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I am submitting herewith a thesis written by David J. Tieman entitled "Deformation Textures in Barite and Fluorite of the Del Rio District and Their Implications as to the Relative Timing of Deformation and Mineralization." I recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Geology.

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DEFORMATION TEXTURES IN BARITE AND FLUORITE OF THE DEL RIO DISTRICT AND THEIR IMPLICATIONS AS TO THE RELATIVE TIMING OF DEFORMATION AND MINERALIZATION

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

David J. Tieman

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ABSTRACT

The purpose of this study was to investigate two distinctive types of vein mineralization in the Del Rio barite district, Cocke County, Tennessee. These vein types are distinguished on the basis of contrasting mineral assemblages and textural appearance. Of primary importance was the examination of deformational fabric in the vein barite and fluorite. This fabric included both intra-crystalline microstructures and cataclastic ore textures. Chemical analyses of minor and trace element contents of vein barite and fluorite were also attempted in an effort to determine the genetic relationship between the two types.

The main investigative method consisted of the examination of prepared thin-sections with a petrographic microscope. Possible cathodoluminescence of the barite and fluorite was sought using a luminoscope, but no unique zoning patterns were observed.

X-ray fluorescence was utilized to obtain a limited amount of semi-quantitative chemical data. Other procedures were also required to separate the complexly intergrown barite and fluorite ore mixtures for separate chemical analysis. These chemical analyses did not provide adequate data to draw any conclusions concerning a possible source of the mineralization or the existence of unrelated mineralizing events in the district. Continued research is needed to more fully understand the mineral variation displayed between the two vein types in the district.

The major contribution of the study was a reinterpretation of the relative timing of deformation and mineralization in the district. Based on the progressive sequence of deformation fabrics observed in the vein minerals, it is hypothesized that mineralization was definitely not post-deformation as originally contended. In fact, the penetrative shearing stress has undoubtedly facilitated contemporaneous emplacement of the vein minerals by both open space and replacement processes. The ore textures were produced in response to deformation of the vein minerals and not by the replacement of previously sheared host rock.

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CHAPTER I

INTRODUCTION

Statement of Purpose

The purpose of this study is to investigate two distinctive barite occurrences in the Del Rio district of upper East Tennessee. These barite deposits are differentiated primarily on the basis of contrasting textural features and mineralogic associations (see Table I for a complete comparison). An attempt is made to utilize textural evidence to determine the relative timing of deformation and mineralization. In this manner the influence of deformation on textural development and mineral assemblage paragenesis, if any, might become more apparent. The exact origin(s) of the mineralization in the district cannot readily be determined. However, by examining the trace element contents of the two barite types and associated mineral phases, it might be possible to suggest whether one or several distinctive mineralizing events have occurred in the Del Rio district.

Previous Work

Two publications, Geology and Barite Deposits of the Del Rio District (Ferguson and Jewell, 1951) and Barite Resources of Tennessee (Maher, 1970) are standard references concerning the Del Rio barite district. Ferguson and Jewell (1951) remains the most comprehensive discussion of the district. It contains detailed descriptions of the

TABLE I

CHARACTERISTICS OF THE TWO DEL RIO VEIN TYPES

Characteristics	Vein Type: Moccasin Gap	Vein Type: Williams
1. Barite purity	95-98% $BaSO_4$	60-90% $BaSO_4$
2. Ore textures	Coarsely-crystalline, white to glassy clear barite. Cleavage surfaces 5-10 cm (2-4 in.) in length are common and occasionally display coarse twinning.	Dense, platy, white to pinkish barite. Banded fine-grained barite and fluorite are also common.
3. Mineral assemblage paragenesis	Sericite ——— Pyrite ——— Ankerite ——— Quartz ——————— Barite ——————— Limonite Secondary Turgite (?) " Quartz " Manganese oxide " Dolomite " Calcite " Pyrite " Witherite (?) "	Sericite ——— Quartz ——— Specularite ——— Pyrite —— Chalcopyrite —— Sphalerite —— Barite ——————— Fluorite ——————— Limonite Secondary Malachite " Covellite " Manganese oxide " Calcite " Quartz " Witherite (?) "

TABLE I (Continued)

Characteristics	Vein Type	
	Moccasin Gap	Williams
4. Type of fault mineralized	Moccasin Gap bedding plane fault.	Brushy Mountain overthrust
5. Vein thickness	A maximum of 2 meters (7 feet) though usually considerably less.	1-4.5 meters (3-14 feet).
6. Host stratigraphic units	Moccasin Gap orthoquartzite	Snowbird metarkose overlying Sandsuck slate

*Within a given deposit both coarsely-crystalline and dense, platy barite textures may be represented (and often appear to be gradational) although one always greatly predominates over the other.

Source: After Ferguson and Jewell (1951).

stratigraphic and structural setting, mine locations, mining history and production, vein mineralogy, ore textures, possible origins and age of the barite mineralization, and estimates of the potential reserves. Maher (1970) includes an abbreviated description of the Del Rio district. In addition, substantial background information is supplied concerning the barite industry, including crude ore milling techniques, exploration methods, marketing procedures, physical and chemical properties governing barite usage, barite grade categories, importation data, etc. In addition, topics such as mineralogic associations, characteristics of "Mississippi Valley" type deposits, types of barite occurrences, and the geochemistry and origin of barite are more extensively discussed than in Ferguson and Jewell's earlier work.

Earlier references pertaining specifically to the Del Rio district are limited to details of mining activities compiled by the Bureau of Labor Statistics and Mines, Tennessee Mining Department, the Tennessee Division of Geology, or private mining companies. The U. S. Bureau of Mines conducted drilling programs at the Moccasin Gap and Krebs mines, details of which are disclosed in Dahners (1949). Core log descriptions are included in Ferguson and Jewell (1951). Several publications discuss other possibly related barite deposits such as those at Sweetwater, Tennessee (Laurence, 1960), Stackhouse-Hot Springs, North Carolina (Dahners, 1949; Stuckey, 1942), and Cartersville, Georgia (Kesler, 1950; Rife, 1971).

Barite Deposits in East Tennessee

Exploration for and development of barite deposits has been intermittent in East Tennessee since the late 1800's. Significant production has been largely confined to the Sweetwater district, which has accounted for nearly 85% of the estimated 1,750,000 tons produced in Tennessee between the years 1870 and 1970. In addition, numerous smaller scale operations have been conducted in the Del Rio and Fall Branch-Greeneville districts and in isolated workings such as the Lost Creek mine (Fig. 1). Commercial grade barite occurs as vein and breccia fillings (Del Rio district) although more commonly as concentrated residual deposits (Sweetwater, Fall Branch-Greeneville district, Lost Creek mine) derived from the weathering and removal of associated carbonate host formational rock. For the purposes of this study only the barite deposits of the Del Rio district will be considered in detail.

Location of the Del Rio District

The barite deposits of the Del Rio district are located in the southeast corner of Cocke County (Fig. 1) in an area roughly "19 miles northeast-southwest by 7 miles north-south at the widest place" (Ferguson and Jewell, 1951, abstract). The area is traversed by the French Broad River, U. S. Highway 70-25, State Highway 107, and the Southern Railway. The topography is generally of high relief with slopes commonly near 30°, while some ridge flanks may be even steeper. Elevations range from about 300 meters (1000 feet) in the valley of the French Broad to over 900 meters (3000 feet) on nearby mountain tops. The Paint Rock, Tennessee-North Carolina 7.5 minute quadrangle map

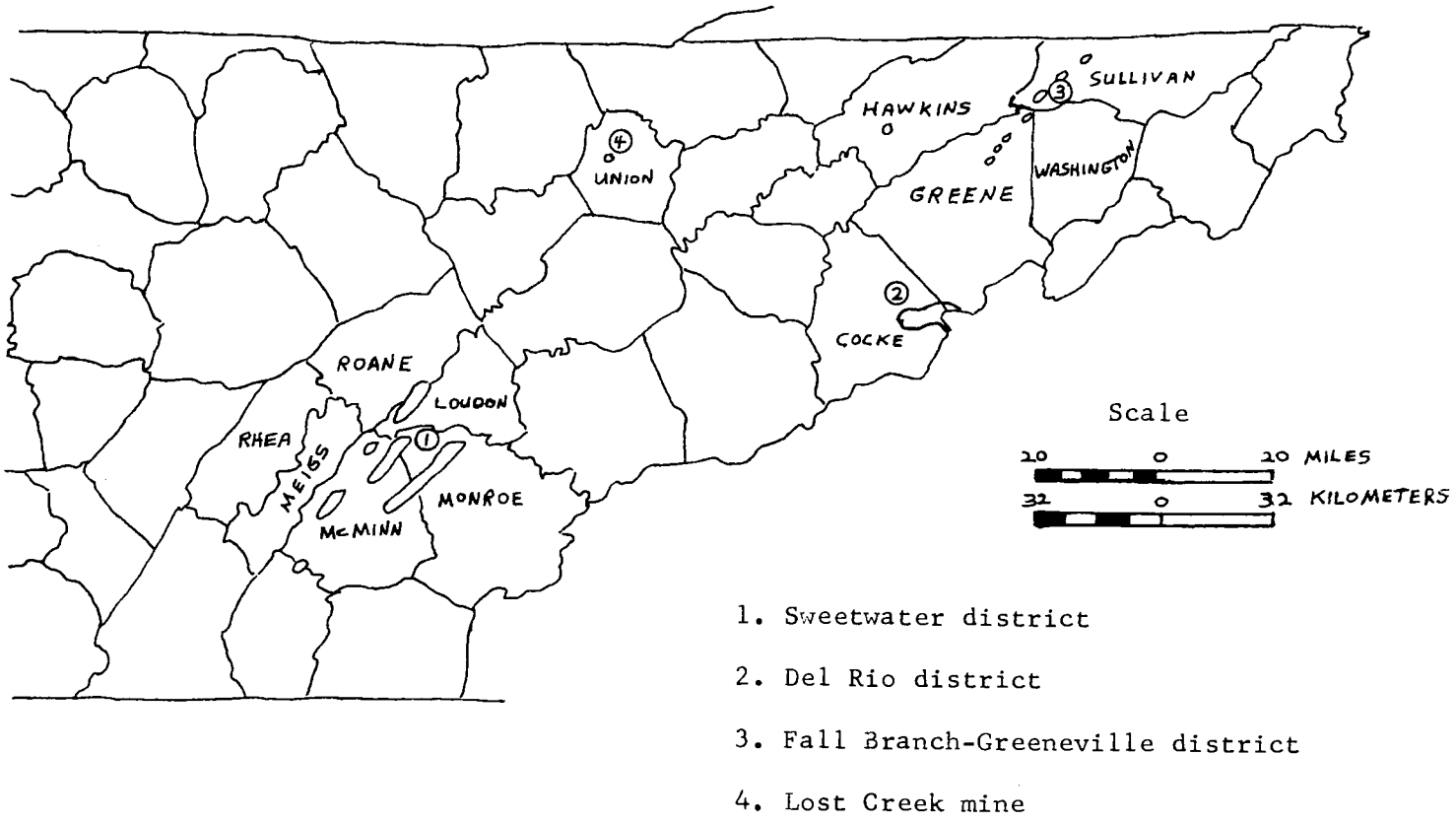


Figure 1. Location of commercial barite deposits in East Tennessee.

covers most of the district. The geology of the district was mapped in detail most recently by Ferguson and Jewell (1951).

Structural and Stratigraphic Setting

The Del Rio district is located within the westernmost portion of the Blue Ridge thrust belt. Compressive stresses directed from the southeast during the Alleghenian Orogeny resulted in the overriding of Ordovician carbonates and shales of the Valley and Ridge province by several thrust sheets composed of Precambrian and Cambrian clastic rocks (although there is some evidence indicating that the lowermost sheets may have been emplaced during Taconic time; personal communication, F. Keller, 1977). The clastic units containing commercial barite are described in Table II.

Ferguson and Jewell (1951) hypothesized a three-stage deformayional history for the district. Initially a bedding plane fault, the Moccasin Gap fault, developed at the base of the 15 meter (50 feet) thick Moccasin Gap Quartzite Member of the Unicoi Formation. As the compressive stress intensified, two overlapping thrust sheets composed of Precambrian to lower Cambrian clastic and carbonate sediments were emplaced within the district. The uppermost (Brushy Mountain) thrust sheet is limited to the extreme southeastern corner of the district. It involves only clastic units of Precambrian age (Snowbird and Sandsuck Formations). The overridden Del Rio sheet, which was transported along the Meadow Creek Mountain overthrust, underlies most of the district. This sheet has been broken into eight distinctive fault blocks, causing the Moccasin Gap fault to be offset and repeated in

TABLE II

DESCRIPTION OF STRATIGRAPHIC UNITS ASSOCIATED WITH THE BARITE MINERALIZATION

Age	Formation	Member	Description
Cambrian	Unicoi	Upper quartzite member	White coarse-grained quartzite and conglomeratic quartz grit (carbonate present in the cement).
		Upper shale member	Dark-green slightly silty argillaceous shale with a basal unit of feldspathic grit and conglomerate (carbonate cement).
		Moccasin Gap quartzite	White coarse-grained quartzite.
			White to dark-greenish gray grit, quartzite, and conglomerate (carbonate cement present) interbedded with dark-green shale.
Precambrian	Sandsuck		Dark-green silty to argillaceous shale which commonly displays slaty cleavage. The lower portion of the formation contains interbedded dolomite or dolomitic sandstone beds.
Precambrian	Snowbird		A coarse-grained, greenish-gray to light-brown, pyritic arkose. The angular to well-rounded quartz and feldspar grains are usually poorly-sorted. Dolomite cement may be present. Bedding is generally very massive and indistinct. Intervals of gray to black shale and slate containing coarse dolomitic sandstone or conglomerate may be present in lower sections.

Source: After Ferguson and Jewell (1951), Table I, p. 11.

many areas of the district. The boundary faults include one normal fault and numerous high angle thrusts which appear to splay upward from the low angle Meadow Creek Mountain thrust. The spatial arrangement of the major overthrusts and of the fault blocks, related fold axes, boundary faults, and Moccasin Gap bedding plane fault within the Del Rio sheet are shown in Figure 2. Cross sections across the thrust sheets are illustrated in Figure 3. More complete details describing the stratigraphic units involved and the relationship of major faults to folds and minor faults in each individual block of the Del Rio sheet are given by Ferguson and Jewell (1951). The last phase of deformation resulted in a broad, gentle folding of the imbricate fault pattern. Evidence of this event is provided by three klippen of the Brushy Mountain sheet, the presence of the Hot Springs window, and a reversal in dip of the Meadow Creek Mountain thrust fault creating a synformal structure (the Meadow Creek Mountain thrust fault is referred to as the Mine Ridge thrust fault in the eastern portion of the district by Ferguson and Jewell, 1951). Bearce (1969) is of the opinion that the imbricate fault pattern developed during the broad folding of the thrust sheet after emplacement.

Regional metamorphism within the district appears to be of a very low grade. The lack of thermally-induced recrystallization textures indicates that deformation was not accompanied by widespread, elevated temperatures. In thin section the detrital grain textures of the clastic host rocks are essentially retained, although the quartz grains sometimes appear to be locally modified by plastic flowage, pressure solution, and possible minor recrystallization. As would be expected,

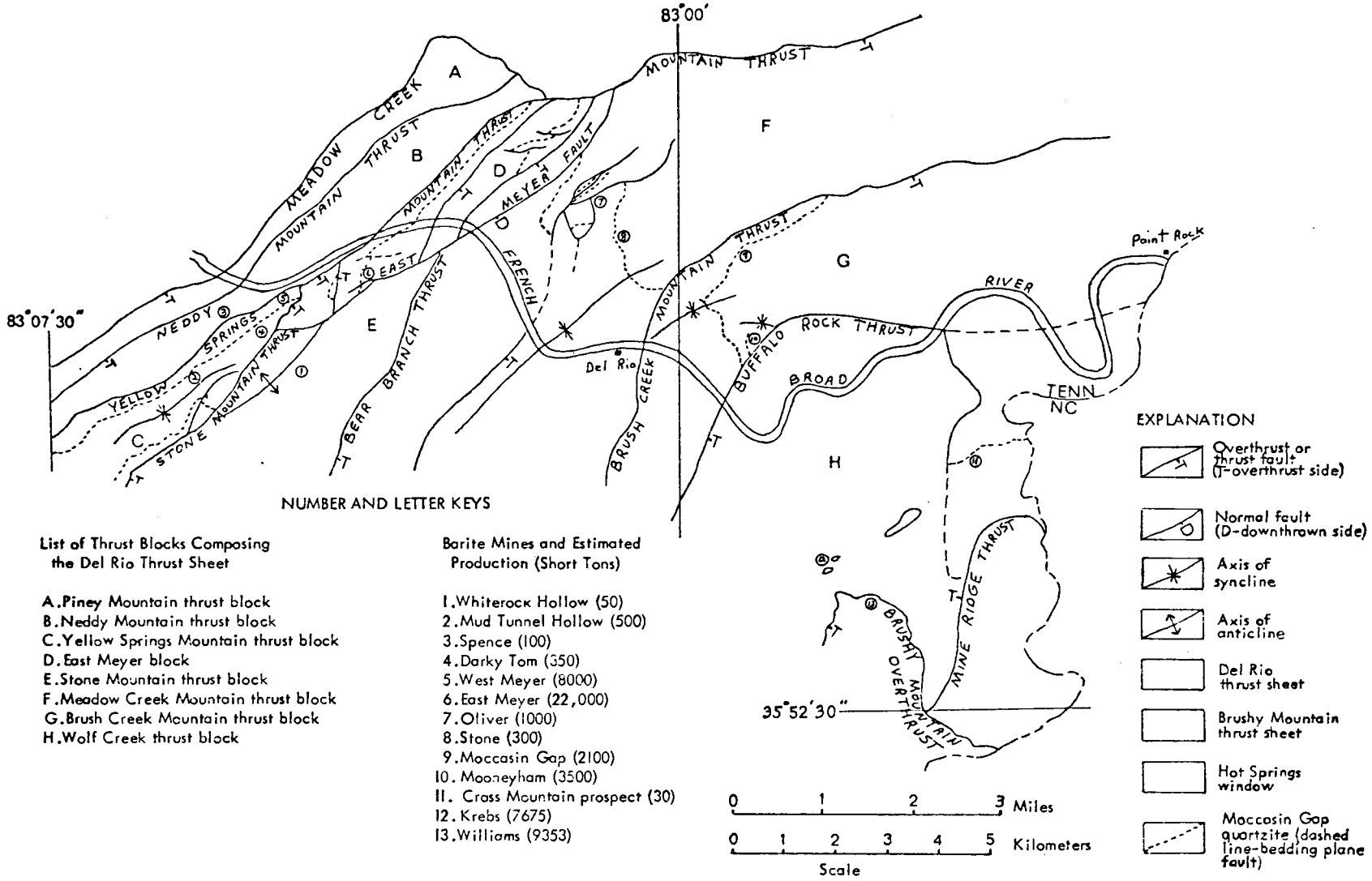


Figure 2. Sketch Map of the Del Rio District after Ferguson and Jewell (1951, Figure 2 and Plate 1).

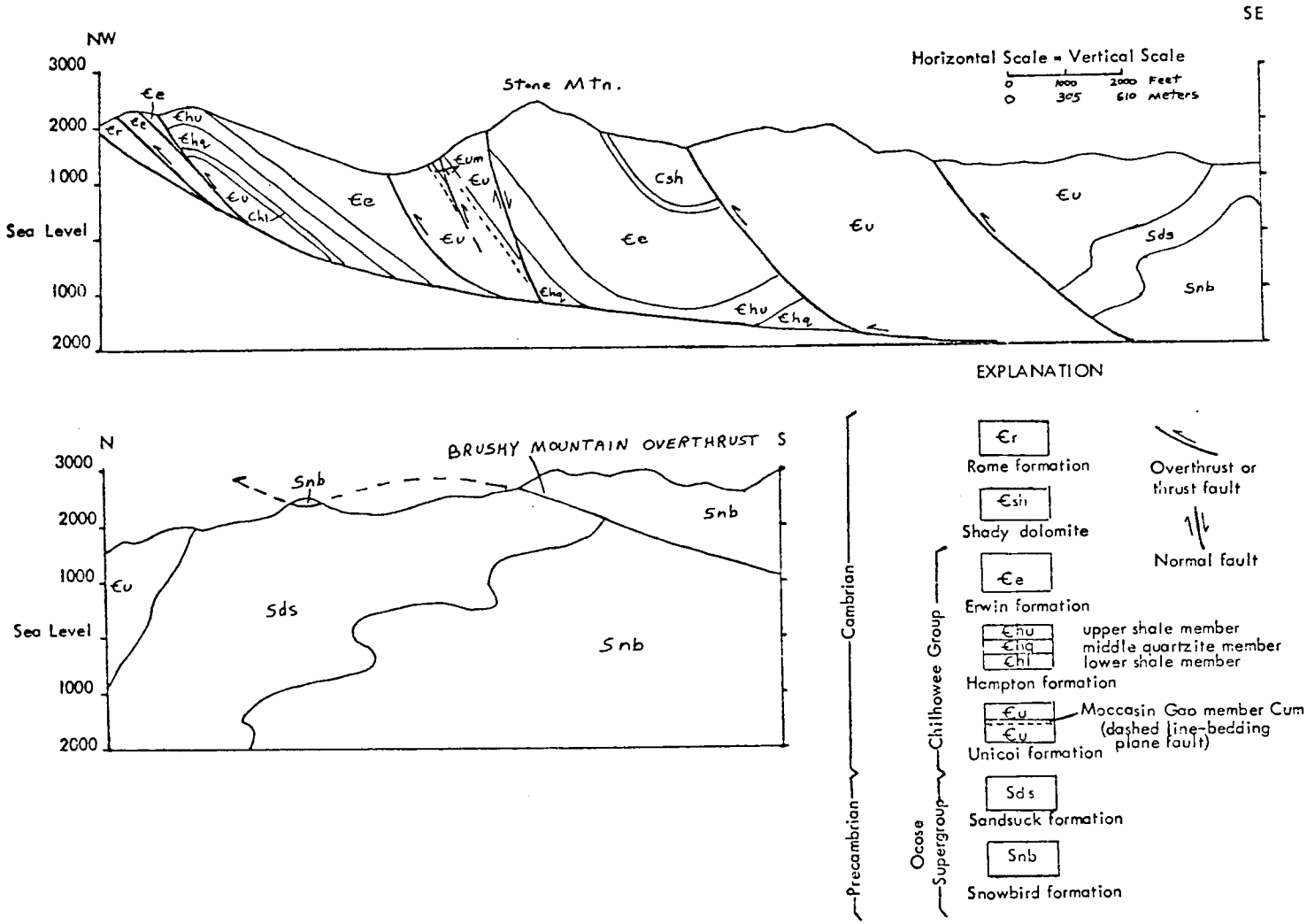


Figure 3. Cross-Sections Across the Del Rio Sheet (A) and the Brushy Mountain Overthrust (B) after Ferguson and Jewell (1951, Plate 1).

no reconstituted metamorphic phases were observed in the nonpelitic rocks associated with the hanging wall of the barite-bearing fault zones. The influence of localized dynamic metamorphism is well represented. Mylonitic textures and tectonic breccias are found associated with the fault zones while slaty cleavage is present in the slaty shales of the footwall.

Classification of Productive Veins

Barite mineralization in the district was strongly controlled by structural features. Barite is found localized along most of the major and even many minor faults in the district. However, commercial barite deposits are restricted to the fault zones of the Brushy Mountain overthrust and the Moccasin Gap fault (Fig. 2, p.10). These deposits are unique because they represent the only known occurrences in Tennessee of ore grade mineralization (of any type) localized along overthrusts (Maher, 1970). Along the fault structures, barite has extensively penetrated minor tear faults, fracture zones, breccia bodies, and joint systems within the hanging wall. The footwall is much less mineralized, although shear and cleavage surfaces may contain barite. The productive veins dip from 25° southeast to nearly vertical and average about 50° southeast. Ferguson and Jewell (1951) categorized the productive veins into two types--the Williams-type and the Moccasin-Gap type (both named after mines displaying the distinctive characteristics of each). Their two-fold classification is summarized in Table I (p. 2).

Production and Potential Reserves

Since 1880, 11 mines (each producing over 100 tons) and six prospects have accounted for production of over 55,000 tons of barite concentrate in the Del Rio district (Maher, 1970). Extensive underground workings--drifts, stopes, adits, crosscut tunnels, inclines, shafts, raises, and winzes have been utilized to intersect and follow the often steeply-dipping barite-bearing veins. The entrances to many of these workings have collapsed due to the weathered nature of the penetrated vein and/or host quartzite. Open pit (Krebs mine) and trenching techniques have also exploited near-surface deposits. The district has been inactive since the late 1950's, although known barite reserves are conservatively estimated to be around 200,000 tons. Escalation of offshore exploration activity along the eastern coast could possibly encourage renewed interest in the district as a nearby source of weighted drilling muds. The substantial reduction in shipping costs (over western or foreign sources) might provide the financial incentive necessary for exploration and development work.

The main reserves of the district are found in the lower grade Williams-type vein. At the Williams mine dense, platy barite (80-90% $BaSO_4$) appears to be concentrated in an elongate lens-shaped mass which has been projected by Jewell (in Ferguson and Jewell, 1951) to extend some 190 meters (625 feet) northeastward paralleling the trace of the Brushy Mountain overthrust. If this is true the reserves of the Williams mine alone would be substantial. Major contaminants of the barite ore are fluorite, vein quartz, and remnant fragments of unreplaced quartzite.

The most economical exploitation of the Moccasin Gap-type barite has been from weathered, near-surface portions of the vein. Here the barite has been concentrated by the weathering of the associated ankerite to a reddish, limonitic, sandy clay with subsequent slumping. These residual deposits contain much more barite than the downdip unaltered portions of the vein which contain considerable ankerite with only sporadic barite shows (as indicated by the core logs of the U. S. G. S. drilling program at the Moccasin Gap mine). Hence, future operations would be limited to the residual deposits unless, as at the East Meyer mines, the unaltered barite veins are proven thick and continuous enough with increasing depth to warrant hardrock mining.

CHAPTER II

INVESTIGATIVE TECHNIQUES

Textural Analysis

The textural nature of the Del Rio vein mineralization was examined by the following two methods:

1. A petrographic microscope was utilized to observe deformation textures and mineral assemblage paragenesis.

2. A luminoscope was used to check the barite and fluorite for possible cathodoluminescence. Since barite from other localities is known to fluoresce, it was hoped that distinctive zoning patterns (imperceptible under transmitted light) might be revealed in the Del Rio barite upon exposure to cathode rays. Such textural patterns, indicating variation in trace element activator content, might contribute information regarding fluctuations in the chemical composition of the ore fluids (unique generations) or the nature of crystal growth in barite. Unfortunately, no such zoning was observed in the barite. Either insufficient activator was present, or the activator was in the wrong oxidation state to generate visible fluorescence. Heating experiments were conducted in an attempt to convert any included activator into a more excitable state. However, these treatments were unsuccessful in producing any discernible patterns. Fluorite luminesced in contrasting colors of yellow and bluish-purple, but intensive deformation may have obliterated any possible zoning.

Chemical Analysis

Semi-quantitative analyses of Del Rio barite were previously run by Brobst (1958) and the Tennessee Division of Geology (Table III). The trace element suites appear to be similar in both barite types. However, the strontium (the major element which can substitute for barium in the barite lattice) contents of both barite types were examined by X-ray fluorescence in hopes of providing more conclusive evidence concerning their genetic affinity and the possibility of unique generations of barite mineralization in a given vein.

It was thought that strontium might be a potentially good indicator of original contrasts in the chemical composition of the ore fluids (reflecting changes in precipitation temperatures or source fluids) due to the physical chemistry of the (Ba, Sr)SO_4 solid solution. According to Hanor (1968, 1973), (Ba, Sr)SO_4 behaves as an inert, unreactive precipitate in terms of Ba-Sr exchange, and as a result, the solid-state diffusion coefficients of cations in the barite lattice are very low. Therefore, "a given solid composition will tend to reflect conditions prevailing at the time of precipitation of that particular increment of solid rather than a composition significantly modified by later solid state diffusion and exchange" (Hanor, 1973, p. 2686). Re-equilibration promoted by later deformation/metamorphism-induced diffusion or exchange processes would thus be inhibited. Considerable variation in strontium contents would not be unexpected since equilibrium is maintained only between the liquid and the last formed increment of precipitate.

TABLE III

MINOR ELEMENTS IN DEL RIO BARITE

Location (mine)	Elements Analyzed For (%)[1]																	
	Ag	Al	Ca	Sr	Co	Cr	Cu	Fe	Hg[3]	K	Mg	Mo	Ni	Pb	Si	Ti	V	Zr
Moccassin Gap																		
(Brobst)	--[2]	.004	.006	.4	--	--	.0001	--	--	--	--	--	--	--	.04	--	--	--
(T.D.G.)	.005	.01	.015	--	.005	.002	.005	.02	.022	.04	.01	.002	.01	.01	.015	.005	.002	.002
Williams																		
(Brobst)	--	.02	.8	.6	--	--	.001	.001	--	--	--	--	--	--	.5	--	--	--
(T.D.G.)	.005	.015	5.0	--	.005	.002	.03	.02	.015	.04	.01	.002	.01	.01	.22	.005	.002	.002

1. Analyzed spectrographically (x-ray fluorescence).

2. Not analyzed for.

3. Wet microchemical determination.

Source: After Moher (1970), Table 2, p. 10 and Brobst (1958), Table 9, p. 80-81.

Chemical analysis of the fluorite might also prove useful in determining its genetic relationship to the barite mineralization; however, the fluorite is too intimately associated with the barite in the Williams mine. An attempt was made to separate a relatively pure sample of fluorite for analysis. Three methods were tried to accomplish this objective:

1. A combined X-ray diffraction-X-ray fluorescence method - This indirect approach proposed to compare the trace or minor element contents of a series of samples (as determined by X-ray fluorescence) as the proportion of fluorite in the sample varied (as determined by X-ray diffraction). The attempt to utilize this method was unsuccessful and a written account of the procedures and results is kept on file with Dr. O. C. Kopp of the Department of Geological Sciences, University of Tennessee, Knoxville.

2. Froth flotation technology - This method was only marginally considered and provided no satisfactory sample for analysis.

3. Heavy liquid separation technique - The specific gravity difference between the barite and fluorite was considered potentially useful in affecting a separation. However, the heavy liquid method was not successful for fine-grained samples as discussed in Appendix A. A separation was finally achieved by a combination of heavy liquid separation of coarse-grained barite and fluorite, staining of the barite (Appendix B), and optical separation of fluorite grains as described in Appendix A.

Difficulties in obtaining a reliable data base affected the application of trace element studies to the problem of the source of

the barite and fluorite in the district. At best, the chemical analyses presented in this study represent a preliminary attempt to determine the degree of variation of strontium contents in the Del Rio barite deposits. Details concerning the analytical method utilized, difficulties encountered, and the limited results are given in Appendix C.

CHAPTER III

MEGASCOPIC AND MICROSCOPIC ANALYSIS OF MICROSTRUCTURES AND CATACLASTIC ORE TEXTURES

Introduction

Thin and polished sections from mines of both vein types within the district were examined by Jewell (in Ferguson and Jewell, 1951). He presents numerous photomicrographs (pp. 60-84) illustrating the textural relationships of the vein minerals (paragenesis) and the nature of the boundary between the host rock and later vein mineralization. His observations can be summarized in the following related statements for further discussion and introduction of new textural evidence:

1. Mineralization definitely postdates the thrusting event(s). The fault zones served as access routes for the ore solutions.

2. The ore textures are inherited (relict textures) from the sheared, brecciated and often intensely granulated quartzite by replacement processes.

3. The high grade ore (both in terms of barite purity and reserves) in the Williams-type vein, and to a lesser extent the Moccasin Gap type, has been emplaced by replacement of mylonitic quartzite or gouge directly within the fault zone rather than open space infilling of associated breccia zones.

4. The localized intensity of deformation controls the textural type of the barite ore.

5. Stratigraphic, as well as structural, controls may have been important in localizing the ore (especially in the Moccasin Gap type vein).

6. In the Williams vein, barite and fluorite appear to be contemporaneous, although fluorite mineralization continued after the barite was deposited.

The Present Study

In the present study emphasis is placed not only on the relationship between vein mineral phases (most importantly the barite and fluorite) but also on the textural features displayed by individual crystals or monomineralic aggregates (barite is the principal mineral investigated using the petrographic microscope, as the ankerite is too badly weathered to be thin-sectioned and the fluorite is optically isotropic). As a result, it was determined that the barite mineralization of the Del Rio district displays definite deformational fabrics. These fabrics, summarized in Table IV, can be categorized into two types:

1. Plastic deformation, recovery, and brittle deformation microstructures which are best illustrated in the coarsely-crystalline Moccasin Gap type barite.

2. Cataclastic ore textures representative of the intensely sheared barite-fluorite mineralization of the Williams-type vein. Since the two vein types are texturally very distinguishable, a separate discussion of deformation fabrics is devoted to each even though some similar features are found in both.

TABLE IV

SUMMARY OF MICROSTRUCTURES AND ORE TEXTURES OBSERVED IN THE BARITE VEIN MINERALIZATION, DEL RIO DISTRICT

	FEATURE	DEFINITION	REFERENCE
1.	Slip Lines	Straight or curvilinear features, with negligible thickness, which denote the existence of a series of parallel slip planes oriented transverse to the observed surface.	Olivine, kyanite* Raleigh (1965)
2.	Undulose Extinction	Regions of extinction which sweep across a strained crystal upon rotation of the microscope stage. The extinction pattern may range from broad zones to narrow bands.	Quartz Carter et al. (1964)
3.	Deformation Bands	Narrow, subplanar structures which possess crystallographic orientations different from the adjacent host crystal. The bands are produced by a bending of the crystal lattice and lack a precise symmetrical relation with the host.	Quartz Carter et al. (1964) Spry (1969)
4.	Kink Band	A sharply defined layer within a crystal differing from adjacent regions by a low to moderate angle. Kink bands are produced when external rotation accompanies intracrystalline slippage resulting in structural shortening approximately parallel to the slip surface.	Mica, pyroxene Spry (1969)
5.	Deformation Twins	Narrow, wedge-shaped structures similar to deformation bands but originating from glide displacements of precisely defined geometry and magnitude.	Pyrrhotite Clark and Kelly (1969) Calcite Spry (1969)

TABLE IV (Continued)

	FEATURE	DEFINITION	REFERENCE
6.	Polygonized Structure	A texture formed by the dynamic recovery of a strained crystal lattice, in which portions of the crystal are sufficiently misorientated from each other to appear as clusters of individual subgrains.	Quartz White (1973)
7.	Cleavage Lines	Coherent cleavage breakage of the barite crystal structure occurs parallel to {001} and {110}. Subsequent granulation along these planes produces parallel cleavage plates separated by fine-grained partitions.	Kerr (1959)
8.	Mortar Texture	A texture characterized by a fine-grained matrix, produced by granulation and/or recrystallization, which surrounds surviving porphyroclasts and infills sheared zones between unground fragments.	Higgins (1971)
9.	Fluxion Structure	A cataclastically-produced texture in which well-defined shear surfaces reflect the directed penetrative nature of the deformation (cataclastic foliation).	Higgins (1971)
10.	Compositional Banding	The segregation of contrasting mineral phases into discrete, alternating layers observable on either a microscopic or megascopic scale (in the Williams vein barite and fluorite are the predominant phases involved in the segregation).	Higgins (1971)
11.	Protomylonite	A coherent, cataclastic rock in which megascopic generally lenticular fragments (megaporphyroclasts), composing greater than 50% of the rock, are enveloped by shear surfaces filled with finely granulated and/or recrystallized material.	Higgins (1971)
12.	Ultramylonite	An extremely fine-grained, coherent cataclastic rock, in which the remaining porphyroclasts are generally smaller than 0.2 mm in diameter and compose less than 10% of the rock. Mechanical granulation is the predominant process responsible for grain size reduction, although some recrystallization also occurs.	Higgins (1971)

*The same feature has been observed in the mineral(s) listed as discussed in the references cited.

Microstructures in the Moccasin Gap Barite

The microstructures observed in the Moccasin Gap barite are examples of stress-activated adjustments by a crystal lattice in response to imposed directed stress. These features (see Table IV, 1-7, p. 22, 23 for definitions) can be classified according to the mechanism(s) responsible for their formation. Slip lines, undulose extinction, deformation bands, and deformation twins are produced by plastic deformation mechanisms. Polygonized subgrain formation is a result of dynamic recrystallization (recovery) processes. Cleavage plates and granulation partitions are created by brittle destruction of the crystal lattice.

All of the features displayed in the Moccasin Gap barite have been described in the literature as occurring in various other deformed minerals (Table IV, p. 22). Although none are unique, several of the micro-structures are particularly well developed in the barite. Difficulties in identifying some of the textures may be due to the simultaneous operation of distinctive mechanisms along contrasting crystallographic directions. Thus, a random thin-section cut might reveal a pattern of intergrown structures. The present study has concentrated mainly on the description of prominent features and has not attempted to present an elaborate discussion on possible combinations of features.

Plastic Deformation Features

Intracrystalline slip (translation or gliding) is the principal mechanism involved in the plastic deformation of a crystal lattice.

Slip results when one plane of atoms is displaced across an adjacent plane of atoms without loss of cohesion. Displacement, generally occurring along numerous parallel planes, does not require any change in the internal structure but does result in a change in the external shape of the crystal (Spry, 1969). Translational gliding has occurred in the Moccasin Gap barite as indicated by parallel arrays of slip lines (Fig. 4). Movement has probably taken place along $\{001\}$ in the $[100]$ direction and $\{011\}$ in the $[011]$ direction, both of which have been found to possess good glide potential by Grigorev (1965).

Most of the Moccasin Gap barite crystals have undergone plastic bending, a process attributed to differential layer slippage (bend gliding) or the formation of edge dislocations of the same sign along a glide plane (Spry, 1969). The reorientation of the crystal lattice (accompanied by variation in optical properties across the crystal) caused by permanent bending produced abundant undulose extinction and deformation bands. Carter et al. (1964) distinguish between the two features in quartz on the basis of the radius of lattice curvature. Undulose extinction results if the bending occurred with a radius of curvature equal to or greater than the width of the reoriented zone. As the radius of curvature approaches the half width of the reoriented zone, distinct extinction bands form. When the radius is smaller than the half width, the features are called deformation bands.

The deformation bands are the most unusual of the Moccasin Gap microstructures. Although the physical appearance of the deformation bands varies, several general observations can be made to describe a single, well-developed band (five prominent bands are illustrated in



Scale: 1 mm

(cross-nicols)

Figure 4. Closely-spaced, slightly curved, slip lines in coarsely-crystalline barite, Moccasin Gap mine. The crystal is riddled with fractures (filled with granulated barite) which offset the slip lines indicating a later brecciation stage of deformation.

Fig. 5). In plane polarized light the trace of the band is vaguely outlined. Between crossed nicols the following were observed:

1. The bands are ribbonlike, usually with tapered ends which gradually die out into the host crystal (Fig. 6).

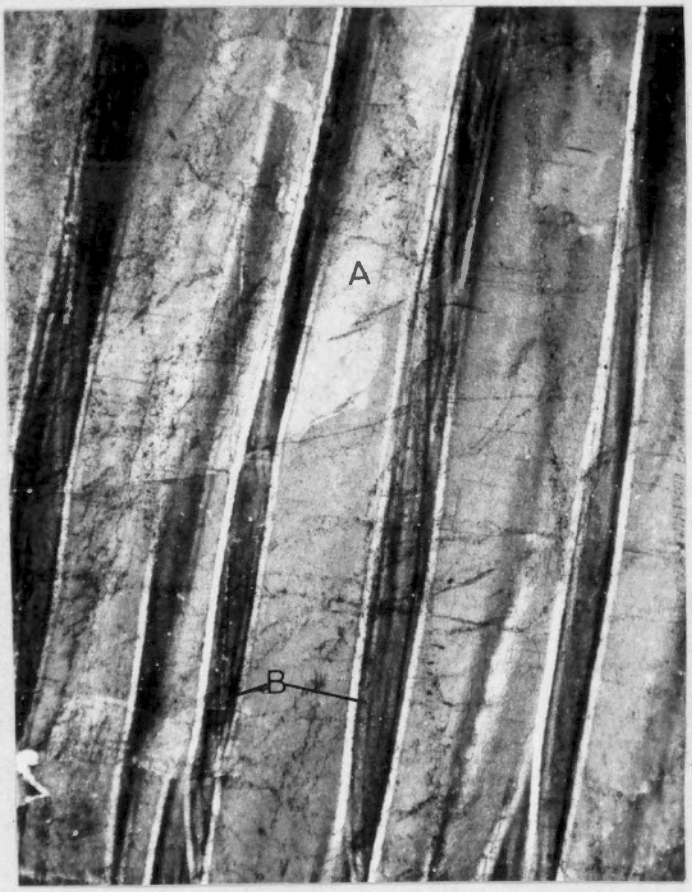
2. The boundary between the band and the host crystal in generally very sharp.

3. The band consists of two distinct zones--an interior zone and a border zone (in contact with the host crystal) on either side of the interior zone. The interior zone displays the same birefringence as, or slightly higher than, the host crystal; whereas, the border zone is of a lower birefringence. The border zone never completely becomes extinct but is composed of two distinctively birefringent bands which upon rotation alternately become extinct. The position of maximum illumination for the interior zone marks an extinction position for the host crystal and vice versa. In an extinction position, the interior region of the band commonly exhibits finer scale illuminated bands oriented parallel or sub-parallel to the outline of the major band (see Fig. 5). Bundles of these finer scale bands may also display a spiral extinction pattern. Toward the ends, the major bands sometimes bifurcate into several smaller bands.

4. The width of the bands is variable. An individual band usually maintains a fairly constant width along its length (before it tapers off toward the end) although it may swell or constrict slightly in localized areas.

5. Numerous inclusions are often aligned along the bands.

6. The bands may be either continuous or discontinuous in relation to crystal boundaries (Fig. 7).



Scale: 1 mm

(cross-nicols)

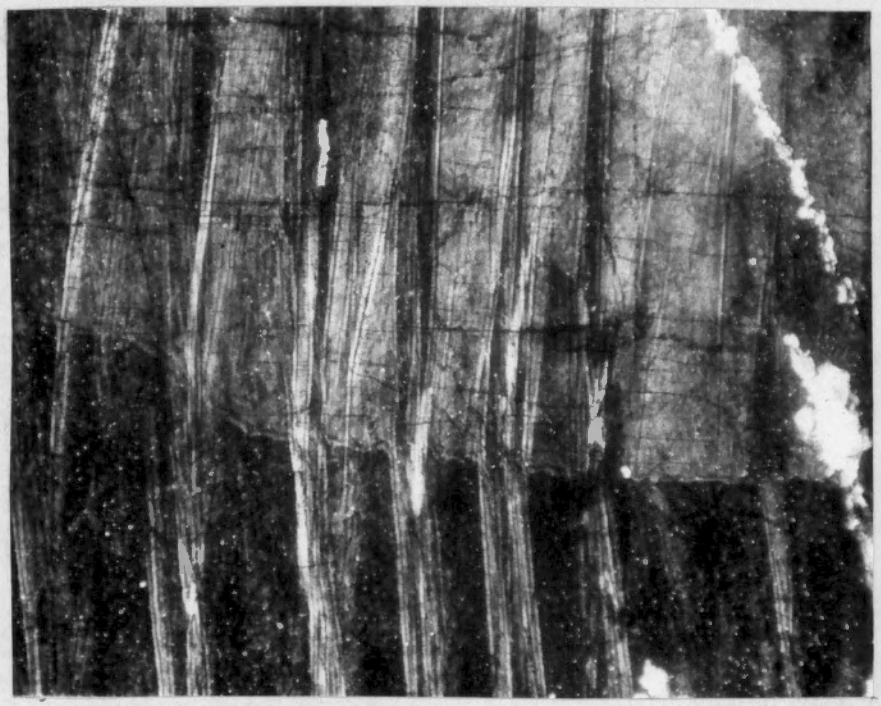
Figure 5. Prominent deformation bands showing internal structure in coarsely-crystalline barite, Moccasin Gap mine. Point A locates a section of host crystal between two deformation bands (as indicated by B).



Scale: 1 mm

(cross-nicols)

Figure 6. Tapering ends of deformation bands in coarsely crystalline barite, Moccasin Gap mine. These occur in the lower portion of the photo near C.



Scale: 1 mm

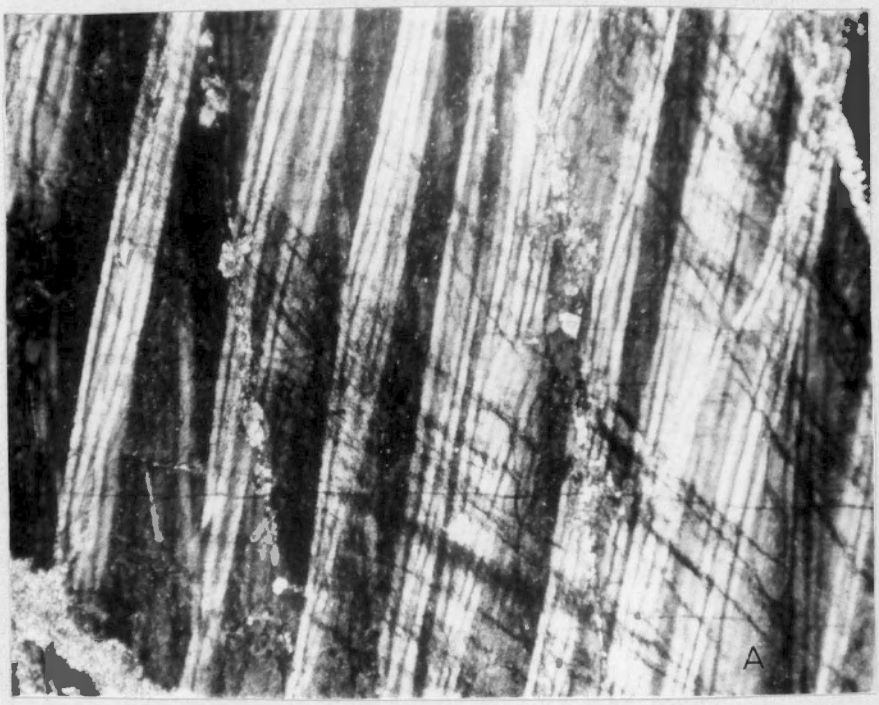
(cross-nicols)

Figure 7. Deformation bands in coarsely-crystalline barite, Moccasin Gap mine. The bands are jointed across what appears to be a somewhat distorted crystal boundary. Note the speckled appearance of the crystals which is caused by inclusions of unreplaced metarkose.

Complex textures are often created by the intersection, overlapping, or crowding together of the deformation bands into dense, cross-hatched patterns (Fig. 8). Some deformation bands intersect to form boxwork (grill) patterns (Fig. 9). In Figure 10, an earlier band set has been kinked by the overprinting of a later set. Some of the deformation bands may actually be better defined as kink bands, although it is difficult to determine the sense of external rotation of the glide surface.

Twin lamellae (Fig. 11) were also observed in the Moccasin Gap barite. They resemble deformation bands but possess several distinguishing characteristics. The twin lamellae pattern is composed of two parallel twin sets which alternately become illuminated and extinct upon rotation of the stage. Each twin set shows very sharp, simultaneous extinction. This is in contrast to the variable extinction positions of adjacent deformation bands and the generally undulose extinction displayed by an individual band. The ends of the twins are also more blunt than the tapered ends of the deformation bands.

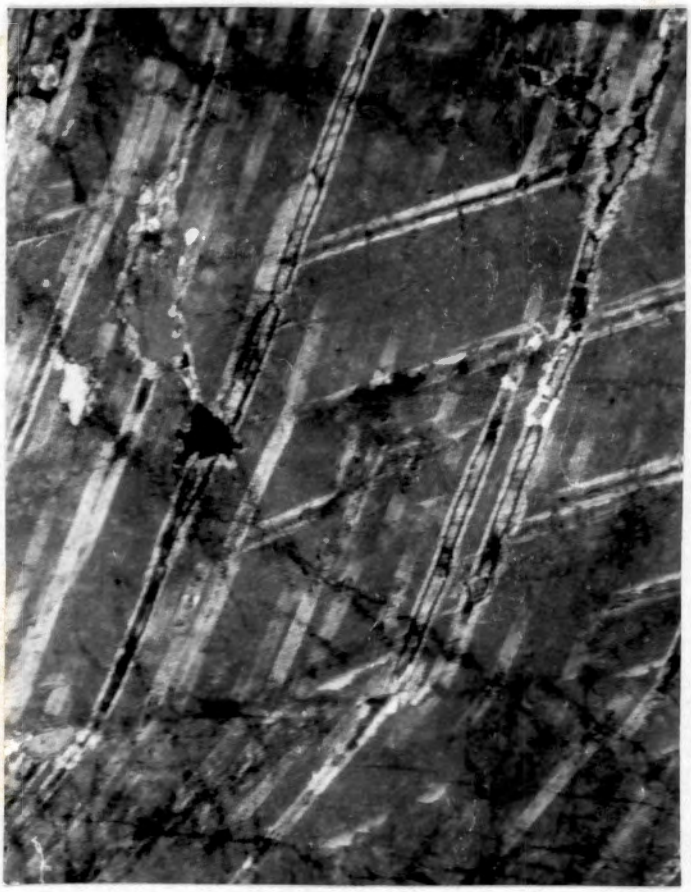
The exact origin of the twin lamellae is uncertain. They may be either primary growth twins or secondary deformation twins. Grigorev (1965) has determined that a twin glide plane corresponding to {110} does exist in barite. Therefore, formation of these twin lamellae may be due to mechanical twinning accomplished by simple shear displacements along this twin glide plane or possibly more complex reconstructive movements (Spry, 1969). Deformation twins may also have formed within previously twinned (by growth) portions of the strained crystal.



Scale: 1 mm

(cross-nicols)

Figure 8. Dense array of deformation bands in coarsely-crystalline barite, Moccasin Gap mine. A prominent NE-SW-trending set of bands overshadows a less conspicuous N-S-trending set (best illustrated near A).



Scale: 1 mm

(cross-nicols)

Figure 9. Intersecting sets of deformation bands in coarsely-crystalline barite, Moccasin Gap mine.



Scale: 1 mm

(cross-nicols)

Figure 10. Prominent NW-SE-trending deformation bands appear to kink an earlier set of bands (trending NE-SW) in coarsely-crystalline barite, Moccasin Gap mine. Anastomosing fractures filled with fine-grained, granulated (?) barite may indicate the crystalline mass has undergone a later brecciation phase.



Scale: 1 mm

(cross-nicols)

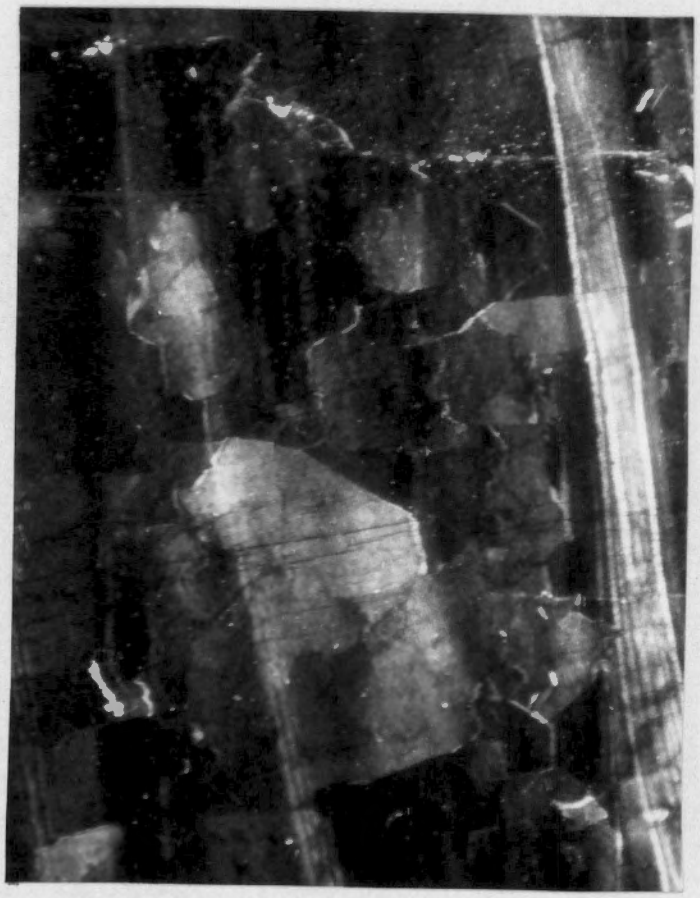
Figure 11. Twinning in coarsely-crystalline barite, Moccasin Gap mine.

Polygonized Subgrain Texture

Polygonization (dynamic recovery) is often intimately associated with deformation bands (Fig. 12). It is a process by which randomly distributed dislocations of the same sign in a strained crystal lattice migrate together to form planar arrays. The result is the formation of unstrained (uniform extinction) subgrains separated by walls of stable dislocation arrays (Spry, 1969, p. 65). Within polygonization zones the deformation bands may be obscured or entirely obliterated depending on the stage of recovery reached. The newly-formed subgrains display unique extinction positions (distinctive orientations) and are often delineated by narrow zones of contrasting birefringence. The grain boundaries are usually somewhat serrated illustrating the important role of stress-induced grain boundary migration. However, very few of the subgrains possess uniform extinction. Most display undulose extinction and some may even exhibit extinction bands. This indicates that migration of dislocations toward the edges of the subgrain is incomplete. Thus the subgrains have not attained a strain-free condition. Polygonization is considered a thermally-activated process and the formation of subgrains has undoubtedly been inhibited by the low temperatures accompanying the directed stress.

Brittle Deformation Features

Barite possesses three good directions of cleavage. Thus cleavage lines are conspicuous features in the barite on both a microscopic and megascopic scale. They are often curved indicating the crystal structure has been bent. Granulation appears to have occurred along many of the more extensive cleavage breaks producing elongate, commonly curved,



Scale: 1 mm

(cross-nicols)

Figure 12. Polygonization of the barite with associated deformation bands, Moccasin Gap mine. Many of the bands appear to fade as subgrain formation becomes more pronounced.

plates separated by intervening fine-grained granulation zones (Fig. 13). These cleavage plates display similar optics and appear to be kinked.

More extensive examples of brittle deformation appear in the form of brecciation texture. Many of the previously described features are offset by later anastomosing fractures (see Fig. 4, p. 26 and Fig. 10 p. 34) which are sometimes filled with euhedral quartz crystals but generally contain fine-grained, granulated (?) barite. It is not known whether these brecciation features, associated with variably oriented deformation bands, formed in response to more than one unique deformational event or reflect the simultaneous operation of several mechanisms during a single deformation.

Cataclastic Ore Textures of the Williams Vein

The textures observed within the Williams vein are representative of dynamically metamorphosed or cataclastic rocks. They have been deformed under conditions of comparatively low temperatures and often intense directed stress. Several classifications of cataclastic rocks have been proposed, the most recent of which are by Spry (1969), Higgins (1971), and Zeck (1974). These classifications are based to varying degrees on the following textural criteria: presence or absence of primary cohesion, dominance and relative timing of ruptural deformation (cataclasis) recrystallization reached, presence or absence of fluxion (foliated) structure, abundance of porphyroclasts, and predominant size of the porphyroclasts. Descriptions of ore textures in this paper will conform to the nomenclature of Higgins (1971, Table I) given in Table V. As can be seen from Table V, microscopic as well as megascopic



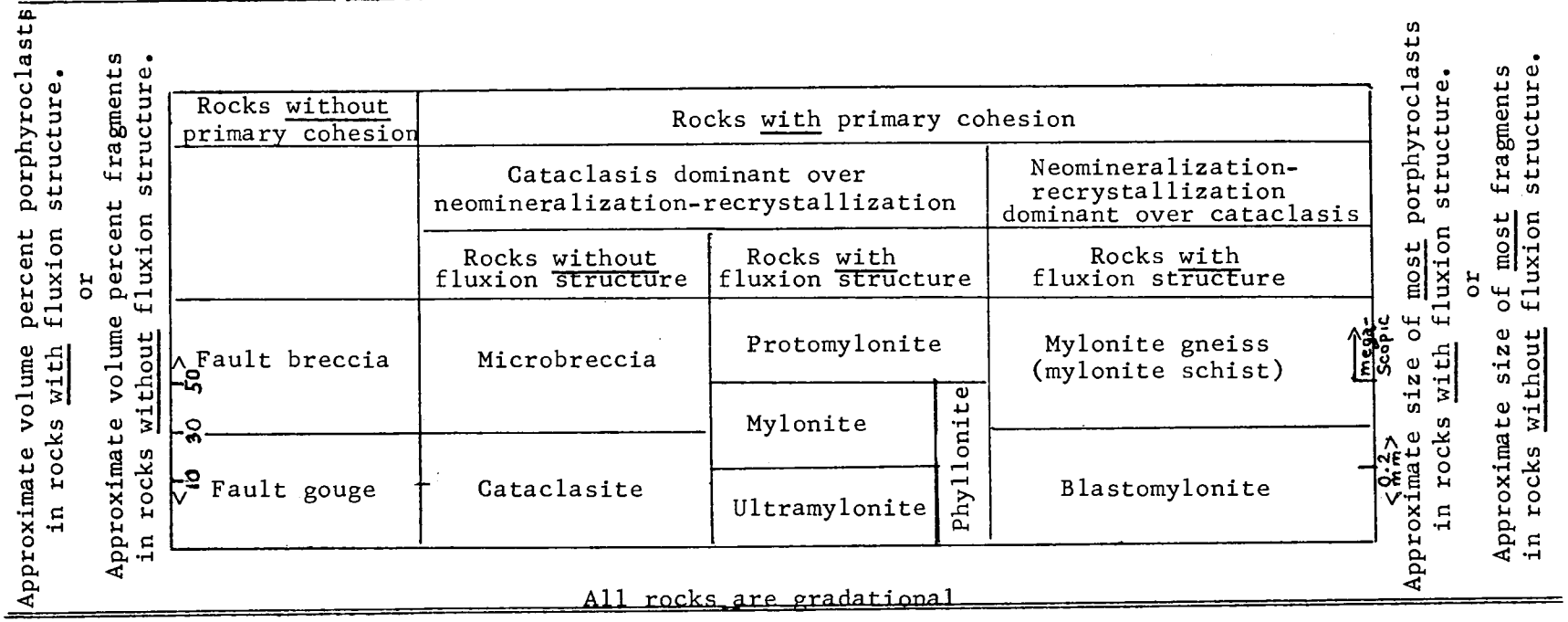
Scale: 1 mm

(cross-nicols)

Figure 13. Cleavage plates of coarsely-crystalline barite separated by fine-grained barite granulation partitions, Moccasin Gap mine. The plates are somewhat curved.

TABLE V

CLASSIFICATION OF CATACLASTIC ROCKS



Source: After Higgins (1971), Table I.

observations are generally necessary to specifically classify a cataclastic rock.

The Williams mine is characterized by extensively sheared and mylonitized barite (and fluorite) which is significantly more deformed than most of the Moccasin Gap ore as seen in Fig. 14. The vein displays three distinct textural zones whose location in the vein is illustrated in Fig. 15. These include: breccia bodies (with sericite, quartz, fluorite, and barite filling between the misoriented quartzite clasts) which delineate the boundary between the upper portion of the vein and the hanging wall; an updip, intensely-sheared vein zone in which barite and fluorite form an intimately banded ultramylonite; and a downdip core of "platy" high grade vein barite (which contains no optically visible fluorite) six to eight feet thick. The vein textures displayed by the latter two zones are distinctive; therefore, an understanding of their origin is critical to the determination of the relationships between mineralization and deformation.

The updip zone of the vein is composed of interlaminated bands of fluorite and fine-grained barite displaying a conspicuous compositional layering. The fluorite ribbons are often intricately kinked and crenulated and wrap around small elliptical inclusions of quartz and barite. Extensive external rotation is indicated by the frequent attenuation of the fluorite ribbons to produce frayed, discontinuous, tightly-folded stringers (Fig. 16). The proportion of fluorite to barite varies in any given sample, and one may greatly predominate over the other. The abundant fluorite often occurs as thick lenses riddled with thin, parallel stringers of barite. It ranges from a translucent dark purplish or



Scale: 1 mm

(cross-nicols)

Figure 14. Lensoid-shaped barite pod within a thick fluorite (dark) lens, mylonititic ore, Williams mine. An irregular remnant of coarsely-crystalline barite (A) displaying extinction bands is enveloped by fine-grained, granulated barite.

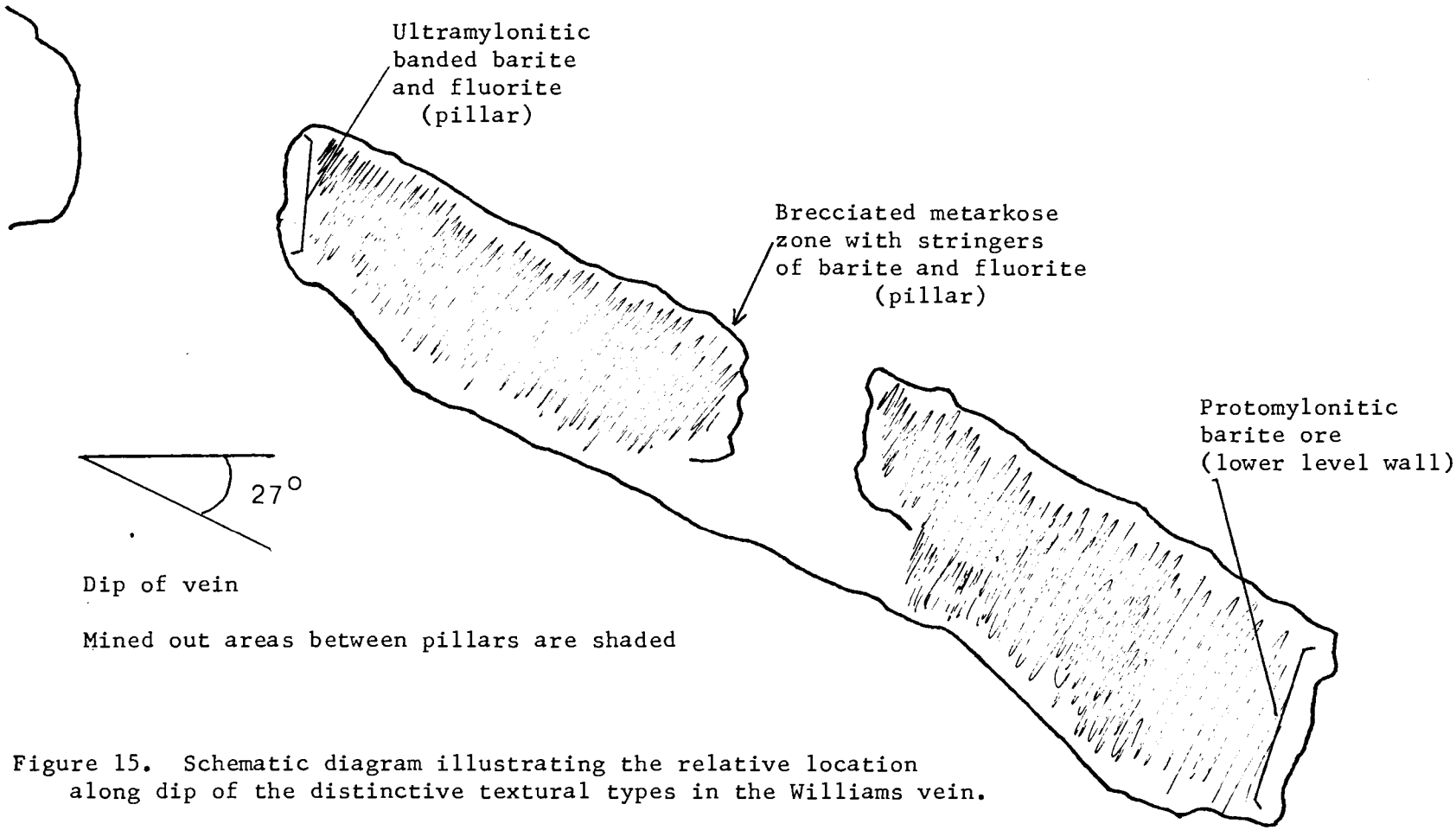
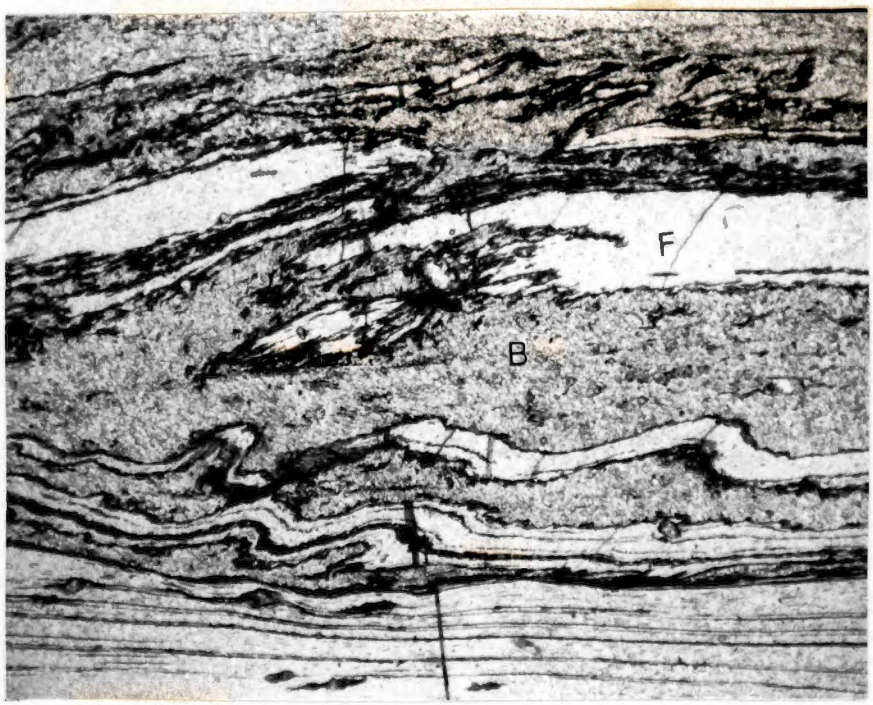


Figure 15. Schematic diagram illustrating the relative location along dip of the distinctive textural types in the Williams vein.



Scale: 1 mm

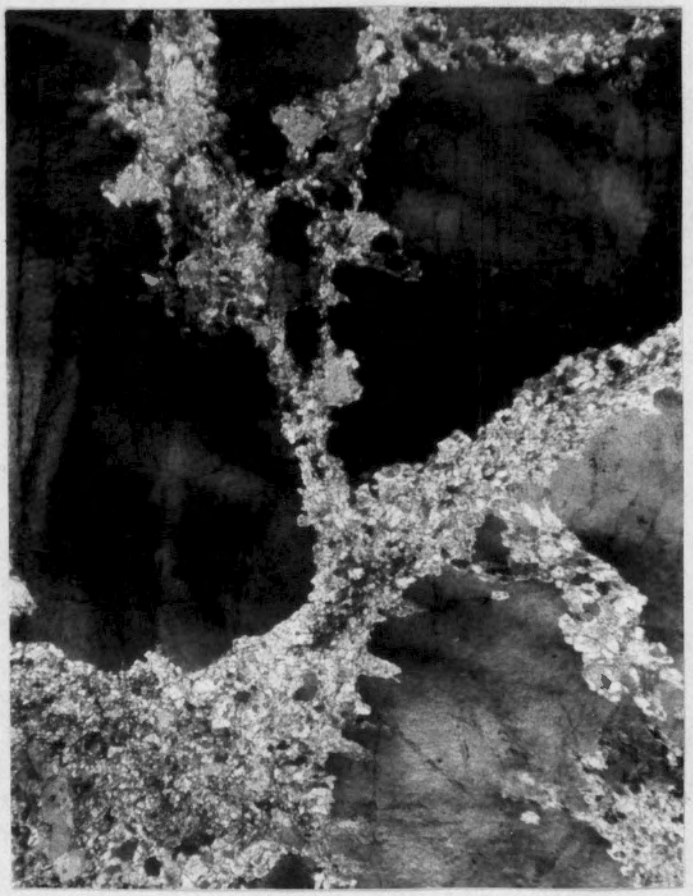
(plane-polarized light)

Figure 16. Banded fine-grained barite (B) and fluorite (F), Williams mine. The fluorite ribbons are often crenulated and extensive rotation of the marked band has caused it to become attenuated and frayed.

light bluish-green to a dense, opaque whitish or pinkish material (finely granulated). In thin-section, the fluorite exhibits a ropy, splintered, or flour-like appearance.

The core of relatively pure "platy" barite is much less intensely sheared than the banded ore. It is composed of thick, irregular wedges of barite stacked one atop the other and differentiated by well-developed shear surfaces. According to Table V (p. 40), the dynamically metamorphosed ore would be classified as a protomylonite grading in some areas into a mylonite. Scattered within this protomylonite are small pods of microbrecciated barite identified by the presence of large (dimensions may be measured in terms of several centimeters), blocky crystalline barite fragments. These microbrecciated sections lack a well-developed fluxion structure although the crystalline barite may be broken into misoriented, often elongate fragments separated by thin zones of finely-granulated barite. These fragments often display coherent cleavage breakage and deformation bands with some granulation occurring along these planar features.

Increased shear transforms the blocky masses into elliptical or lenticular megaporphyroclasts enveloped by an increased amount of fine-grained barite, typical of mortar texture in protomylonites (Figs. 17 and 18). A fluxion structure is apparent especially in the form of numerous parallel thin stringers of crystalline barite separated by fine-grained barite (Fig. 19). Individual porphyroclasts may display either brittle or plastic deformation substructure. Undulose extinction, extinction bands, slip lines, deformation bands and possible large-scale kink bands are common in the irregular, generally elongate porphyroclasts



Scale: 1 mm

(cross-nicols)

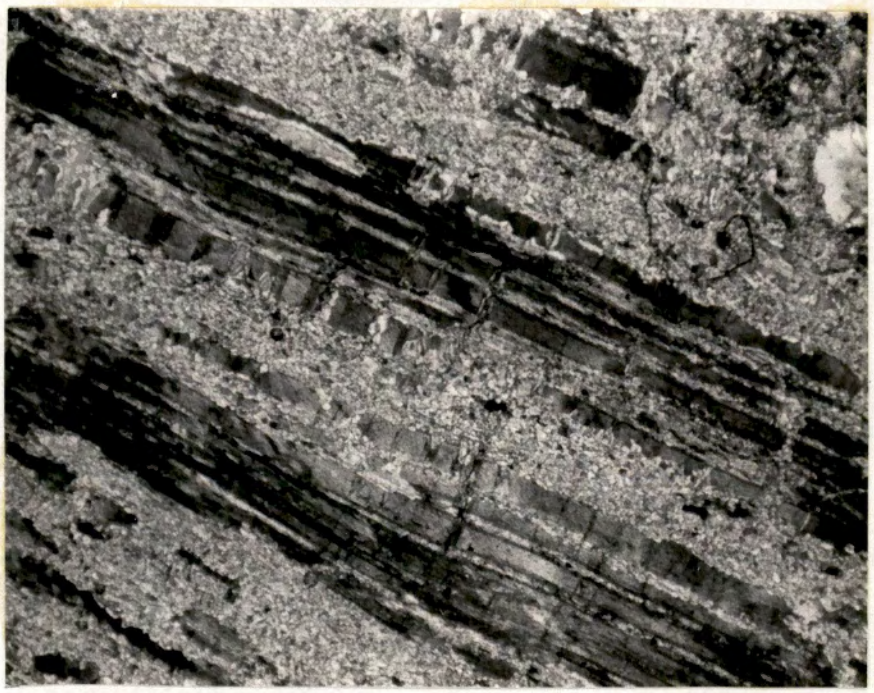
Figure 17. Mortar texture in protomyonitic barite ore, Williams mine. Irregular coarsely-crystalline barite porphyroclasts (displaying undulose extinction) surrounded by fine-grained, granulated or possibly recrystallized barite mortar.



Scale: 1 mm

(cross-nicols)

Figure 18. Irregular boundary between remnant coarsely-crystalline barite and fine-grained barite, protomylonitic barite ore, Williams mine. This photo illustrates the destruction of the coarsely-crystalline barite (displaying deformation bands) by marginal granulation and possible recrystallization.



Scale: 1 mm

(cross-nicols)

Figure 19. Fluxion structure displayed by elongate, segmented plates of coarsely-crystalline barite (trending NW-SE in an extinction position), protomylonitic barite ore, Williams mine.

(Fig. 20). The elliptical or lenticular forms exhibit an internally-segmented structure (Fig. 21) produced by granulation along cleavage lines and deformation bands. The resultant parallel crystal plates (oriented perpendicular to the direction of elongation) are separated by fine-grained partitions and are often curved.

The extent of recrystallization is difficult to determine due to the fine-grained nature of much of the matrix. The visible grain boundaries often appear irregular and somewhat blurred and lack the straight, serrate, or dentate boundaries associated with recrystallization (grain boundary migration) (Fig. 22). However, according to Spry (1969), formation of a mortar texture involves some grain margin recrystallization, as well as, mechanical granulation. Temperatures along the fault zone may not have been sufficiently high to promote significant recrystallization.

Development of the Microstructures and Ore Textures

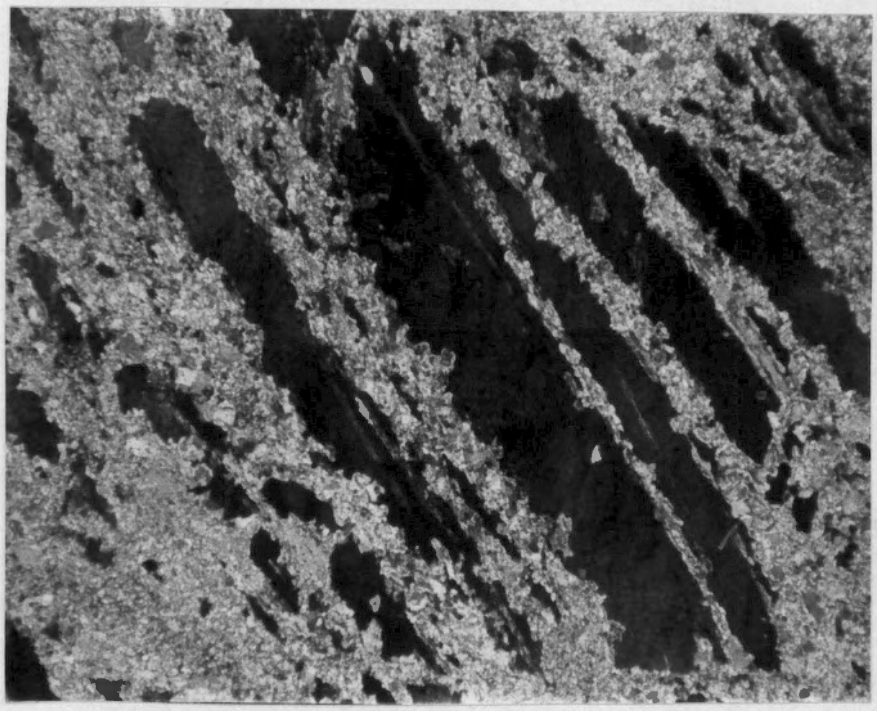
The fabrics previously described are controlled by the intensity of deformation (measured in terms of total stress rate) as well as the mechanical properties (lattice strength, brittleness, ductility, and tendency to recrystallize) of the barite and fluorite. The orientation of the crystal lattice relative to the principal stress directions plays a critical role in determining its reaction to stress. Other factors such as confining pressure and temperature may greatly influence the development of foliation and the tendency for a distorted crystal lattice to recrystallize. An increase in confining pressure under constant temperature promotes an increase in rupture strength and the amount of



Scale: 1 mm

(cross-nicols)

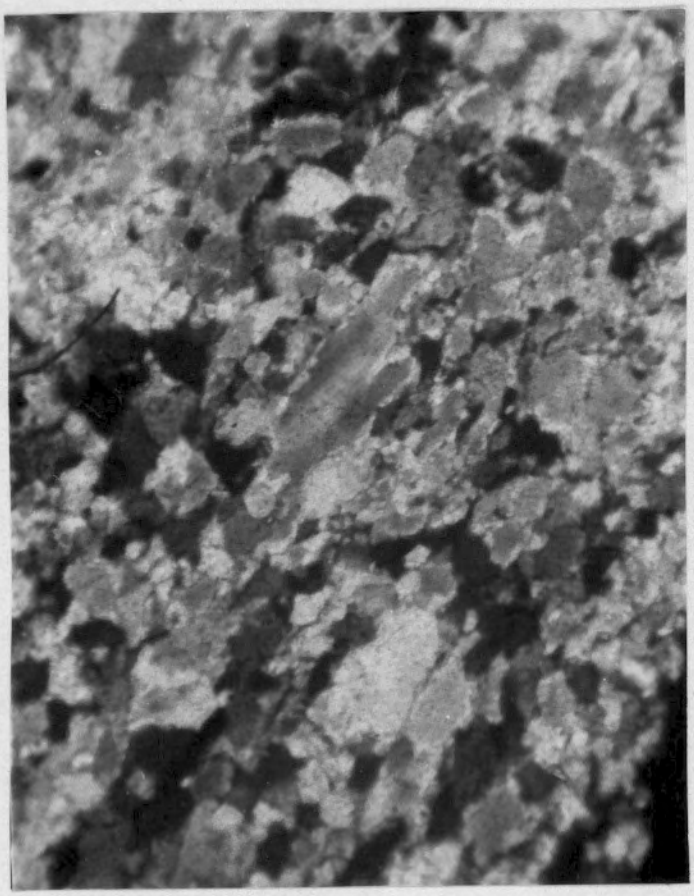
Figure 20. Deformation bands in a barite porphyroclast proto-mylonitic barite ore, Williams mine. Note cleavage lines cutting perpendicular to the NE-SW-trend of the bands.



Scale: 1 mm

(cross-nicols)

Figure 21. Segments of coarsely-crystalline barite (trending NW-SE in an extinction position) separated by fine-grained barite partitions, protomylonitic barite ore, Williams mine.



Scale: .25mm

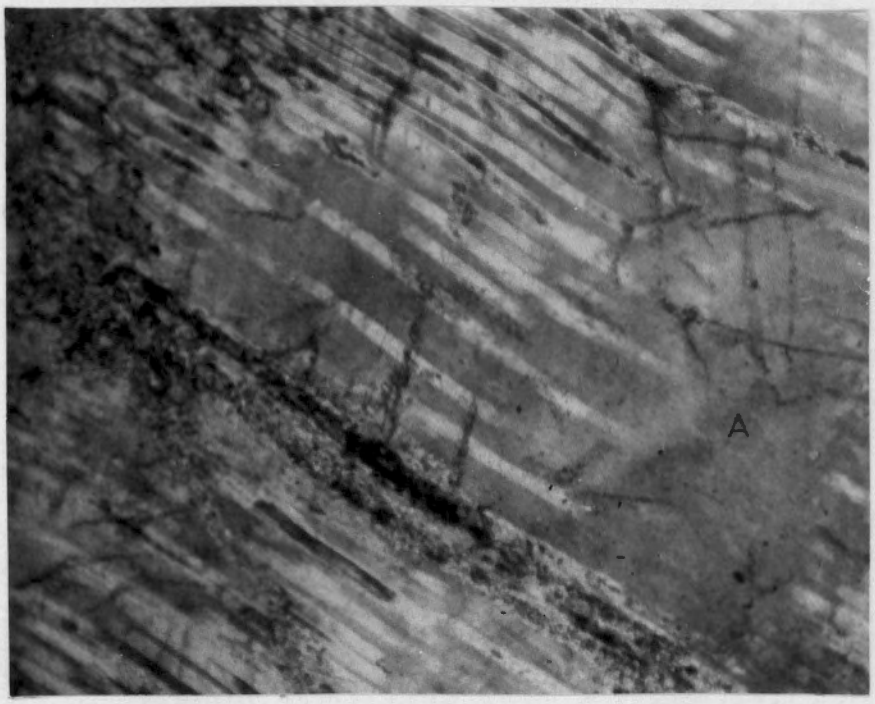
(cross-nicols)

Figure 22. Close-up of fine-grained barite in figure 14 (p. 42).

plastic deformation (ductile shear) undergone before rupture. Higgins (1971) adds that water pressure and oxygen and carbon dioxide fugacity also contribute to the evolution of cataclastic rocks.

Both vein types display gradational sequences of barite morphologies which reflect the interinvolvement of the above factors, and more importantly, the localized impact of inhomogeneous deformation. The coarsely-crystalline barite is thought to represent the original, unstrained form of the mineral. Upon exposure to compressive stress, signs of lattice distortion become apparent. Plastic deformation features are commonly observed. The ultimate consequence of excessive strain (in response to intense stress) is the reduction of the thick tabular crystals to fine-grained aggregates. This sequence of progressive adjustment of a coarsely-crystalline barite sample to increased inhomogeneous stress can be illustrated in the following textural description of a single thin-section: The barite (Moccasin Gap type) consists of three distinctive though somewhat gradational textural zones (Figs. 23, 24 and 25)--a central coarsely-crystalline zone possessing undulose extinction, an intermediate zone composed of coarsely-crystalline barite displaying prominent deformation bands, and a peripheral granulated zone. The boundary between the banded and granulated zones is usually very gradational (though it may be abrupt) and within these areas banded, coarsely-crystalline barite is being transformed into fine-grained matrix. In these breakage zones it appears that granulation of the coarsely-crystalline barite is initiated along deformation bands and cleavage surfaces in an intersecting pattern.

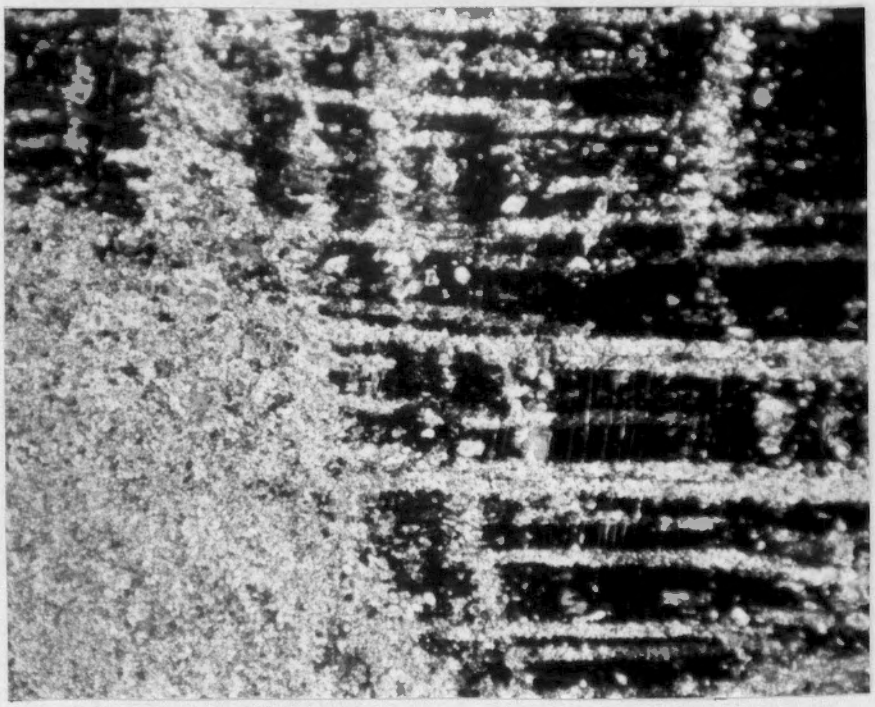
This suggests that the formation of the deformation bands has



Scale: 1 mm

(cross-nicols)

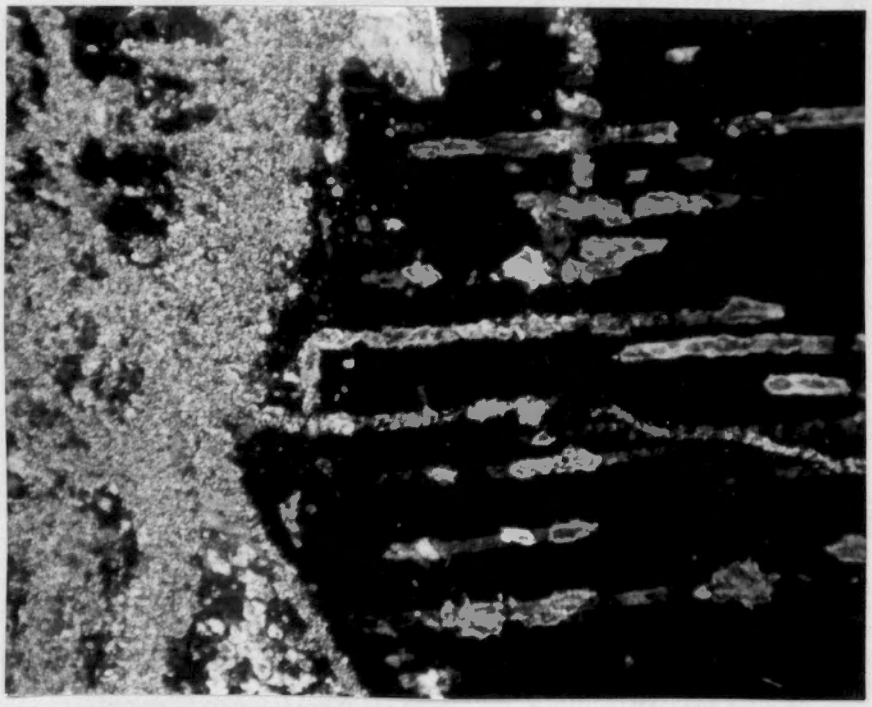
Figure 23. Undulatory zone (A) surrounded by deformation bands in coarsely-crystalline barite, Moccasin Gap mine.



Scale: 1 mm

(cross-nicols)

Figure 24. Breakage zone (right-hand portion of photo) transitional between the coarse- and fine-grained barite textures, Moccasin Gap mine. Note the several directions of linear granulation which appear to coincide with deformation bands and cleavage surfaces.



Scale: 1 mm

(cross-nicols)

Figure 25. Abrupt contact between coarse- (displaying deformation bands containing elongate inclusions) and fine-grained barite, Moccasin Gap mine. Remnants of coarse-grained barite in the process of being granulated can be seen in the fine-grained barite.

promoted strain hardening in the barite lattice. There may be a strain threshold past which intracrystalline adjustments to the original lattice (ductile behavior) can no longer accommodate increased strain. Thus other recovery mechanisms such as marginal recrystallization and mechanical granulation become important.

In the Williams vein, the penetrative stress is much more intense and unidirectional. Fluxion structure forms as planar masses of material are differentially moved along developed shear planes. Scattered pods of less-deformed, microbrecciated barite are preserved between numerous sub-parallel planes of active movement. Along the zones of intense shearing the coarsely-crystalline barite is ground down into smaller and smaller porphyroclasts, creating a protomylonitic or mylonitic texture. In the monomineralic barite samples the shear surfaces are obscured by granulation, but movement is indicated by the elongate porphyroclasts. The eventual result of a sustained shearing (granulation) event is the formation of banded ultramylonites.

The origin of compositional banding (and color lamination) in ultramylonites is not totally understood, but has been explained by two different processes (Sclar, 1958):

1. Chemical activity with subordinate cataclasis (Sander-Turner hypothesis).

2. Mechanical metamorphic differentiation (Schmidt-Wenk hypothesis). The former process has traditionally received the most recognition. It involves an early granulation stage during which grain size reduction stimulates increased chemical activity. Mineral segregation is produced by selective dissolution and redeposition of soluble

minerals along active shear planes. Shearing stress acts only as a triggering mechanism while chemical activity is the critical differentiation process.

The contribution of mechanical factors to the development of banded textures has been largely overlooked. The process by which shearing stress, restricted to narrow zones of intense penetrative movement, plays a dominant role in producing mineralic segregation is referred to as mechanical metamorphic differentiation (Schmidt, 1932). This theory states that contrasting crystal structures respond differently to intense penetrative stress under moderate to high confining pressures. "More ductile minerals adjust to stress by translation and development of slip surfaces and by recrystallization, eventually being smeared out in distinct layers of intense shear motion. More brittle minerals are rotated and segregated into layers" (Prinz and Poldervaart, 1964).

There is considerable evidence in support of mechanical metamorphic differentiation. An obvious direct correlation between compositional banding and intense shearing deformation has been observed by Prinz and Poldervaart (1964), Sclar (1965), and Wenk (1934). In addition, the importance of chemical activity has been questioned by Sclar (1958), who contends that increased pore solutions should promote the formation of coarse-grained laminated blastophyllonites and not the retention of an ultramylonitic texture. It appears that compositional banding can most likely be attributed to mechanical processes (cataclasis) with recrystallization (chemical activity) along privileged planes or layers developed by the intense shearing playing a less critical role.

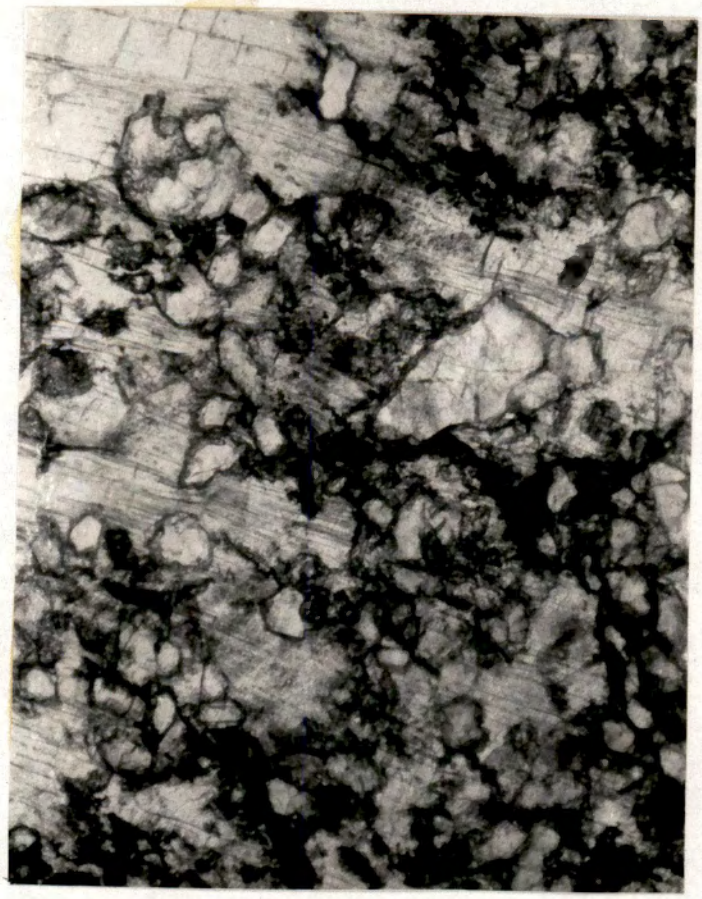
The exact origin of the banded ultramylonite in the Williams vein is uncertain but might be best explained by one of two hypotheses. If the barite and fluorite were precipitated along active shear planes simultaneously, then the process of mechanical differentiation previously described may have been instrumental in producing the banded textures. However, it is not specifically known how a mixture of barite and fluorite would react to an imposed directed stress and whether a compositionally segregated rock would result. An alternative hypothesis, which is supported by evidence elsewhere in the vein (as described in a later section), involves the deposition of barite (early) and fluorite (late) along active shear planes in successive stages. In this manner, the barite and fluorite would be initially segregated, and continued movement along the shear planes would produce the characteristic contorted, fine-grained bands of barite and fluorite. It is unlikely that the banded textures could result simply from post-deformational replacement processes involving the rhythmic introduction of chemically active solutions of contrasting composition as implied by Ferguson and Jewell (1951).

Mode of Emplacement of the Vein Minerals

The method of emplacement of the barite (and associated vein minerals is somewhat questionable. Ferguson and Jewell (1951) illustrated numerous examples of the corrosion and embayment of both detital quartz and the vein ankerite by the barite. The coarse Moccasin Gap barite crystals contain abundant microscopic inclusions of what are presumably remnant quartz grains (Fig. 6, p. 29). Thus,

replacement processes seem to be dominant, although little is known about the chemical and crystal structure transformations which take place. However, early stages of the replacement process are identified by clusters of unreplaced quartz grains enveloped by barite which in a given area appears optically continuous (Fig. 26). In addition, the Moccasin Gap barite is commonly found as pods and thick lenses resembling bedding. This suggests that stratigraphically receptive beds (or zones) may have facilitated crystal growth. The presence of grit beds and chemically susceptible carbonate cement may have localized ore deposition. In these horizons both infilling of void spaces and replacement of host grains would be important processes.

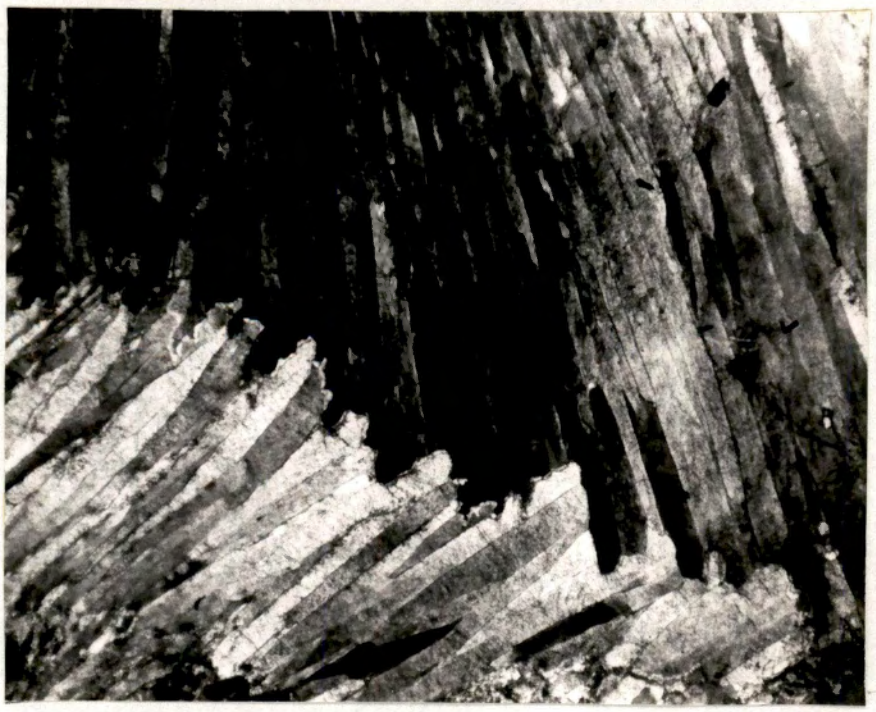
The extreme coarseness of the Moccasin Gap barite is difficult to explain especially when compared to the barite crystal habits exhibited in other known open cavity and replacement type deposits. Barite observed in thin-section from the Sweetwater breccia bodies and vein fillings (open cavity filling within carbonate host rock) forms masses of elongate blades or thin plates and rosettes possessing a plumose aggregate texture (Fig. 27). A replacement deposit in the southern Independence Mountains of Nevada (Ketner, 1975) reportedly consists of interlocking laths or rosettes of barite which transect host rock (chert, quartzite, and greenstone) textures. A bladed, lathy, or rosetted morphology seems to be the common form of barite regardless of the dominant emplacement process. Crystal size could be controlled by such environmental, thermodynamic, and kinetic factors as ease of nucleation, crystal growth rates, initial fluid temperature, cooling rates, confining pressure, rate of diffusion of materials (both toward



Scale: 1 mm

(plane-polarized light)

Figure 26. Replacement texture in Moccasin Gap quartzite, Moccasin Gap mine. Coarsely-crystalline barite (displaying prominent cleavage lines) has enveloped clusters of irregular quartz grains.

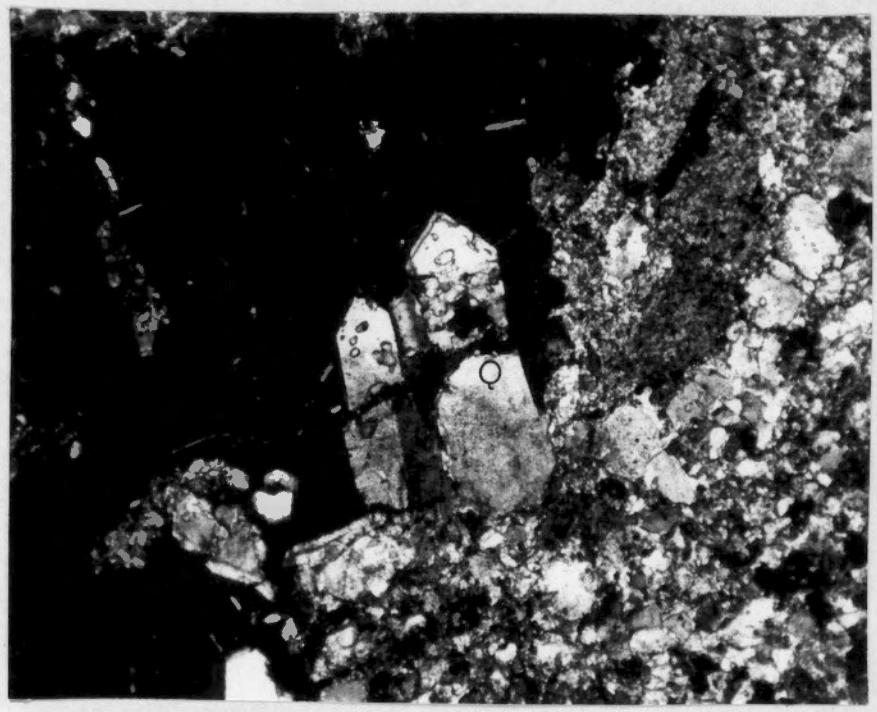


Scale: 1 mm
(cross-nicols)

Figure 27. Contact boundary between two barite rosettes, Ballard Pit, Sweetwater district. Note thinly-bladed morphology of the individual barite crystals.

and away from the nucleation sites), presence of impurities, presence of solvent phases, and chemistry and strain condition of the host grains. A sustained directed pressure may also affect the orientation of crystal growth.

In the Williams vein, shearing has been so intensive that it is almost impossible to determine the dominant process responsible for emplacement of the vein minerals. There is no doubt that the fault zones have served as conduits for the migration of the ore fluids, but it seems unlikely that a replacement front could penetrate along a previously shattered fault zone so thoroughly as to produce the thick, heavily mineralized vein (as suggested by Ferguson and Jewell, 1951). It is the author's opinion that deformation and mineralization were contemporaneous events. Active movement along numerous parallel shear planes undoubtedly created abundant open spaces (representing low pressure areas) into which the vein minerals would be immediately deposited. The existence of such open spaces is indicated in the less sheared hanging wall breccia bodies. Here euhedral quartz crystals can be seen (in thin-section) protruding from the walls of metarkose clasts into cavities subsequently filled with fluorite (Fig. 28). As deformation progressed, the surviving metarkose clasts became extensively sheared increasing their susceptibility to replacement by the infiltrating ore solutions. Thus, emplacement of the vein minerals was probably accomplished by both open space and replacement processes continually activated by deformation. Once deposited, the vein minerals were deformed into the cataclastic textures previously described.



Scale: 1 mm

(cross-nicols)

Figure 28. Terminated quartz crystals (Q) growing into a cavity filled with fluorite (dark), breccia zone of hanging wall, Williams mine. A quartzite clast served as a base for crystal growth.

Significance of the Microstructures and Ore Textures

The importance of the microstructures and ore textures described is that they tend to indicate that mineralization and deformation were contemporaneous. The vein minerals are involved in the thrusting and not merely replacements of previously sheared host rocks. It does not seem possible that the originally deformed quartzite textures would be perfectly preserved by replacement of later vein minerals. The dense, "platy" texture of the Williams barite is not inherited from the replacement of "gouge, microbrecciated planes or mylonitic quartzite" (Ferguson and Jewell, 1951, p. 47) but results from shearing of coarsely-crystalline barite to form platy porphyroclasts surrounded by a fine-grained, granulated matrix. The highly strained quartz grains would be replaced by unstrained vein minerals if mineralization was post-deformational.

The vein textures suggest but do not confirm that several stages of mineralization may be involved. An obvious trend is the dramatic increase in fluorite content of the vein as the intensity of shearing increases. The moderately deformed Moccasin Gap veins bear only traces of fluorite. Along the intensely sheared Williams fault zone three predominant textural types--protomylonites (with included microbrecciated pods), mylonites, and ultramylonites--are intimately associated (indicating the inhomogeneous nature of the stress on a large scale). The mylonites and ultramylonites often contain abundant fluorite. However, the protomylonites (represented by the "platy" barite core and other isolated pods) carry virtually no fluorite. It might be

hypothesized from this textural evidence that the barite in both vein types could have originated during the same mineralizing event. Fluorite may have been introduced in the Williams vein accompanying a later deformational phase along the Brushy Mountain overthrust. The fluorite seems most abundant near the hanging wall and footwall portions of the vein. This might imply that renewed movement occurred in these areas where reactivated or newly created fractures and shear planes may have localized contemporaneous fluorite deposition. The banded, ultramylonitic textures were produced as continued movement further deformed the barite-fluorite mixtures. More central portions of the vein (such as the "platy" barite core) were unaffected by the renewed movement and thus were not penetrated by the fluorine-enriched solutions.

CHAPTER IV

CONCLUSIONS AND RECOMMENDATIONS

The results of this study indicate that, contrary to previous opinion, deformation and mineralization were not independent, successive events in the Del Rio district. Introduction of the ore fluids was definitely not post-deformational but occurred contemporaneously with at least the final stages of the deformation. This major conclusion is substantiated by the abundance of deformational fabrics observed in the barite ore. Such fabrics formed in direct response to deformation of the vein barite and were not inherited by replacement of previously deformed host rock as originally contended by Ferguson and Jewell (1951). The inhomogeneous nature of the deformation produced a progressive sequence of deformational fabrics in the barite. The appearance of plastic deformation features such as slip lines, deformation bands and twins, polygonized grains, etc. marked the onset of stress-induced transformations in the coarsely-crystalline barite. As the intensity of the directed stress increased, mechanical granulation became a dominant process resulting in the formation of protomylonitic, mylonitic, and eventually ultramylonitic textures.

The reinterpretation of the relative timing of deformation and mineralization introduces the following possible considerations regarding mineralization in the district:

1. Fluorite may have been introduced independently of the barite in the Williams-type vein accompanying later renewed movement along

the Brushy Mountain overthrust. This conclusion is supported by the fact that large masses of partially mylonitized barite contain no fluorite; yet more thoroughly sheared zones display abundant fluorite. Increased movement along these latter zones may have facilitated the introduction of late-stage, fluorine-rich solutions, deposition of fluorite, and subsequent granulation of the associated barite and fluorite.

2. The ore fluids themselves may have been partially responsible for initiating or maintaining movement along a group of shear planes. According to Hubbert and Rubey (1959) and Miller (1973), fluid overpressure may be an important mechanism in promoting thrust faulting.

3. The deformation may have caused changes in sources or the rerouting of the plumbing system which could promote the mineral variation displayed in the district.

4. Replacement processes such as fluorite replacing ankerite in the Williams-type vein may have been facilitated by deformation, resulting in the modification of originally similar mineral assemblages.

The present study was not able to contribute any additional information regarding the exact origin and genetic relationships of the two types of vein mineralization in the Del Rio district. Attempted chemical analyses of the various vein mineral phases were not sufficiently detailed to determine whether a single or multiple mineralizing events occurred in the district. The potential usefulness of comparing trace element contents (especially strontium and yttrium) between the barite types and between mineral phases associated in a single vein as an indication of the involvement of similar or unrelated source fluids was not adequately determined.

The vein mineralization of the Del Rio barite district certainly warrants further investigation. Such a renewed study might concentrate on one or more of the following:

1. A petrofabric analysis (involving the examination of oriented thin-sections according to universal stage procedures) of the barite might be useful in identifying the operative slip mechanisms responsible for the plastic deformation of the barite. In addition, the deformation fabric displayed by the vein minerals could be utilized to reconstruct the principal stress system for the final phase of dynamic metamorphism.

2. Experimental deformation studies could be conducted to determine the textural development of relatively undeformed coarsely-crystalline barite in response to progressive changes in temperature, confining pressure, strain rate, differential stress, and/or interstitial fluid pressure. Thus, the artificially produced textures might be useful in roughly delineating the prevailing conditions of formation of the natural analogs.

3. More detailed chemical analyses of the strontium and rare earth contents of the barite and fluorite might clarify the genetic relationship between the two distinctive vein types in the Del Rio district.

4. A textural and chemical study of unweathered vein ankerite might explain its apparent restricted distribution to the Del Rio thrust sheet (Moccasin Gap type vein).

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APPENDICES

APPENDIX A

HEAVY LIQUID DENSITY SEPARATION METHOD

Since the mylonitic barite and fluorite in the Williams vein are intimately associated, it was necessary to separate the two before a chemical analysis of the individual phases could be conducted. The density difference between fluorite (3.180) and barite (4.3-4.5) seemed sufficient to consider heavy liquids to achieve a clear-cut gravity separation of the intermixed components. Two heavy liquids, methylene iodide (3.325) and Clerici's solution (4.28) have maximum specific gravities intermediate between barite and fluorite. Clerici's solution (thallous formate-malonate), however, is very expensive and is an extremely toxic substance in terms of vapor inhalation, skin absorption, and subsequent damage to internal organs. Because methylene iodide (diiodomethane) is relatively safe provided adequate ventilation is maintained, it was utilized as the separation medium. Initially, experimental runs were conducted in 30 ml beakers to test the reaction of the solid samples to the heavy liquid. Actual separations were attempted in a 125 ml separatory funnel with an enlarged stopcock aperture. Substantial information on heavy liquid separation and recovery techniques can be obtained from Hutchinson (1974), Carter (1971), and Allman (1972).

The heavy liquid separation technique presented an unexpected problem. The barite-fluorite ore mixtures were ground to -325 mesh to insure liberation of the two phases. However, upon addition of the

powdered mixture to the heavy liquid, the sample coagulated into an agglomerate of large particles. Upon stirring the entire mass then sank to the bottom. Experimental 1 gm runs were conducted with monomineralic samples of barite (Moccasin Gap mine) and fluorite (southern Illinois) mixed in known proportions (generally 1:1). The fluorite was added to the liquid first and found to float. The liquid below the floating particles completely cleared within 30 minutes. The barite was then added and the mixture was stirred vigorously. Once again, almost immediately the entire solid mass sank to the bottom with clear liquid above it. Centrifuging at various speeds and times did not produce any indication of a separation. Other size fractions, -270+325 and -200+270, were also tested with the same result.

A library search revealed that the same phenomenon was described in the Treatise on Analytical Chemistry (pt. 1, v. 5) in a section concerning growth and stabilization of colloidal systems. In this discussion $BaSO_4$ particles precipitated from BaCl solution were examined by nephelometric techniques to determine variation in angular distribution of scattered light as the precipitant aged. From this information it was found that increased particle dimensions resulted from the formation of "a loose flocculated structure rather than by larger crystals or aggregates" (Kolthoff, 1964, p. 3303). The polarization effects of the chemical environment on the formation of these large particles is unknown to the author. Both $BaSO_4$ and CaF_2 are virtually insoluble in organic solvents. Thus, particle size growth is most likely attributed to the existence of molecular surface charges. A surface potential may be formed by the concentration of potential

determining ions at the surface of the particles. The system's attempt to achieve electroneutrality may create an expanded $BaSO_4$ particulate structure into which CaF_2 is somehow incorporated.

A deflocculating agent, glycerol, and several surface active agents, Magnofloc solutions #507c, #521c, #515c (acid colloid-cationic charge), were added in droplet proportions in an attempt to prevent agglomeration. However, no beneficial results were obtained and too little heavy liquid was available to experiment with other compounds. Also, addition of these agents at optimum concentration levels may have lowered the density of the heavy liquid rendering it useless for its intended gravity separation purpose.

Due to the difficulties encountered in utilizing very fine-grained powders to achieve a clear-cut separation, coarser size fractions were also experimented with in hopes of evading the coagulation problem. The barite and fluorite standards were ground to mesh sizes -140 +200, -120 +140, -100 +120, -80 +100, -60 +80. One to one mixtures of each size category were then run through the separatory funnel procedure. The -140 +200 and -120 +140 samples again completely sank; however, in the three coarser size fractions a separation was observed. The coagulation problem had been eliminated, but in natural ore samples the two phases would no longer be liberated from each other (as demonstrated by X-ray diffraction analysis of the settled and floating fractions). However, the small specific gravity difference between the fluorite and methylene iodide might facilitate procurement of a relatively pure fluorite sample. Those grains containing appreciable barite would sink to the bottom; whereas, fluorite grains with only

minor barite content should float. Since barite samples containing less than 1% fluorite had been collected at the Williams mine, contamination of the settled barite fraction with fluorite was not critical.

A further refinement of the procedure was the use of an optical scan to remove those fluorite grains which contained small stringers of barite. $KCrO_4$ solution (Appendix B) was utilized to stain the barite a bright yellow allowing those grains still containing barite to be removed from the fluorite sample. Ore samples displaying large pods or stringers of fluorite were selected to be used in the separation. Even then the barite and fluorite were so intimately intermixed that optically sorting the floatant was tedious. Three fluorite samples containing only minor barite were obtained in this way.

APPENDIX B

BARITE STAINING TECHNIQUE

The use of a stain to promote easy recognition of barite proved beneficial in two respects. It facilitated the optical separation of barite and fluorite grains (Appendix A, p. 75) and allowed quartz and barite to be readily distinguished from each other in cut slabs. The staining procedure (Carlson, et al, 1975) consisted of two steps. The first step involved boiling the sample in a concentrated solution of sodium carbonate (400 gm $NaCO_3$/liter). The sample was stirred periodically and after about 15 minutes removed from the heat source. The solution was then decanted, and the barite sample was washed repeatedly with cool tap water. This resulted in the formation of a porous coating of witherite along the exposed surface of the barite by the reaction:

$$BaSO_4 + Na_2CO_3(l) \rightarrow BaCO_3(s) + Na_2SO_4$$

The second step in the procedure was to simmer the witherite-coated barite sample in a solution of 0.5 molar potassium chromate (97.1 gm K_2CrO_4/liter) which had just been removed from the heat source. The sample was stirred at regular intervals. After 15 minutes the solution was decanted and the sample was rinsed with cool water. The original barite could now be readily identified by a bright yellow color. Deep penetration of chromate solutions into the porous witherite rind created the stained zone according to the reaction:

$$BaCO_3(s) + K_2CrO_4 \longrightarrow BaCrO_4(\text{yellow solid}) + K_2CO_3(l)$$

The color intensity of the stain increased linearly with increased contact time of the sample in both the carbonate and chromate solutions. Since the boiling and stirring was destructive to the sample, a maximum of 15 mimutes contact time was utilized even although the color intensity could be enhanced by longer times. In this way the grain size of a particulate sample was not severely reduced, and the mounting surface of a prepared chip was not overly pitted. The staining of prepared thin-sections ground down to thickness was attempted; however, the boiling destroyed the epoxy bond causing the rock surface to flake off.

APPENDIX C

INVESTIGATION OF TRACE AND MINOR ELEMENT CONTENTS OF THE DEL RIO VEIN MINERALS

It was thought that a comparison of strontium contents between the Moccasin Gap and Williams type barite might indicate whether the two barites originated from the same source. However, due to time limitations and difficulties in securing suitable barite samples from the mylonitic barite-fluorite ores of the Williams vein, it was not possible to obtain sufficient chemical analyses to develop an adequate data base. The data collected, consisting of three samples from each vein type (Table VI) indicates some variation in strontium contents exists, but no conclusive interpretation of the chemical nature of the ore fluids can be made based on such limited data. The affect of other factors such as phreatic leaching of strontium from the barite on the strontium contents of the barite is also uncertain. The possibility of leaching is demonstrated by the drastic reduction in strontium levels (Table VI) observed between highly weathered (chalky with hazy birefringence) and fresh (clear, coarsely-crystalline with sharp birefringence) barite samples from the Sweetwater district.

Fluorite from the Williams vein was also analyzed by XRF to determine whether any trace or minor element contents might be useful in determining its genetic relationship to the barite. As can be seen in Table VI the strontium and yttrium contents of the barite and fluorite are significantly different. The contrasting values could be attributed

TABLE VI

STRONTIUM AND YTTRIUM LEVELS IN
BARITE AND FLUORITE

Sample		Strontium[1]	Yttrium
Moccasin Gap barite sample	#1	5.19	---[2]
	#2	4.22	---
	#3	4.28	---
Williams barite sample	#1	4.04	---
	#2	4.49[3]	---
	#3	2.86	---
Williams fluorite sample[4]	#1	.13	.07
	#2	.67	.03
	#3	.15	.15
Sweetwater barite (B.C.Wood mine)			
fresh sample		11.27	---
weathered sample		2.55	---

1 Strontium and yttrium values expressed in wt.%.
2 No yttrium peaks observed.
3 This sample was collected from an exposed outcrop outside the mine entrance.
4 Barium peaks were present in these samples indicating possible barite (and thus $SrSO_4$) contamination.

to partitioning of the available ions in distinctive source fluids. Strontium appears to be incorporated much more readily into the barite structure than into the fluorite structure. Yttrium and other rare earths readily substitute for calcium in the fluorite structure. Rare earths, even in trace amounts are not common in barite.

The analytical method used consisted of a semi-quantitative spectrographic technique. A TEFA 6110 energy dispersive unit provided elemental spectra from which half peak heights could be determined. The following formulas (provided by ORTEC) were then used to calculate the unknown strontium and yttrium concentrations:

1) $MDC=[2.33\times(B_1+B_2/2)\times\#Ch)]/[\text{Gross peak}-((B_1+B_2/2)\times\#Ch)]\times\text{conc. of stand.}$

2) $\text{unknown conc.} =(MDC)\times[\text{Gross peak}-((B_1+B_2/2)\times\#Ch)]/[2.33\times((B_1+B_2/2)\times\#Ch)]$

where MDC = Minimum Detectable Concentration

B_1 = background value of peak

B_2 = background value of peak

#Ch = number of data channels measured

Gross peak = sum of counts measured in individual channels

conc. of stand. = concentration of standard

The fact that the strontium values came out higher than anticipated (as compared to those of Brobst in Table III, p. 17) raises some questions concerning the data reported here. The discrepancies might be attributed to the quality of the standards or to improper technical or mathematical data manipulation. It was necessary to determine the gross peaks manually and to make the data reduction without the use of the instrument's computer because suitable standards were not available.

VITA

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