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To the Graduate Council:

I am submitting herewith a thesis written by James Richard Kyle entitled "Preliminary Investigation of Brecciation, Alteration, and Mineralization in the Upper Knox Group of Smith and Trousdale Counties, Tennessee." I recommend that it be accepted for nine quarter hours of credit in partial fulfillment of the requirements for the degree of Master of Science, with a major in Geology.

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PRELIMINARY INVESTIGATION OF BRECCIATION, ALTERATION, AND MINERALIZATION IN THE UPPER KNOX GROUP OF SMITH AND TROUSDALE COUNTIES, TENNESSEE

A Thesis

Presented to

the Graduate Council of

The University of Tennessee

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

---

by

James Richard Kyle

August 1973

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ABSTRACT

The Lower Ordovician upper Knox Group is covered by a minimum of several hundred feet of younger strata in Smith and Trousdale Counties, Tennessee. The Mascot Dolomite and differing amounts of the Kingsport Formation are present in the core studied. The Mascot ranges from 760 to 850 feet thick and is divided into upper, middle, and lower members, each containing distinctive stratigraphic markers.

Fracturing, crackle breccia, and rubble breccia indicate the character or degree of brecciation in the upper Knox, and such breccias may be cemented by fine rock matrix, coarse rock matrix, or introduced mineral matrix. Fine rock matrix breccias generally occur in stratigraphic positions which contain limestone equivalents in the upper Mascot and may be related to solution during the pre-Chazyan erosional interval. They formed significantly earlier than the breccias that host mineralization. Coarse rock matrix breccias are developed in limestone equivalent intervals, especially of the Kingsport, and represent the residue from later limestone dissolution which resulted in collapse of overlying strata thus forming the ore-stage breccia bodies. Mineral matrix breccias are best developed in the middle Mascot in Smith County, but significant amounts also occur in the lower Mascot in the core studied from Trousdale County.

Alteration processes include formation of reaction rims, dolomitization, and silicification. Reaction rims are single or multiple dark concentric bands containing redistributed iron sulfide which parallel the bleached borders of some "primary" dolostone blocks in the fine rock matrix breccias. Although they also occur in mineral matrix breccia intervals, this association is fortuitous, and the rims are not related to the ore-forming process. Dolomitization of limestone strata and silicification with attendant quartz druse occur early in the history of ore-stage brecciation and appear to be more pervasive in the drill holes studied than generally recognized for the East Tennessee districts.

Calcite is the dominant mineral cement in the ore-stage breccias of Smith and Trousdale Counties. Sphalerite, galena, fluorite, and barite occur in varying amounts, perhaps in overlapping zones with depth within the Knox. Minor amounts of dolomite and quartz, and rare amounts of marcasite, celestite, and bituminous residue are present.

The mineral deposits of Smith and Trousdale Counties are similar in many respects to the East Tennessee deposits. Both occur in dissolution collapse breccia bodies in the upper Knox Group which contain sphalerite, carbonate gangue, and accessory mineralization as open space filling. Fine rock matrix and coarse rock matrix breccia are present. Alteration includes bleaching, dolomitization, and

silicification. The deposits of both areas are characterized as Mississippi Valley base metal type.

The Knox deposits of East Tennessee are exposed in strata which have been faulted and folded and which are inclined at 10°-40°. The Central Tennessee deposits are undeformed and are not exposed at the surface. The East Tennessee deposits consist of yellow sphalerite, primarily dolomite gangue, and minor accessory minerals. The deposits of Smith and Trousdale Counties consist of reddish brown sphalerite, primarily calcite gangue, and significant amounts of barite, fluorite, and galena; abundant open space remains in some areas. Numerous veins are present in post-Knox strata in Central Tennessee. If the veins are related to the Knox deposits, mineralization in Central Tennessee may have occurred significantly later than the Middle Ordovician age commonly proposed for the East Tennessee deposits.

The need for additional research concerning the genesis, ore controls, and mineral zoning in the recently discovered Central Tennessee district is evident, and possible projects are outlined.

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CHAPTER I

INTRODUCTION

Purpose of Investigation

The overall aspects of brecciation, mineralization, and associated features in the Lower Ordovician upper Knox Group of Smith and Trousdale Counties, Tennessee, are described and are compared with similar features in the better studied mineral deposits in the upper Knox Group of East Tennessee. Six diamond drill cores, from holes aligned along a northwest-southeast fence approximately perpendicular to the trend of the Cincinnati Arch (Figures 1 and 2), are described to determine the stratigraphic distribution of brecciation, alteration, and mineralization. Samples of breccia and mineralization from the Elmwood are also described. The information presented will hopefully serve as background for future research concerning the mineral deposits of an area which seems destined to become a major mining district.

Area of Study

The newly discovered zinc mineralization in the upper Knox Group of Central Tennessee and South Central Kentucky underlies an area along and to both sides of the crest of the Cincinnati Arch. Most of the region is within

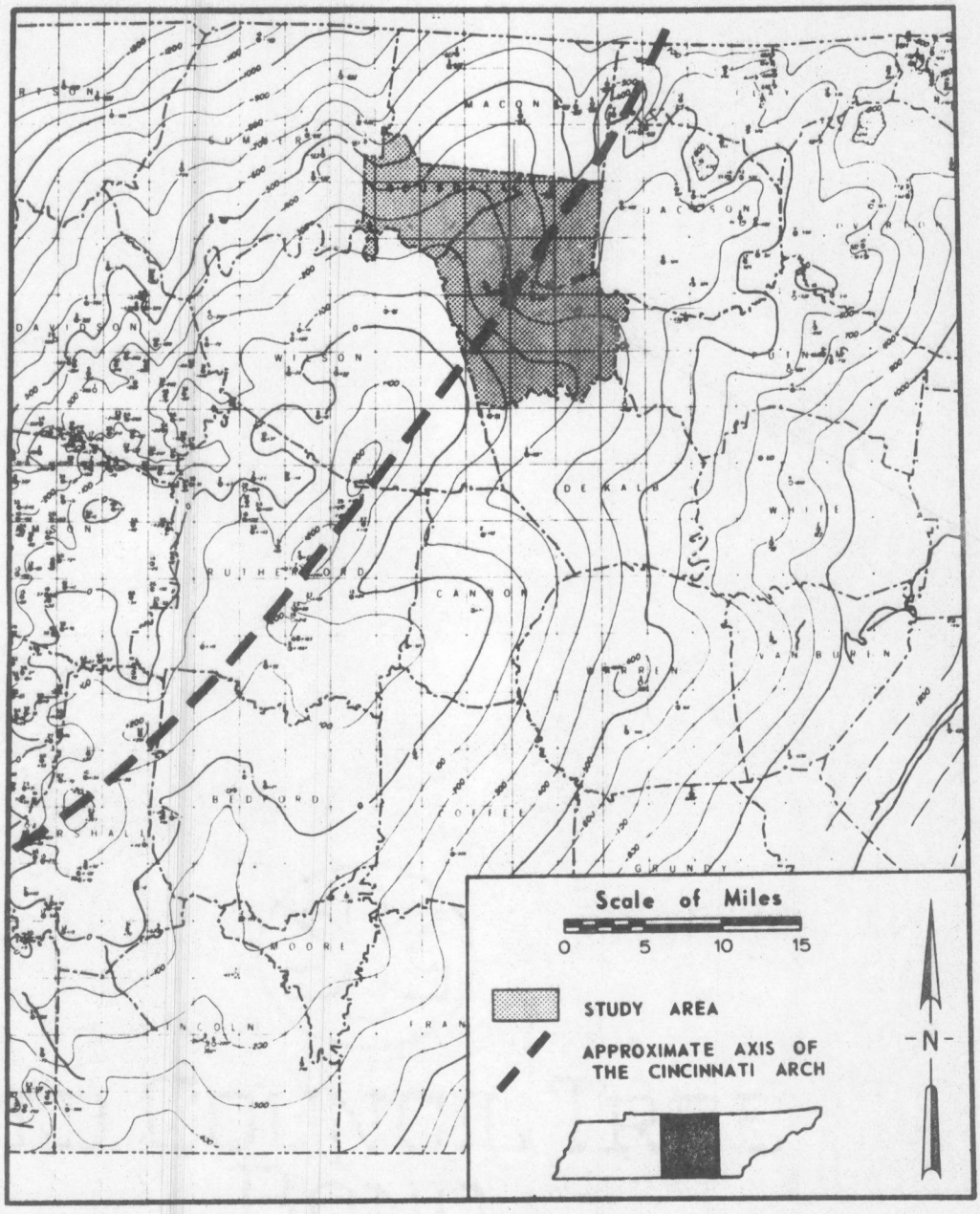


Figure 1

Structural Contour Map on Top of
Knox Group, Central Tennessee

Modified from Preliminary Structure Map on Top of Knox Group
(Tennessee Division of Geology)

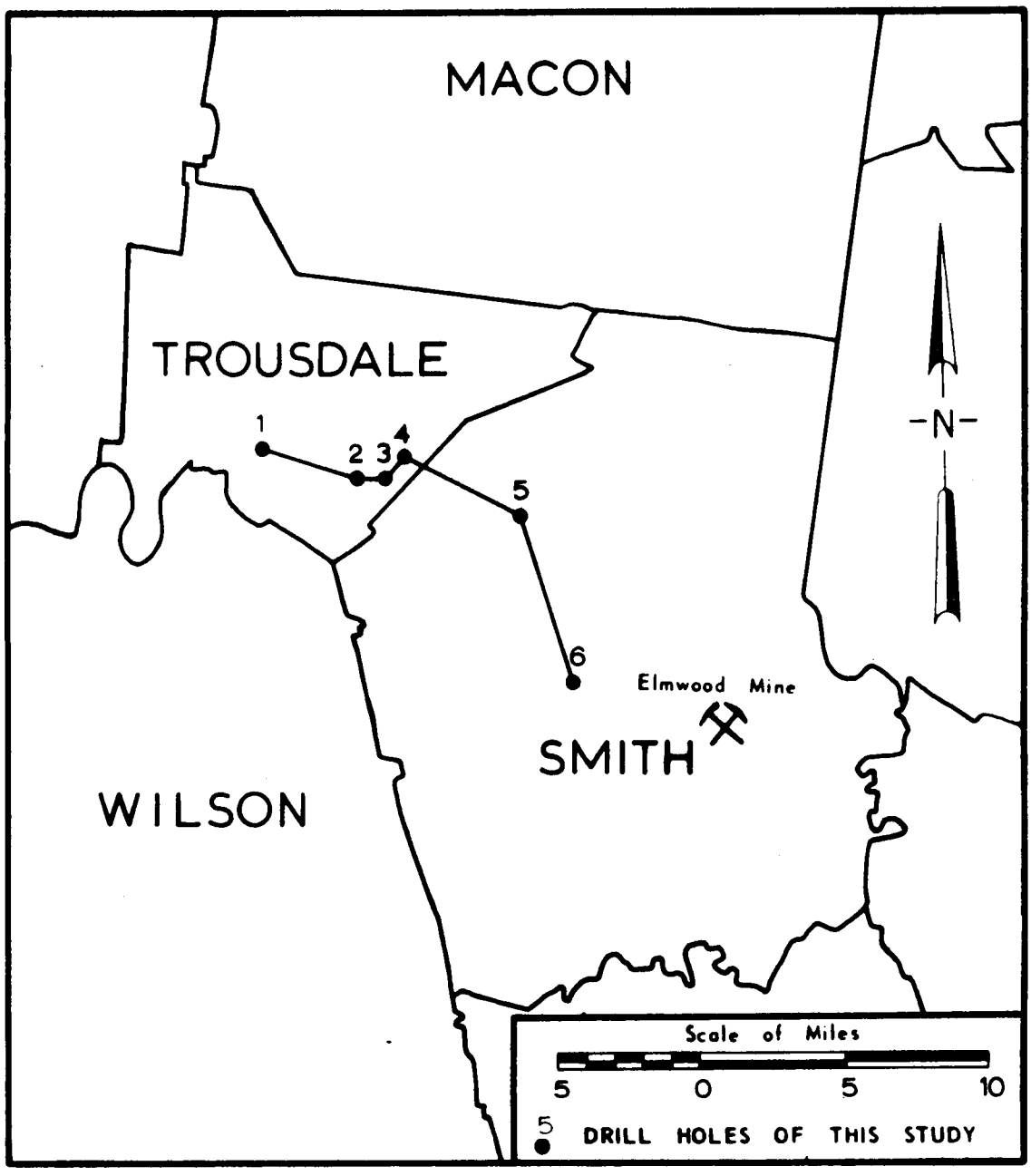


Figure 2

Location Map

the Central Basin Physiographic Province and passes into the Highland Rim Province to the east and north. Smith and Trousdale Counties, Tennessee, were chosen for this study because the area centers along the axis of the Cincinnati Arch, includes the only announced zinc deposit, contains well developed Knox stratigraphic marker units, and offers information from extensive core drilling.

Exploration History

In 1964 the New Jersey Zinc Company began a core-drilling program in Central Tennessee. This project was initiated by knowledge that the top of the upper Knox Group in Central Tennessee is within a few hundred feet of the surface in some areas, that the important zinc deposits of the Mascot-Jefferson City and Copper Ridge districts in East Tennessee are in the upper Knox Group, and that traces of sphalerite had been reported in oil and gas well cuttings from several counties in Central Tennessee (Winslow and Hill, 1973). Initial widespread drilling with holes one to five miles apart began in Rutherford County along the apex of the Nashville Dome and spread to the northeast and southwest (Figure 1). After approximately 100 reconnaissance drill holes containing only minor zinc mineralization, an ore intersection was drilled about five miles southeast of Carthage near the Elmwood community in Smith County. On January 8, 1969, a formal announcement was made of the discovery of a 13- to 50- million ton ore body averaging

between 5 and 10 percent zinc and occurring in gently dipping strata 900 to 1700 feet below the surface. Initial drilling results suggested that "the potential of the area may far exceed the known occurrences of zinc in the Mascot-Jefferson City and Copper Ridge districts" (Mining Engineering, 1969). Exploration was initiated by numerous other mining companies and has progressed along the flanks of the Cincinnati Arch. To the east as the flanks of the arch become progressively deeper, the elevations also increase as the result of transition from the Central Basin to the Eastern Highland Rim. This increased depth to the Knox results in much higher drilling costs in these areas and undoubtedly will determine the eastward limit of exploration. Exploration is continuing at the present time, but the Elmwood deposit remains the only formally announced ore body. The Elmwood mine is currently in the developmental stage with production scheduled to begin in early 1974.

CHAPTER II

GENERAL GEOLOGY

Stratigraphy

Post-Knox Formations

The Middle Ordovician to Lower Mississippian stratigraphy of Smith and Trousdale Counties is summarized in Figure 3. The Middle Ordovician formations in the subsurface differ somewhat from surface descriptions, and some contacts have been redefined by companies working in the district. These formations were not studied in detail in this thesis and will be referred to only as post-Knox strata.

Knox Group

Except for two small cryptoexplosive areas, the Wells Creek structure in Stewart County and the Flynn Creek structure in Jackson County, the Knox Group is not exposed at the surface in Central Tennessee. Therefore, details of Knox stratigraphy in Central Tennessee were unknown prior to the extensive core drilling programs. Although there is regional variation in lithology, certain stratigraphic marker units have been recognized by New Jersey Zinc Company geologists (Stagg and Fischer, 1970; Appendix A). These markers are remarkably persistent over large areas and are invaluable for defining intervals of brecciation and

PERIOD	FORMATION		THICKNESS		GENERALIZED DESCRIPTION
MISSISSIPPIAN	Fort Payne Formation		180+'		Silicastone, brownish gray, calcareous, contains lenses and nodules of medium to dark gray chert and small quarts geodes.
MISSISSIPPIAN	Chattanooga Shale		20'-30'		Shale, grayish black, carbonaceous, very thinly laminated, fissile. 1' of greenish gray shale with dark gray phosphatic nodules at top (Maury Shale).
	UNCONFORMITY				
MISSISSIPPIAN and DEVONIAN	Leipers and Catheys Formations		200'-360'		Limestone of very variable lithology, light gray to dark brownish gray, cryptocrystalline to fine grained, thin to medium bedded, argillaceous and nodular in part.
ORDOVICIAN	Cannon Limestone		85'-95'		Limestone, light gray to dark brown gray, cryptocrystalline to coarse grained, thin to medium bedded. 5' unit of light gray ("dove" colored), cryptocrystalline limestone 15'-20' below top.
ORDOVICIAN	Hermitage Limestone	Silty-Nodular Member	65'-80'	30'-40'	Limestone, light to medium gray, cryptocrystalline to very fine grained, thin bedded, nodular, argillaceous. 0-5' unit of brownish gray, coarse grained, phosphatic limestone at base.
ORDOVICIAN	Hermitage Limestone	Laminated Argillaceous Member		25'-50'	Limestone, medium to dark gray, cryptocrystalline to fine grained, thin bedded with abundant shale partings. 2'-4' of green shaley bentonite (T-5) 12' to 15' above base. 0-5' unit of dark gray, coarse grained, fossil fragmental limestone at base (Curdsville Member).
	UNCONFORMITY				
ORDOVICIAN	Carters Limestone	Upper Member	90'-120'	20'-30'	Limestone, light gray, cryptocrystalline, thin bedded with abundant shale partings. Up to 1' of green bentonite (T-4) at top although locally absent.
ORDOVICIAN	Carters Limestone	Lower Member		90'-100'	Limestone, pale to dark yellow brown, cryptocrystalline, thick to massive bedded. Contains some coarse grained, fossil fragmental units. 1'-1.5' of green bentonite (T-3) with biotite flakes at top.
	UNCONFORMITY				
ORDOVICIAN	Lebanon Limestone		115'-125'		Limestone, medium gray, cryptocrystalline, thin bedded with abundant thin irregular shale partings giving the unit a "ribbony" appearance.
ORDOVICIAN	Ridley Limestone		120'-140'		Limestone, light brownish gray to pale yellow brown, cryptocrystalline to fine grained, thick to massive bedded with zones of dolomitic blebs near top and base of formation. Some zones contain dark gray chert nodules.
ORDOVICIAN	Pierce Formation		10'-25'		Limestone, pale yellow brown to medium gray, very fine grained, thin bedded with very abundant shale.
ORDOVICIAN	Murfreesboro Limestone		320'-330'		Limestone, pale yellow brown to gray brown, cryptocrystalline to very fine grained, thick to massive bedded. Upper part contains dense cryptocrystalline limestone unit with dark gray chert nodules. Thin, irregular bedding in lower section. A 10'-15' laminated unit with abundant shale and calcite blebs is usually present about 180' above base.
ORDOVICIAN	Wells Creek Formation	Upper White Member	70'-110'	70'-110'	Limestone, light to medium blue gray, cryptocrystalline to very fine grained, massive bedded, dolomitic in part with varying degrees of bluish mottling.
ORDOVICIAN and CAMBRIAN	Wells Creek Formation	Lower Green Member		0-40+'	Dolostone, medium blue gray, very finely crystalline, massive bedded, mottled. The lower few inches to several feet may contain fine chert and dolostone fragments, sand grains, and argillaceous residue (Knox detritus).
	UNCONFORMITY				
ORDOVICIAN and CAMBRIAN	Knox Group				

Figure 3

Post-Knox Stratigraphy

Smith and Trousdale Counties, Tennessee

Modified from Wilson (1949, 1971) by unpublished drill data

mineralization and for determining stratigraphic and structural trends within the Knox.

The top of the Knox Group is generally regarded as a major unconformity of regional extent (Harris, 1969), and pre-Chazyan erosion is responsible for as much as 125 feet of relief on the Knox surface in Central Tennessee. The Lower Green unit of the Wells Creek Formation is thickest in paleotopographic lows, and similar material is found in fractures at least as much as 150 feet below the top of the Knox (Gilbert and Hoagland, 1970).

For the purposes of this thesis the Mascot Dolomite and the Kingsport Formation are considered to be the upper Knox Group, and the redefined contact between these formations is made at the top of the R-bed (Harris, 1969). The Mascot Dolomite consists of predominantly very finely crystalline dolostone units of various shades of brown and gray interbedded with some limestone units or their dolomitized medium and coarsely crystalline equivalents. In the drill cores studied, the thickness of the Mascot ranges from 759 feet to 847 feet.

The very finely crystalline Knox dolostones with uniform characteristics over large areas have been considered to be "primary" in origin by earlier workers (Kendall, 1960; Hoagland et al,1965; McCormick et al, 1971; Fulweiler and McDougal, 1971; and others). These dolostones were formed very early in the history of the strata, that is, before brecciation and alteration. They will be referred to

as "primary" in this thesis, although the dominant dolomitization mechanism is probably penecontemporaneous replacement of calcium carbonate. The term "limestone equivalent" will be hereafter used to denote intervals which contain medium and coarsely crystalline dolostone units or coarse rock matrix breccias which were formed by secondary dolomitization and dissolution of limestone units (Stagg and Fischer, 1970).

The upper Mascot includes the interval from the Knox unconformity to the M-3 marker (Figure 4). Thickness of this section is very variable primarily due to removal of upper units by pre-Chazyan erosion; in some areas of Central Tennessee most of the interval is missing. In Smith and Trousdale Counties the upper Mascot ranges from about 135 to 225 feet.

The middle Mascot includes the interval from the M-3 marker to the Chert Matrix marker. In unaltered sections the thickness is fairly consistent at about 315 feet. If the upper dolostone units have been displaced downward by collapse resulting from dissolution of underlying upper limestone strata while lower units were relatively unaffected, then an apparent thinning of the interval occurs. If the lower units were displaced downward because of dissolution of the lower limestone units, an apparent thickening of the section takes place. Where solution and collapse of the entire section has occurred, the relative

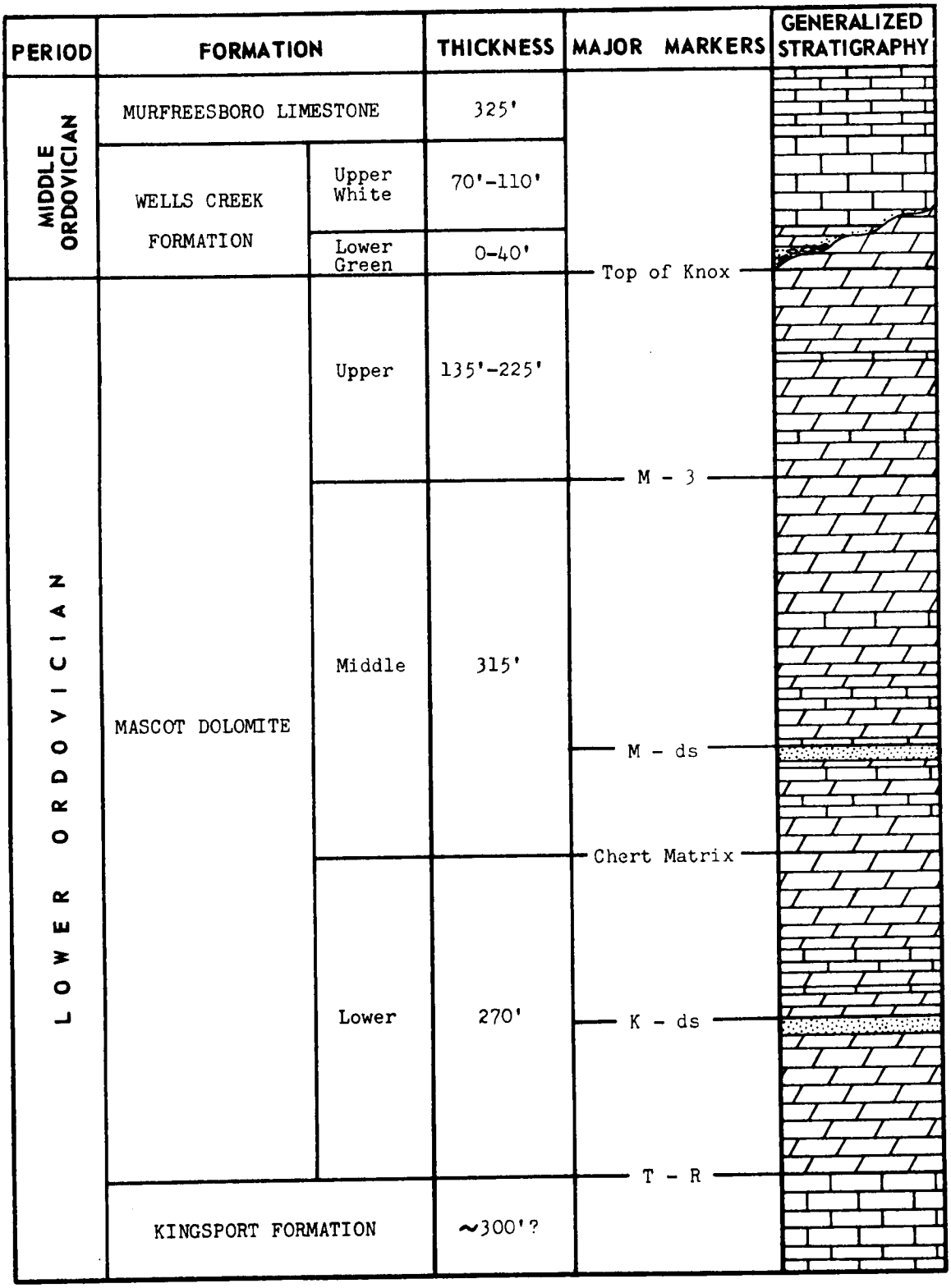


Figure 4

Generalized Upper Knox Group Stratigraphy
of Central Tennessee

displacement will determine whether the section appears inflated or deflated. The middle Mascot of Smith and Trousdale Counties contains a quartz sandstone unit, the M-ds marker, up to sixteen feet thick about ninety feet above the Chert Matrix. The section between the M-d and the Chert Matrix contains two thick limestone units.

The interval from the Chert Matrix to the top of the R-bed, the T-R marker, comprises the lower Mascot. The normal thickness of about 270 feet may vary in brecciated sections because of dissolution and collapse. In Smith and Trousdale Counties the lower Mascot also contains a quartz sandstone unit, the K-ds marker, up to fifteen feet thick about 130 feet above the T-R marker.

The Kingsport Formation includes the strata from the top of the R-bed to the top of the Chepultepec Dolomite. The redefined Kingsport consists primarily of thick limestone units or their dolomitized medium and coarsely crystalline equivalents interbedded with some very finely crystalline "primary" dolostones (Harris, 1969). In the drill holes studied, varying amounts of the Kingsport Formation were penetrated, ranging from 9 feet to 246 feet. Although the contact with the underlying Chepultepec has not been adequately established in Central Tennessee, it is believed that the base of the Kingsport was not reached with any of these cores.

Structure

The dominant structural feature in Central Tennessee is the Cincinnati Arch whose axis trends northeastward through Smith County (Figure 1). Regional dip away from the crest is about fifty feet per mile (Fischer and Hoagland, 1970). Local folds of small amplitude are visible in surface exposures of post-Knox strata; such features may possibly reflect gentle fold systems within the Knox. Minor faults are occasionally intersected in drill holes. The displacement along these faults is believed to be small, and regional stratigraphic and structural trends are not appreciably affected.

CHAPTER III

BRECCIATION OF THE UPPER KNOX GROUP

Various authors have applied a large number of terms to describe brecciation in the Knox deposits of East Tennessee (Table 1 and Appendix B). These names have been used in somewhat different senses by various workers; therefore, some ambiguity exists. Reasonably close agreement occurs in the use of the terms fine rock matrix breccia and coarse rock matrix breccia, although the relative importance of these types differs considerably depending upon the author. The term dry breccia has also been applied to the rock matrix breccias because of their generally unmineralized nature. The most confusion arises in discussion of the breccia systems which host ore mineralization. Some authors stress the matrix components (ore matrix, dolomite matrix, and hybrid breccias) in their classifications while most emphasize the form of brecciation (crackle, mosaic, and rubble breccias).

The scheme adopted for this study makes use of three terms for the geometry or degree of brecciation: fracturing, crackle breccia, and rubble breccia. These forms may be cemented by fine rock matrix, coarse rock matrix, or introduced mineral matrix. This classification is better suited for studies of drill core because it allows concise physical descriptions without definite genetic implications.

TABLE 1

DEVELOPMENT OF THE NOMENCLATURE FOR BRECCIATION IN THE UPPER KNOX GROUP

<table>
<tr><th colspan="2" rowspan="2">GENERALIZED DESCRIPTION</th><th>Oder and Hook (1950)</th><th>Kendall (1960)</th><th>Oder and Rickette (1961)</th><th>Hoagland et al (1965)</th><th colspan="2">Crawford and Hoagland (1968)</th><th>Crawford et al (1969)</th><th colspan="2">Hill (1969)</th><th>Hill et al (1971)</th><th colspan="2">Present Study</th></tr>
<tr><td colspan="2">Very finely crystalline primary dolostone, and occasionally limestone, blocks and unbleached chert fragments cemented by a matrix of pale green to light brown, finely crystalline dolomite rhomb aggregates containing local siliceous and argillaceous material.</td><td rowspan="2"></td><td>Fine matrix breccia
Dry breccia</td><td rowspan="2">Dry breccia ?</td><td>Red matrix breccia
Gray fine matrix breccia</td><td colspan="2">Fine rock matrix rubble breccia</td><td>Pre-ore rock matrix rubble breccia</td><td colspan="2">Fine rock matrix breccia</td><td>Fine rock matrix breccia</td><td>Fracturing
Crackle breccia
Rubble breccia</td><td rowspan="2">Fine rock matrix</td></tr>
<tr><td colspan="2">Very finely to coarsely crystalline dolostone blocks and bleached and unbleached chert fragments cemented by a matrix of light brown, medium and coarsely crystalline dolomite rhomb aggregates containing abundant shaley material and sand grains.</td><td>Coarse matrix breccia</td><td>Coarse matrix breccia</td><td colspan="2">Coarse rock matrix rubble breccia</td><td>Coarse matrix breccia</td><td colspan="2">Coarse rock matrix breccia</td><td>Coarse rock matrix breccia</td><td>Fracturing
Crackle breccia
Rubble breccia</td></tr>
<tr><td rowspan="2">Ore stage brecciation in which the strata have been fractured without appreciable rotation and displacement of breccia blocks.</td><td rowspan="2">Cemented by an introduced mineral matrix of primarily carbonate minerals and sphalerite with minor amounts of galena, quartz, pyrite, marcasite, barite, and fluorite.</td><td>Crackle breccia</td><td>Mosaic (domino) breccia</td><td>Crackle breccia</td><td>Crackle breccia</td><td colspan="2">Crackle breccia</td><td>Crackle breccia</td><td>Crackle breccia</td><td rowspan="2">Ore matrix breccia</td><td rowspan="2">Ore matrix breccia</td><td>Fracturing
Crackle breccia</td><td rowspan="2">Introduced mineral matrix</td></tr>
<tr><td>Rubble breccia (Founder breccia?)</td><td>Rubble breccia</td><td>Rubble breccia</td><td>Hybrid breccia</td><td>Rubble breccia</td><td>Dolomite matrix
Ore matrix</td><td>Rubble breccia</td><td>Rubble breccia</td><td>Rubble breccia</td></tr>
</table>

Three geometric forms of brecciation are recognized in the drill cores studied. The term fracturing is used for thin and/or isolated fractures. These features may actually be indications of breccia systems containing large blocks; however, in drill core it is often difficult to justify such an interpretation. Crackle breccia is applied to intervals which contain abundant fractures along which the strata appear to have been separated without appreciable rotation and displacement of breccia blocks. The most intensive brecciation is termed rubble breccia. Rubble breccias contain fragments which are rotated to all degrees and are displaced downward from their original stratigraphic position. As a result of stratigraphic disorder, blocks of differing lithologies may be contiguous in the breccia pile. Rubble breccias contain the largest percentage of matrix relative to fragments. An intermediate stage of brecciation between crackle and rubble may be termed mosaic breccia.

Any of the above breccia types may be cemented by fine rock matrix, coarse rock matrix, or introduced mineral matrix. Fine rock matrix consists of pale green, finely crystalline dolostone which cements fragments of "primary" dolostone and, locally, limestone. In thin section, fine rock matrix appears to be an aggregate of jumbled dolomite rhombs which may be detrital grains. Fine rock matrix breccias are unmineralized except where transected by later ore-stage fractures and appear to have formed significantly earlier than breccias that host ore mineralization. The

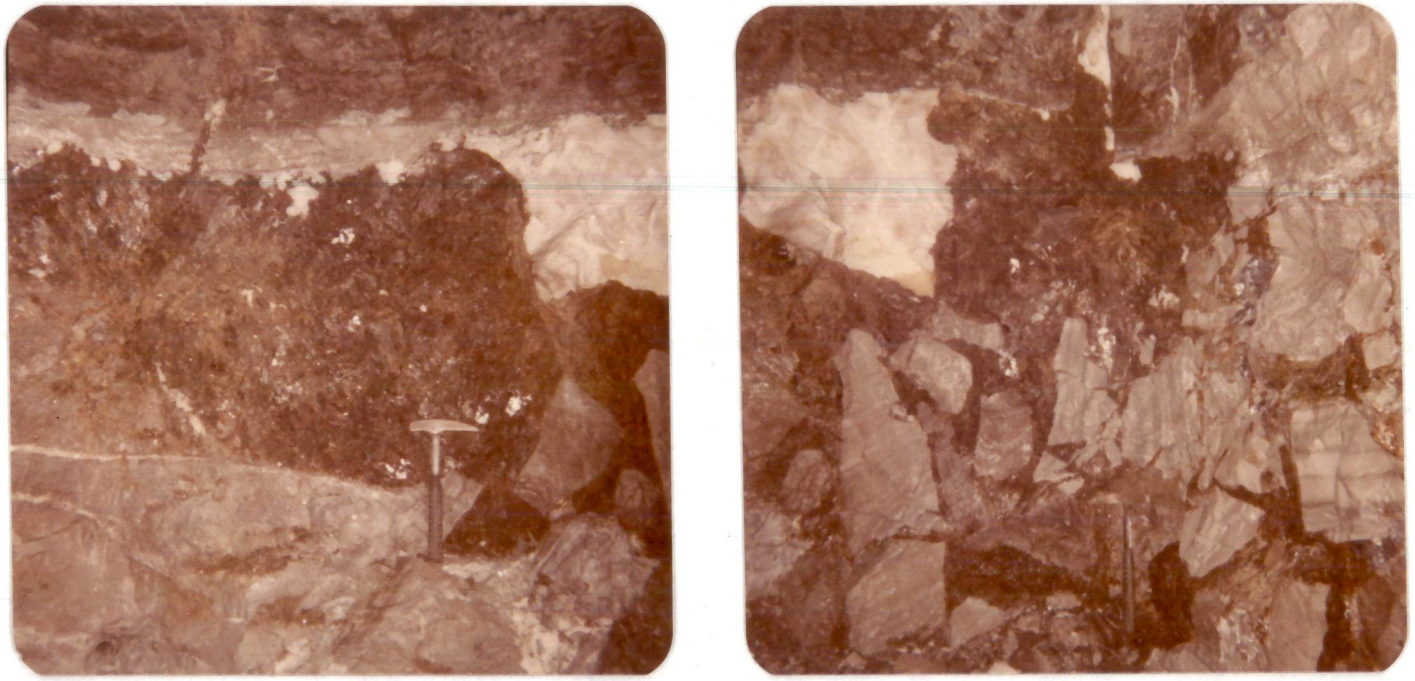
fine rock matrix was fairly well cemented by the time of ore-stage brecciation because this later fracturing often took place without preference to matrix or breccia blocks. However, the relative weakness of the fine rock matrix cement resulted in much of this subsequent fracturing occurring along earlier fractures. Fractures and breccias cemented by fine rock matrix are present at various intervals within the Mascot Formation (Plate I) and often have an associated alteration feature termed reaction rims (Kyle, 1973). Of the core studied, these breccias are best developed in drill hole 1. Fine rock matrix breccias occur in intervals near the top of the Knox and in stratigraphic positions which in other areas may be occupied by limestone equivalents. These relationships suggest that the fine rock matrix breccias were formed by dissolution and collapse related to removal of limestone units, perhaps during the pre-Chazyan erosional interval.

The ideally developed ore-stage breccia system has two matrix components. The lower part of the breccia may be cemented by coarse rock matrix. This material consists of medium and coarse dolomite rhombs with differing amounts of very finely to coarsely crystalline dolostone blocks, chert fragments, argillaceous material, sand, and silt. This cement is believed to represent the residue from dolomitization and dissolution of limestone units which resulted in the collapse of overlying strata thus forming the ore-stage breccia systems. The vague boundaries which are often

present between medium and coarsely crystalline dolostone fragments and coarse rock matrix indicates that dolomitization and dissolution may be contemporaneous processes. Coarse rock matrix breccias appear to have been somewhat lithified prior to the latest stages of brecciation as they are occasionally transected by mineral-healed fractures. This relationship suggests that some enlargement of the ore-stage breccia systems may have continued into the period of mineral deposition. Coarse rock matrix breccias are best developed in the thick limestone intervals below the top of the R-bed, although lesser amounts may be present in the Mascot where limestone dissolution has occurred (Plate I).

Introduced mineral matrix is applied to those breccias which are cemented by a combination of quartz, dolomite, calcite, sphalerite, galena, fluorite, and barite (Figure 5). The proportions of these cementing minerals may change greatly over short distances. By far the dominant mineral cement in the breccias of Smith and Trousdale Counties is calcite. If an appreciable amount of sphalerite and/or galena is present over a mineable interval, a special case of the mineral matrix breccia may be termed ore breccia. However, the general use of ore matrix for ore-stage mineral matrix is not encouraged because of the definite economic connotation of the word ore.

Ore grade mineralization is not distributed uniformly throughout breccia structures. As in the East Tennessee deposits, the best mineralization occurs along the periphery



(a) (b)

Sphalerite (reddish brown), barite (large cream-colored mass), calcite (small white crystals), galena (metallic gray), dolostone fragments (light gray).

Figure 5

Ore Matrix Rubble Breccia from the Elmwood Mine

Photographs Courtesy of The New Jersey Zinc Company

of the bodies (Winslow and Hill, 1973). Often large amounts of open breccia are present with fragments poorly cemented by a thin veneer of quartz druse such as the interval from 1345 to 1510 feet in drill hole 2.

Mineral matrix breccias are present from the top of the Knox to below the top of the Kingsport Formation with best development from the M-d marker to the T-R marker in the drill holes examined (Plate I). The most intensely mineralized and consistently brecciated interval at the Elmwood mine is the ninety-foot zone from the M-1 marker to the Chert Matrix marker (Figure 6). This section is particularly favorable for mineralization because of the development of lateral breccia structures related to dissolution of the thick limestone units above the Chert Matrix marker (Winslow and Hill, 1973). In the core studied from Smith County, that is, in the drill holes nearest the Elmwood mine, brecciation is best developed in the interval between the M-d and K-1 markers. Drill holes 1, 2, 3, and 4 from Trousdale County contain abundant mineral matrix breccia from the M-d marker to the T-R marker. Therefore, data from a limited number of holes indicates that brecciation and mineralization in Trousdale County may occur significantly lower than the majority of that in the Elmwood area.

The idealized relationships among the various breccia types are believed to be similar to that shown in Figures 21 and 23 which illustrate generalized breccia systems from the East Tennessee districts (Appendix B).

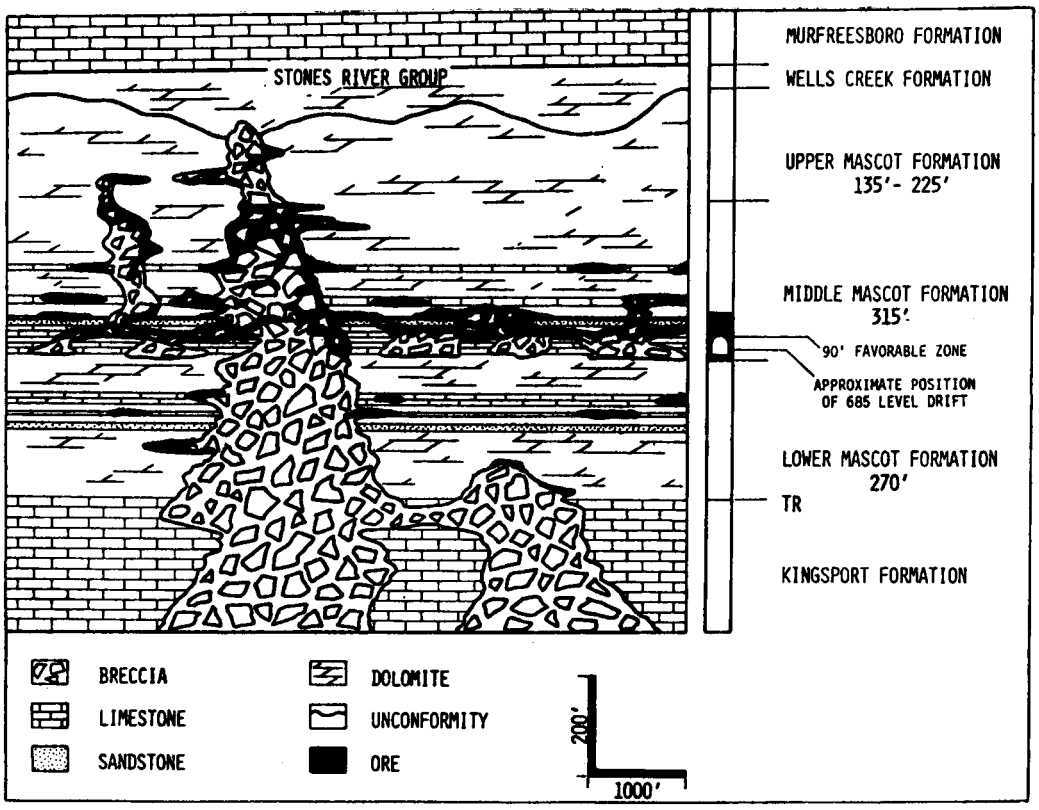


Figure 6

An Interpretation of the Knox
Geology in the Elmwood Area

From Winslow and Hill (1973)

Mixtures of these breccia classes have been termed hybrid breccia by Hoagland et al (1965). Remnants of fine rock matrix are occasionally present in the mineralized intervals. They may indeed be the framework for the ore-stage breccias, although they also occur without associated mineral matrix breccias.

Of the core studied, mineral matrix brecciation is best observed in drill holes 1, 2, and 4, each of which contains in excess of 200 feet of crackle and rubble breccia cemented by introduced mineral matrix. Crackle and mosaic mineral matrix types occur along the edges of the main breccia mass; these contain the most concentrated sphalerite mineralization. Rubble breccias occupy the central part of the structure. Here, blocks are rotated, and downward displacement of up to fifty feet has been reported from East Tennessee (Crawford et al, 1969). Comparable figures can be expected for the large breccia structures in Central Tennessee. In the widely spaced drill holes of this study, it is not possible to determine exact displacement. In diamond drill hole 2, however, the K-3 marker is only 24 feet below the K-ds marker in a rubble breccia, an apparent displacement of about 20 feet from its normal stratigraphic position of 45 to 50 feet below the K-ds.

In East Tennessee white gangue dolomite with minor sphalerite forms the matrix for the rubble breccia core. The central portion of the breccia systems in Smith and Trousdale Counties consists of rubble breccia which is

cemented primarily by calcite gangue or which is poorly healed with quartz druse leaving abundant open space between blocks. In addition to the breakthrough breccia structures, thin bodies of breccia are developed along certain favorable horizons.

CHAPTER IV

ALTERATION OF THE UPPER KNOX GROUP

Alteration of upper Knox Group strata in Smith and Trousdale Counties includes formation of reaction rims and associated bleaching, dolomitization, and silicification. In this study of widely spaced drill holes, it is not possible to assess the spatial aspects of alteration relative to individual breccia bodies.

Reaction Rims

Reaction rims are single or multiple dark concentric bands which parallel the bleached borders of some breccia fragments. The blocks affected range in size from less than one inch to at least two feet (Figure 7). These features have not been reported from dolostone terrains elsewhere, including the Knox of East Tennessee. The rims are best developed in very light gray to light brown gray, very finely crystalline "primary" dolostone fragments with iron sulfide speckled mottling (Figure 8). In lithologies lacking iron sulfide, this phenomenon appears to manifest itself as simple bleaching without the development of well defined reaction rims.

Microprobe and atomic absorption analyses show that the dark bands contain significant trace amounts of iron (Table 2); the bleached borders contain lesser concentrations

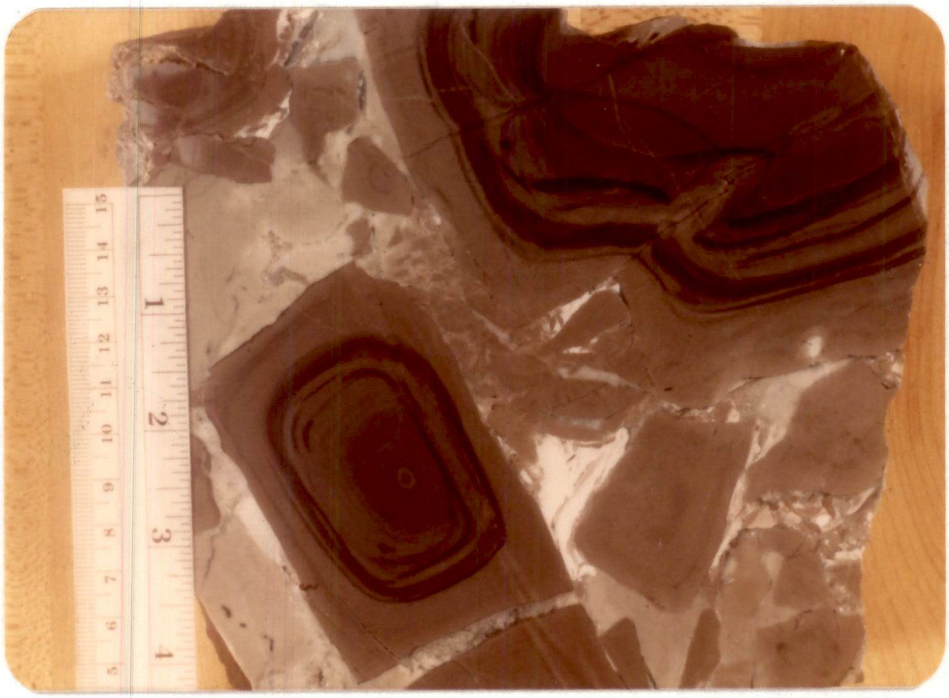


Figure 7

Fine Rock Matrix Breccia with Reaction Rims from the Elmwood Mine

Photograph by Permission of The New Jersey Zinc Company

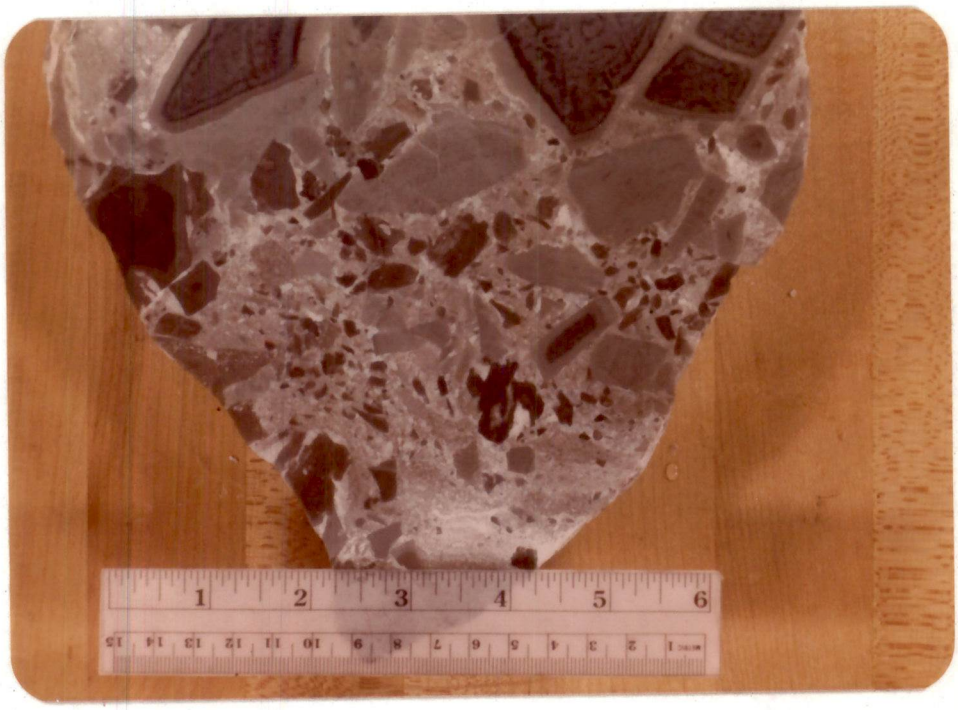


Figure 8

Well Developed Reaction Rims in Speck
Mottled Dolostone Fragments

Photograph by Permission of The New Jersey Zinc Company

TABLE 2

IRON CONTENT OF REACTION RIMS IN DOLOSTONES FROM THE ELMWOOD MINE

Sample	Part of Dolostone Fragment	Iron Concentrations (parts per million)
1	Bleached Border	512
	Unaltered Interior	1640
2	Unaltered Interior	3638
3	Bleached Border	1555
	Multiple Reaction Rims	3056
4	Unaltered Interior	2753

Atomic absorption analyses by R. J. Bayer and J. F. Snyder of the University of Tennessee

of iron. Observations of polished sections reveal the presence of finely disseminated crystals of marcasite within the dark rims and in the unaltered speck mottled dolostone. Although the majority of the material responsible for the reaction rims is too small to be identified under the reflecting microscope, it is believed that the bands are caused at least in part by iron sulfide which has been mobilized from the iron sulfide responsible for the mottling.

Reaction rims are usually associated with fracturing and brecciation that formed fine rock matrix breccias (Figure 9). Fine rock matrix breccias are developed at various intervals within the Mascot Dolomite (Plate I) and are more common in the upper and middle sections. This relationship seems to offer support for an origin related to oxidation during the post-Knox erosional interval as has been suggested (Hoagland et al, 1965).

In the six diamond drill cores studied, reaction rims occur from the top of the Knox to as much as 655 feet lower (Table 3). The features are present in all holes to at least 552 feet below the Knox unconformity. Stratigraphically, reaction rims occur as low as the K-ds marker. None were observed below the K-ds in the lower Mascot or in the Kingsport Formation. Reaction rims are present in "primary" dolostone intervals which contain iron sulfide mottling and early fracturing (Plate I). Extensive brecciation is not necessary for good development of the rims; often otherwise

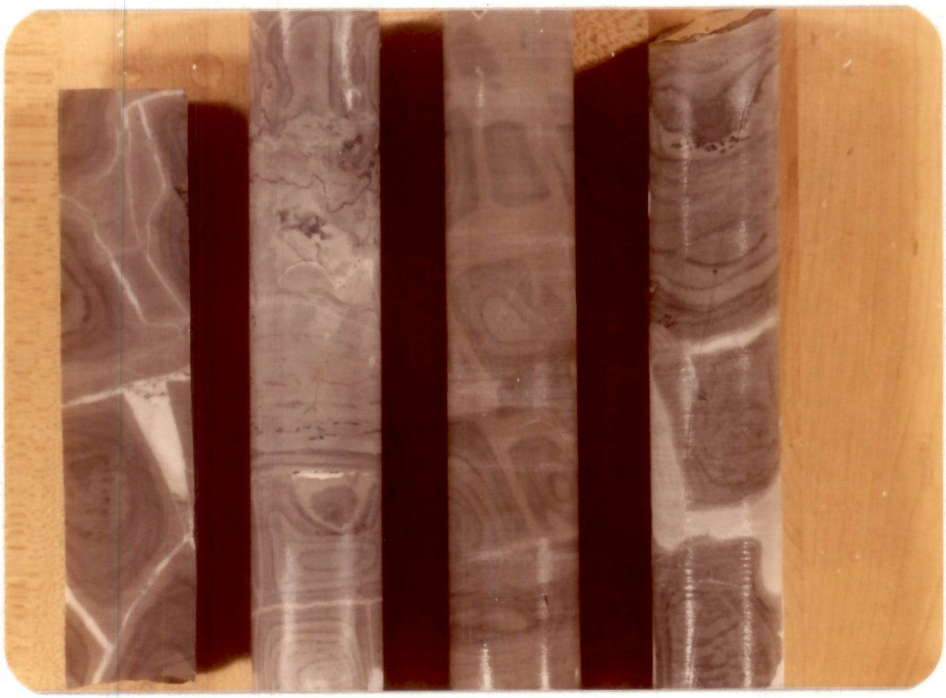


Figure 9

Core Containing Fine Rock Matrix Breccia
with Reaction Rims

TABLE 3

INTERVALS OF REACTION RIM OCCURRENCE
IN THE DRILL CORES STUDIED

INTERVAL (Structural Elevations in Feet)	1	2	3	4	5	6
TOP OF KNOX GROUP	-205	-282	-247	-251	-286	-231
M - 3 MARKER	-392	-467	-406	-445	-450	-380
CHERT MATRIX MARKER	-779	-802	-732	-788	-774	-706
TOP OF R - BED	-1052	-1100	-1008	-1081	-1051	-989
REACTION RIM INTERVAL -- FOOTAGE	-336 to -847	-282 to -851	-295 to -799	-300 to -825	-502 to -941	-315 to -832
REACTION RIM INTERVAL -- MARKERS	B & W to K - 1	Top of Knox to K - 1	Top of Knox to K - c	Top of Knox to K - 1	Wispy to K - 1	M - 5 to K - ds
MAXIMUM DISTANCE BELOW TOP OF KNOX	642	569	552	574	655	601

insignificant fractures are made obvious by bleached borders. Occasionally these very thin fractures contain iron sulfide.

Reaction rims are present in ore breccia intervals. However, this association is believed to be fortuitous since ore matrix breccia blocks only rarely display rims, and fragments with broken rims are sometimes present (Figures 10 and 11). The absence of reaction rims in most mineral matrix breccia blocks, even those of the most favorable lithologies, indicates that rim formation is not genetically related to the ore fluids. Blocks with unbroken rims are often present because of the weakness of the fine rock matrix relative to "primary" dolostone at the time of ore-stage brecciation.

Reaction rims have not been reported from the East Tennessee zinc deposits although bleaching of some "primary" dolostone beds in the ore interval is commonly acknowledged. As in Central Tennessee, this local bleaching occurred prior to ore-stage brecciation. Fractures filled with sphalerite and dolomite clearly transect both bleached and unbleached "primary" dolostone (Figure 22, Appendix B). Blocks with one side bleached are found in the ore rubble breccia where they have been removed from their original site of bleaching by later fracturing and displacement. The absence of reaction rims in East Tennessee could possibly be due to the lack of favorable lithologies, but this seems unlikely.

If the alteration were accomplished by the relatively hot mineralizing fluid, the origin of reaction rims

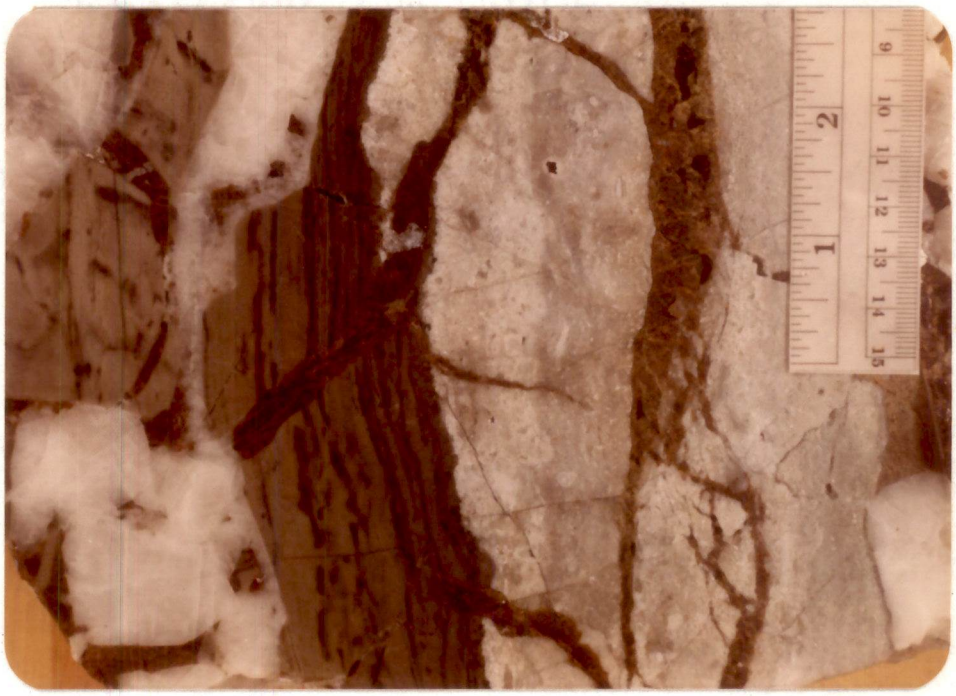


Figure 10

Ore Breccia from the Elmwood Mine

Notice the sharp, unbleached contacts between speck mottled "primary" dolostone and introduced minerals (sphalerite and calcite)

Photograph by Permission of The New Jersey Zinc Company



Figure 11

Ore Breccia with Broken Reaction Rims
from the Elmwood Mine

Bleaching in lower right along a fracture cemented by fine rock matrix; bleached and unbleached dolostone transected by a later sphalerite filled fracture. Compare with Figure 22.

Photograph by Permission of The New Jersey Zinc Company

would be less of a problem. "Primary" dolostone lithologies can be bleached by heating to 150° C. for a few hours (Hoagland et al, 1965). The evidence presented above, however, precludes formation of the reaction rims by ore related processes. Furthermore, the pulsating nature of the process that seems to be required by the multiple bands greatly complicates the picture. Because of its complexity, this local bleaching and reaction rim formation in Central Tennessee may be an entirely different phenomenon from the overall bleaching which surrounds the ore breccias in East Tennessee which may indeed be related to the ore-forming process (Hoagland et al, 1965; Hill et al, 1971).

The association of unbroken rims with fine rock matrix breccias indicates related processes for their development. The fine rock matrix breccias and reaction rims are most abundant in the upper part of the Mascot Dolomite, that is, in the sections closest to the Knox unconformity (Plate I).

It is suggested that the origin of reaction rims may be somewhat similar on a smaller scale to that of the redistributed iron sulfide in epigenetic roll-type uranium deposits in sandstones. The highest concentrations of pyrite in the roll deposit occur at the interface of oxidized strata and unoxidized strata containing background amounts of iron sulfide. The oxidized strata is barren of pyrite and carbonaceous matter and is lighter in color than the unaltered host rock (Warren, 1972).

The oxidized portion of a reaction rim in the Mascot Dolomite of Central Tennessee consists of the bleached border of the breccia fragment which atomic absorption analyses show to be impoverished with respect to iron. The front is represented by the dark reaction rim proper, and the unaltered central portion of the breccia block is the unoxidized host rock containing minor amounts of iron sulfide as mottling. The presence of carbonaceous material in the reaction rims is suspected, but a suitable analytical method for detection of organic carbon in a carbonate rock was not available to the author.

Significant differences exist in the details of this comparison. The roll deposits occur in a sandstone host rock, while the reaction rims occur in dolostones. The permeability of the sandstone is provided by intragranular porosity; permeability in the dolostone appears to be largely controlled by the early fractured zones along which reaction rims are found.

Although the exact mechanism for development remains unclear, it is believed that the formation of reaction rims was accomplished by oxidizing solutions probably related to the erosional interval represented by the pre-Chazyan unconformity and was not directly related to the ore-forming process. It is difficult to determine if the solutions causing reaction rim development could have been responsible for establishment of a favorable chemical environment for later brecciation and/or mineralization.

Dolomitization

Dolomitization as it is used here refers to the late conversion of limestone units to medium and coarsely crystalline dolostone in the upper Knox Group. These dolostones are distinctively different from the very finely to finely crystalline "primary" dolostone units. The presence of undolomitized limestone fragments in fine rock matrix breccias dates dolomitization as occurring after early breccia development (Hoagland et al, 1965); the existence of partly silicified, coarsely crystalline dolostone units indicates dolomitization prior to quartz introduction. In the East Tennessee deposits, limestone beds are dolomitized adjacent to ore breccia structures (Crawford and Hoagland, 1968; McCormick et al, 1971). Primary structures, such as shale partings, sandstone beds, and chert nodules can be traced laterally in a single exposure from limestone into coarsely crystalline dolostone (Harris, 1971).

With the exception of two feet of limestone in drill hole 3, all intervals which in some areas of Central Tennessee are limestone have been altered to medium and coarsely crystalline dolostone in the cores studied (Plate I). This dolostone generally contains varying amounts of porous tripolitic chert ranging from interstitial filling to almost solid chert with scattered dolomite rhombs. The vague boundaries which are often present between medium and coarsely crystalline dolostone fragments and coarse rock

matrix suggests that dolomitization and dissolution are contemporaneous processes.

Silicification

Silicification for the purposes of this thesis is restricted to the late introduction of quartz into the upper Knox Group. The process does not include early chert formation or tripolitic chert deposition. In East Tennessee silicification is generally regarded as a breccia edge condition of rather limited extent (McCormick et al, 1971). In the widely spaced diamond drill holes used in this study, it is impossible to determine the true relationship of silicification to individual breccia bodies. Based on the wide vertical and lateral range of silicified units (Plate I), however, silicification is apparently more pervasive in the Central Tennessee district, especially in certain areas. Silicification with attendant quartz druse occurs early in the history of the ore-stage breccias. As a result, most breccia blocks are coated with a thin layer of quartz druse. From a limited amount of petrographic work with silicified dolostone units, it appears that quartz introduction in the drill core studied is largely restricted to open space filling of fractures, vugs, and interstitial space. Replacement of dolostone by quartz occurs locally adjacent to these features. Complete conversion of dolostone or limestone units to quartz was not observed in the core studied.

CHAPTER V

MINERALIZATION IN THE UPPER KNOX GROUP

Mineralogy

The only ore mineral in the upper Knox Group breccia bodies of Trousdale and Smith Counties is dark reddish brown, resinous sphalerite. Sphalerite occurs in large crystalline intergrowths with calcite, fluorite, barite, and galena, or in monominerallic masses up to four feet thick (Figure 5). The faces of sphalerite crystals are almost black in appearance (Figure 12). Individual crystals up to two inches in the longest dimension have been observed. A later generation of sphalerite occurs as poorly formed crystals along fractures in the early sphalerite. This stage is believed to be insignificant in terms of total amount of zinc. The Central Tennessee sphalerite differs markedly in color from that of the East Tennessee deposits (Figure 13). Microprobe analyses for zinc, iron, cadmium, and manganese of three specimens from the Elmwood mine when compared with published data for the East Tennessee districts fail to reveal the cause of the color difference (Table 4). It is apparently not due to variations in iron content. The apparent higher zinc content of the Central Tennessee sphalerite may be the result of different analytical techniques instead of an actual compositional



Figure 12

Fluorite and Sphalerite Crystals
from the Elmwood Mine

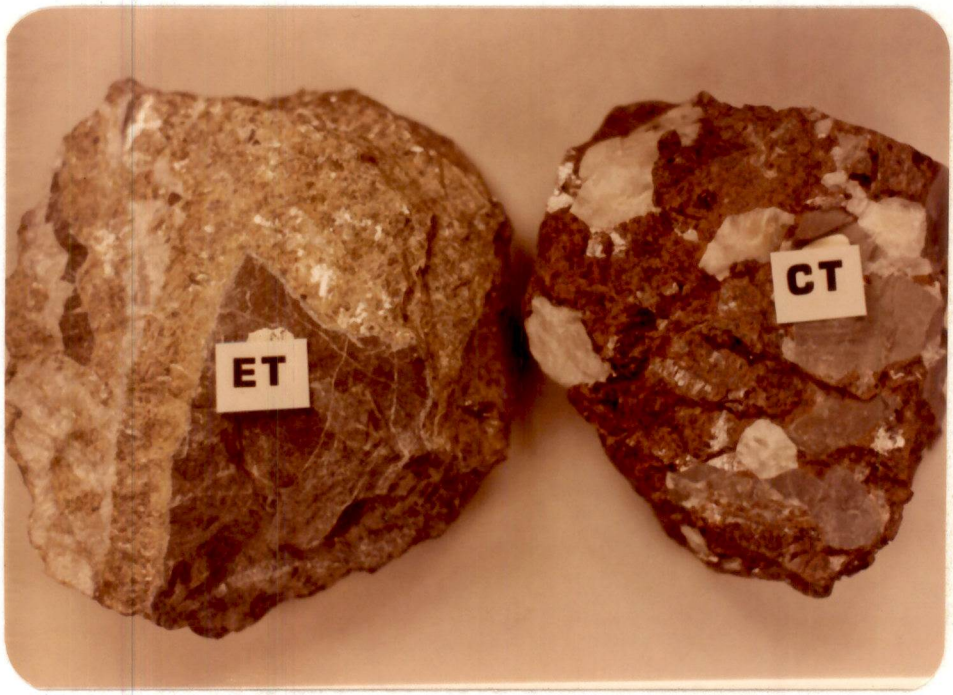


Figure 13

Ore Breccias from East and Central Tennessee

Yellow sphalerite and dolomite from the Young Mine (ET); reddish brown sphalerite and early calcite from the Elmwood Mine (CT)

TABLE 4

METAL CONTENT OF SPHALERITES FROM THE UPPER KNOX GROUP

District	(Weight Percent) Zinc	Iron	Cadmium	Manganese
Elmwood Mine[1]	65.9-66.5	0.15-0.32	0.00-0.28	n.d.
Mascot-Jefferson City District[2]	63.5-64.0	0.25-0.45	0.35-0.80	0.005
Copper Ridge District[2]	63.6	0.6-0.8	0.17-0.45	0.005

[1]Microprobe analyses by N. D. MacRae of the University of Western Ontario
Manganese detection limit 300 ppm
Cadmium detection limit 100 ppm

[2]Maher and Fagan (1970), zinc analyses by ferrocyanide titration; iron, cadmium, and manganese analyses by spectrochemical methods

difference. Of the cores studied, significant sphalerite mineralization occurs only in drill hole 2, primarily in the M-2 to K-ds interval.

Galena is present in varying amounts in the Elmwood deposit, but it does not constitute a major part of the ore. Galena occurs only in drill hole 1 of the cores examined. Galena deposition apparently overlapped that of sphalerite because specimens are found with galena both earlier and later than sphalerite.

Fluorite and barite in places comprise a large portion of the cement of the mineral matrix breccias in Smith and Trousdale Counties. The faces of most fluorite crystals are pale blue or purple in color. The color is largely in the outer rim of most crystals, and massive or broken samples are almost colorless. Attractive specimens with fluorite crystals up to four inches on masses of sphalerite crystals have been taken from the Elmwood mine (Figure 12). Studies of primary fluid inclusions in fluorite from the Elmwood deposit yield homogenization temperatures ranging from 99° to 126° C. (DeGroodt, 1973). Aggregates of small cream-colored barite crystals often take the shape of spheres up to twelve inches in diameter when formed around sphalerite rosettes or fluorite crystals (Figure 14).

Fluorite and barite mineralization is best shown by core from drill hole 1. Observations of fluorite, barite, and sphalerite occurrences in the core studied yields a vague overlapping mineral zonation with depth within the



Figure 14

Barite Spheres and Fluorite
from the Elmwood Mine

Knox (Plate I). In most cores fluorite and barite occur at higher intervals than sphalerite, although they may all be present in the same section. This zoning may actually be the reflection of late-forming accessory mineralization most commonly occurring around the periphery of the breccia systems as in East Tennessee and needs more study before its validity can be established.

Calcite is the dominant gangue mineral in the Mascot breccia bodies of Smith and Trousdale Counties. At least two ages of calcite are present. The main amount of calcite cement was deposited early at least in part before the sphalerite. Well formed crystals of early calcite are often completely enclosed by sphalerite (Figure 13). A second generation of calcite appeared toward the close of mineral deposition. It can be easily recognized because of the orange hue and the tendency to occur in well developed crystals, often as complex scalenhedrons twinned with the basal pinacoid (0001) (Figure 15). Such crystals in excess of eighteen inches long have been found at the Elmwood mine. The centers of some late calcite crystals have a faint lavender tint of unknown cause. Similar coloration has been reported in calcite crystals from the Central Kentucky mineral district (Jolly and Heyl, 1964) and from the Tri-State district (McKnight and Fischer, 1970). Analyses of lavender calcite from Central Kentucky reveal the presence of small quantities of lanthanum, yttrium, ytterbium,



Figure 15

Late Generation Calcite Crystals
from the Elmwood Mine

strontium, manganese, and copper which may be responsible for the color (Jolly and Heyl, 1964).

Quartz druse is ubiquitous in the ore-stage breccia bodies. Quartz deposition occurred very early and accompanied silicification of the enclosing strata. Often large intervals of open breccia are present cemented only by a thin veneer of quartz druse.

Minor dolomite is present usually as early formed crystals and groups on quartz. In Smith and Trousdale Counties dolomite forms an insignificant amount of the ore breccia cement.

Rare amounts of marcasite and small transparent blue crystals of celestite have been observed. Small crystals of marcasite are found on dolomite crystals and within the outer rim of some early calcite crystals. Tiny globules of bituminous residue may coat any of the earlier formed minerals.

Paragenesis

The generalized paragenetic sequence for mineralization in the upper Knox breccia systems of Smith and Trousdale Counties is summarized in Figure 16. This sequence is the result of preliminary investigations of relationships among crystal specimens and is believed to be correct in general terms. Changes in the details of paragenesis will undoubtedly be made as more relationships are observed.

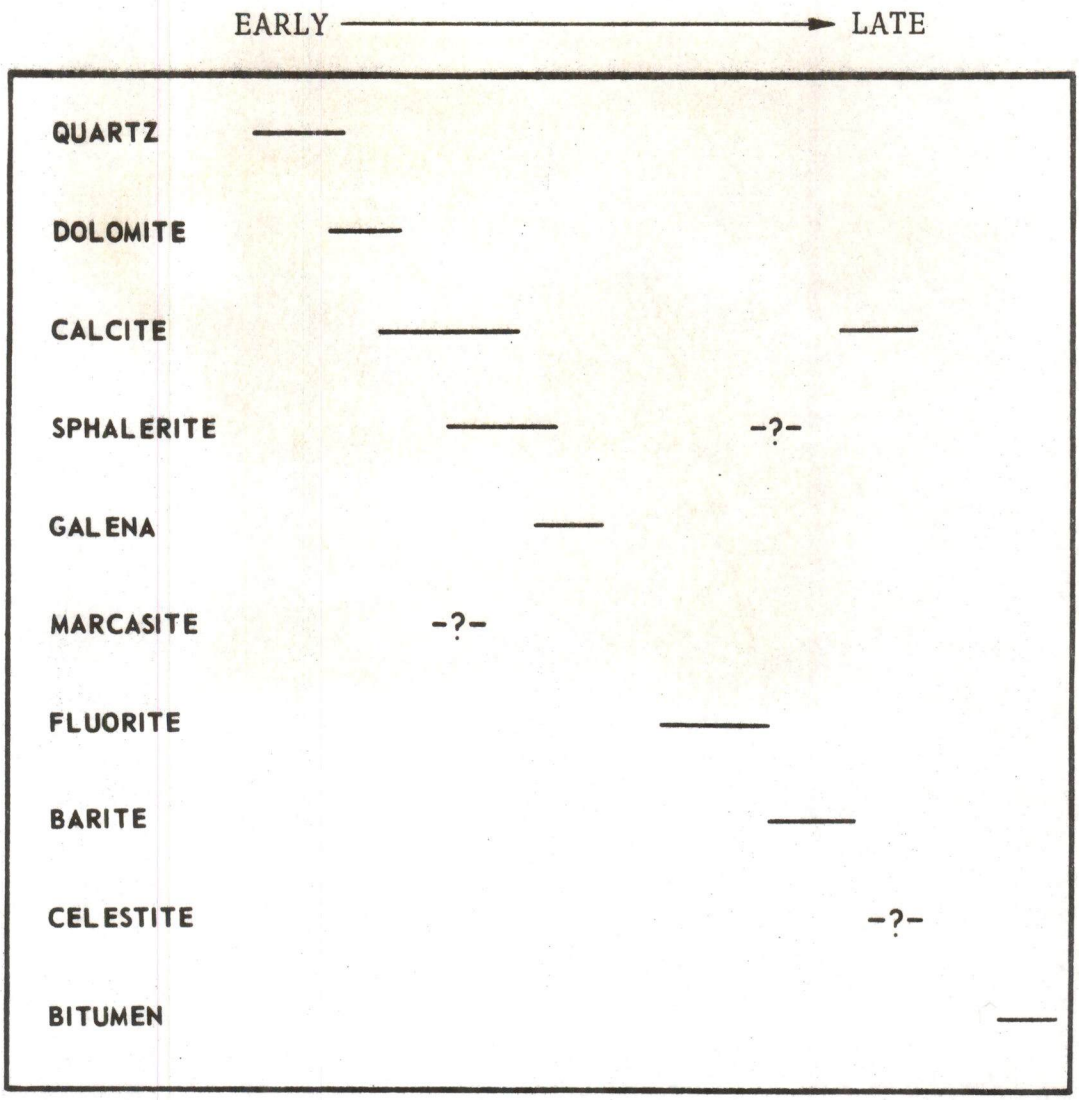


Figure 16

Generalized Paragenetic Sequence of Mineral Deposition in the Upper Knox Breccia Systems of Smith and Trousdale Counties, Tennessee

CHAPTER VI

DISCUSSION

Comparison of Upper Knox Group Mineralization in East Tennessee and in Smith and Trousdale Counties

The zinc and associated mineralization in the upper Knox Group of Smith and Trousdale Counties is geologically similar to, yet significantly different from, that in the upper Knox Group of East Tennessee (Appendix B). Table 5 clearly delineates the major similarities and differences. The deposits of both areas occur as predominantly open space filling in irregular dissolution collapse breccia bodies developed in the Lower Ordovician carbonate rocks of the upper Knox Group. An early stage of brecciation preceded formation of the breccias which host ore mineralization. Sphalerite is the only ore mineral, and varying amounts of galena, fluorite, barite, pyrite, marcasite, calcite, dolomite, and quartz are present. The breccia bodies are roughly zoned with a central core of carbonate gangue and sub-economic zinc mineralization and a peripheral zone with the most concentrated sphalerite and accessory mineralization. Alteration of enclosing strata largely preceded ore deposition and includes dolomitization, silicification, and bleaching. Fluid inclusion thermometry indicates a

TABLE 5

COMPARISON OF THE ZINC DEPOSITS IN THE UPPER KNOX GROUP OF EAST TENNESSEE AND OF SMITH AND TROUSDALE COUNTIES

Similarities

1. Host Rock	Dolostones and limestones of the Lower Ordovician Upper Knox Group
2. Brecciation	Early and later dissolution collapse breccias with similar characteristics in both areas; mineralization associated with last stage of brecciation
3. Mode of Occurrence	Open space filling with minor amounts of replacement
4. Ore Mineral	Sphalerite
5. Accessory Minerals	Calcite, dolomite, quartz, fluorite, barite, galena, pyrite, and marcasite
6. Paragenesis	Similar in general terms — ore mineral early, most gangue minerals later
7. Zoning within Breccia Bodies	Weakly mineralized central portion; best sphalerite and accessory mineralization around periphery
8. Alteration Features	Dolomitization, silicification, bleaching, and sanding
9. Temperature of Formation	Low (100° - 150° C.)
10. Type of Deposit	Mississippi Valley type base metal deposit

Differences

CHARACTERISTIC	EAST TENNESSEE	SMITH AND TROUSDALE COUNTIES
1. Surface Exposure	Some surface outcrop or expression	No known surface expression
2. Deformation	Faulting and gentle folding	Insignificant faulting and folding
3. Attitude of Strata	Dips 10° - 40° SE; strikes NE	Essentially horizontal
4. Main Ore Horizon	Lower Mascot - Upper Kingsport	Middle Mascot
5. Color of Sphalerite	Pale yellow	Resinous dark reddish brown
6. Dominant Gangue Mineral	Dolomite	Calcite
7. Amounts of Accessory Minerals	All accessory minerals minor or rare	Significant barite, fluorite, and galena
8. Alteration	Local; no reaction rims	Silicification, dolomitization more pervasive; abundant reaction rims
9. Cementation of Breccia Systems	Tightly cemented	Abundant open space in some areas
10. Post-Knox Mineralization	Minor mineralization in basal Middle Ordovician strata	Numerous veins in Middle Ordovician to Lower Mississippian strata
11. Age of Mineralization	Middle Ordovician	Post-Middle Ordovician
12. Temperature of Formation	82° - 149° C. (Higher?) (Sphalerite, dolomite, fluorite, quartz)	99° - 126° C. (Lower?) (Fluorite only)

relatively low temperature of formation (100°-150° C.), and this range and other characteristics categorize the deposits as Mississippi Valley base metal type.

The paramount difference with exploration significance between the deposits is the lack of surface exposure of the Knox Group, and therefore of the mineral deposits, in Central Tennessee. The Knox in the East Tennessee districts is exposed in a series of imbricate thrust-faulted belts and dips from 10° to 40° to the southeast. Therefore, the known deposits have some type of surface expression and lend themselves to surface geologic and geochemical investigation. The Knox Group in Central Tennessee is covered by a minimum of several hundred feet of nearly horizontal Middle Ordovician and younger strata. The deposits have no apparent surface expression.

The principal ore horizon in the Mascot-Jefferson City and Copper Ridge districts is the lower 60 feet of the Mascot Dolomite and the upper 160 feet of the Kingsport Formation. At the Elmwood mine the most intensely mineralized interval is the lower 90 feet of the middle Mascot although significant mineralization is found above and below this section (Figure 6). The mineralization in the tightly cemented breccia bodies in East Tennessee consists of pale yellow sphalerite in a gangue of predominantly dolomite (Figure 20, Appendix B) and minor to rare amounts of pyrite, marcasite, calcite, galena, fluorite, and barite. The mineralization in Smith and Trousdale Counties consists of

resinous dark reddish brown sphalerite with primarily calcite gangue and significant amounts of galena, barite, and fluorite (Figure 5). Minor quartz and dolomite are present. Abundant open space exists in portions of the breccia systems in Central Tennessee. In the drill holes studied, silicification, and perhaps dolomitization, appear to be more pervasive than generally recognized in East Tennessee. The abundant reaction rims, the formation of which preceded ore-stage brecciation in Central Tennessee, have not been recognized in East Tennessee.

Very minor barite, sphalerite, pyrite, and hematite mineralization occurs in the basal Middle Ordovician strata in East Tennessee and has been interpreted as the result of the final pulse of mineralization responsible for the Knox deposits (Maher, 1971; Carpenter et al, 1971). Significant vein deposits consisting of sphalerite, fluorite, barite, galena, and calcite occur in several Central Tennessee counties in various post-Knox formations as young as the Lower Mississippian Warsaw Limestone (Jewell, 1947). Fluid inclusion studies of fluorite from several veins in Middle Ordovician strata reveal slightly lower homogenization temperatures than for fluorite from the Elmwood mine (DeGroodt, 1973). Traces of fluorite and sphalerite, perhaps unrelated to older mineralization, are found in vugs in the lower part of the Upper Mississippian Pennington Formation. Mineralized fractures and weak breccia, which in core appear to be continuous with Knox breccia systems, are

occasionally intersected in the lower 200 feet of the post-Knox strata. These relationships indicate that mineralization may have occurred significantly later in Central Tennessee than that proposed for East Tennessee. Primary fluid inclusions in fluorite from the Mascot-Jefferson City district homogenize mostly in the temperature range of 110° to 160° C. (Roedder, 1971); fluorite from the Elmwood mine yields temperatures primarily in the 99° to 126° C. range (DeGroodt, 1973). Since fluorite from both districts occupies approximately the same paragenetic position, these data perhaps indicate that the Knox mineralization in Smith and Trousdale Counties formed at a lower temperature than that in East Tennessee.

CHAPTER VII

CONCLUSIONS AND RECOMMENDATIONS

The following generalized sequence is considered a probable chronology of events culminating in mineralization in the upper Knox Group of Smith and Trousdale Counties (Figure 17). Following deposition of the primary dolostone and limestone strata now known as the Knox Group, the area became exposed to subaerial erosion, and the post-Knox, pre-Chazyan unconformity was developed. Probably related to this erosional interval was early dissolution and fracturing which resulted in the formation of the fine rock matrix breccias. Oxidizing solutions moving through these breccia systems locally bleached and altered "primary" dolostone around the fractures forming reaction rims. The fine rock matrix breccias were somewhat cemented by the time of later dissolution and dolomitization of limestone units. Collapse of the strata overlying these zones of dissolution resulted in the formation of ore-stage breccia systems. The lower part of some ore-stage breccia bodies became filled with the residue which resulted from dissolution and dolomitization and which consisted of dolostone and chert fragments, argillaceous material, sand, and silt in a coarsely crystalline dolomite matrix. Quartz, dolomite, calcite, sphalerite, galena, fluorite, barite, marcasite, and celestite were later deposited in the sequence indicated in

1. Deposition of Upper Knox Dolomite and Limestone.

2. Pre-Chazyan Erosion.

3. Dissolution and Fracturing Resulting in the Formation of Fine-Rock Matrix Breccias.

4. Local Bleaching and Formation of Reaction Rims.

5. Dissolution and Dolomitization of Limestone Units in the Upper Knox.

6. Formation of Ore-Stage Breccia Bodies.

7. Silicification with Attendant Quartz Druse.

8. Deposition of Dolomite, Calcite, Sphalerite, Galena, Fluorite, Barite, Marcasite, and Celestite.

9. Coating of Bituminous Residue.

Figure 17

Generalized Sequence of Events for the Deposits of Smith and Trousdale Counties, Tennessee

Figure 16. Abundant open space remained in some areas, and small amounts of bituminous residue were deposited on the earlier formed crystals.

Hoagland (1973) has proposed that the metal content of Central Tennessee deposits was supplied by dense, warm Na-Ca-Mg-Cl connate brines derived by compaction of the thick Middle Ordovician shales of the Appalachian Basin to the east. The metal-rich basinal fluids were transported through early breccia systems until they encountered concentrations of hydrogen sulfide where precipitation of the ore minerals would occur. If a supply of metal-rich brines and sulfur-bearing fluids were available for a sufficient length of time, an economic accumulation of sulfide mineralization could be formed. The absence of a source of sulfur in a particular area would account for the lack of sulfides. Alternative possibilities relating genesis of the Central Tennessee deposits to cryptoexplosive structures or to an unknown magmatic source at depth may be suggested, but in the present stage of development of the district, insufficient information is available to test the validity of the models.

Much work remains to be done, both here and in East Tennessee, concerning the ore controls, genesis, and mineral zoning in the deposits of the upper Knox Group. The need for various research projects related to the Central Tennessee mineral deposits has become evident during this investigation. These proposed projects include:

1. Isotopic composition of the Knox and later vein mineralization.
   a. Lead isotopes--possible determination of age of mineralization and source of the metal content.
   b. Sulfur isotopes--source of the sulfur content.
   c. Carbon and oxygen isotopes--source of the carbonate cement.
   d. Genetic relationships between the two types of deposits.
2. Growth patterns of horizontally assymetrical crystals. The abundant crystal specimens in the Central Tennessee deposits would furnish excellent material for such a study.
   a. Determination of the direction of flow of the mineralizing fluid such as has been determined for the Tri-state and Pine Point districts (Stoiber, 1946; Kesler, Stoiber, and Billings, 1972).
   b. Changes in fluid movement during stages of mineral deposition.
   c. Source of the mineralizing fluid.
3. Homogenization temperatures and composition of primary fluid inclusions.
   a. Changes in temperature and composition of

the mineralizing fluid during stages of deposition.

b. Regional temperature and compositional variations.

c. Source of the mineralizing fluid.

d. Genetic relationships between the two types of deposits.

4. Details of upper Knox mineralization.

a. Regional variation in paragenesis.

b. Regional variation in trace element content.

c. Mineral zonation.

5. Brecciation.

a. Relationships among breccia types.

b. Form of the ore-stage breccia systems.

6. Dolomitization and silicification.

a. Regional variations.

b. Relationships to individual breccia bodies.

7. Reaction rims.

a. Regional occurrence.

b. Theoretical (experimental) considerations for their origin.

c. Significance of their presence.

8. Geophysical exploration.

a. Regional exploration guides.

b. Location of breccia bodies not exposed at the surface.

9. Knox stratigraphy.

a. Regional variations.

b. Depositional model to account for remarkable uniformity of certain sequences over wide areas.

c. Origin and significance of tripolitic chert.

10. Post-Knox stratigraphy.

a. Regional variations.

b. Time-stratigraphic correlation of the Middle Ordovician bentonites and intervening units.

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APPENDIXES

APPENDIX A

GRAPHIC DESCRIPTIONS OF CORE FROM SMITH AND TROUSDALE COUNTIES, TENNESSEE

Introduction

Six diamond drill holes penetrating the upper Knox Group were logged to determine intervals of brecciation, alteration, and mineralization. The graphic system adapted for this study was modified from systems currently used by several mining companies in Central Tennessee. This logging scheme makes use of various symbols and colors to represent lithology and accessory information. Standard abbreviations (Blanchet and Godwin, 1972) and rock colors (Goddard, 1948) are adopted whenever possible. Abbreviations consisting of two capital letters represent a major lithologic type, such as DL (dolostone). Minerals are indicated by one capital and one lower case letter; for example, Sp designates sphalerite. Three, four, and five letter abbreviations consisting of lower case letters represent accessory information, such as silic (silicified). Shades of brown are used to indicate the presence of "primary" dolostone units with similar color values (lightness) (Goddard, 1948). Limestone units are colored dark blue, and light blue is used to represent their dolomitized medium and coarsely crystalline equivalents. Sand and shale are colored the

traditional yellow and green, respectively. A separate column with appropriate colors indicates the presence of sphalerite, galena, barite, fluorite, and marcasite. Fractures and breccia filled by fine rock matrix are colored olive green; coarse rock matrix is colored dark gray; mineral cemented breccia is represented by orange. Generalized descriptions of The New Jersey Zinc Company's Mascot markers and the immediately overlying and underlying units are presented using the same system.

Logs of all holes include the Lower Green unit of the Wells Creek Formation, if present. Logging of drill hole 2 was begun in the lower part of the Murfreesboro Formation. A maximum of 847 feet of Mascot Dolomite is present in diamond drill hole 1. Varying amounts of the Kingsport Formation were penetrated, ranging from 9 feet to 246 feet. The underlying Chepultepec Dolomite was not reached in any of these drill holes.

The cores studied contain varying amounts of sphalerite, fluorite, and barite. Traces of marcasite are present in all holes, and galena occurs in drill hole 1. Calcite, dolomite, and quartz occur in all the cores. In consideration of the companies making available the core used in this study, no attempt is made to indicate the exact amounts of mineralization. However, none of the holes are ore grade with respect to zinc. Ore-stage brecciation reaches a maximum in drill hole 2 with a total of 275 feet

of mineral matrix breccia. Fine rock matrix breccia and associated reaction rims are best developed in hole 1. Large intervals of coarse rock matrix breccia occur in those drill holes which penetrate a significant thickness of the Kingsport Formation.

ABBREVIATIONS

A

abu ---------- abundant
alt ---------- altered
& ---------- and
ang ---------- angle
app ---------- approximate(ly)
arg ---------- argillaceous
@ ---------- at

B

Ba ---------- barite
bec ---------- become, becoming
bed ---------- bed(ded), bedding
blk ---------- black
blu ---------- blue
bnd ---------- band(ed), banding
BR ---------- breccia
brac ---------- brachiopod
BRc ---------- crackle breccia
BRm ---------- rock matrix breccia
brn ---------- brown
BRr ---------- rubble breccia
bse ---------- base

C

Ca ---------- calcite
calcr ---------- calcareous
CE ---------- chert
cem ---------- cement(ed)
clt(s) ---------- clast(s)
contd ---------- continued, continuing
crpxl ---------- cryptocrystalline
crs ---------- coarse
cx ---------- coarsely crystalline

D

DDH ---------- diamond drill hole
decr ---------- decreases, decreasing
den ---------- dense
dev ---------- develop(ed)
dk ---------- dark
DL ---------- dolostone
dlmic ---------- dolomitic
Do ---------- dolomite
doloc ---------- dolocastic
dru ---------- druse
dstbd ---------- disturbed

E

est ---------- estimate(d)
ext ---------- extremely

F

fi ---------- fine
Fl ---------- fluorite
' ---------- foot, feet
frg(s) ---------- fragment(s)
frc(s) ---------- fracture(s)
fsl ---------- fossil(iferous)
ft ---------- faint
fx ---------- finely crystalline

G

Ga ---------- galena
gast ---------- gastropod
gen ---------- general(ly)
grn ---------- green
gra ---------- gray
gnd ---------- grained

H

hld ---------- healed
hi ---------- high

I

" ---------- inch(es)
incr ---------- increases, increasing
irreg ---------- irregular(ly)

L

lam ---------- laminae
loc ---------- local
LS ---------- limestone
lt ---------- light
lyr(s) ---------- layer(s)

M

mas ---------- massive
med ---------- medium
mnr ---------- minor
mot ---------- mottled, mottling
Mr ---------- marcasite
mtx ---------- matrix
mx ---------- medium crystalline

N

nod(s) ---------- nodule(s)

O

o/ ---------- over
occ ---------- occasional(ly)
Ok ---------- Kingsport Formation
olv ---------- olive
Om ---------- Murfreesboro Limestone
Oma ---------- Mascot Dolomite
oo ---------- ooliths, oolitic
orn ---------- orange
Owc ---------- Wells Creek Formation

P

pbl(s) ---------- pebble(s)
pnk ---------- pink
pl ---------- pale
pred ---------- predominant(ly)
prly ---------- poorly
prp ---------- purple
ptng(s) ---------- parting(s)
Py ---------- pyrite

Q

Qz ---------- quartz
? ---------- questionable

R

reac ---------- reaction
rel ---------- relative(ly)
rk(s) ---------- rock(s)

S

sc ---------- scattered
sed ---------- sedimentary
sgs ---------- sand grains
SH ---------- shale
shy ---------- shaley
silic ---------- siliceous, silicified
Sp ---------- sphalerite
spec ---------- speckled
SS ---------- sandstone
st ---------- straight
str ---------- strong (well developed)
strat ---------- straticulate
sty(s) ---------- stylolite(s)

T

TD ---------- total depth
thk ---------- thick
thn ---------- thin
trc ---------- trace
trp ---------- tripolitic

V

vfx ---------- very finely crystalline
vug(s) ---------- vug(s), vuggy
vy ---------- very

W

w/ ---------- with
w/o ---------- without
wht ---------- white
wk ---------- weak (poorly developed)

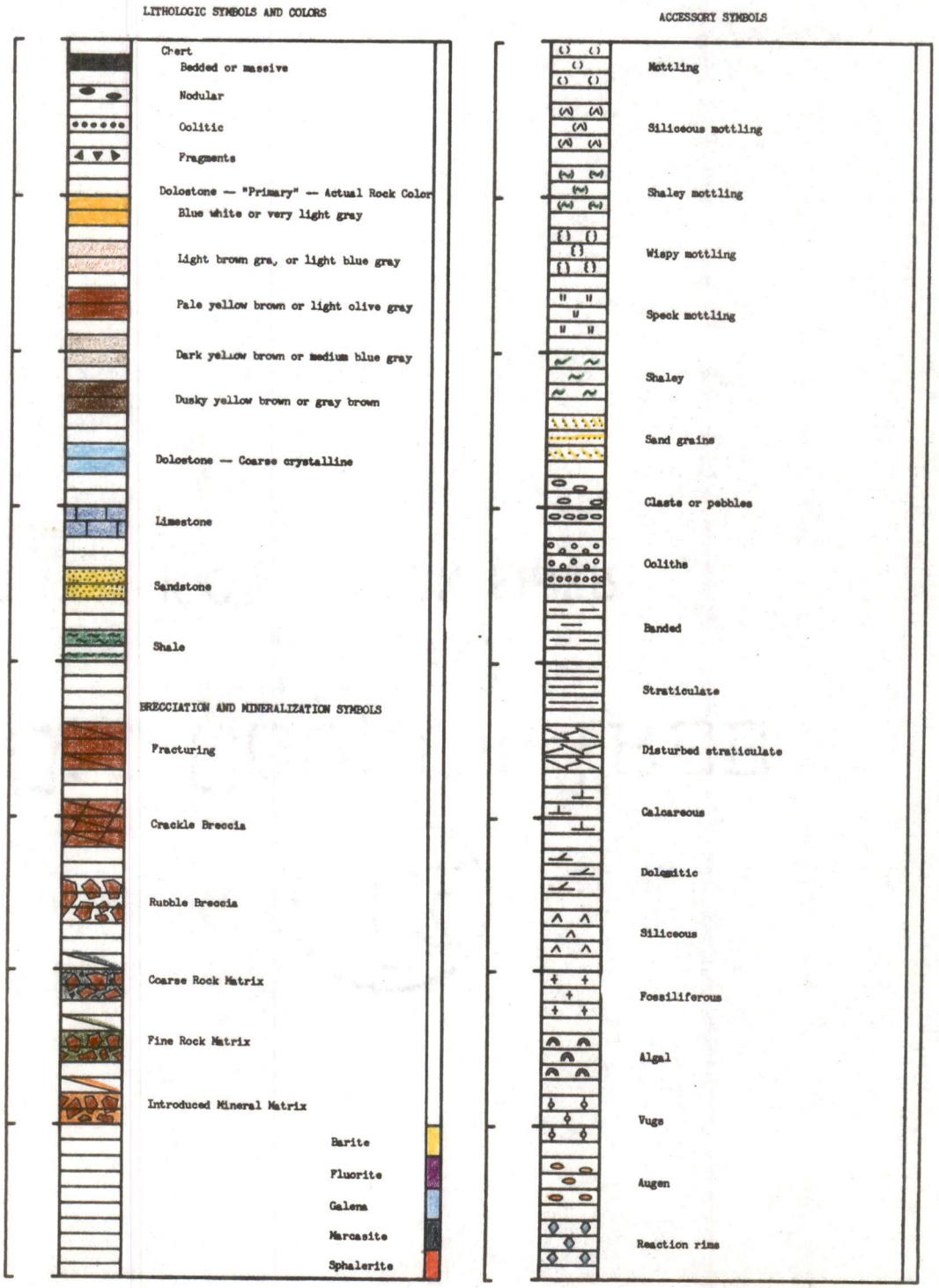
X

xtl(s) ---------- crystal(s)

Y

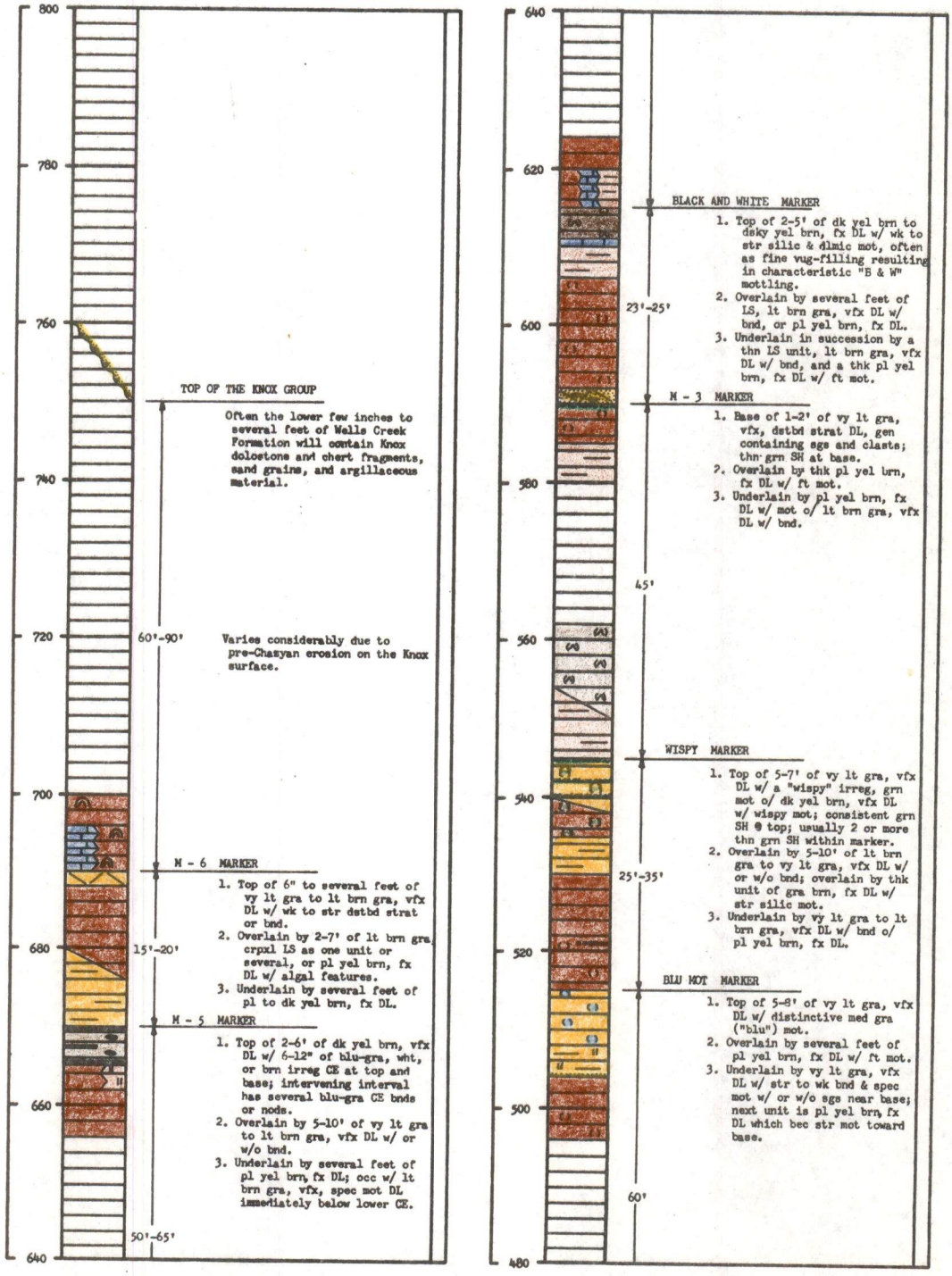
yel ---------- yellow

ROCK TYPES AND DESCRIPTIVE MODIFIERS



GENERALIZED MASCOT MARKER DESCRIPTIONS

Smith and Trousdale Counties, Tennessee



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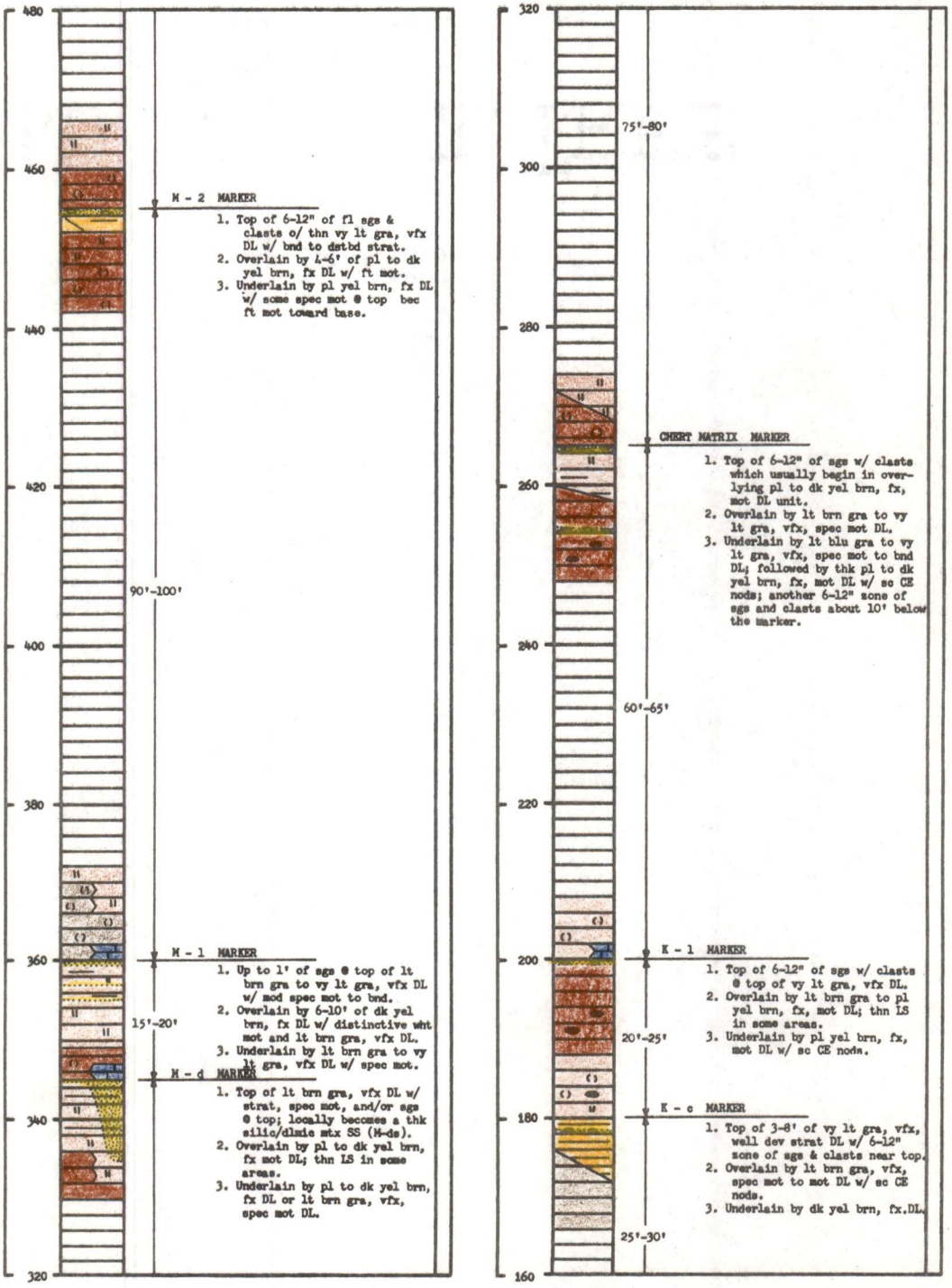
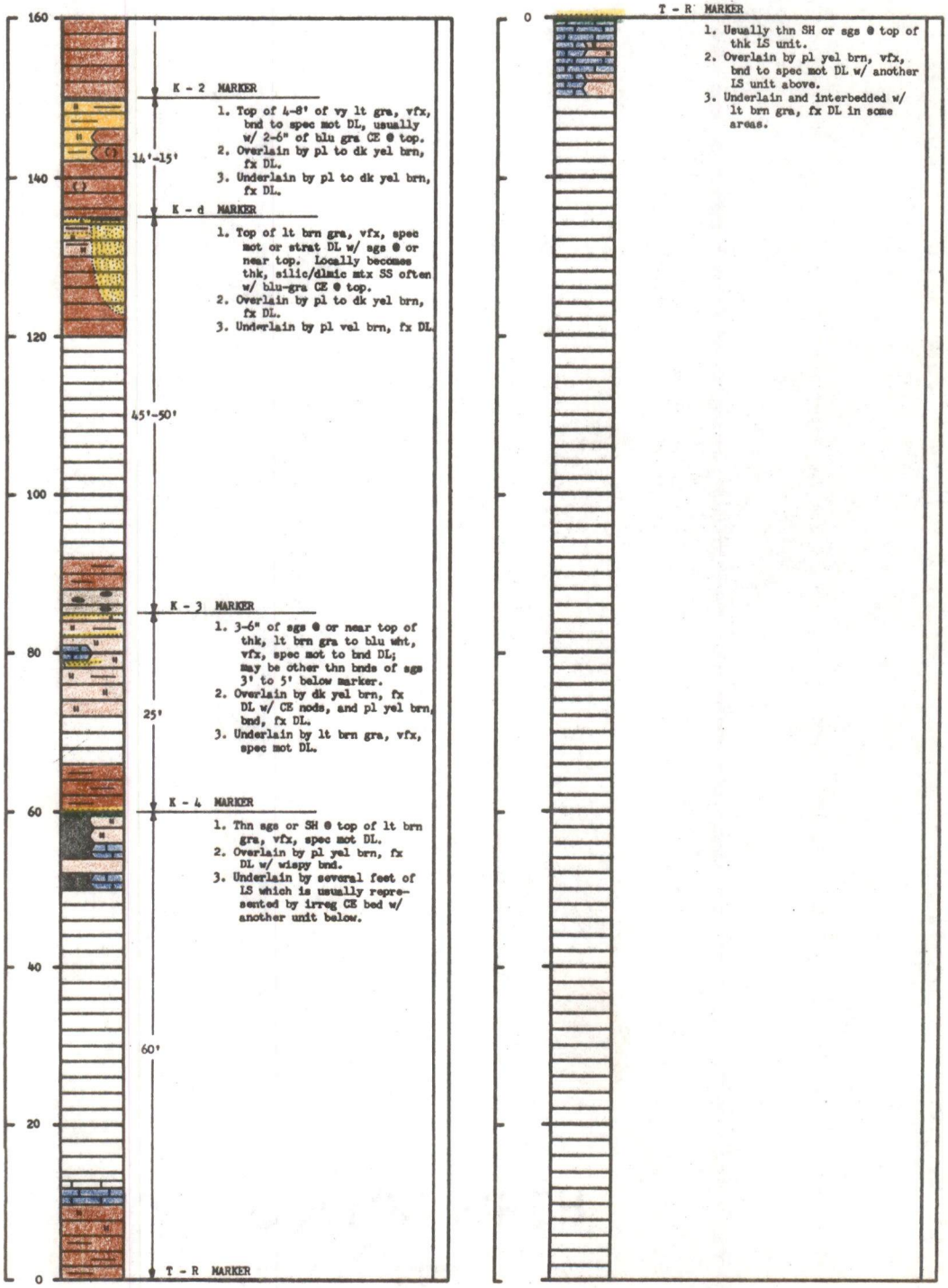
Smith and Trousdale Counties, Tennessee



GENERALIZED MASCOT MARKER DESCRIPTIONS

Smith and Trousdale Counties, Tennessee



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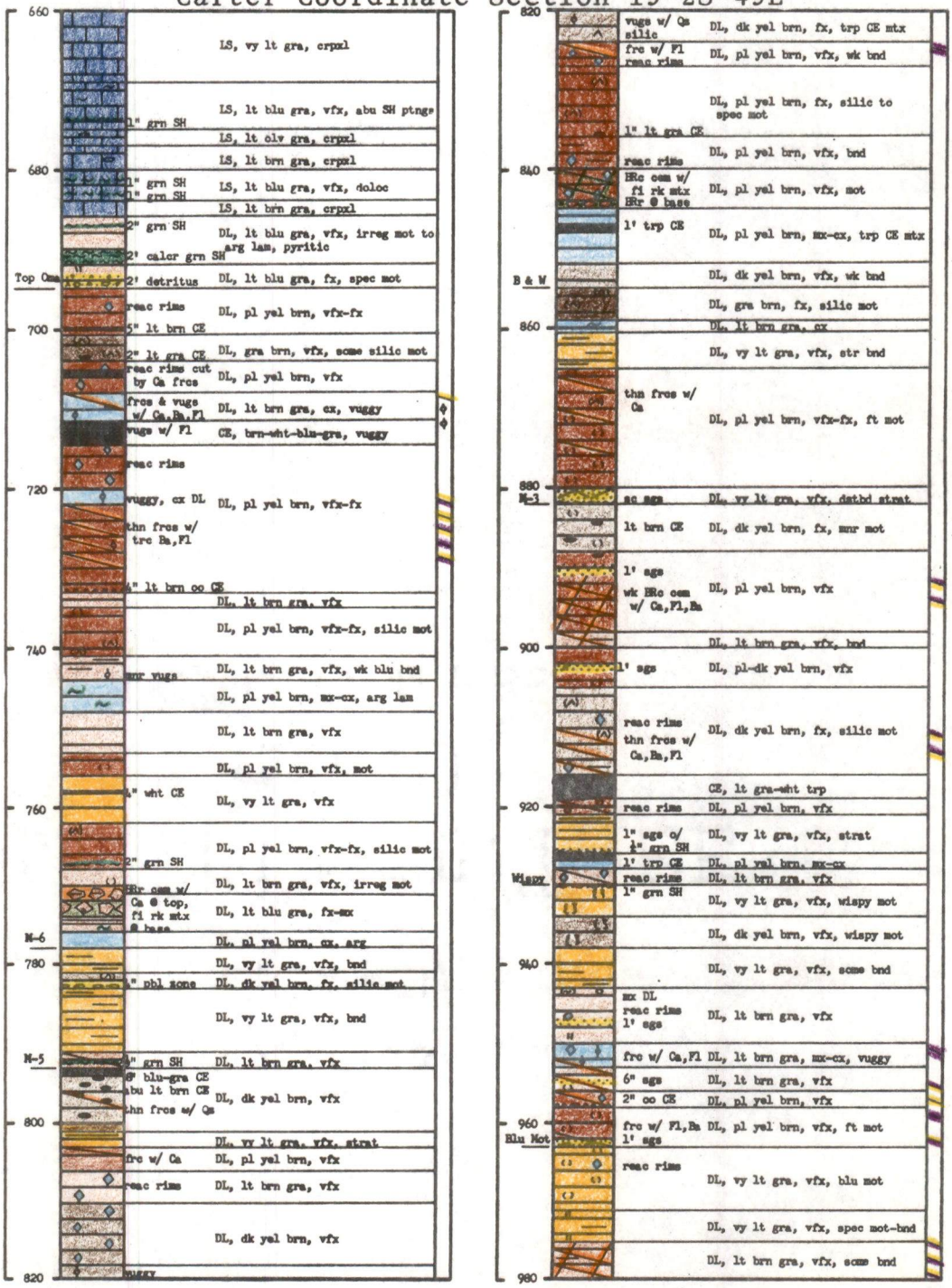

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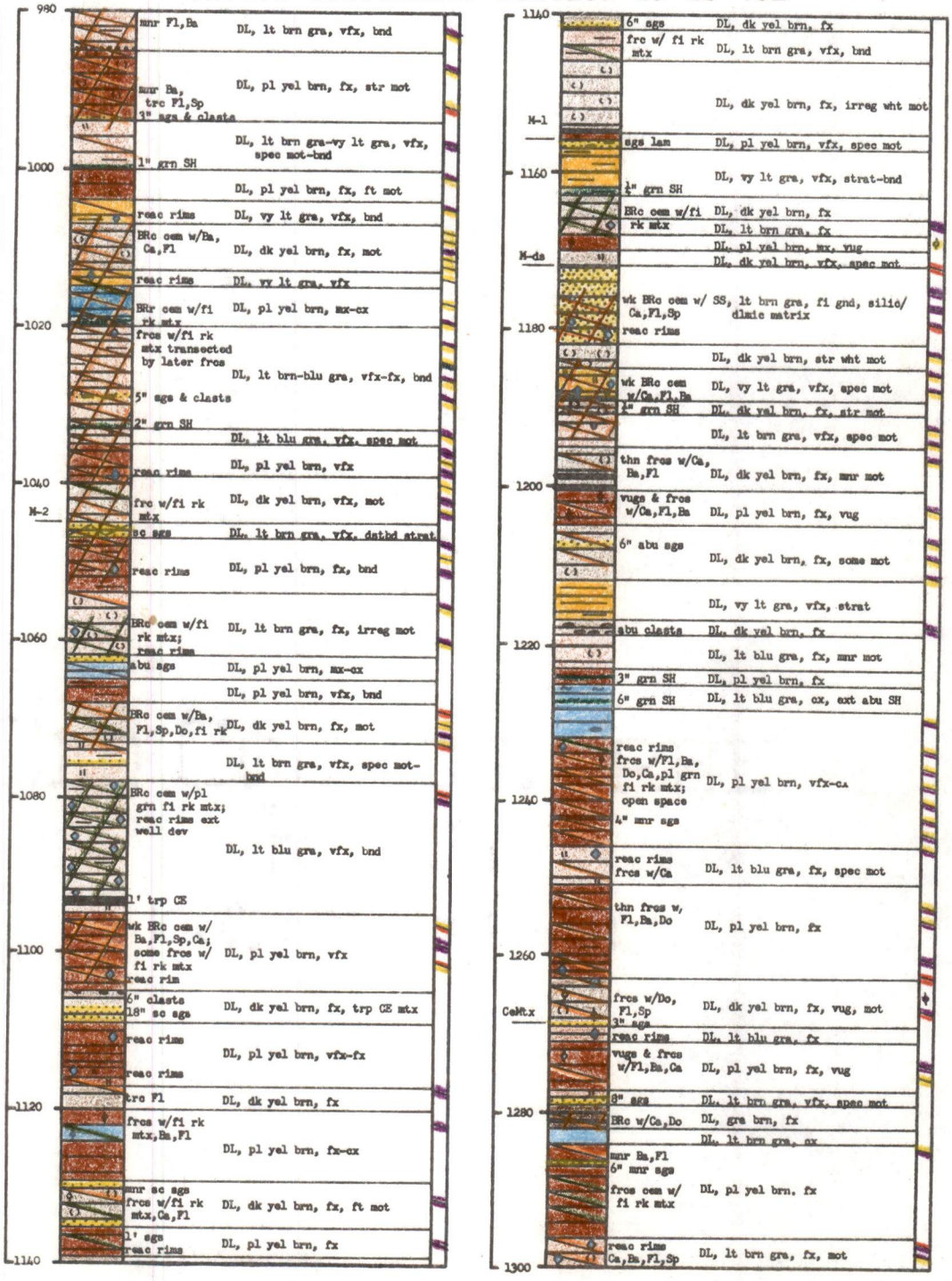

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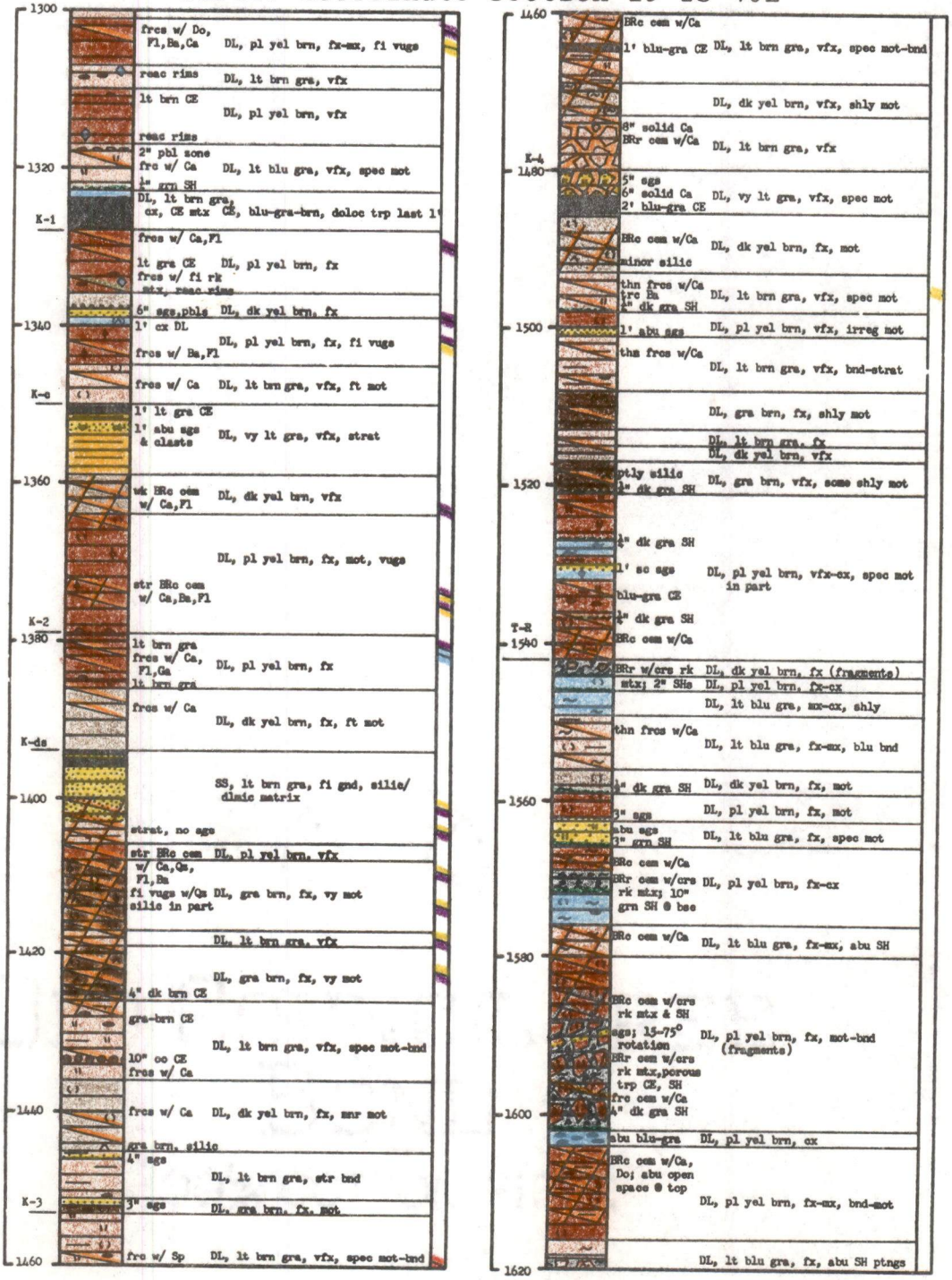

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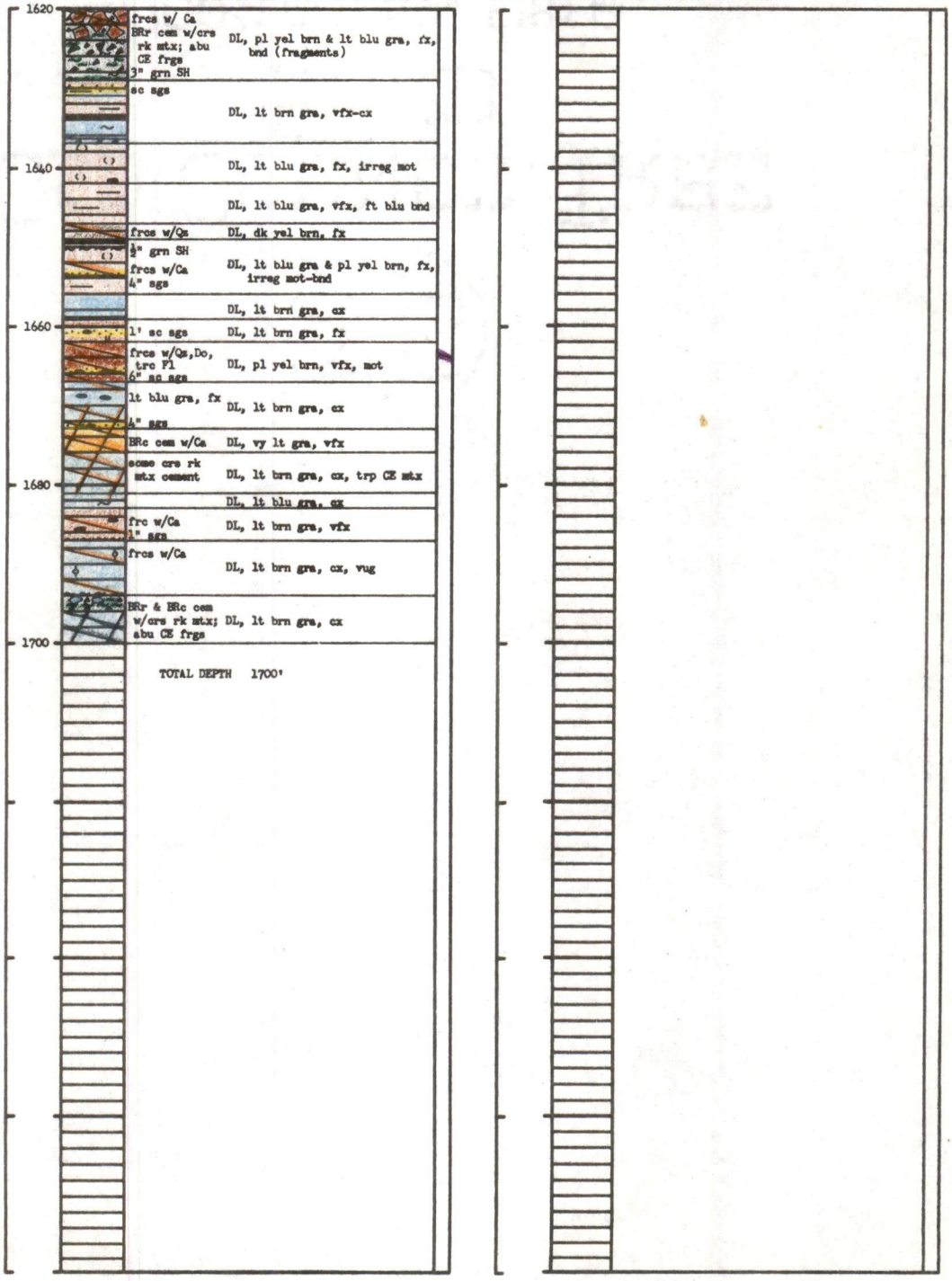

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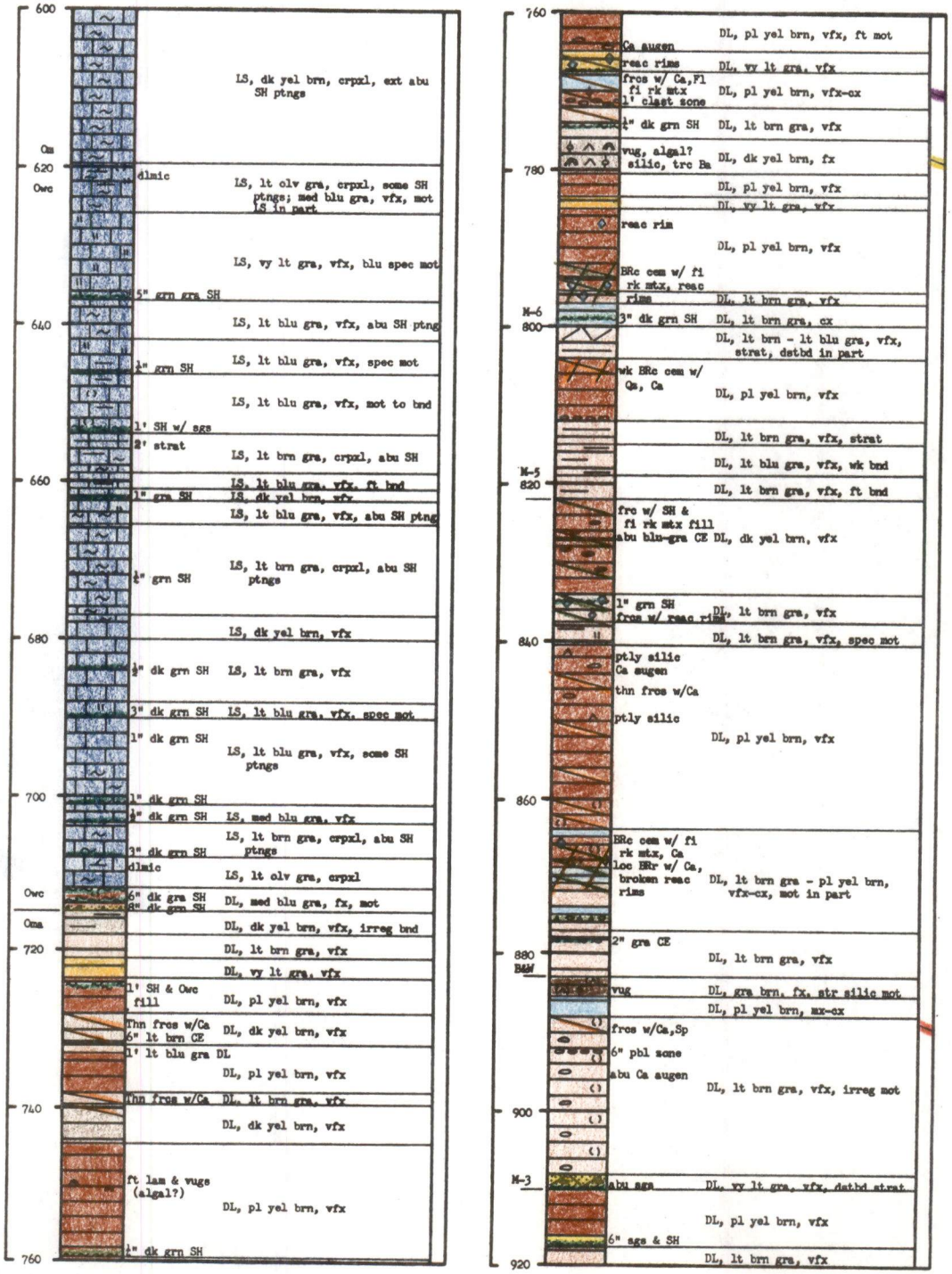

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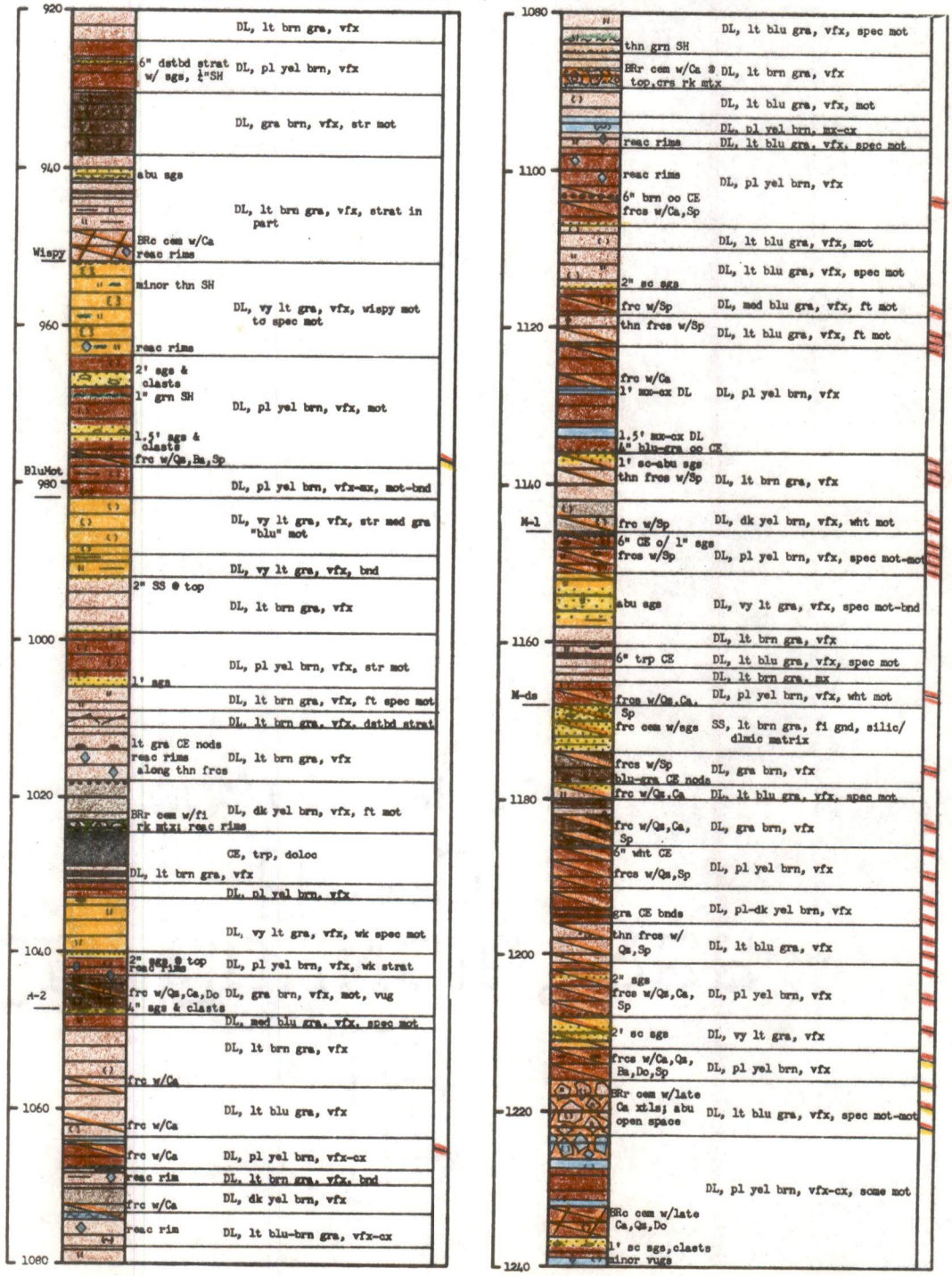

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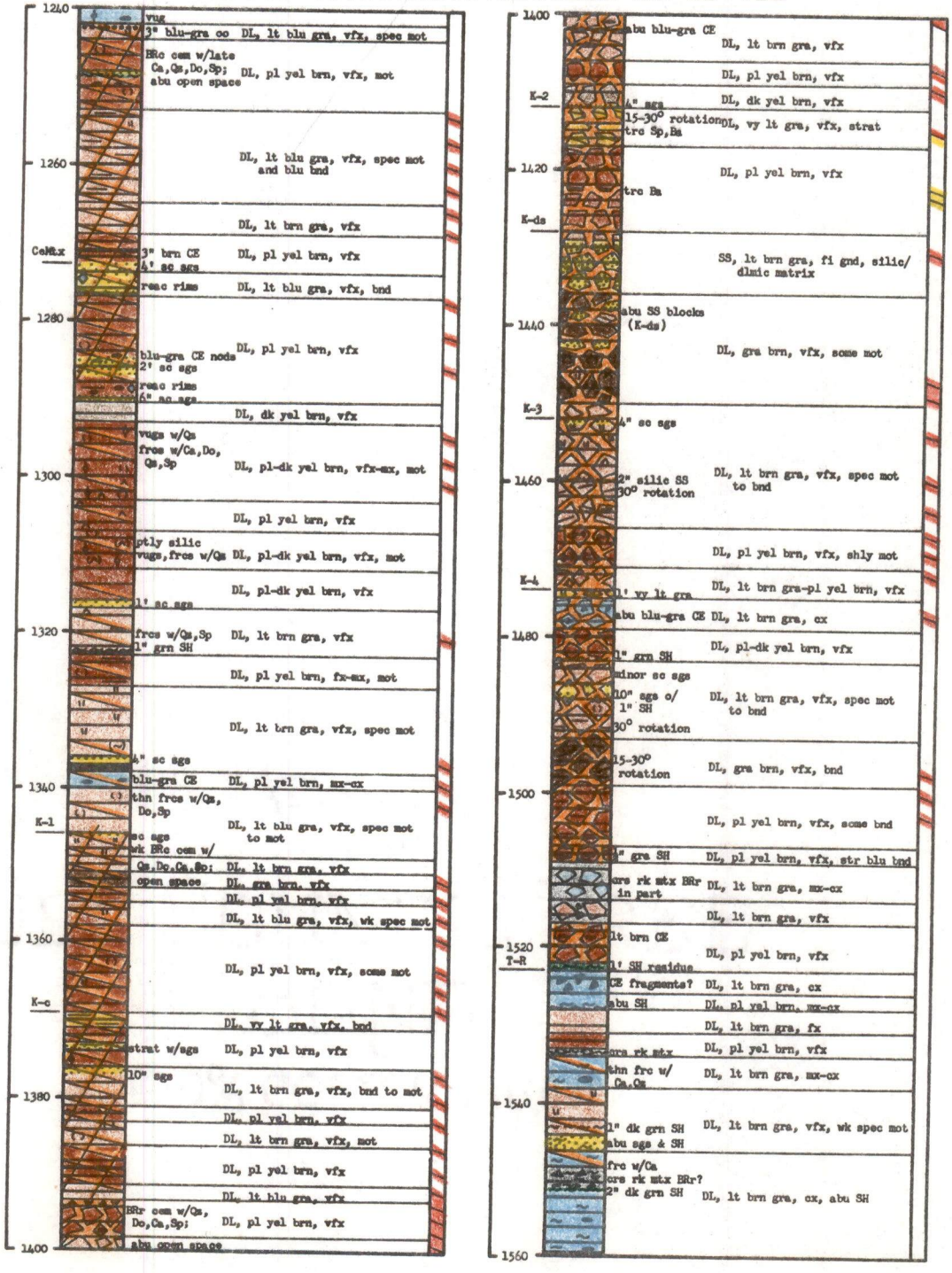

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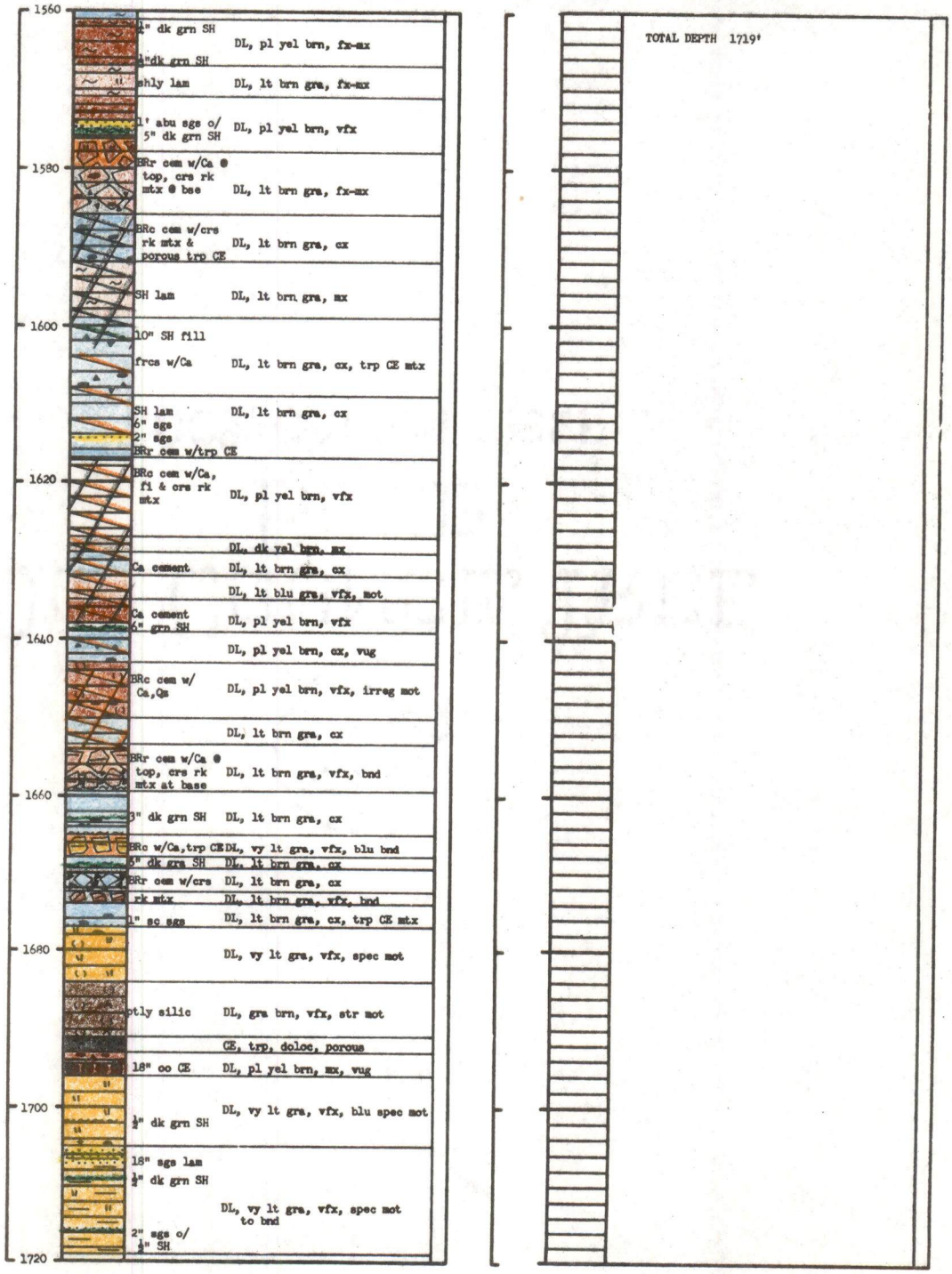

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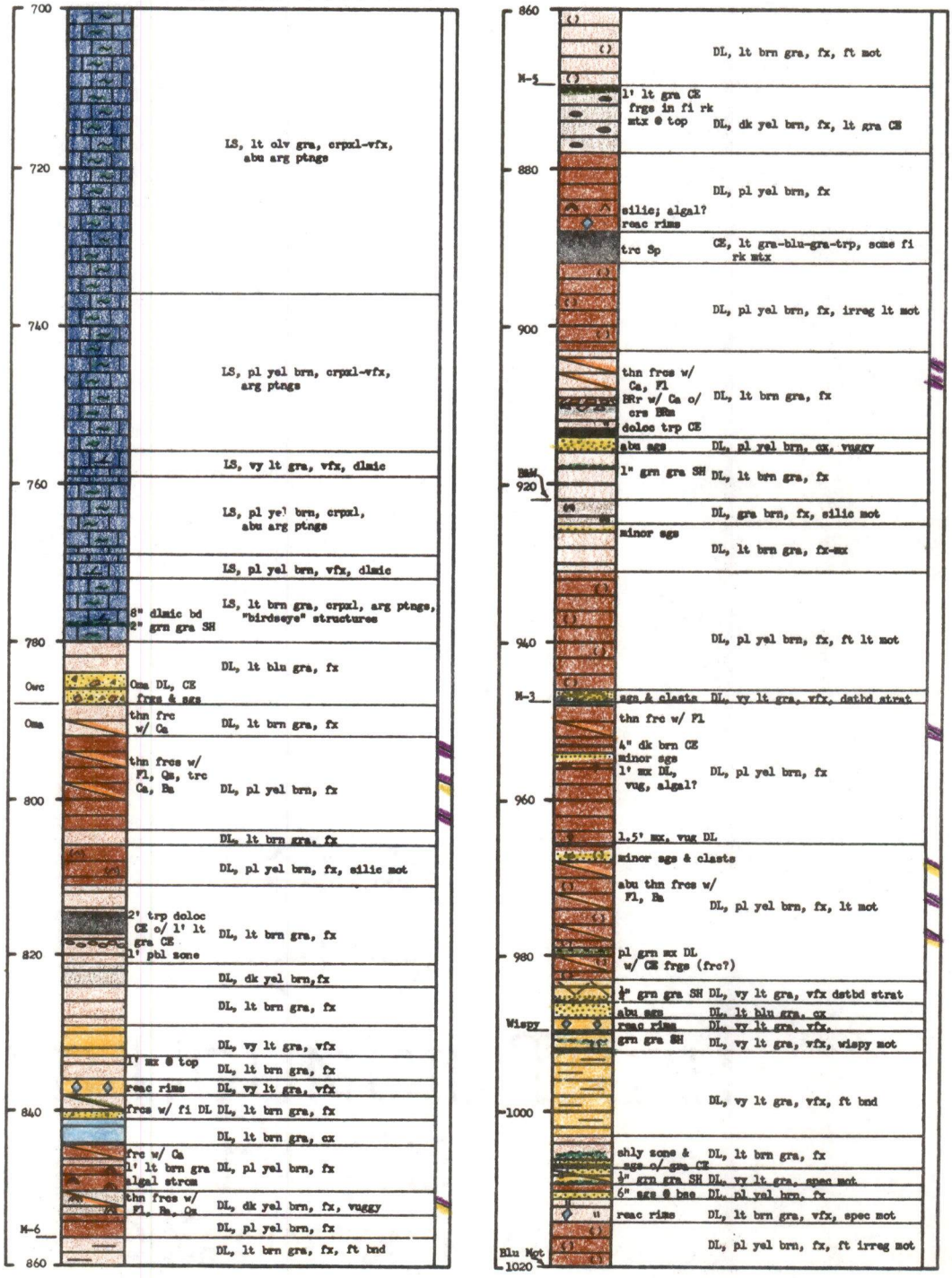

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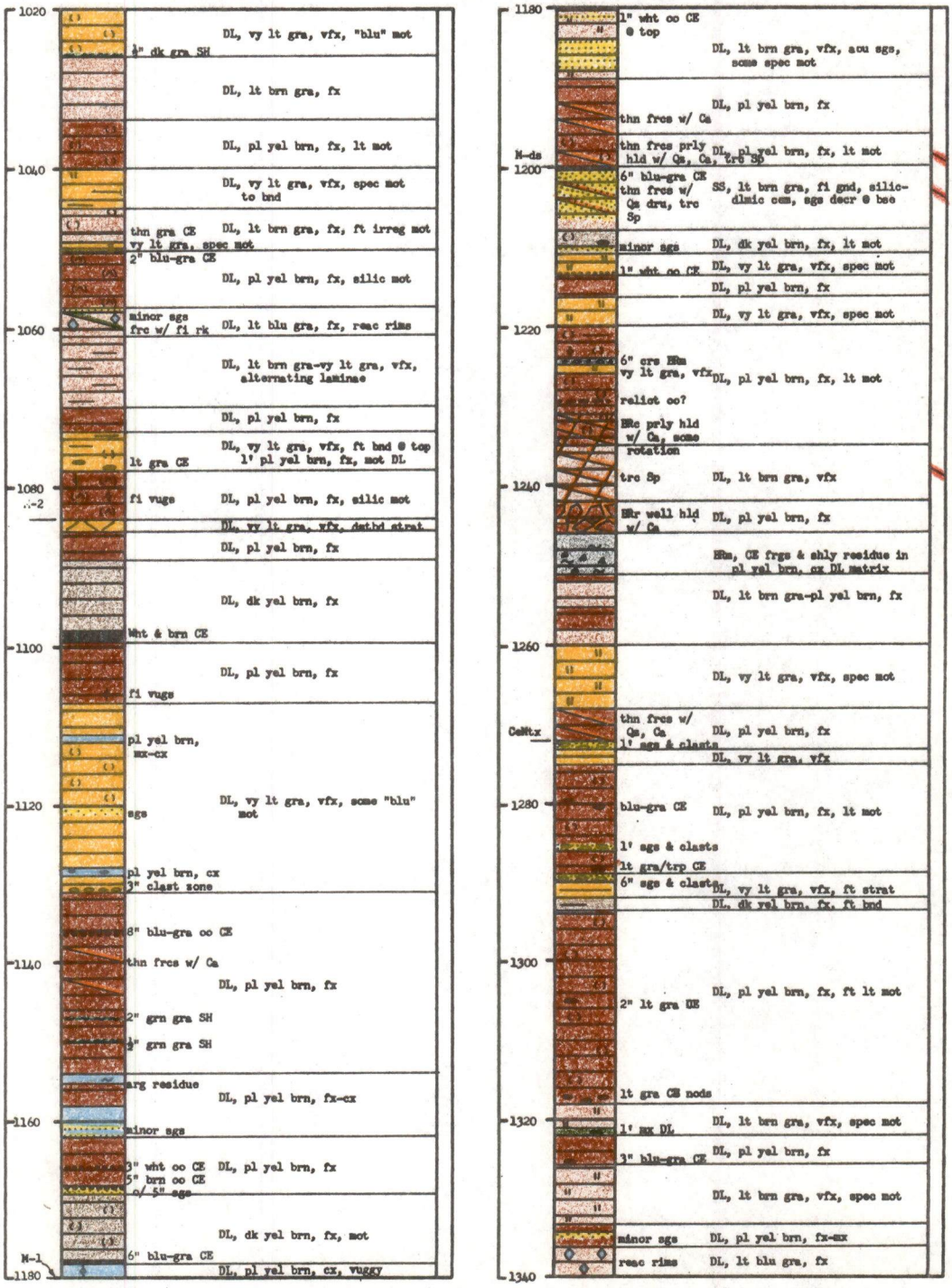

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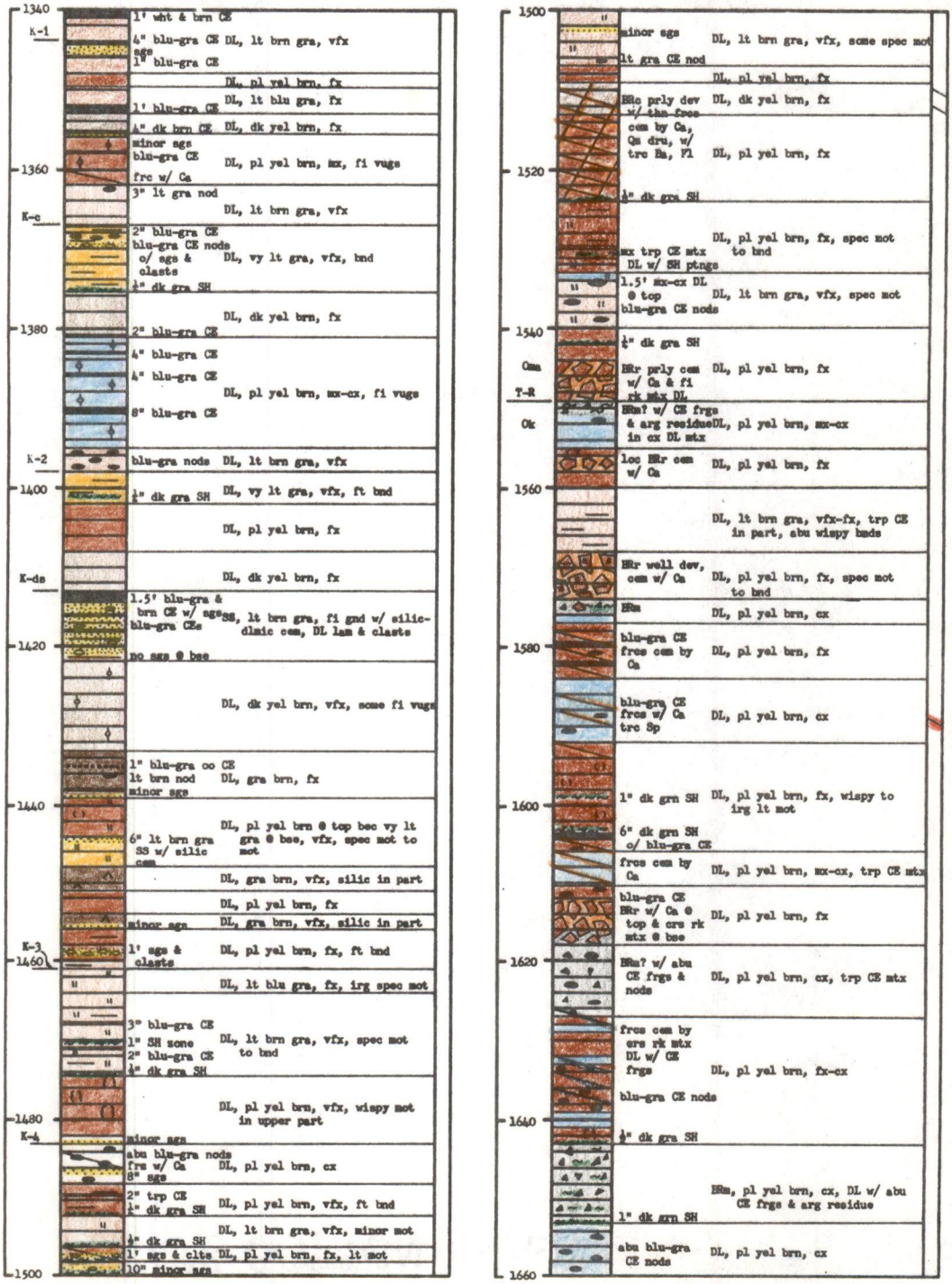

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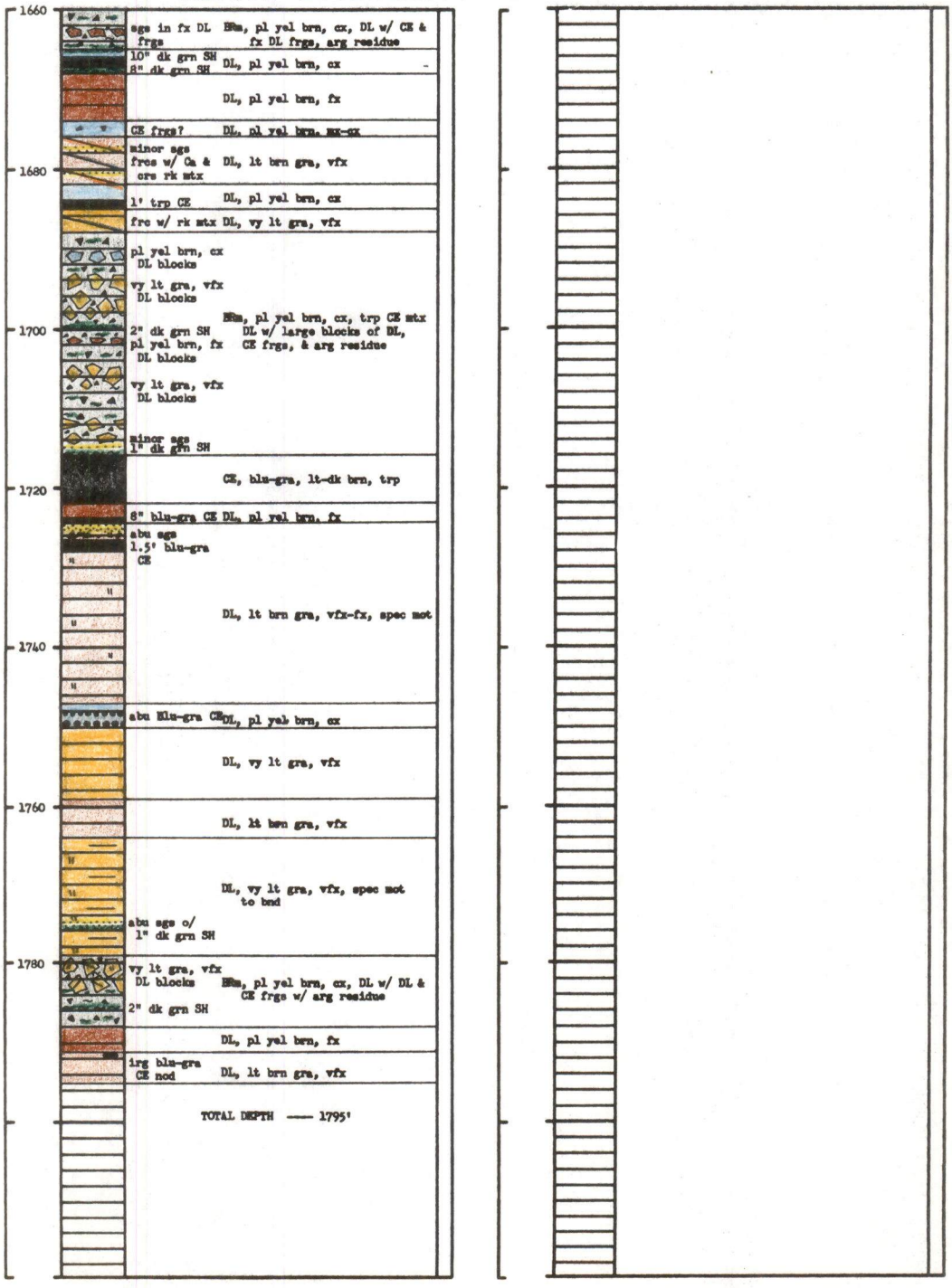

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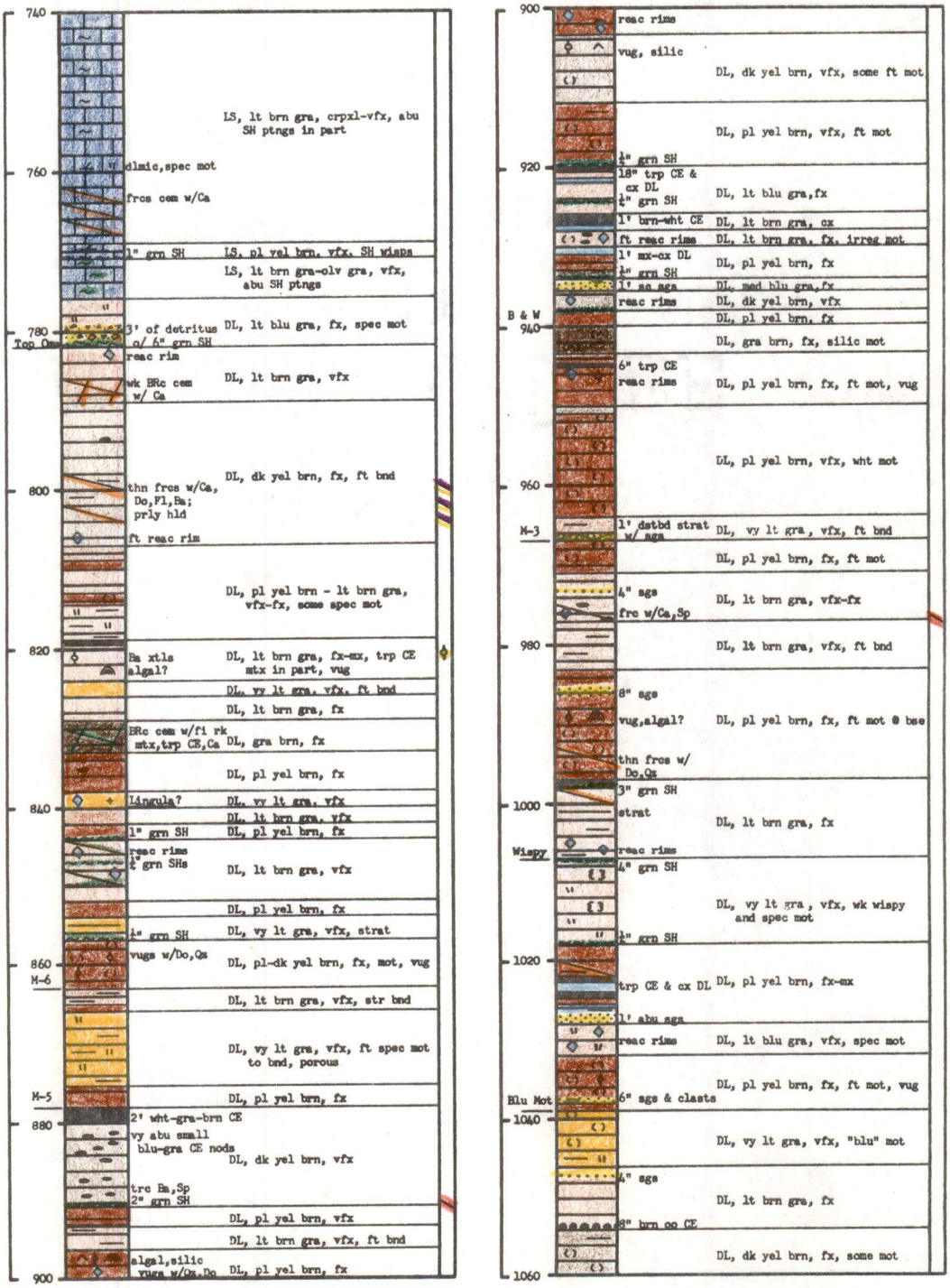

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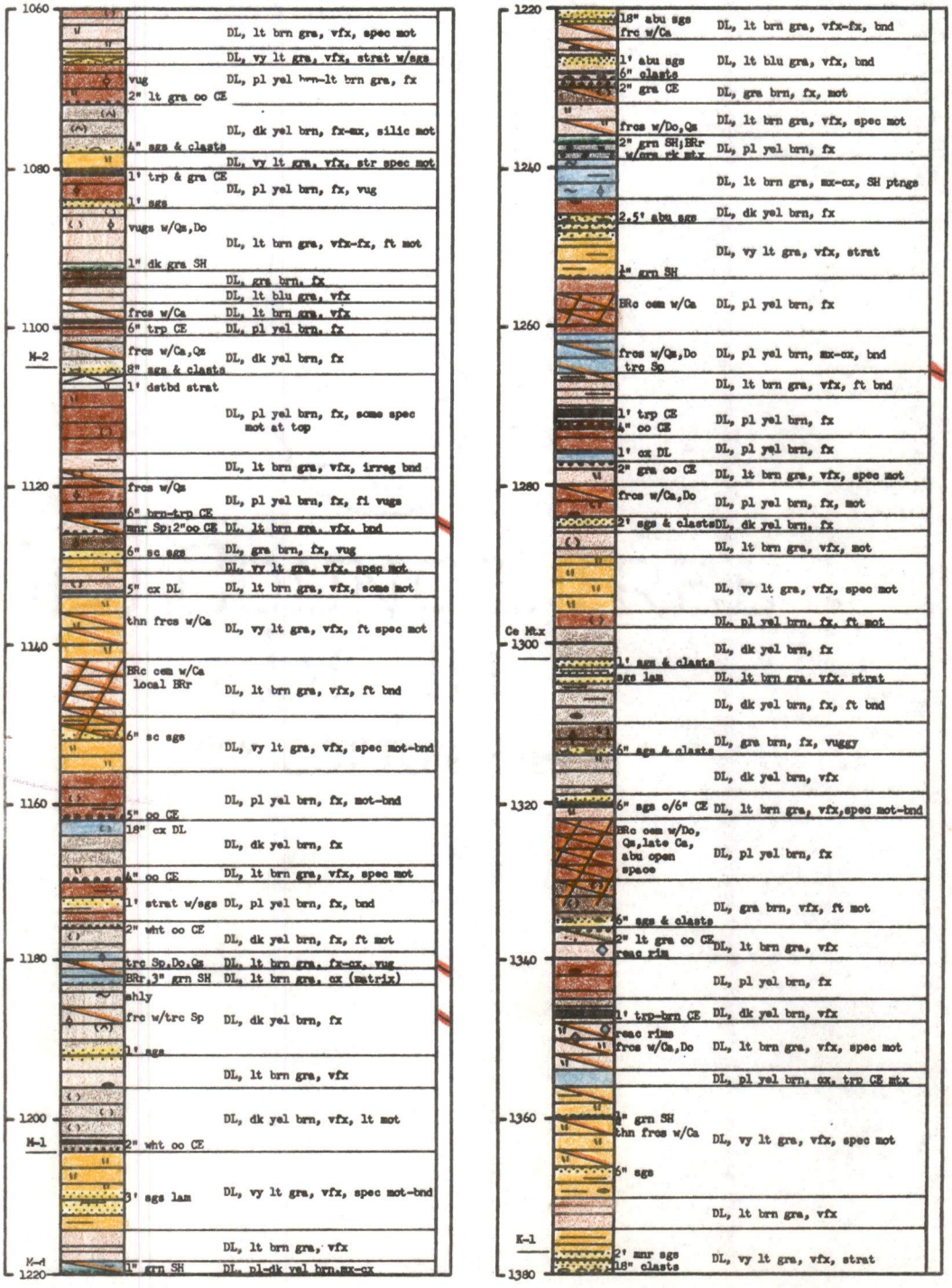

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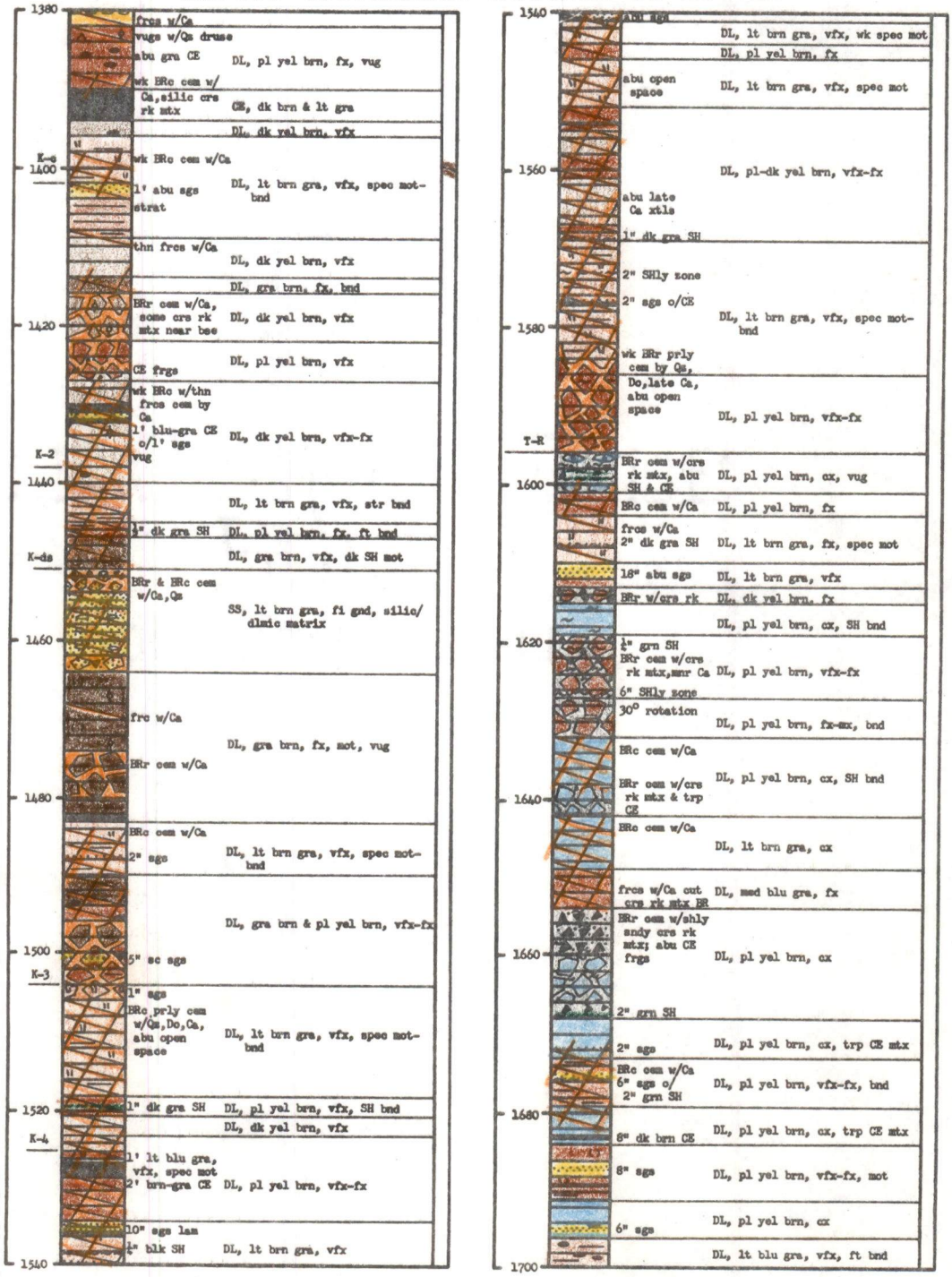
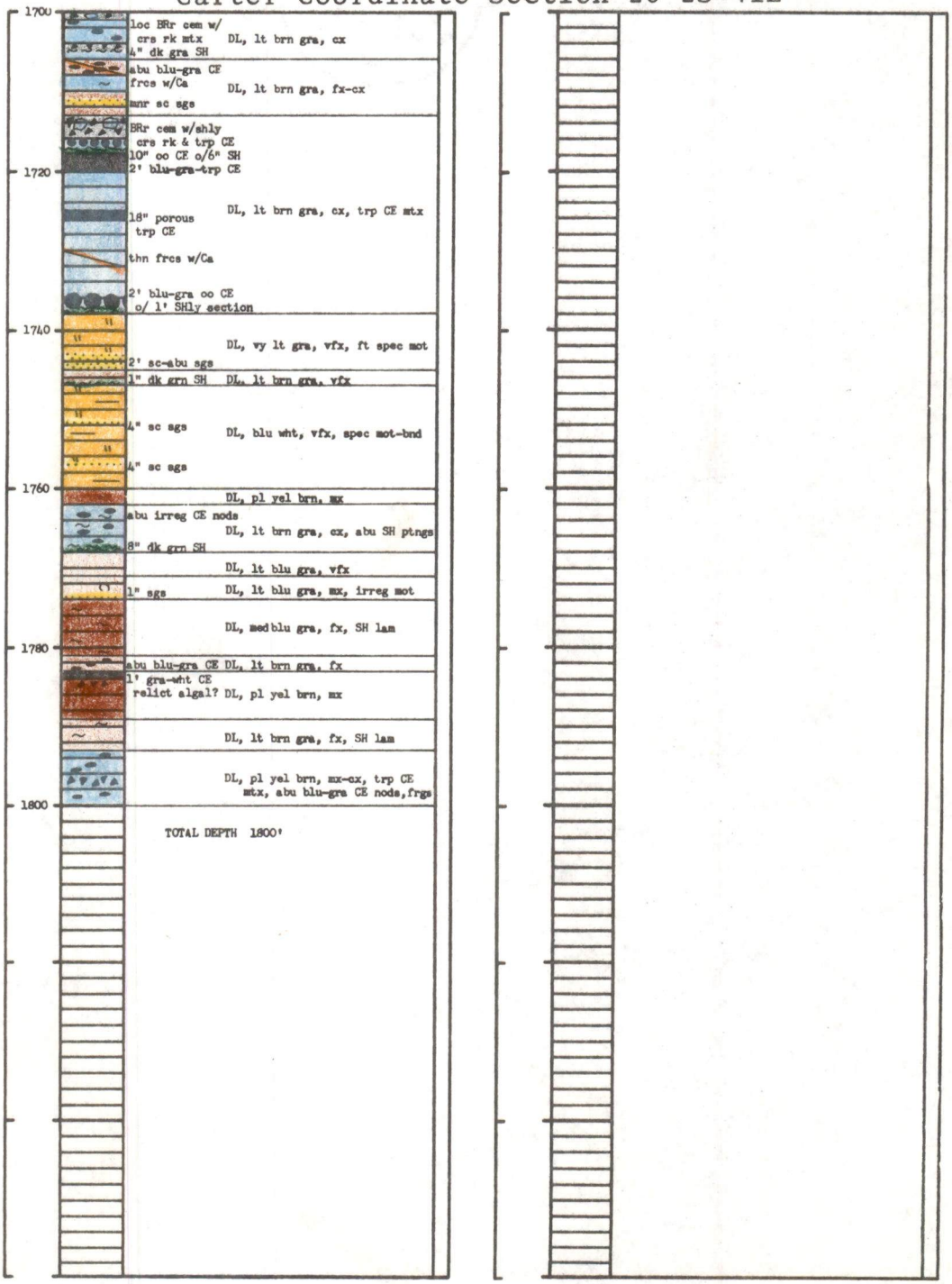


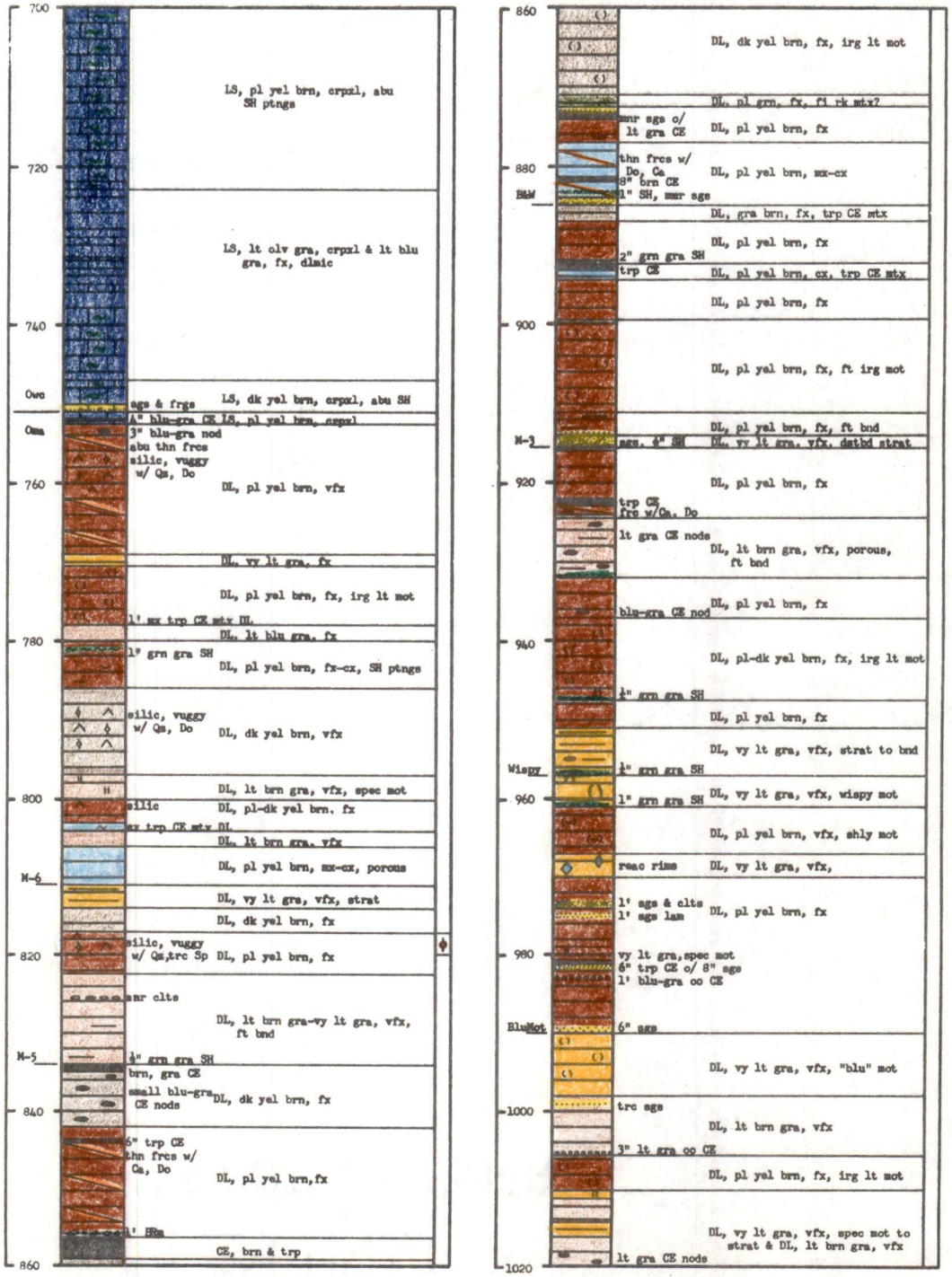
DRILL HOLE #4

Trousdale County, Tennessee
Carter Coordinate Section 20-2S-41E



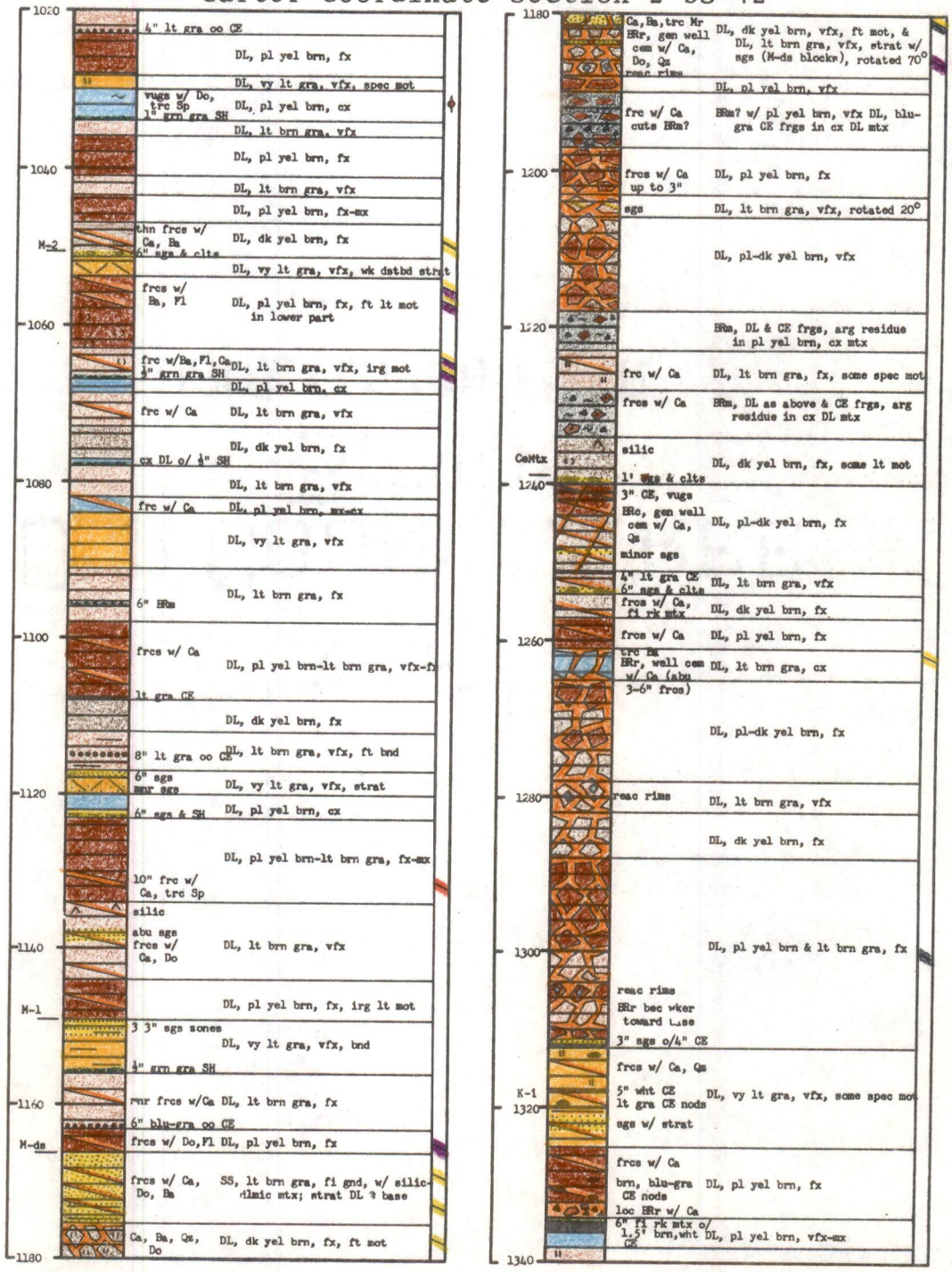
DRILL HOLE #5

Smith County, Tennessee
Carter Coordinate Section 2-3S-42E



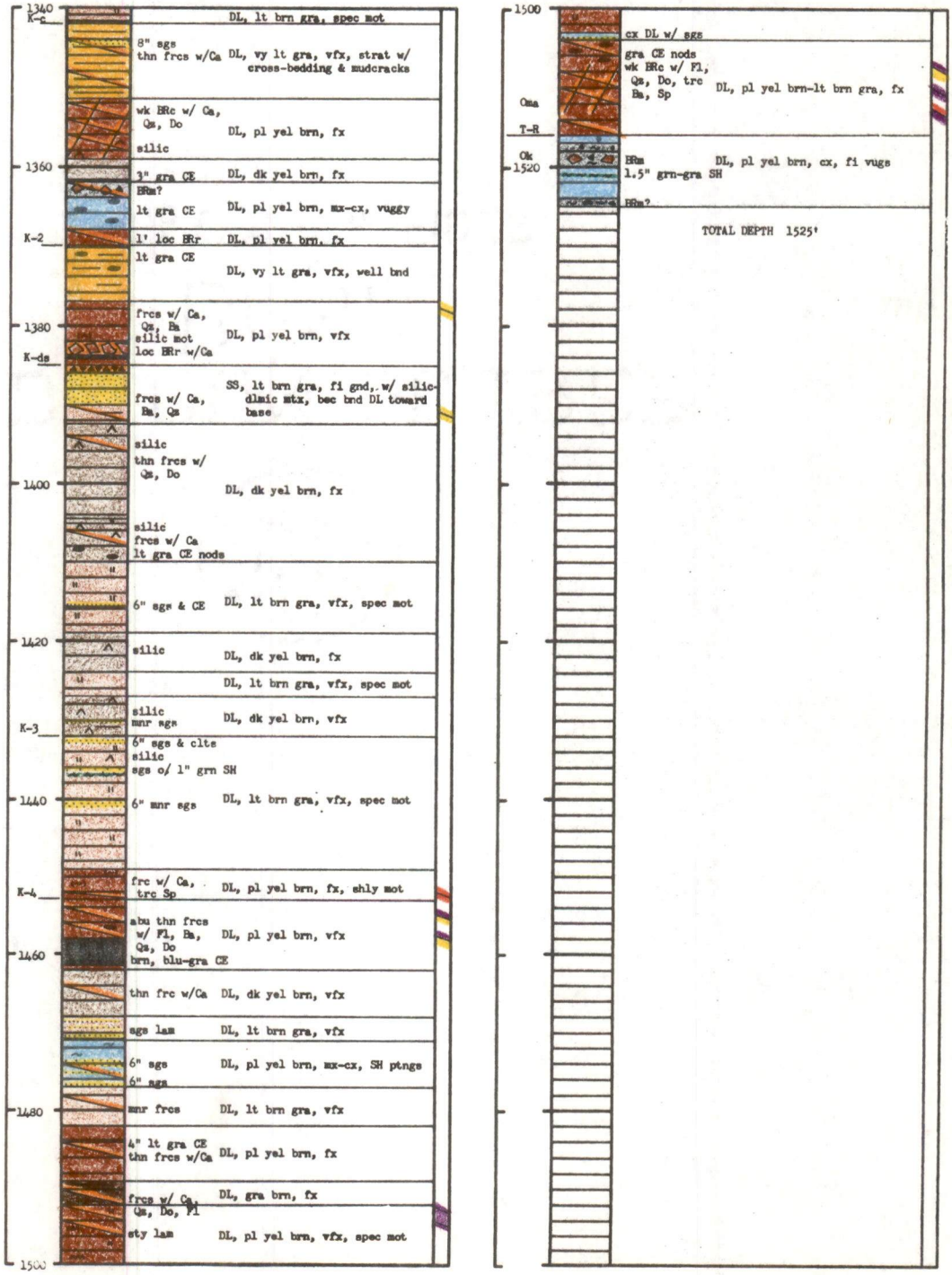
DRILL HOLE #5

Smith County, Tennessee
Carter Coordinate Section 2-3S-42



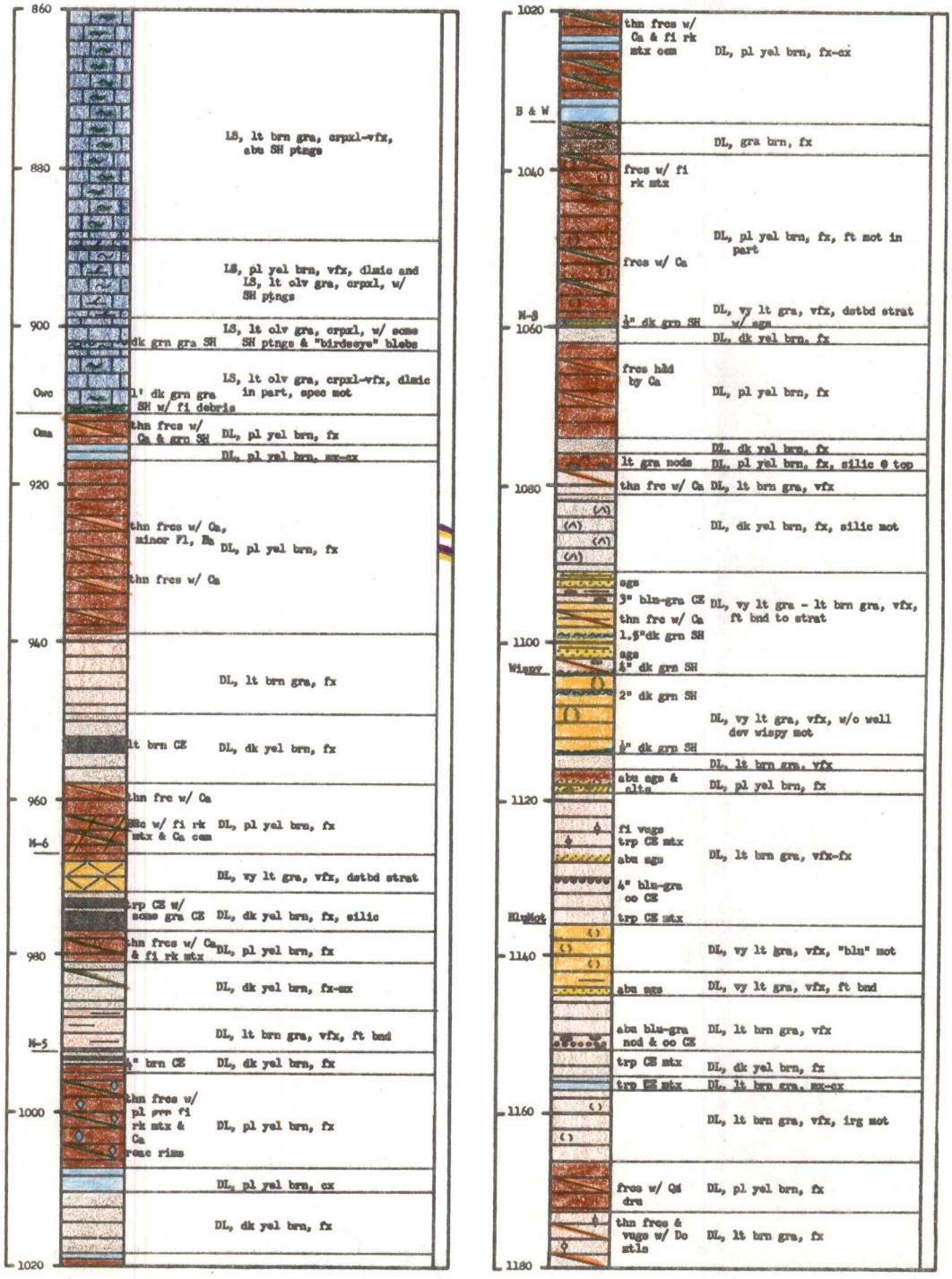
DRILL HOLE #5

Smith County, Tennessee
Carter Coordinate Section 2-3S-42E



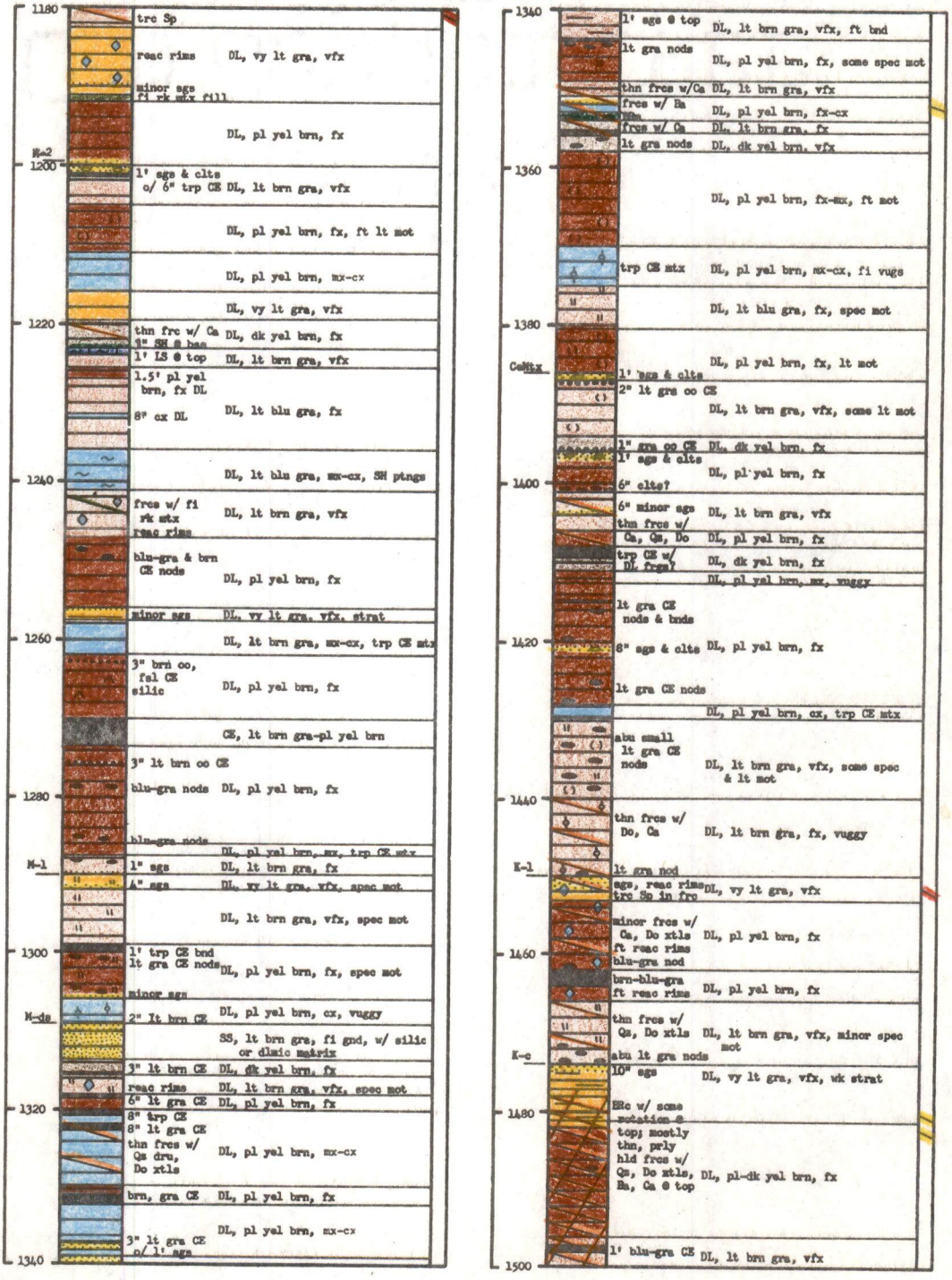
DRILL HOLE #6

Smith County, Tennessee
Carter Coordinate Section 5-4S-43E



DRILL HOLE #6

Smith County, Tennessee
Carter Coordinate Section 5-4S-43E



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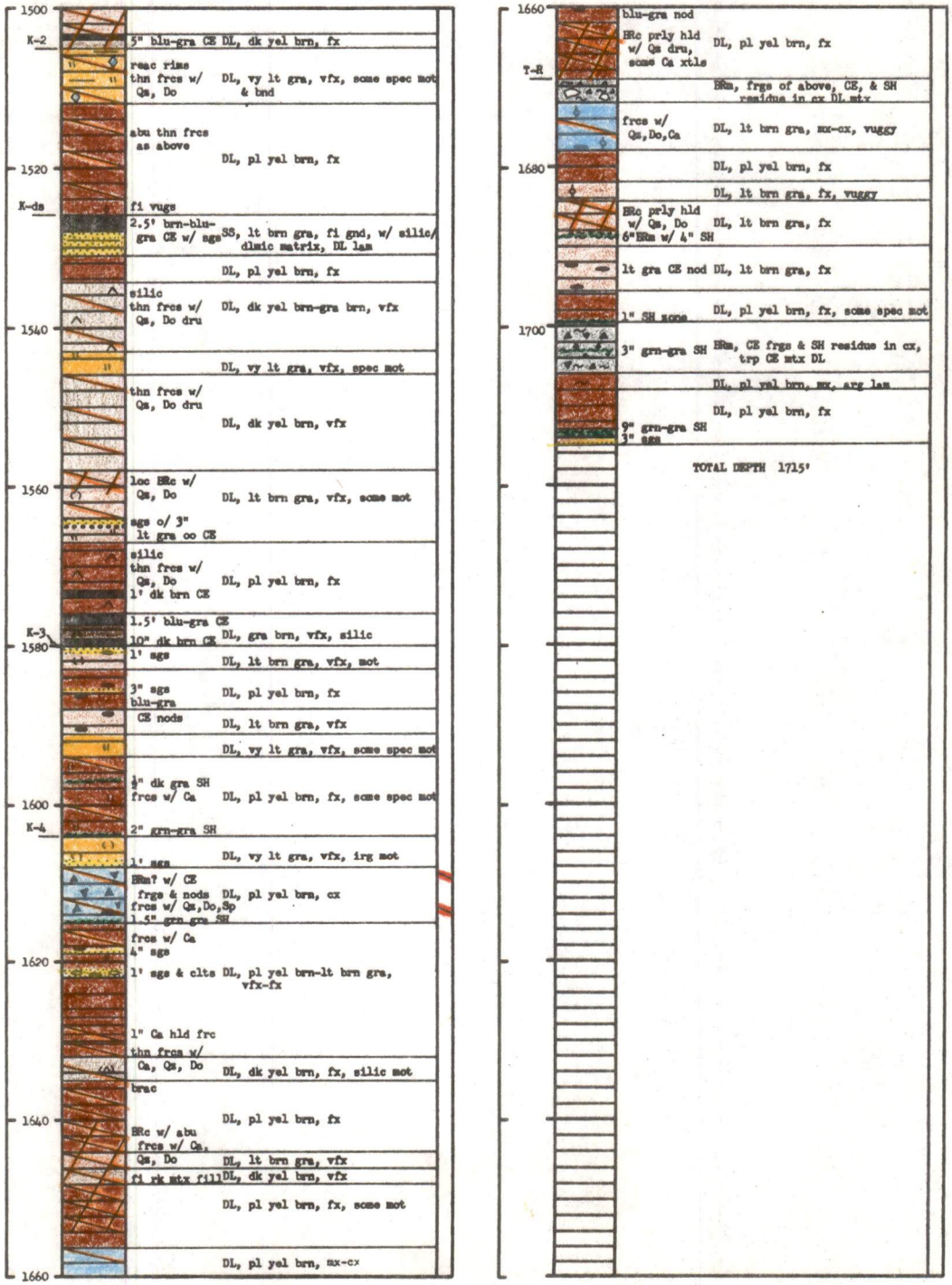
Smith County, Tennessee
Carter Coordinate Section 5-4S-43E



APPENDIX B

GEOLOGY OF THE KNOX GROUP MINERAL DEPOSITS IN EAST TENNESSEE

Introduction

The zinc deposits in the upper Knox Group of Central Tennessee are similar in many respects to the better studied deposits in the upper Knox Group of East Tennessee. For detailed information on the East Tennessee districts the reader is referred to many excellent recent articles such as Crawford and Hoagland (1968) and those in volume 66, number 3 of Economic Geology (1971). The major zinc deposits in East Tennessee are found in the Mascot-Jefferson City district and the Copper Ridge district (Figure 18). These districts are more than 100 miles east of Smith and Trousdale Counties and are located in the Valley and Ridge Physiographic Province.

Mascot-Jefferson City District

The typical zinc deposit in the Mascot-Jefferson City district consists of primarily open space filling in irregularly shaped breccia bodies (Figures 19 and 20) with some local replacement of limestone units adjacent to the breccia structure. The breccia masses are believed to have resulted from collapse of overlying "primary" dolostone

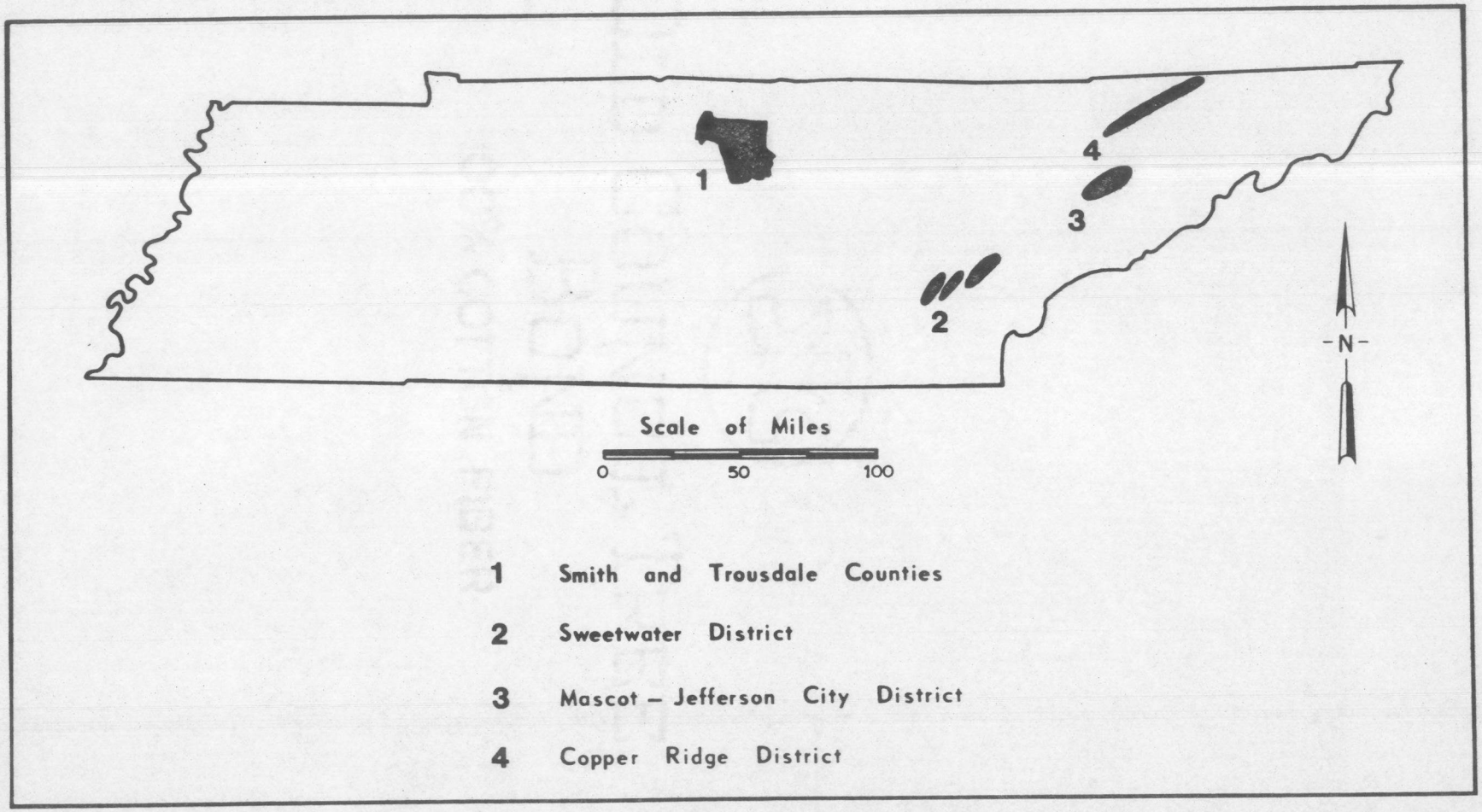


Figure 18

Known Areas of Upper Knox Group Mineralization in Tennessee



Figure 19

Crackle Breccia Cemented by White Dolomite and Minor Sphalerite from the Young Mine

Width of field--15 feet

Photograph by Permission of American Smelting and Refining Company

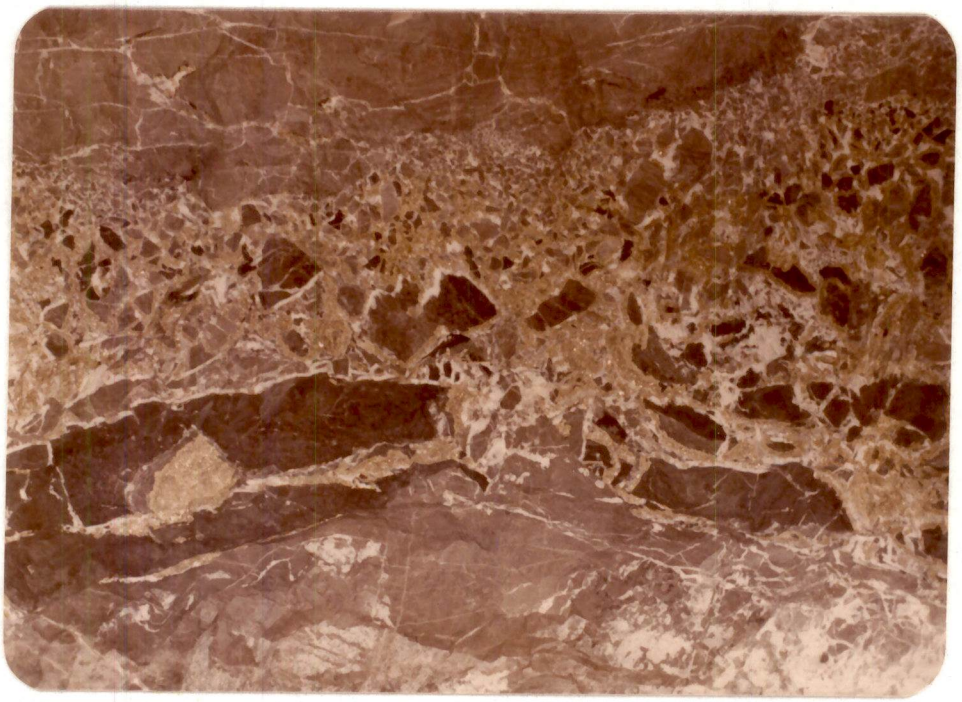


Figure 20

Rubble Breccia Cemented by Yellow Sphalerite and White Dolomite from the Young Mine

Width of field in back--20 feet

Photograph by Permission of American Smelting and Refining Company

units following dissolution of the thick S-bed limestone units (McCormick et al, 1971). Fine rock matrix and coarse rock matrix breccias are spatially related to the ore breccias (Figure 21). It has been suggested by Hoagland et al (1965) that the fine rock matrix breccias were formed by dissolution activity associated with the development of the post-Knox, pre-Chazyan unconformity and that they formed the framework upon which the ore breccias developed. Coarse rock matrix is thought to be the residue from later limestone dissolution. Breakthrough breccia structures may have dimensions of up to 1,500 feet long, 900 feet wide, and 170 feet or more high (McCormick et al, 1971). Manto breccia structures are important ore hosts in portions of the district. These bodies are lateral extensions from main breccia structures and are usually restricted to single stratigraphic units. Manto structures average 200 to 300 feet in length and 40 feet in width (McCormick et al, 1971).

The only ore mineral is pale yellow sphalerite associated with a gangue of predominantly white dolomite, minor amounts of calcite and pyrite, and rare amounts of galena, fluorite, and barite. The main ore zone includes the lower 60 feet of the Mascot and the upper 160 feet of the Kingsport Formation (Crawford and Hoagland, 1968). Breccia structures are not uniformly mineralized. The best sphalerite mineralization generally occurs around the periphery of the breccia body, and the central portion of the larger structures is seldom mined because of the low

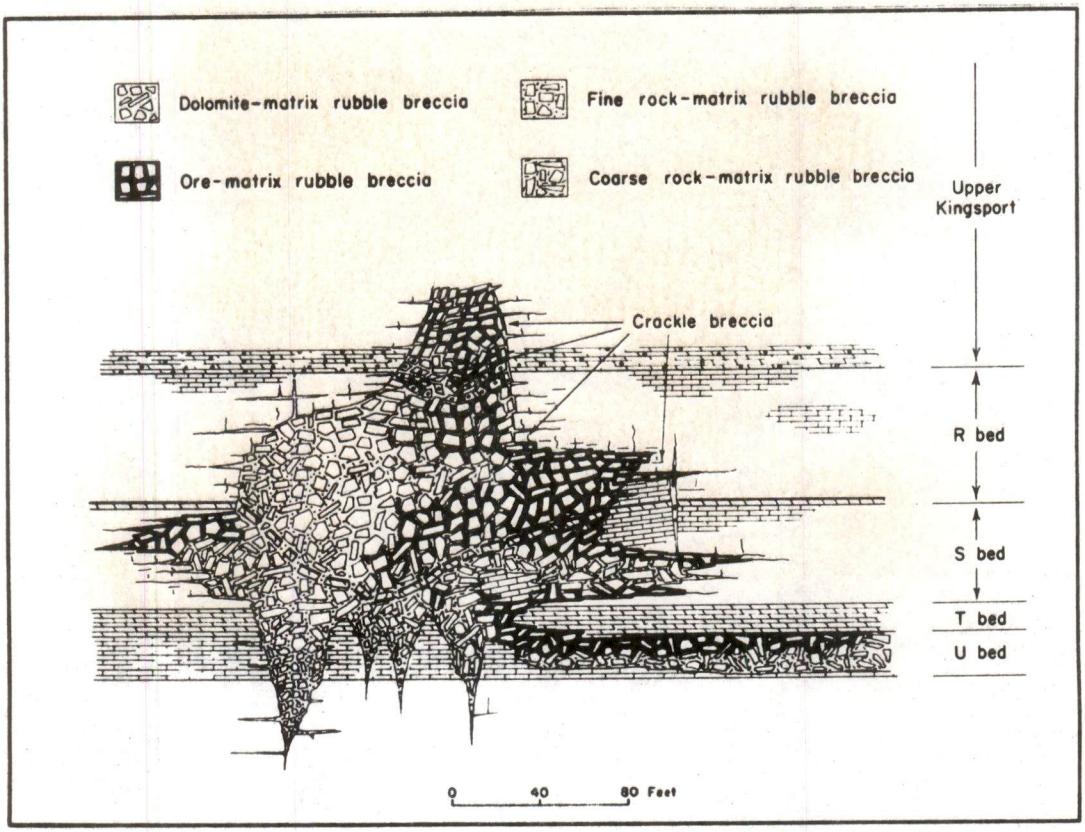


Figure 21

Generalized Relationships of Brecciation Types in the Jefferson City Mine, East Tennessee

From Crawford and Hoagland (1968)

sphalerite content. Pyrite, fluorite, and calcite normally occur around the outer edge of the breccia bodies (McCormick et al, 1971). Primary fluid inclusions in sphalerite, fluorite, dolomite, and quartz from East Tennessee homogenize in the temperature range of 82° to 149° C. (Roedder, 1971).

Alteration features include dolomitization of limestone strata adjacent to and within the breccia structures and silicification of limestone and dolostone units around the periphery of the breccia (McCormick et al, 1971). The dolostone strata overlying the ore zones is lighter in color due to bleaching (Figure 22) by unknown processes (Crawford and Hoagland, 1968).

In certain breccia structures Kendall (1960) observed post-ore detrital dolomite and sphalerite with laminations parallel to the dip and strike of the country rock. This relationship, termed sanding, indicates that mineralization took place while the formations were essentially horizontal and preceded the Appalachian orogeny which had been generally regarded by earlier authors as responsible for the brecciation and the generation of the ore fluids (Secrist, 1924; Currier, 1935; Brokaw, 1950). The present interpretation is that mineralization could have occurred as early as the pre-Chazyan erosional interval (Hoagland et al, 1965; Crawford and Hoagland, 1968; Hill and Wedow, 1971). The main influence of the Appalachian disturbance was to

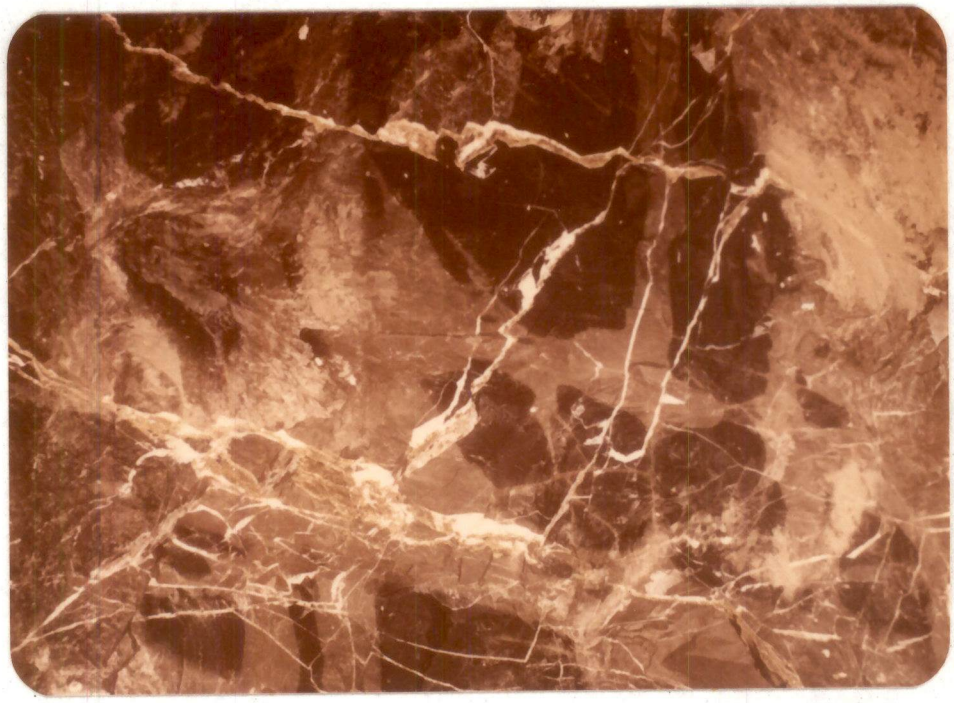


Figure 22

Bleaching of "Primary" Dolostone Along Pre-Ore Fractures in the New Market Mine

Bleached and unbleached areas transected by fractures containing white dolomite and yellow sphalerite

Width of field in back--10 feet

Photograph by Permission of American Smelting and Refining Company

displace the ore deposits by a series of thrust faults from their original site of formation and to incline the strata about 10° to the southeast (Crawford and Hoagland, 1968).

Copper Ridge District

The zinc deposits in the Copper Ridge district are similar in most respects to those of the Mascot-Jefferson City district. The major breccia structures at the Flat Gap mine are largely the same (Figure 23), and intrafragmental spaces are filled by pale yellow sphalerite and dolomite gangue with minor amounts of galena, fluorite, barite, pyrite, marcasite, calcite, anhydrite, and gypsum. The galena is associated with an early colloform, dark reddish brown sphalerite which in places is brecciated and forms fragments in later ore and coarse rock matrix breccias. The main ore zone includes the lower 60 feet of the Mascot and the upper 160 feet of the Kingsport Formation. Bleaching, dolomitization, silicification, and sanding are associated with the breccia structures. The ore bodies have been offset by a series of cross faults, and the strata dips at an average of 37° to the southeast (Hill et al, 1971).

Sweetwater District

Barite is mined from residuum resulting from weathering of similar upper Knox breccia systems in the Sweetwater district about fifty miles southwest of Mascot.

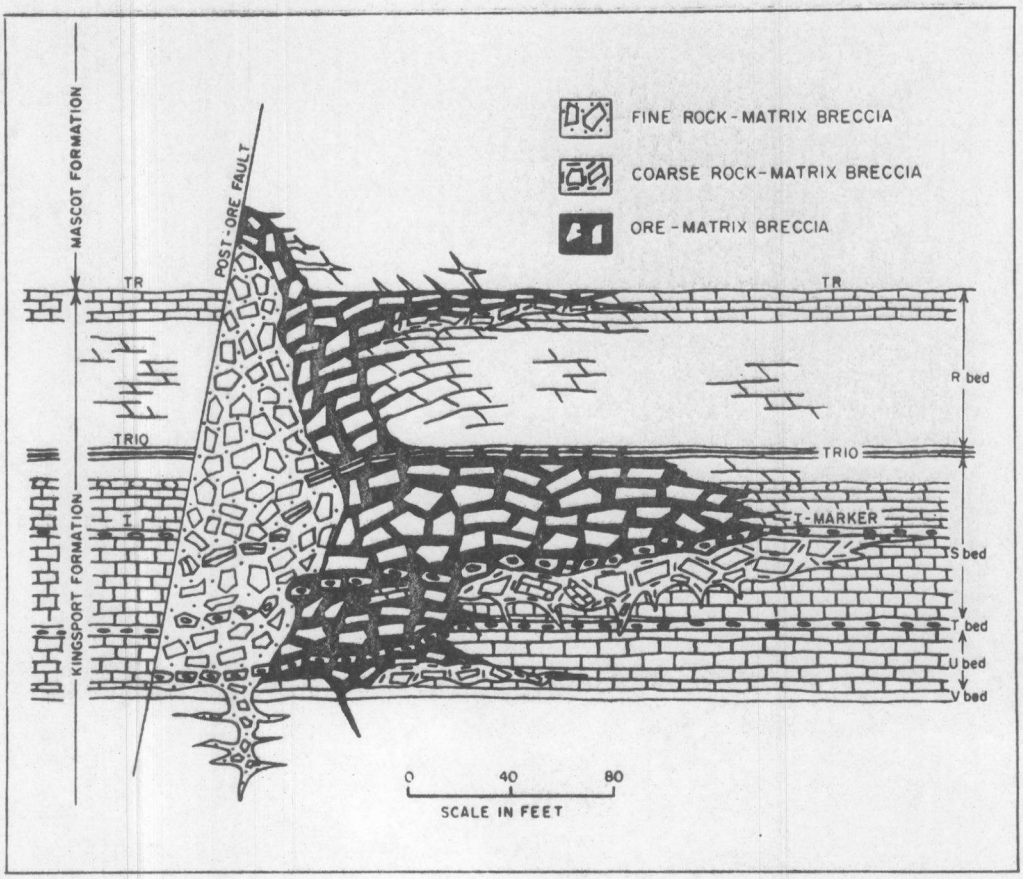


Figure 23

Generalized Geology of the Breccia Bodies in Flat Gap Mine, Copper Ridge District

From Hill et al (1971)

The principal mineral cement is colloform barite with abundant fluorite, minor sphalerite, marcasite, pyrite, calcite, and dolomite. Exact stratigraphic ranges of mineralization are unavailable at the present time.

VITA

James Richard Kyle was born in Athens, Tennessee, on March 23, 1947. He attended elementary school in that city and was graduated from McMinn County High School in 1965. In September of that year he entered Tennessee Technological University, and in June, 1970, he received a Bachelor of Science degree in geology. In September, 1970, he entered The University of Tennessee where he was a member of Sigma Gamma Epsilon. He was employed by Cominco American Incorporated from January until September of 1973. He received the Master of Science degree in August, 1973.

He entered the Graduate School of The University of Western Ontario in September, 1973, to begin studies toward a Doctor of Philosophy degree in geology.

He is married to the former Linda S. Davis of Cookeville, Tennessee.