ABSTRACT

Michael John Kirkland. PETROLOGY AND DIAGENESIS OF SANDSTONES OF THE BLUEFIELD FORMATION (UPPER MISSISSIPPIAN), SOUTHEAST WEST VIRGINIA. (Supervising Professor, Dr. Donald W. Neal), Department of Geology, December, 1985.

The Bluefield Formation comprises interbedded shales, limestones and sandstones representing deposition transitional between marine carbonates and shallow marine to deltaic siliciclastics. Bluefield sandstones vary lithologically from relatively coarse-grained, clean, and orthoquartzitic (up to 95.0% quartz) to very fine-grained, matrix- and rock fragment-rich (as low as 41.0% quartz) varieties. In this study, sandstones are subdivided into two groups: Type 1, which are very fine-grained and argillaceous; and Type 2, which are coarse-grained, clean, and quartzitic.

Diagenetic alteration of Type 1 sandstones was dominated by mechanical compaction. Quartz authigenesis, accompanied by intergranular pressure solution, was the principal diagenetic process in Type 2 sands. Minor secondary porosity is present in Type 1 sands. Type 2 sandstones contain small amounts of both primary and secondary porosity.

The lower part of the Bluefield Formation consists of marine limestones, calcareous shales and thin, carbonate-cemented shelf sands

deposited in a shallow marine setting. The Droop Sandstone, located approximately at the boundary between the upper and lower Bluefield, was deposited as a prograding barrier island complex. Upper Bluefield strata were deposited in a prograding delta.

PETROLOGY AND DIAGENESIS OF SANDSTONES OF THE BLUEFIELD FORMATION (UPPER MISSISSIPPIAN), SOUTHEAST WEST VIRGINIA

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Michael John Kirkland

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PETROLOGY AND DIAGENESIS OF

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INTRODUCTION

The Bluefield Formation, at the base of the Upper Mississippian Mauch Chunk Group in West Virginia, is a marginal marine deposit transitional between the underlying marine Greenbrier Limestone and overlying shallow marine to deltaic sediments of the upper Mauch Chunk Group and Pennsylvanian System. The Bluefield Formation is composed of intercalated sandstone, shale, limestone and minor coal. West Virginia Geological Survey reports indicate eight prominent sandstone bodies, some of which are natural gas producers. From oldest to youngest, they are the Edray, Webster Springs, Droop, Indian Mills, Bradshaw, Bertha, Graham, and Clayton Sandstones. They vary from greenish-gray to buff, fine- to very fine-grained, calcareous varieties in the lower part of the Bluefield to greenish-gray and reddish-brown, fine- to very fine-grained varieties in its upper parts. The distinctive Droop Sandstone, located at the transition between upper and lower parts of the Bluefield Formation, is coarse-grained, white, and cross-bedded. These sandstones have been briefly described in West Virginia Geological Survey County Reports (Reger, 1926; Price and Heck, 1939; Price, 1939), but descriptions are restricted to color, characteristic bedding and grain size, and thickness. Other references to the Bluefield are found as part of a general overview of Mississippian stratigraphy (Englund, 1979; Arkle and others, 1979). McColloch (1957), Manspeizer (1958) and Humphreville (1981) dealt with stratigraphic and paleontological aspects of the Bluefield Formation. However, detailed studies of the texture, mineralogy, and diagenetic histories of Bluefield sandstones are lacking.

PURPOSE

An investigation of Bluefield outcrops was undertaken in order to accomplish the following objectives:

1) determine composition and textures of the sandstones;
2) characterize diagenesis within the sandstones;
3) interpret the depositional environments; and
4) evaluate compositional, textural, and diagenetic changes relative to depositional environments and stratigraphic position.

LOCATION

The study area encompasses Monroe, Summers, and part of southern Greenbrier Counties, West Virginia (Fig. 1). It is located within the Appalachian Plateau physiographic province, a rugged and mountainous area dissected by numerous streams which have created V-shaped erosional valleys. Maximum relief for the area is 955 meters. The three counties encompass a total of 4829 square kilometers (Reger, 1926).

GEOLOGIC SETTING

Rocks of the study area crop out in a band of horizontal to gently northwestwardly dipping strata that form part of a northeast trending monoclinal structure (Arkle and others, 1979). The Bluefield Formation is underlain by the Greenbrier Group and is overlain by the Hinton Formation (Figure 2).

The Greenbrier Group ranges to a maximum thickness of 550 meters in

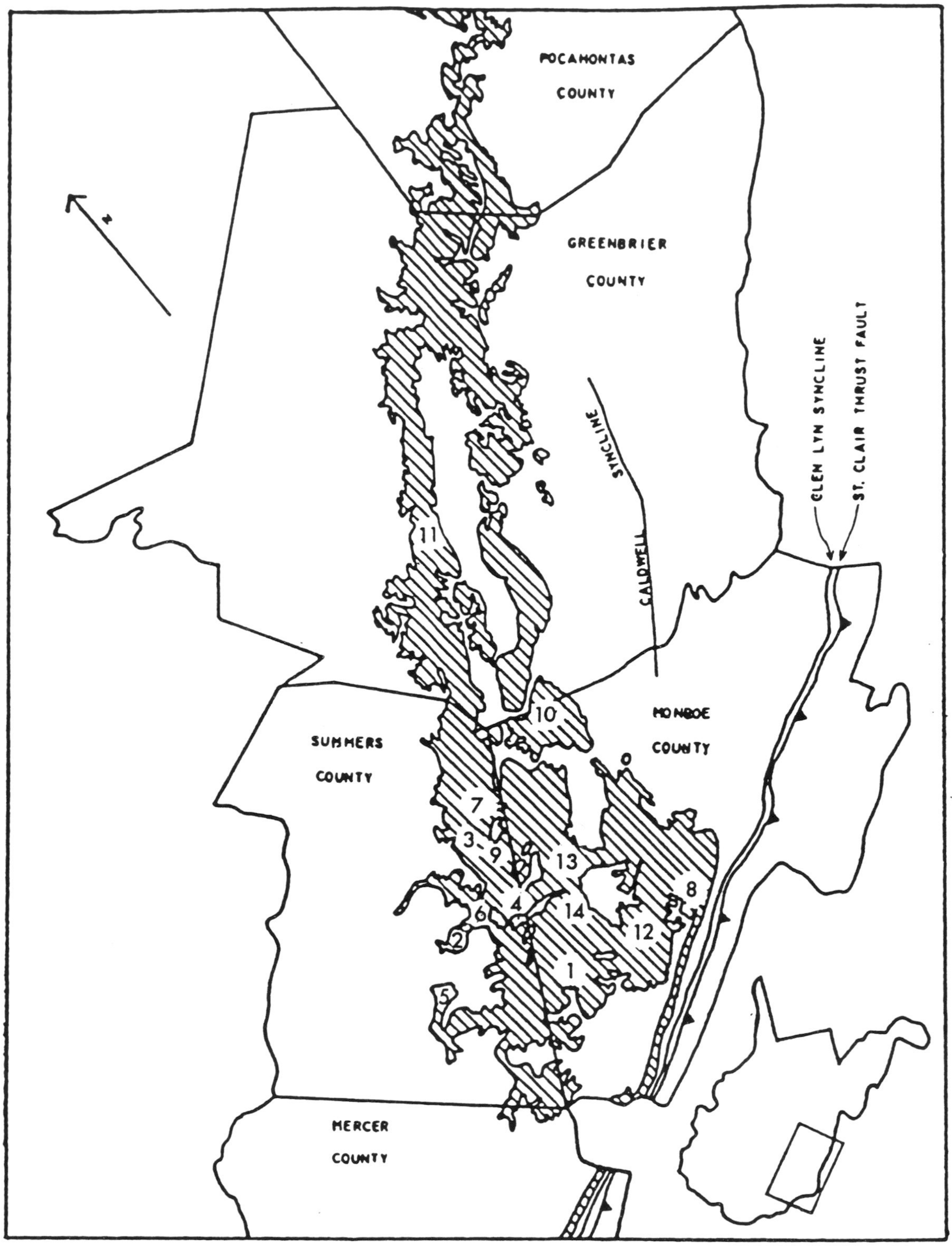

Figure 1. Location map: Summers, Monroe and Greenbrier Counties, West Virginia showing location of sections (after Cardwell and others, 1968). The striped area shows the outcrop of the Bluefield Formation.

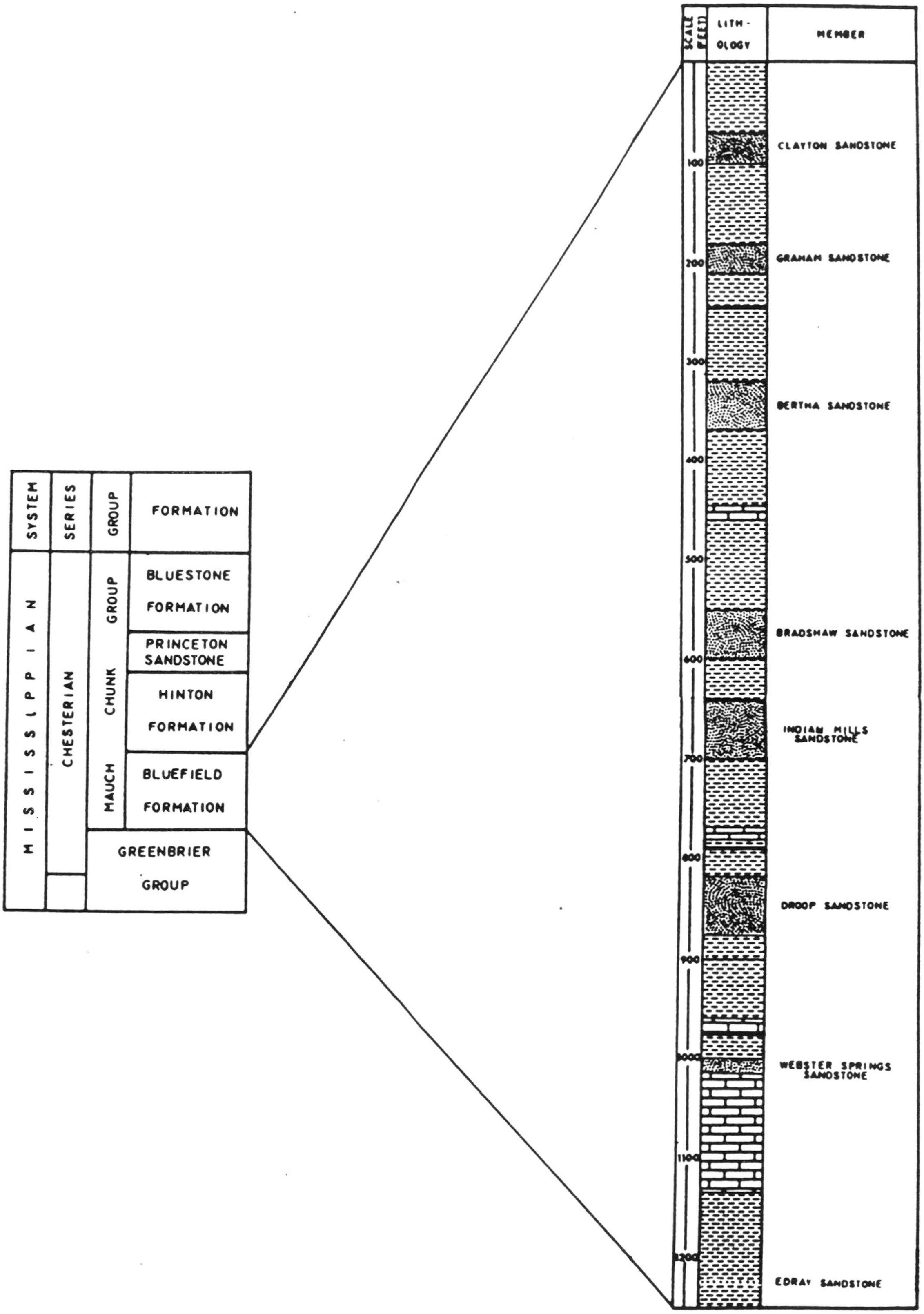

Figure 2. Generalized stratigraphic section for the Upper Mississippian of southeastern West Virginia (after Reger, 1926; Arkle and others, 1979).

Mercer County, West Virginia, and thins northwestwardly to a minimum of 15 meters. It consists predominantly of cherty, argillaceous, sandy and oolitic limestone with some interbedded shale (Arkle and others, 1979); and it was deposited in a shallow open marine setting (Englund, 1979).

The Bluefield Formation is composed of intercalated gray and green shale, limestone, and sandstone with minor red shale in its lower part; and green, gray and red sandstone and shale with minor limestone and coal in its middle and upper portions (Arkle and others, 1979; Reger, 1926). It reaches its maximum thickness of 400 meters in Mercer County, West Virginia, and thins to the north and northwest. This is due partly to stratigraphic convergence and partly to Early Pennsylvanian erosional truncation. This same thickness trend holds for all Mississippian rocks in the region, but erosion is a factor mainly in the upper part of the Mississippian (Arkle and others, 1979; Youse, 1964). The Bluefield was deposited largely under nearshore marine conditions in a shallow, slowly subsiding basin (Arkle and others, 1979; Englund, 1979; Whisonant and Scolaro, 1979; Humphreville, 1981). Depositonal environments represented by Bluefield strata range from normal marine carbonates to nearshore muds, sands, and freshwater marshes deposited in a system influenced by tidal energy (Whisonant and Scolaro, 1979; Humphreville, 1981).

The Hinton Formation is composed of interbedded red, partly calcareous shale and siltstone, ferrugenous and calcareous sandstone, fossil-bearing limestone and minor coal (Arkle and others, 1979). It represents shallow marine, barrier bar, tidal flat and fresh-water marsh environments (Craig and Varnes, 1979; Hobday and Horne, 1979; Colton, 1970).

The main structural feature in the study area is the St. Clair thrust fault. It extends from Allegheny County, Virginia southward at least to Richlands, Virginia (Gwinn, 1964), and it represents the major structural boundary separating the gently folded Appalachian Plateau Province from the more extensively deformed Valley and Ridge Province (Rogers, 1963).

Another important feature in the area is the Hurricane Ridge Syncline, described by Reger (1926) in both Mercer and Monroe Counties, West Virginia, with the St. Clair Fault forming the eastern margin of the syncline (Fig. 1). McDowell (1982) separated the Hurricane Ridge Syncline of Reger into the Glen Lyn, Hurricane Ridge, and Caldwell Synclines. He defined the Glen Lyn as the overturned syncline which runs parallel and adjacent to the St. Clair Fault. The Hurricane Ridge Syncline is found in southern Mercer County, West Virginia. The Caldwell is a broad, open fold extending northward from central Monroe County, West Virginia (Fig. 1). McDowell considers this to be an extension of the Caldwell Syncline of Price and Heck (1939). In addition, Reger (1926) mapped the Abbs Valley Anticline throughout Mercer and Monroe Counties, West Virginia, but McDowell (1982) stated that this anticline extends only to Mercer County and is not found in Monroe County.

Elsewhere in Monroe and Summers Counties, West Virginia, Reger (1926) named numerous anticlines and synclines, the limbs of which dip on the order of a few degrees. Folds extending from northern Monroe County north into Greenbrier County become more more steeply dipping.

METHODS

Nineteen sandstone outcrops from 14 localities were measured, described, and sampled for this study (Fig. 1). They were chosen according to accessibilty and completeness of section. Samples were taken to best represent the dominant lithology and any variations in lithology (Table 1).

Ninety-five thin sections were examined, 82 of which were point-counted to determine mineralogy by identifying 300 grains along a traverse normal to bedding. Average grain size was determined by measuring the apparent long axes of 100 quartz grains per thin section. Quartz alone was used in order to eliminate bias.

X-ray diffraction analysis (XRD) utilized uncovered thin sections and whole-rock oriented slides. All thin sections were examined via XRD to determine the composition of carbonate (where present) and presence or absence and type of feldspars. This analysis also aided in determination of clay mineralogy. Twenty samples, selected to best represent dominant lithologies within Bluefield sandstones, were crushed, wetted, and allowed to settle on glass slides in order to enhance basal clay reflections. These oriented slides were used to further analyze the clay mineralogy.

A modified version of Folk's 1974 sandstone classification scheme is used for this study. The basic method and format is retained for those rocks that are relatively clean (matrix less than 10%). Rocks with more than 10% matrix are treated similarly to Dott's 1964 classification but superimposed on Folk's basic format. For example, a

TABLE 1

Section	Sandstone	Outcrop	Sand-stone Type	Number Samples	Number Thin Sections
1-Red Sulpher Springs	Clayton	1a	1	7	2
	Graham	1b	1	6	2
	Bradshaw	1c	1	6	2
	Indian Mills	1d	1	5	2
2-Buck	Clayton	2a	1	10	2
	Graham	2b	2	17	10
3-Talcott #1	Clayton	3a	1	9	2
	Bertha	3b	1	4	2
4-Marie	Bertha	4	mixed	14	7
5-Bertha	Bertha	5	mixed	13	6
6-Big Bend	Bradshaw	6	mixed	15	8
7-Pence Springs	Bradshaw	7	1	6	4
8-Rock Camp	Indian Mills	8	2	14	6
9-Talcott #2	Droop	9	2	15	8
10-Alderson	Droop	10	2	34	8
11-Alta	Droop	11	2	22	7
12-Assurance	Webster Springs	12	1	7	4
13-Wayside	Webster Springs	13	1	11	9
14-Greenville	Edray?	14	1	4	4
				219	95

litharenite under Folk's classification with greater than 10% matrix is called a lithic wacke (Fig. 3).

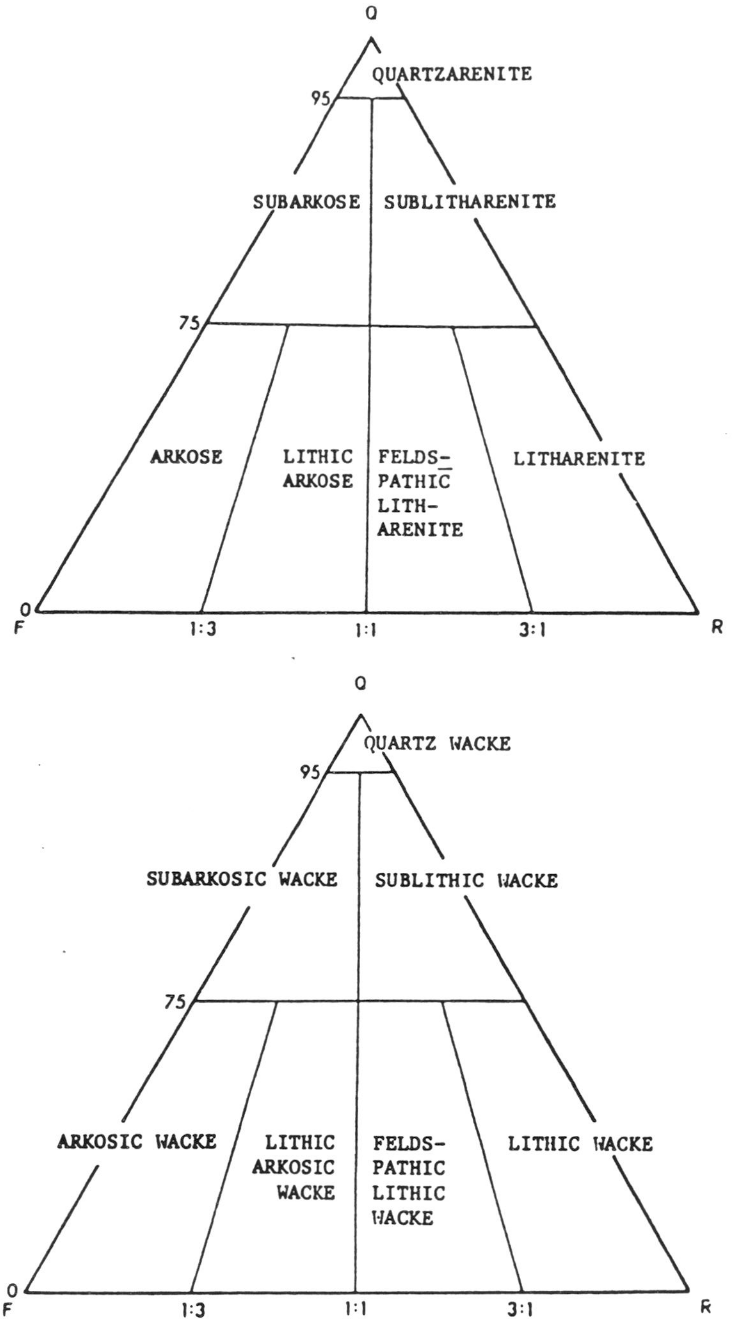

Figure 3: Classification scheme used for Bluefield Formation sandstones (after Dott, 1964 and Folk, 1974). Q represents quartz, F, feldspar and R, rock fragments.

SUBDIVISION OF SANDSTONES

The sandstones of this study represent the coarser-grained detrital units of the Bluefield Formation. Based on compositional and textural criteria, including grain size, petrography, and outcrop development, they have been divided into two groups, termed Type 1 and Type 2 sandstones.

Outcrops of Type 1 sandstones, the most common type, tend to be thin (10 to 20 feet). In outcrop, Type 1 sandstones are generally green, red, or mixed green and red on fresh surfaces, shaly to flaggy and occasionally massive, and ripple-marked. Most are shaly towards their base and have a gradational lower contact. Coarsening upward sequences are common, the uppermost beds ranging from flaggy to massive with a sharp upper contact.

Type 2 sandstones, which contain the coarsest-grained detritus within the Bluefield, occur in thicker exposures (greater than 20 feet) of its sand members. In outcrop, they are thick-bedded and coarse-grained and range from flat-bedded to cross-bedded to massive. Cross-bedding is typically medium- to large-scale and high angle. Both planar and trough cross-bedding are present. Most Type 2 sandstones are white to buff in color but may, in part, be greenish or brownish. Typically, they are composed of coarse-grained, clean sand but may have shale interbeds or lenses. No fining or coarsening trends are noticeable in outcrops composed entirely of Type 2 sandstone; however, fining upward sequences can be recognized in thin section.

Type 2 sandstones are best represented by the Droop Sandstone which provides three of the five outcrops (9, 10, and 11) that are composed entirely of Type 2 sandstone. Only two other outcrops (2b and 8) are composed entirely of Type 2 sandstone. These outcrops represent localized areas of thickening and coarsening within the Graham and Indian Mills Sandstones, respectively. Three outcrops (4, 5, and 6) contain both Type 1 and Type 2 sandstone intervals. The basal portion of outcrop 4 (Bertha Sandstone) is composed of Type 2 sandstone which fines upward into Type 1 sandstone. Outcrop 5 (Bertha Sandstone) includes Type 2 sandstone at the top and bottom of the outcrop, between which there is Type 1 sandstone. Outcrop 6 (Bradshaw Sandstone) is composed of intercalated Type 1 and Type 2 sandstones with minor limestone and shale interbeds.

Figure 4 is a plot of quartz percentage vs grain size for all samples in this study. The line on the diagram separates Type 1 from Type 2 sandstones. Type 2 sandstones are coarser-grained and richer in quartz than Type 1 sandstones. The dividing line was drawn visually and is somewhat arbitrary, serving primarily for descriptive purposes. Note that quartz percentage varies dramatically in Type 1 sandstones, whereas grain size, and not quartz percentage, varies widely in Type 2 sandstones. Other differences are associated with this subdivision. Type 1 sandstones are generally more mineralogically diverse and are typically richer in matrix, rock fragments, feldspar, carbonate and accessory minerals. Type 2 sandstones are richer in quartz, cleaner (better washed), better sorted, and constituents are better rounded than Type 1 sandstones. Typical examples of Type 1 and Type 2 sandstones, as seen in thin section, are shown in Plates 1 and 2, respectively.

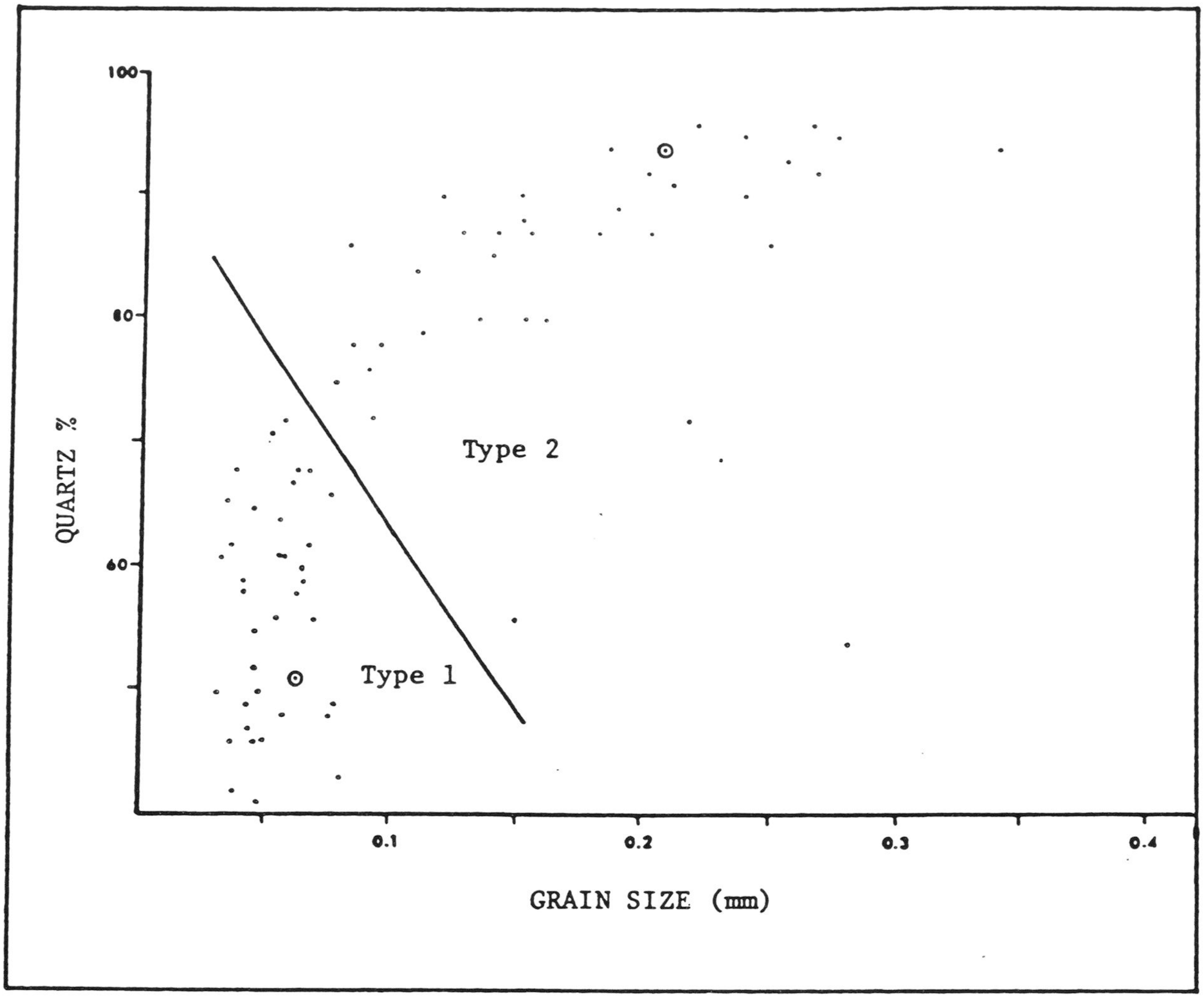

Figure 4: Quartz percentage vs grain size. Type 2 sandstones are to the right of the line; Type 1 sandstones are to the left of the line. Circles indicate multiple samples.

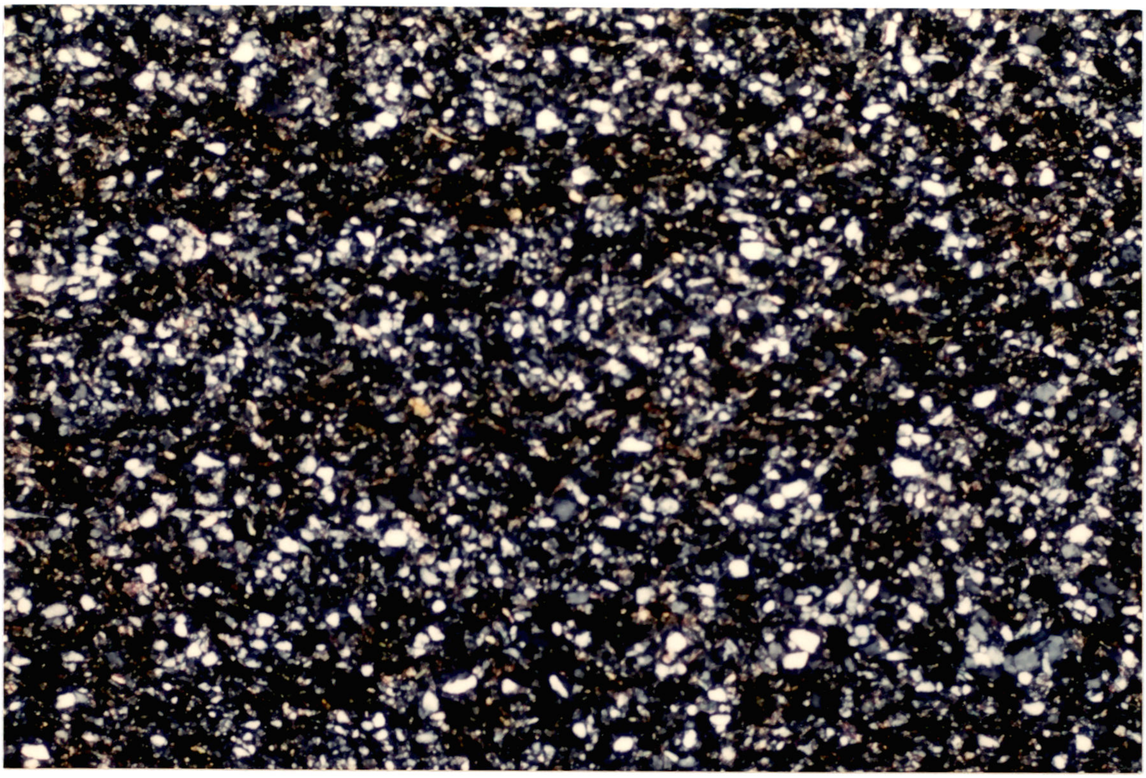

Plate 1: Typical development of Type 1 sandstone (crossed nichols, 25x).

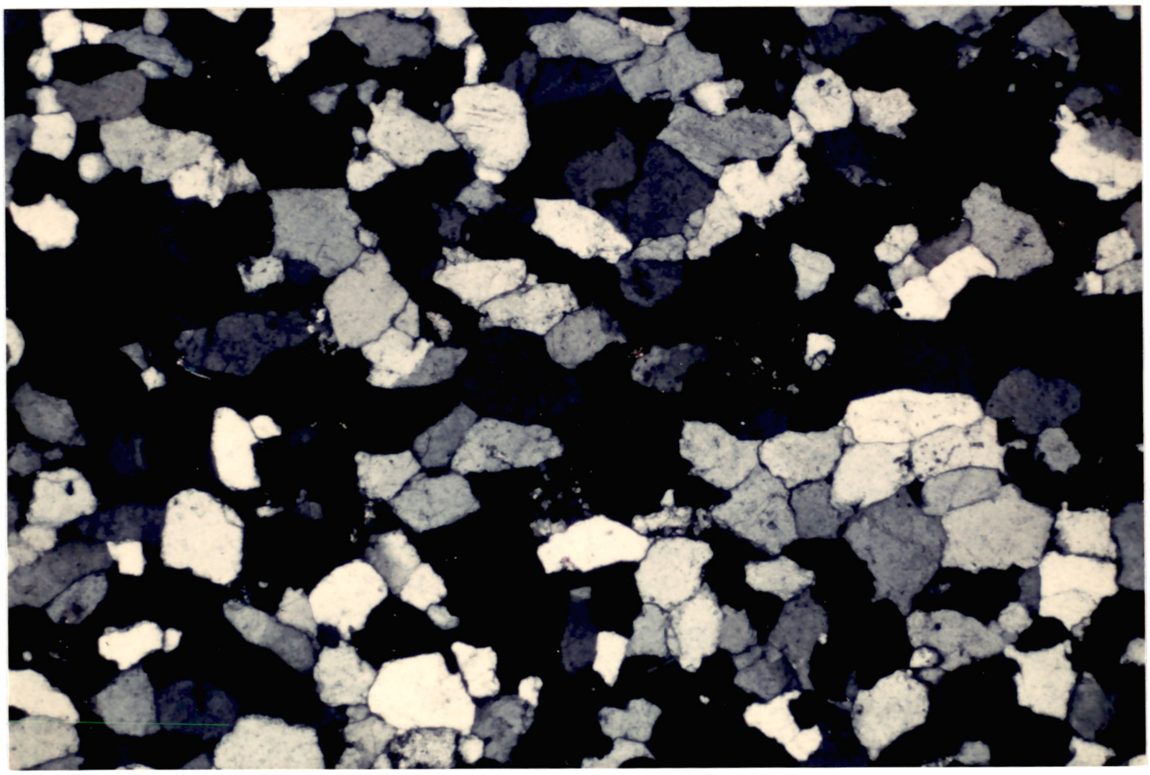

Plate 2: Typical development of Type 2 sandstone (crossed nichols, 25x).

TYPE 1 SANDSTONES

CLASSIFICATION

Individual samples of Type 1 (fine-grained, impure) sandstones are plotted on a ternary QFR diagram in Figure 5. Data for this diagram are listed in Appendix B. Outcrops 4 and 5 of the Bertha Sandstone and outcrop 6 of the Bradshaw Sandstone contain samples of both Type 1 and Type 2 sandstone which are plotted on Figures 5 and 7, respectively. More than half of the samples of Type 1 sandstone are litharenites or lithic wackes, which are, in turn, approximately even in number. The remainder are sublitharenites or sublithic wackes with the exception of one quartzarenite. This sample, as well as those that plot at the quartz-rich end of the sublitharenite region, is high in either matrix, carbonate or a combination of both constituents. All but three of the samples which fall in the sublitharenite/sublithic wacke and quartzarenite regions are from sandstones in the lower part of the Bluefield (Webster Springs and Edray Sandstones).

The averages for each outcrop of Type 1 sandstone are plotted in Figure 6. Most outcrops are lithic wackes or litharenites. Outcrops 13 and 14 (lower Bluefield sandstones), however, plot as sublitharenite and sublithic wacke, respectively. The grand mean of Type 1 sandstones falls near the quartz-rich end of the lithic wacke range. Outcrops 4 and 5 of the Bertha Sandstone and outcrop 6 of the Bradshaw Sandstone are composed of both Type 1 and Type 2 sandstone. Similar samples from these outcrops are grouped, averaged and plotted together in Figure 6. Therefore, each of these outcrops is represented by 2 plots, one

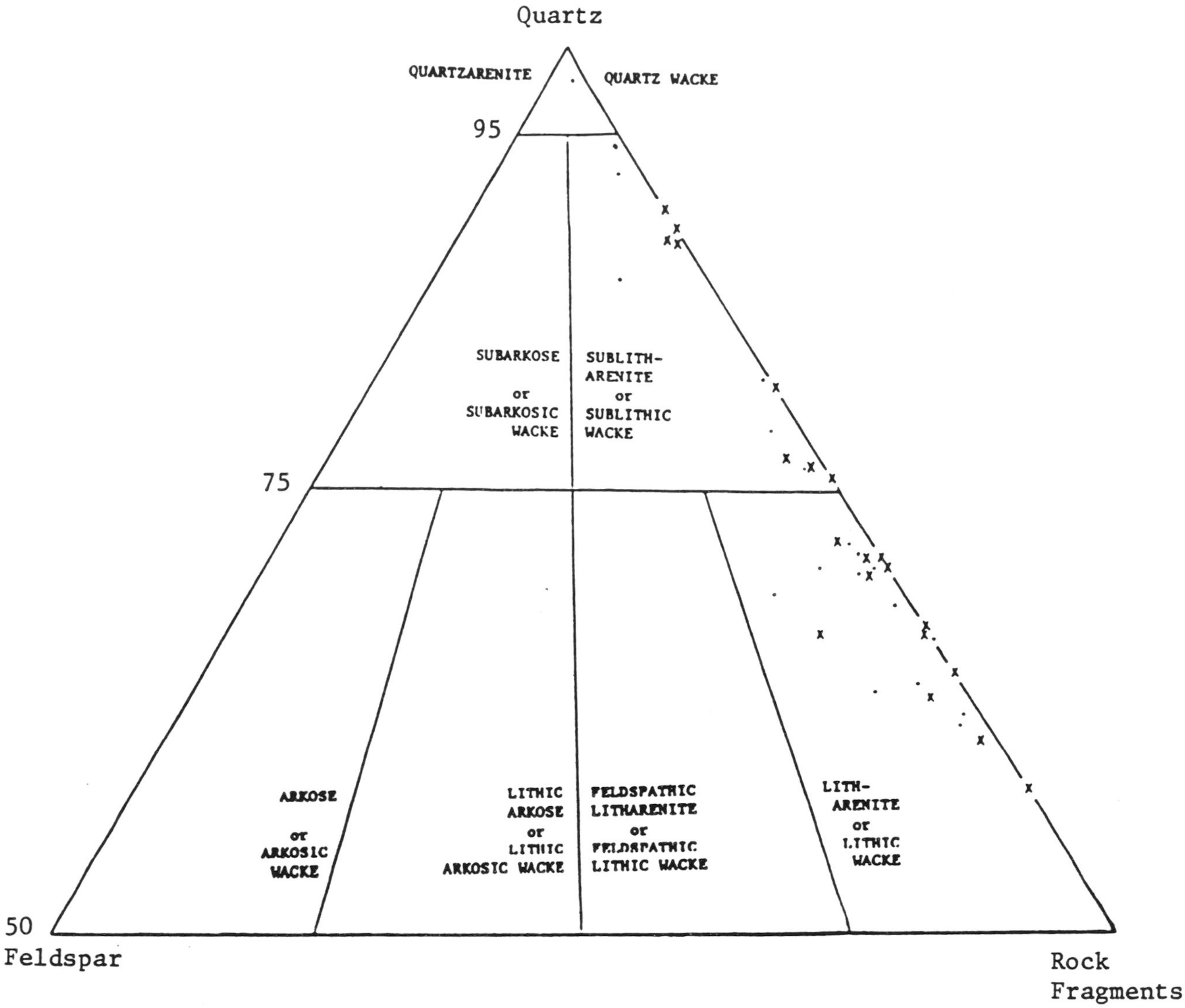

Figure 5: Classification of Type 1 Bluefield Formation sandstones showing all samples. Arenites (less than 10% matrix) are symbolized as dots. Wackes (greater than 10% matrix) are shown with an "x".

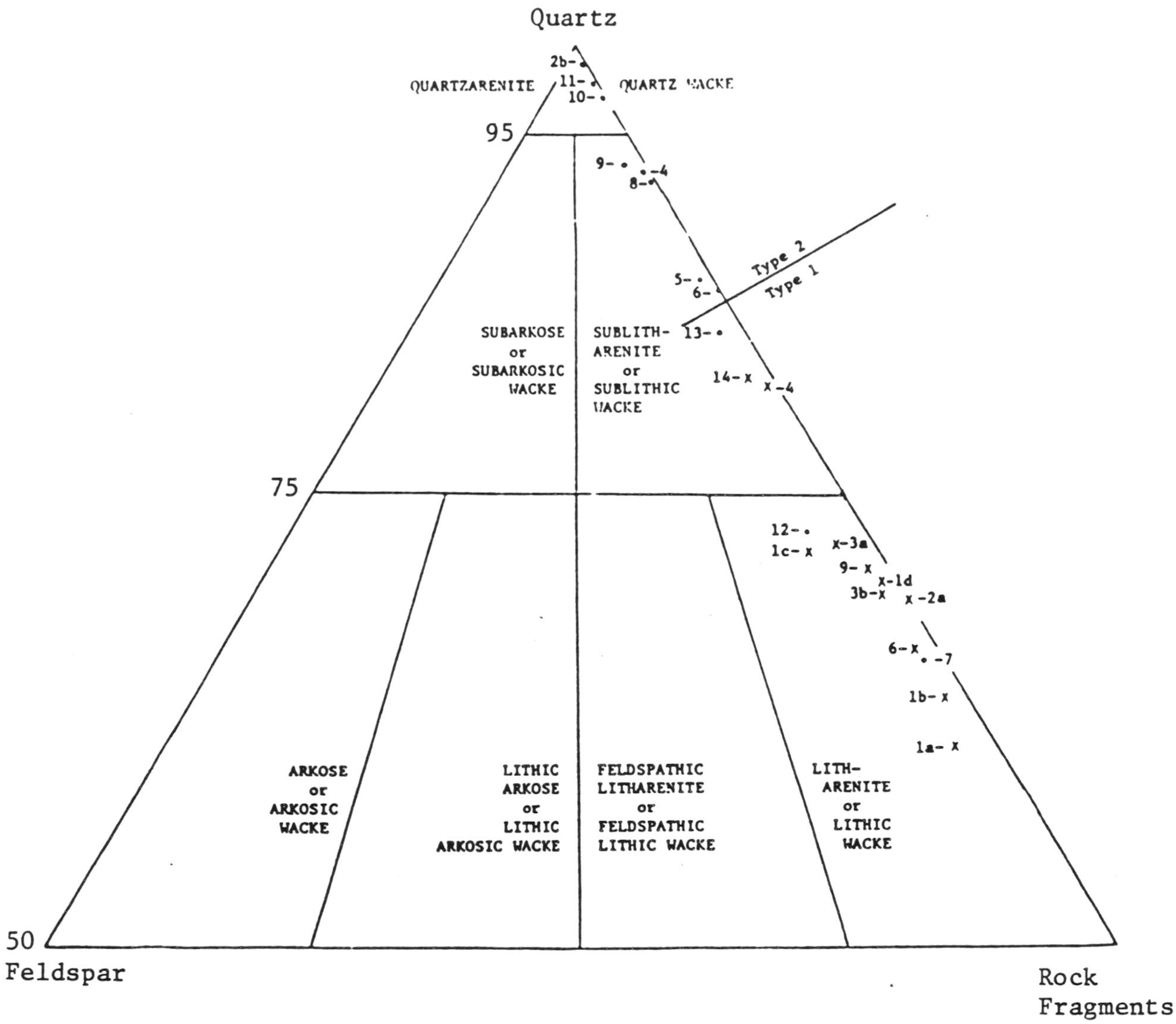

Figure 6: Classification of outcrops of Bluefield sandstones. Numbers refer to outcrops. Arenites (less than 10% matrix) are symbolized as dots. Wackes (greater than 10% matrix) are shown with an "x".

representing Type 1, and one representing Type 2 components within each sandstone.

GRAIN SIZE

Type 1 sandstones range from medium silt to very fine sand as measured in thin section. Calculated grain size averages for all but one Type 1 sandstone outcrop fall in the coarse silt size range. All are composed of both silt and sand interbeds. Approximately half (outcrops 2a, 1c, 7, 12 and 14) are dominated by sand interbeds and the calculated coarse silt grain size is due to sampling bias. Remaining Type 1 outcrops (outcrops 1a, 1b, 3b, 1d, and 13) are dominated by silt interbeds and represent siltstone horizons of the sandstones. Calculated grain size averages for outcrops which contain both Type 1 and Type 2 sandstone interbeds (outcrops 4, 5 and 6) fall in the very fine sand range; but they contain rocks ranging from coarse silt to fine sand.

PETROGRAPHY

Quartz

The most abundant detrital constituent in Type 1 sandstones is quartz. The mean for all samples is 55.8% and the range is from 41.0% to 71.7%. Grain shape varies from subround to angular and most grains possess low sphericity. Most grains are monocrystalline with straight to slightly undulose extinction. Polycrystalline grains and grains with strongly undulose extinction are rare. Quartz grain size is generally uniform throughout a given sample, but many samples consist of interlayered quartz-rich and phyllosilicate-rich intervals. Most grains are clear and lack inclusions. Vacuoles and inclusions (e.g., rutile) are present in trace amounts.

Rock Fragments

Rock fragments, the second most abundant constituent in Type 1 sandstones, are predominantly metamorphic rock fragments (MRFs). Rock fragments range from 0.0% to 43.7% and average 21.5%.

MRFs range from 0.0% to 30.0% and average 18.3%. MRFs consist of slate, phyllite and schist fragments, with phyllite fragments predominating. They are distinguished from sedimentary rock fragments (SRFs) by the orientation of clays and/or the large size and parallel orientation of micas within the fragments. The most abundant mica within the MRFs is muscovite, followed by biotite, chlorite and undifferentiated micas. Chlorite schist fragments are present in small amounts and are distinguished by their color. MRFs are typically elongate, with their long axes usually greater than those of associated quartz grains.

SRFs range from 0.0% to 30.7% and average 3.2%. SRFs consist of shale fragments, rare chert, and very rare siltstone clasts. They are distinguished from MRFs by lack of orientation of their constituent clays. Many grains are gradational between MRF and SRF. Some orientation may occur in SRFs due to extremely low energy during deposition, or due to diagenetic alteration during lithification. Most SRFs are well-rounded, equant to elongate, and are often somewhat larger than surrounding quartz grains. Rip-up clasts are also present. These clasts are often very large relative to other constituents (typically 2 to 3 mm, but up to 1cm in length); they are typically elongate and highly angular, indicating very short transport distances, and hence are considered intrabasinal.

Deformation of both MRFs and SRFs is very extensive in some cases. This feature has been called pseudomatrix (Scholle, 1979). This phenomenon, plus the fine-grained nature of these samples, makes the precise differentiation of rock fragments and matrix difficult.

Feldspars

Feldspar percentages, as measured by point count, range from a trace to 5.3%, and average 1.0%. Feldspar grains are typically equant to somewhat elongate, and vary from rounded to subangular. Plagioclase was the only type of feldspar encountered during microscopic examination. Using the Michel-Levy method to estimate composition, grains appear to be high sodium plagioclase (oligoclase or perhaps higher). Uncovered thin sections were examined by X-ray diffractometry. In almost every case, plagioclase is indicated by the X-ray pattern. It is generally believed that plagioclase must make up at least 5% of a given sample in order to register on an X-ray pattern (Carroll, 1970). Point count data may, therefore, underrepresent feldspar. Staining of selected samples for plagioclase and potassium feldspar yielded negative results, indicating that no potassium feldspar is present. The stain for plagioclase requires the presence of calcium in the feldspar structure, thus high sodic-low calcic plagioclase does not stain. Therefore, plagioclase in these samples is considered to be highly sodic. Plagioclase may be overlooked during optical examination due to lack of twinning, lack of alteration, small size, or inclusion within rock fragments.

Alteration of feldspars within Type 1 sandstones is variable. Much of the feldspar is clear, but some is cloudy due to varying degrees of alteration, generally kaolinitization. The degree of alteration often varies widely within a given sample, probably due to compositional differences or variations in microporosity.

Carbonate

Carbonate occurs in most Type 1 sandstones, ranging from 0.0% to 48.3% among samples, from 0.0% to 20.9% within the individual sandstones (i.e., the averages for individual sandstones), and averaging 4.0% overall. Dolomite, the predominant carbonate mineral, appears to be secondary after calcite. Traces of high-Mg-calcite are present. Carbonate occurs as large pore-filling, occasionally poikiolitic grains and as a granular matrix-like texture. Calcite occurs as large pore-filling grains while dolomite occurs both as large grains and as a granular matrix-like texture. Carbonate grains are clear and unaltered or partly to wholly stained or replaced by hematite.

Accessory Minerals

Accessory minerals found in Type 1 Bluefield sandstones include muscovite, biotite, chlorite, hematite, pyrite, zircon, tourmaline, rutile and opaques. Together they constitute from a trace to 13.3% and average 3.8% of Type 1 sandstones. The micas (muscovite, biotite, and to a lesser extent chlorite) are the most abundant of these minerals in most samples. Occasionally, hematite and, more rarely, opaques predominate. The micas are elongate and usually bent or kinked due to compaction. They occur as randomly distributed grains, but coarse-grained micas are often concentrated along bedding planes. Fine-grained micas associated with MRFs and clay minerals are concentrated into zones alternating with quartz-rich zones. Hematite is found as a stain, grain coatings, pore-filling cement, along stylolites, in association with carbonate as a replacement mineral, as fracture-fill, and as large subhedral to euhedral crystals which may be pseudomorphic after pyrite.

Pyrite is found in only a few samples where it forms large euhedral crystals. In a few samples it is found as shapeless masses, or as pyrite framboids. In one sample it is found filling circular pores within a plant fossil. Zircon is ubiquitous in trace amounts. Grains are typically small, well-rounded and highly spherical to slightly elongate. A minor fraction is larger, more elongate, and often exhibits euhedral terminations. Well-rounded, highly spherical, blue and green pleochroic tourmaline is present in trace amounts. Some types of accessory minerals are found concentrated along bedding planes.

Matrix

Matrix material ranges from 0.0% to 28.7% and averages 13.7% of Type 1 sands. Matrix includes very fine-grained material (approximately 0.02mm or less) and grains without definite shape. Shapeless material includes deformed grains, a feature called pseudomatrix (Scholle, 1979).

Pseudomatrix occurs during compactional deformation when softer grains, such as SRFs and low grade MRFs, are squeezed into the interstices between harder grains such as quartz (Scholle, 1979). Thus, matrix includes pseudomatrix, detrital clays, authigenic clays, and fine-grained and/or shapeless material. Matrix is often stained by iron oxide (hematite) which severely hampers differentiation.

DIAGENESIS OF TYPE 1 SANDSTONES

Diagenetic alteration of Type 1 (fine-grained) Bluefield sandstones takes the form of reduction or occlusion of primary porosity through mechanical compaction, carbonate cementation, hematite cementation, and pressure solution. Porosity reduction due to growth of authigenic clay also occurred. Stylolites are common in these sandstones. Rare secondary porosity is present in the form of moldic and fracture porosity.

MECHANICAL COMPACTION

Mechanical compaction was the most important process in lithification and occlusion of primary porosity in Type 1 sandstones. This is evidenced by the distortion of labile fragments (MRFs, SRFs, and micas), which are typically bent or kinked at one or more points along their lengths. The compression squeezes portions of the relatively soft labile grains into the interstices between more rigid grains (largely quartz), thereby filling pore space and affecting lithification. Some labile grains were so distorted as to obscure their original character, creating pseudomatrix. Larger grains, particularly the large micas, appear to have undergone greater amounts of distortion than smaller grains. Compaction was particularly effective in reducing porosity and enhancing lithification in samples with high percentages of labile grains. Plagioclase grains also show signs of deformation. Occasional grains were fractured and separated parallel to twin planes, while others were kinked at high angles to twin planes.

Fractures are common in Type 1 sandstones. Most are oriented parallel to bedding; but a few are oriented at high angles to bedding, probably due to overburden stress (i.e., vertically oriented compressive stress causes horizontal tensional strain and fracturing). Fractures oriented parallel to bedding are most likely caused by release of overburden stress.

CARBONATE CEMENTATION

Carbonate cementation is common in Type 1 sandstones. It is found largely as pore-filling cement in clean, quartz-rich samples, but is also found in oversized pores, randomly distributed "patches" and as fracture-fill cement.

The pore-filling carbonate cement and the carbonate found in random patches is mostly dolomite, with lesser amounts of calcite; although in some samples calcite is more abundant than dolomite. Trace amounts of high-Mg-calcite are also present. Calcite usually occurs as remnants within dolomite, suggesting dolomitization of an original calcite cement (Plate 3). Dolomitization may have occurred due to migration of Mg-rich fluids derived from diagenesis of clays in associated shales or from within the sandstones themselves. Permeabilities in calcitic zones, however, may have been too low to permit infiltration of Mg-rich fluids. Alternatively, the Mg-bearing fluids may have become depleted in magnesium during the course of dolomitization allowing preservation of some original calcite cement.

In some cases, carbonate appears to replace quartz grains along their margins. The quartz grains are corroded and embayed at their

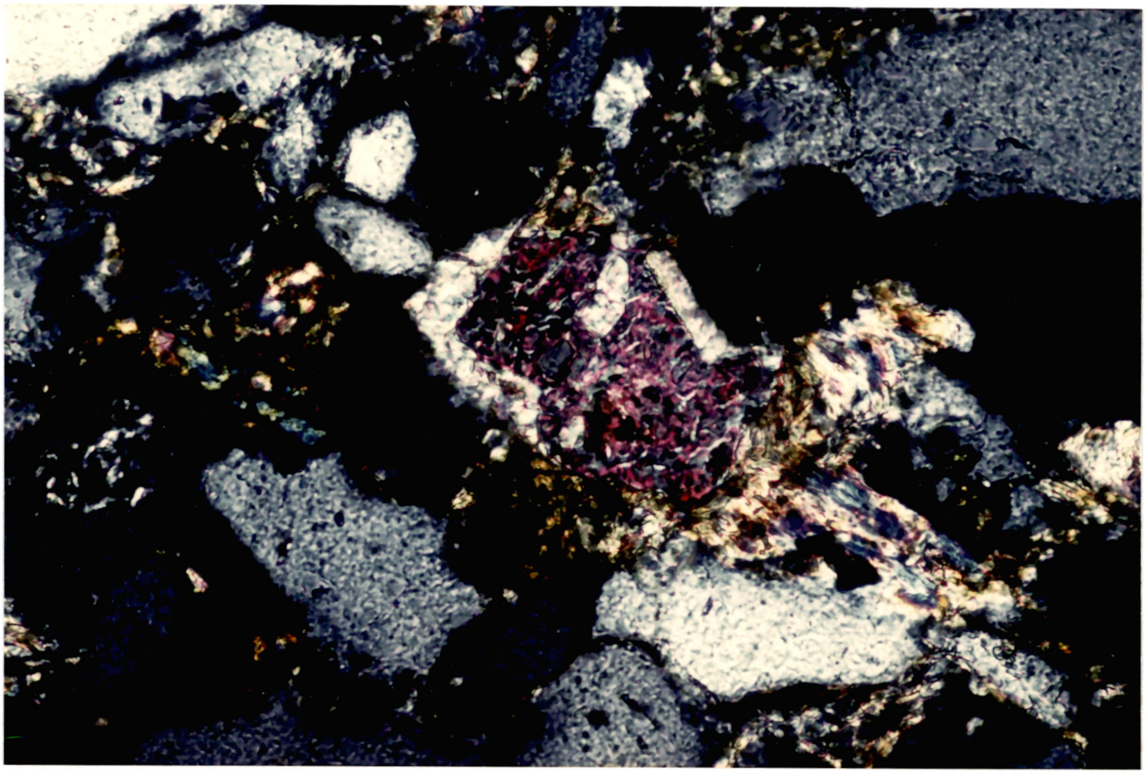

Plate 3: Carbonate grain with calcite core and dolomite rim in Type 1 sandstone (crossed nichols, 250x).

contacts with the replacing carbonate. Dolomite rhombs sometimes penetrate quartz grains, suggesting replacement rather than a solution-precipitation event. Alternatively, quartz overgrowths may have included the dolomite rhombs. Carbonate also occupies isolated, oversized pores in many of these sandstones, as well as pores approximating the average grain size of the sample involved. In these cases, precipitation of carbonate in pre-existing moldic or intergranular pores, perhaps with additional replacement of surrounding grains, may be indicated.

Carbonate "patches" on the order of 0.5mm in diameter occur within the lower Bluefield sands. These are typically ovoid in shape, resembling the cross-section of a small bivalve. The ovoid may be completely cemented by large calcite crystals, but the central portion is usually cemented by megaquartz (coarse-grained authigenic quartz), hematite, and/or calcite with dolomite surrounding the ovoid and decreasing in abundance away from it. Organic matter is often intermixed with the surrounding dolomite. These features are interpreted as follows: an original articulated fossil preserved pore space within the fossil; later the original shell material was mobilized and/or recrystalized and dolomitized; the central cavity was then cemented by calcite, quartz, and/or hematite (Plate 4).

Carbonate also fills fractures. Unlike other carbonate found in Type 1 Bluefield sandstones, the fracture-fill carbonate is composed entirely of calcite. This indicates that a second carbonate cementation phase occurred after dolomitization. Pore space is sometimes present between fracture-fill cement and walls of the fracture, indicating that

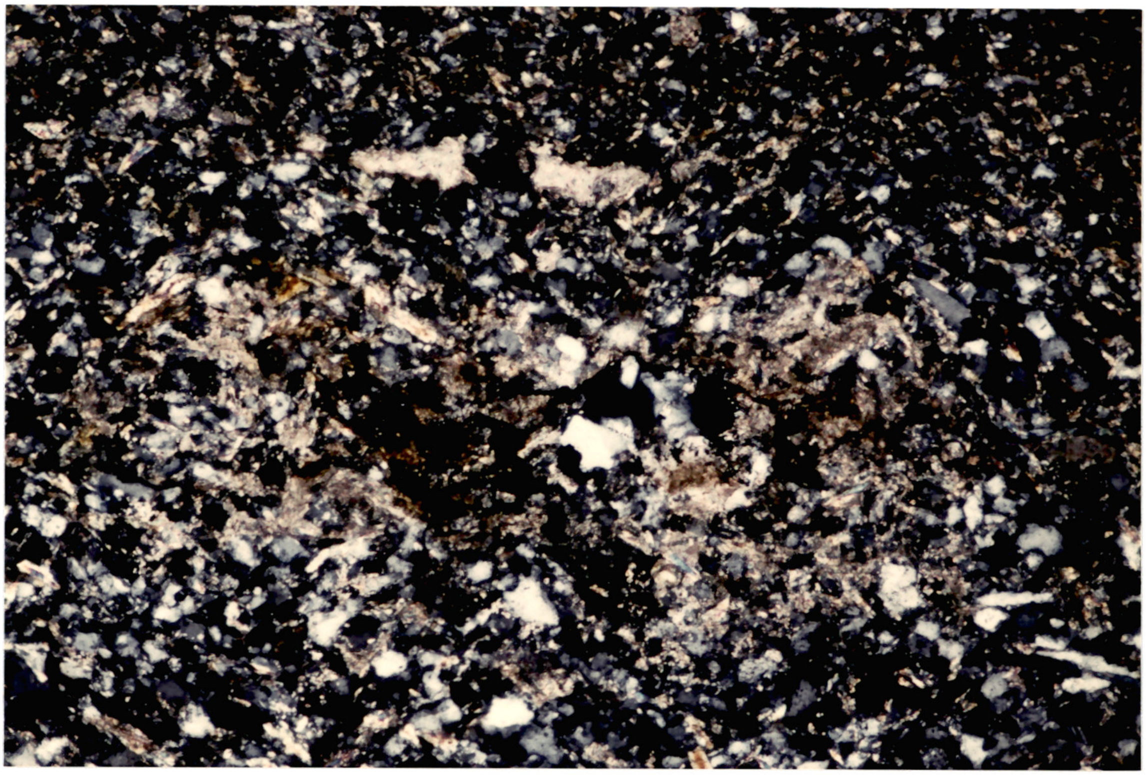

Plate 4: Ovoid in lower Bluefield sandstone largely cemented by quartz (crossed nichols, 63x).

reactivation of the fracture occurred after cementation, that leaching of the cement occurred, or that spreading of the fractures occurred during the thin section process. Generally, the calcite shows no sign of corrosion, suggesting that the pore space associated with the fracturing is due to reactivation or is a thin-section artifact. Other fractures are devoid of cement because they were not originally cemented or any original cement was totally leached out.

IRON MINERALS

Iron oxide (hematite) is present in Type 1 sandstones as 1) a stain and disseminated fine particles, 2) a replacement of carbonate, 3) large euhedral crystals, and 4) fracture-fill. Iron oxide in Bluefield Formation occurs as a stain and disseminated fine particles in red sands which are intercalated, often finely, with green sands. The color difference reflects the oxidation state of the iron. Chlorite is partly responsible for the coloration of the green sandstones. The degree of staining and abundance of iron oxide varies widely, possibly due to permeability differences. Hematite mixed with matrix and strongly strained labile fragments often make differentiation of these components difficult or impossible. Small disseminated grains of hematite are present in association with the hematite stain.

Calcite and dolomite were both subject to replacement by iron oxide, ranging from staining along cleavage traces to total replacement. The occurrence and degree of replacement often varies greatly over small distances, perhaps indicating an advanced stage of lithification at the time of hematitization. Scholle (1979) notes that hematitization may occur late in diagenesis. Small-scale permeability differences may have been the controlling factor in replacement.

Hematite also occurs as subhedral to euhedral crystals up to 0.25mm in diameter. In a few samples of green Type 1 sandstones, pyrite also occurs as large euhedral crystals of approximately the same size and shape. A few of these crystals have a pyrite core and a hematite rim (Plate 5). Hematite is probably pseudomorphic after pyrite. The large size and euhedral shape of the pyrite crystals indicates diagenetic origin. Pyrite also occurs in other forms in Type 1 sandstones.

Some of the fractures present in Type 1 Bluefield sandstones are cemented by hematite. Often surrounding the hematite-filled fractures are "halos" of hematite stain and cement caused by lateral migration from the fracture through pore space and along microfractures. Scholle (1979) points out that fracturing infers extensive lithification, so this hematite phase was emplaced in a relatively late stage of diagenesis and possibly after exposure.

The source of the hematite is problematical. Hematite cementation is generally attributed to intrastratal solution of iron-bearing minerals (Blatt, Middleton, and Murrey, 1980; Walker, 1974, 1977). Iron-bearing minerals, such as pyroxenes and amphiboles, are lacking in both red and green Type 1 sandstones, although some magnetite may be present in the opaque accessory mineral fraction. The dearth of iron-bearing minerals in both red and green Type 1 sandstones suggests that they were not present at the time of deposition. Hence, the iron oxide probably originated from sources other than constituent iron-bearing minerals, possibly from iron-bearing fluids produced by

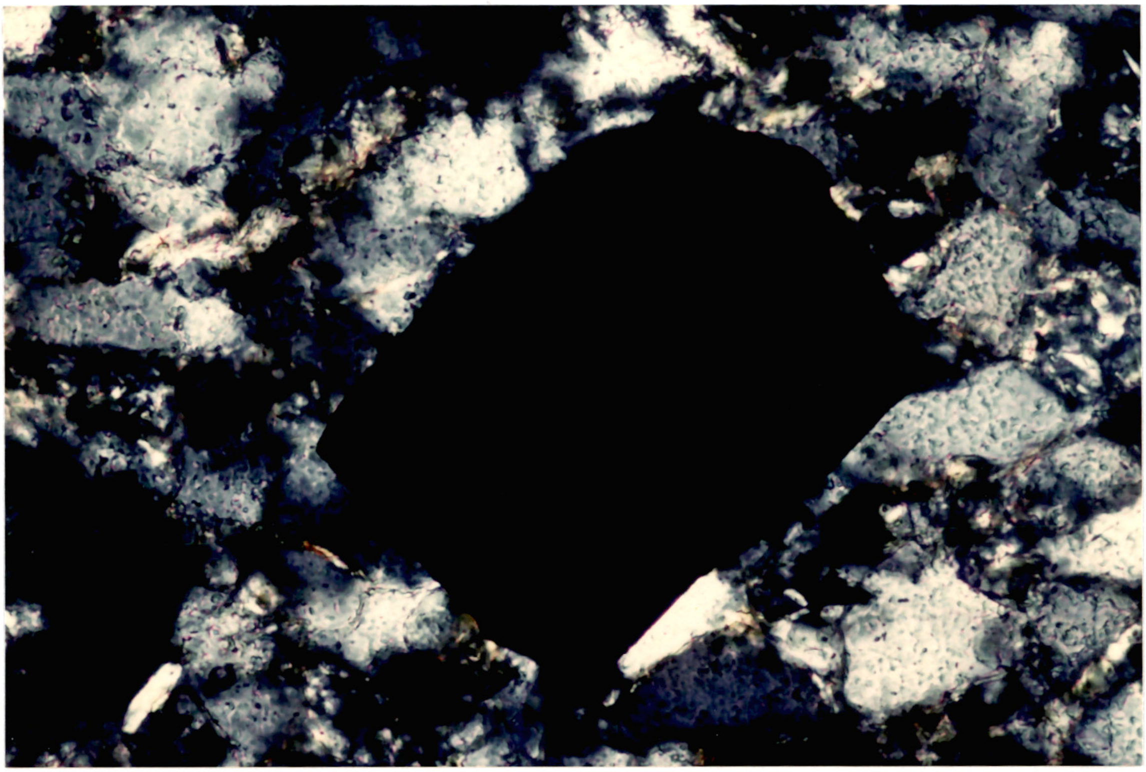

Plate 5: Euhedral hematite with pyrite core (crossed nichols, 250x).

solution of iron-bearing minerals in associated shales or by diagenesis of clay minerals in associated shales or within the sandstones themselves. Oxidation of pyrite may have contributed minor amounts of iron to the system.

PRESSURE SOLUTION FEATURES

When pressure from overburden or tectonism exceeds hydrostatic pore pressure, solution may occur. Two types of pressure solution features occur within Type 1 Bluefield sandstones; intergranular pressure solution and stylolites. Intergranular pressure solution involves mutual dissolution and interpenetration between individual grains; the solution surface generally does not extend into adjacent grains. Stylolites are much larger-scale features in which a solution surface extends across many grains. Intergranular pressure solution tends to occur prior to extensive lithification when stresses are concentrated at grain-to-grain contacts. After extensive lithification, stresses are more evenly distributed throughout the rock and dissolution, if it occurs, will tend to proceed along the larger scale more continuous stylolitic surfaces (Heald, 1956). However, stylolites have been known to occur prior to extensive lithification (Heald, 1959).

In samples that are relatively free of ductile material, such as rock fragments and matrix, and where carbonate cementation did not occur, intergranular pressure solution between quartz grains essentially occluded porosity. Where pressure solution occurred, quartz-to-quartz contacts are generally straight or curved, and a few are sutured. Such grain-to-grain contacts are characteristic of pressure solution (Heald, 1956). Sprunt and Nur (1977), in experimental studies on pressure solution, found that porosity loss (degree of pressure solution) increases with increased surface area; hence, finer grains are more susceptible to pressure solution. The fine grain size of Type 1 sandstones would have made them susceptible to pressure solution. Epitaxial quartz overgrowths, identified by thin "dust rims" present between the detrital core of the grain and its overgrowth, can be observed on some grains in samples that have undergone pressure solution. Straight, smooth and sutured contacts are characteristic of, but, not diagnostic of pressure solution; they may also be caused by simple epitaxial quartz cementation unrelated to pressure solution (Sibley and Blatt, 1976; Sippel, 1968). Therefore, quartz cementation unrelated to pressure solution may have been in part responsible for porosity occlusion in these areas.

Stylolites or solution features which are not restricted to contacts between individual grains are common in Type 1 Bluefield sandstones. Most stylolites reported in the literature are relatively large scale features that, according to Wanless (1979), "have a cross-section resembling the trace of a stylus on a chart recorder", with "relief along stylolite surfaces anywhere from less than 1 mm to tens of centimeters". Stylolites in Type 1 sands are of a smaller scale and lack the vertical relief referred to by Wanless. Stylolitic development occurs in Type 1 sands in two forms: 1) as "stylolitic seams" where solution has taken place along a distinct surface, and 2) as "solution seams" where solution has taken place not along a distinct surface but throughout a "broad vertical section" (Plate 6).

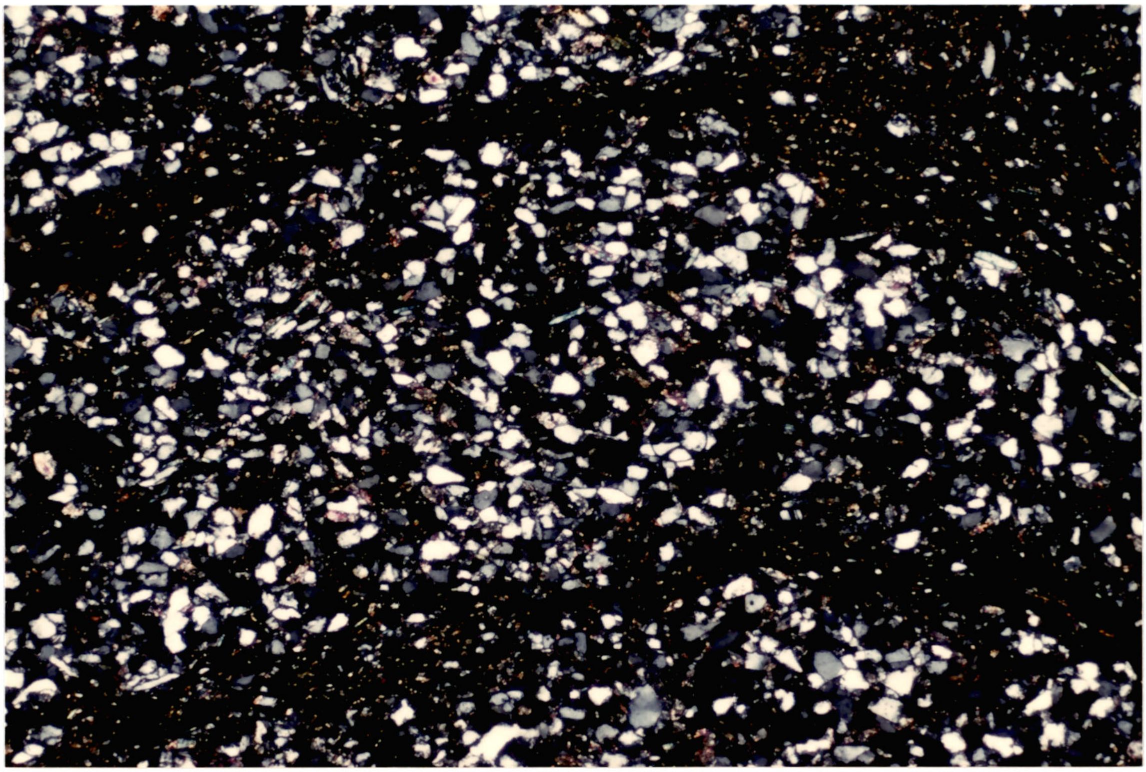

Plate 6: "Stylolitic seam" and "solution seam" in Type 1 sandstone (crossed nichols, 25x).

"Stylolitic seams" are identified by concentrations of insoluble materials such as clay, heavy minerals and/or organic material along the solution surface (Heald, 1955). "Stylolitic seams" in Type 1 sands are generally marked by clay and organic matter. These seams often bifurcate into "swarms" of smaller seams similar to the anastomosing swarms described by Wanless (1979). "Stylolitic seams" occur most commonly in matrix-rich samples and at the contacts between matrix-rich and matrix-poor intervals within samples. The concentration of the "stylolitic seams" in these intervals is due to differences in resistance to compressive stress between matrix-rich and matrix-poor intervals (i.e., solution will tend to occur in intervals less resistant to stress). The matrix-rich intervals are less resistant than the carbonate or quartz cemented matrix-poor intervals. These seams have frequently been stained by hematite which suggests that "stylolitic seams" may have served as conduits for migrating fluids during diagenesis. Also, some fractures are lined with residues of insoluble materials. Apparently, fracturing occurred preferentially along stylolites.

As with "stylolitic seams", insoluble materials are concentrated within "solution seams". These seams sometimes display vertical offsets which were apparently caused by differential movement resulting from continued compressional stress after or during solution. The vertical offsets frequently have hematite seams parallel to their lengths (perpendicular to bedding and parallel to overburden stress direction). Small scale dislocations must have developed allowing infiltration of the hematite.

AUTHIGENIC CLAY MINERALS

Authigenic clays are clearly indicated in only one sample where kaolinite, perhaps mixed with minor amounts of silica and/or chlorite, cements part of a fracture. Elsewhere, growth of authigenic clays probably occurred but, because of the combined effects of compactional deformation, hematite staining and the presence of detrital clays, identification of authigenic clays is impossible in Type 1 sandstones.

TYPE 2 SANDSTONES

CLASSIFICATION

Individual samples of Type 2 sandstones are plotted on a ternary QFR diagram (Figure 7). Data for this diagram are listed in Appendix B. Twenty-four samples plot as quartzarenites, two as quartz wackes, 11 as sublitharenites, and two as sublithic wackes. The two quartz wackes may be so classified because hematite was so thoroughly intermixed with other matrix material that it calculated as matrix. All sublitharenites are from the mid portion of the Bluefield (outcrops 4 of the Bertha Sandstone, 6 of the Bradshaw Sandstone, 8 of the Indian Mills Sandstone, and 9 of the Droop Sandstone). Feldspar percentages are much higher in outcrops 8 and 9 than in other Type 2 sandstones. Outcrops 4, 5 and 6 are composed of both Type 1 and Type 2 sandstone interbeds. Samples of Type 2 sandstone from these outcrops are also plotted on Figure 7.

Figure 6 plots the average of each outcrop. Three outcrops (2b of the Graham Sandstone, and 10 and 11 of the Droop Sandstone) plot as quartzarenites, whereas 5 outcrops (4 and 5 of the Bertha Sandstone, 6 of the Bradshaw Sandstone, 8 of the Indian Mills Sandstone, and 9 of the Droop Sandstone) plot as sublitharenites. The grand mean for Type 2 sandstones plots at the quartz-rich end of the sublitharenite region.

GRAIN SIZE

Grain size in Type 2 Bluefield sandstones ranges from 0.083mm to 0.281mm. Within individual samples, grain size is relatively uniform. The mean for the Droop Sandstone (outcrops 9, 10, and 11) is 0.181mm.

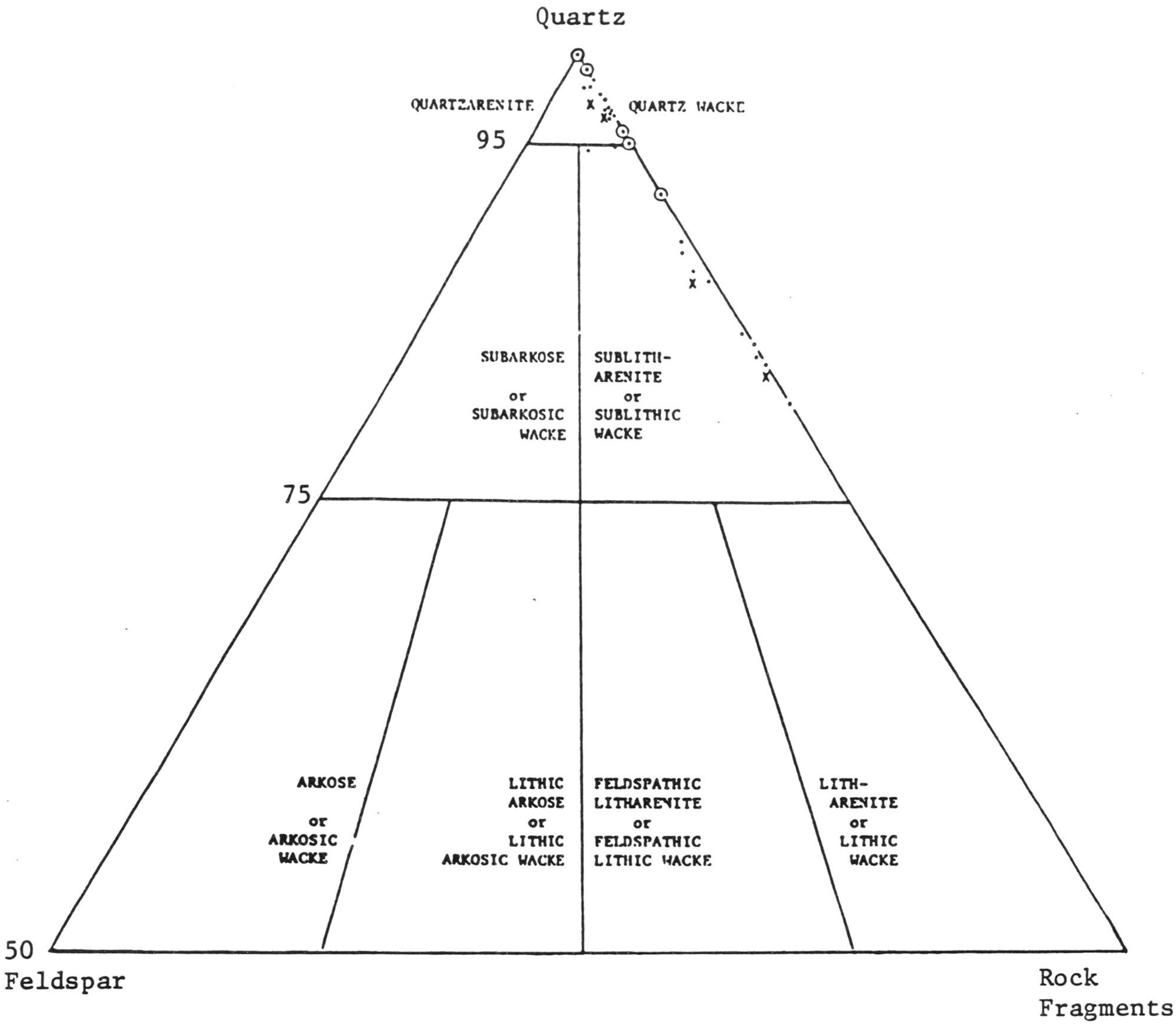

Figure 7: Classification of Type 2 Bluefield sandstones. Arenites (less than 10% matrix) are symbolized as dots. Wackes (greater than 10% matrix) are shown with an "x". Circles indicate multiple samples.

The mean for the Graham sandstone at Buck (outcrop 2b) is 0.255mm, marking the coarsest-grained detrital sediment found within the Bluefield during this study. The mean for the Indian Mills Sandstone at Rock Camp (outcrop 8) is 0.118mm. Grain size for Type 2 interbeds within outcrops composed of both Type 1 and Type 2 sand interbeds are; 0.103mm in outcrop 4 , 0.176mm in outcrop 5, and 0.092mm in outcrop 6; but they contain rocks ranging from coarse silt to fine sand. Quartz overgrowths and/or pressure solution obscures original detrital grain size in most samples.

PETROGRAPHY

Quartz

Quartz, the most abundant detrital constituent in Type 2 Bluefield sands, ranges in abundnce from 54.3% to 95.7% and averages 83.8%. Quartz overgrowths and/or pressure solution usually obscure original detrital grain shape. Where grain coats or dust rims outline the detrital grain, grains are rounded to very well rounded and moderately to highly spherical. Extinction is typically straight to slightly undulose. Monocrystalline grains predominate, but polycrystalline grains and grains with strongly undulose extinction are present. The quartz is clear but vacuoles are common. Inclusions, such as rutile, are rare. Some grains have subparallel lines of vacuoles known as Boehm lamellae. It is unclear if such lamellae in the Bluefield sands are caused by stress in the diagenetic environment or are inherited from an earlier depositional cycle.

Rock Fragments

Rock fragments compose from 0.0% to 15.7% and average 6.4% of Type 2 sandstones. Metamorphic rock fragments (MRFs) include phyllite, schist and quartzite fragments. Shale and chert fragments compose the sedimentary rock fragments (SRFs).

MRFs constitute from 0.0% to 14.7% and average 4.0% of Type 2 sandstones. Phyllitic and schistose grains, the predominant MRFs, are typically well rounded and slightly elongate in the B-axis direction of their constituent micas. Muscovite and lesser amounts of biotite compose the bulk of these micas. Rarer quartzose MRFs are well-rounded and spherical and consist of either stretched or equant subgrains.

SRFs range from 0.0% to 6.0% and average 1.7% of Type 2 sandstones. Clay-shale and chert fragments are present in approximately equal amounts. Clay-shale fragments, which lack orientation of their constituent clays, are usually well-rounded, except where they have undergone extensive deformation. Some larger fragments are elongate and angular, reflecting short transport distances and suggesting intrabasinal origin. Well-rounded, highly spherical chert grains are present in small amounts.

Feldspars

Feldspars, although a minor constituent, occur in all but two outcrops (10 and 11 of the Droop Sandstone) of Type 2 sandstones. They range in abundance from 0.0% to 2.0% and average 0.3%.

In outcrops 8 and 9 (Indian Mills and Droop Sandstone, respectively) the feldspar, which averages 0.6%, appears to be a plagioclase, although it is untwinned and staining attempts were unsuccessful. Where unaltered, feldspar grains are equant and somewhat angular and exhibit cleavage. They are clear except along cleavage planes which are dark due to alteration. Typically, grains are partially dissolved. Dissolution appears to have started along cleavage traces and progressed inward, dividing grains into equant to elongate subgrains. The degree of this dissolution is variable within any given sample. While some grains are unaffected, moldic porosity is caused by total dissolution of other grains. The majority of the porosity in outcrops 8 and 9 originates in this way. Moldic porosity in outcrops 10 and 11 may be due to complete dissolution of a similar grain type.

Twinned plagioclase is present in trace to minor amounts in Type 2 interbeds in outcrops 4, 5 (Bertha Sandstone) and 6 (Bradshaw Sandstone), as well as in the more argillaceous samples of outcrop 8 (Indian Mills Sandstone). Trace amounts of feldspars occur in the carbonate-cemented basal part of outcrop 2b (Graham Sandstone). These feldspars have been extensively replaced by the carbonate, making accurate identification of the type of feldspar impossible.

Carbonate

Carbonate occurs in only one Type 2 sandstone. It occurs abundantly in the lower part of outcrop 2b (Graham Sandstone) where it constitutes as much as 44.7% of one sample. In outcrop 2b, carbonate averages 8.8%. The carbonate is poikiolitic, iron-stained and heavily twinned. As in Type 1 sandstones, dolomite, as well as calcite, is present; and, similarly, it is probably secondary after calcite. Rock fragments, micas, and to a lesser extent quartz have been extensively replaced by the carbonate.

Accessory Minerals

Accessory minerals include detrital muscovite, biotite, zircon, tourmaline, rutile and opaques, as well as authigenic hematite and/or limonite and clays. Together they range in abundance from a trace to 1.5% and average 0.4%. Muscovite, the most abundant accessory mineral, is ubiquitous in Type 2 sandstones in minor to trace amounts. It occurs as discrete flakes of variable size which are sometimes bent or kinked due to compressional deformation. Biotite is present in trace amounts in a few Type 2 sandstones.

Zircon is also ubiquitous in trace to minor amounts and is by far the most abundant heavy mineral. Most grains are well-rounded, but a few are subhedral to euhedral. Large, well-rounded, highly spherical opaques are present in trace amounts. A few very well-rounded, highly spherical, pleochroic tourmaline grains were found. Opaques, zircon, and other accessory minerals are concentrated along stylolites.

Iron oxide is present as pore-filling cement, fracture-fill, stain on grain coatings, and disseminated granular material. Trace amounts of authigenic clay form booklets and flakes lining and filling pores, and lining grain-to-grain contacts. Clay flakes are typically oriented randomly or parallel to grain surfaces, but, rarely are oriented normal to these surfaces. Clays are sometimes stained by iron oxide.

Matrix

Matrix material ranges from a trace to 17.3% and averages 4.7%. Matrix includes fine-grained phyllosilicate material, clay minerals, very fine-grained mineral particles, and iron oxide. Clays and iron oxide are included because they are often intermixed and cannot be differentiated. Hence, matrix includes grain coats and pore-filling clay and iron oxide.

DIAGENESIS OF TYPE 2 SANDSTONES

Diagenetic alteration of Type 2 (coarse-grained, clean) sandstones includes porosity reduction due to mechanical compaction, quartz cementation, intergranular pressure solution, and minor amounts of calcite cementation and growth of authigenic clays. Other diagenetic processes include stylolitization, fracturing, and precipitation of iron oxides. Most porosity in these sands is primary, but some secondary porosity was produced by dissolution of feldspars and by fracturing.

MECHANICAL COMPACTION

Mechanical compaction is evidenced by deformation of labile fragments (MRFs, SRFs, and micas). MRFs and micas are typically bent or kinked at one or more points. This deformation squeezes parts of the grains into surrounding pore space, contributing in a minor way to lithification by cementing adjacent grains together. Occasionally, localized compression of micas caused separation along cleavage planes. Pore space between cleavage planes was later filled by quartz cement. Clays of SRFs lack orientation and show no evidence of internal deformation as do the MRFs. Rather, portions of the relatively soft SRFs are "injected" into the interstices between more rigid surrounding grains (i.e., quartz).

The degree of deformation of labile fragments, particularly MRFs, varies widely both between samples and within samples. Some variation is attributable to the type or orientation of the fragment involved. MRFs with finer-grained micas underwent more deformation than those with coarser-grained micas. Deformation also varies widely between compositionally similar MRFs, because of variation in their orientation in the timing of cementation. Early cemented intervals undergo less mechanical compaction and preserve the integrity of the labile fragments. Uncemented intervals undergo more mechanical compaction causing more deformation of the labile grains.

POROSITY

Type 2 sandstones are not highly porous, yet both primary and secondary porosity are present. All Type 2 sandstones contain some porosity, with the exception of outcrop 2b (Graham Sandstone) in which porosity is totally occluded.

Primary intergranular porosity occurs only in clean, coarse-grained samples. There are minor amounts in all outcrops of the Droop Sandstone and in outcrop 8 (Indian Mills Sandstone). Intergranular pores are highly angular, often three-sided, and result from incomplete pore closure by quartz overgrowths (Plate 7). No evidence was found for a precursor cement. Hence, intergranular porosity in these sections is considered to be reduced primary porosity.

With the exception of outcrop 2b, moldic porosity occurs in all Type 2 sandstones, but it is most common in the clean, coarse-grained samples. It is particularly abundant in the Droop Sandstone and in outcrop 8 (Indian Mills Sandstone). In outcrops 10 and 11 (Droop Sandstone), moldic pores are void and offer no evidence of the dissolved grain. In outcrops 8 and 9 (Indian Mills and Droop Sandstones) a single grain type (untwinned plagioclase) has undergone dissolution and is

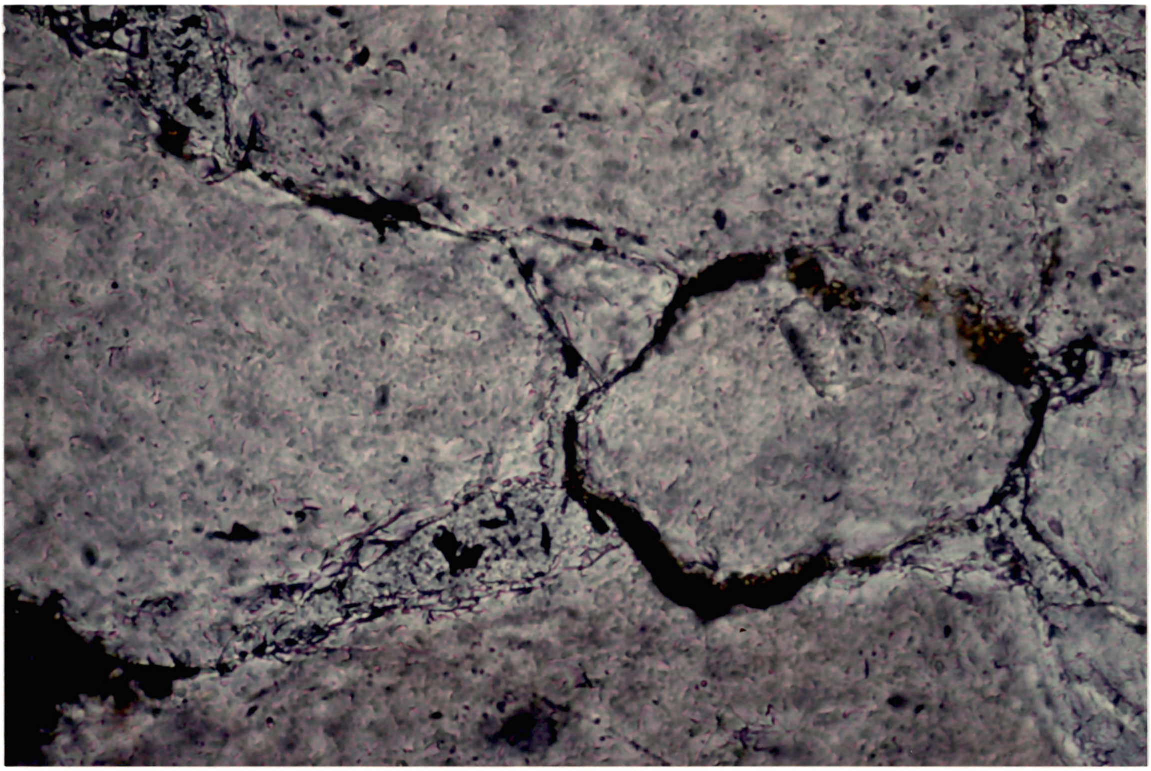

Plate 7: Primary intergranular porosity in Type 2 sandstone (crossed nichols, 250x).

responsible for moldic porosity. Dissolution proceeded from grain margins and cleavage traces. Undissolved portions of these plagioclase grains remain clear and unaltered. The same grain type may have been responsible for moldic porosity in outcrops 10 and 11 (Plate 8).

Porosity associated with fracturing is present in a few Type 2 sandstones. Fracturing occurred only in relatively impure, fine-grained samples, but it is abundant where present. Overall, fracture porosity constitutes a minor proportion of the porosity in Type 2 sands. Most fractures contain no cement, and lack of remnant patches of cement within them suggests they were never cemented and probably formed late in the diagenetic history of these rocks. One fractured sample contains quartz cement.

CARBONATE

Carbonate occurs in only one Type 2 sandstone (the basal part of outcrop 2b, Graham Sandstone). The carbonate is composed of both calcite and dolomite. It is poikilotopic, iron-stained, and heavily twinned; and it replaces, in part or completely, all observed grain types. It was particularly effective in replacing rock fragments, micas, and feldspars, which frequently appear as "skeletal" grains in which the original nature of the grain is barely preserved (Plate 9). While feldspars occur in the carbonate-cemented basal part of outcrop 2b, its upper part contains no feldspar. Although the feldspars are extensively replaced, the carbonate cement in the base of the outcrop prevented feldspar dissolution during quartz diagenesis. This suggests that carbonate cementation was early (i.e., the carbonate cement

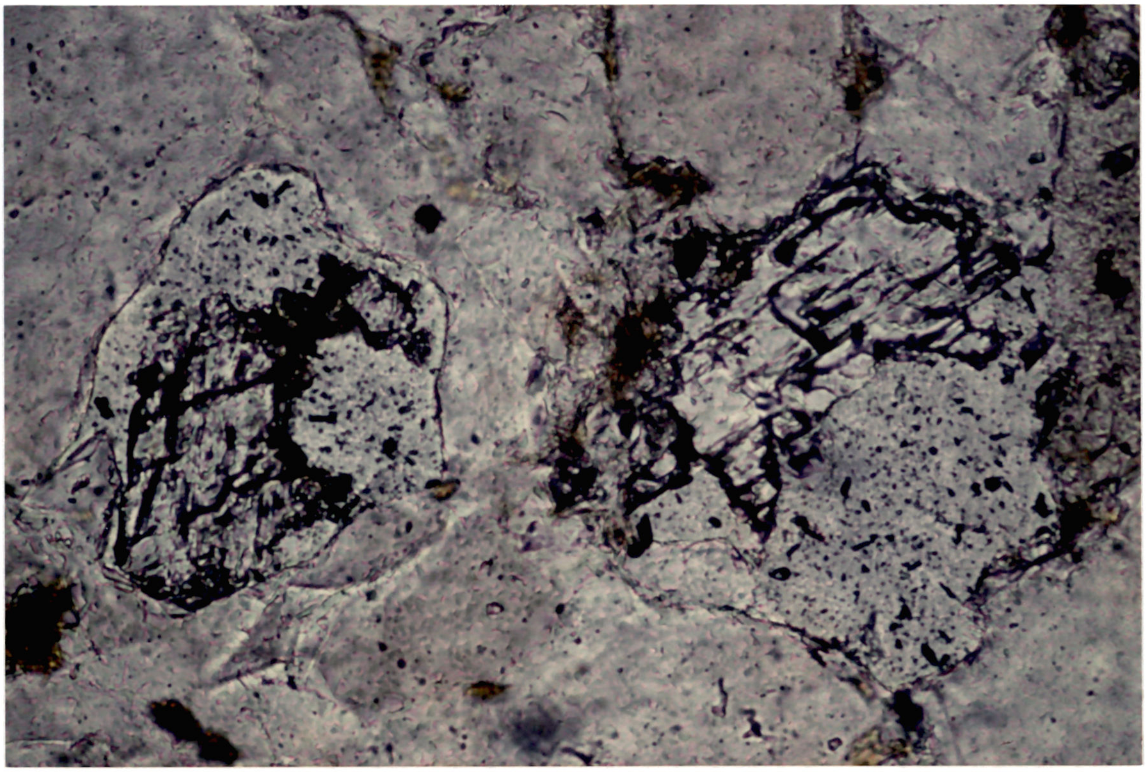

Plate 8: Moldic porosity formed through partial dissolution of feldspar in Type 2 sandstone (crossed nichols, 250x).

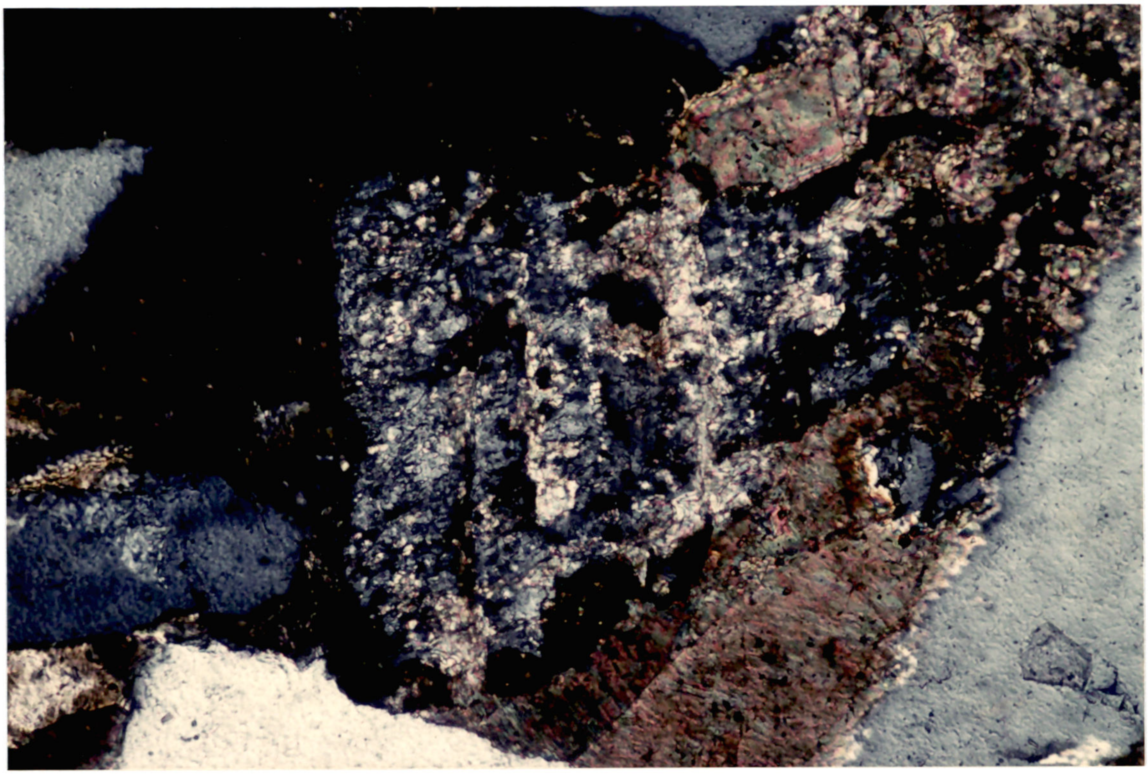

Plate 9: Carbonate replacement of feldspar (crossed nichols, 160x).

prevented dissolution of the feldspars which apparently occurred in the upper part of the outcrop).

Quartz also underwent replacement by the carbonate. Replacement proceeded from the margins of the grains, as evidenced by irregular grain boundries where carbonate-filled embayments penetrate quartz (Plate 10). The quartz grains are also replaced along internal linear zones of weakness, perhaps along pre-existing vacuole trains. Replacement of quartz was extensive in some cases. Quartz "shards", apparently remnants of an extensively replaced quartz grain, are found floating in the carbonate. Alternatively, such cases may represent the remnants of an originally quartz-rich rock fragment where carbonate selectively replaced other constituents.

Most quartz grains are surrounded by "halos" of unstained, untwinned carbonate (Plate 10). Where quartz grains have been partially replaced internally by carbonate, that carbonate is also untwinned and unstained. At least two possibilities exist for the formation of these "halos": 1) a two-stage replacement of quartz by carbonate in which a second phase of replacement produced the "halos" after twinning and staining of the early carbonate; 2) grain rotation accompanied by recrystallization of carbonate adjacent to quartz grains.

HEMATITE

Hematite occurs in Type 2 sandstones as a stain, as finely disseminated grains, and as pore-filling cement. Hematite stains clay minerals and to a lesser extent micaceous rock fragments. All three types of hematite occur together, suggesting only one phase of

Plate 10: Carbonate-cemented Type 2 sand. Note marginal replacement of quartz by carbonate; clear carbonate"halo" around quartz grain in lower left of photo and; partial replacement of feldspar in lower right of photo (crossed nichols, 63x).

hematitization. Hematite fills both primary and secondary porosity. Secondary porosity in Type 2 sands shows no evidence of reduction and, therefore, probably occurred relatively late in diagenesis. Early formed secondary porosity would have been at least partly occluded by mechanical compaction or quartz cementation. Because hematite infills secondary porosity, hematitization must have occurred late in diagenesis, possibly at outcrop.

CLAY MINERALS

Clay minerals in Type 2 Bluefield sands occur as discrete flakes and coatings around quartz grains, as inclusions within authigenic quartz, and rarely as pore-filling material. The clay is composed largely of illite but may contain some kaolinite. Clays are sometimes stained by iron oxide, making accurate optical identification difficult or impossible. Clay minerals in Type 2 sandstones may be both detrital and authigenic. Authigenic clays are generally distinguished from detrital clays by their distinctive morphologies. However, the combined effects of mechanical compaction, quartz cementation and pressure solution can make distinction between authigenic or detrital origins impossible. In a few cases, it is possible to identify the origin of the clay. For instance, clay grain coatings between the detrital cores of quartz grains probably developed prior to deposition. Clays are sometimes clearly authigenic, as where kaolinite booklets are found filling pores and where clays are oriented perpendicular to quartz grain boundaries (Plate 11). But, the precise origin of clays could not be routinely determined.

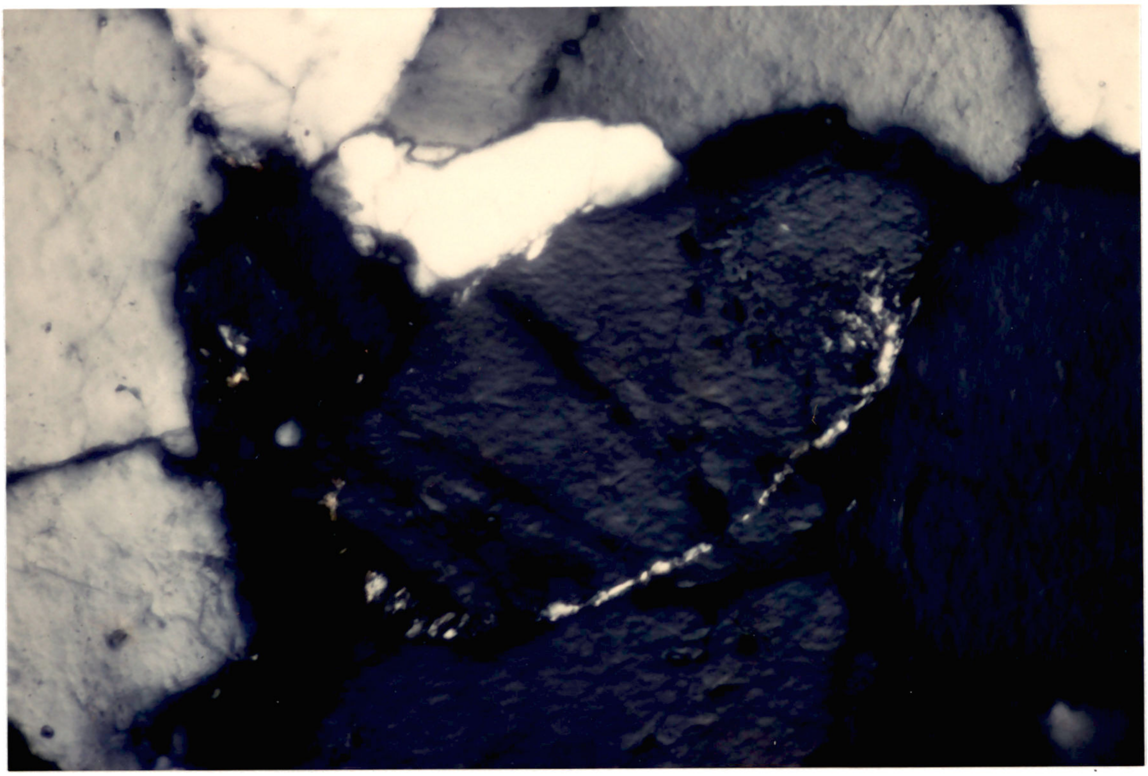

Plate 11: Authigenic clay surrounding quartz grain and between quartz grain and its overgrowth (crossed nichols, 160x).

QUARTZ AUTHIGENESIS

The most important processes in porosity reduction and lithification of Type 2 Bluefield sandstones were quartz cementation resulting from pressure solution and "quartz enlargement" (quartz cementation unrelated to pressure solution). Together, these two processes significantly reduced and sometimes occluded primary porosity (Plate 12).

Both "quartz enlargement" and intergranular pressure solution are relatively early diagenetic events. "Quartz enlargement" requires pore space into which overgrowths can expand and so must precede extensive lithification. Lithification also hinders pressure solution by distributing stresses more evenly throughout the rock, rather than at the grain-to-grain contacts where intergranular pressure solution occurs (Heald, 1956).

An important factor in controlling which of these two processes occur is the presence and thickness of clay coatings on detrital quartz grains (Plate 13). Clay coatings inhibit the formation of quartz overgrowths by blocking nucleation sites on the surfaces of quartz grains (Heald and Larese, 1974). Grain coatings of sufficient thickness (thick enough to prevent diffusion across the coating?) will prevent "quartz enlargement" and preserve primary porosity. Where such coatings are lacking or incomplete, nucleation sites are available and quartz overgrowths will form, provided that silica is available and that conditions are otherwise favorable for quartz growth (Heald and Larese, 1974). Where clay coatings are absent, overgrowths totally surround

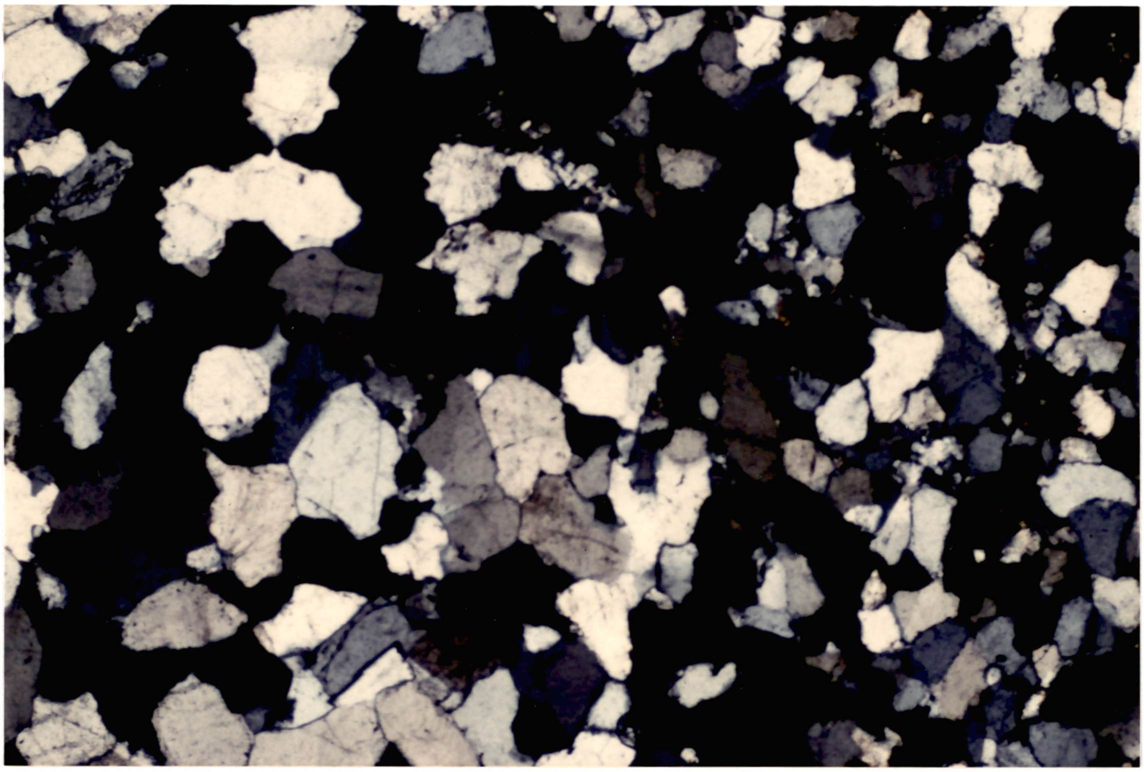

Plate 12: "Quartz enlargement" vs pressure solution in Type 2 sandstone. Area in top of photo dominated by "quartz enlargrment. Bottom part of photo shows pressure solution (crossed nichols, 25x).

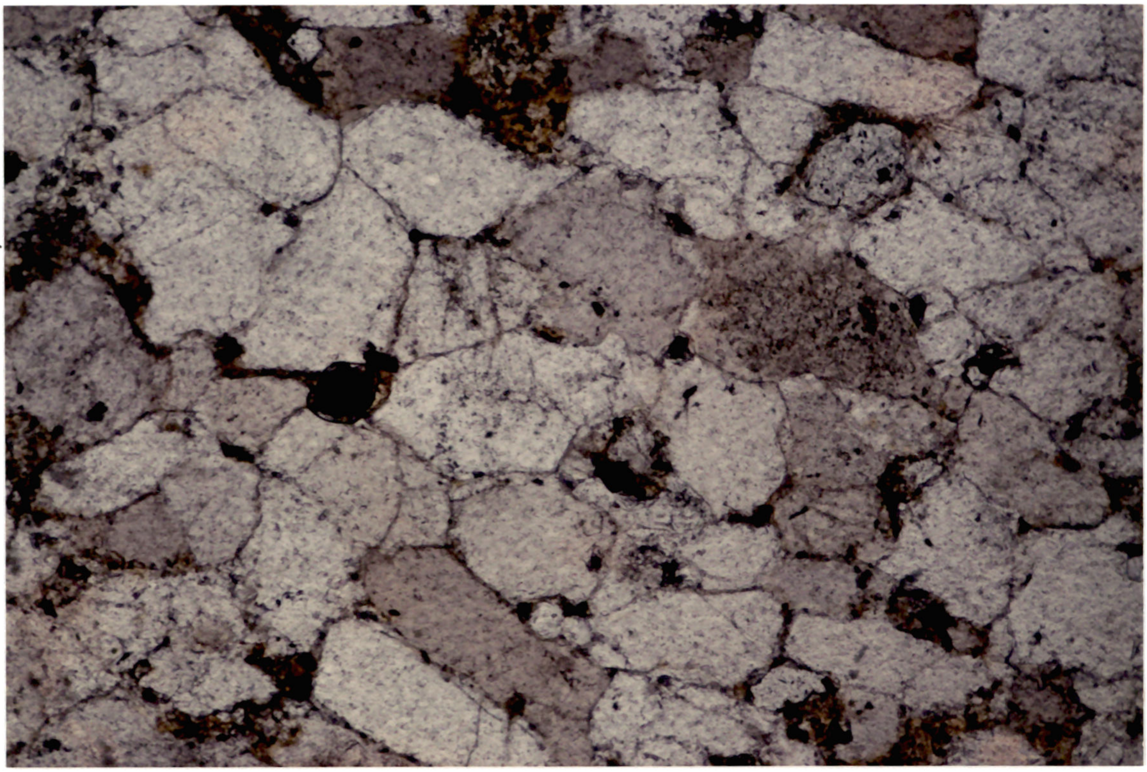

Plate 13: Grain coatings, incomplete overgrowths and moldic porosity in Type 2 sandstone (plain light, 25x).

detrital grains and most grain-to-grain contacts are between overgrowths. Where grain coatings are incomplete, "irregular overgrowths" are formed (Heald, and Larese, 1974) because localization of nucleation sites causes restriction of the overgrowths. A given detrital grain may possess a well developed overgrowth along part of the grain, but the overgrowth may be absent along other parts of the grain (Plate 14). Detrital grain-to-overgrowth contacts become common (i.e., overgrowths from one grain often are in contact with detrital cores of adjacent grains on which clay coatings prevented overgrowth formation).

Where grain coatings are thin or absent, epitaxial quartz overgrowth formation ("quartz enlargement") was the dominant process by which Type 2 sandstones were cemented. Epitaxial overgrowths are identified by "dust rims" between detrital cores and the overgrowths, or by variations in other characteristics between the detrital cores and their overgrowths. For example, overgrowths typically contain fewer inclusions (except for clays) than the detrital cores, which contain vacuole trains and other linear features that terminate against overgrowths. Overgrowths in Type 2 sands are largely "irregular overgrowths". Contacts between clay-coated detrital cores and overgrowths of adjacent grains are common in these intervals. These contacts are fairly weak and sands cemented in this manner are often friable (Heald and Larese, 1974). The friable nature of the Droop Sandstone is likely due to cementation in this fashion.

While "quartz enlargement" was the dominant cementation process in intervals where grain coatings are thin, evidence of pressure solution is rarely lacking. Most grain-to-grain contacts are smooth or straight,

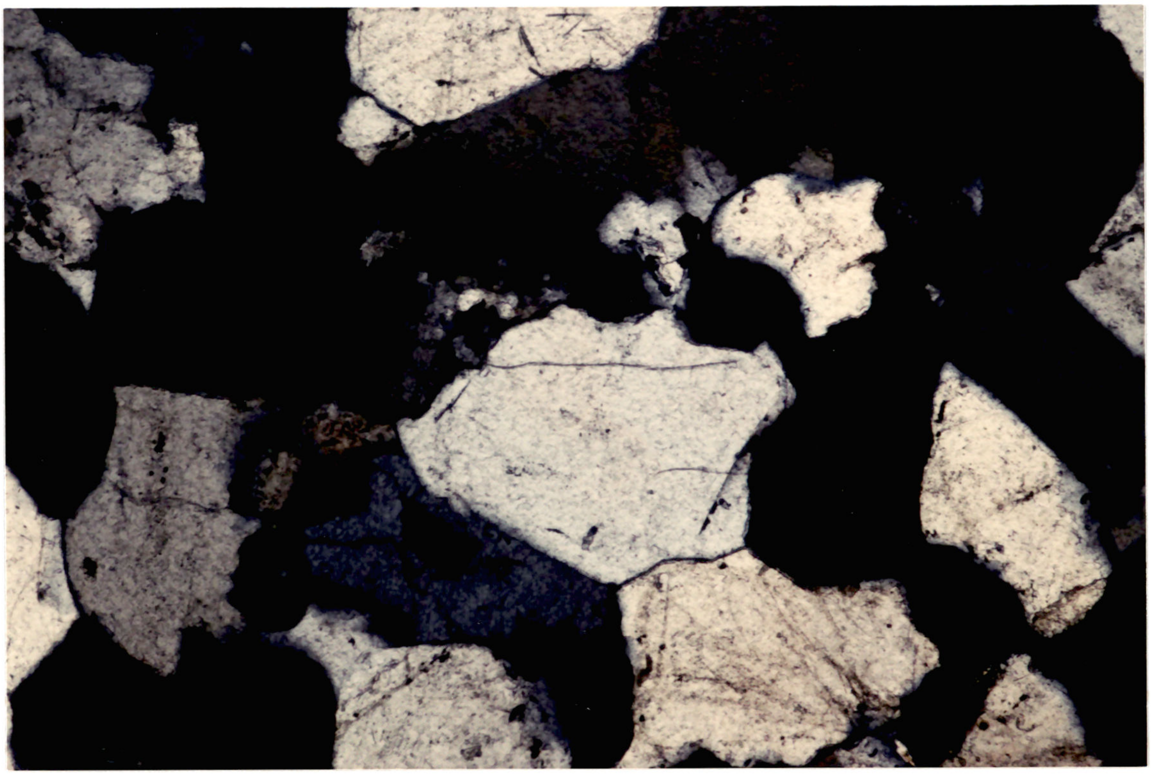

Plate 14: Incomplete quartz overgrowth (crossed nichols, 63x).

but the interpenetration of detrital cores, marked by sutured contacts, suggests that some pressure solution occurred. Cementation by overgrowths was apparently incomplete when overburden (?) pressure initiated pressure solution. In intervals with thin grain coatings, pressure solution was relatively minor and contributed little cement to the system.

Where grain coatings are complete and of sufficient thickness, quartz enlargement is inhibited and primary porosity is often preserved. When overburden or tectonic stress becomes great enough, solution may occur. Pressure solution involves solution at grain-to-grain contacts. Dissolved silica migrates along grain boundaries and is precipitated in areas of lower stress (i.e., within adjacent pore space). When pressure solution occurs in sands that lack grain coatings (clean sands), a water layer adsorbed at the margin of the grain is the only migration path available to dissolved silica. Clay coatings tend to enhance pressure solution by providing a wider diffusion path for the silica. The silica migrates either between the clay coating and the detrital grain or between the clay layers (Weyl, 1959). During the latter process, clay may become incorporated within the authigenic quartz as inclusions. Sometimes such inclusions are oriented parallel to prism planes within the authigenic quartz, creating a feature termed "polygonal-grid" quartz (Heald and Larese, 1974).

In intervals where clay coatings are relatively thick, intergranular pressure solution was the dominant lithification process. Compared to intervals cemented mostly by "quartz enlargement", pressure solution intervals contain more detrital core-to-detrital core contacts, more sutured contacts, and fewer and smaller overgrowths identifiable by dust rims. Solution is most easily identified at detrital core-to-detrital core contacts, but it also probably occurred between overgrowths and detrital cores, and between adjacent overgrowths.

Grain coatings in Type 2 sandstones may cover both a detrital grain and its overgrowth, indicating that silica diffused mainly between the clay coating and detrital grain. As quartz precipitated on the detrital grain, the clay coating "migrated" away from it, leaving the overgrowth between the detrital grain and the clay coating. More commonly, clay flakes are included within the authigenic quartz. Most clay inclusions within authigenic quartz in Type 2 Bluefield sands are oriented randomly. "Polygonal-grid" quartz is present but not common.

Most of the authigenic quartz formed by pressure solution in Type 2 Bluefield sandstones formed epitaxially. Some authigenic quartz is not in optical continuity with any observed grain, but this authigenic quartz may be epitaxial on grains outside the plane of the thin section.

Grain size tends to be smaller in zones with extensive pressure solution than in zones cemented by "quartz enlargement". These zones are small in scale and may vary within a single thin section. Early formed overgrowths tend to increase grain size, while pressure solution has less effect on grain size; and so grain size difference may reflect authigenesis. Alternatively, the grain size difference may be depositional in nature. Sprunt and Nur (1977) found that degree of pressure solution increases with decreased grain size, and so intervals of finer grain size would have been more susceptible to pressure solution. A combination of these two factors may be responsible for the observed correlation between grain size and method of lithification.

Clay coatings of sufficient thickness will inhibit pressure solution by cushioning the effects of overburden pressure and reducing stress at grain-to-grain contacts. The thickness at which clay coatings cease promoting and begin inhibiting pressure solution has not been documented (Sibley, 1975; Sibley and Blatt, 1976). In a few samples of Type 2 sandstones grain coatings were apparently of sufficient thickness to prevent pressure solution.

Summary

Type 2 Bluefield sandstones were cemented by both "quartz enlargement" and intergranular pressure solution. Most intervals show the effects of both processes, and all gradations between cementation totally by "quartz enlargement" and totally by pressure solution can be observed.

Clay coatings (largely illite) on detrital grains are almost ubiquitous in Type 2 sands, but they vary in thickness. The thickness of clay coatings correlates with changes in diagenetic processes within the sands.

"Quartz enlargement" began before pressure solution where nucleation sites were available for quartz growth. In intervals with relatively thick and complete clay coatings "quartz enlargement" was inhibited. Increased overburden stress later in diagenesis initiated solution at grain-to-grain contacts (intergranular pressure solution). Pressure solution, aided by the presence of clay coatings, produced additional free silica for quartz authigenesis, which completed cementation of Type 2 sandstones.

STYLOLITES AND FRACTURES

Stylolites occur in only a few of the Type 2 sandstones sampled. They are characterized by concentrations of insoluble materials such as clay minerals, heavy minerals, and organic matter along the stylolitic surface. Most stylolites occur in the more argillaceous samples of Type 2 sandstone, and most are oriented parallel to bedding. They were probably caused by overburden pressure. Fracturing later occurred preferentially along these stylolites. One sample, taken from the base of outcrop 9 (Droop Sandstone), contains stylolites which are oriented normal to bedding. These were caused by directed stress, possibly associated with folding and thrust faulting in the region, in the horizontal plane.

Quartz overgrowth formation and stylolitization tend to occur in mutually exclusive samples of Type 2 sandstones, stylolites in argillaceous samples and quartz overgrowths in "cleaner" samples. Therefore, no cross-cutting relationships were observed and relative timing of these two events could not be determined.

All fractures observed in Type 2 sandstones are oriented parallel to bedding, and were probably caused by release of overburden pressure. Fractures which occurred along pre-existing stylolite surfaces may have been opened during the thin section process. Most of the fractures contain no cement and were probably never cemented. This suggests that fracturing occurred late in the diagenetic history of these rocks.

One fracture set was cemented by quartz. This indicates that either a second generation of quartz authigenesis followed quartz cementation, or free quartz which remained in the system after primary porosity reduction cemented this fracture.

DIAGENETIC SEQUENCE

Diagenesis within Bluefield sandstones can be separated into early, middle and late stages. The sequence discussed below refers to both Type 1 and Type 2 sandstones except where noted. Diagenetic events are summarized in Figure 8.

EARLY STAGE OF DIAGENESIS

Early diagenetic events include mechanical compaction and formation of authigenic pyrite, clay minerals (largely illite), calcite, and hematite. The first minerals to form were pyrite and calcite. Calcite probably formed from carbonate present at or near the sediment-water interface. Some early formed calcite was subsequently dolomitized. Detrital quartz grains and other grain types were partially replaced by calcite. Evidence from the base of outcrop 2b (Graham Sandstone), where calcite authigenesis prevented dissolution of feldspars, suggests that this replacement occurred early. Oxidation of some of the pyrite to hematite occurred and, probably concurrently, some calcite and dolomite were also partly replaced by hematite.

Authigenic illite formed grain coatings (of variable completeness and thickness) on quartz grains in Type 2 sandstones. Some of these grain coatings may be predepositional. The fact that they were "involved or mobilized" during quartz authigenesis, a process which occurred in the middle stage, suggests that they formed early. Illite probably formed in Type 1 sandstones as well. This illite, as well as other authigenic clay minerals, is mixed with detrital clays.

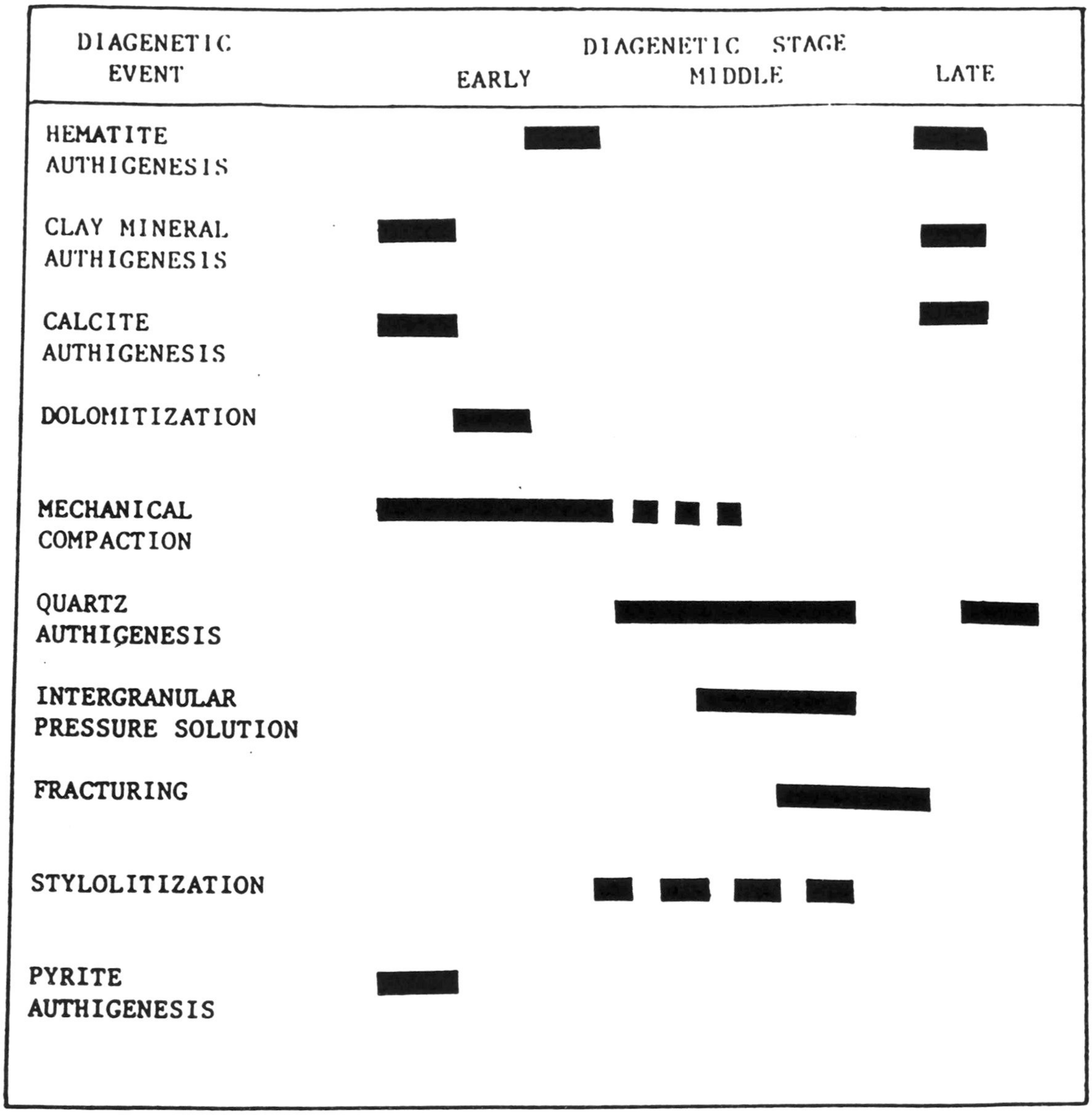

Figure 8. Sequence of diagenetic events.

Mechanical compaction, especially through deformation of labile fragments, begins only after shallow burial (Blatt and others, 1980). Compaction began early and continued throughout the early stage of diagenesis.

MIDDLE STAGE OF DIAGENESIS

The middle stage of diagenesis is characterized by formation of quartz overgrowths and stylolites, and by intergranular pressure solution. Free silica began to precipitate as epitaxial overgrowths on quartz grains, a process particularly important in Type 2 sandstones. Mechanical compaction during the early stage of diagenesis in Type 1 sandstones prevented significant quartz authigenesis by occluding primary porosity. Later, as overburden pressure increased, intergranular pressure solution began. This process, aided by the presence of clay coatings on detrital grains, released additional silica which precipitated as epitaxial overgrowths and randomly oriented pore-filling cement.

Stylolitization may occur prior to, during, or after quartz cementation within sandstones. In fact, it may be an important contributor of silica when it occurs before or during cementation (Heald, 1959). Stylolites occur most frequently in the more fine-grained and argillaceous components of the Bluefield sandstones, which contain only minor amounts of authigenic quartz. Therefore, cross-cutting relationships could not be observed. Stylolitization is placed in the middle stage of diagenesis based on its relationship with fractures. Fracturing occurred preferentially along stylolites during the late stage of diagenesis. Stylolitization clearly preceded fracturing and is considered to be a middle stage event.

LATE STAGE OF DIAGENESIS

The late stage of diagenesis includes events which occurred after extensive lithification of Bluefield sandstones. Important events include fracturing; the infilling of many fractures by authigenic quartz, calcite, hematite and clay minerals; and the formation of moldic porosity by dissolution of feldspars.

Fracturing typically occurs after extensive lithification, when repacking at the grain-to-grain level can no longer close the fractures. Stylolites served as preferred sites for fracturing, suggesting that fracturing occurred relatively late in the diagenetic sequence. Bluefield sandstones were fractured both parallel and at high angles to bedding. Fractures at high angles to bedding were probably formed at depth by overburden pressure, and may have occurred in either the middle or late stage of diagenesis. Fractures parallel to bedding probably occurred late in response to release of overburden pressure. Many of these fractures were later cemented by calcite, hematite, quartz, or clay minerals. Only one of these mineral phases is usually present in any given fracture, and so relative timing of these events could not be determined. One fracture contains both calcite and clay minerals. The calcite appears somewhat corroded, which possibly indicates that calcite authigenesis preceded clay mineral authigenesis. Variation in pore fluid chemistry may have been responsible for variations in cement type.

Feldspar dissolution produced secondary moldic porosity during this diagenetic stage, particularly in Type 2 sandstones. Moldic pores contain no quartz cement. Had this porosity been produced before or during quartz authigenesis, the pores would have been at least partly infilled by quartz cement. Feldspar dissolution must, therefore, have occurred after quartz authigenesis (i.e., in the late stage of diagenesis). Occasionally pores are partially cemented by hematite, but otherwise they contain no late stage cement, suggesting that late-stage quartz, calcite and clay mineral authigenesis preceded feldspar dissolution and, possibly, hematite authigenesis. Hematite authigenesis either postdated or co-occurred with feldspar dissolution.

SUMMARY

The most important diagenetic events in Bluefield sandstones were mechanical compaction and quartz cementation. During the early stage of diagenesis, mechanical compaction was the dominant diagenetic process in the Type 1 sandstones which contain large percentages of ductile grains. At the end of the early stage of diagenesis, lithification was essentially complete and primary porosity essentially occluded in Type 1 sandstones. At the beginning of the middle stage of diagenesis, significant primary porosity remained in Type 2 sandstones. Large amounts of silica available to the system initiated formation of quartz overgrowths. Continued burial during the middle stage of diagenesis induced intergranular pressure solution. This released additional silica, further promoting quartz authigenesis and completing lithification of Type 2 sands. Late stage diagenetic events include minor secondary porosity formed through fracturing, feldspar dissolution, and partial infilling of secondary porosity by various authigenic minerals.

DEPOSITIONAL SETTING

GENERAL

During the late Mississippian the study area was located approximately 5 to 10 degrees south of the paleoequator (Humphreville, 1981; Scotese and others, 1979; Bambach and others, 1980; deWitt and McGrew, 1979). Figure 9 is a map adapted from deWitt and McGrew (1979) showing generalized Chesterian paleogeography. To the east, Appalachia was developing as an Andean-type mountain chain (Scotese and others, 1979). Uplift to the east caused large volumes of detritus to be deposited in the area (Bambach and others, 1979; deWitt and McGrew, 1979). These sediments were deposited in a shallow, slowly subsiding basin which occupied southeastern West Virginia during this time (Scotese and others, 1979).

PROVENANCE

Metamorphic rock fragments (MRFs), such as slate and phyllite fragments, are very abundant in Bluefield sandstones. Slate, phyllite and chlorite-bearing MRFs suggests erosion of a low-grade metamorphic source. Higher metamorphic grade fragments, such as biotite and coarser-grained (schistose) fragments, are also present. This suggests that source rocks were composed of multiple metamorphic facies or that multiple sources contributed sediments to the area.

Minor quantities of sedimentary rock fragments are present. These are primarily claystone clasts and a few siltstone clasts. Although they may represent erosion of a sedimentary source, they are most likely

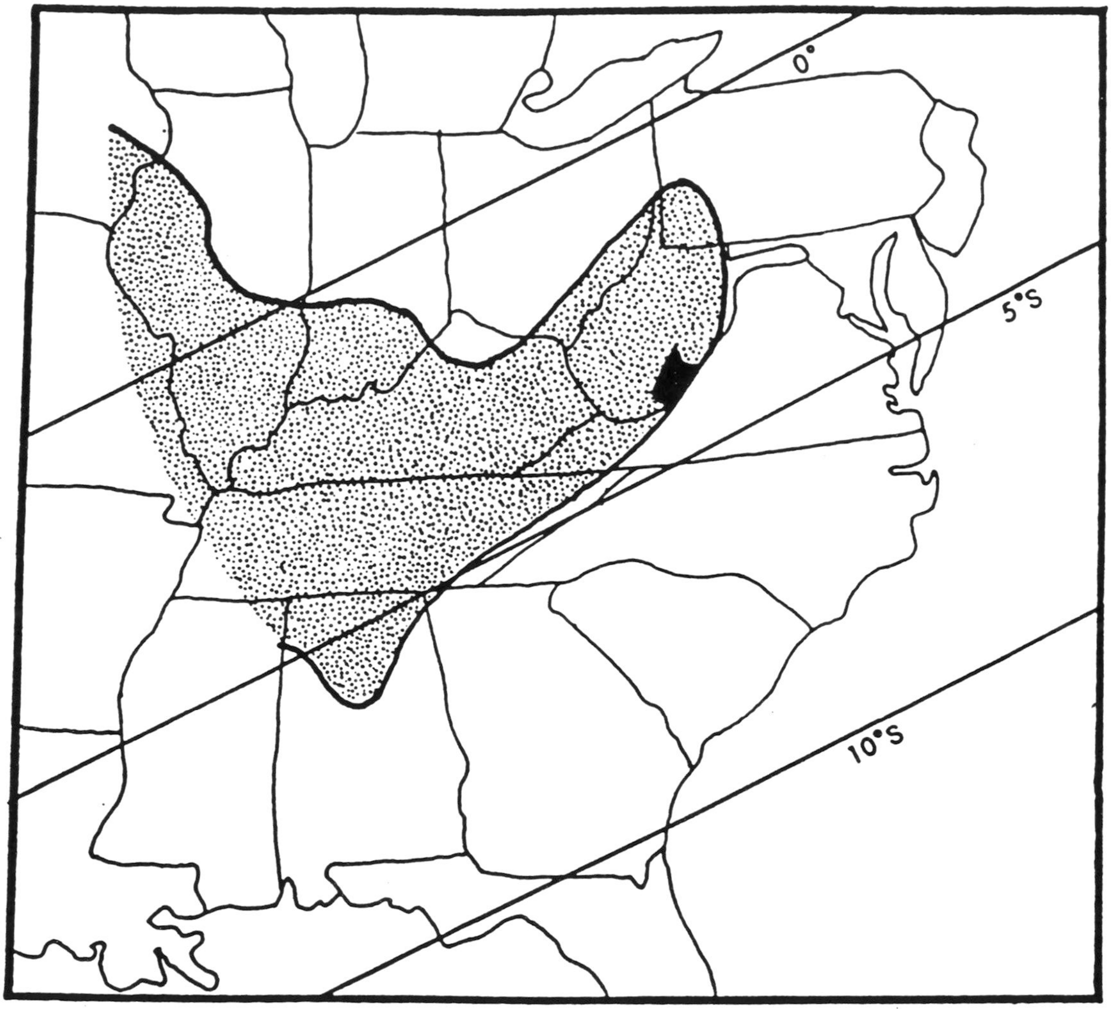

Figure 9: Upper Mississippian (Chesterian) paleogeography (after Craig and Varnes, 1979). Shaded area represents marine conditions. Darkened area indicates study area.

intrabasinal. No rock fragments clearly indicative of a plutonic source were found.

PREVIOUS INTERPRETATIONS

Whisonant and Scolaro (1980) interpreted a stratigraphic section from the middle part of the Bluefield Formation in Mercer County, West Virginia as a nearshore deposit. Inferred environments included shallow subtidal, lower intertidal, middle intertidal, and higher intertidal. The section was found to be regressive in nature.

Humphreville (1981) investigated the stratigraphy and paleoecology of the Bluefield Formation in Mercer County, West Virginia and Tazewell County, Virginia. The lower Bluefield, composed primarily of argillaceous wackestones, was interpreted to represent deposition during the waning periods of storm events. The upper Bluefield, composed of olive-green and maroon mudstones lacking both marine and terrestrial fossils, was interpreted to represent deposition as a prograding muddy shoreline or in a muddy marsh setting. Humphreville interpreted the Indian Mills Sandstone, a coarse quartzose sandstone between the upper and lower Bluefield, as a crevasse splay and stated that it is the only one of Reger's (1926) members still recognized. Interbedded clays and coals are interpreted as terrestrial swamp deposits. In summary, he stated that the formation represents a shallow water, muddy environment with tidal flats, crevasse splay sands, and muddy shoreline and swamp deposits.

Swires (1972) studied sediments of the Mauch Chunk Group in the Hurricane Ridge Syncline in Mercer, Monroe, and Summers Counties, West

Virginia. He interpreted the lower Bluefield as open marine deposits which grade upward into "deltaic/fluvial" and lagoonal sediments. He, like Humphreville (1981), recognized only the Indian Mills Sandstone as a member within the Bluefield. He intrepreted the Indian Mills as a "deltaic/fluvial" deposit.

McColloch (1957) studied the Bluefield Formation in Mercer, Monroe, Summers, and southern Greenbrier Counties, West Virginia. He noted that the basal Bluefield is predominantly marine limestone and shale with minor terrestrial sandstones and shales, and that the upper Bluefield is predominated by terrestrial shales and sandstones with minor marine and freshwater limestones. Unlike Swires and Humphreville, McColloch places the Droop Sandstone of Reger (1926) at the boundary between the lower and upper Bluefield.

McColloch claimed that the limestones of the lower Bluefield can be traced throughout the study area, but that the marine limestones of the upper Bluefield, including the Raines Corner and Bertha Limestones of Reger (1926), lens out or undergo facies changes north of Pence Springs (sample site 12 of this report). He also noted that the Bluefield is thinnest at Pence Springs and thickens both to the north and south from there. He reported deltaic deposits to the north in his Clintonville section, while his southern sections (not specifically designated but certainly south of Pence Springs) were deposited in marine conditions. Otherwise, he referred to upper Bluefield deposition as "terrestrial".

Manspeizer (1958) studied the Bluefield Formation in Greenbrier and Pocahontas Counties, West Virginia. He interpreted those units below the Droop Sandstone to be largely of marine origin (Lillydale, Glenray, Reynolds, and Ada members of Reger), with minor lagoonal (Bickett Shale) and "transitional-littoral" deposits (Webster Springs Sandstone). Units above the Droop were interpreted variously as transitional-deltaic, littoral, and lagoonal deposits within an overall deltaic setting. The Droop was interpreted as a beach (littoral) sand. Manspeizer recognized a delta distributary north of Droop Mountain in Pocahontas County. He noted that the Droop Sandstone thickens toward the north, reaching its maximum thickness at Droop Mountain, north of which it undergoes facies changes. He stated that north-flowing currents piled up Droop sediments against the delta producing the increased thickness.

DEPOSITIONAL ENVIRONMENTS

LOWER SANDSTONES

Lower Bluefield sandstones include the Webster Springs and Edray as named by Reger (1926). These sands are most prominant north of the study area and attempts to trace them into the area are tenuous at best. Lower sandstones of this study are best thought of as sands which occur at horizons similar to those of the named sandstones to the north and not necessarily contiguous units.

Three outcrops were sampled in the lower part of the Bluefield Formation. Two of the outcrops sampled (outcrops S and J) were first described by Reger (1926) who assigned them to the Webster Springs Sandstone. The third outcrop sampled (outcrop R) was located lower in the Bluefield and may be the equivalent of the Edray sandstone of Reger (1926). All three outcrops consisted of Type 1 sandstone.

Outcrop S consists of calcareous, very fine-grained sand which shows no grain size sequence. It ranges from greenish-brown to buff, cross-bedded sand in its lower part to green, flaggy and ripple-marked sand in its upper part. Quartz percentage is low (mean = 61.7%). Rock fragment percentage is relatively high (mean = 21.2%).

Outcrop J is composed of 3 units of Type 1 sandstone which are intercalated with yellow-brown calcareous shale. The coarse-grained units are variously brown, greenish-brown or gray and massive to ripple-marked. Grain size in the "coarse-grained" units ranges from coarse silt to very fine sand. The mean grain size falls in the coarse silt range. Quartz percentage is low (mean = 56.1%). Rock fragment percentage is highly variable, ranging from a trace to 30.0% and averaging 10.6%. Carbonate percentage ranges from a trace to 48.3%.

Stratigraphic evidence suggests that the Webster Springs Sandstone is encased in marine deposits. The Webster Springs Sandstone (outcrops S and J) is underlain by the marine Glenray Limestone. The overlying Bickett Shale contains a red zone, but also contains interbedded limestones, particularly in its upper portion where it grades upward into the marine Reynolds Limestone (Reger, 1926; McColloch, 1957). The Bickett is sandy at its base.

This sequence suggests that a "pulse" of clastic sedimentation occurred in what was otherwise a basin dominated by carbonate deposition. This influx of clastics temporarily displaced carbonate deposition. Resumption of carbonate deposition is recorded by the transition of the top of the Bickett Shale into the overlying Reynolds Limestone. Moreover, while the Webster Springs is massive at outcrop S, it interfingers with apparent marine shales at outcrop J. This suggests that the Webster Springs was deposited under marine conditions.

Similar sands, particularly in the Cretaceous of Texas and the Rocky Mountain region, have been interpreted as "shelf ridge sands" (Swift and Rice, 1984). These sands are formed by winnowing of sandy shales (muds) largely by storm induced currents (Swift and Rice, 1984). Ripple-marks, cross-bedding and horizontal bedding are the most common sedimentary structures in these sands (Swift and Rice, 1984). They are also the most common structures in the Webster Springs Sandstone. Most documented shelf sands are, however, more extensively cross-bedded and somewhat coarser-grained and better sorted than outcrops of the Webster

Springs observed in this study. Grain size is in part a function of the grain size of available sediment; i.e., grain size in the Webster Springs may include the coarsest materials that were available. Size and kind of bedform (especially cross-bedding) are a function of the energy of the depositional environment. The difference in bedforms, finer grain size, and poorer sorting suggests that basin energy, and more precisely the size and intensity of storms, was higher in the Cretaceous examples than in the Appalachian basin when the lower Bluefield was being deposited.

The Webster Springs Sandstone probably developed through winnowing of the muds of the lower Bluefield shale and represents shelf sand ridge deposition. Most shelf sand ridges are linear features. Outcrop S is relatively thick, coarse-grained and massive and probably was deposited near the axis of a sand ridge. Outcrop J, which is interbedded with marine shales, probably represents deposition along the lateral margin of a ridge. Such intercalation of sands with shale or mud is common at the margins of shelf sand ridges (Swift and Rice, 1984).

Outcrop R (Edray Sandstone?) is calcareous, ripple-marked and very fine-grained. Grain size ranges from coarse silt to very fine-grained sand and averages 0.046mm. Quartz percentage is low (mean = 65.6%). Rock fragment and matrix percentages are high (averages of 14.6% and 13.5%, respectively). Like outcrops J and S, outcrop R is surrounded by marine sediments. Processes that formed outcrop R were probably similar to those that formed outcrops J and S. Outcrop R, therefore, is interpreted as a shelf sand ridge. The fine grain size and lack of cross-bedding suggests that outcrop R was deposited at the distal margin of a sand ridge.

DROOP SANDSTONE

The Droop is a Type 2 sandstone. It is sheet-like in geometry, clean, and coarse-grained, and it lies at the transition between the upper and lower parts of the Bluefield Formation.

Grain size within the Droop ranges from 0.09mm to 0.34mm and averages 0.19mm (fine sand). Grain size fines upward; however, quartz authigenesis obscures original detrital grain size and so this trend may not be significant. Quartz percentage is high (88.3%). Rock fragment and matrix percentages are low (combined mean = 7.2%).

The Droop overlies fossiliferous marine shales (Talcott Shale) and is overlain by a sequence of shales (Raines Corner and Possumtrot) which include coal horizons (Reger, 1926). The overlying shales are highly variable in appearance. They may be gray, blue-green, black or olive and occasionally red in color. They include carbonaceous material as well as pyrite, siderite and carbonate nodules. Both plant and marine fossils have been reported. Sandstone interbeds and lenses are also found (Reger, 1926; McColloch, 1957). These shales would appear to be estuarine and/or lagoonal deposits associated with marsh environments. The Droop appears to be a nearshore coastal sand.

The upper part of the Droop is typically horizontally stratified or exhibits low angle cross-bedding, and it is sometimes ripple-marked. The upper contact is gradational. The lower part is extensively cross-bedded. Most of the cross-bedding is trough cross-bedding, but tabular planar cross-bedding is present at some exposures. A relatively narrow zone, sometimes present just above the lower contact, is horizontally stratified or massive. The lower contact is erosional.

The clean, well-sorted, coarse-grained, quartz-rich (orthoquartzitic) lithology of the Droop is characteristic of barrier island and strand plain deposits (Galloway and Hobday, 1983; Balazs and Klein, 1972). Strand plain and barrier island models, as summarized by McCubbin (1983), show a general beach to offshore trend consisting of 4 environments: 1) horizontally stratified beach deposits; 2) cross-bedded upper shoreface deposits; 3) horizontally stratified lower shoreface deposits and; 4) offshore deposits. The contact between the beach and upper shoreface is sharp. The contact between the upper shore-face and lower shoreface is gradational. The lower shoreface grades into and is interbedded with the off-shore environment (McCubbin, 1982; Galloway and Hobday, 1983). Beach and upper shoreface deposits are present in the middle and upper portions of the Droop. However, the lower contact of the Droop Sandstone is erosional and its basal portion is cross-bedded, unlike the horizontally stratified and gradational lower portion described in these models.

Tidal inlet deposits, which are associated with barrier islands, have erosional lower contacts and are characterized by extensive high-angle cross-bedding (McCubbin, 1982; Galloway and Hobday, 1983). Lateral migration results in replacement of the normal beach to offshore sequence by cross-bedded tidal inlet sands. Continued migration allows reestablishment of beach and upper shoreface environments which then overlie the tidal inlet deposits. Large proportions of the barrier island may be comprised of tidal inlet deposits as a result of this process. The vertical progradational sequence thus formed consists of a lower cross-bedded zone with a scoured base overlain by a horizontally stratified zone (Galloway and Hobday, 1983). This is very similar to the sequence observed in the Droop.

The Droop was deposited as a barrier island complex and consists primarily of tidal inlet and beach deposits. The lower, cross-bedded zone represents tidal inlet deposition. The upper, horizontally stratified zone of the Droop represents beach (foreshore) deposition, but may also contain washover fan and/or flood tidal delta deposits. Cross-bedded upper shoreface environments would accompany re-establishment of the beach environment after tidal inlet migration (Galloway and Hobday, 1983). Therefore, upper shoreface deposits are probably present between in the middle part of the Droop.

No dune deposits were identified. Dickenson and others (1972) noted that such deposits would likely be destroyed during reworking. In addition, the low offshore slope of the basin would have been conducive to barrier island formation provided a source of sand existed. The sheet-like geometry of the Droop is due to the progradation of the barrier island.

UPPER SANDSTONES

Introduction

Clastic Mississippian strata in southeast West Virginia are considered to be deltaic in origin (deWitt and McGrew, 1979; Craig and Varnes, 1979). The upper Bluefield consists of interbedded red, green and variegated shales (many of which are fossiliferous) with thin silts and sands. The sands are highly variable in lithology but most commonly are fine-grained and impure. Several sands were named by Reger (1926). More recent workers (Manspeizer, 1957; McColloch, 1958) have noted that upper Bluefield sandstones are highly localized and cannot be traced laterally for any significant distance. This pattern of discontinuous sandstone distribution is common in deltaic settings, particularly in those that are dominated by fine-grained sediments. Intercalated with the shales, silts and sands are thin marine and nonmarine limestones, coals and dark gray to black shales (Reger, 1926; McColloch, 1957; Manspeizer, 1958). The close association of these lithologies is also diagnostic of deltaic deposition (Visher and others, 1975).

Environments of deposition in a deltaic setting include shelf, prodelta, distal bar (also known as delta platform and delta front), and distributary mouth bar in the lower delta plane (subaqueous delta). Environments in the upper delta plane (subaerial delta) include natural levee (overbank splay), distributary channel, beach, interdistributary bay, crevasse splay (bay fill), marsh, and lacustrine delta fill. Barrier islands are sometimes formed at the distal margins of deltaic lobes (Coleman, 1981). Major deltaic depositional environments are summarized in Table 2.

INDIAN MILLS SANDSTONE

Outcrop 8 (Indian Mills Sandstone) is composed of intercalated sandstone and shale. The sandstones are composed entirely of Type 2 sandstone. Four sand units are present. The lowermost sand, which coarsens upward, is 2.6 meters thick, slightly shaly at its base and

TABLE 2

MAJOR DELTAIC DEPOSITIONAL ENVIRONMENTS

INTERDISTRIBUTARY BAY:	Shales and silts; lenticular laminations; scattered macro and micro brackish water fauna.
CREVASSE SPLAY:	Coarsens upward from shales to sands; sands usually poorly sorted and contain 70-80% quartz; sands contain small-scale cross-beds; sequence may be repeated several times.
DISTRIBUTARY CHANNEL	Sand fining upward into clays or, sands with one or more fining upward sequences; cross-bedding common; usually scoured lower contact.
NATURAL LEVEE:	Alternating thin sand, silt, and shale; sands and silts have poor lateral continuity; sands often well sorted; base of sands usually gradational; ripple marked.
BEACH:	Clean, medium sorted sand with transported organics.
DISTRIBUTARY MOUTH BAR:	Sands and silts with small scale cross-bedding and high mica content; coarsens upward ;
DISTAL BAR:	Coarsening upward sequence of alternating sand, silt and shale laminations; sand and silt become more abundant near top; ripple marks common; faunal content decreases upward.
PRODELTA:	Finely laminated shale with scattered shells; faunal content decreases upward; grain size increases upward; silt-sand laminations become thicker upward.
TIDALLY PRODUCED SHELF SANDS	Coarsening upward sand with scoured base.
SHELF:	Marine shales or sediments indigenous to receiving basin.

(after Coleman, 1981)

massive in its upper part, and is composed of very fine-grained (0.08-0.09 mm), moderately clean sand. The lower middle sand is 2 meters thick, cross-bedded, and massive. It is composed of clean, fine-grained (0.14mm) sand which shows no grain size trend. The upper 2 sands are each approximately 0.5 meter thick, massive and are composed of very fine- to fine grained sand. These sands are interpreted as distributary mouth bar sands. The outcrop represents stacking of multiple bars which interfinger with prodelta clays.

Outcrop 1d consists of intercalated shale, silt and sand. Individual laminae are on the order of 2 to 4 cm thick. Maximum grain size is very fine-grained sand. Shale and silt decrease in abundance upward. Quartz percentage is low. Rock fragment and matrix percentages are high. The coarsening upward trend and overall lithology of this unit closely approximates that of distal bars.

BRADSHAW SANDSTONE

Outcrop 1c consists of finely intercalated sand, silt and shale with most laminae on the order of 2 to 4 cm in thickness. Grain size in the coarse-grained laminae ranges from coarse silt to very fine-grained sand. Shale and silt abundance decreases upward. Quartz percentage is relatively low. Rock fragment and matrix percentages are high. This deposit resembles the coarsening upward sequence of distal bar deposits. The intercalation of sand, silt and shale and overall lithology are typical of distal bar deposits.

Outcrop 6 is composed of 2 coarsening upward sequences. The upper sequence grades from fine-grained, matrix-rich (Type 1) sandstone at its base to massive, coarse-grained, clean (Type 2) sandstone in its upper portion. Grain size ranges from coarse silt (0.04mm) in the Type 1 sand in the lower part of the sequence to very fine sand (0.097mm) in the upper part of the sequence.

The lower sequence grades from shale at its base to Type 1 sand in its middle part to Type 2 sand in its upper part. Grain size ranges from very coarse silt (0.06mm) in the Type 1 sand to very fine sand (0.08mm) in the Type 2 sand.

The lithology and grain size trend of the upper sequence are characteristic of distributary mouth bar deposits. The lithology of the lower sequence is intermediate between upper distal bar and distributary mouth bar deposits. The upper sequence is interpreted as a distributary mouth bar. The lower sequence may represent upper distal bar deposition or deposition in the distal portion of a distributary mouth bar.

Outcrop 7 is a coarsening upward sequence from shale and silt at the base to fine-grained (Type 1) massive sandstone at the top. The outcrop is 3.05 meters thick. The upper contact is sharp and the sequence is overlain by green, fossiliferous shale. The overall sequence is similar to that of the distributary mouth bar, but the outcrop is thinner and more fine-grained than typical distributary mouth bar deposits. Outcrop 7 probably represents the distal portion of a distributary mouth bar.

BERTHA SANDSTONE

Outcrop 5 is composed of 2 strata of Type 2 (coarse-grained) sandstone located at the top and bottom of the outcrop. The Type 2 sand at the base of the outcrop is coarse-grained, contains abundant clay matrix, and is poorly sorted. Where clay matrix is absent, the sand is cemented by carbonate. The Type 2 sand at the top of the outcrop is coarse-grained, very clean, well-sorted and quartz cemented. The central portion of the outcrop is composed of intercalated calcareous Type 1 sand (very fine-grained, impure), silt and shale.

The central portion of the outcrop was largely covered and could not be examined closely. Its general lithology (intercalated sand, silt and shale) can be found in a variety of deltaic environments and so the origin of the sand could not be determined precisely. However, the upper sand provides helpful information. Its white color and very clean, coarse-grained (medium sand) lithology is rare in the upper Bluefield. Moreover, it is very thin (0.5m) unlike most coarse-grained sands in the deltaic environment. This sand is interpreted as a beach sand developed through reworking of sediments. Deposits of the central part of the outcrop were deposited in relatively shallow water proximal to the beach.

Outcrop 4 consists of 4 separate parts. The upper three parts are coarsening upward sequences which range from 2.3 to 3 meters in thickness. These are shaly at their base and coarsen up to massive sand. The sands in the upper sequences are fine-grained (Type 1 sand) and matrix-rich.

The lowermost part of outcrop 4 is a fining upward sequence. It is composed of 2 meters of Type 2 (coarse-grained, clean) sandstone at its base which fines upward into silts and shales. The lower contact is sharp and undulatory (scoured).

The scoured base and coarse-grained lithology of the base of the lowermost part of outcrop 4 suggests a distributary channel. The channel was abandoned, allowing infilling by finer grained materials. Establishment of an interdistributary bay above the distributary channel resulted in later deposition of crevasse splay deposits represented by the upper sequences of outcrop 4.

Outcrop 3b consists of intercalated shale, silt and sand. Individual beds are on the order of 2 to 4 cm thick. Maximum grain size is very fine-grained sand. Shale and silt beds decrease in abundance upward. Quartz percentage is low. Rock fragment and matrix percentages are high.

This outcrop is lithologically similar to distal bar deposits. The red color of the outcrop suggests that it was subject to subaerial exposure. Such exposure is characteristic of subaerial natural levee deposits. Outcrop 3b is interpreted to be a natural levee deposit.

GRAHAM SANDSTONE

Outcrop 2b, a Type 2 sandstone, is white in color, coarse-grained (medium sand), very clean, well-sorted and quartz-cemented. It is extensively cross-bedded but also contains planar bedding. Crossbedding is generally high angle and unidirectional. Most cross-bedding is planar tabular but accretion bedding and trough cross-bedding are also present. Scour surfaces are present within the sand.

Outcrop 2b is interpreted as a braided stream deposit. Trough cross-bedding probably represents channel deposition, while scour surfaces record lateral channel migration. Planar tabular cross-bedding and lateral accretion bedding record downstream bar migration, while planar beds indicate upper flow regime conditions, probably along bar crests. A complex assemblage of these types of bedforms and deposits is characteristic of braided channel deposits (Galloway and Horne, 1983; McCubbin, 1982; Coleman and Prior, 1982).

Channel and bar migration within braided channels produces fining upward sequences. Repeated channel and bar migration commonly truncates the earlier sequence, resulting in multiple but often incomplete fining upward sequences (Galloway and Horne, 1983; McCubbin, 1982; Coleman and Prior, 1982). In thin section, outcrop 2b shows two fining upward sequences, perhaps recording channel and bar migration. However, extensive quartz cementation obscures original detrital grain size and so these trends may not be significant.

Outcrop 1b is composed of interbedded shale, silt and sand. Individual laminae are on the order of 2 to 4 cm thick. Maximum grain size is very fine-grained sand. Grain size distribution is uniform. Quartz percentage is low. Rock fragment and matrix percentages are high. The unit is calcareous and overlies calcareous and fossiliferous shale. This unit resembles the lower parts of crevasse splay deposits. The absence of a coarser sand, usually found at the top of these units, suggests that outcrop 1b was formed at the distal margin of a crevasse splay.

CLAYTON SANDSTONE

Outcrops 1a, 3a, and 2a of the Clayton Sandstone are coarsening upward sequences. The outcrops consist of shaly to flaggy sandstone and silt at their bases and coarsen up into massive sandstone. The main sand units range from 1.8 to 4.9 meters in thickness. Sand units on the order of 1m thick or less are associated with the main sand bodies. Ripple marks and small scale cross-bedding are commonly present. The sands contain abundant matrix. Grain size in the sands ranges from coarse silt to very fine sand.

Associated with the sands are green, black and red shales, some of which are calcareous and/or fossiliferous, and yellow unfossiliferous limestones. Most of these units are interdistributary bay deposits. Some of these may have been subject to restricted or semirestricted conditions.

Grain size trends and lithologies are similar to those of crevasse splays. Associated sediments are typical of those of interdistributary bays. Therefore, these sands are interpreted as crevasse splays.

Summary

Sandstone depositional environments within the upper Bluefield reflect a shift from subaqueous delta deposition in the lower part of the upper Bluefield to subaerial delta deposition in the uppermost Bluefield. Sandstones of the lower part of the upper Bluefield (Indian Mills to Bertha Sandstones) consist largely of distal bar and distributary mouth bar deposits. Uppermost Bluefield sandstones (Bertha to Clayton Sandstones) consist largely of crevasse splay and distributary channel deposits. The upper Bluefield, therefore, is a progradational deltaic sequence with subaerial delta deposits prograding over subaqueous deposits.

Interpreted depositional environments of upper Bluefield sandstones are summarized in Figure 10. Note that subaerial delta deposits are found as low as the Bertha Sandstone in the northwestern part of the study area but only as low as the Graham Sandstone in the southeastern part of the study area. This indicates that progradation proceeded from northeast to southwest across the study area.

DISCUSSION

Basin Energy

DeWitt and McGrew (1979) suggest that conditions in southeast West Virginia may have shifted from high to lower energy during lower Bluefied time due to "shoaling of the sea and restriction of wave energy along the front of the growing Mauch Chunk-Pennington delta complex in mid-Chester time". Most deposits of the Bluefield Formation below the Droop indicate low energy conditions.

Whisonant and Scolaro (1980) studied a stratigraphic section from the middle part of the Bluefield Formation in Mercer County, West Virginia. Primarily on the basis of paleocurrent data, the section was interpreted as having been deposited in a nearshore, tide-dominated environment. No specific tidal range was suggested for the section, however they suggested that tidal currents were oriented north-south.

Lower Bluefield shelf sands in the study area are finer-grained than sands deposited in similarly reported environments. Swift and Rice (1984) note that such shelf sands are generally not formed by fair weather processes (currents) but rather by large storms (hurricanes). Most documented shelf sands from the Cretaceous mid-continent area

	SOUTHWEST													NORTHEAST	
SECTIONS	1	5	2	12	6	4	14	8	13	3	9	7	10	11	
CLAYTON SANDSTONE	CREVASSE SPLAY		CREVASSE SPLAY							CREVASSE SPLAY					SUBAERIAL DELTAIC
GRAHAM SANDSTONE	CREVASSE SPLAY		BRAIDED CHANNEL												
BERTHA SANDSTONE		BEACH				CREVASSE SPLAY and DISTRIB-UTARY CHANNEL				LEVEE					
BRADSHAW SANDSTONE	DISTAL BAR				DISTRIB-UTARY MOUTH BAR							DISTRIB-UTARY MOUTH BAR			SUBAQUEOUS DELTAIC
INDIAN MILLS SANDSTONE	DISTAL BAR							DISTRIB-UTARY MOUTH BAR							
DROOP SANDSTONE											BARRIER ISLAND		BARRIER ISLAND	BARRIER ISLAND	COASTAL
LOWER SANDSTONES				SHELF SAND			SHELF SAND		SHELF SAND						SHELF

Figure 10: Bluefield sandstone depositional environments.

referred to by Swift and Rice (1984) are from the north-south trending, east-facing shelf and, therefore, were subject to hurricanes. During the Late Mississippian the Appalachian basin was a south and west facing basin and so storm intensities may have been lower than those of the east-facing Cretaceous shelf (i.e., they would not have been subject to the direct impact of hurricanes). The finer-grained nature of the lower Bluefield sandstones, therefore, does not necessarily indicate that normal (fair weather) energy conditions were low.

The coarse-grained, clean, cross-bedded lithology of the Droop Sandstone suggests that basin energy was high at least through deposition of the middle Bluefield. Both wave and current energy were probably important contributors. The preponderence of shales and fine-grained, impure lithology of the sandstones in the upper Bluefield suggests that basin energy was low (deWitt and McGrew, 1979). Deltaic sands in high energy environments are typically thicker, cleaner and more laterally extensive than those found in the upper Bluefield.

Conclusions

The Droop Sandstone was likely deposited as a barrier island complex fronting a delta complex as it prograded over the lower Bluefield shelf sediments. The delta was deposited into esturine and/or lagoonal environments which were protected by the barrier island complex. Basin energy was largely absorbed by the barrier island complex. Wave and tidal energy were lower in the back barrier area allowing less winnowing of fines and less concentration of coarse-grained materials resulting in the largely fine-grained shaly nature of upper Bluefield sands. Coarse-grained, clean (orthoquartzite) sands in the uppermost part of the Bluefield were produced by fluvial processes (subaerial delta).

SUMMARY

The Bluefield Formation represents deposition transitional between the marine Greenbrier Limestone below and the shallow marine to deltaic upper Mauch Chunk sediments above. Most lower Bluefield units are laterally continuous and readily identifiable. Upper Bluefield units are laterally discontinuous. The Droop Sandstone, located at the transition between the lower and upper Bluefield, is a sheet-like, coarse, white, cross-bedded unit of distinctive lithology (orthoquartzite) which can serve as a marker unit separating the upper and lower Bluefield in the study area. Sandstones within the Bluefield range from greenish-gray to buff, fine-grained, calcareous varieties in the lower part to greenish-gray and reddish-brown, fine- to very fine-grained or, rarely, coarse, white, cross-bedded varieties in its upper part.

Bluefield sandstones fall into two groups, Types 1 and 2. Type 1 sands are thin, fine-grained, ripple-marked, and coarsen upward in outcrop. Quartz abundance is low, averaging 55.8%, and they are rich in rock fragments and matrix. Type 2 sands are relatively thick, coarse-grained, well-sorted and cross-bedded and are quartz-rich (averaging 83.8%).

Diagenetic alteration of Type 1 sands was dominated by mechanical compaction. Other diagenetic events include carbonate, quartz, pyrite, hematite and clay mineral authigenesis, intergranular pressure solution, stylolitization and fracturing. All primary porosity was occluded in Type 1 sandstones. Minor secondary moldic and fracture porosity is

present.

Quartz authigenesis, accompanied by intergranular pressure solution and stylolitization, was the principal diagenetic process in Type 2 sandstones. Quartz authigenesis did not totally occlude primary intergranular porosity. Secondary moldic porosity was formed by the solution of feldspars (moldic porosity) and by fracturing. Carbonate and clay mineral authigenesis and mechanical compaction also occurred in Type 2 sandstones.

Lower Bluefield units consist of marine limestone, calcareous shale and thin carbonate-cemented shelf sands deposited in a shallow marine setting. The Droop Sandstone was deposited as a prograding barrier island complex. Uplift of a largely metamorphic source to the east of the study area caused large volumes of detritus to be eroded and transported to the area. Upper Bluefield units reflect encroachment into the area of prograding deltaic environments in which red and green shales and sandstones, minor coals and limestones were deposited. Sandstones found within the upper Bluefield include distal bar, distributary mouth bar, beach, crevasse splay, natural levee and distributary channel deposits.

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APPENDIX A:

MEASURED SECTIONS

GENERAL

Named units in the Bluefield are largely those of Reger (1926). More recent workers have found that most of the units named by Reger, particularly in the upper part of the Bluefield, cannot be traced laterally for significant distances. Manspeizer (1958) and McColloch (1957) combined many of these units into various "intervals". For example, the Bertha Sandstone, Limestone, and Shale were combined into the "Bertha Interval". These "intervals" generally can be traced laterally and can be identified at most outcrops of the Bluefield Formation, whereas its individual components (Bertha sandstone, Bertha Limestone etc.) cannot be so identified. The names given to the sandstones by Reger (1926) are used in this report. Most sample sites chosen in this study were those identified by Reger (1926).

RED SULPHUR SPRINGS SECTION

Location

This section begins just north of the town of Ballard in Monroe County, West Virginia, and continues, in descending stratigraphic order, northward to Red Sulphur Springs along state road 12. Reger (1926) measured this section along a road (which is no longer in use) parallel to state road 12.

Unit Lithologies

Outcrop 1a - Clayton Sandstone	Thickness (meters)	Total
Sandstone, reddish-brown to greenish-brown, fine-grained, massive to ripple-marked, slightly flaggy in parts, becomes shaly at top; upper contact sharp to narrowly transitional	3.66	6.15
Shale, green, partly covered	0.91	2.49
Sandstone, green, fine-grained, massive	0.76	1.58
Shale, covered	0.36	0.82
Sandstone, green, fine-grained, flaggy to shaly, ripple-marked; plant fossils present; lower contact sharp with underlying shales	0.46	0.46

Outcrop 1b - Graham Sandstone	Thickness (meters)	Total
Sandstone, green, very fine-grained, shaly, becomes more shaly in center of section, ripple-marked; upper contact covered, lower contact narrowly transitional; underlying shales are sandy and fossiliferous	2.90	2.90

Outcrop 1c - Bradshaw Sandstone	Thickness (meters)	Total
Sandstone, green, fine-grained, massive in upper and lower parts, shaly to flaggy and ripple-marked in center; upper contact covered	1.49	3.93
Sandstone, green, fine-grained, shaly to flaggy, ripple-marked; lower contact covered	2.44	2.44

Outcrop 1d - Indian Mills Sandstone	Thickness (meters)	Total
Sandstone, green, fine-grained, shaly at bottom, grades upward into massive sandstone at top; upper contact covered	1.52	3.78
Sandstone, green, fine- to very fine-grained, lower 1.83 meters shaly to very shaly and ripple-marked, upper 0.43 meters massive; lower contact transitional with underlying shales	2.26	2.26

BUCK SECTION

Location

The village of Buck is located in Summers County, West Virginia, on county road 14. The Clayton and Graham Sandstones are exposed in the vicinity of Buck and are included in this section. The Clayton Sandstone is found on the north side of county road 14, 1.5 miles west of Buck. Reger (1926) described this outcrop as "25 feet thick and shaly". The Graham Sandstone is found in the bed of Wolf Creek just east of Buck on the south side of county road 14. Reger described this outcrop as "coarse, massive" and "30 to 40 feet thick".

Unit Lithologies

Outcrop 2a - Clayton Sandstone	Thickness (meters)	Total
Sandstone, reddish-brown, fine-grained, massive, medium-bedded, ripple-marked; minor shale lenses present; upper part becomes shaly and grades into overlying red shales	4.48	7.16
Shale, red	1.22	2.28
Limestone, yellow	0.15	1.06
Sandstone, reddish-brown, fine-grained, massive; sharp bounding contacts; underlying units consist of red shales	0.91	0.91

Outcrop 2b - Graham Sandstone	Thickness (meters)	Total
Sandstone (orthoquartzite), medium- to coarse-grained, white to buff; uppermost portion horizontally bedded, middle portion extensively cross-bedded; cross-beds are large scale (up to 2 feet) and generally high-angle (up to 25 degrees), and are apparently unidirectional; planar cross-bedding most abundant; lowermost portion is calcareous and cross-bedded and contains lenses and lobes of non-calcareous orthoquartzite	14.02	14.02

TALCOTT #1 SECTION

Location

This is the Talcott Section of Reger (1926) and is located just east of the town of Talcott in Summers County, West Virginia, on state road 12. It begins just north of the eastern portal of Big Bend Tunnel and continues, in descending stratigraphic order, northeast toward Talcott.

Unit Lithologies

Outcrop 3a - Clayton Sandstone	Thickness (meters)	Total
Sandstone, reddish-brown, fine-grained, massive becoming flaggy at top; upper contact sharp to narrowly transitional with overlying red shales	1.83	7.61
Shale, green	0.91	5.78
Sandstone, green, massive	0.15	4.87
Shale, green, calcareous, fossiliferous	0.15	4.72
Shale, reddish-brown	1.22	4.57
Sandstone, reddish-brown, fine-grained, upper two thirds massive, lower third shaly to very shaly; lower contact narrowly transitional with underlying yellow limestone and gray calcareous shale	3.35	3.35

Outcrop 3b - Bertha Sandstone	Thickness (meters)	Total
Sandstone, reddish-brown, fine-grained, ripple-marked; lower shaly part coarsens upward to flaggy upper part; upper and lower contacts covered	2.44	2.44

MARIE SECTION

Location

This outcrop is located southeast of the village of Marie in Monroe County, West Virginia, on county road 19. Reger (1926) described the outcrop as "shaly at top, massive at base" and 30 feet thick.

Unit Lithology

Outcrop 4 - Bertha Sandstone	Thickness (meters)	Total
Sandstone, green, fine-grained, shale at base grading up to massive sandstone in upper part; upper contact sharp with overlying shales	2.74	11.58
Sandstone, green, fine-grained, shaly at base, grades up to flaggy sandstone	1.16	8.84
Shale, dark gray	0.82	7.68
Shale, green, upper 0.38 meters consists of green, flaggy to massive sandstone	1.68	6.86
Sandstone, green, fine- to very fine-grained, upper and lower portions shaly, center part flaggy to massive	1.37	5.18
Shale, green; mostly covered	1.83	3.81
Sandstone, brown becoming greenish toward upper part, fine- to medium-grained, massive; more massive at base and fines upward; shaly zone in center; lower contact sharp and wavy with underlying shales and yellow limestone	1.98	1.98

BERTHA SECTION

Location

Reger (1926) first described this section on what is now county road 33 near the village of Bertha in Summers County, West Virginia. Bertha is now covered by water of the Bluestone Reservoir. The outcrop is located on county road 33 west of its juncture with county road 14/2 and west of and below the Bluestone Conference Center. This is the type section for the Bertha Sandstone. Reger (1926) described the outcrop as being "shaly and 45 feet thick".

Unit Lithology

Outcrop 5 - Bertha Sandstone	Thickness (meters)	Total
Sandstone, white to buff with iron stains, medium to coarse-grained, massive; sharp bounding contacts; overlain by shales	0.30	10.81
Shale, green, mostly covered	0.76	10.51
Sandstone, green, fine-grained, massive and ripple-marked; calcareous; intercalated with green shale, most of which is covered	5.33	9.75
Sandstone, green, fine-grained, flaggy to shaly	0.61	4.42
Sandstone, green, fine- to medium-grained, cross-bedded	0.46	3.81
Sandstone, green, fine-grained, shaly to flaggy; intercalated with green shale	0.91	3.35
Sandstone, green to dark gray, fine- to very fine-grained, very shaly; coarsens upward from lower shaly part into coarser upper part	1.92	2.44
Sandstone, greenish-brown, medium-grained, massive; calcareous; underlying shales are covered	0.52	0.52

BIG BEND SECTION

Location

This outcrop is located in Summers County, West Virginia, just east of the mouth of Spruce Run, and just northeast of the juncture of state road 12 and county road 29, on the southeast side of county road 29. Reger (1926) described this outcrop as shaly and 50 feet thick.

Unit Lithology

Outcrop 6 - Bradshaw Sandstone	Thickness (meters)	Total
Sandstone, green, fine- to medium-grained, massive with minor shale lenses; upper contact and overlying sediments eroded	2.44	10.81
Sandstone, green, fine-grained, very shaly at base coarsening upward into flaggy sandstone	2.71	8.37
Sandstone, gray, fine- to medium-grained; cross-bedding present and especially prominant in upper part; ripple-marks also common	1.46	5.66
Shale, dark green to dark gray, fisile	0.27	4.20
Sandstone, greenish-brown, fine-grained, with shaly portion in center	1.34	3.93
Sandstone, green, fine-grained, shaly to flaggy; partly covered	1.22	2.59
Sandstone, gray to green to brown, fine-grained, ripple-marked; contains brown carbonate interbeds, lower contact is sharp; underlying shales are green, gray and red and nodular and contain coal seams	1.37	1.37

PENCE SPRINGS SECTION

Location

This outcrop is located in Summers County, West Virginia, on county road 3/18 just northeast of the juncture of county road 3/18 and state road 12. This locality is the Pence Springs Section of Reger (1926). Reger described the Bradshaw Sandstone here as being green, hard and 10 feet thick.

Unit Lithology

Outcrop 7 - Bradshaw Sqandstone	Thickness (meters)	Total
Sandstone, green, fine-grained, massive, ripple-marked; minor shale lenses; upper contact sharp with overlying green, calcareous, fossiliferous shale	1.22	3.05
Sandstone, green, fine-grained, shaly to flaggy; contains one thin massive sand layer; lower contact transitional with underlying green, black and gray shales	1.83	1.83

ROCK CAMP SECTION

Location

This outcrop is located in Monroe County, West Virginia, on the north side of U.S. Route 219, approximately 0.1 miles north of the junction of U.S. Route 219 and county road 29 at the town of Rock Camp. Reger (1926) described this outcrop as "gray, coarse, massive, and hard".

Unit Lithology

Outcrop 8 - Indian Mills Sandstone	Thickness (meters)	Total
Sandstone, green, fine-grained, massive; sharp bounding contacts; overlying rocks are covered	0.46	7.71
Shale, green, largely covered	0.67	7.25
Sandstone, green, fine-grained, massive; sharp bounding contacts	0.61	6.58
Shale, green, sandy; largely covered	0.64	5.97
Covered	1.28	5.33
Sandstone, green, fine-grained; low angle cross-bedding; becomes shaly in center; sharp bounding contacts	1.52	4.05
Shale, green, partly covered; coal seam at top	1.01	2.53
Sandstone, green shaly at base coarsening upward into fine-grained sand; sharp lower contact; underlying sediments are shale with thin sand stringers	1.52	1.52

TALCOTT #2 SECTION

Location

This outcrop is located in Summers County, West Virginia, just southeast of the town of Talcott, on the south side of county road 15/2 approximately 0.25 miles east of the juncture of county roads 17 and 15/2. The outcrop was measured along a private road which ascends Wind Creek Mountain.

Unit Lithology

Outcrop 9 - Droop Sandstone	Thickness (meters)	Total
Sandstone (orthoquartzite), white to buff, weathers buff to brown; medium-grained, friable; lower part characterized by abundant high angle (up to 25 degrees), large-scale (up to 2 feet), trough and minor planar cross-bedding; upper part characterized by low-angle, small-scale cross-bedding, horizontal bedding and minor ripple-marks; lower contact sharp and undulatory with underlying greenish-brown, calcareous, highly fossiliferous shale	21.34	21.34

ALDERSON SECTION

Location

This outcrop is located in Monroe County, West Virginia, southwest of the town of Alderson on the north side of county road 1 approximately 0.3 miles east of the juncture of county road 1 and state road 3. Reger (1926) noted that the exposure "makes a great white cliff 80 feet thick".

Unit Lithology

Outcrop 10 - Droop Sandstone	Thickness (meters)	Total
Covered; includes Droop float	3.66	24.54
Sandstone (orthoquartzite), white to buff, weathers buff to brown; medium-grained, friable; lower part characterized by abundant high angle (up to 25 degrees), large-scale (up to 2 feet), trough and minor planar cross-bedding; upper part characterized by low angle, small-scale, cross-bedding, horizontal bedding and minor ripple-marks; upper contact covered, lower contact sharp and wavy	20.88	20.88

ALTA SECTION

Location

This outcrop is located in Greenbrier County, West Virginia, on the southeast side of U.S. Route 60, just northeast of the bridge which spans Interstate 64, and 1.5 miles northwest of the town of Alta. Price and Heck (1939) described this outcrop as white, massive, cross-bedded and 50 feet thick.

Unit Lithology

Outcrop 11 - Droop Sandstone	Thickness (meters)	Total
Sandstone (orthoquartzite), white to buff, weathers buff to brown; medium-grained, friable; lower part characterized by abundant high angle (up to 25 degrees), large-scale (up to 2 feet), trough and minor planar cross-bedding; upper part characterized by low angle, small-scale cross-bedding, horizontal bedding and minor ripple-marks; upper and lower contacts covered	13.72	13.72

ASSURANCE SECTION

Location

This outcrop is located in Monroe County, West Virginia, approximately 2 miles south of the town of Greenville, on the north side of county road 25/4. Reger (1926) described this outcrop as "being massive but having some green shale in the upper portion, the entire thickness being 35 feet".

Unit Lithology

Outcrop 12 - Webster Springs Sandstone	Thickness (meters)	Total
Sandstone, green, shaly to flaggy, ripple-marked; upper contact covered	1.22	7.32
Sandstone, greenish-brown, shaly, ripple-marked; thin shale seam at top	2.44	6.1
Sandstone, greenish-brown, fine-grained, medium-bedded to flaggy; contains a few shale lenses; cross-bedded at base, fines upward	1.68	3.66
Sandstone, greenish-brown to buff, cross-bedded; lower contact covered	1.98	1.98

WAYSIDE SECTION

Location

This outcrop is located in Monroe County, West Virginia, on the north side of county road 7 approximately 2 miles northeast of the village of Wayside. Reger (1926) described this outcrop as "15 feet thick, calcareous and shaly".

Unit Lithology

Outcrop 13 - Webster Springs Sandstone	Thickness (meters)	Total
Sandstone, partly gray and calcareous and partly greenish-brown; fine-grained, massive at top becoming shaly at base; upper and lower contacts sharp; overlying sediments largely calcareous shales	1.75	10.37
Shale, yellow, calcareous	2.29	8.62
Sandstone, greenish-brown, fine-grained, massive	0.23	6.33
Shale, yellow, calcareous	3.66	6.10
Sandstone, greenish-brown, fine-grained, upper part massive, lower part massive to slightly shaly, central part shaly; ripple-marks present in shaly part; upper contact with shale sharp; lower contact covered	2.44	2.44

GREENVILLE SECTION

Location

Approximately 2 miles west of the town of Greenville in Monroe County, West Virginia, a road cut on the north side of state road 122 exposes a sandstone in the lower part of the Bluefield Formation. This sandstone may be equivalent to the Edray Sandstone of Reger (1926).

Unit Lithology

Outcrop 14 - Edray Sandstone	Thickness (meters)	Total
Sandstone, green, very fine-grained, very shaly to flaggy; calcareous; upper contact gradational; overlain by shale	4.22	6.86
Sandstone, gray, very fine-grained, ripple-marked; calcareous; lower contact covered	2.44	2.44

APPENDIX B1:

POINT COUNT DATA

Type 1 Sandstones

Sample Number	Quartz	MRFs	SRFs	Matrix	Feld-spar	Pore Space	Carbon-ate	Other
Ka8	56.0	27.0	1.3	6.0	3.7	0.0	0.3	5.7
Ka2	46.7	17.3	16.7	19.3	T	0.0	0.0	T
Avg.	51.3	22.2	9.0	12.6	1.8	0.0	0.1	2.8
F11	49.0	18.0	T	26.0	1.0	0.0	0.0	6.0
F6	64.7	16.0	T	15.0	1.3	0.0	0.0	3.0
Avg.	56.8	17.0	T	20.5	1.1	0.0	0.0	4.5
B3	59.0	23.7	T	10.3	T	0.0	0.0	7.0
B7c	43.3	21.0	T	28.7	T	0.0	0.0	7.0
Avg.	51.1	22.4	T	19.5	T	0.0	0.0	7.0
Kb1	46.3	23.0	6.3	18.3	0.7	0.0	1.3	4.1
Kb2	51.3	25.0	0.3	13.0	0.3	1.0	5.7	3.4
Avg.	48.8	24.0	3.3	15.6	0.5	0.5	3.5	3.8
L3	46.0	25.3	T	19.3	1.3	0.3	0.0	7.8
L1	60.7	19.7	T	10.3	T	1.0	0.0	8.3
Avg.	53.3	22.5	T	14.8	0.6	0.6	0.0	8.0
Ke6	48.0	10.7	9.7	19.3	3.7	0.0	6.0	2.6
Ke4	65.3	18.3	T	11.7	1.3	0.3	0.0	3.1
Avg.	56.6	14.5	4.8	15.5	2.5	0.1	3.0	2.8
V4	67.7	19.3	1.0	2.7	1.0	0.0	4.7	3.6
V6	58.7	20.7	1.3	7.3	1.0	0.7	5.7	4.6
V8	42.3	13.0	30.7	6.7	0.3	0.0	2.7	4.3
Avg.	56.2	17.7	11.0	5.6	0.8	0.2	4.4	4.2
Kc5	45.7	2.0	17.0	26.3	T	0.7	4.3	4.0
Kc2	56.3	22.3	0.7	19.0	1.0	0.0	0.0	0.7
Avg.	51.0	12.1	8.8	22.6	0.5	0.3	2.2	2.3
S7	58.3	13.3	T	7.3	0.3	0.0	15.7	5.1
S3	66.0	24.3	0.3	2.7	3.0	0.0	2.3	1.4
S2	62.3	25.0	0.3	5.0	1.3	?	?	6.1
S1	60.3	21.0	0.7	9.7	5.3	0.3	2.3	0.4
Avg.	61.7	20.9	0.3	6.2	2.5	0.1	5.1	3.2

J5	41.0	T	0.0	7.0	2.0	0.0	47.7	2.3
J4	50.0	0.3	0.0	0.0	0.3	?	48.3	1.0
J3	71.7	7.3	0.0	16.7	T	0.7	0.0	3.6
J2b	71.0	4.7	0.0	2.3	1.0	0.0	18.0	3.0
Ja4	51.0	23.0	7.0	6.3	0.7	1.7	8.3	2.0
Ja3b	58.0	6.7	0.0	13.7	T	0.0	20.0	1.6
Ja2	49.7	25.0	0.0	8.0	T	0.0	4.0	13.3
Avg.	56.1	9.6	1.0	7.7	0.6	0.3	20.9	3.8
R4	67.7	7.0	0.7	18.7	0.7	0.3	2.3	2.6
R3	62.0	18.7	0.0	14.3	0.7	0.0	2.3	2.0
R1	67.0	16.7	0.7	7.6	1.3	0.0	5.3	1.4
Avg.	65.6	14.1	0.5	13.5	0.9	0.1	3.3	2.0
Type 2 Sandstones								
C1a	90.3	2.3	0.7	4.0	0.3	1.7	0.0	0.7
C3	79.7	T	T	17.3	T	3.0	0.0	T
C4	87.3	1.3	T	6.0	0.3	5.0	0.0	T
C5	85.0	1.3	6.0	3.3	T	4.3	0.0	T
C9	72.0	7.3	2.3	13.0	1.0	3.7	0.0	0.7
C10	75.0	10.3	3.3	8.3	0.3	1.3	0.0	1.3
Avg.	81.6	3.8	2.0	8.6	0.8	3.2	0.0	0.4
D2	93.0	0.7	2.0	0.7	0.3	3.3	0.0	T
D3c1	95.7	1.3	T	0.7	0.0	2.3	0.0	T
D6	95.7	T	T	0.3	0.0	4.0	0.0	T
D9	95.3	T	0.0	1.7	0.0	2.7	0.3	0.3
D20	86.0	T	0.0	8.7	0.0	5.0	0.3	T
D18	72.3	T	T	3.7	0.0	4.3	19.7	T
D17	54.3	0.3	T	T	0.7	0.0	44.7	T
D16	92.3	0.7	0.3	T	0.0	1.0	5.7	T
Avg.	85.6	0.4	0.3	2.0	0.1	2.8	8.8	T
M16	76.3	7.7	3.0	9.0	0.3	3.7	0.0	T
M11	78.7	1.0	1.3	15.0	0.3	2.7	0.0	1.0
M10	84.0	7.0	2.0	1.3	T	4.7	0.0	1.0
M7	80.0	0.3	1.3	10.0	0.7	7.0	0.0	0.7
M5b	89.7	3.0	1.3	1.7	1.0	3.0	0.0	0.3
M4	87.3	2.3	0.7	2.3	2.0	5.0	0.0	0.3
M3	79.7	9.3	T	5.3	0.7	5.0	0.0	T
Avg.	82.2	4.4	1.4	6.4	0.7	4.4	0.0	0.5
DB67	87.0	T	3.0	5.0	0.0	5.0	0.0	T
DB49	87.3	T	4.3	8.0	0.0	T	0.0	T
DB35	94.3	0.7	T	0.3	0.0	4.3	0.0	0.3
DB20	89.7	3.0	1.0	1.7	0.0	4.7	0.0	T
DB12	87.7	2.3	0.3	1.7	0.0	8.0	0.0	T
DB1	94.0	0.3	T	2.0	0.0	3.7	0.0	T
Avg.	90.0	1.0	1.4	3.1	0.0	4.3	0.0	0.1

DD40	89.3	T	2.3	5.0	0.0	3.3	0.0	T
DD26	93.7	1.7	1.7	0.7	0.0	2.3	0.0	T
DD20	94.7	T	2.7	1.3	0.0	1.3	0.0	T
DD8	94.3	0.7	T	0.3	0.0	4.3	0.0	0.3
DD4	91.0	1.3	T	2.3	0.0	5.3	0.0	T
Avg.	92.6	0.7	1.3	1.9	0.0	3.3	0.0	0.1

Mixed Type 1 and Type 2 Sandstones

I16	61.3	24.3	0.7	8.7	0.7	1.0	0.0	3.3
I14	64.0	13.3	T	21.7	T	T	T	1.0
I7	68.3	4.3	4.0	20.7	0.3	T	0.0	2.3
I6	78.3	7.0	3.0	9.7	0.7	1.3	0.0	T
I4	87.0	T	2.0	3.0	T	5.3	0.0	0.7
Avg.	71.8	9.8	1.9	12.8	0.3	1.5	T	1.5
A19b	55.3	26.3	4.0	10.7	T	0.3	T	3.3
A16	61.3	23.7	0.7	12.0	0.7	T	0.0	1.7
A13	86.0	5.7	1.4	5.5	T	T	0.0	1.5
A11	80.3	11.0	4.7	2.7	T	T	0.0	1.3
A8	56.0	30.0	T	9.3	1.7	0.3	T	2.7
A2	78.0	14.7	1.0	2.0	0.3	2.7	0.0	1.3
Avg.	70.3	18.2	1.9	6.7	0.4	0.6	T	1.9
H13	92.3	0.7	3.3	2.3	0.0	1.0	0.0	0.3
H11	55.3	21.7	3.0	14.7	0.7	1.3	T	3.3
H7	48.3	18.3	0.3	8.7	0.7	0.0	22.0	1.7
H4	49.3	24.3	5.3	6.7	1.0	0.3	11.0	2.0
H3	52.0	11.3	1.0	10.7	T	T	21.7	3.3
H1	56.3	14.7	1.0	9.3	0.7	2.7	15.0	0.3
Avg.	58.9	15.2	2.3	8.7	0.5	0.9	11.6	1.8

APPENDIX B2:

GRAIN SIZE DATA

Sandstone	Sample Number	Mean long axis diameter (in mm)
Clayton	Ka8	.07
	ka2	.0441
	F11	.043
	F6	.038
	B3	.042
	B7c	.081
Graham	Kb1	.05
	Kb2	.0626
	D2	.256
	D3c1	.2225
	D6	.2669
	D9	.2757
	D20	.2505
	D18	.2191
	D17	.2808
	D16	.2693
Bertha	H13	.2023
	H9	.0503
	H7	.0577
	H4	.0781
	H3	.0470
	H1	.1504
	I16	.0594
	I14	.0557
	I7	.0645
	I6	.0847
	I5	.0954
	I4	.1281
	L3	.0474
	L1	.0328
Bradshaw	Ke6	.0764
	Ke4	.0456
	V4	.0688
	V5	.0636
	V6	.0657
	V8	.0378

	A19b	.0464
	A17	.0357
	A16	.0559
	A13	.0826
	A8	.0551
	A7	.0652
	A2	.0974
Indian Mills	Kc5	.0366
	Kc2	.0562
	C1a	.1198
	C3	.1347
	C4	.1419
	C5	.1391
	C9	.0933
	C10	.0783
Droop	M16	.0923
	M11	.1131
	M10	.1095
	M7	.153
	M5b	.1512
	M4	.1553
	M3	.1608
	DB67	.1824
	DB49	.204
	DB35	.2093
	DB20	.2403
	DB12	.1516
	DB1	.3426
	DD40	.19
	DD26	.209
	DD20	.24
	DD8	.1872
	DD4	.2115
Webster Springs	J5	.0494
	J4	.0478
	J3	.0590
	J2b	.0528
	JA4	.0628
	JA3a	.0419
	JA3b	.0392
	JA2	.0309
	S7	.0645
	S3	.0768
	S2	.0694
	S1	.0647
Edray	R4	.0390
	R3	.0371
	R1	.0615