Robert A. Hines. PETROLOGY OF THE STONY GAP SANDSTONE (UPPER MISSISSIPPIAN), MERCER COUNTY, WEST VIRGINIA. (Under the direction of Dr. Donald W. Neal) Department of Geology, April, 1983.

The Stony Gap Sandstone Member of the Hinton Formation serves as a useful marker unit within the gas-producing sandstone units in southeastern West Virginia. The Stony Gap is a well sorted, fine- to very fine-grained quartzose sandstone which is typically more than 90% quartz (78% detrital, 12% authigenic) with minor to trace amounts of clay minerals, accessory minerals and feldspar.

Diagenetic alteration of the unit is characterized by mechanical compaction and pressure solution of detrital quartz, which results in a net porosity reduction, and by cementation with silica derived from within the unit.

The distinctive character of the Stony Gap persists in the subsurface where it is readily distinguishable in terms of its gamma-ray signatures. Tectonic overprint has eliminated all porosity in outcrops; however, examination of drillers' logs and gamma-ray signatures reveal that the unit produces natural gas in northwestern portions of the study area.

Multivariate statistical analysis defines subtle facies changes suggesting that the Stony Gap Sandstone was deposited as a series of coalescing offshore bars within a sequence of peritidal shales and siltstones of the Mauch Chunk Group in southeastern West Virginia.

PETROLOGY OF THE
STONY GAP SANDSTONE (UPPER MISSISSIPPIAN),
MERCER COUNTY, WEST VIRGINIA

A Thesis

Presented to

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Master of Science in Geology

by

Robert A. Hines

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STONY GAP SANDSTONE (UPPER MISSISSIPPIAN),

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I wish to express my deepest love for the members of my family, and my sincere appreciation to my friends, both personal and professional, for their considerable contributions of love, patience, understanding and moral support.

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INTRODUCTION

The Stony Gap Sandstone Member of the Hinton Formation is an important marker unit within the Upper Mississippian, gas-producing strata of the Central Appalachian Basin. It provides a useful point of reference within the red sandstone and shale sequence which typifies Carboniferous stratigraphy between the final major marine incursion, represented by the Greenbrier Limestone, and the Pennsylvanian coal measures of deltaic origin. Published references to the Stony Gap are brief field descriptions of isolated exposures in southeastern West Virginia, prepared as part of a general catalogue of regional stratigraphy (Reger, 1926; Cooper, 1948; Englund and others, 1976; Englund, 1979). Detailed studies of the sedimentary and mineralogic characteristics of the unit are lacking.

PURPOSE AND SCOPE

The objective of my investigation was to detail the petrology of the Stony Gap Sandstone. Characterization of the mineralogic and petrographic properties and an interpretation of the effects of diagenesis upon the unit were undertaken. The unit's depositional environment and its spatial relationship to other Upper Mississippian strata of southeastern West Virginia were assessed to evaluate its utility as a marker within the gas-producing, Upper Mississippian rocks of the Central Appalachians.

GEOGRAPHIC AND GEOLOGIC SETTING

The area of investigation is located in Mercer County, West Virginia, and focuses on outcrops in the vicinity of the city of Bluefield (Figure 1). The county incorporates 423.9 square miles located at the boundary between the Valley and Ridge and the Appalachian Plateau physiographic provinces. Locally the county is dissected by numerous streams exhibiting deep, "V"-shaped erosional valleys. Maximum topographic relief is 2570 feet, with elevations ranging from 1450 feet on the New River at the mouth of Roundbottom Creek in the extreme northeastern corner of the county, to 4020 feet at Buckhorn Knob on East River Mountain, 3 miles southwest of Oakvale (Reger, 1926).

The Mississippian rocks of the study area are exposed in a broad, folded and faulted belt extending from the Virginia-West Virginia state line westward to where they dip gently northwestward beneath horizontal strata of Pennsylvanian age (Russ, 1969; Ryan, 1969). The Mississippian is divided into two series in southeastern West Virginia (Englund and others, 1976). The Lower Mississippian Series correlates with the Price Formation and Maccrady Shale (Englund and others, 1976; Englund, 1979) and consists predominantly of shallow-marine sandstone and shale (Arkle and others, 1979; Craig and Varnes, 1979). The Upper Mississippian Series correlates with the Greenbrier Limestone and the Mauch Chunk Group (Weller and others, 1948; Sprouse, 1954; Dyar, 1957) and exhibits a transition from marine limestone to shale and sandstone and near-shore tidal flat, beach and marsh deposits (Colton, 1970; Craig and Varnes, 1979;

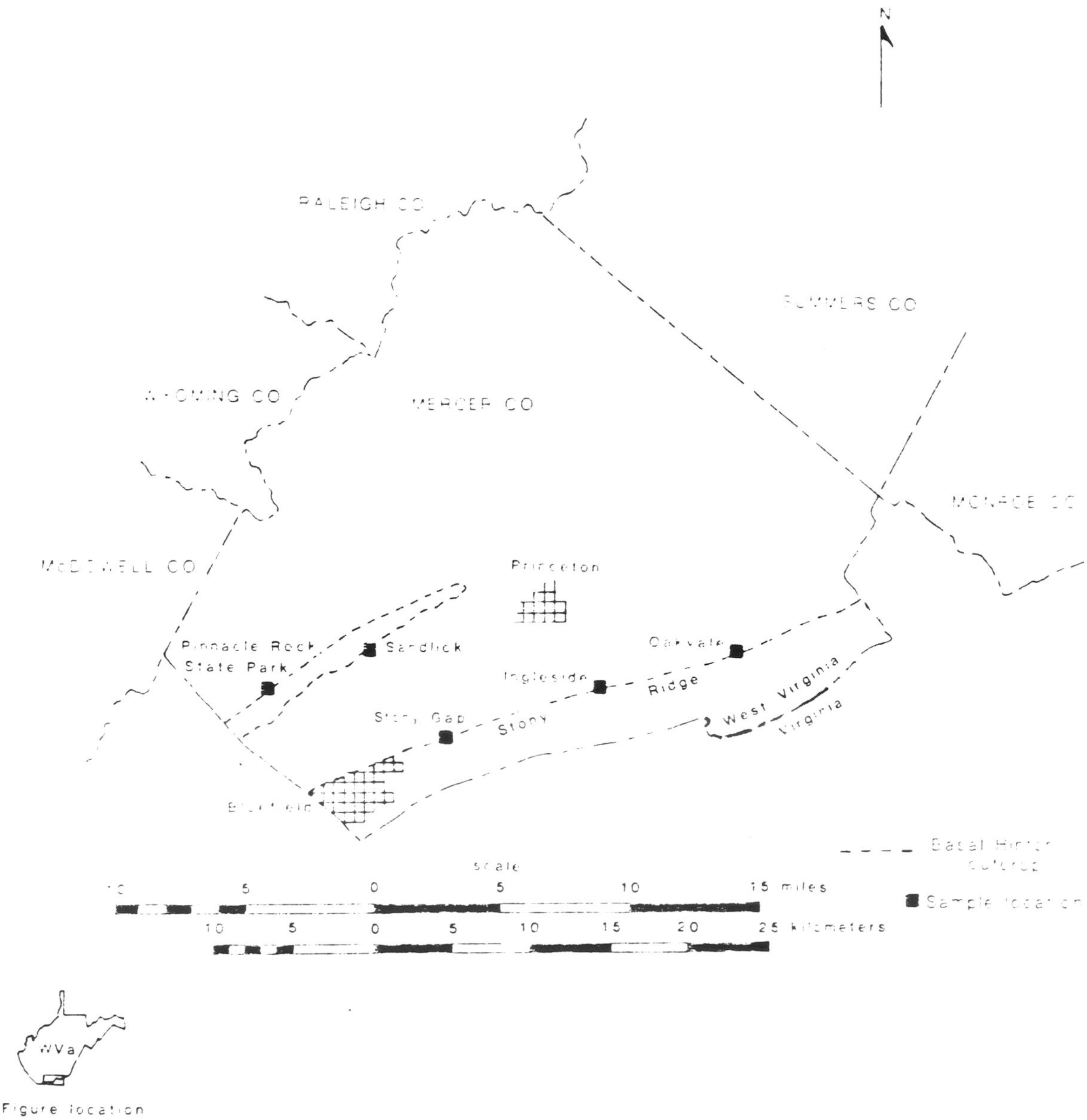


Figure 1. Mercer County, West Virginia showing location of outcrops.

Englund and others, 1976; Englund, 1979). The upper series is composed of five formations in southeastern West Virginia: the Greenbrier Limestone, the Bluefield Formation, the Hinton Formation, the Princeton Sandstone, and the Bluestone Formation (Dyar, 1957; Kanes, 1958).

The Stony Gap Sandstone Member marks the base of the Upper Mississippian Hinton Formation (Figure 2) which is composed mostly of grayish-red, partly calcareous shale and siltstone (Englund, 1979). Lesser amounts of medium-gray and greenish-gray shale, sandstone, fossiliferous limestone, and occasional, thin beds of coal are also present (McCulloch, 1957). The Hinton is up to 1300 ft (396 m) thick and correlates with the lower portions of the Pennington Formation in southwestern Virginia and with part of the Mauch Chunk Group in northern West Virginia (Cooper, 1948; Weller and others, 1948). Westward across the Appalachian Basin, the Hinton is truncated by the basal Pennsylvanian unconformity (Arkle and others, 1979). The Hinton is generally considered to reflect shallow marine, barrier bar, tidal flat and freshwater marsh environments (Colton, 1970; Craig and Varnes, 1979; Hobday and Horne, 1979).

The Hinton Formation is underlain by the Bluefield Formation. Marine deposition prevailed during accumulation of the Bluefield sediments. Episodes of seaward encroachment of nearshore mud, sand and freshwater marshes are also represented in the Bluefield (Whisonant and Scolaro, 1979; Humphreville, 1981).

Overlying the Hinton is the lithologically distinct Princeton Sandstone. It is typically a massive, coarse, conglomeritic sub-

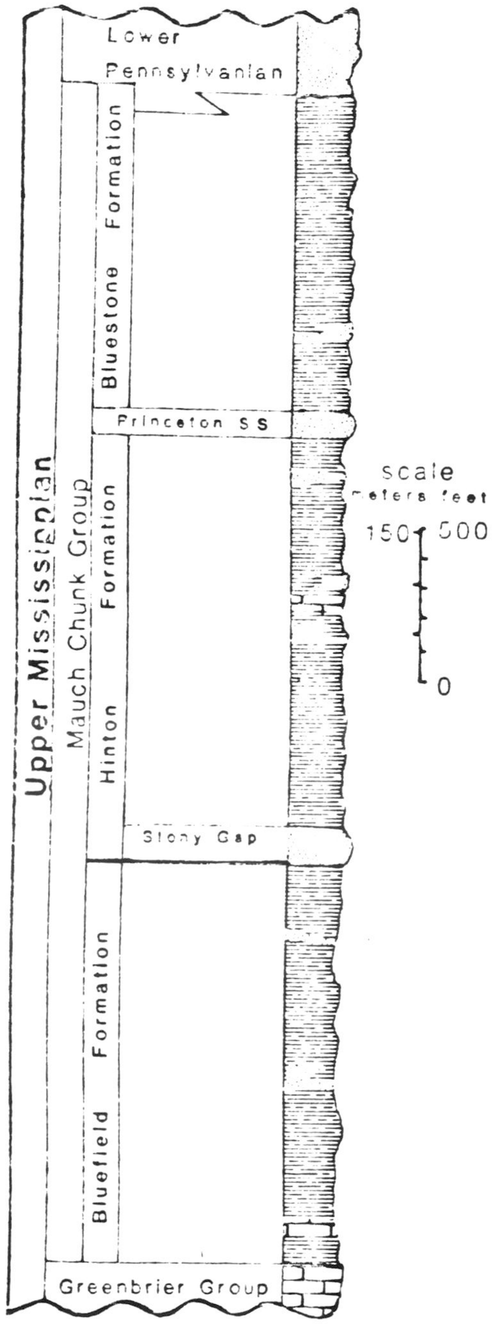


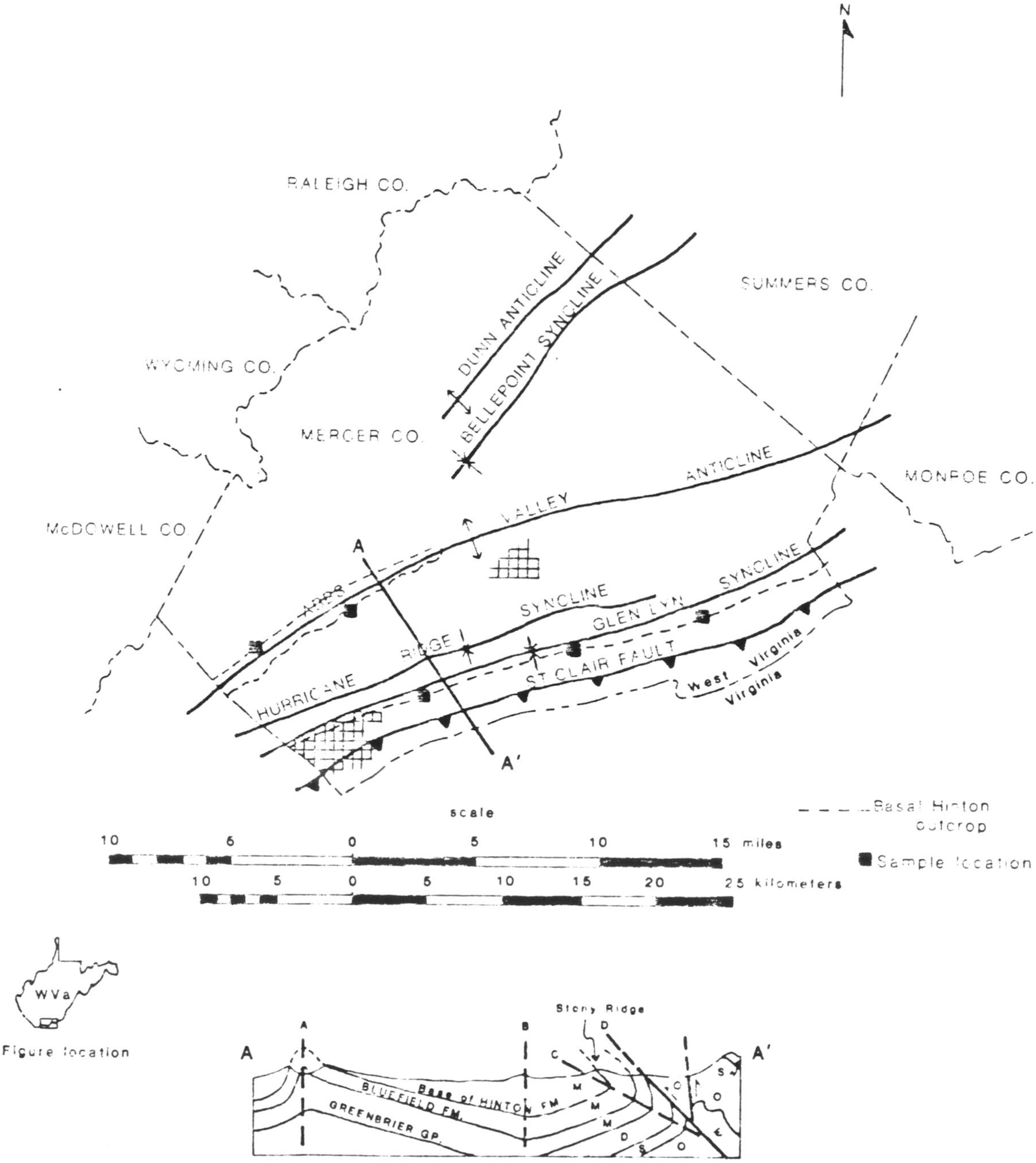
Figure 2. Generalized stratigraphic section for the Upper Mississippian of southeastern West Virginia.

graywacke attributed to the rapid influx of fluvial clastic sediments into a coastal area with intensive storm waves and longshore currents (McKirgan, 1971; Englund, 1979). The youngest Mississippian strata in the study area are included in the Bluestone Formation which intertongues and grades laterally into sediments of Pennsylvanian age (Englund and others, 1976; Englund, 1979).

STRUCTURAL SETTING

In southeastern West Virginia the principal geologic feature is the St. Clair thrust fault, which extends from Allegheny County, Virginia southwest to Richlands, Virginia (Gwinn, 1964). Within the study area this feature manifests itself topographically as the East River Valley (Englund, 1968; Olson, 1979). The St. Clair fault separates Ordovician rocks from underlying Devonian beds and younger strata. It is considered a major structural boundary, known as the Appalachian Structural Front (Price, 1931) or the Allegheny Front (Rodgers, 1963), and lies between the deformed strata of the Valley and Ridge Province and the relatively horizontal rocks of the Appalachian Plateau.

Another prominent geologic feature is the Hurricane Ridge Syncline (Figure 3), first noted by Campbell (1896), and named and described by Reger (1926). The St. Clair fault forms the eastern boundary of the syncline. The axial trace of the Hurricane Ridge Syncline has been widely used in structural interpretations with only minor modifications (Cooper, 1948; Thomas, 1960; Englund, 1968). Within Mercer County, however, McDowell (1982) has suggested



Horizontal scale of cross-section A - A' is expanded 2 x from map scale. V.E. = 4.5

Figure 3. Structural setting in southeast West Virginia (adapted from Thomas, 1966; McDowell, 1982).
A) axial trace of Abbs Valley Anticline,
B) axial trace of Hurricane Ridge Syncline,
C) axial trace of Glen Lyn Syncline of McDowell,
D) St. Clair fault

that this feature may be resolved into two separate synclines that differ in form and trend: 1) an overturned syncline, parallel to the St. Clair fault; and 2) a broad, open syncline in Mercer County with its western flank associated with the Abbs Valley Anticline. McDowell also suggested the name "Hurricane Ridge Syncline" be restricted to the open fold in Mercer County, the axial trace of which passes along Hurricane Ridge. The overturned syncline parallel to the St. Clair thrust was given the name "Glen Lyn Syncline" due to excellent exposures along the Mercer County, West Virginia - Giles County, Virginia, boundary near the New River at the village of Glen Lyn.

Deformation of the area is most often associated with the Alleghenian Orogeny, which was responsible for the St. Clair thrust (Woodward, 1957; Gwinn, 1964). The Hurricane Ridge Syncline, regarded as genetically separate from the St. Clair fault, is more closely related to the formation of the Abbs Valley Anticline as a syntectonic feature (Thomas, 1960, 1966; Burford and others, 1969). The Hurricane Ridge syncline was an actively subsiding depositional trough during the Late Mississippian, with its southeastern flank overturned and over-ridden by the St. Clair thrust (Cooper, 1964, 1971; Thomas, 1960, 1966; Burford and others, 1977). The Glen Lyn Syncline seems to be related to movement along the St. Clair thrust fault and may be the result of ramping of a deep decollement with drag effects along the footwall (McDowell, 1982).

METHODS OF INVESTIGATION

Outcrop Analysis

Petrographic data for the investigation of the Stony Gap were derived from a thorough examination of five outcrops in Mercer County, West Virginia (Figure 1). Outcrops were selected that best characterize lateral and vertical variations of the unit and that take advantage of several fresh exposures uncovered by construction activity. Samples obtained at various stratigraphic intervals from each exposure were designated by a three-digit numbering system in which the first numeral denotes outcrop location, and the last two numerals identify the sample, numbered upward from the base of the unit. Described and measured sections are presented in Appendix A.

Modal Analysis

Forty-three commercially prepared thin sections were examined and described. All thin sections were left without permanently fixed cover slides to facilitate X-ray diffractometry. Residual grinding impurities were removed by treatment in an ultrasonic cleaner prior to analysis.

Quantitative modal analyses were obtained from the thin sections by employing the point count method of Chayes (1956). Data derived from modal analysis is presented in Appendix B. Eight parameters were measured by point counting, utilizing 300 points per slide in six traverses of 50 points normal to bedding over the entire thin section. According to Pettijohn and others

(1972), a count length of 200 - 500 grains per thin section would suffice for estimates of composition. A chart published by van der Plas and Tobi (1965) illustrates the expected reliability of such point count data to achieve consistent results. This reliability is based upon the estimated proportion of a particular percentage of a mineral constituent within the total number of points counted per thin section. The estimated reliability (95 percent confidence level) of a count length of 300 points would produce precision within $\pm$ 5 to 6 percent for parameters constituting 25 to 75 percent of the sample; within $\pm$ 4 to 5 percent for those parameters making up 14 to 25 percent of the sample; and within $\pm$ 1 to 4 percent for parameters which are less than 14 percent of the sample.

Grain Size Measurement

Average grain size measurement for each sample was obtained by measurements of the long axes of 50 quartz grains using an ocular micrometer. It was determined quantitatively that homogeneity existed in the samples and that any grain size measurement based on 50 counts per thin section would closely approximate the actual grain size of the sample.

Luminescence Petrography

Samples for examination through electron excited luminescence (Nuclide Model ELM2A Luminoscope) were prepared from chips remaining after the thin section making process, thus allowing close comparison with corresponding thin sections. The samples were affixed to glass slides and polished to yield a slab approximately 200 microns thick. This technique, highly recommended by Furbish (1974), proved useful because petrographic thin sections of standard thickness are incapable of properly dispersing heat generated by the electron beam at operating voltages necessary for quartz luminescence. Inadequate heat dispersion resulted in the destruction of several standard thin sections.

The use of luminescence petrography permits observation of many features which are otherwise difficult to distinguish in many orthoquartzites (Smith and Stenstrom, 1965). Modal analyses under these conditions were performed by counting 300 points on each sample slab. Due to the presence of alternating zones of intense and moderate pressure solution parallel to bedding, precautions were taken to avoid bias in the data. Specimens were cut normal to bedding to insure adequate representation of the rock and point counts were made at an angle of 30^{o} to bedding. This angle of inclination was demonstrated by Chayes (1956) to contain, at most, a 2% analytical error associated with measurement of a banded sample.

Each point encountered during analysis was recorded, using the technique of Sibley (1975) and Sibley and Blatt (1976), as detrital quartz, authigenic quartz, an area of pressure solution, clay, pore space, or other.

Scanning Electron Microscopy

Portions of chips remaining after thin sectioning were mounted on stubs and examined under various magnifications with an ISI-40 Scanning Electron Microscope to detail mineralogy and to evaluate the effects of diagenesis upon the rock.

X-ray diffractometry

X-ray diffractograms were made from thin sections and from concentrations of argillaceous material from various intervals within the Stony Gap Sandstone. The analysis was done on a General Electric X-ray Diffractometer using copper K_a radiation. Scanning of thin sections from 3 to 50 degrees 2θ revealed dominant first order basal reflections of quartz with occasional basal reflections of alkali feldspar and, rarely, calcite. Selected specimens of the rock were pulverized and prepared for clay mineral analysis using methods outlined by Carroll (1970) and Thorez (1976). Minor amounts of illite, kaolinite and chlorite were detected. Attempts to quantify the data from these processes met with limited success due to the scarcity of argillaceous material in many samples. Illite appears to be the predominant clay mineral type, with traces of kaolinite and chlorite.

PETROGRAPHY

The composition of the Stony Gap Sandstone is predominantly that of a quartz arenite, with upper and lower portions of the unit approaching sub-arkosic composition. The most common constituent is quartz with lesser amounts of feldspar, calcite and clay. There are also small amounts of muscovite, zircon, tourmaline and various opaque minerals (Appendix B - Modal Analysis).

The majority of the grains are sub-rounded to angular, fine to very-fine grained and moderately-to-well sorted. Small-scale cross and flaser bedding and abundant microstylolite seams (Plate I) may be observed in thin section. Upper and lower portions of the Stony Gap contain abundant argillaceous minerals and frequent alkali feldspar grains. The lower units contain calcite at some locations. Petrographically, the upper and lower portions of the Stony Gap approach sub-arkosic compositions.

QUARTZ

Detrital Quartz

Detrital quartz is the most abundant constituent in each sample, ranging from 53 to 89 percent by volume. The great majority of the grains are monocrystalline. Polycrystalline quartz is frequently observed in many samples but does not exceed 0.10 mm in size. Most monocrystalline grains exhibit strongly undulose extinction. Vacuoles and Boehm lamallae are frequently observed. A few grains contain inclusions of micaceous material. Monocrystalline grains are little altered except for pressure solution

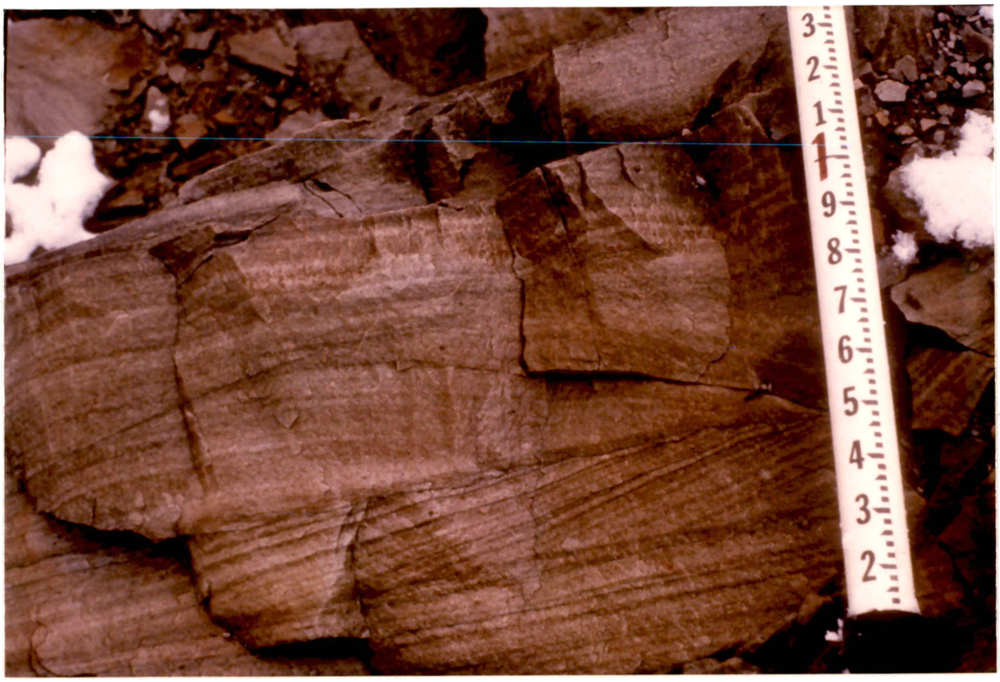


Plate Ia. Cross-bedding development in the Stony Gap Sandstone.

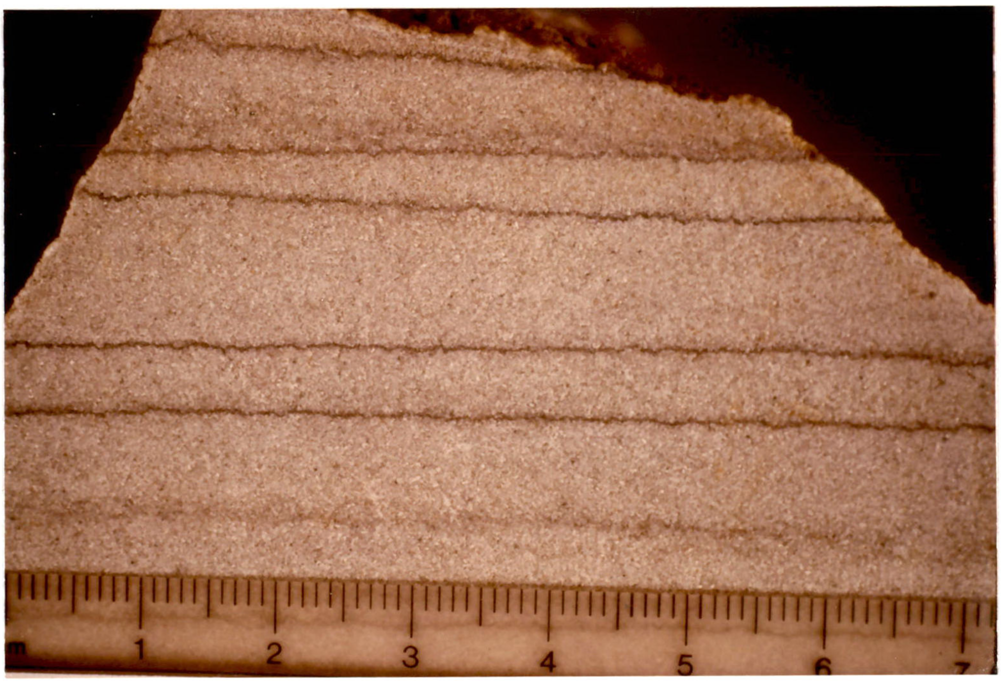


Plate Ib. Stylolite development in Stony Gap hand sample.
Scale is in centimeters.

and development of authigenic overgrowth.

The detrital quartz occurs as subrounded to subangular grains which are well sorted and vary in size from fine to very-fine sand (0.10 to 0.15 mm).

Authigenic Quartz

Secondary quartz commonly occurs as the main cementing agent in the Stony Gap, comprising up to 18% of the total rock volume. Authigenic quartz within the unit occurs in two forms. In some cases, clear secondary quartz overgrowths give the grains an angular appearance and completely fill the interstices (Plate II). Authigenic quartz is often tightly interlocked and optically continuous with the host grain. Authigenic quartz also occurs as pore fillings and overgrowths which contain inclusions of illite that are layered parallel to crystal planes in the quartz. Random sections through these overgrowths display polygonal grid patterns formed by argillaceous material outlining the crystal planes (Plate III). Heald and Larese (1974) first observed similar grid patterns in the Tuscarora Sandstone. The term "polygonal-grid quartz" is used hereafter to describe this peculiar texture.

CLAY MINERALS

Detrital clay accounts for a mean of 4 percent by volume of the Stony Gap interval. This material ranges from less than one percent within the massive, central quartz arenites to 14% in the

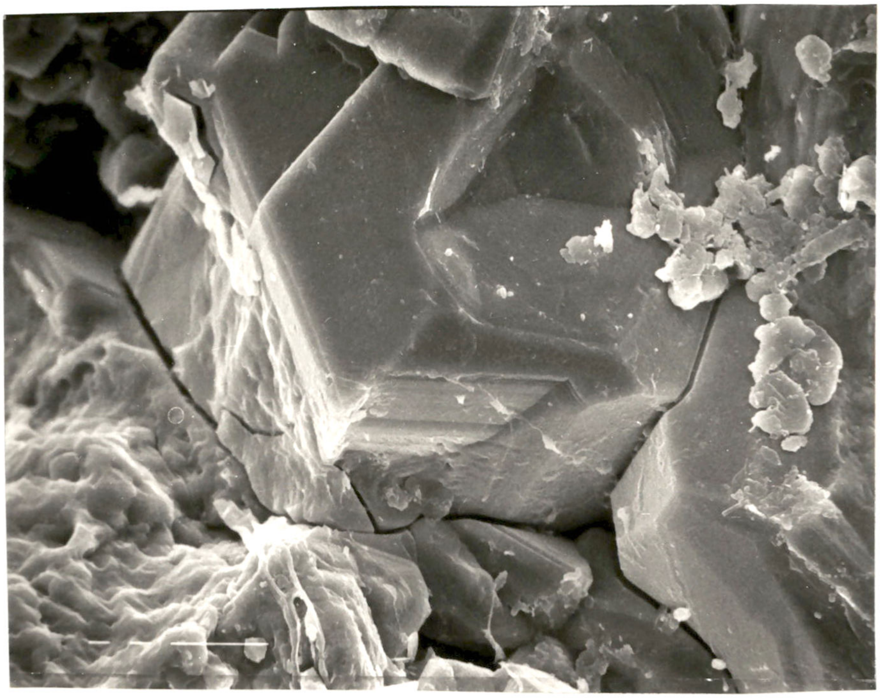


Plate II. Scanning Electron Micrograph of secondary quartz overgrowth. Note development of crystal faces and almost total destruction of porosity at grain boundaries (longest bar in lower left corner is 10 microns).

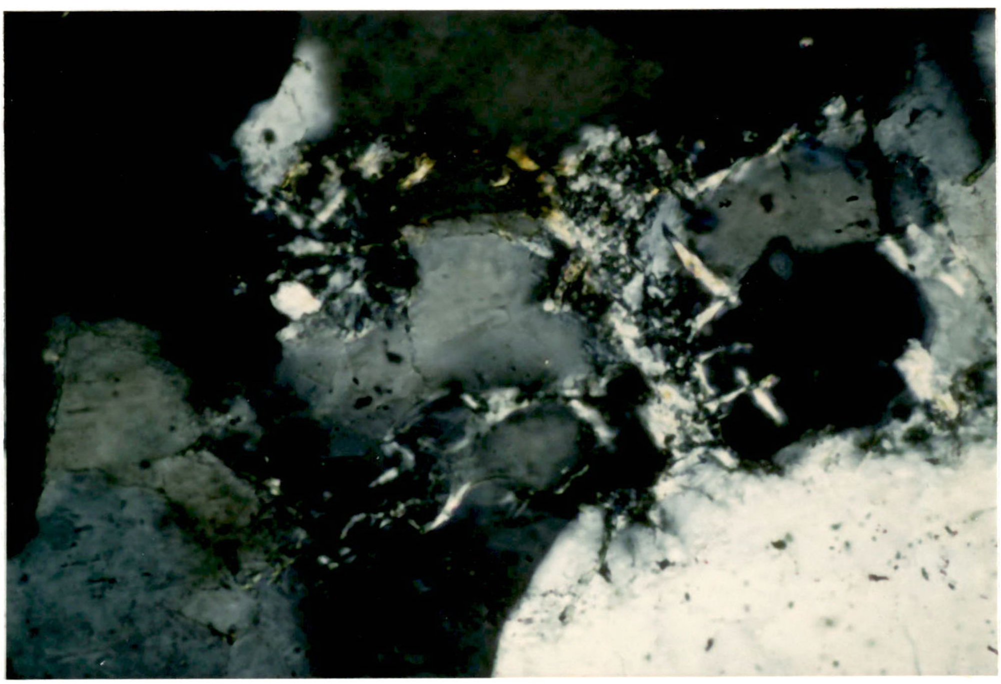


Plate III. Polygonal-grid patterns in authigenic quartz formed by clay inclusions along crystal faces (crossed nichols, 63x).

thin-bedded, sub-arkosic, upper and lower portions of the unit. Within the quartzose portions of the Stony Gap, clay minerals occur as illite coatings on detrital quartz. Locally, these coatings appear to have been incorporated into authigenic quartz as inclusions along crystal planes to form a distinctive polygonal grid-pattern. In the sub-arkosic portions of the unit, the clay minerals occur as interstitial fillings.

Authigenic clay material occurs in trace amounts in the Stony Gap Sandstone. Kaolinite and chlorite are the most abundant authigenic clay minerals. They occur as thin, platy flakes replacing feldspar along cleavage planes (Plate IV). Kaolinite also occurs as an alteration product of detrital muscovite within the sub-arkosic portions of the unit.

FELDSPAR

Detrital feldspars comprise less than one percent of the total volume of the Stony Gap Sandstone and may range from trace amounts to 8%. Feldspar occurrence is limited to the thinly-bedded, sub-arkosic portions of the unit. Potassic varieties, orthoclase and microcline, predominate. In all cases, feldspar grains appear severely altered, exhibiting a murky appearance in plain light. Microcline appeared to be the least altered of any feldspar type and displayed recognizable gridiron twinning. Alteration of the feldspar to kaolinite and chlorite appears to take place along cleavage planes (Plate IV).

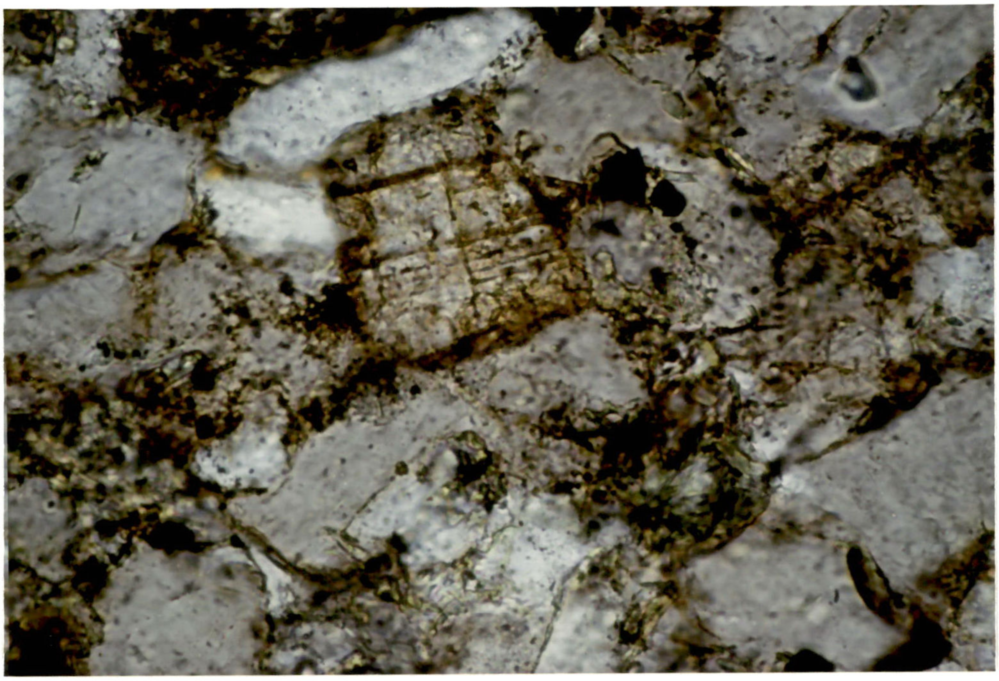


Plate IV. Replacement of feldspar by chlorite and kaolinite along cleavage planes (plain light, 63 x).

HEAVY AND ACCESSORY MINERALS

The heavy and accessory mineral types comprise less than 3 percent by volume of the Stony Gap samples. Muscovite is the most abundant, occurring as crushed and deformed flakes. Zircon and tourmaline are also present as rounded grains with diameters up to 0.10 mm. Tourmaline frequently displays green, brown and rarely, light blue pleochroism. These accessory mineral types are concentrated along zones of stylolite development. Residues of opaque minerals are also concentrated as distinct coatings along stylolite seams in the Stony Gap (Plate V). Stockdale (1936, 1945) believed that these coatings are composed of residues of argillaceous and carbonaceous materials remaining after solution of the more soluble constituents of the rock. Within the Stony Gap, these stylolite seams range in thickness from less than 0.01 mm to 1.00 mm.

CARBONATE

Carbonate averages less than one percent by volume of the Stony Gap, and ranges from zero to 23 percent. It occurs as calcite in three samples (RH 401, 402, 403) from the basal Ingleside, W.Va., exposure (Figure 1). These samples range from 7 to 23% calcite by volume and average 14%. Calcite is found as irregularly shaped patches surrounding detrital grains and as pore filling. It is anhedral and colorless in plain light and luminesces a bright orange-red color under cathodoluminescence (Plate VI).

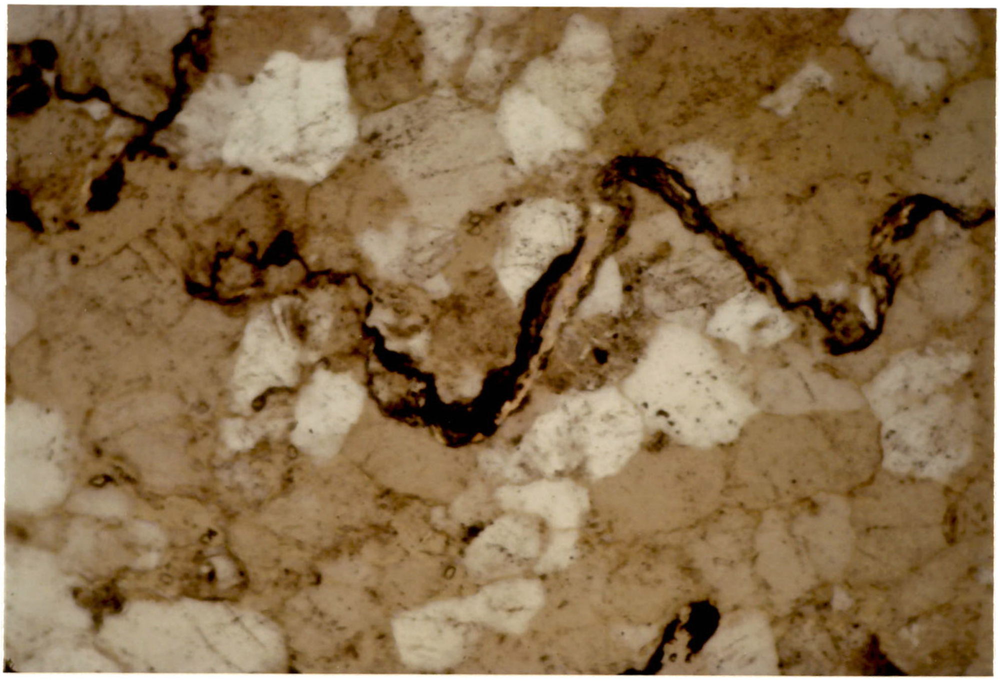


Plate Va. Photomicrograph of stylolite development (plain light, 63 x).

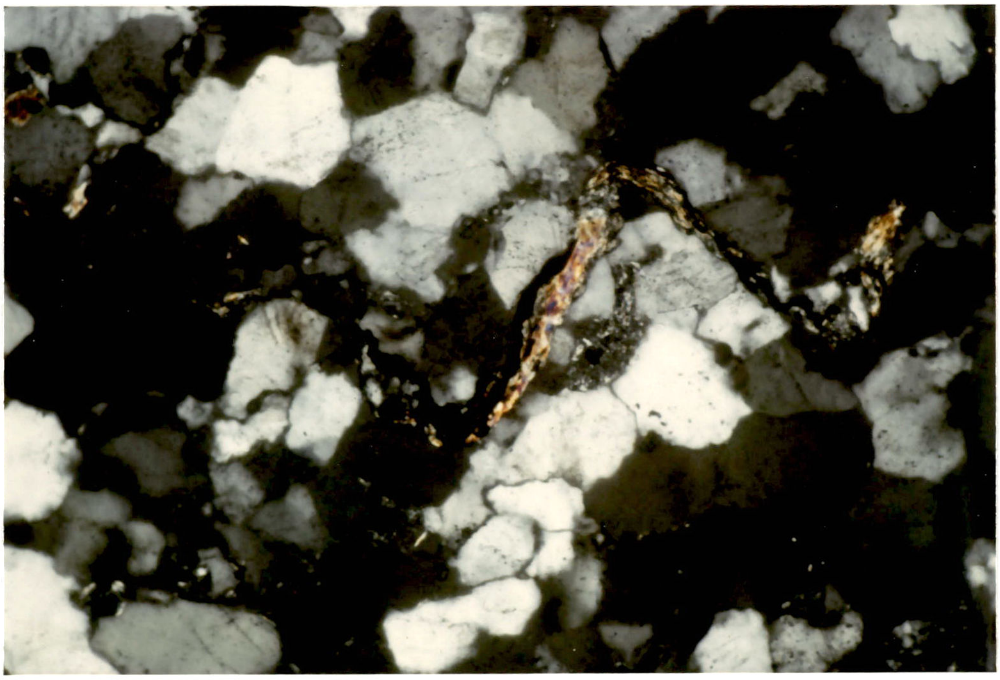


Plate Vb. Photomicrograph of stylolite development (crossed nichols, 63 x).

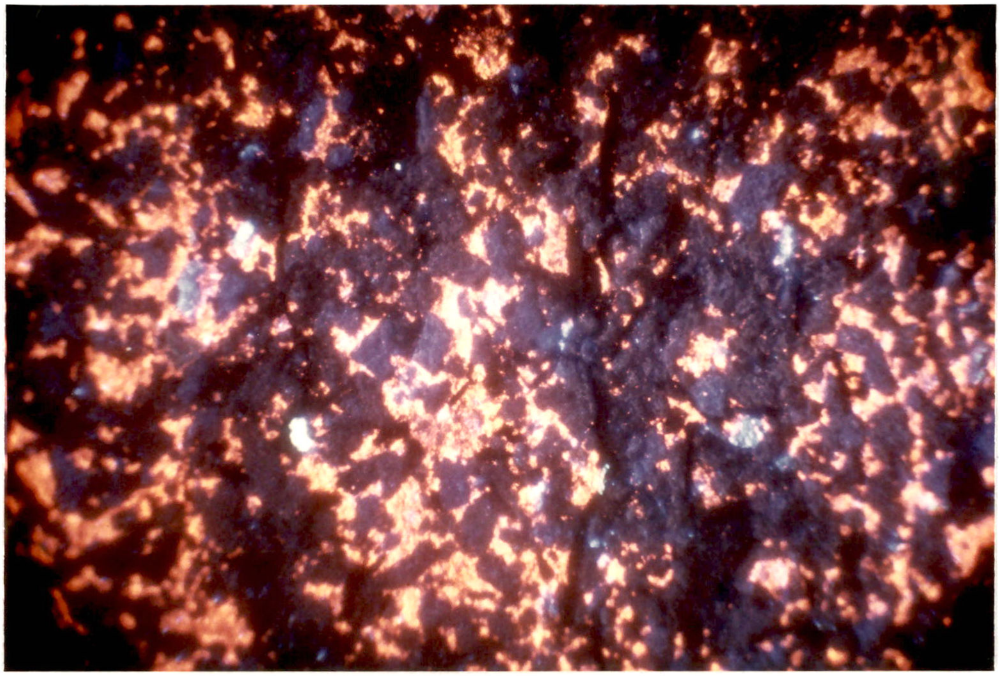


Plate VI. Red-orange cathodoluminescence of calcite in basal Stony Gap samples from Ingleside, West Virginia. Note faint blue luminescence of detrital quartz (14 kv luminescence, 35 x).

FOSSILS

Several examples of plant fossils have been reported from the basal Stony Gap Sandstone (Reger, 1926). The most common of these is Lepidodendron sp., a type of Carboniferous scale tree, which may be observed at Pinnacle Rock State Park (Plate VII and Figure 1).

Ostracods were observed within the basal portion of the Stony Gap in thin sections taken at Ingleside, W.Va. (Plate VIII). Specimens are articulated, relatively well preserved, and appear to have undergone little to no reworking. Their preservation is attributed to the presence of significant amounts of calcite cement in this basal section.

Plate VIIa. Lepidodendron sp. fragments on underside of basal Stony Gap, Pinnacle Rock State Park, W.Va. Pocket knife is 3 1/2 inches in length.

Plate VIIb. Detail of fossilized Lepidodendron sp. fragments at Pinnacle Rock State Park, W.Va.

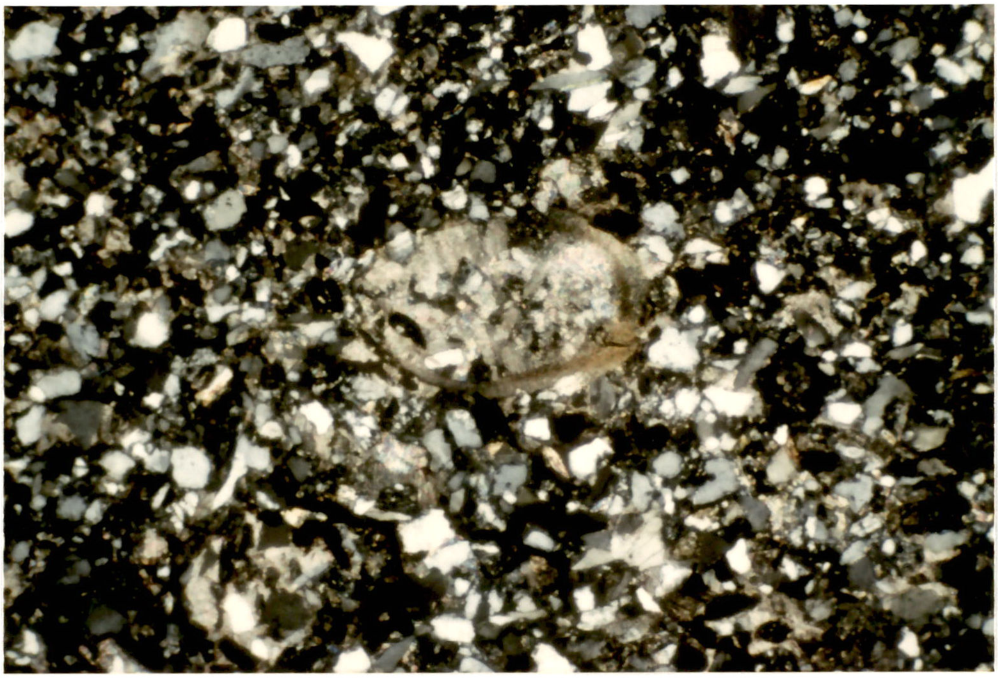


Plate VIII. Ostracod specimen in basal Stony Gap exposure at Ingleside, West Virginia (crossed nichols 63x).

DIAGENESIS

GENERAL

Diagenetic alteration of the Stony Gap Sandstone takes the form of porosity reduction through intergranular pressure solution and mechanical compaction. Pressure and temperature conditions responsible for diagenesis of the Stony Gap may be assessed within varying degrees of certainty, depending upon the technique being utilized.

Renton and others (1969), Deelman (1975), DeBoer and others (1977) and Sprunt and Nur (1977) have conducted the most recent experimental investigations regarding porosity reduction and pressure solution. Renton and others (1969) produced pressure solution and quartz growths using a variety of simulated pore solutions and discovered that angular grains, fine grains and chert were most susceptible to pressure solution. Deelman (1975) concluded that there was no such thing as pressure solution, after producing sutured grain contacts normally attributed to pressure solution, through experimental compaction and plastic deformation of a dry mixture of grains. Investigations by DeBoer and others (1977) indicated that water is a prerequisite for pressure solution (which may explain Deelman's conclusions based on dry mixtures). DeBoer and others also concluded that pressure solution is enhanced by increasing temperature and confirmed observations by Renton and others (1969) that pressure solution is relatively unaffected by the composition and pH of the aqueous pore solution. Sprunt and Nur (1977) were successful in reducing porosity up to

50% through pressure solution without grain crushing. They determined that porosity loss will increase with increased surface area of the grains involved. This translates to an increase in porosity loss when smaller grains are involved.

Accurately estimating the pressures associated with diagenetic alteration of the Stony Gap is difficult. Heald (1956) and Blatt (1979) indicate that high pressures are not necessary to initiate pressure solution. Experimental studies by Sprunt and Nur (1977) have demonstrated that at a pressure of 1.0 kb, temperature changes become the controlling factor in the solubility of a clean quartz sample. Coal isoreflectance studies by Kisch (1968) and by Cole and others (1979) indicate that burial depths of Middle Pennsylvanian coals reached 2500 m (8200 ft) in the Mercer County area. Measured sections of Lower Pennsylvanian and Upper Mississippian sediments above the Stony Gap add an average of 1722 m (5650 ft) (Arkle, 1974; Arkle and others, 1979; Englund, 1979) to this figure to yield 4220 m (13,850 ft) of sediment. Using a pressure gradient of 2.3 kg/cm^2 (1.0 psi/ft) for each 10 meters of burial (Maxwell, 1964; Tissot and White, 1978), 0.95 kb is the approximate minimum pressure on the Stony Gap due to overburden.

Estimates of the pressures resulting from tectonism are even more difficult; however, field evidence suggests that diagenetic alteration due to pressure solution occurred both prior to, and during application of tectonic stress associated with deformation of the Stony Gap. The presence of stylolite seams parallel to bedding indicates paleostress applied normal to bedding during early lithification (Heald, 1955, 1956; Nelson, 1981). Plate IX illustrates stylolites which are cross-cut and offset by small fractures which are, in turn, re-cemented through the effects of silica dissolution and re-precipitation. These re-cemented micro-faults are material discontinuities developed in response to tectonic stress (Pittman, 1981; Jamison and Stearns, 1982). This offsetting fabric is produced during brittle deformation of sand-stone at relatively low temperatures and pressures (T = 80^{o} C, P = 0.25 kb)(Stearns, 1978; Jamison and Stearns, 1982). By these estimates, paleostress due to tectonic deformation of the Stony Gap would increase total diagenetic pressure to approximately 1.2 kb. More significantly, the presence of microfaulting indicates continuation of diagenetic alteration through pressure solution and mechanical compaction prior to and during tectonic deformation.

Estimates of diagenetic temperatures are more easily established. Reports of coal isoreflectance (Cole and others, 1979) place the area of investigation near the 162^{o} C isotherm (Figure 4). Further indications of diagenetic temperature may be found through examination of conodont color alterations in Upper Mississippian sediments. The abundance and distribution of conodonts in the Hurricane Ridge Syncline has been well documented by Chaplin (1971, 1975, 1977). The Conodont Alteration Index (CAI) of the area has been placed as high as 3.5 for sections of Mercer County near the New River water gap (Figure 5)(Epstein and others, 1977). A CAI of this magnitude corresponds to temperatures of 110 to 200^{o} C (Harris, 1979).

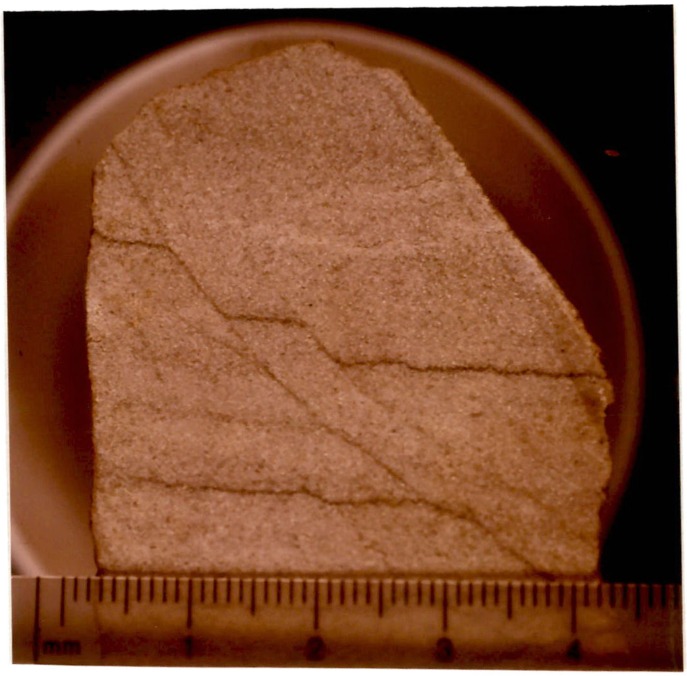


Plate IX. Microfault development in the Stony Gap Sandstone. Sample is taken from the type locality. Note the offset stylolites cross-cut by small fractures which are, themselves, re-cemented through silica dissolution and re-precipitation.

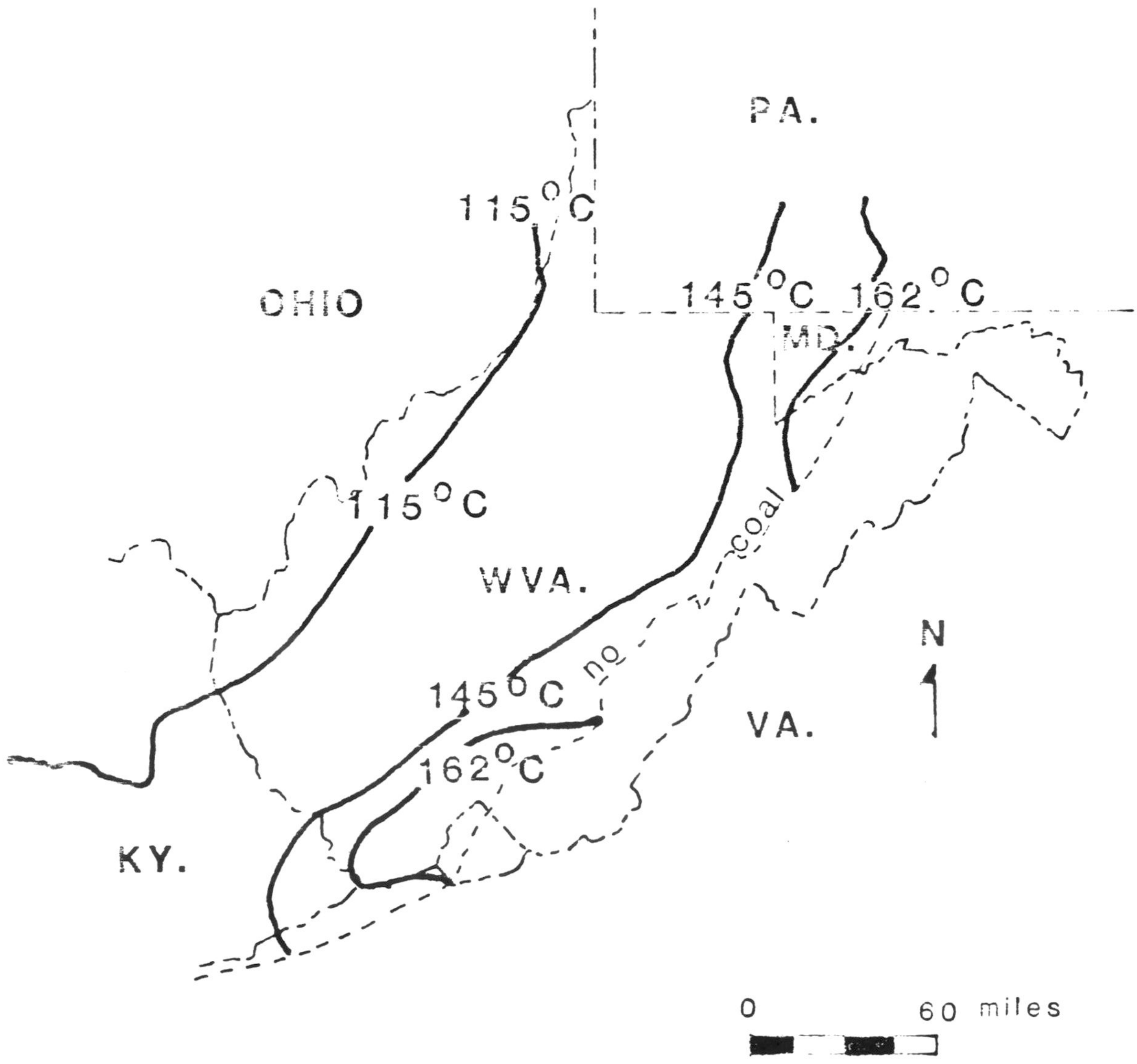


Figure 4. Coalification temperatures in the central Appalachians (adapted from Cole, Williams and Smith, 1979).

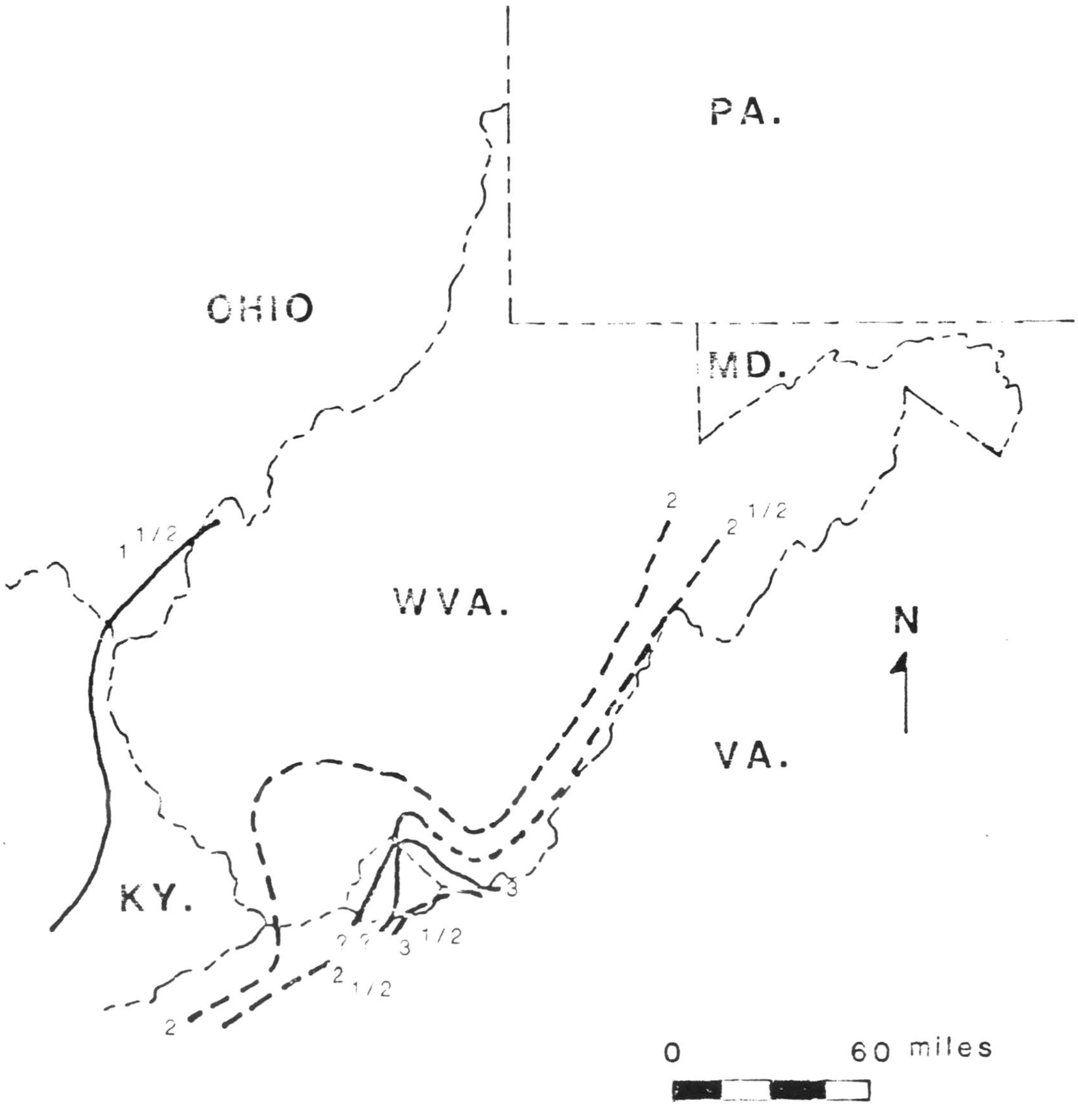


Figure 5. Conodont Alteration Index (CAI) patterns for the central Appalachians (adapted from Epstein, Epstein and Harris, 1977).

POROSITY REDUCTION

It is necessary to make some assumptions regarding the initial porosity of the Stony Gap before the process of porosity reduction can be properly evaluated. Prior to lithification, a well-sorted, medium compacted, fine sand-sized sediment, such as the Stony Gap, will have an estimated porosity of 40 $\pm$ 3% (Graton and Fraser, 1935; Gaither, 1953; Beard and Weyl, 1973).

Fraser (1935), Folk (1974) and Blatt and others (1980) suggest that the porosity of a pure quartz sand may be altered by three major processes: 1) compaction, 2) solution, and 3) cementation. Intergranular pressure solution involves a reduction in porosity through repacking due to solution and by precipitation of silica derived from the dissolved detrital grains.

The effects of mechanical compaction in the reduction of porosity have been analyzed through the use of simple geometric models (Marvin, 1939; Rittenhouse, 1971a; Manus and Coogan, 1974). Due to lack of data to demonstrate that the packing of natural sands is non-random, any model based upon a regular arrangement of particles must be viewed with caution. However, Rittenhouse (1971a) and Manus and Coogan (1974) felt that an orthorhombic packing of spheres best represents a natural situation. Orthorhombic packing results in a porosity of 39.5% (Rittenhouse, 1971a), which is within the 40 $\pm$ 3% range expected for the Stony Gap. Also, a study of randomly packed lead spheres (Marvin, 1939) demonstrated that at atmospheric pressure approximately 7.5 contacts per sphere could be expected. Orthorhombic packing closely approximates this with 8 contacts per sphere (Manus and Coogan, 1974). Rittenhouse (1971b) and Beard and Weyl (1973) examined sands with various grain sizes and degrees of sorting, and found that other variations in packing, sorting, roundness and grain sphericity do not result in higher solution-to-porosity loss ratios than those found for equal-sized spheres in orthorhombic packing. Therefore, a model utilizing orthorhombic packing is a good approximation for maximum pressure solution-to-porosity loss ratios.

Figure 6 displays several curves illustrating the relationship between porosity and volume percent of grains dissolved, assuming that none of the dissolved material precipitates as cement. Curve "A" is adapted from Rittenhouse (1971b) and represents an approximation of the maximum percent pressure solution necessary to account for a given remaining porosity; assuming 40% original porosity, orthorhombic packing and vertical strain. Curve "B" is from Sibley and Blatt (1976) who made the same assumptions with the exception that strain was assumed equal in all directions. These authors indicate that this is a limiting case, since areas of intense pressure solution clearly indicate that most strain is in the horizontal plane. Sibley (1975) and Sibley and Blatt (1976) point out that neither model of strain is entirely valid for natural sands. Because natural sands are not composed of uniformly sized spheres, the true curve should lie to the right of "A" and "B" (Sibley and Blatt, 1976; Harrell, 1981). Thus, pressure solution-to-porosity ratios should be somewhat less than depicted in the

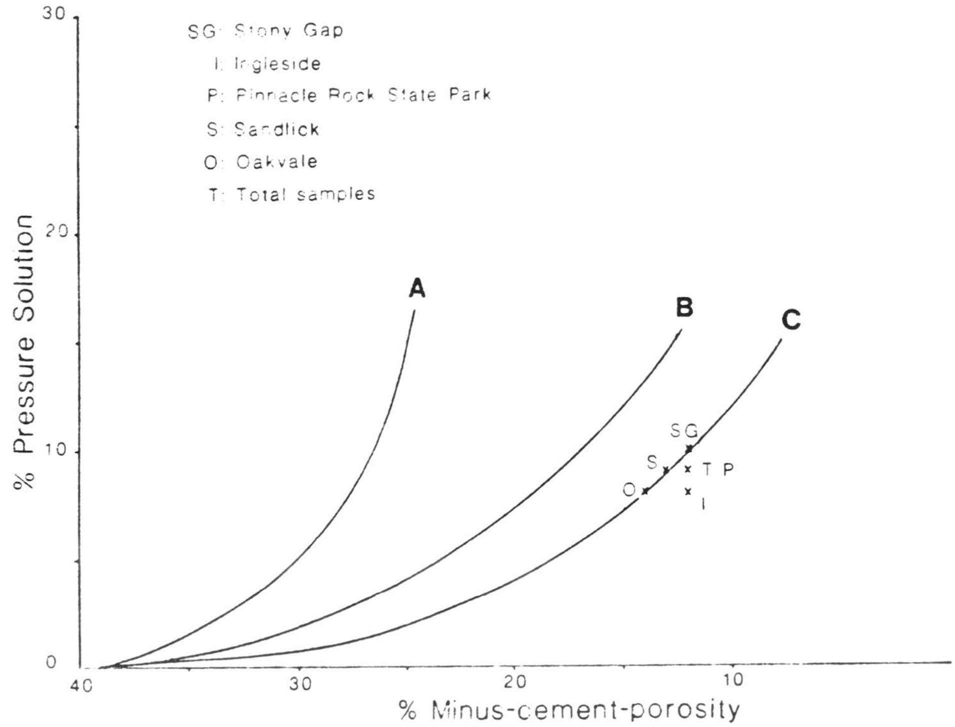


Figure 6. Pressure solution-to-porosity relationships.
A - Rittenhouse (1971b),
B - Sibley and Blatt (1974),
C - Estimated relationship for the Stony Gap data

diagram.

Sibley and Blatt (1976) have provided an explanation for use of the diagram in Figure 6. Using their estimates on curve "B":

> If one determines that a sandstone is composed of 75% detrital grains and 25% authigenic cement then the "minus-cement-porosity" is 25%. By reference to the solid curve one can determine the maximum amount of dissolution at grain contacts which might have occurred. In this instance a "minus-cement-porosity" of 25% indicates a maximum of 3.2% by volume of the grains has been dissolved. If it is assumed that all of the material dissolved reprecipitated as cement, then 3.2/25 or approximately 13% of the cement found in the rock may have been derived from pressure solution at grain contacts.

The values for authigenic quartz and pressure solution obtained through luminescence petrography are plotted on the diagram in Figure 6. The mean values of the Stony Gap Sandstone lie to the right of the curves proposed by Rittenhouse (1971b) and approximate the values estimated by Sibley and Blatt (1976) for actual sands.

FORMATION OF PRESSURE SOLUTION FEATURES

Pressure solution of quartz grains during burial has been considered the primary source of silica for quartz cement in sandstones (Arkle and Hunter, 1957; Heald, 1956, 1965). A common observation in quartzose sandstones is the presence of long, concavo-convex, and sutured contacts between detrital quartz grains. These contacts were believed to originate by pressure solution, whereby a mineral is dissolved at a point of stress with precipitation occurring on surfaces of lower stress.

Because quartz forms epitaxially, and may lack delineation of the contacts between nucleus and overgrowth, it is often difficult to determine the presence and amount of cement. This has led to misinterpretation regarding the nature of grain contacts.

Cathodoluminescence techniques provided a means of resolving this problem because detrital quartz grains luminesce blue (common) or red (rare) in contrast to secondary quartz which frequently lacks luminescent properties (Sippel, 1968; Gorz and others, 1970). The color of the luminescence depends upon the concentration and interaction of various trace elements (Claffy and Ginther, 1959; Long and Argell, 1965).

Plate Xa is a photomicrograph of a thin section of the Stony Gap in plane polarized light. Plate Xb is the corresponding slab viewed with the luminoscope. The differential luminescence of the detrital and authigenic quartz suggests that this is an area of pressure solution. The blue luminescing detrital quartz grains interpenetrate each other. Without the luminoscope it is difficult to tell how much pressure solution has taken place.

Pressure solution boundaries may be either smooth or sutured. Both types of boundaries may be observed in all samples. Sutured contacts appear more commonly in the areas of intense pressure solution parallel to bedding planes and stylolites. Similar observations in other sandstones have been noted by Heald (1956) and by Sibley and Blatt (1976).

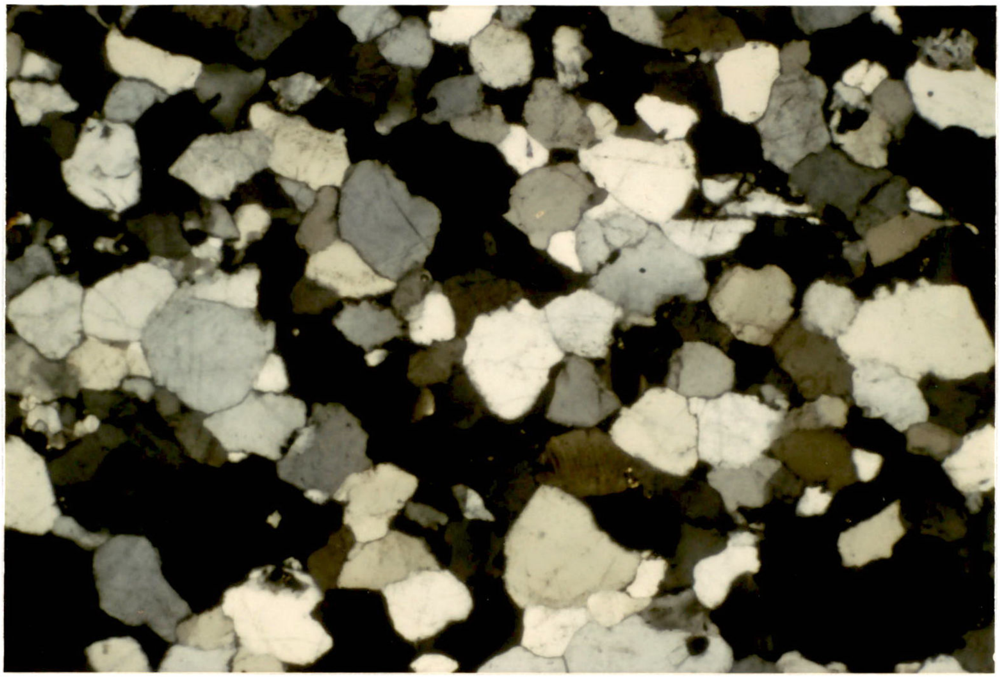


Plate Xa. Photomicrograph of detrital quartz in the Stony Gap Sandstone (crossed nichols, 63x).

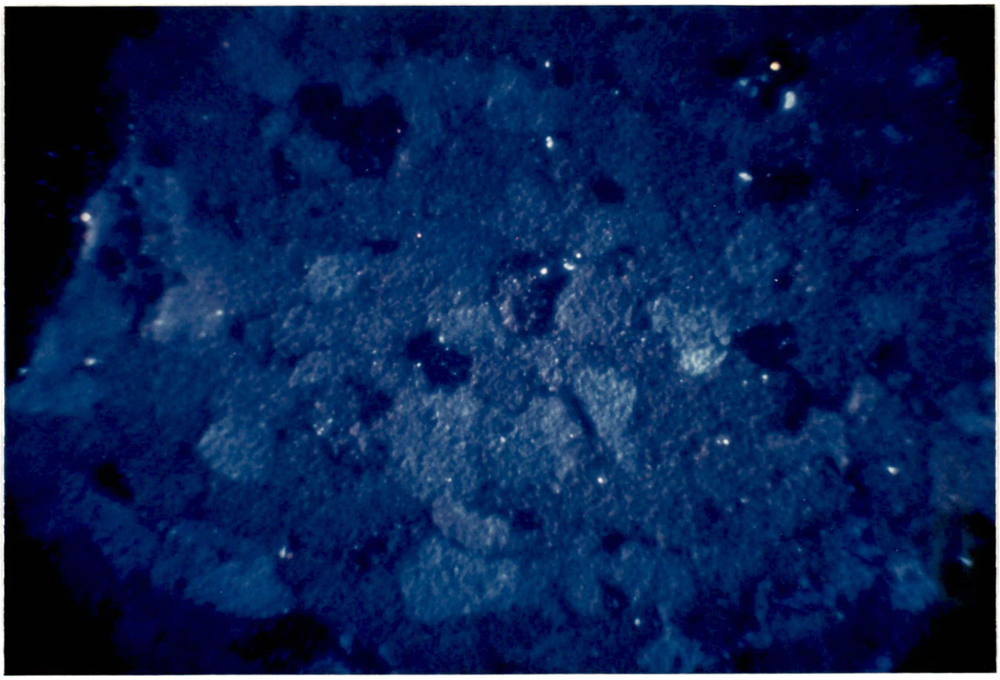


Plate Xb. Detrital quartz of the Stony Gap under cathodoluminescence (18 kv luminescence, 35x).

POINT COUNT DATA

The results of the point count performed under luminescence are summarized in Table 1. The most useful data in the table are the percentages of authigenic quartz and pressure solution. The percent pressure solution was determined as a volume percent of the luminescing quartz which appeared to interpenetrate with other luminescing quartz (Sibley and Blatt, 1976). The volume percent pressure solution is equal to the amount of authigenic cement which may have been derived through pressure solution. The mean percentages of pressure solution and authigenic cement for all samples are 9 and 12 percent, respectively. Therefore, of the 12% authigenic quartz, a maximum 9%, or three-quarters of the authigenic cement may have been derived through intergranular pressure solution. The remaining one-quarter may originate through other processes.

Table 2 gives the correlation coefficients between the amount of pressure solution and each of the other variables measured. A strong correlation exists between pressure solution and detrital quartz for this is a primary source of authigenic silica. The strong correlation with sorting would be expected in light of data by Renton and others (1969) and Sprunt and Nur (1977) which indicate that well-sorted, fine grained samples are more susceptible to pressure solution. The strong negative correlation with clay for all samples suggests that argillaceous materials act as a cushion for mechanical compaction. However, this correlation becomes less significant upon re-examination of clay to pressure solution relationships in quartzose samples.

	Detrital Quartz	Authigenic Quartz	Clay	Pore Space	Other	Size(mm)	Sorting	Pressure Solution
all samples n = 43	76	12	5	1	6	.15	2	9
Stony Gap n = 12	83	12	3	1	1	.20	1	10
Pinnacle n = 4	85	12	1	1	1	.30	1	9
Oakvale n = 9	74	14	5	1	6	.25	2	8
Ingleside n = 12	64	10	7	1	18	.15	3	7
Sandlick n = 6	79	13	4	1	3	.20	1	9

Sorting was calculated by: 1 = moderately sorted, 2 = well sorted, 3 = very well sorted (adapted from Sibley and Blatt, 1976).

Table 1. Summary of modal analysis data for the Stony Gap Sandstone (percent mean values).

	Detrital Quartz	Authigenic Quartz	Clay	Pore Space	Size	Sorting
all samples	+.89	+.34	-.73	-.63	+.22	+.87
samples over +80% quartz	+.45	-.01	-.22	-.03	+.16	-.64

Table 2. Correlation Analysis. Pressure solution *vs* selected variables

In a number of studies of pressure solution, it has been suggested that a small amount of clay along grain boundaries may serve to enhance pressure solution (Thompson, 1959; Weyl, 1959; Heald, 1965; Heald and Renton, 1966; DeBoer and others, 1977). Further testing of this relationship by Sibley (1975) and Sibley and Blatt (1976) indicated that the presence of thin clay coatings on detrital quartz promotes the process of pressure solution and that thicker coatings of clay inhibit pressure solution. Their data does not specify at what thickness a coating acts to enhance pressure solution, nor at what point a coating of clay would inhibit formation of solution features.

Table 3 shows the results of point counts of quartz arenites other than the Stony Gap, as well as mean values from the Stony Gap. The data from the Stony Gap are similar to values reported from other quartz arenites.

SOURCES OF SILICA

The point count data presented in Table 1 demonstrate that intergranular pressure solution may account for not more than three-quarters of the authigenic silica in the Stony Gap Sandstone. The remaining one-quarter of the silica must be derived from other sources. The sources most commonly suggested are stylolitization, clay mineral diagenesis, replacement of silica by carbonates and decomposition of feldspars (Dapples, 1967; MacKenzie and Gees, 1971; Pittman, 1979).

Heald (1955, 1959) noted that stylolites may form as large

	Detrital Quartz	Authigenic Quartz	Clay	Pore Space	Other	Pressure Solution
Roubidoux Ss. Ord. MD	67	31	2	0	0	2
Keefer Ss. Sil. W.Va.	80	16	3	0	1	10
Juniata Fm. Ord. PA	76	24	0	0	0	4
Oriskany Ss. Dev. W.Va.	68	23	1	7	1	4
Tuscarora Ss. Sil. W.Va.	74	21	2	2	1	7
Stony Gap Ss. all samples	76	12	5	1	6	9
Stony Gap Ss. type loc.	83	12	1	1	1	10

Table 3. Mean values for selected quartz arenites (adapted from Sibley and Blatt, 1976).

scale pressure solution features in sandstones with up to 26% remaining porosity and may, therefore, be a significant source of authigenic silica. Stylolites in the Stony Gap probably formed prior to cementation because they do not appear to truncate authigenic silica. However, whether or not the unit was completely lithified at the time is difficult to determine. Estimates of the amount of silica derived from stylolitization can be based on measurement of maximum stylolite column heights (Heald, 1956). Stylolites were found in 25 of 43 thin sections. To arrive at an estimate, stylolite column heights were measured using an ocular micrometer. Three measurements were taken for each stylolite and the averages were totaled to give an estimated column height for each thin section. The sum of all stylolite column heights (approximately 21mm) represents a minimum thickness of material dissolved (Heald, 1955; Sibley, 1975). The total thickness of the section sampled is approximately 1100mm (43 thin sections x 25.4 mm per thin section). The cement which could not be accounted for by intergranular pressure solution (approximately 3% of the total rock volume) requires 0.03 x 1092 mm or 33 mm of silica. The 21 mm (minimum estimate) of silica dissolved by stylolitization processes very nearly succeeds in providing the remaining silica cement required for the Stony Gap. The proportion of silica cement left unaccounted for after minimum stylolite column height estimates is approximately 1% ([33 mm - 21 mm = 6 mm] - 1092 mm) of the total rock volume.

The importance of clay mineral diagenesis as a source of silica was suggested by Siever (1962) and Towe (1962). The transformation from smectite to illite may be written such that for every 2 grams of illite formed, 1 gram of quartz is formed (Siever, 1962). To apply this model to the Stony Gap, it is necessary for the unit to be associated with a shaly sequence. The Stony Gap is indeed surrounded by the shales and siltstones which comprise the Mauch Chunk Group. However, this model is not universally accepted. Oxygen isotope data of Yeh and Savin (1973) indicate that in such sequences shales act as a closed system with respect to SiO_2 during diagenesis and, therefore, cannot be a major source of silica in adjacent sandstones.

Replacement of silica by carbonate does not appear to be a major source of silica within the Stony Gap. Carbonate material averages less than one percent of the total volume of the unit and is found only at the basal section of the Ingleside sample location (Figure 1). Petrographic observations indicate that this carbonate is an original cement in these locations and may be, itself, in the process of replacement by silica.

Likewise feldspar dissolution does not seem likely to be a major source of silica. Feldspars account for less than one percent of the total volume of the rock and are confined to the more argillaceous upper and lower portions of the unit.

INTERPRETATION OF DIAGENESIS

The previous observations allow important inferences to be drawn concerning the variables affecting pressure solution in the Stony Gap. Two important variables are the amount of cement and the presence of argillaceous material, both as clay coatings between grains and as inclusions within authigenic "polygonal-grid quartz".

The correlation co-efficient between percent pressure solution and percent authigenic silica is 0.34 for all samples (Table 2). This correlation becomes negative if only quartzose samples (+ 80% detrital quartz) are considered, which may indicate an increase in pressure solution with decreasing cement. Sibley (1975) and Sibley and Blatt (1976) noted a similar relationship between pressure and cement content. This negative correlation may be, at least in part, a function of decreasing pore space with increasing pressure solution. There exists a strong correlation between pressure solution and detrital quartz for all samples because, as pore space decreases, the detrital fraction must increase. However, this correlation becomes less significant if only quartzose samples are considered. Furthermore, there are qualitative observations which support the relationship between cement and pressure solution. Pressure solution is an early diagenetic feature which must preceed extensive lithification. Those areas cemented early in diagenesis would undergo less pressure solution because, as cementation occurs, stresses become more homogeneously distributed throughout the rock rather than becoming concentrated at grain contacts (Heald, 1956).

Although data from the Stony Gap are not conclusive, investigations by Sibley (1975) indicate that quartz arenites with intense pressure solution contain more clay coatings than similar rock types with only minor pressure solution. Various explanations have been proposed to explain the association of clay with pressure solution. Thompson (1959) proposed that intergranular illite may alter the pH of the pore fluids adjacent to quartz crystals. This proposal seems unlikely in light of data by Renton and others (1969) and by DeBoer and others (1977) which indicate that, although pore fluids were necessary for pressure solution, the composition and pH of the pore fluid was of little consequence. Weyl (1959) suggested that clay minerals promote pressure solution by enhancing diffusion of dissolved silica along grain boundaries. Observations from the Stony Gap appear consistent with this hypothesis.

Clay coatings may also promote pressure solution by impeding quartz overgrowth formation. Pittman and Lumsden (1968) and Heald and Larese (1974) reported that chlorite coatings inhibit overgrowth formation in the Spiro Sand and the Tuscarora Formation, respectively. Moore (1976) has suggested that similar processes inhibit overgrowth formation in the Big Injun sandstone. This data is consistent with other correlations reported between pressure solution and cementation.

The Stony Gap Sandstone, however, contains an abundance of both authigenic quartz and clay coatings around detrital grains which have undergone pressure solution. This inconsistency with reported data is made more puzzling by the presence of clay inclusions along crystal faces within the authigenic quartz. Furthermore, the "polygonal-grid quartz" appears both as epitaxial overgrowth and as randomly oriented fillings within the adjacent pore space without apparent regard to the presence of clay coatings or detrital host grains.

The unusual association of authigenic quartz with both pressure solution and detrital clay coatings probably results from: 1) early (prelithification) formation of detrital clay coatings, 2) diffusion of presolved silica along adsorbed water layers at the grain surface and within or between clay layers, and 3) mobilization of large amounts of silica which saturate the diffusion paths and force aside clay layers, leaving them as inclusions within authigenic quartz (Weyl, 1959; Heald and Larese, 1974).

Experimental investigations by Cecil (1966) and Cecil and Heald (1971) indicate that adsorbtion would involve a polarization of surface and near-surface oxygen anions present in a freshly fractured crystal lattice of quartz. With the silicon-oxygen bonds broken, the electron density of the oxygen anions is shifted in such a manner as to partially "screen" the exposed silicon cations. At the surface of quartz, the oxygen anions are not symmetrically surrounded by silicon cations; therefore, the anion electrons become shifted toward the high positive charge of the cations. Polarization of the anions by the silica "screening" process facilitates formation of a disordered layer. At a silica surface, silicon cations will attempt to maintain a tetrahedral co-ordination. Water will adhere to the surface with a proton co-ordinating with surface anions and the hydroxyl ion co-ordinating with surface cations. The surface is then composed of a monomolecular layer of adsorbed water. The surface of silica, having adsorbed a hydroxyl ion, now has an adsorbtion site for a suitable cation such as those found in clay minerals (Weyl, 1959; Cecil, 1966).

Observations of experimental pressure solution by DeBoer (1977) and DeBoer and others (1977) indicate that the presence of amorphous silica precipitated around detrital quartz grains happens at an early diagenetic stage. This occurrence of amorphous silica strongly supports Weyl's (1959) postulated mechanism in which quartz dissolves under pressure solution at grain contacts, after which the dissolved silica would diffuse to pore spaces along a layer of water adsorbed to the quartz. The presence of clay layers accelerates the process by providing a wider diffusion path. Furthermore, the presence of amorphous silica supports the conclusion that supersaturation must have existed within the pore space. The process of silica diffusion through adsorbed water layers can easily create the supersaturation necessary to form amorphous silica (DeBoer, 1977).

Such processes may have combined to yield the "polygonal-grid quartz" textures observed in the Stony Gap Sandstone. Heald and Larese (1974) postulate that inclusions of illite and smectite are formed by authigenic quartz forcing aside the argillaceous layers of a clay coating around a detrital quartz grain. This procedure would require mobilization of large amounts of silica, which would then diffuse along adsorbed water layers between either the host grain and adsorbed clays or between the clay layers themselves. Continued mobilization of silica by pressure solution would saturate the diffusion paths and begin to force aside the clay layers, leaving them as inclusions along the crystal faces of the authigenic quartz. That portion of the authigenic silica which had diffused along the adsorbed water layer next to the host grain would form epitaxial overgrowth. The authigenic silica diffused along the clay lattices would not be in optical continuity with a host grain. The apparently anomalous association of authigenic quartz, pressure solution, and clay coatings within the Stony Gap Sandstone may have formed through such processes.

SUBSURFACE ANALYSIS

Analysis of the Stony Gap in the subsurface of Mercer County was undertaken through use of selected gamma-ray logs from the West Virginia Geological and Economic Survey. Such logs record the natural radioactivity of a rock unit and reflect variations in the argillaceous content of a unit due to the presence of radioactive isotopes commonly concentrated in the argillaceous minerals (Schlumberger, 1972).

Figure 7 locates selected stratigraphic cross sections through Mercer County and identifies the outcrops and wells involved in their construction. Figure 8 displays the generalized stratigraphic sections for Mercer County. Section B - B' was constructed from gamma-ray logs which are reproduced in Figure 9.

Several inferences may be drawn from the subsurface stratigraphy of the study area. First, the Stony Gap is readily identifiable in subsurface. It appears as a persistent unit which retains a thickness of 50 to 100 feet everywhere in the study area. The gamma-ray signature of the Stony Gap is characterized by visible changes in API (American Petroleum Institute) unit values and bulk density readings which contrast sharply with readings for the surrounding shales of the Hinton and Bluefield Formations. Typical gamma-ray variations include a drop in API unit values from 125 to 150 in shale units to 25 or less within the Stony Gap interval. This commonly corresponds to approximate changes in bulk density from 2.75 g/cc in shales to 2.65 g/cc in the Stony Gap. Subsurface porosity often registers 2 to 4% above that of the surrounding

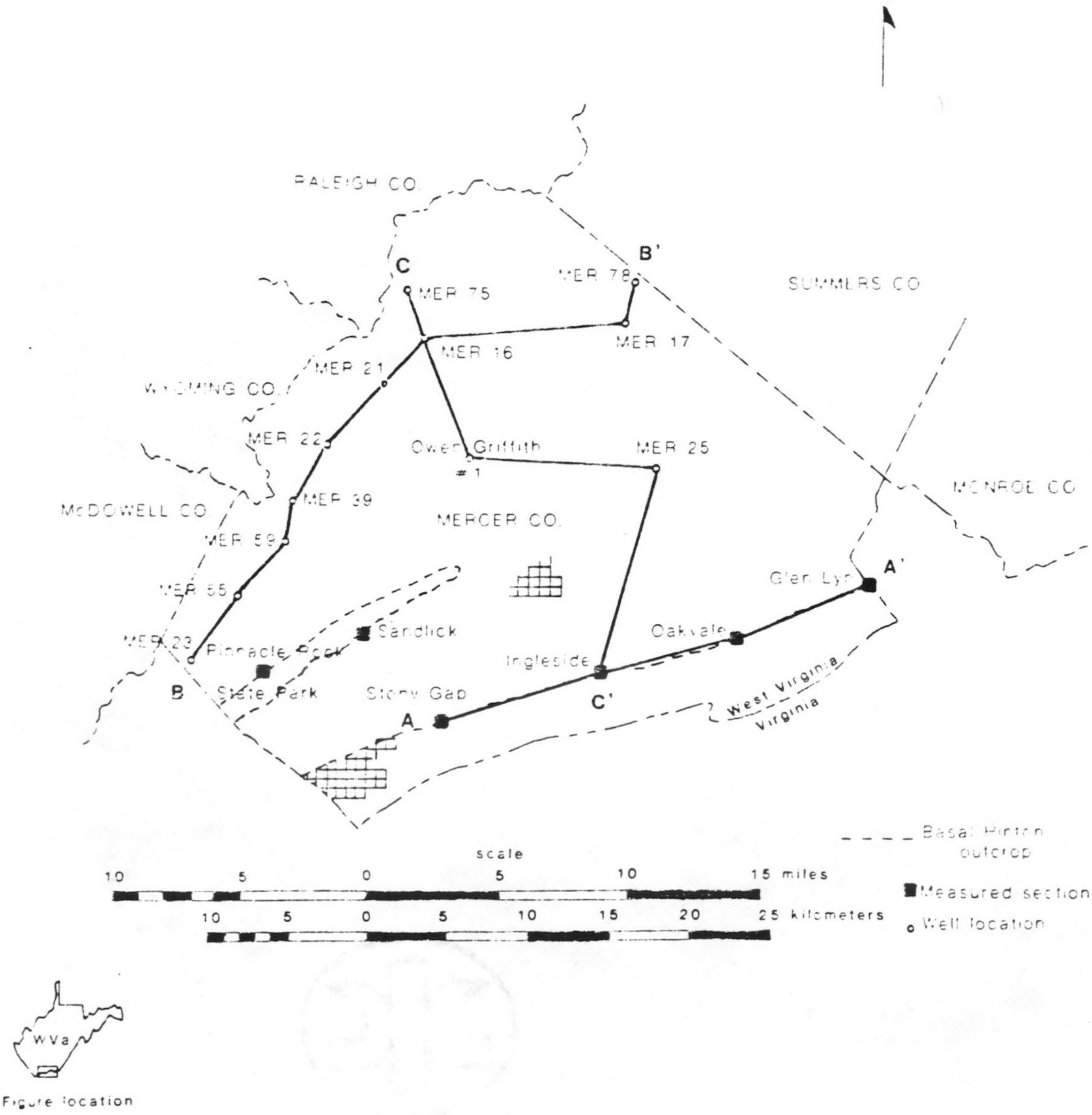


Figure 7. Location of generalized stratigraphic cross-sections.

Figure 8A Generalized stratigraphic section A - A'

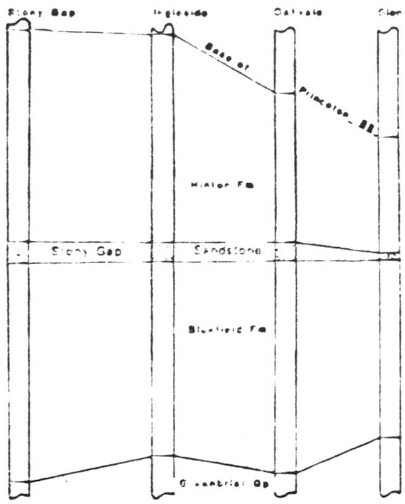


FIGURE 8B Generalized stratigraphic section B - B'

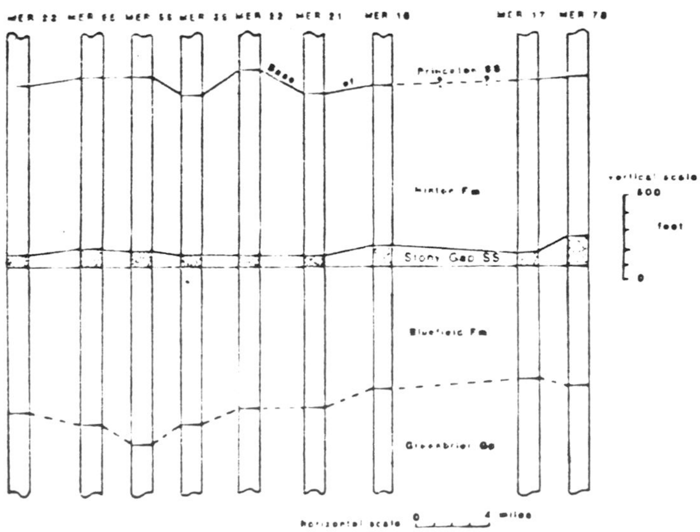
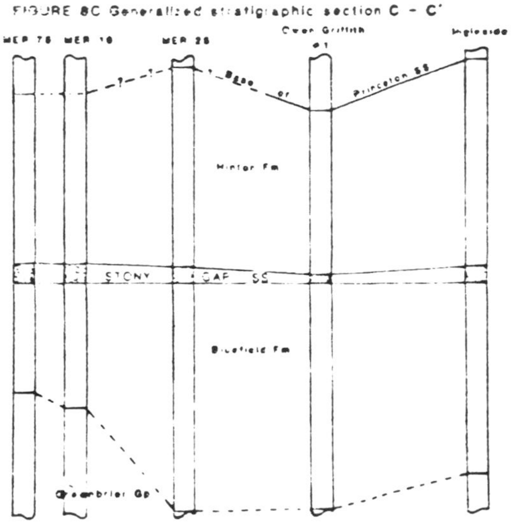
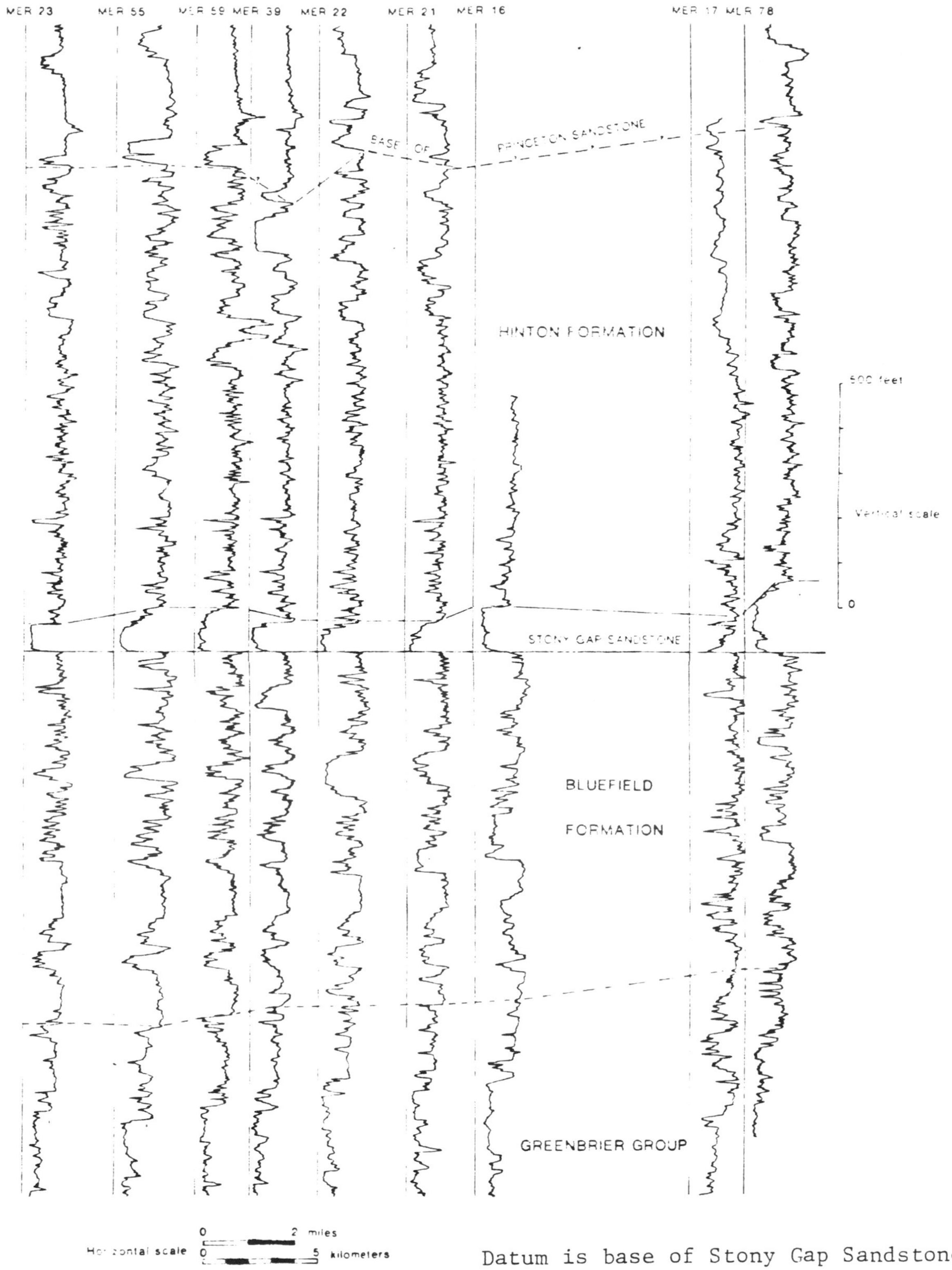


FIGURE 8C Generalized stratigraphic section C - C'



Datum is base of Stony Gap Sandstone



Datum is base of Stony Gap Sandstone

Figure 9. Gamma-ray stratigraphic section B - B'.

shale intervals and seldom exceeds 6% overall.

The Stony Gap can be recognized on the basis of this subsurface signature as well as by its stratigraphic position in relation to the Greenbrier Group. The massive limestones of the latter may often be reliably identified from driller's logs and/or gamma-ray logs due to its lithology and gamma-ray signature. Measured sections in Mercer County indicate that the Stony Gap is a 50 to 100 ft thick sandstone which lies 1000 to 1300 feet above the Greenbrier (Reger, 1926; Thomas, 1960; McKirgan, 1971; Englund, 1979). Examination of gamma-ray logs reveals as many as four sandstone bodies within that stratigraphic interval. Widespread confusion exists due to the common usage of the drillers' term "Maxon" to name any sandstone body within that interval, particularly if the unit in question produces natural gas. Where multiple units exist, the sandstones may be differentiated into "Upper", "Middle", and "Lower Maxon" sandstones. None, some, or all of these units may produce natural gas within the study area. The Stony Gap is generally taken to be the uppermost of these sandstone units and may often correspond with the "Upper Maxon". More reliably, the Stony Gap signature reflects the massive character of the unit as displayed in outcrop. Moreover, the unit remains a laterally persistent sequence within the study area. Other sandstone bodies within the Hinton and Bluefield Formations lack the massive, laterally persistent character which typifies the Stony Gap.

A second inference to be derived from examination of the generalized stratigraphic sections concerns the overall behavior of the Hinton and Bluefield Formations. These units thin in a northeasterly direction along Stony Ridge from Stony Gap Village (2500 ft) to Glen Lyn (1700 ft) at the Mercer County, West Virginia - Giles County, Virginia, border (Figure 8. Cross-section A-A'). This tendency is also reflected in subsurface as the units are traced from outcrops along Stony Ridge into the subsurface in the northern portion of the study area (Figure 8. Cross-section C-C'). Maximum thicknesses of 2500 ft are attained in the Hurricane Ridge Syncline and decrease to approximately 1700 feet in wells located in northern Mercer County.

Throughout the study area the thickness of the Stony Gap remains relatively unchanged. Apparent deviation from this trend occurs only in two wells (MER-17, MER-78) in the northeastern sections of the county where the units appear to develop shale partings (Figure 9). In well MER-78 the unit thickness increased to 170 feet.

Porosity values for the Stony Gap increase from traces detectable in outcrop to averages of 4% in the subsurface. This increase may be due to the lessening effects of tectonic overprint which dominate the outcrops. It has been revealed that brittle deformation, and microfault granulation and pressure solution are responsible for reduction of porosity and permeability in sandstones of the Ordovician Simpson Group of Oklahoma (Pittman, 1981), and the Triassic Wingate Formation in Colorado (Jamison and Stearns, 1982). Similar mechanisms of mechanical compaction and pressure solution associated with tectonism are responsible for eliminating porosity in the Stony Gap along Stony Ridge and in the Hurricane Ridge Syncline.

DEPOSITIONAL SETTING

GENERAL

North American Paleozoic stratigraphy prior to the Carboniferous was dominated by marine conditions. A reconstruction of Upper Mississippian paleogeography places the study area on the southeastern edge of a shallow sea located about 5 degrees south of the paleoequator (Swires, 1977; Humphreville, 1981). During the Carboniferous, tectonic disturbances raised portions of the craton above sea level. The developing highlands of Appalachia are represented as a mountainous belt along the east coast of modern North America. The Appalachian highlands were elevated by northward-directed thrusting and folding during the Alleghenian Orogeny (Windley, 1977). continued uplift and erosion shed large volumes of clastic sediments into the study area. Patterns of sedimentation in the Carboniferous rocks of southeastern West Virginia record the fluctuations of marine and continental environments that mark a carbonate-to-clastic transition in a shallow, slowly subsiding basin (Colton, 1970; Scotese and others, 1979). Swires (1977) suggested a general Mauch Chunk facies gradient from southeast to northwest and noted that the Mauch Chunk sediments decrease in total thickness to the northwest. Inferences drawn from subsurface data in the area of investigation appear consistent with this observation.

Southeastern West Virginia was inundated by a shallow sea during which subtidal to supratidal clastic and non-clastic Greenbrier sediments were deposited. Marine organisms flourished during this period and the fragmental condition of many of the fossils is considered indicative of shallow nearshore or tidal environments (Heckel, 1972; Craig and Varnes, 1979). Seaward encroachment of nearshore muds and sands with brief periods of marine transgression are recorded in the Bluefield Formation (Whisonant and Scolaro, 1979, 1980; Humphreville, 1981). At times, brackish- or freshwater swamps supported growth of vegetation and peat accumulation. Detailed paleoecologic analyses of the Bluefield sediments suggest that deposition occurred in a tide-dominated coastal setting in which frequent influxes of sand and silt and random storm surges are evident (Whisonant and Scolaro, 1979, 1980; Humphreville, 1981).

Repetition of the cycle of marine and terrestrial environments continued throughout deposition of the Hinton Formation, as demonstrated by local occurrences of coal, lagoonal shale, bar sandstone and limestone (Dyar, 1957; McCulloch, 1957; Swires, 1977). The Stony Gap Sandstone Member at the base of the Hinton Formation may represent the record of converging off-shore bars, as indicated by the proximity of marine beds above and below the unit, and by the distributional pattern of this well-sorted, fine-grained sandstone (Englund and others, 1976; Englund, 1979).

STATISTICAL ANALYSIS

Variations in the character of the bedding in the Stony Gap Sandstone at Ingleside and Oakvale, W.Va. (Figure 1), suggest the presence of facies changes within the unit. Further evidence (alkali feldspars and clay, or carbonate, matrix material) is provided by petrographic examination of samples taken from these locations. Therefore multivariate statistical analysis was performed to supplement field and laboratory observations regarding the depositional history of the Stony Gap. Modal analysis data was subjected to Q-mode Cluster and Factor analysis to assist in reconstruction of depositional environments.

FACTOR ANALYSIS

Q-mode Factor analysis treats each sample as a vector, the co-ordinates of which are determined by the magnitude of the variables. If the samples are related in terms of composition, the vectors will form groups. Each group is represented by an individual eigenvector or "factor". The minimum number of factors which can account for the variation in the original data are calculated (Davis, 1973). Table 4 gives the cumulative proportion of total variance explained by each factor. Four of seven variables are needed to explain 95% of the variance in the original data for the Stony Gap Sandstone. This indicates that the Stony Gap samples are related in terms of composition.

CLUSTER ANALYSIS

Cluster analysis is a statistical method of classification whose purpose is to place objects into groups (clusters) suggested by the data, where no "a priori" knowledge exists. Objects in a given cluster tend to be similar in some sense, and objects in different clusters tend to be dissimilar (SAS Institute, 1982).

Table 4. Cumulative proportion of total variance explained by factors

Factor	Variance
Total Quartz	.650
Feldspars	.787
Pore Space	.909
Clay Minerals	.953
Accessory Minerals	.980
Carbonate	.999
Other	1.000

Q-mode cluster analysis of the Stony Gap data is used to supplement field observations regarding variability of mineralogy at selected outcrops where the existence of facies changes within the Stony Gap was suspected. Figure 10 represents a dendrogram produced by cluster analysis of the Stony Gap point count data. Although the program used does not provide confidence levels of clustering, several inferences may be made from the results. The absence of distinct early-stage clustering within the Stony Gap may be indicative of the relative uniformity of the unit overall. Q-mode Factor analysis supports this observation by suggesting that four of seven variables are needed to account for the majority of the variance displayed by the samples.

Of greater interest is the general clustering of all samples classified on the basis of field observation as characteristic of the massive quartz arenite traditionally identified as the Stony Gap Sandstone, and the segregation of all samples from outcrops known or suspected to be lithologically distinct from the central portion of the unit. Figure 11 is a generalized representation of five potential facies identified through cluster analysis. Detailed comparison of the clusters is presented in Table 5. The minimum number of clusters was chosen to best implement criteria cited by Orford (1976) regarding practicality of dendrogram data generated by cluster analysis. Briefly, the variables responsible for the clustering are: Cluster 1) feldspar; Cluster 2) total quartz; Cluster 3) clay, accessories and other minerals; and Clusters 4) and 5) carbonate material. Cluster analysis at this level clearly indicates

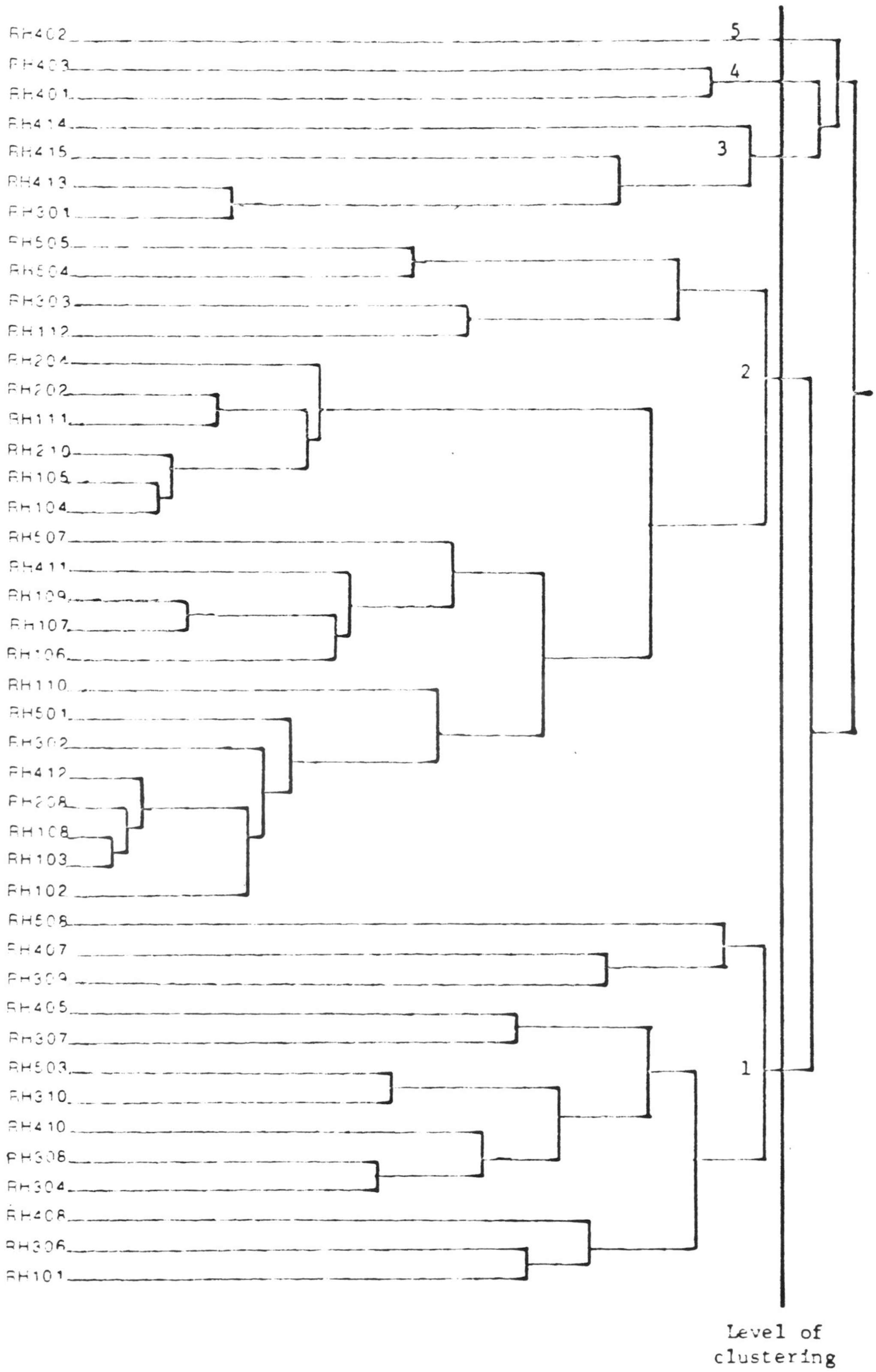


Figure 10. Dendogram produced by cluster analysis program. Samples are grouped by mineralogic similarity. Cluster numbers represent identification as explained in text.

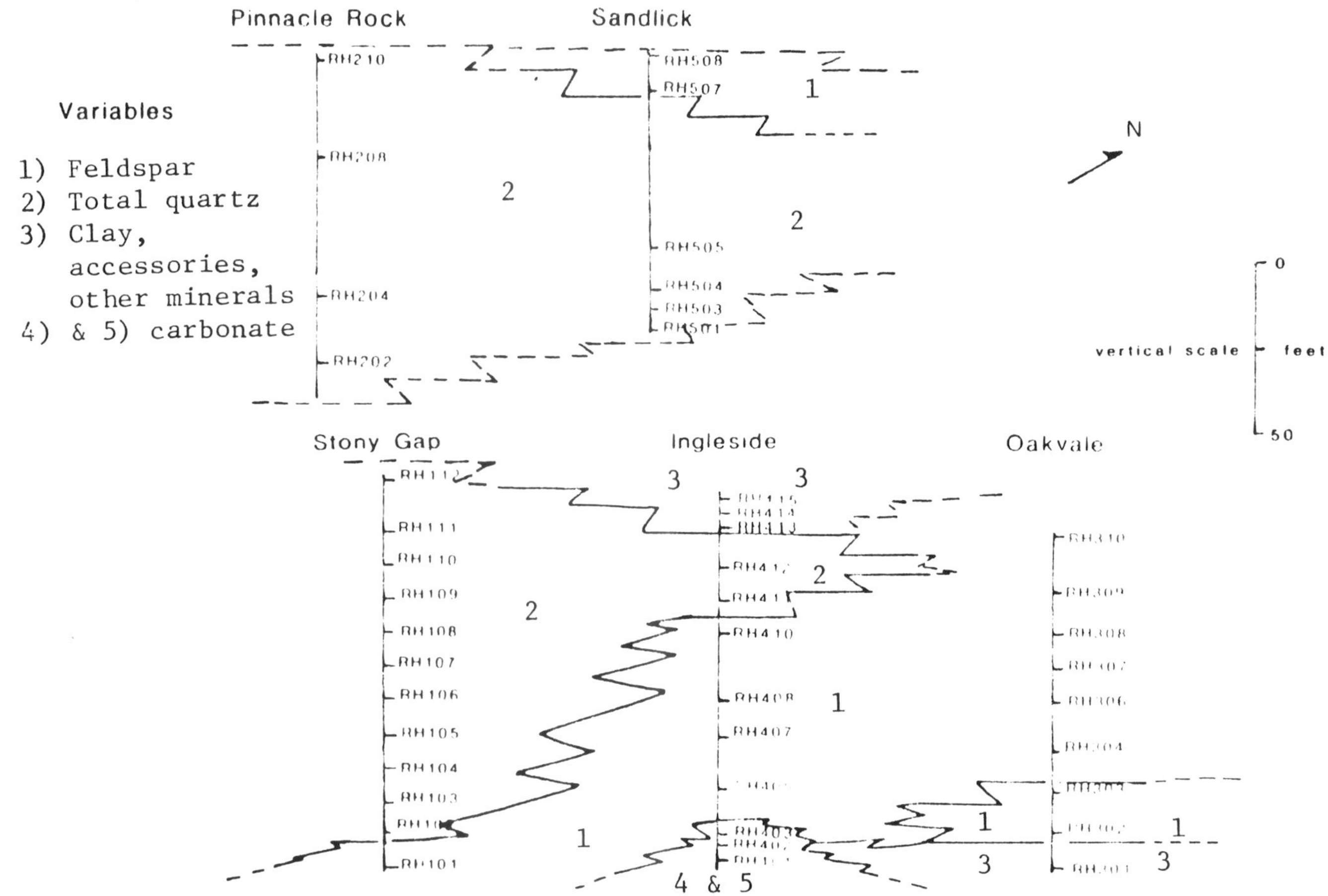


Figure 11. Generalized representation of facies identified through cluster analysis.

Table 5. Detailed cluster comparisons. Mean values for all variables.

Cluster	Total Quartz	Feldspar	Pore	Clay	Accessory	Carbonate	Other
1	87.5	1.2	0.5	5.1	3.0	0.0	2.6
2	95.5	0.1	0.4	2.1	1.0	0.0	0.8
3	76.5	4.8	0.0	8.8	5.5	0.0	4.5
4	64.5	7.0	0.0	9.0	6.0	9.0	4.5
5	53.0	4.0	0.0	13.0	3.0	23.0	4.0

the presence of a quartzose unit which dominates the type locality at Stony Gap Village, and the outcrops at Pinnacle Rock State Park and Sandlick (Figure 11). Outcrops of the Stony Gap Sandstone at Ingleside and Oakvale, while retaining the resistant, cliff-forming character of the type locality, have a somewhat varied mineralogical content from that of the "traditional" Stony Gap. Both of the latter outcrops may be observed in the field as less quartzose, more argillaceous in character. A ternary plot of mineralogy (Figure 12) reveals that Facies (Cluster) 2 may be classified as a quartz arenite on the basis of total quartz content. Facies (Clusters) 1 and 3 are feldspathic arenites, whereas Facies (Clusters) 4 and 5 (containing only samples RH 401, 402 and 403) resemble feldspathic wackes.

DEPOSITIONAL ENVIRONMENT

Mineralogic variation of the Stony Gap may be related to four factors: 1) provenance, 2) modification during transport, 3) modification during deposition, and 4) modification during diagenesis (Suttner, 1974).

Insight into provenance provided by Jones (1972), Mann and Cavaroc (1973) and by Suttner and others (1981) indicates that sands with compositions similar to that of the Stony Gap are largely derived from metamorphic and plutonic source terrains under humid weathering conditions. Paleogeographic reconstruction of the Upper Mississippian of southeastern West Virginia supports these observations (Swires, 1977; Humphreville, 1981) by providing

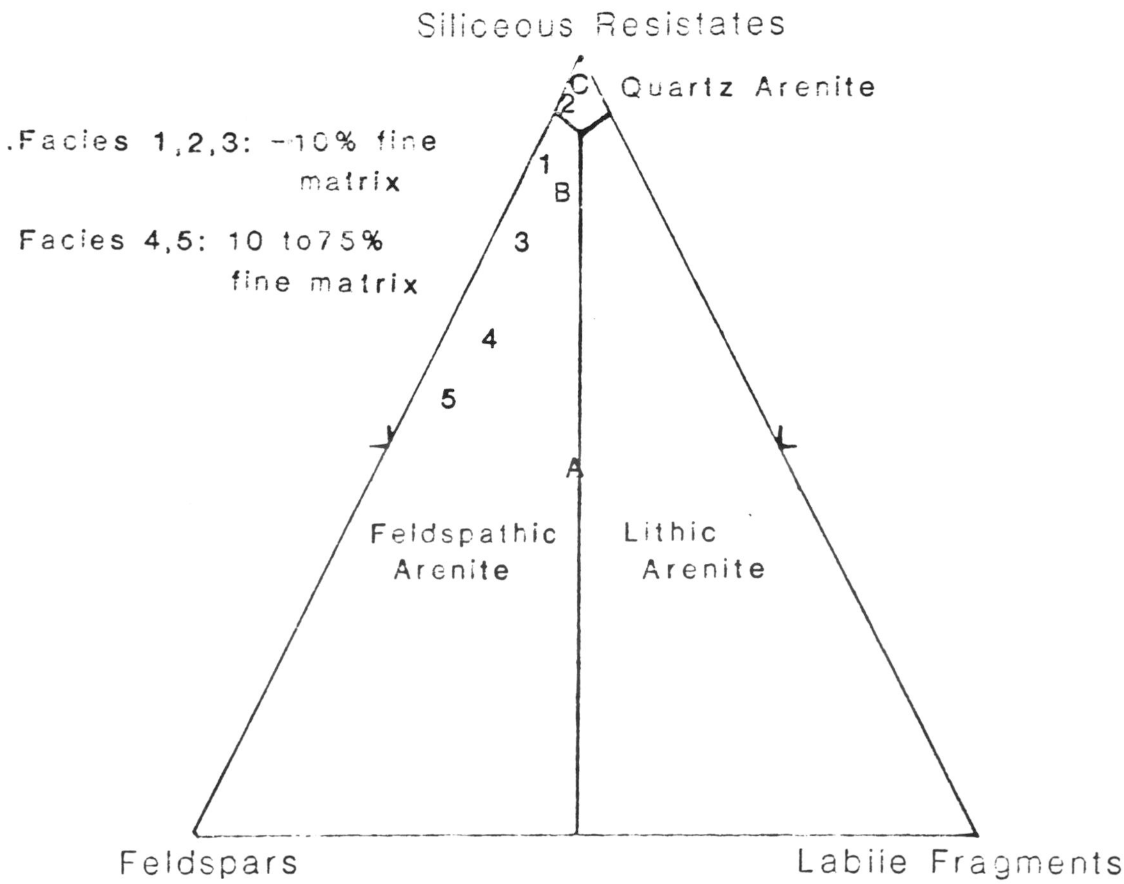


Figure 12.
Classification of Stony Gap Sandstone facies (after Dott, 1964).

an active source region located to the southeast of the study area.

Data presented by Mack (1978) and Suttner and others (1981) suggest that transport distances of 75 km will significantly modify the compositional maturity of sand with expected reductions of 16 percent in feldspar content and 20 percent in the amount of lithic fragments. Both studies cite evidence to indicate that estimates from modern and ancient examples are of the same order of magnitude.

The effects on the composition of first-cycle detritus processed in a shallow marine or beach-coastal dune environment are approximated by Mack (1978). Inferred estimates of destruction of feldspars and lithic fragments during deposition are 64 percent and 78 percent, respectively, for such a system.

Investigations of the overlapping effects of transport and depositional environment suggest that only 5 percent of sands derived from granitic sources will reach first-cycle compositional supermaturity characterized by +95% quartz (Jones, 1972; Mann and Cavaroc, 1973; Suttner and others, 1981). In contrast, sand derived from low-grade metamorphic terrain containing abundant labile minerals will mature more rapidly. Pettijohn and others (1972), Mack (1978) and Suttner and others (1981) examined sands derived from metamorphic sources and determined that 80 percent of the samples examined fell into the category of super-mature after a minimum of 75 km transport and deposition in a shallow marine or beach-coastal dune environment. However, schistose source rocks rich in labile minerals would be relatively deficient in quartz and production of quartz arenites would require large volumes of parent material.

Recent studies document the destruction of labile minerals during diagenesis (Aalto, 1970; Heald and Larese, 1973), yet, quantifiable data regarding the efficiency of the process is lacking (Pittman, 1979). Data from the Stony Gap indicate that silica was derived internally from pressure solution of detrital quartz and that the unit as a whole acted as a closed system with respect to SiO_2.

Facies changes within the Stony Gap Sandstone are probably a product of subtle variations in environment within a shallow marine system. Table 6 demonstrates the effects of transport of +75 km, and of deposition in a shallow marine system upon a sand of theoretical composition and from a theoretical source terrain. Original source composition plots as point A in Figure 12, while first-cycle and second-cycle compositions plot as points B and C, respectively. First-cycle sediments of this nature closely approximate compositions observed in Facies 1 of the Stony Gap, whereas one additional cycle (reworking) within the shallow marine system produces sand of composition nearly identical to Facies 2. This model does not consider multiple cycles of reworking nor are the effects of chemical weathering included.

It is therefore suggested that the Stony Gap may be the result of deposition within a shallow marine system (Figure 13) of clastics derived from plutonic and low-grade metamorphic source terrains under humid weathering conditions. The product of such first-cycle deposition is typified by Facies 1 and 3.

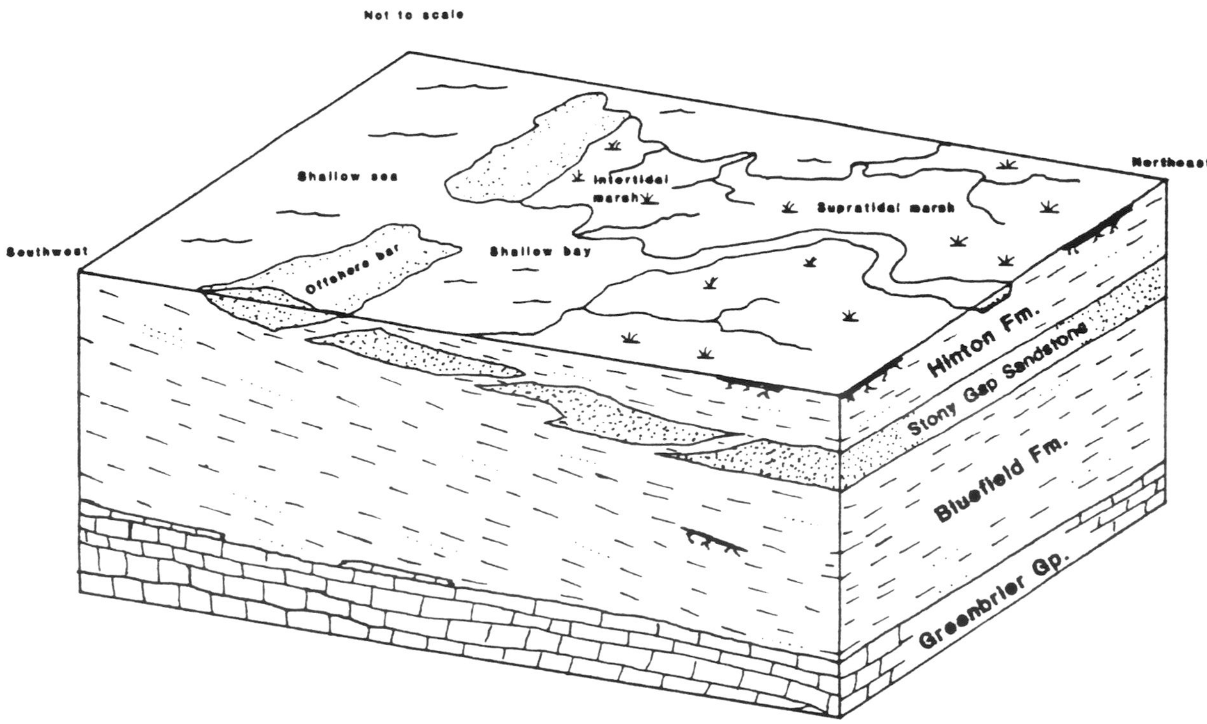


Figure 13.
Upper Mississippian generalized depositional model for the Stony Gap Sandstone

Offshore currents were responsible for reworking (second-cycle) portions of this sediment into relatively clean, well-sorted, barrier bars typified by Facies 2. These observations support the conclusions of Englund (1979), suggesting that the sheet-like geometry of the unit is the result of gradual migration and coalescing of barrier bars within a fluctuating terrestrial and marine system represented by the Mauch Chunk sedimentary sequence in southeastern West Virginia.

CONCLUSION AND SUMMARY

The Stony Gap Sandstone Member of the Hinton Formation serves as a useful marker unit within the Upper Mississippian rocks of southeastern West Virginia. The distinctive lithology of the unit allows recognition in outcrop and is reflected in the subsurface to the west, providing a point of reference within the gas-producing sandstone units of the Mauch Chunk.

Detailed field and laboratory studies, while revealing the Stony Gap is less dominated by quartz and is more fine-grained than reported through field observations, support conclusions of previous authors regarding the overall lithologic nature of the unit. Diagenetic alteration of the unit takes the form of porosity reduction and cementation by authigenic silica associated with mechanical compaction and pressure solution of detrital quartz.

The distinctive character of the Stony Gap persists in the subsurface, where it is readily distinguishable from the "Maxon" sandstones in terms of gamma-ray signatures. Tectonic overprint has eliminated all porosity in outcrops of the Stony Gap; however, examination of drillers' logs and gamma-ray signatures reveal that the unit produces quantities of natural gas in northwestern portions of the study area.

Subtle facies changes defined through multivariate statistical analysis clarify the depositional history of the unit as a series of coalescing offshore bars deposited within the carbonate-to-clastic transitional sequence which typifies Mauch Chunk stratigraphy in southeastern West Virginia.

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APPENDIX A - MEASURED SECTIONS

GENERAL

The Stony Gap Sandstone was named by Reger (1926) as an expedient way to avoid confusion caused by use of an earlier name, "Hinton Sandstone", proposed by Stevenson (1893) from exposures in the vicinity of Hinton, in Summers County, West Virginia. The term "Hinton" was later employed as a major subdivision describing outcrops along the New River and became entrenched in the literature (Campbell, 1896). Reger chose the village of Stony Gap, 2 miles east of Bluefield, as the type locality of the unit, where the rock was particularly well exposed along either side of the Bluefield-Princeton road (now U.S. Route 460). The Stony Gap, as defined by Reger is a "light gray or white, massive, coarse, and extremely hard and quartzitic ledge usually varying in thickness from 35 to 85 feet".

In the area of investigation the thickest and most prominent exposures appear along Stony Ridge. Here the unit is slightly overturned to the northwest as a result of the nearby St. Clair overthrust, which also forms East River Mountain, parallel to, and somewhat to the south of Stony Ridge along the Virginia-West Virginia state line (Dyar, 1957). The Stony Gap extends as a single unit of almost vertical sandstone, forming the spine of Stony Ridge, from the city of Bluefield, northeast to the vicinity of the New River water gap at Glen Lyn Virginia.

STONY GAP SECTION

At the type locality, the unit is "almost vertical but slightly overturned, so that it now dips southeastward 70 degrees ... it is 115 feet thick, white, hard and quartzitic, but not pebbly, and contains plant fossils near its base" (Reger, 1926). The type locality has been altered by recent construction activity, including a redesigned highway and the erection of a shopping mall on the site of Stony Gap Village. The Stony Gap Sandstone is a very prominent, clean quartz sandstone which is well exposed on the southwest corner of the intersection of U.S. Route 460 and the Old Stony Gap Road (now an entrance to the Mercer Mall). The unit may also be seen on the northeast corner of this intersection.

Unit Lithology	Thickness (meters)	(total)
Quartz sandstone, fine grained with minor amounts of medium sized material, subangular to subrounded, well-sorted, light gray to white with tan, dull orange and maroon surface stains; abundant parallel and cross-bedding visible, varying in thickness from 5 to 70 cm. Stylolite development is visible upon close examination of bedding surfaces. Basal contact is sharp and wavy; upper contact is sharp. Overlying this unit is an interval of maroon, black and brown carbonaceous shale, mudstone and siltstone, partly covered and removed by construction, belonging to the Hinton Formation. Underlying the Stony Gap is a thick sequence of maroon, tan and black mudstone and shale forming the top of the Bluefield Formation. The Bluefield has been reported by Humphreville (1982) to be 407 meters (1335 ft) thick along U.S. Route 460 at this location	32.0	32.0

INGLESIDE SECTION

This section was measured along the northbound lane of Interstate 77 where construction of the highway through Stony Ridge near the village of Ingleside, West Virginia, has provided a fresh exposure of the Stony Gap Sandstone for examination. Although debris from the construction activity has covered portions of this outcrop, gradational changes are visible at the base and top of the unit, marked by changes in the character of the bedding.

Unit	Lithology	Thickness (meters)	(total)
4	Sandstone, micaceous, fine to very fine grained, subangular to subrounded, well-sorted, maroon to tan with dull orange and red surface stains. Parallel and flaser bedding is visible, varying in thickness from 2.5 to 60 cm. Upper and lower contacts are sharp. Overlying the unit is a sequence of maroon, black and olive shale and siltstone of the Hinton Formation.	3.96	33.51
3	Quartz sandstone, fine grained, subangular, well-sorted, light gray to tan with gray weathered surfaces. Parallel bedding is 60 to 120 cm in thickness. This exposure is partly covered by debris used to stabilize hillslope after construction of I-77. Upper and lower contacts are sharp to slightly wavy.	7.62	29.55
2	Sandstone, micaceous, fine to very fine grained, subangular to subrounded, well-sorted; gray to maroon, with gray, maroon or dull red-brown surfaces. Parallel and flaser bedding visible, varying in thickness from 30 to 120 cm. Upper and lower contacts are slightly wavy with several cm relief.	18.28	21.93
1	Sandstone, micaceous, fine to very fine grained, subangular, slightly calcareous, moderately sorted; maroon to brown or dull red; some flaser bedding visible with shale lenses. Bedding varies from 2.5 to 70 cm.	3.65	3.65

Unit	Lithology	Thickness (meters)	(total)
1	This is judged to be a lower contact, gradational with the underlying shales of the Bludfield Formation.	3.65	3.65

OAKVALE SECTION

Construction of an access ramp to U.S. Route 460 exposed this section (c. 1975). The access ramp from the highway emerges opposite Oakvale School.

Unit	Lithology	Thickness (meters)	(total)
3	Sandstone, quartzose, micaceous, fine- to very-fine grained, subangular, gray, maroon or brown, with brown or dull red surfaces; parallel and flaser bedding is visible varying from 2.5 to 12 cm thick. Contacts are sharp and parallel. Overlying this unit is a partly covered sequence of red and black shales belonging to the Hinton Formation.	22.86	29.25
2	Sandstone, quartzose, fine grained, subangular, well-sorted, light gray to tan with tan and dull red surfaces. Parallel and cross bedding variable from 7.5 to 15 cm is visible. Upper and lower contacts are sharp.	3.96	6.39
1	Sandstone, quartzose, micaceous, fine to very fine grained, subangular, well-sorted, buff to gray with tan and gray surfaces; parallel bedding, flaser and cross-bedding; bedding is variable in thickness from 2 to 15 cm. Upper and lower contacts are sharp. Lower surface displays plant fossils. Unit is underlain by brown, maroon and black, carbonaceous shales and siltstones of the Bluefield Formation.	2.43	2.43

PINNACLE ROCK SECTION

Approximately five miles northwest of Bluefield, the Stony Gap is exposed along U.S. Route 52, at Pinnacle Rock State Park on the northwest flank of the Abbs Valley Anticline. Here, the unit is in a vertical position, forming the spine of Abbs Valley Mountain. Pinnacle Rock is a precipitous ledge at the ridge crest formed by the Stony Gap. The well-sorted, highly quartzose character of the sandstone makes it the principle ridge and cliff-forming unit at the edge of the coal fields. The unit displays large, well-preserved plant fossils at its base in the confines of the park (Plate VII a and b).

Unit Lithology	Thickness (meters)	(total)
Quartz sandstone, fine grained, subangular, well-sorted, buff to white with tan or dull red surfaces; abundant cross and parallel bedding varying in thickness from 5 to 50 cm. Unit is heavily weathered and may be friable in sections. Abundant plant fossils may be found at the base, consisting of 15 to 76 cm fragments of *Lepidodendron* sp. Upper and lower contacts are covered.	24.38	24.38

SANDLICK SECTION

The village of Sandlick is situated on a gently sloping (15^{o}) exposure of the Stony Gap Sandstone which forms a prominent exposure on the southeast limb of the Abbs Valley Anticline. This section was measured at Sandlick and along State Road 71.

Unit Lithologh	Thickness (meters)	(total)
Quartz sandstone, fine to very-fine grained, subangular to subrounded, buff to white with tan or gray surfaces; Abundant cross and parallel bedding varying in thickness from 5 to 75 cm. Unit is heavily weathered and may be friable in portions. Upper contact is eroded (absent) and lower contact is sharp and may be partly covered.	13.71	13.71

APPENDIX B - MODAL ANALYSIS (%)

	Sample	Detrital Quartz	Feldspar	Authigenic Quartz	Pore	Clay	Accessories	Carbonate	Other Minerals	Pressure Solution
STONY GAP VILLAGE (type locality)	101	77	2	10	0	3	4	0	4	7
	102	80	0	15	1	3	0	0	1	9
	103	82	0	13	1	2	1	0	1	13
	104	89	0	9	0	1	0	0	1	8
	105	87	0	11	0	1	0	0	1	12
	106	80	0	16	1	2	1	0	0	9
	107	80	0	16	1	2	1	0	0	16
	108	88	0	7	1	2	1	0	1	9
	109	86	0	10	1	1	1	0	1	6
	110	80	0	16	0	3	1	0	0	10
	111	85	0	12	0	1	1	0	1	11
	112	79	2	12	0	5	1	0	1	10
PINNACLE	202	85	0	12	0	1	1	0	1	9
	204	87	0	11	0	1	1	0	0	9
	208	85	0	10	1	2	1	0	1	9
	210	85	0	13	0	1	0	0	1	9

APPENDIX B (continued)

	Sample	Detrital Quartz	Feldspar	Authigenic Quartz	Pore	Clay	Accessories	Carbonate	Other Minerals	Pressure Solution
OAKVALE	301	63	4	16	0	8	5	0	4	8
	302	83	0	12	1	3	1	0	0	11
	303	77	1	15	1	4	1	0	1	10
	304	79	1	11	1	3	3	0	2	9
	306	68	2	18	0	5	4	0	3	5
	307	74	2	15	0	4	2	0	3	9
	308	71	1	18	1	3	3	0	3	7
	309	75	2	10	0	11	1	0	1	8
	310	77	1	13	0	4	3	0	2	6
INGLESIDE	401	60	6	5	0	8	4	11	6	3
	402	53	4	0	0	13	3	23	4	2
	403	55	8	9	0	10	8	7	3	5
	405	78	2	10	1	5	2	0	2	8
	407	81	1	6	0	9	1	0	2	5
	408	74	0	12	1	5	4	0	4	8
	410	79	0	10	2	4	3	0	2	8

APPENDIX B (continued)

	Sample	Detrital Quartz	Feldspar	Authigenic Quartz	Pore	Clay	Accessories	Carbonate	Other Minerals	Pressure Solution
INGLESIDE	411	82	0	14	0	2	1	0	1	11
	412	84	0	11	1	2	1	0	1	9
	413	64	4	15	0	8	5	0	4	7
	414	59	6	13	0	9	7	0	6	8
	415	63	5	13	0	10	5	0	4	7
SANDLICK	501	84	0	11	0	3	1	0	1	10
	503	78	0	12	0	4	4	0	2	9
	504	83	0	10	0	3	3	0	1	12
	505	81	0	13	0	3	2	0	1	10
	507	82	0	13	0	2	2	0	1	10
	508	64	2	18	1	6	5	0	4	6