaris. Sufficient silica is present in the regional stratigraphic package such that the ore fluids should have been near saturation relative to quartz. Fluid inclusion studies (Kozlowski, 1991) also reveal vertical cooling of the ore fluids within the district which should have deposited quartz. The lack of quartz or significant silicification even though conditions were ideal for silica precipitation suggests that mixing occurred with cooler silica undersaturated fluids. The colloform texture of much of the C-S ore, which texturally resembles much of the ore from the other deposits that lack significant silicification, Pine Point and Polaris, suggests that rapid ore deposition by similar mixing processes may have deposited ore in all three districts. The sulfur isotope data, lead isotope data, and trace and minor element data for the C-S ores to be discussed later are also consistent with rapid ore deposition due to mixing processes.

Trace and Minor Elements

Trace and minor elements were determined in epigenetic ore and ore-related minerals to determine if temporal patterns of element enrichment in paragenetically equivalent minerals could be observed on a district scale. Information on these patterns, in conjunction with other geologic and geochemical data, aid in determining the genesis of the deposits and possibly aid in exploration. Two analytical techniques were used; laser ablation inductively coupled plasma mass spectrometry (LAICP-MS) which semi-quantitatively analyzes 100 by 500 micron samples on traverses of polished sections of sulfide minerals, and semi-quantitative emission spectrography (EMS).

Preliminary LAICP-MS data for samples from the Pomorzany and Olkuzs mines, which contain most of the district paragenesis in crustification sequences, indicate iron sulfides deposited late in the paragenesis frequently contain more than 500 ppm thallium. Sulfides minerals deposited earlier, including early iron sulfides, typically contain 30 ppm thallium. Galena is greatly enriched in Bi relative to other sulfides, typically containing more than 3000 ppm. Low amounts of Ag are present in galena with concentrations generally less than 5 ppm. Galena and iron sulfides are selectively enriched in As relative to sphalerite. The most important host for Ag is dark-colored sphalerite; either early granular sphalerite or dark banded schalenblende which can contain as much as 350 ppm. Very little Ag is found in finely banded tan sphalerite which was deposited between stages of dark sphalerite. Enrichment of Ag in sphalerite rather than in galena is consistent with the data from those MVT districts which contain significant amounts of Ag. Small amounts of late dark sphalerite also occur as bands and blebs in late iron sulfides and these were found to be uniquely enriched in Ge but deleted in Cd and Ag when compared to earlier sphalerite. Continuing work will determine if these depletion and enrichment patterns of minor and trace elements extend to time correlative minerals throughout the district, and vertically in mineral occurrences in rocks both stratigraphically above and below the ore.

Using EMS, minor and trace elements were determined in samples representative of principal paragenetic stages of sphalerite collected from mines and drill core of the C-S district. Preliminary data are compared in Figs, 16, 17, and 18 with Fe, Cd and Ag concentrations determined in samples representative of the main stages of sphalerite from other major MVT districts; Tri-State, Viburnum Trend, Upper Mississippi Valley, East Tennessee, and Pine Point, Polaris, and Nanisivik in Canada.

Compared to other major MVT districts, sphalerite from the C-S deposits has the widest range of Fe and Cd concentration and the second widest range in Ag content. Granular sphalerite accounts for samples with greater than 10,000 ppm Fe, but not all granular sphalerite samples are Fe rich. Several samples contained as little as 2000 ppm Fe, while banded sphalerite contained between 1000 and 5000 ppm Fe.

As observed in the LAICP-MS study, the highest Ag concentrations were found in samples of either granular sphalerite or dark schalenblende. Not all samples of these stages of sphalerite were enriched in Ag however. Some samples of granular sphalerite and dark schalenblende contained as low as 2 ppm Ag. The range in Cd concentration is noteworthy because it ranges from 500 to 30,000 ppm which is clearly the widest range observed in the MVT districts studied.

Although preliminary trace and minor element data reveal a wide range in concentration for samples throughout the district and spanning major stages of sulfide deposition, no clear temporal or spatial relationships are apparent. Although interpretations of the data are preliminary, the wide range in concentrations and apparent lack of district or paragenetic correlations are consistent with multiple sources of the metals <u>or</u> local variations in the geochemical environment (e.g., activity of reduced sulfur) at the site of mineral deposition. It is possible that both processes were important controls on the trace and minor element content.

Lead Isotopes

The variation in the isotopic ratios of lead in galena from the C-S district is very small when compared to values for galena from MVT deposits of the US. A plot in Fig. 19 of the ranges for Pb^{206}/Pb^{204} from a number of literature sources demonstrates that the isotopic character of lead found in the C-S district and the Canadian deposits are very similar. Galena from these deposits contain lead which is considerably less radiogenic than lead found in the US deposits and the lead is isotopically quite homogeneous suggesting relatively short-lived episode of ore deposition with lead derived from an isotopically homogenous source (Church and Vaughn, 1992). The data also illustrate that while J type (radiogenic) leads are characteristic of the many MVT deposits in the US, they are certainly not diagnostic of MVT deposits on a worldwide scale.

Sulfur Isotopes

Sulphur isotope studies show that sulphur in the C-S deposits was derived from crustal sources which could include sulphur-bearing organic material, H_2S reservoir gas, sulfate-bearing evaporites, basinal brines, connate seawater, or diagenetic sulphides. The isotopic range of sulfur measured in galena from the C-S district is quite large compared to values observed for other districts (Fig. 20). The C-S district has the distinction of having the largest range of sulfur isotopic values in galena and the lightest sulfur isotopes observed in any MVT district. The isotopically lightest sulfur observed to date from the C-S district is found in galena from Carboniferous rocks and Bunter sandstone, and in late marcasite from ore deposits in the Muschelkalk Formation. Sulfur isotope compositions for these samples range from -5.2 to -18.6 $d^{34}S$. Sources for the isotopically light sulfur possibly include diagenetic sulfides in the source rocks or biogenic and/or incomplete thermochemical reduction of sedimentary sulfate.

The Viburnum Trend has the second largest range in sulfur isotopes observed for MVT deposits. The large range in sulfur isotopes in the Viburnum Trend has been attributed to multiple sources of reduced sulfur (Sverjensky, 1981) reflecting changes in flow paths between geochemically distinct aquifers through time of ore deposition (Viets and Leach, 1990). Considering the evidence for fluid mixing in in the C-S district, mixing of fluids from multiple sources of reduced sulfur may explain the wide range in sulfur isotopes. Further analyses of sulfur isotopes will provide needed constraints on possible sources of sulfur for the C-S district.

Summary

Observations and interpretations presented in this paper must be considered preliminary in nature because many geochemical, fluid inclusion, and isotopic analyses are still in progress. In addition, the authors observations in the C-S district are undoubtedly biased toward their experience with North American MVT deposits and limited by their relatively short exposure to the complex geological problems in the C-S district. Nevertheless, the preliminary observations and data presented here will hopefully add to a better understanding of the controls on ore distribution in the C-S district. Certainly, the ideas and observations presented in this paper will add to the debate on this important MVT district.

The features of the C-S district are remarkably consistent with the characteristics of MVT deposits throughout the world (Leach and Sangster, in press). However, as pointed out by Leach and Sangster (in press), each district has its own unique set of geological and geochemical characteristics that sets it apart from other districts. This is certainly true for the C-S district.

The important features of the C-S district, preliminary interpretations of observations and geochemical data, and possible analogies to North American MVT districts are as follows:

1) **Geologic and tectonic setting:** The C-S deposits are located within an extensive Mesozoic carbonate platform sequence. The district is situated near a major crustal structural (Cracow-Myszkow zone) zone and reactivation of faults in this area may be responsible, in part, for some faults that localized ore in the district. The district is located near a orogenic foredeep (Carpathian foredeep) that may have provided a mechanism for migration of the ore fluids as well as produced faulting in the district to localize ore. The district is also located near a Carboniferous coal basin which may have provided a source for the ore fluids and controls on fluid migration. Although no North American MVT district has this complex geological setting, the Ozark region MVT deposits (Tri-State, northern Arkansas, and southeast Missouri lead districts) are located near the Reelfoot rift, which has been structurally active since the Proterozoic. In addition, the Ozark MVT deposits are located at the northern flank of the Arkoma and Black Warrior foredeeps of Late-Paleozoic age.

District controls: Important ore controls for the C-S district appear to be a combination of faults, pre-ore karsts, dolomite to limestone transition, and shale edge. In North America, many districts appear to have a close genetic connection to faults and pre-ore karsts. North American districts with a spatial relationship to pre-ore dolomite to limestone transition and shale edge are the Tri-State and southeast Missouri districts. Most North American MVT districts are related to pre-ore karsts.

Ore-bearing dolostone: Economic deposits in the C-S district are contained within the ore-bearing dolostone. Formation of the ore-bearing dolostone is pre-ore and may have provided enhanced fluid flow relative to the surrounding limestones. A similar relationship is present in the southeast Missouri lead district. Some coarsely crystalline or sparry dolomite in the ore-bearing dolostone may represent recrystallization by metal-rich hydrothermal fluids. Similar coarse crystalline dolomites occur near many North

American MVT deposits, such as in East and Central Tennessee, Tri-State, Polaris, and Pine Point districts.

Replacement ore textures: Extensive sulfide replacement of pre-ore karst breccias, fault breccias, and sedimentary fabrics is the most common form of the ore in the C-S district. Extensive replacement of pre-ore karst breccias is also common in North American MVT deposits. Some of the best North American examples are East and Central Tennessee, northern Arkansas, Pine Point, and Tri-State. Most North American MVT replacement ores have preserved remnants of the sedimentary fabric. Good examples of sedimentary fabric preserved in the MVT ores are Daniels Harbour, Tri-State, northern Arkansas, southeast Missouri, and Nanisivik.

Pre-ore karsts: Many C-S ore deposits were emplaced into pre-existing karst breccias. The best examples in the C-S district are ores in the Pomorzany and Olkusz deposits. Several erosional unconformities overlie the Triassic host rocks, notably at the base of the Keuper Formation, top of the Triassic, and in the Jurassic sedimentary sequence. Nearly all North American MVT districts have an important spatial relation to pre-ore karsts and erosional unconformities. Some of the best examples in North America are the Appalachian MVT deposits, east and Central Tennessee, which are related to the extensive Middle Ordovician Knox-Beekmantown unconformity.

Hydrothermal Breccias: The C-S deposits contain clear evidence for hydrothermal dissolution and brecciation during sulfide emplacement. The best examples are observed in the iron sulfide-rich deposits at the Pomorzany and Olkusz mines. However, field evidence suggest the amount of hydrothermal brecciation is not as great as has been previously reported. Much of the apparent ore-stage brecciation in the C-S district appears to be the result of sulfide replacement of pre-ore karsts. In North America, evidence for limited hydrothermal brecciation can be found in most MVT deposits. The best examples of North American MVT deposits with clear evidence for hydrothermal brecciation during mineralization are at Pine Point and Polaris.

Faults: Many of the ore deposits, especially at Trzebionka and Klucze deposits, are largely localized by normal faults. Most of these are graben structures and the ore is localized in dilational structures such as crackle and fault breccias. Faulting has apparently played an important role in allowing the ascent of fluids into permeable portions of the Muschelkalk Formation. Ore-controlling faults are post-Upper Jurassic in age and mineralization in faults can be traced into the Paleozoic rocks beneath the

Triassic-hosted ore bodies. Important fault control on ore deposition in North American MVT deposits are best developed in the Upper Mississippi Valley, northern Arkansas, and Tri-State districts, and in certain areas in southeast Missouri.

Time of Mineralization: The time of ore emplacement is poorly constrained to be post-Upper Jurassic. Field evidence show that ore deposits cut faults that are of post-Upper Jurassic age and ore minerals occur in Upper Jurassic rocks. Some sulfide mineralization of uncertain relationship to the C-S deposits occur in Tertiary faults.

Fluid Inclusion data: The C-S ore deposits were formed from brines with a wide range in salinity (and density) at temperatures from about 50 to 140° C. Fluid inclusion homogenization temperatures show a distinct trend of decreasing temperatures with decreasing depth of mineralization. This thermal trend is unusual for MVT deposits and has been documented only in North America at the Nanisivik mine in Canada. Hydrocarbons are present as liquid and solid inclusions and as dispersed sub-microscopic matter within banded sphalerite. Gases in the fluid inclusions appear to contain two end-member compositions; CO_2-CH_4 and CO_2-H_2S populations. These discrete gas compositions are consistent with fluid mixing as a precipitation mechanism.

Lead Isotopes: Lead isotopes are remarkably uniform in composition and are consistent with a sedimentary source that was well homogenized by sedimentary processes. In addition, the narrow range of lead isotopes suggests ore deposition was a single but short-lived event. Similar homogenous isotopes are characteristic of the Pine Point district.

Sulfur isotopes: The C-S ores have a remarkably wide range in sulfur isotopic composition and include the lightest isotopic values observed for any MVT district. This wide range in sulfur isotopes is suggestive of multiple sulfur sources. As similar but smaller range of sulfur isotopes is characteristic of the Viburnum Trend where fluid mixing has been called upon to explain ore deposition.

Trace and minor elements: The wide range in concentrations of minor and trace elements and apparent lack of district or paragenetic correlations are consistent with multiple sources of the metals or local variations in the geochemical environment (e.g., activity of reduced sulfur) at the site of mineral deposition. It is possible that both processes were important controls on the trace and minor element content of the ores. Compared to sphalerite from MVT districts in North America, the C-S sphalerite contains the widest range in Fe, Cd, and the second widest range in Ag.

Mineral textures: The C-S ores are typically fine-grained, colloform, dendritic, and highly banded ores indicative of episodic and rapid precipitation from supersaturated solutions. Particularly interesting are speleothem-like stalactites, stalagmites, and drapestones of iron and zinc sulfides.
Precipitation mechanism: The most likely precipitation mechanism for sulfide deposition in the C-S district is fluid mixing. Evidence suggestive of fluid mixing are fine-grained, colloform, and dendritic ore textures, variable fluid inclusion salinities, distinct populations of fluid inclusion gas compositions, and highly variable sulfur isotopes.

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Figure captions

Fig.1. Distribution of Mississippi Valley-type deposits and districts: 1, Polaris; 2, Eclipse; 3, Nanisivik; 4, Gayna; 5, Bear-Twit; 6, Godlin; 7, Pine Point district; 8, Lake Monte; 9, Nancy Island; 10, Ruby Lake; 11, Robb Lake 12, Monarch-Kicking Horse; 13, Giant; 14, Silver Basin; 15, Gays River; 16, Daniel's Harbour, Newfoundland; 17, Metaline district; 18, Upper Mississippi Valley district; 19, Southeast Missouri district (Old Lead Belt, Viburnum Trend, Indian Creek); 20, Central Missouri district; 21, Tri-State district; 22, Northern Arkansas district; 23, Austinville; 24, Friedensville; 25, Central Tennessee district; 26, East Tennessee district; 27, San Vicente; 28, Vazante; 29, Harberton Bridge; 30, Cracow-Silesian district; 31, Alpine district; 32, Pering; 33, Sorby Hills; 34, Coxco; 35-37, Lennard Shelf district (Cadjebut, Blendvale, Twelve Mile Bore), 38, El-Abad-Mekta district. Modified slightly from Sangster (1990).

Fig. 2 Pre-Cretaceous geology of the Cracow-Silesian region. Modified from Wodzicki (1987).

Fig. 3 Generalized geologic cross-section of the Cracow-Silesian region. Modified from Wodzicki (1987).

Fig. 4 Stratigraphic column of post-Paleozoic rocks. Modified from Wodzicki (1987).

Fig. 5 Distribution of ore-bearing dolomite in the Cracow-Silesian district and the distribution of ore deposits relative to limestone to dolomite transition. Modified from Gruscczyk (1967).

Fig. 6 Geological cross-section through an ore body at the Klucze deposit. Note that (1) ore occurs in Upper Jurassic rocks; (2) ore cuts faults of post-Jurassic age; and (3) ore and faults cut ore-bearing dolomite. Modified from Gorecka (1991).

Fig. 7 Schematic representation of an ore-bearing breccia body in the East Tennessee district, U.S.A. Note that not all breccia is mineralized. Modified from Ohle (1985).

Fig. 8A Sphalerite selectively replaced dark organic-rich layers in algal boundstone from the Monte Cristo mine, northern Arkansas.

Fig. 8B Sparry dolomite selectively replaced portions of a bioturbated dolostone from Middle Ordovicain rocks in the Daniels Harbour deposit, Newfoundland, Canada.

Fig. 8C Zebra texture produced by sparry dolomite filling open spaces in dilational parting in dolostone from the Polaris district, Canada.

Fig. 8D Pre-ore karst internal sediment replaced by jasperoid (silicification of carbonate minerals) and sphalerite. Sphalerite and jasperoid preserve the original fabric of the internal sediment in a pre-ore karst breccia from the Tri-State district.

Fig. 9A Ore-matrix breccia from the Lucky Dog mine, northern Arkansas district. Sphalerite and sparry dolomite replaced original fine-rock matrix in a pre-ore karst breccia.

Fig. 9B Sparry dolomite and sphalerite replacing fine rock matrix in the Mattie May mine, northern Arkansas. Note the unaltered pre-ore karst breccia. Such a process of ore emplacement first selectively replaces fine-rock matrix.

Fig. 9C Ore-replacement texture from the Trzebionka mine, Cracow-Silesian district. The original rock fabric is preserved. Sphalerite occurs as fine grain replacement and interlayered banded sphalerite filling open-spaces produced during ore emplacement.

Fig. 9D Edge of small karst breccia in the Trzebionka mine, Cracow-Silesian district. Sulfides have selectively replaced fine-rock matrix in a portion of the pre-ore karst breccia (a) whereas remaining breccia is unaltered and unmineralized.

Fig. 10A Polished sample of mineralized, pre-ore karst breccia shown in Fig. 9D, Trzebionka mine, Cracow-Silesian district. Sulfides have replaced only a small portion of the fine-rock matrix (a) and some fine-rock-matrix has been dissolved to produce open-space fill of sphalerite.

Fig. 10B Ore-matrix breccia from the Trzebionka mine, Cracow-Silesian. Sulfides have almost completely replaced pre-ore karst breccia. Sulfides (largely sphalerite) occur as cement, formed by replacement of fine-rock matrix, and as replacement of pre-ore carbonate breccia clasts (SRC). Rotated and broken sulfides (RC) attest to hydrothermal brecciation superimposed on the pre-ore karst breccia.

Fig. 10C Ore-matrix breccia from the Trzebionka mine, Cracow-Silesian district. Sphalerite has completely replaced the fine-rock matrix (a). Sphalerite forms a replacement "rind" encasing carbonate clasts (b), and has completely replaced some carbonate breccia clasts (c).

Fig. 10D Hydrothermal breccia produced through complete replacement and dissolution of pre-ore breccia. Previously formed sulfides are broken and rotated. The ore appears as a "sulfide mineral residue" produced by dissolution of all carbonate clasts in the mineralized pre-ore karst. Sample is from the Trzebionka mine, Cracow-Silesian district.

Fig. 11A Fragments of colloform sphalerite that were formed as breccia clasts during hydrothermal solution collapse, cemented by hydrothermal dolomite. Pine Point district, Canada.

Fig. 11B Highly banded ore from the Pomorzany mine, Cracow Silesia district. Shown are (a) banded sphalerite or schalenblende, (b) colloform sphalerite or brunchite, (c) galena, (d) pyrite and marcasite.

Fig. 11C Granular sphalerite from the Klucze deposit, Cracow-Silesian district. Photograph from E. Gorecka.

Fig. 11D Photomicrograph of banded sphalerite from the Trzebionka mine, Cracow-Silesian district. Note the fibrous nature of the sphalerite.

Fig. 12A Photomicrograph of colloform sphalerite from the Pomorzany mine, Cracow Silesia district.

Fig. 12B Photomicrograph of colloform sphalerite from the Pomorzany mine, Cracow Silesia district in fluorescent illumination. Fluorescence along banding is believed due to sub-microscopic and dispersed organic matter. Other fluorescent spots include liquid hydrocarbon-bearing fluid inclusions and solid organic matter.

Fig. 12C Dendritic galena and colloform sphalerite from the Pomorzany mine, Cracow Silesia district.

Fig. 12D Stalagmite from the Trzebionka mine containing sphalerite (a) and marcasite (b). Cracow-Silesian district. Sample from M. Szuwarzynski.

Fig. 13 Scatter plot of fluid inclusion homogenization and final melting temperatures from granular sphalerite from the Klucze deposit, Boleslaw mine, Trzebionka, mine, and from the Zarki and Zawiercie regions, Cracow-Silesian district.

Fig 14 Triangular plot of the CO_2-CH_4-H_2S concentrations of fluid inclusion gases in samples of sphalerite and galena from several locations in the Cracow-Silesian district.

Fig. 15. The depositional sequence of epigenetic hydrothermal minerals in samples observed from mines and drill locations in the Cracow Silesia district.

Fig. 16. Range and mean of iron concentrations in sphalerite from major MVT districts of the world. CS=Cracow Silesia, Poland, TS=Tri-State, USA, VT=Viburnum Trend, USA, UM=Upper Mississippi Valley, USA, ET=East Tennessee, USA, PP=Pine Point, Canada, PL=Polaris, Canada, NK=Nanisivik, Canada. Unpublished data of the authors.

Fig. 17. Range and mean of cadmium concentrations in sphalerite from major MVT districts of the world. Unpublished data of the authors.

Fig. 18. Range and mean of silver concentrations in sphalerite from major MVT districts of the world. Unpublished data of the authors.

Fig. 19. Range of sulfur delta S34 isotopic values of sulfur in galena from major MVT districts of the world. Data is from unpublished data of the authors and Kulp et al. (1956), Sverjensky (1981), McLimans (1977), Rye (1974), Sasaki and Krouse (1969), Randell and Anderson (1990), and Olson (1984).

Fig. 20. Range of Pb ^{206}/Pb ^{204} isotopic values of lead in galena from major MVT districts of the world. Data from unpublished data of the authors, mine geologists, and Zartman et al. (1979), Russell and Farquhar (1960), Sverjensky (1981), Heyl et al.(1974), Cumming and Robertson (1969), and Sangster (1986).

Table 1. Ore controls in selected MVT districts. (1) White rock-brown rock is an important megascopic and color distinction in the dolostone facies of the Bonneterre Formation in southeast Missouri. With few exceptions, ore is restricted to the brown-rock zones in the Bonneterre Formation. (2) Less important designation for limestone-dolostone transition was assigned to districts where dolomitization of the limestone may have been produced by the ore fluids as described in text. (3) Unconformity features include a variety of dissolution features associated with dissolution of carbonates during subaerial exposure, e.g. fabric selective dissolution or enlargement of pores and fractures, vuggy porosity, boxwork structures.

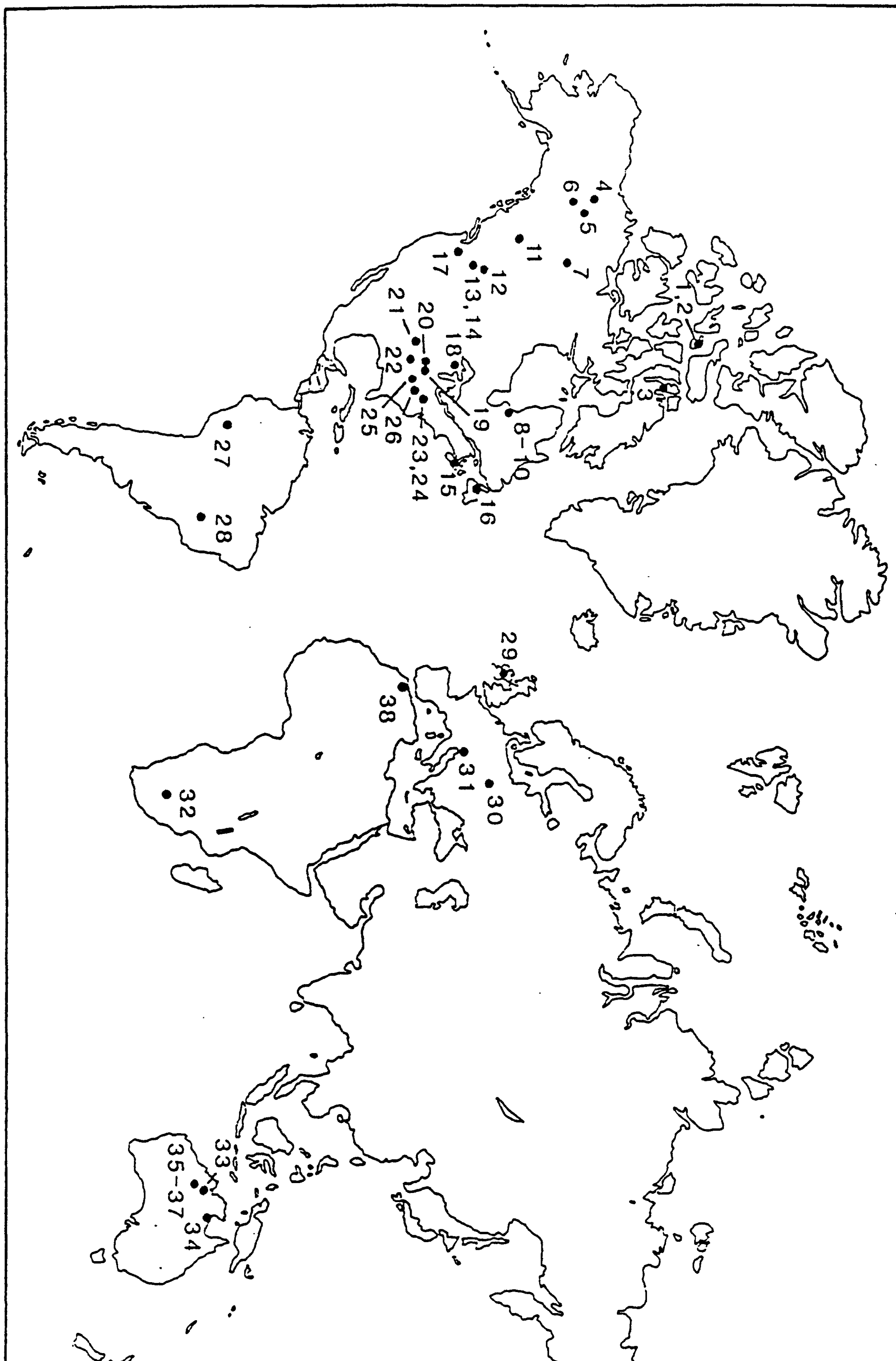
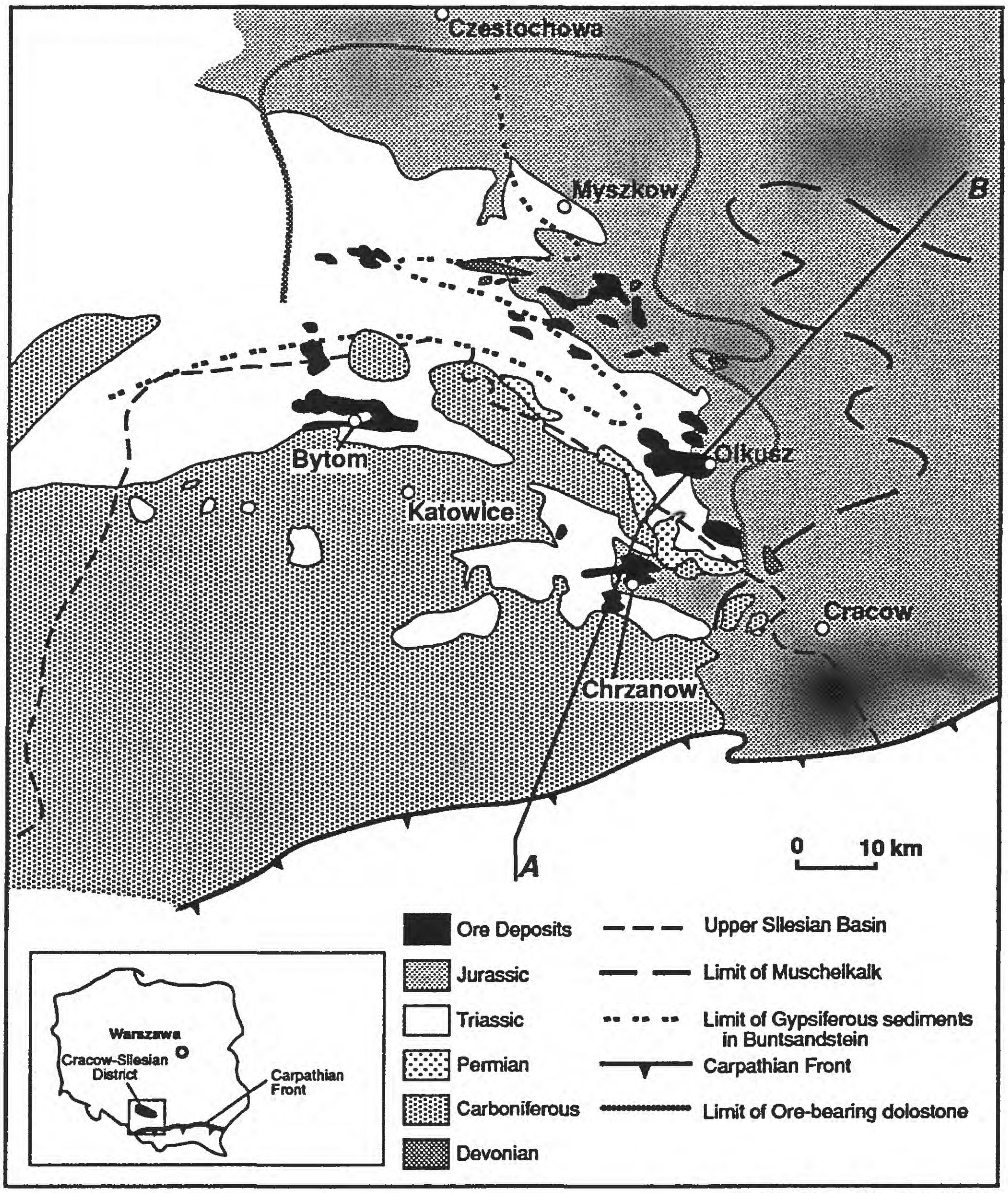

1,2
3
4
5
6
7
8–10
11
12
13,14
15
16
17
18
19
20
21
22
23,24
25
26
27
28
29
30
31
32
33
34
35–37
38

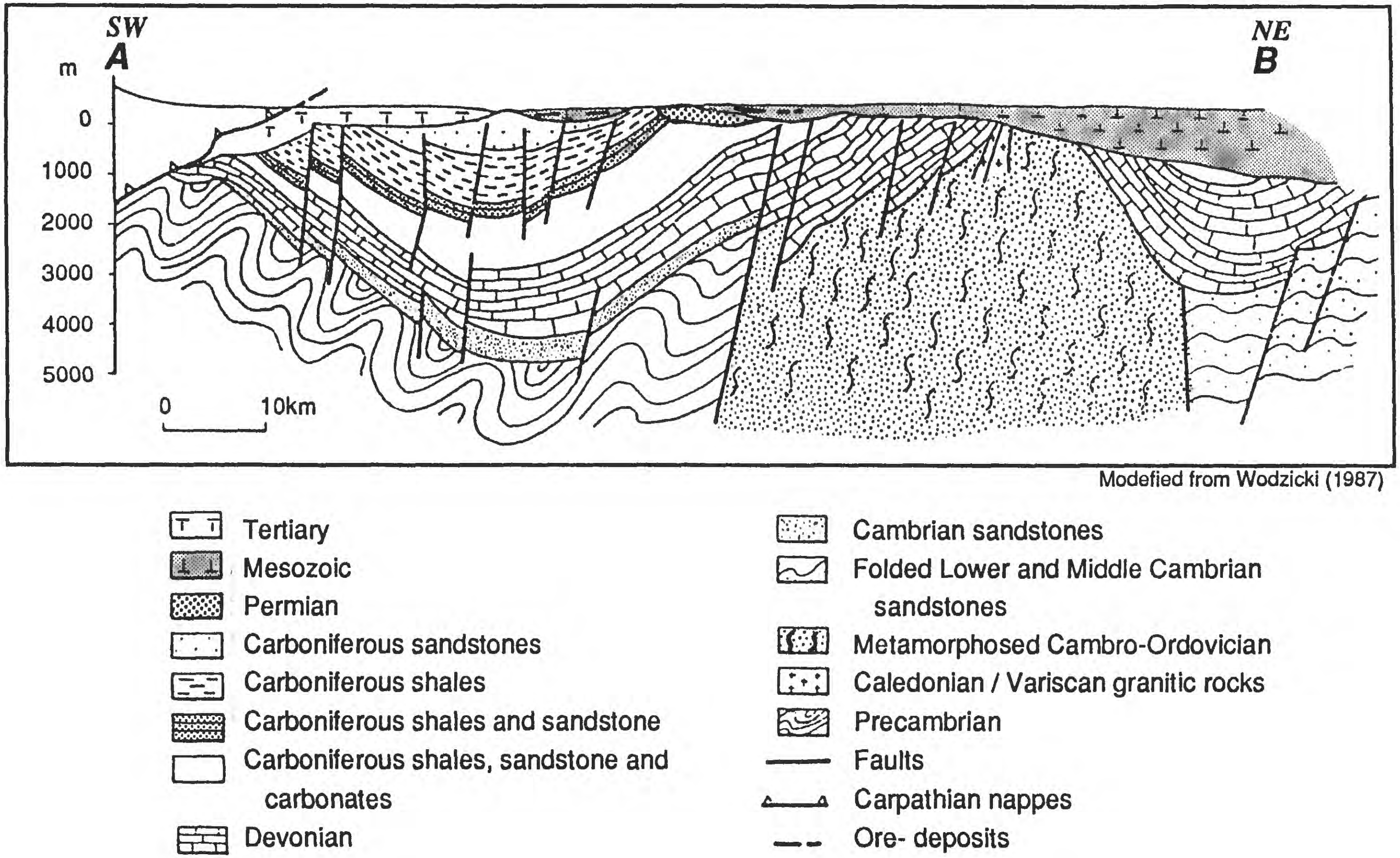
Fig. 1



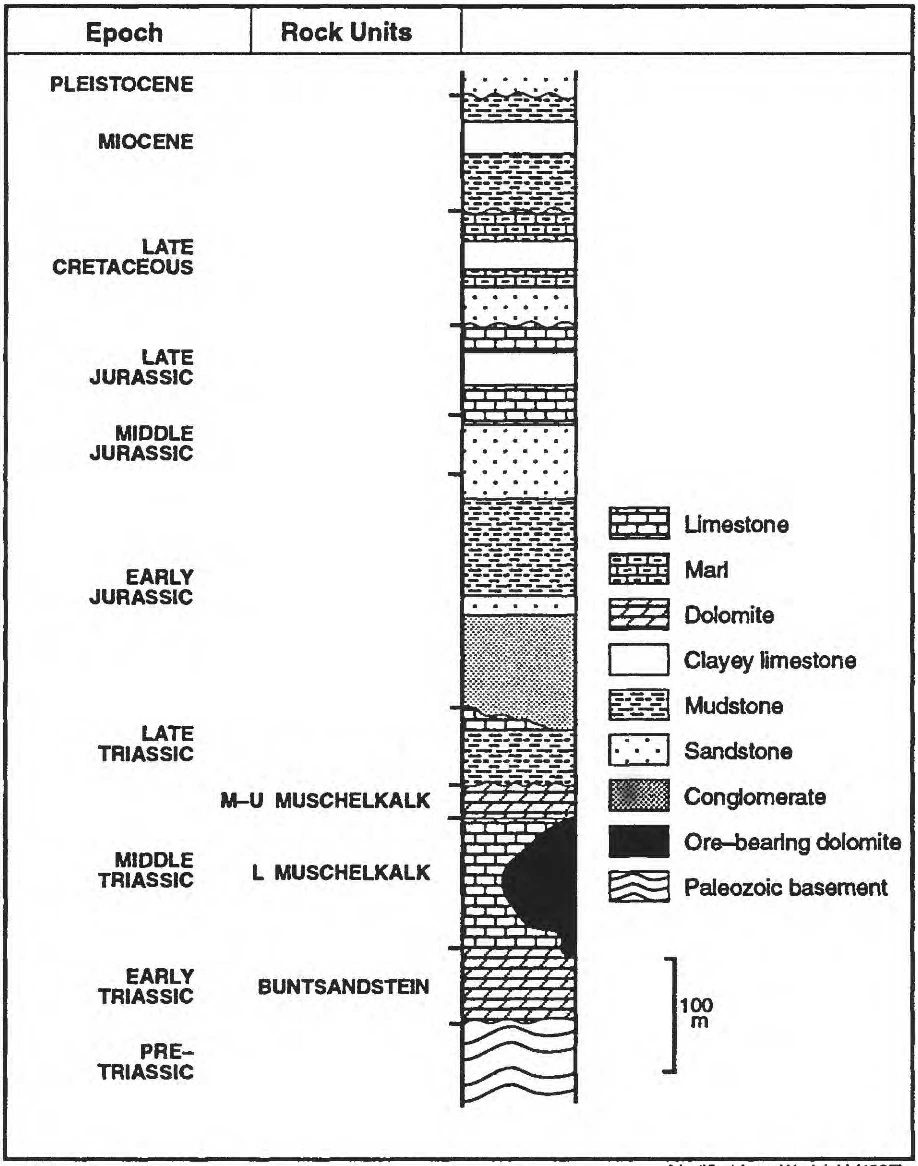
Modified from Wodzick (1987)

Fig. 2

Fig. 3



Modefied from Wodzicki (1987)



Modified from Wodzicki (1987)

Fig. 4

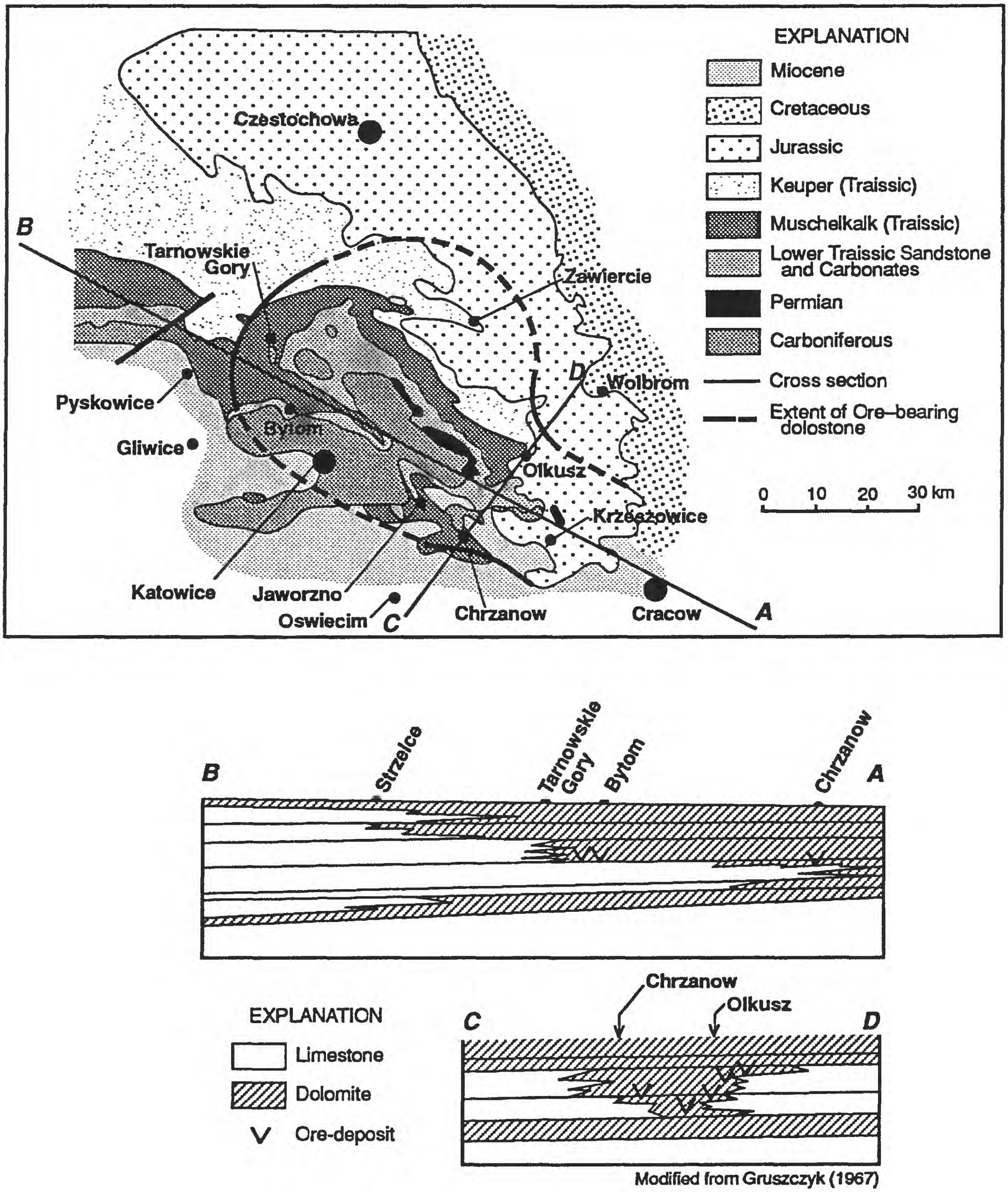
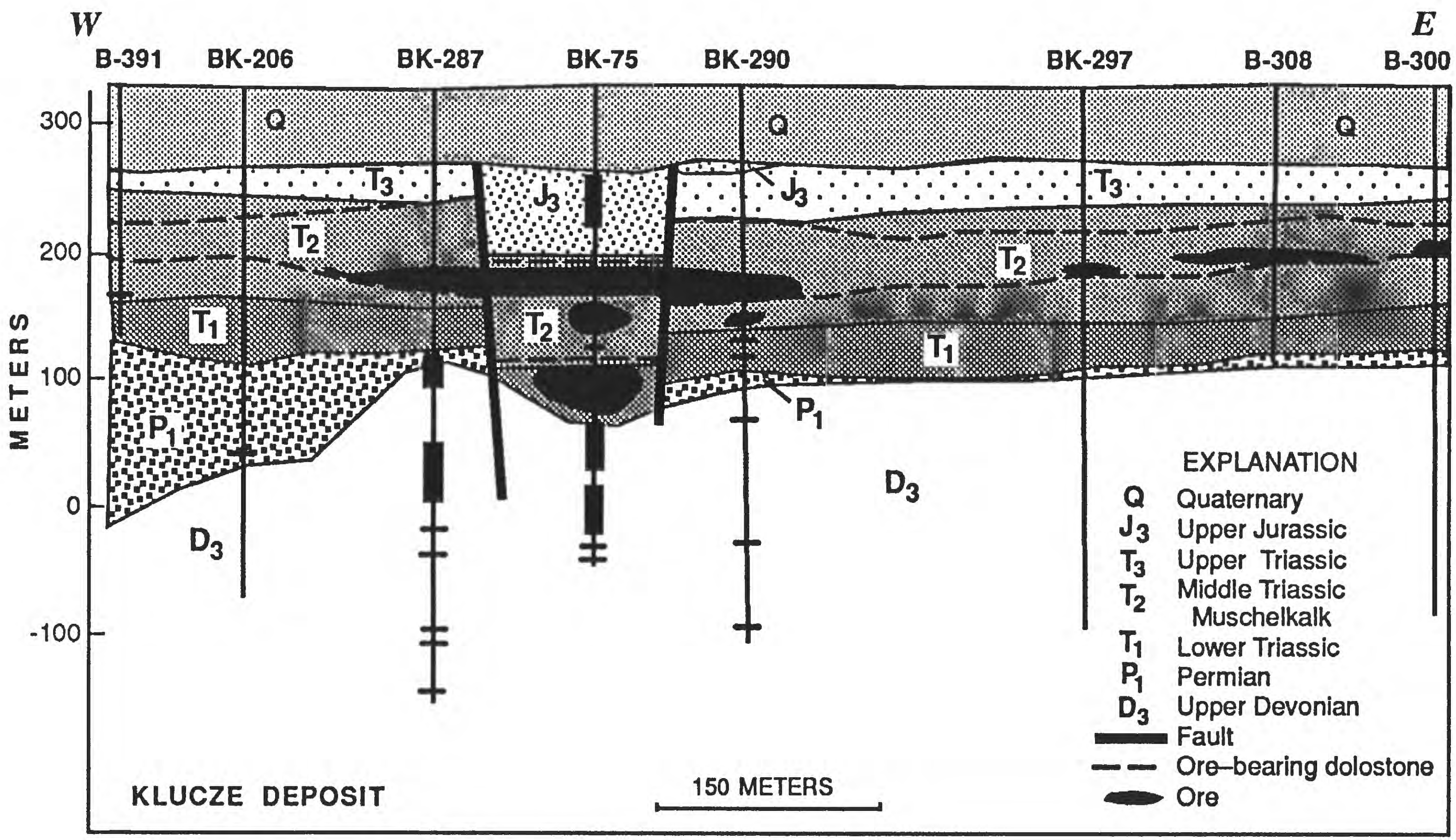

EXPLANATION
Miocene
Cretaceous
Jurassic
Keuper (Traissic)
Muschelkalk (Traissic)
Lower Traissic Sandstone and Carbonates
Permian
Carboniferous
Cross section
Extent of Ore-bearing dolostone
0 10 20 30 km
Czestochowa
B
Tarnowskie Gory
Zawiercie
Pyskowice
D
Wolbrom
Gliwice
Bytom
Olkusz
Krzeszowice
Katowice
Jaworzno
Oswiecim
C
Chrzanow
Cracow
A
B
Strzelce
Tarnowskie Gory
Bytom
Chrzanow
A
EXPLANATION
Limestone
Dolomite
V Ore-deposit
C
Chrzanow
Olkusz
D
Modified from Gruszczyk (1967)

Fig. 5



W
E
B-391
BK-206
BK-287
BK-75
BK-290
BK-297
B-308
B-300
METERS
300
200
100
0
-100
Q
T_3
T_2
T_1
J_3
P_1
D_3
EXPLANATION
Q Quaternary
J_3 Upper Jurassic
T_3 Upper Triassic
T_2 Middle Triassic Muschelkalk
T_1 Lower Triassic
P_1 Permian
D_3 Upper Devonian
Fault
Ore–bearing dolostone
Ore
KLUCZE DEPOSIT
150 METERS

Fig 6

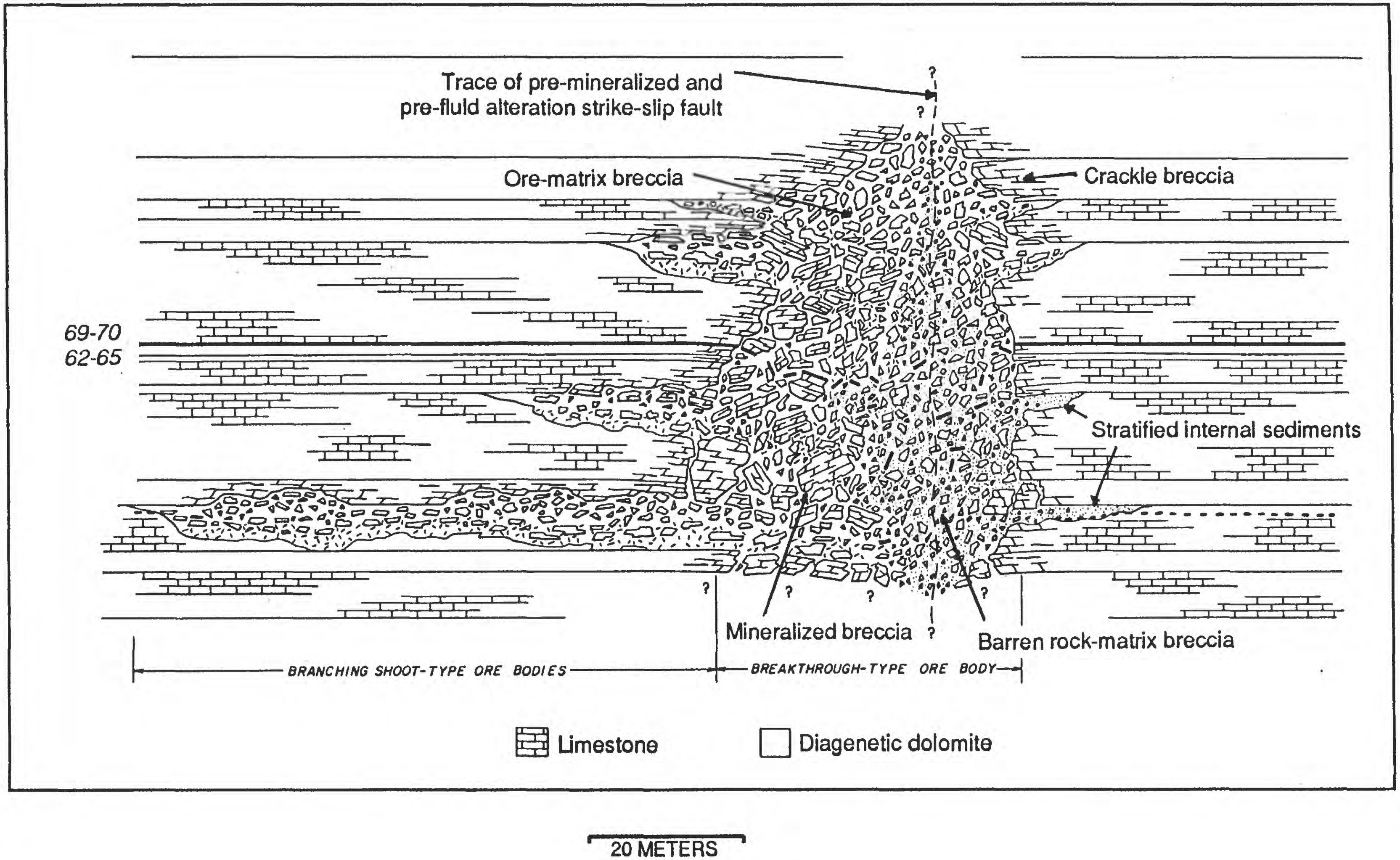

Trace of pre-mineralized and
pre-fluid alteration strike-slip fault
Ore-matrix breccia
Crackle breccia
69-70
62-65
Stratified internal sediments
Mineralized breccia
Barren rock-matrix breccia
BRANCHING SHOOT-TYPE ORE BODIES
BREAKTHROUGH-TYPE ORE BODY
Limestone
Diagenetic dolomite
20 METERS

Fig. 7

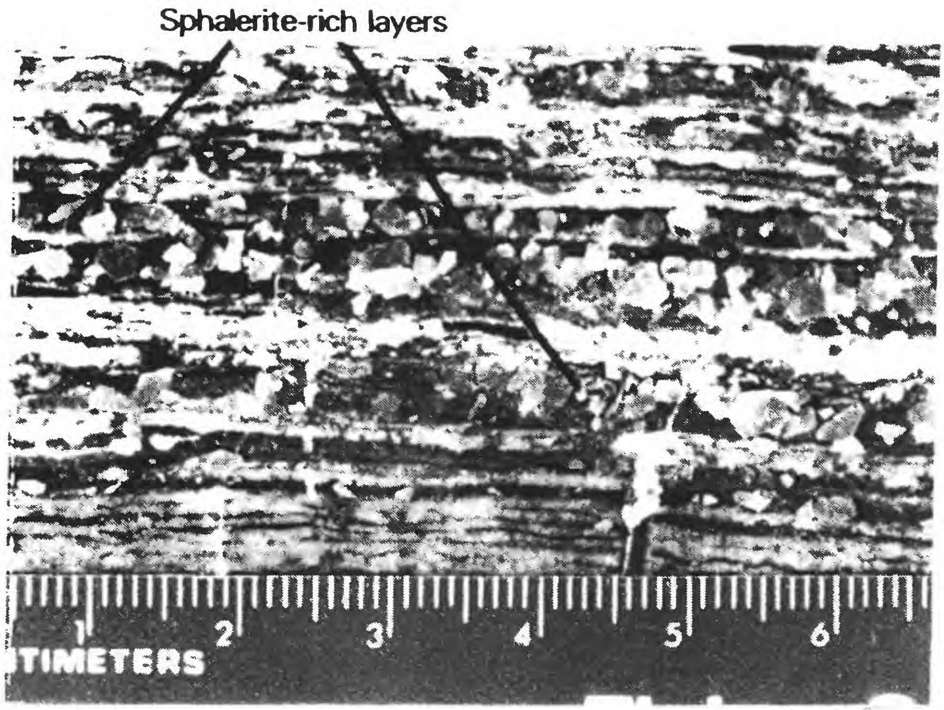


Figure 8A

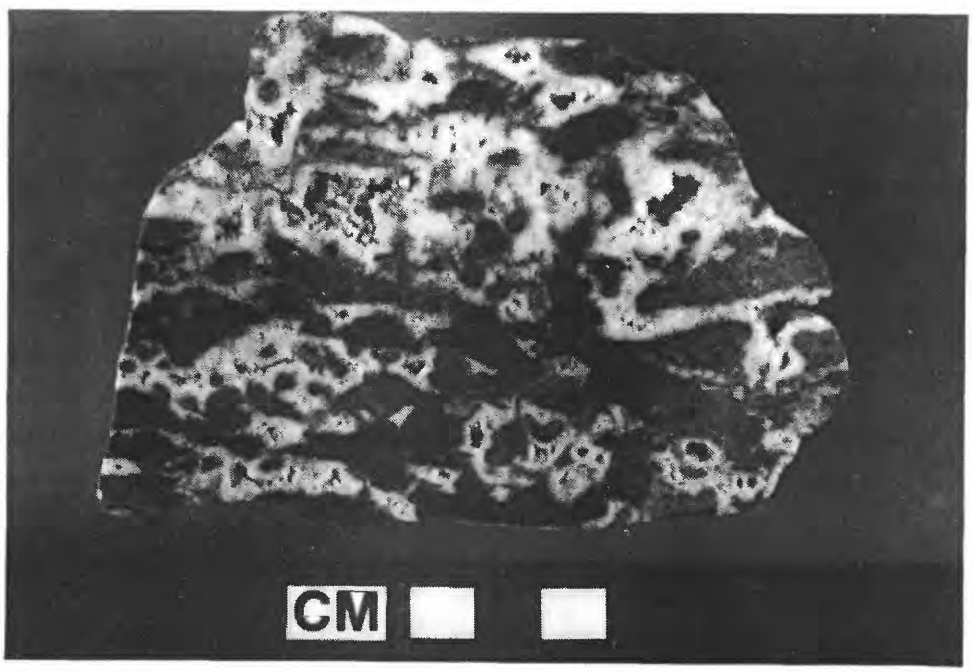


Figure 8B

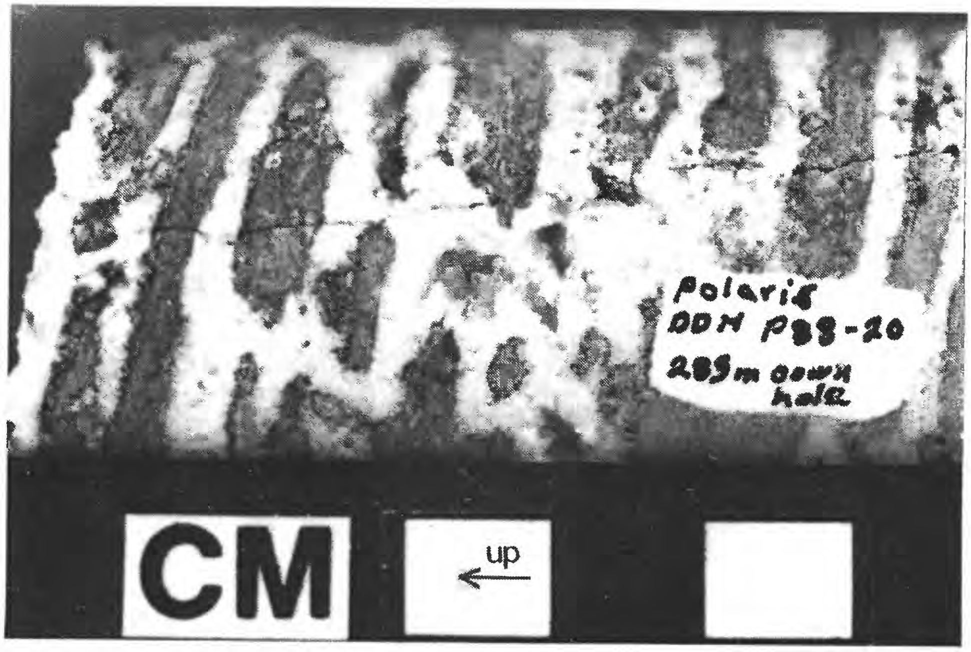


Figure 8C

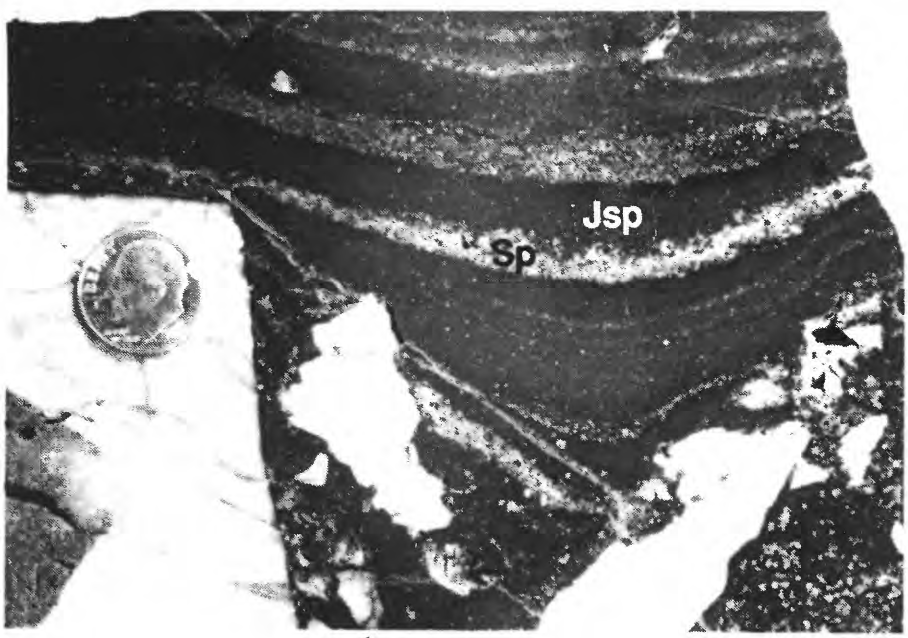


Figure 8D

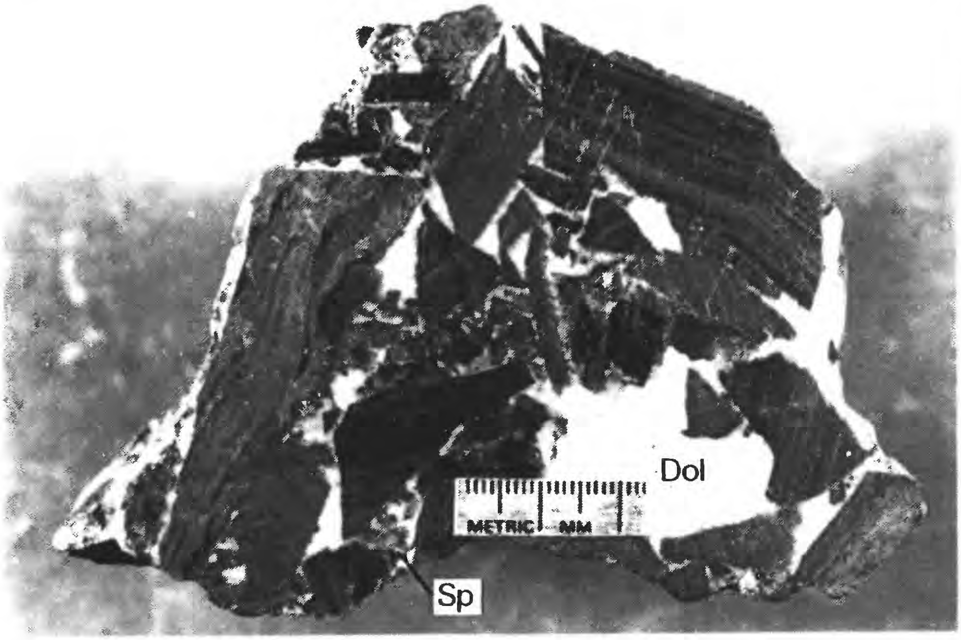


Figure 9A

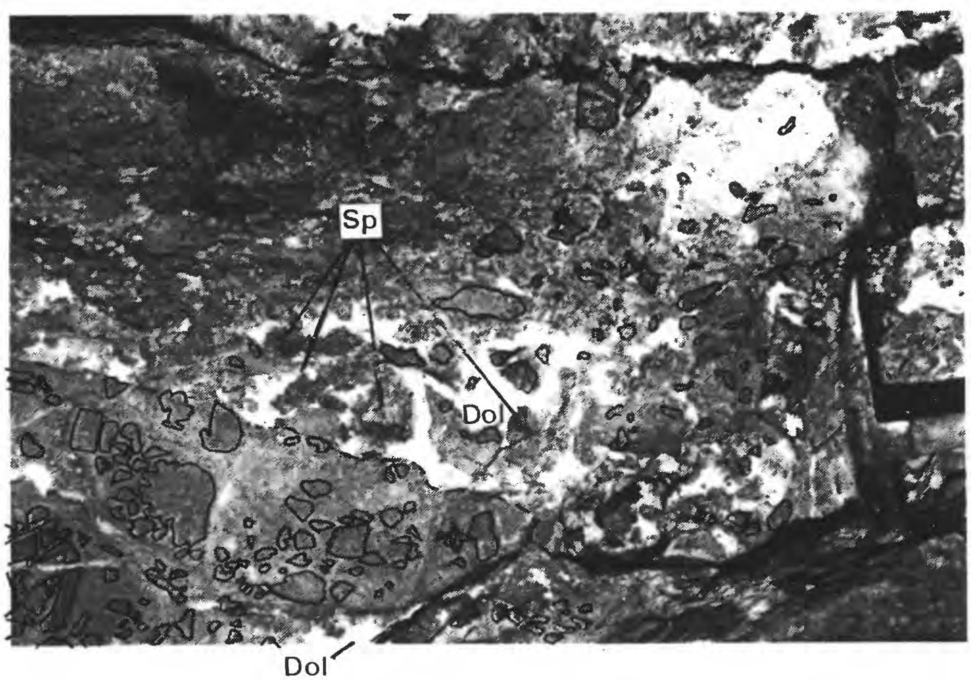


Figure 9B

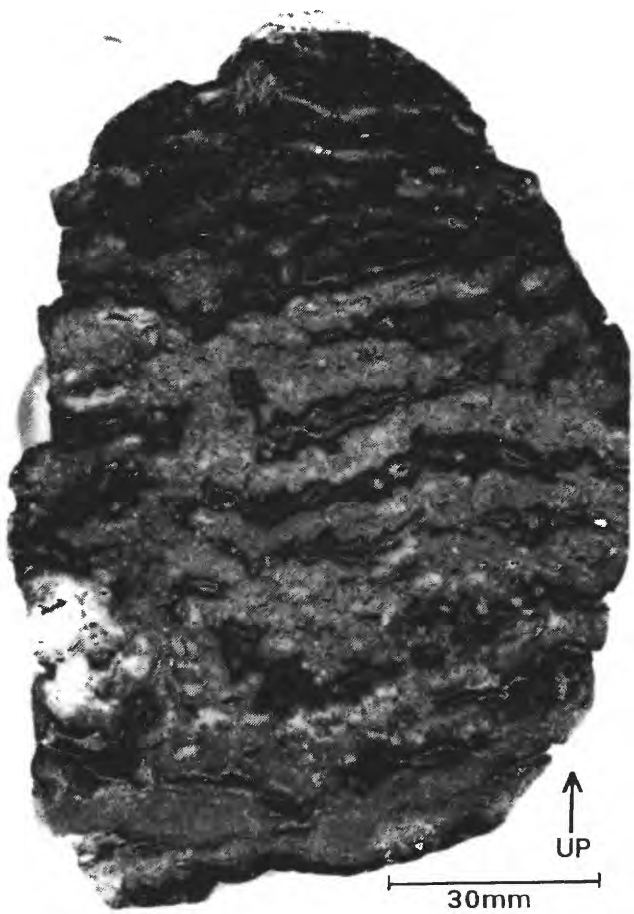


Figure 9C

Figure 9D

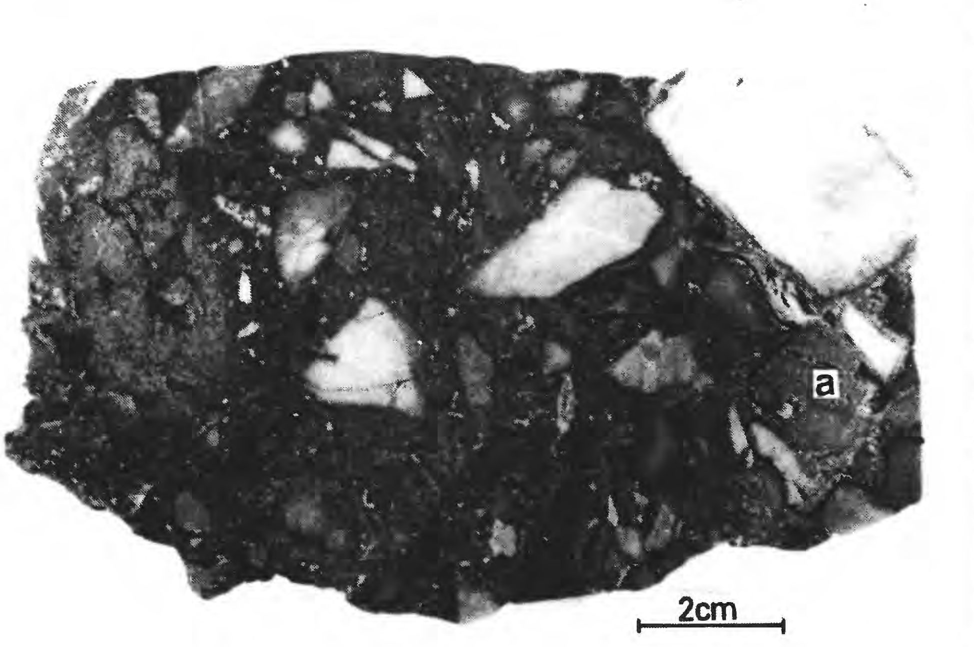


Figure 10A

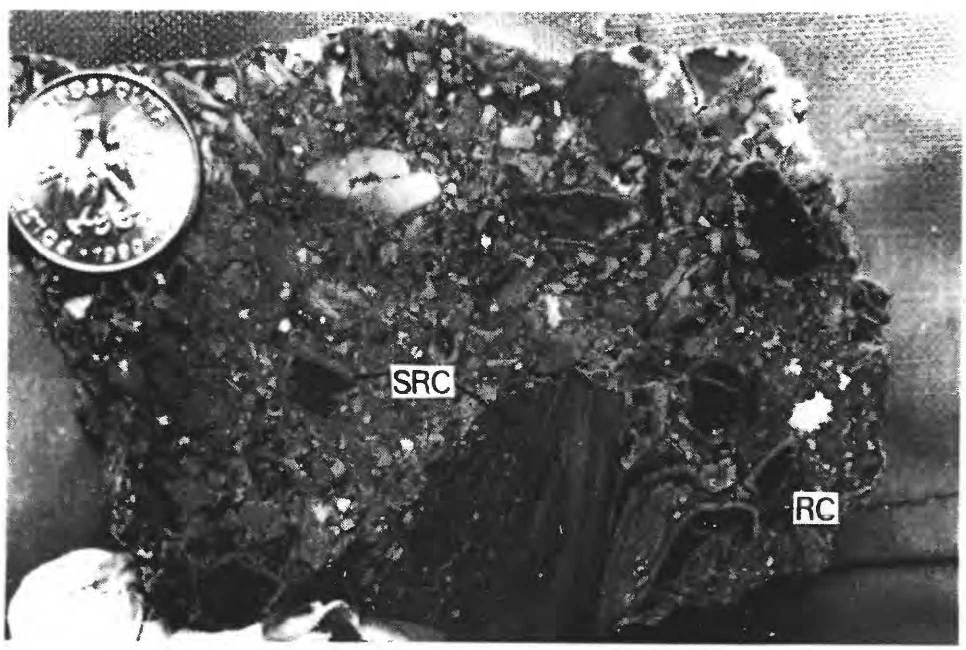


Figure 10B

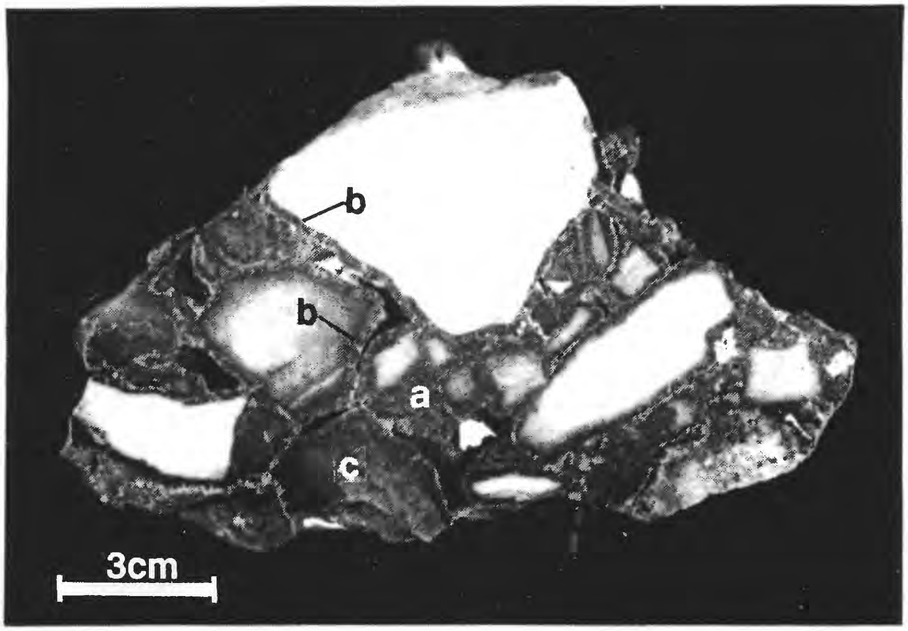


Figure 10C

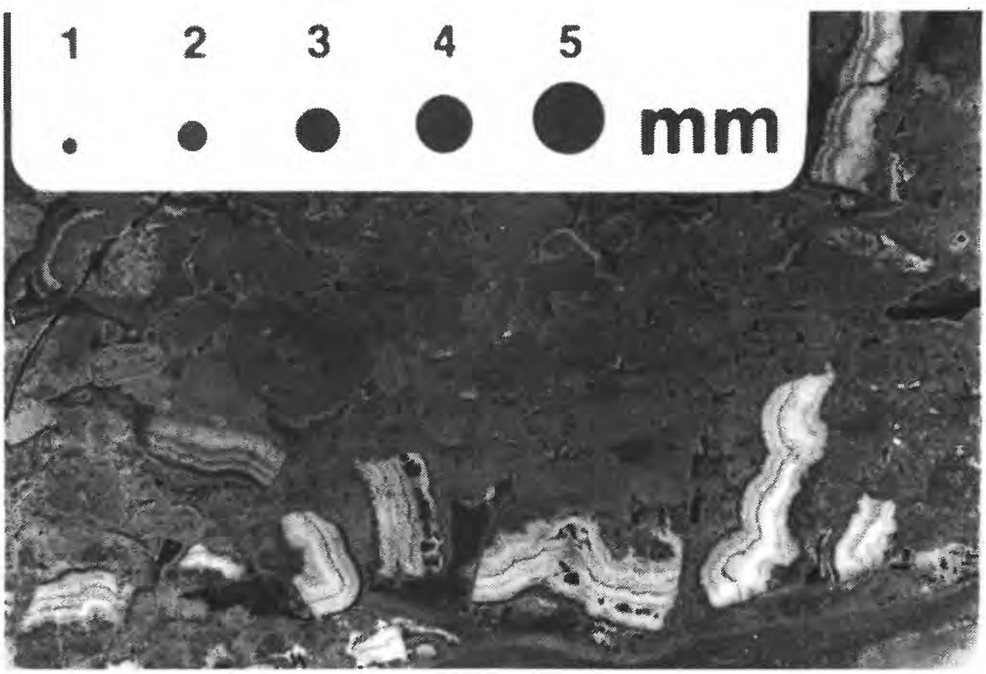


Figure 10D

Figure 11A

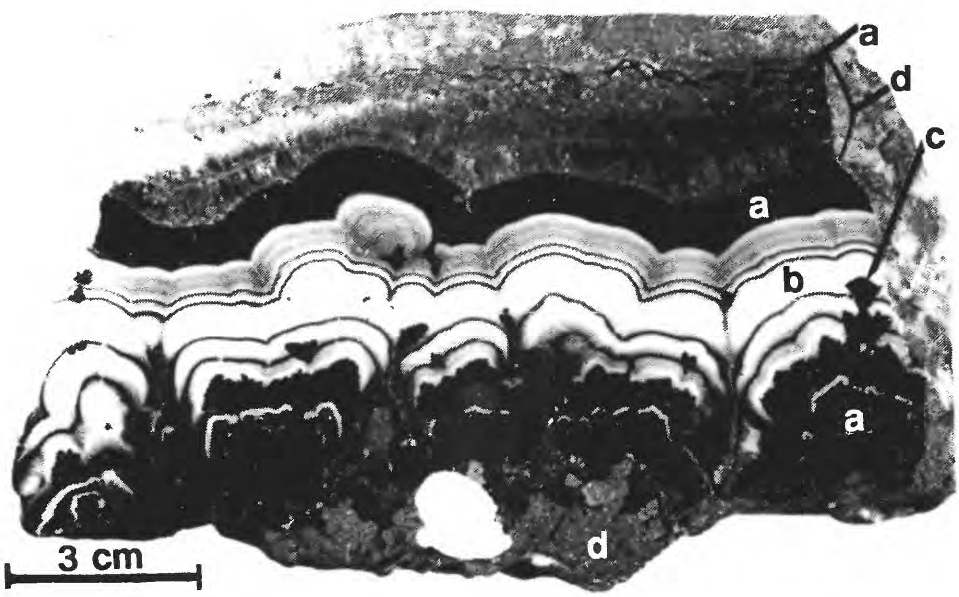


Figure 11B

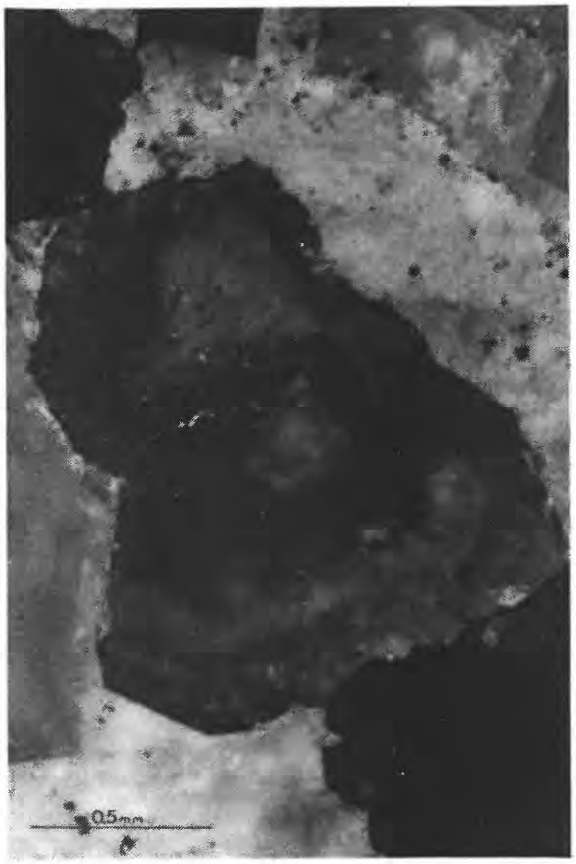


Figure 11C

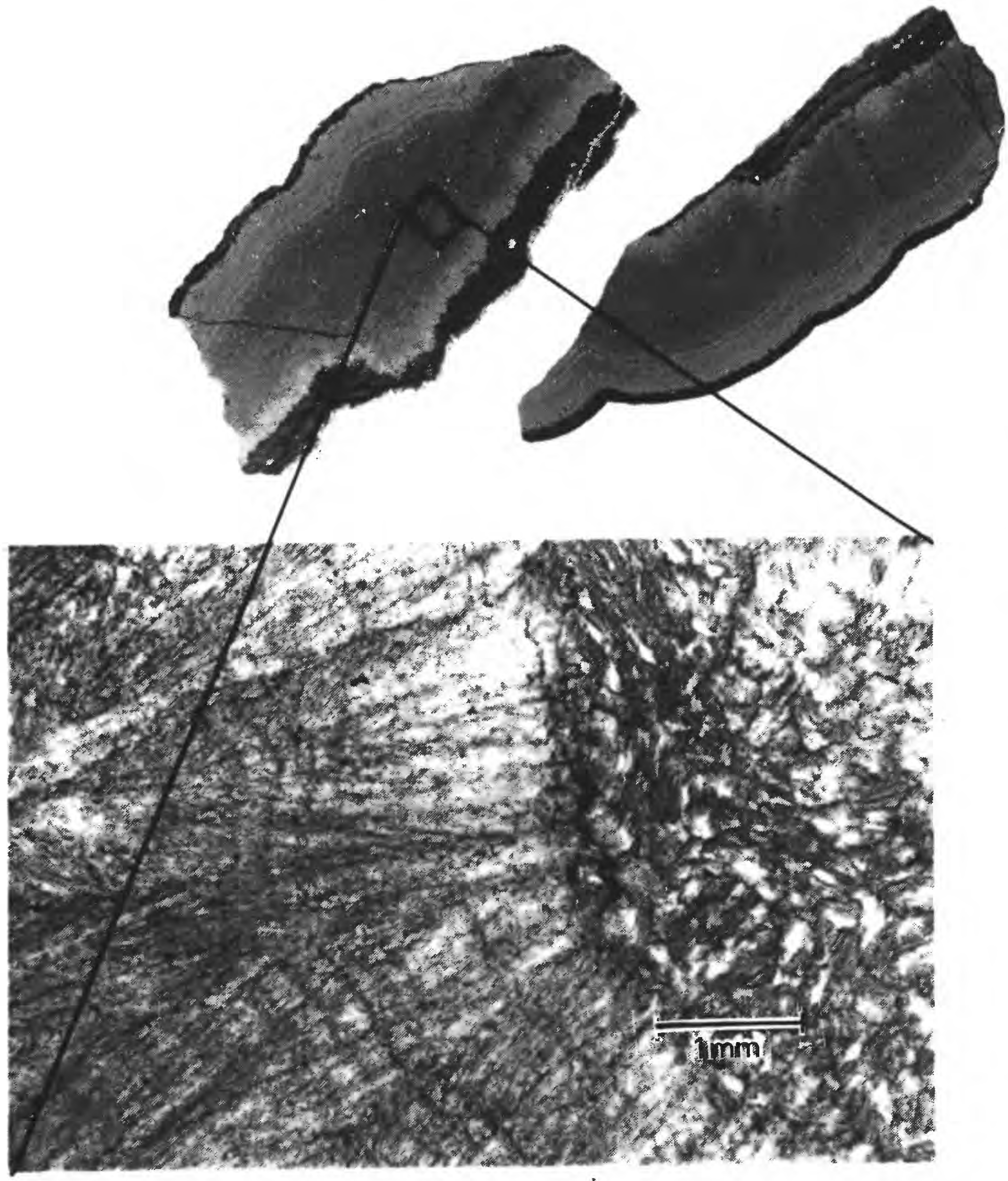


Figure 11D

Figure 12A

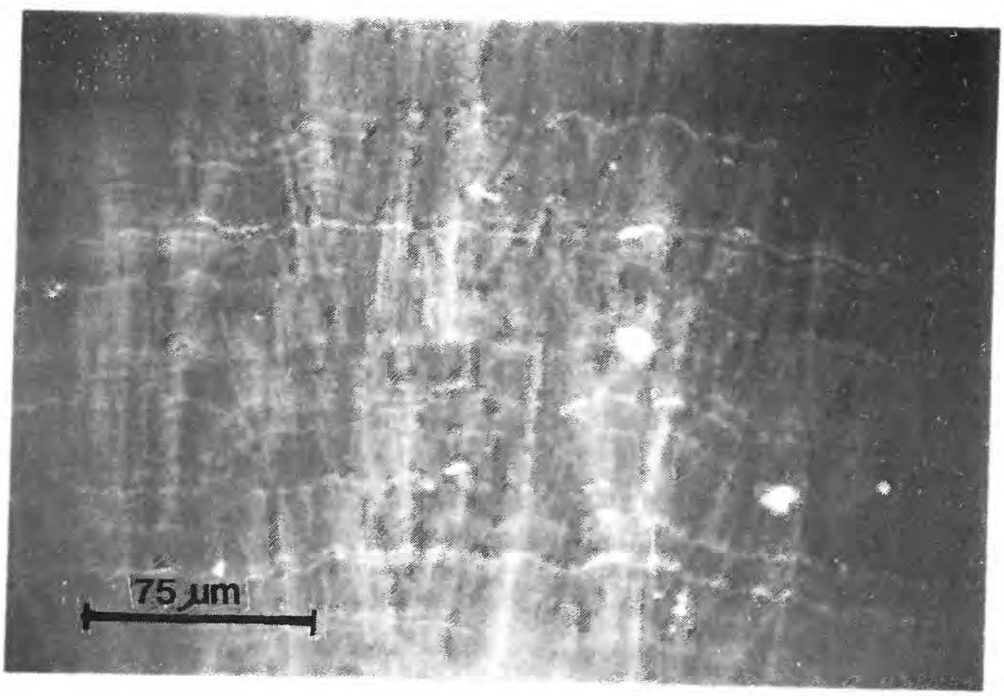


Figure 12B

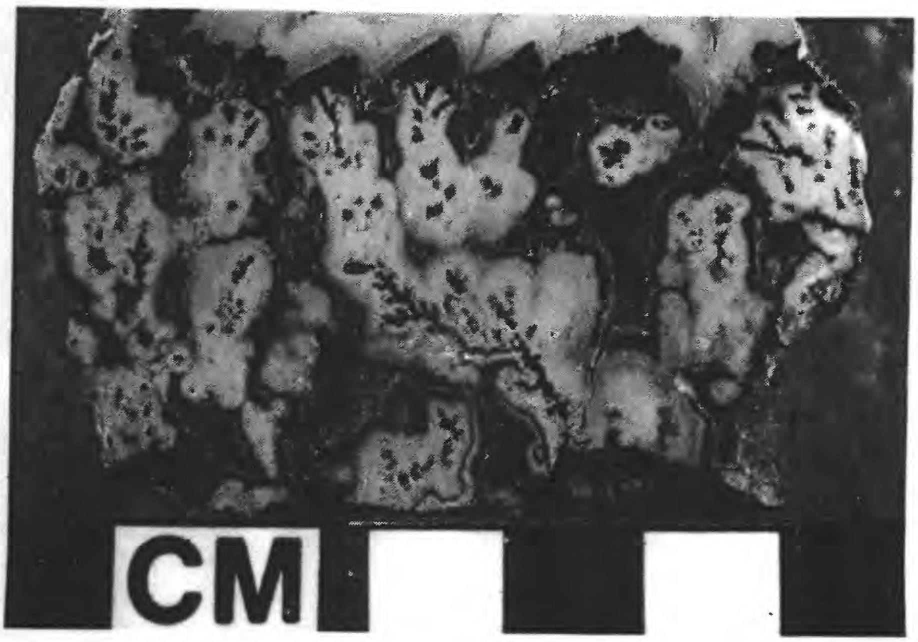


Figure 12C

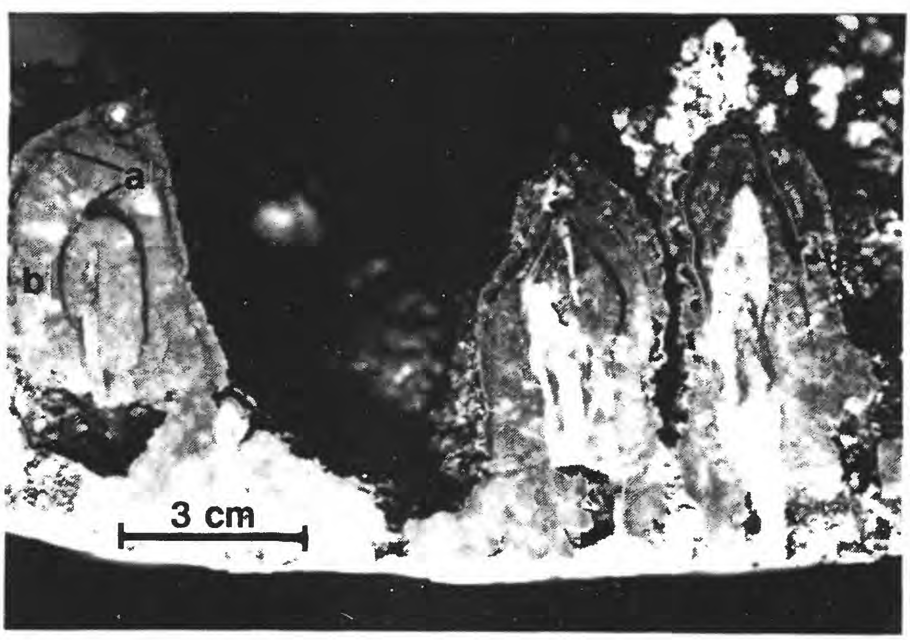


Figure 12D

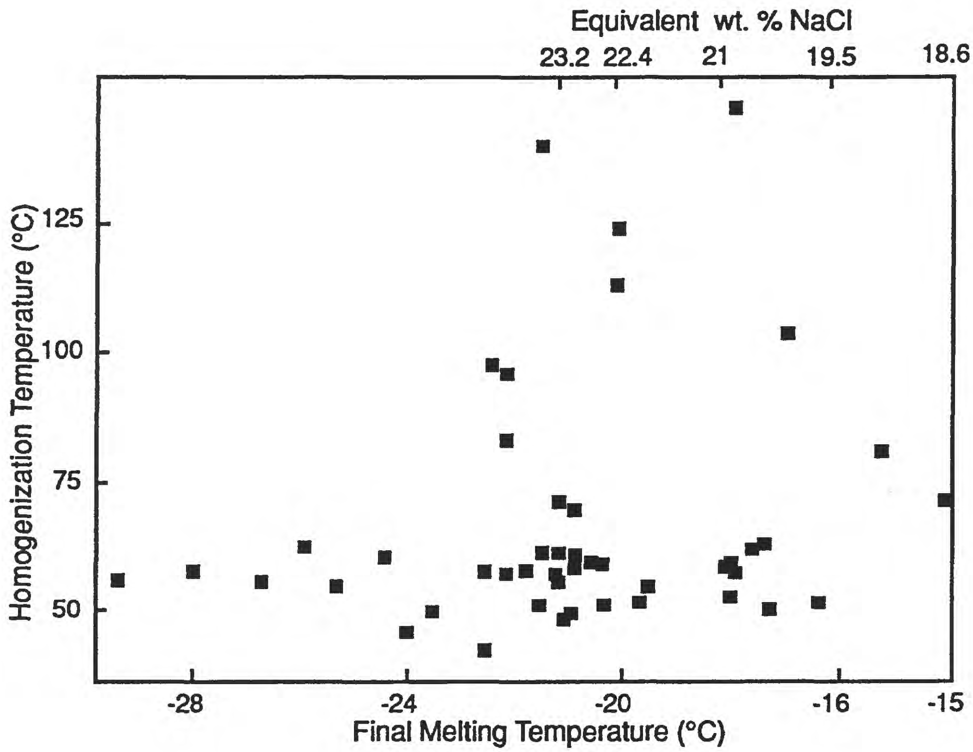

Equivalent wt. % NaCl
23.2
22.4
21
19.5
18.6
Homogenization Temperature (°C)
125
100
75
50
-28
-24
-20
-16
-15
Final Melting Temperature (°C)

Fig. 13

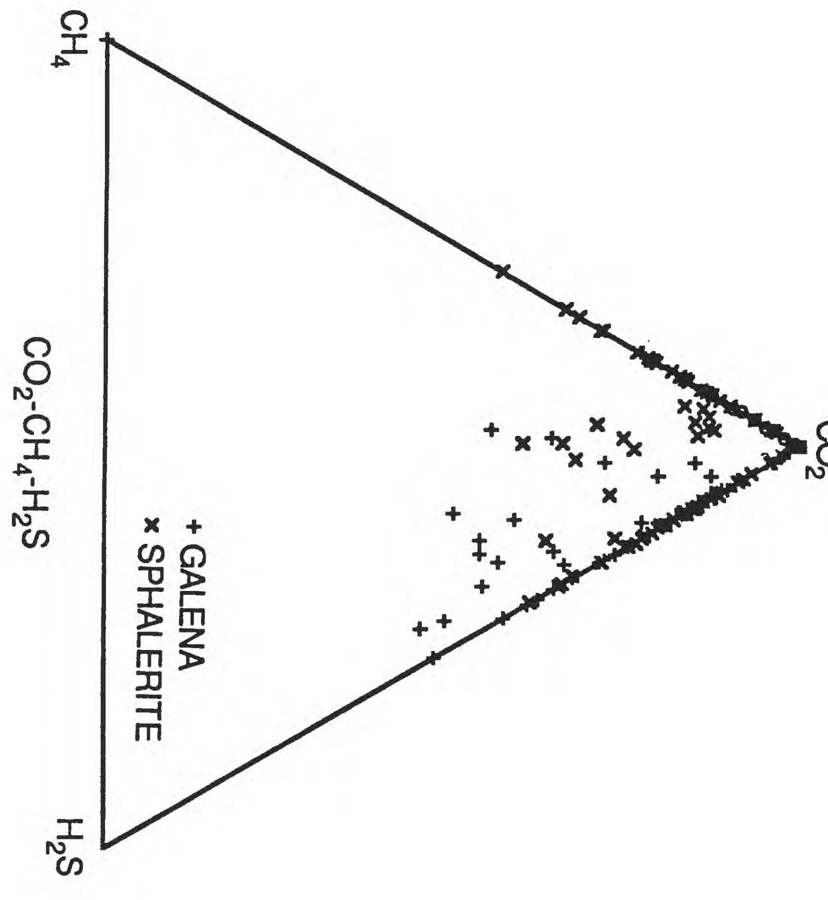


Fig. 14

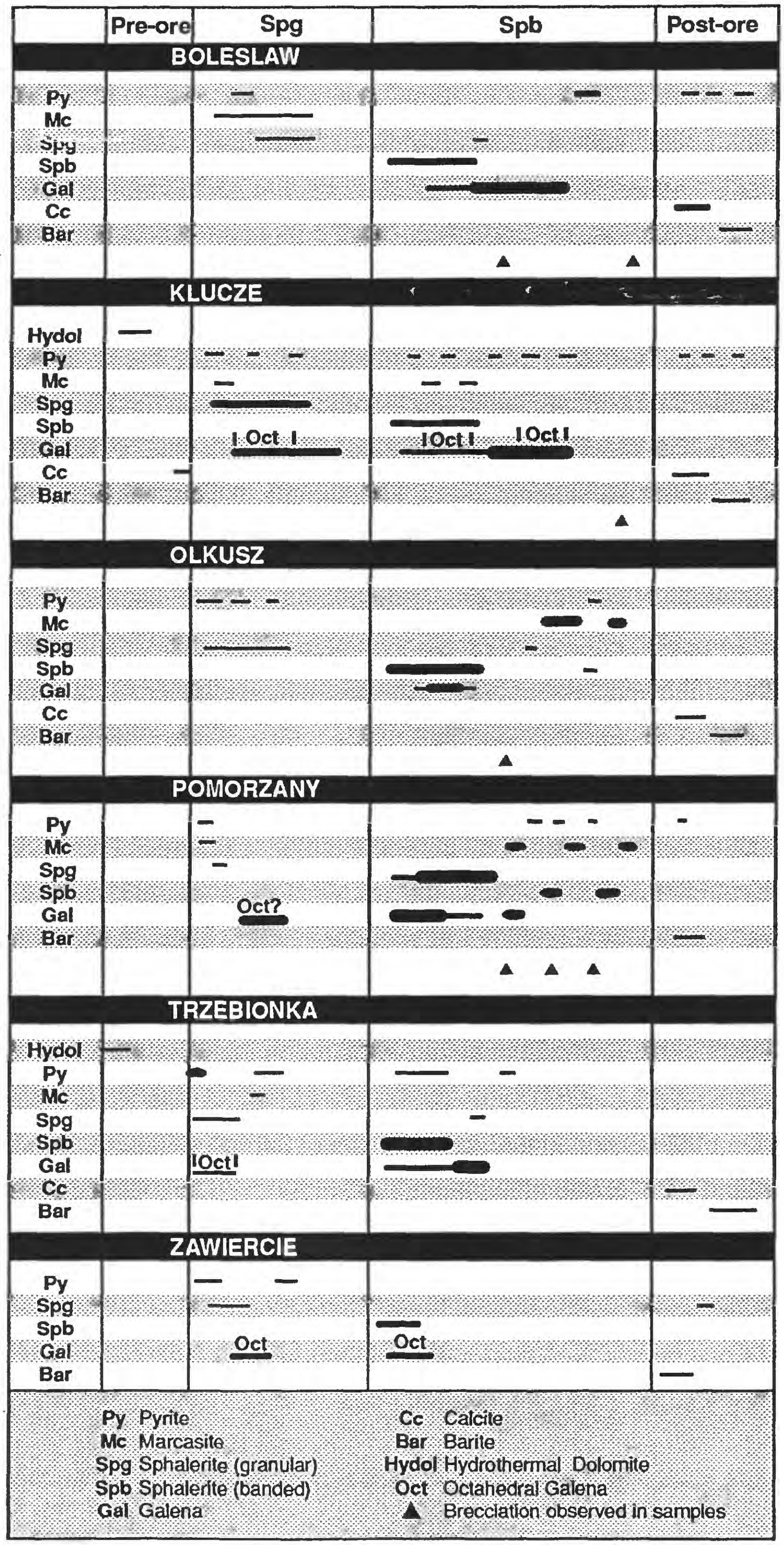

Pre-ore
Spg
Spb
Post-ore
BOLESLAW
Py
Mc
Spg
Spb
Gal
Cc
Bar
KLUCZE
Hydol
Py
Mc
Spg
Spb
Gal
Cc
Bar
Oct
OLKUSZ
Py
Mc
Spg
Spb
Gal
Cc
Bar
POMORZANY
Py
Mc
Spg
Spb
Gal
Bar
Oct?
TRZEBIONKA
Hydol
Py
Mc
Spg
Spb
Gal
Cc
Bar
Oct
ZAWIERCIE
Py
Spg
Spb
Gal
Bar
Oct
Py Pyrite
Mc Marcasite
Spg Sphalerite (granular)
Spb Sphalerite (banded)
Gal Galena
Cc Calcite
Bar Barite
Hydol Hydrothermal Dolomite
Oct Octahedral Galena
Brecciation observed in samples

Fig. 15

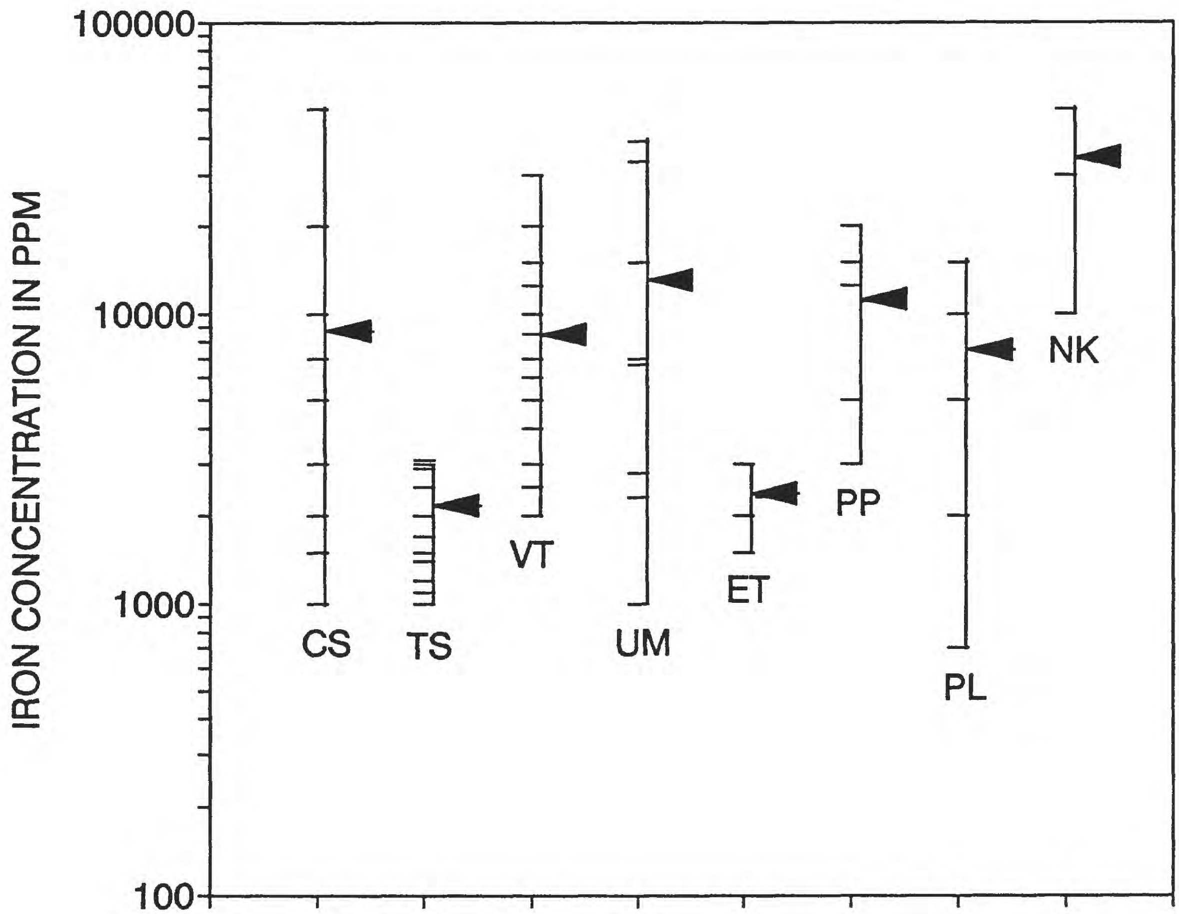
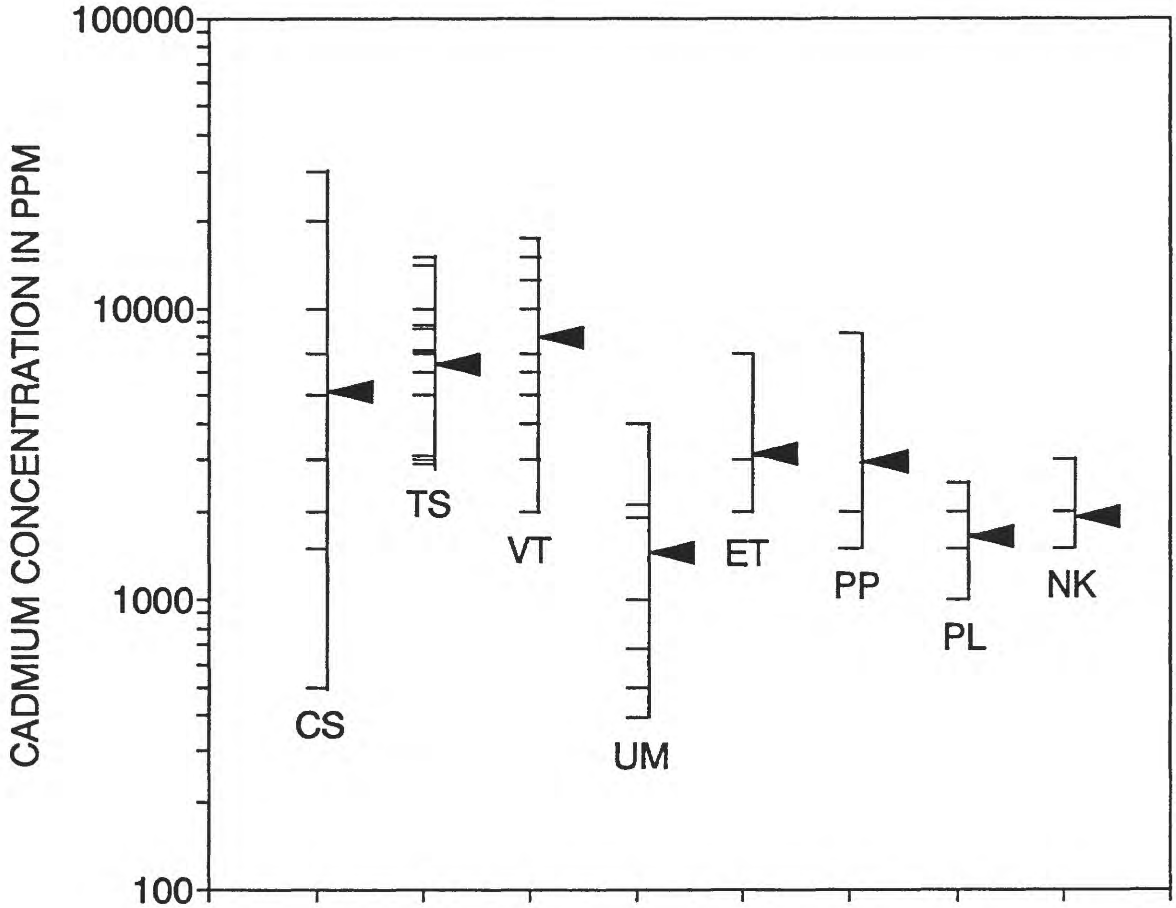

IRON CONCENTRATION IN PPM
100000
10000
1000
100
CS
TS
VT
UM
ET
PP
PL
NK

Fig. 16



100000
10000
1000
100
CADMIUM CONCENTRATION IN PPM
CS
TS
VT
UM
ET
PP
PL
NK

Fig. 17

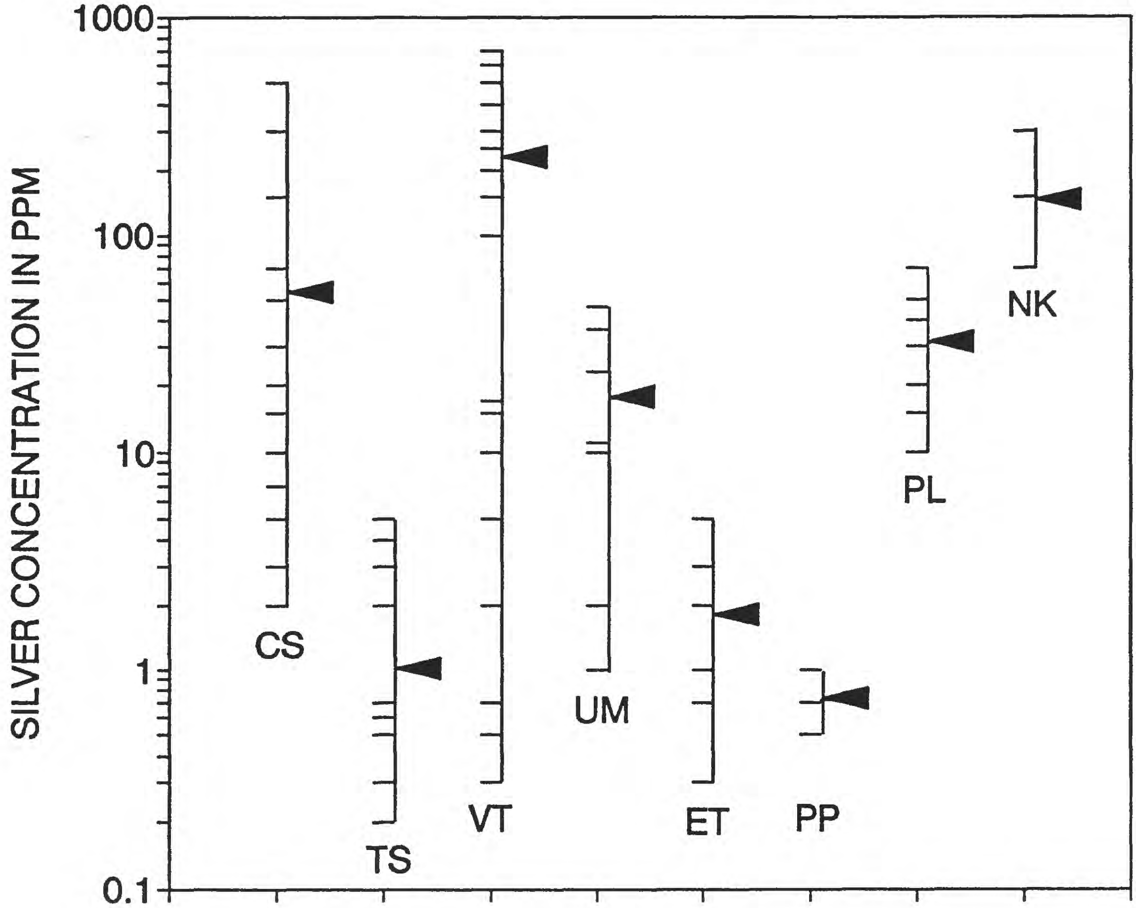

1000
100
10
1
0.1
SILVER CONCENTRATION IN PPM
CS
TS
VT
UM
ET
PP
PL
NK

Fig. 18

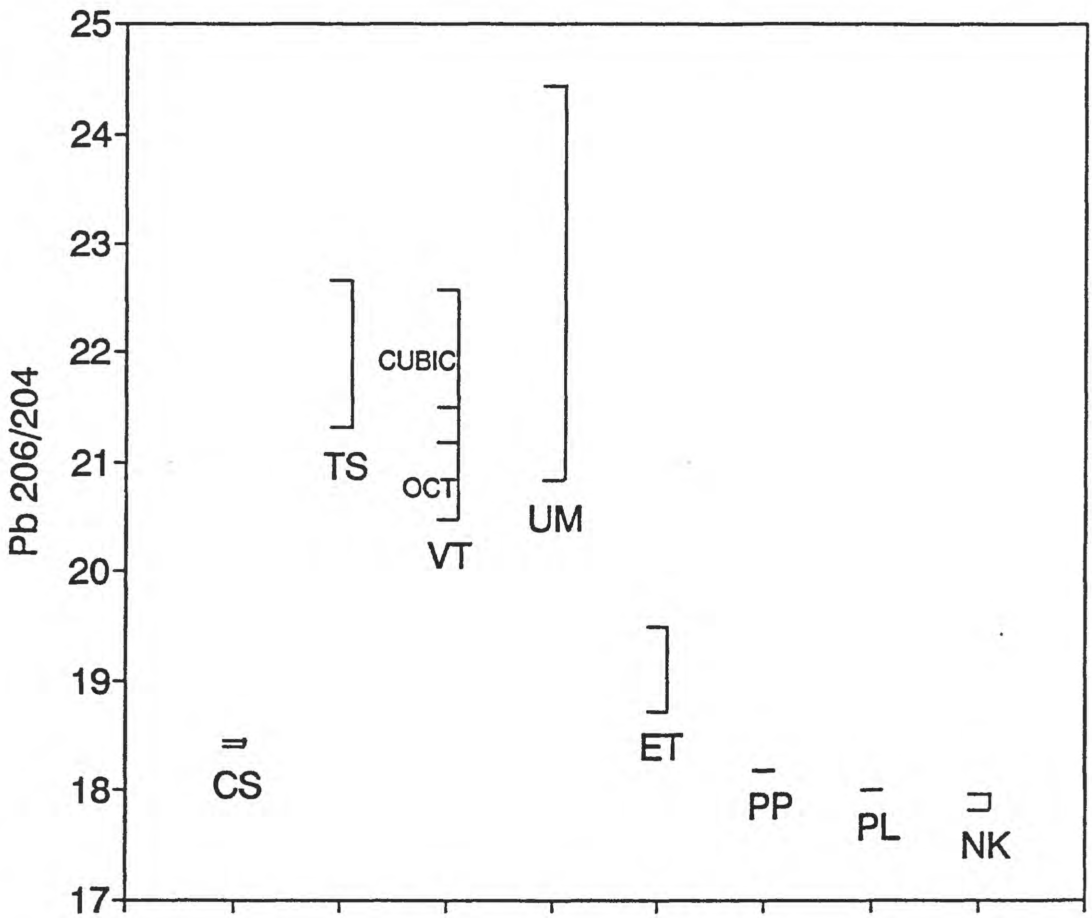

Pb 206/204
25
24
23
22
21
20
19
18
17
CS
TS
CUBIC
OCT
VT
UM
ET
PP
PL
NK

Fig. 19

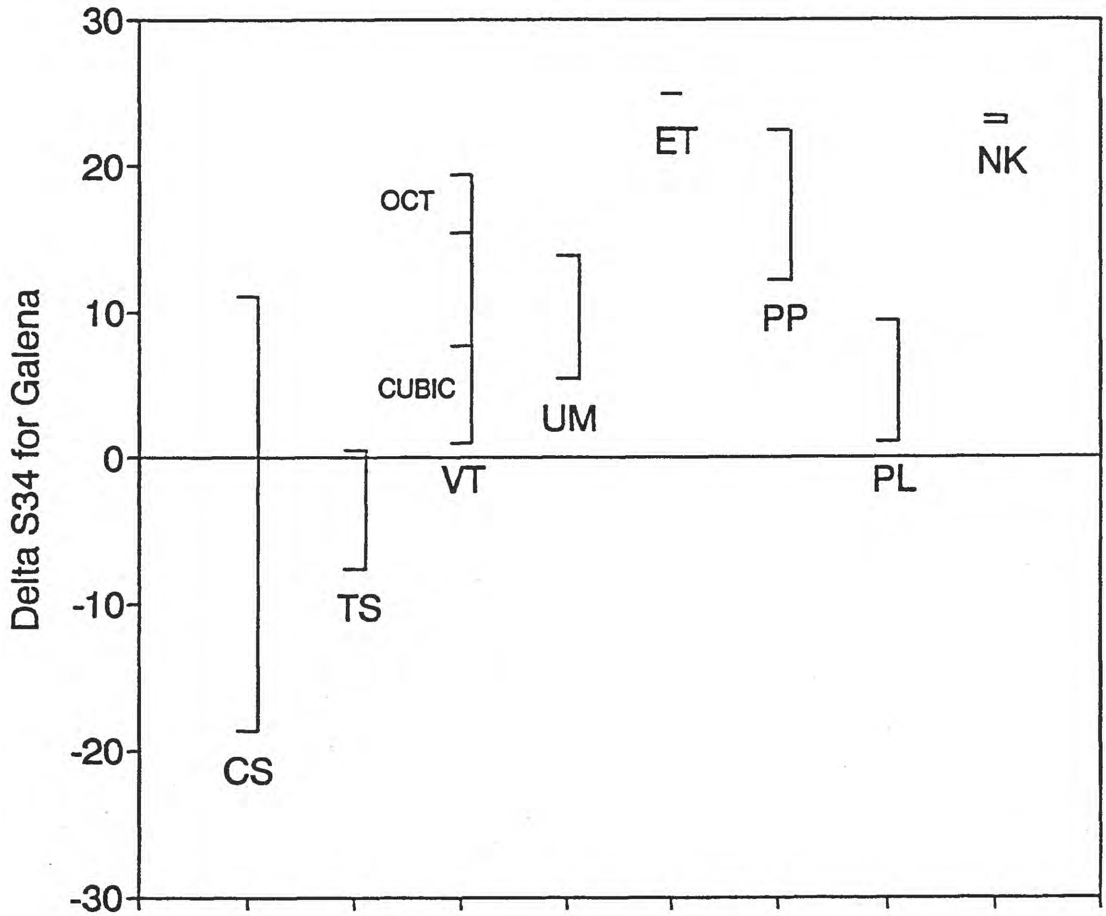

Delta S34 for Galena
30
20
10
0
-10
-20
-30
CS
TS
OCT
CUBIC
VT
UM
ET
PP
PL
NK

Fig. 20

DISTRICT	SHALE EDGES	LIMESTONE/ DOLOMITE (2)	REEF AND BARRIER COMPLEX	SOLUTION COLLAPSE BRECCIAS	BASEMENT TOPOGRAPHY	FAULTS/FRACTURES	UNCONFORMITY FEATURES (3)	OTHER
VIBURNUM TREND	●	●	●	●	●	●		white rock – brown rock (1)
OLD LEAD BELT	●	●	●		●	●		sand bars, various sedimentary facies
SE. MISSOURI BARITE						●	●	
CENTRAL MISSOURI	•			●		•		
TRI-STATE	●	·	•	●		●		sedimentary breccias (?)
NORTHERN ARKANSAS	●	·		●		●		
LLANO TX		·			●	•		porous carbonate sands about basement knobs are hosts
CENTRAL TENNESSEE		·		●			•	
EAST TENNESSEE		·		●				
AUSTINVILLE		·				●		facies change
TIMBERVILLE		·		●		•		
FRIEDENSVILLE		·		●				
GAYS RIVER			●		●	•		
DANIEL'S HARBOUR		●		•		●	●	
NANISIVIK				●		●		
POLARIS	●	●		●				
PINE POINT	●	●	●	●			•	
GAYNA				●				
UPPER MISSISSIPPI VALLEY		·		·		●		
ALPINE	●	·	●	●		●		
ROBB LAKE	●	·		●		·		
MONARCH-KICKING HORSE	●	·		•		●		
CRACOW-SILESIA	●	●		●		●		
CADJEBUT		?				●		sedimentary breccias
COXCO				•		●		

MAJOR ● MINOR • LESS IMPORTANT ·

Table 1