The Sedimentology of the Snowden Member of the Late Precambrian-Early Cambrian (?) Harpers Formation in Central Virginia

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With appreciation for everything he has done for my family and me, this thesis is dedicated to William Barnett.

Acknowledgements

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Abstract

The Snowden Member is the thickest and most mappable of the quartzose sandstone units of the heterogeneous Harpers Formation, the middle unit of the late Precambrian-early Cambrian (?) Chilhowee Group in central Virginia. Petrographic analysis statistically classifies the Snowden as a quartz arenite that has been locally altered through pressure solution to a quartzite. The overall textural and compositional homogeneity of the Snowden, one of its most striking features, presumably reflects both the provenance and depositional environment of the sediment.

The Snowden was derived from the predominently chemical weathering in a humid environment of a low-lying, mixed source terrain of Precambrian high-grade metamorphic rocks (schists and gneisses), acidic plutons, and pre-existing sedimentary rocks located northwest and proximal to the depositional basin. Deposition occurred in an offshore linear barrier island or bar setting during a period of time where the rate of influx of sediment was low enough to allow the reworking of sediment already present or slowly entering the depositional basin. The models of the provenance and depositional environment of the Snowden support the more generalized sedimentary framework proposed previously for the Chilhowee Group in central Virginia.

Introduction

This paper describes and interprets the texture, composition, provenance, and depositional environment of the late Precambrian-early Cambrian (?) Snowden Member, a thin, mappable, quartzose sandstone unit exposed as a belt of outcrop within the Harpers Formation of central Virginia, the middle unit of the Chilhowee Group. The data in this study was obtained from direct field observations, from study of hand specimens, and from the analysis of thin-sections using a petrographic microscope.

The objectives of this study are to qualitatively and quantitatively describe the texture and composition of the Snowden Member and to use this information to infer the most likely provenance and depositional environment for the unit, incorporating the resultant depositional model into the more generalized sedimentary framework proposed previously for the Chilhowee Group (Schwab, 1970, 1971, 1972). The Snowden Member is worthy of study because its position stratigraphically and geographically separates continental and shallow marine deposits below and to the northwest from deep marine deposits above and to the southeast. A more complete understanding of the provenance and depositional environment of the units within the Chilhowee Group (such as the Snowden Member) is critical to analysis of the sedimentation during the early evolution of the Appalachian geosyncline.

Stratigraphy of the Chilhowee Group

The Snowden Member

The Snowden Member was first described as a mappable horizon within the Harpers Formation by Bloomer and Werner (1955). The Harpers Formation itself is one of three subdivisions of the Chilhowee Group and was first named by Keith (1894). The Harpers Formation is the middle unit of the Chilhowee Group and it consists of several hundred to over a thousand feet of alternating argillite, shale, siltstone, and fine-grained subgraywacke interbedded with quartzose sandstone (Werner, 1966; Schwab, 1971). Bloomer and Werner (1955) describe three separate quartzose sandstone units within the Harpers, the lowest, thickest, and most mappable in the area between Balcony Falls, Virginia and Sherando, Virginia being the Snowden Member. They describe the Snowden as being 50 feet thick, but all sections of the Snowden in this study are considerably thicker (60 to 150 feet thick). The base of the Snowden is located 100 to 300 feet above the base of the Harpers.

Lithology of the Chilhowee Group

The Chilhowee Group consists of 1500 to 7500 feet of late Precambrian-early Cambrian (?) clastic sediments exposed along the northwestern flank of the Blue Ridge from Pennsylvania to Tennessee (Fig. 1). The thickness and age of the group is uncertain. Figure 2 shows the stratigraphic relationships in the Chilhowee Group. On the basis of measured sections, the Chilhowee Group thickens to the southwest. The Chilhowee Group invariably consists of three conformable formations. Although the names of the formations vary geographically, the vertical succession of rock types are remarkably consistent. In this paper, the stratigraphic terminology used with reference to the Chilhowee Group applies to central Virginia. The lowermost conglomerate unit is called the Unicoi Formation, the middle sandy and shaly unit the Harpers Formation, and the upper quartzose sandstone the Antietam Formation. Precambrian igneous and metamorphic rocks of the Blue Ridge Basement Complex and the local catoctin Greenstone Formation are found beneath the Chilhowee Group. The lower contact of the Chilhowee Group is conformable above the Catoctin Greenstone Formation but is unconformable above the Blue Ridge Basement Complex. Carbonates, limestones and dolomites, of the Shady-Tomstown Formation conformably overlie the Chilhowee Group.

The Unicoi Formation, the lowermost unit of the Chilhowee Group, consists of 500 to 600 feet of volcanic rocks (greenstone flows and tuff), pebbly quartzite, intergradational conglomerate graywacke, subgraywacke, and arkose interbedded with argillacious rocks. The Harpers Formation, the middle unit of the Chilhowee Group, consists of several hundred to more than a thousand feet of alternating argillite, shale, siltstone, and fine-grained subgraywacke interbedded with quartzose sandstone. The Snowden Member, the object of this study, is the lowest and thickest of the quartzose sandstones. Other quartzose sandstones (25 and 30 feet thick) occur within the Harpers, and they are located at 100 to 300 foot intervals above the Snowden. Separate, thinner beds of quartzose sandstone (a few inches to a few feet thick) occur throughout the Harpers. The Antietam Formation, the uppermost and most homogeneous unit of the Chilhowee Group, consists of 600 to 800 feet of massive beds of compositionally and texturally mature quartz sandstone and orthoquartzite interbedded with subordinate shale and siltstone (Werner, 1966; Spencer, 1968). Additional description of the units of the Chilhowee Group relevant to the interpretation of the depositional environment of the Snowden Member and the Chilhowee Group appears later in this paper.

Age of the Chilhowee Group

Early Cambrian trilobites and brachiopods have been collected, but only from the upper part of the Antietam Formation (Butts, 1940). Therefore, the exact age of the lower part of the Antietam and all of the Harpers and Unicoi Formations remains uncertain. King (1949) states that the Chilhowee Group is "a closely knit sequence of deposits laid down in conformable succession, with none of its parts greatly different in age from the other parts." King therefore suggested that the base of the Cambrian be placed at the base of the Chilhowee Group. I accept King's reasoning and therefore, this paper will regard the Harpers Formation, including the Snowden Member, as early Cambrian in age, although I concede that the issue has not been as yet conclusively resolved.

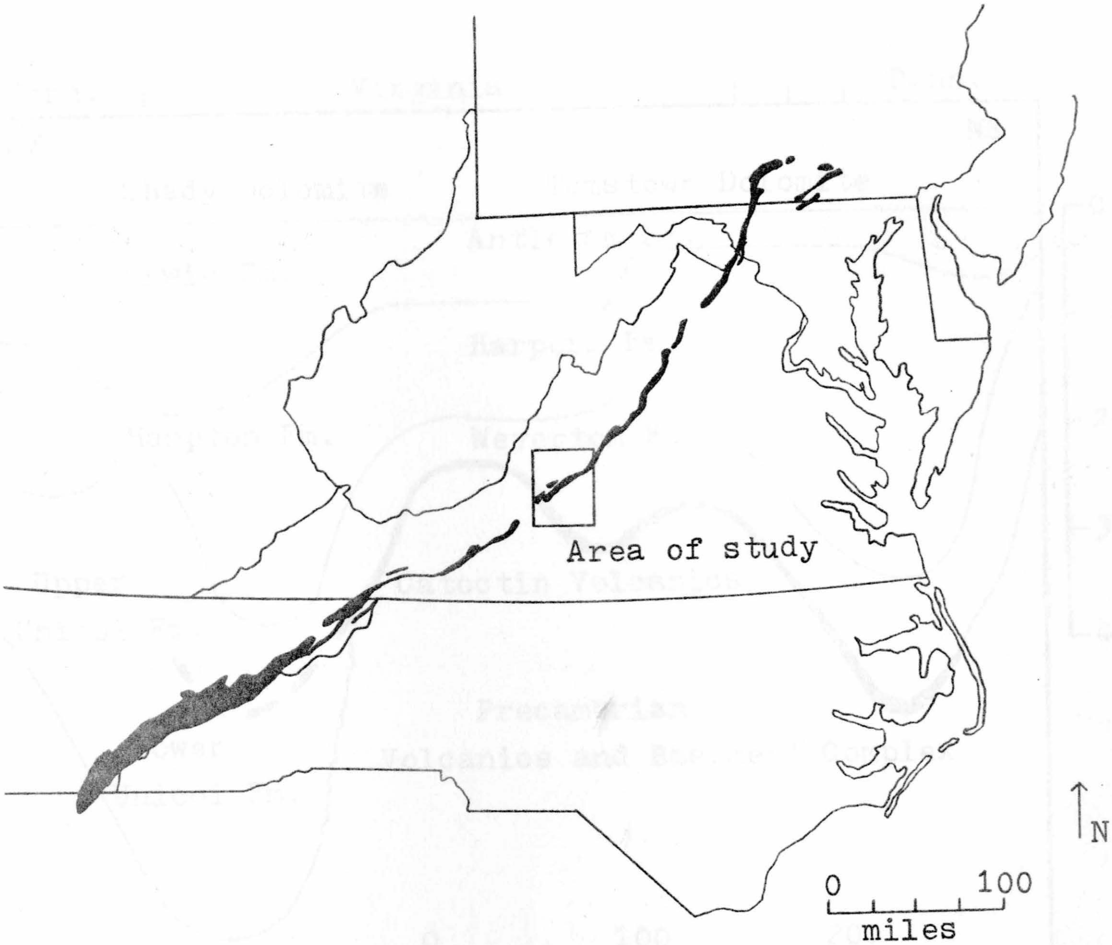


Fig. 1.- Areal distribution of the Chilhowee Group (Schwab, 1970).

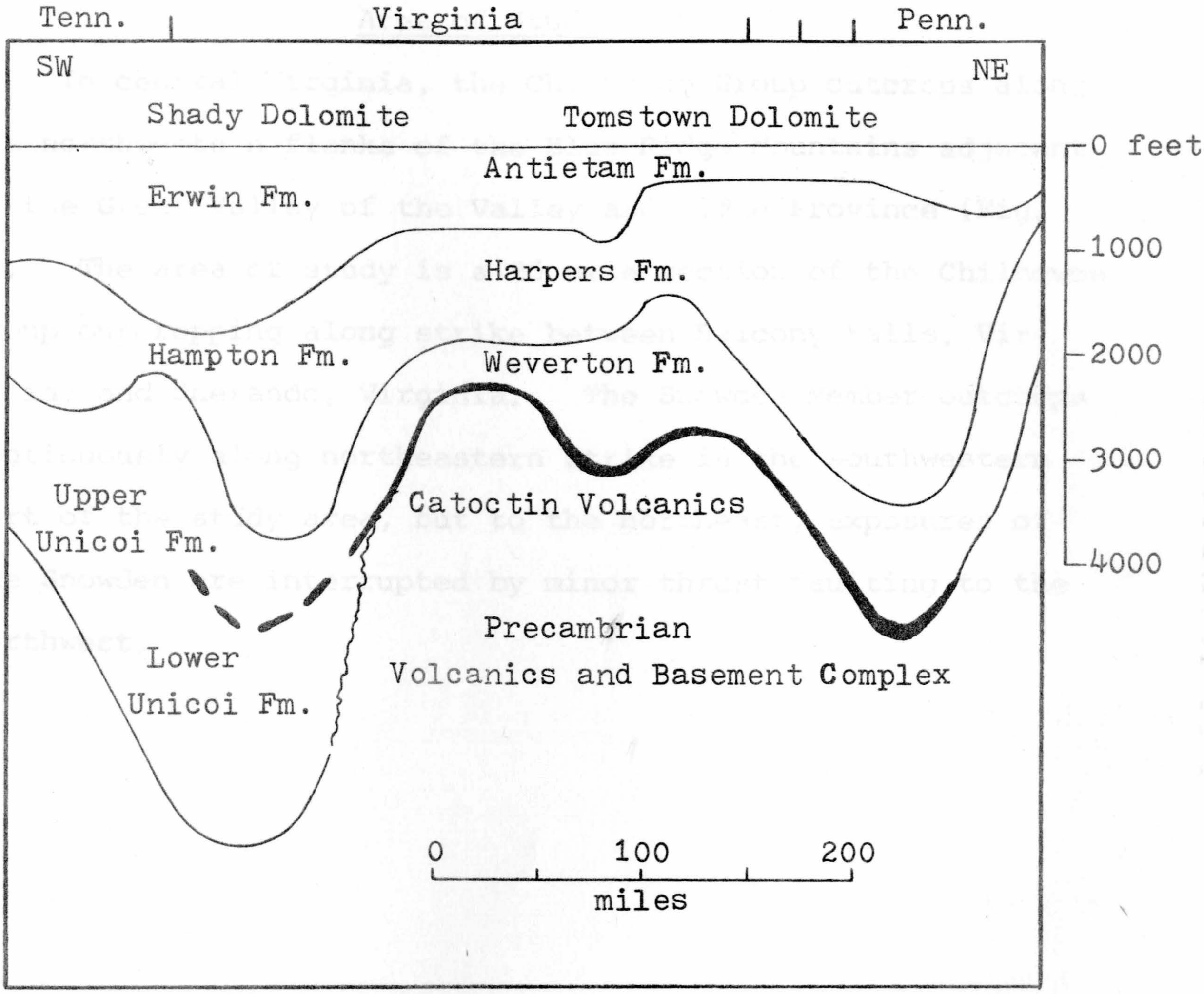


Fig. 2.- Stratigraphic relationships in the Chilhowee Group along the northwestern margin of the Blue Ridge and Reading Prong (Schwab, 1972).

Area of Study

In central Virginia, the Chilhowee Group outcrops along the northwestern flanks of the Blue Ridge Mountains adjacent to the Great Valley of the Valley and Ridge Province (Fig. 3). The area of study is a 25 mile section of the Chilhowee Group outcropping along strike between Balcony Falls, Virginia, and Sherando, Virginia. The Snowden Member outcrops continuously along northeastern strike in the southwestern part of the study area, but to the northeast, exposures of the Snowden are interrupted by minor thrust faulting to the northwest.

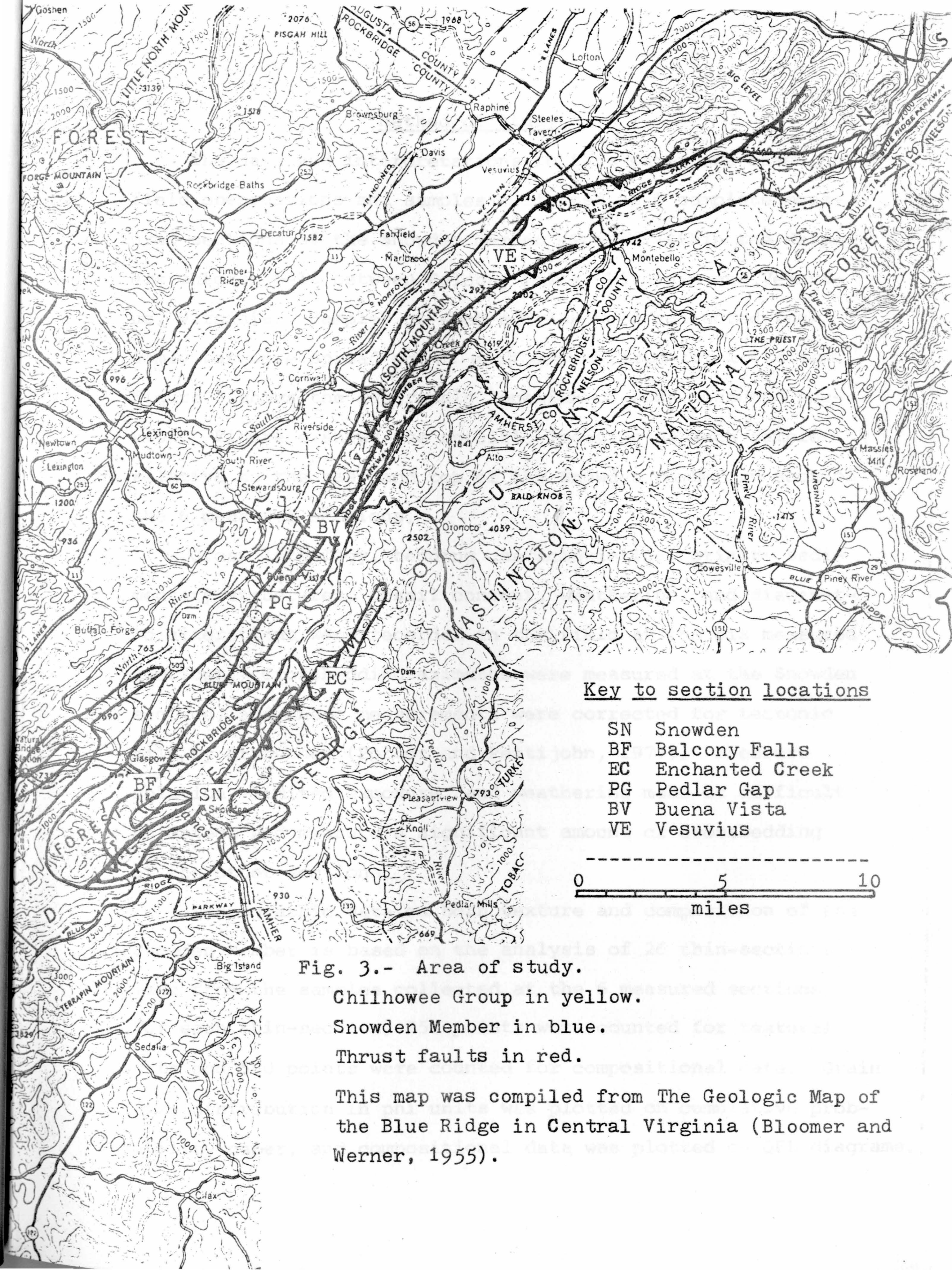


Fig. 3.- Area of study.

Chilhowee Group in yellow.

Snowden Member in blue.

Thrust faults in red.

This map was compiled from The Geologic Map of the Blue Ridge in Central Virginia (Bloomer and Werner, 1955).

Method of Study

The data and interpretations in this paper are based on field observations and samples collected at 6 complete measured sections of the Snowden Member exposed within the Harpers outcrop belt between Balcony Falls, Virginia and Vesuvius, Virginia. Samples of each section were collected randomly but were spread out in each section from top to bottom. Figure 3 shows the geographic location of each measured section. Figure 4 shows the specific location of each sample relative to the base and top of the Snowden Member in each of the 6 measured sections.

Gross lithology, bedding characteristics, primary sedimentary structures, fossil content, weathering, and diagenetic alterations were recorded in the field at the six measured sections. Crossbedding azimuths were measured at the Snowden section, and these measurements were corrected for tectonic tilt by Stereonet (Potter and Pettijohn, 1977). Pressure solution, limited exposure, and weathering made it difficult to detect and measure a significant amount of crossbedding at the other sections.

Petrographic data on both texture and composition of the Snowden Member is based on the analysis of 26 thin-sections made from the samples collected at the 6 measured sections. For each thin-section, 250 points were counted for textural data and 500 points were counted for compositional data. Grain size distribution in phi units was plotted on cumulative probability paper, and compositional data was plotted on QFL diagrams.

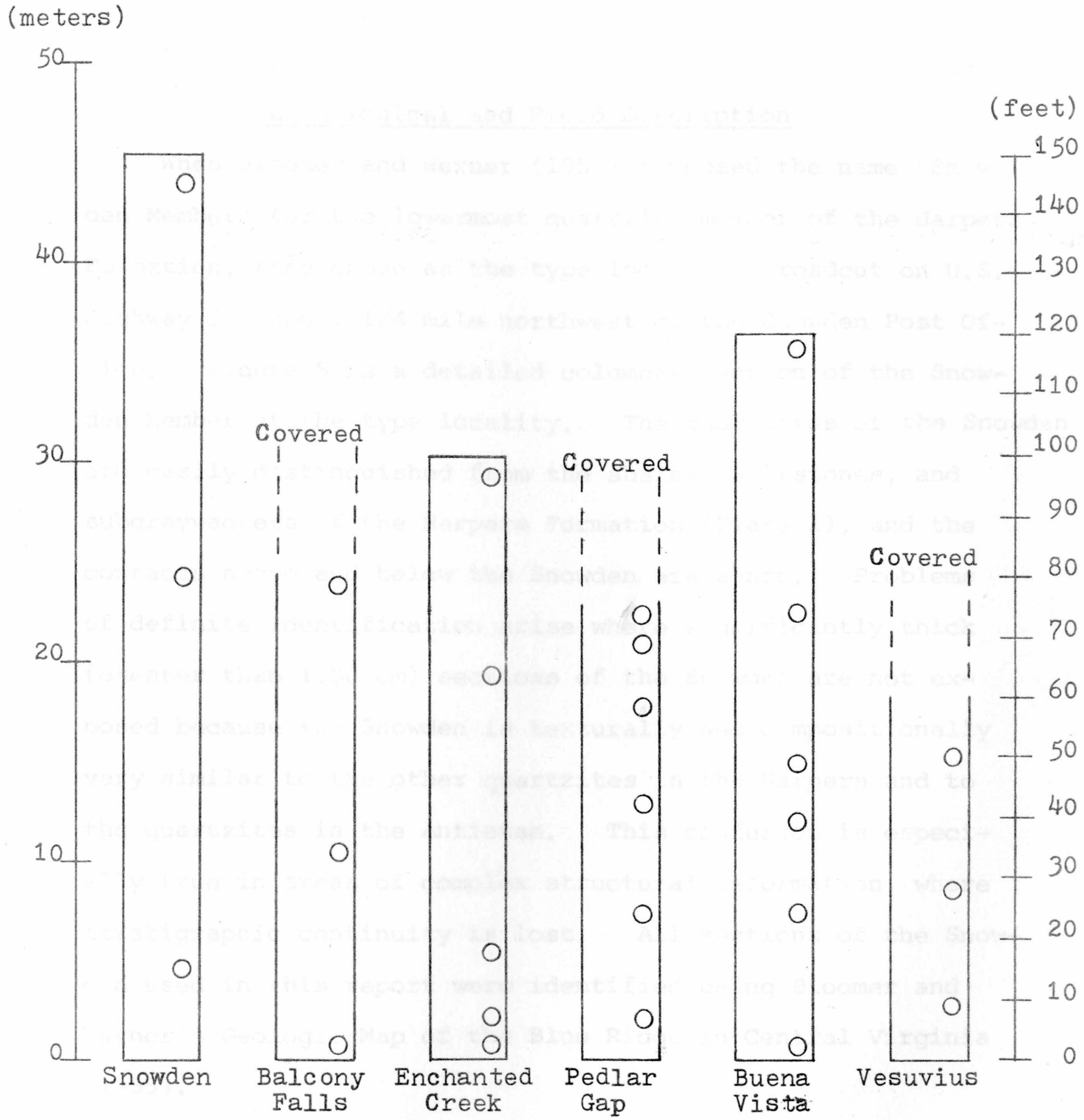


Fig. 4.- Thickness of the Snowden Member along strike. The Snowden thickens to the southwest. The location of the samples used in the petrographic analysis is also indicated.

Lithological and Field Description

When Bloomer and Werner (1955) proposed the name "Snowden Member" for the lowermost quartzite member of the Harpers Formation, they chose as the type locality a roadcut on U.S. Highway 501 about 1/4 mile northwest of the Snowden Post Office. Figure 5 is a detailed columnar section of the Snowden Member at the type locality. The quartzites of the Snowden are easily distinguished from the shales, siltstones, and subgraywackers of the Harpers Formation (Plate 1), and the contacts above and below the Snowden are sharp. Problems of definite identification arise where significantly thick (greater than 1500 cm) sections of the Snowden are not exposed because the Snowden is texturally and compositionally very similar to the other quartzites in the Harpers and to the quartzites in the Antietam. This confusion is especially true in areas of complex structural deformation, where stratigraphic continuity is lost. All sections of the Snowden used in this report were identified using Bloomer and Werner's Geologic Map of the Blue Ridge in Central Virginia (1955).

Most of the Snowden Member is a texturally and compositionally mature, white to light blue gray, medium to fine-grained quartz arenite that has been locally altered to a quartzite through pressure solution (Pettijohn, 1973). All 26 samples show evidence of pressure solution, and approximately 80% of the samples show at least 75% of the grain to grain contacts sutured through pressure solution. Pressure solution presents a problem in interpreting sedimentary textures because it erases original grain boundaries masking roundness and surface textures and obscuring primary sedimentary structures such as crossbedding and laminations.

The white to light blue gray quartzites of the Snowden weather to a characteristic tan to rust brown color (Plate 2). The rust brown coloration is due to the oxidation of ferrous iron to ferric iron. Plate 2 not only shows the darker coloration of the weathered (oxidized) surface, but it also shows a characteristic banding (top and bottom of photograph) that is produced on the weathered surface. Petrographic analysis of fresh surfaces also show a slight oxidation of iron. The degree of oxidation is dependent on the amount of ferric iron present in the rocks. Ferric iron content is variable from locality to locality with no recognizable trend.

Individual quartzite beds within the Snowden are subequal to unequal in thickness, laterally uniform in thickness, and continuous (Plates 1 and 3). In some localities, occasional interbeds of siltstone or shale are laterally uniform in thickness and continuous; elsewhere they can be laterally variable in thickness and discontinuous (Plate 4). The discontinuity of siltstone or shale beds is probably the result of channeling, i.e., scour and fill. The thickness of individual quartzite beds range from medium stratified (30 to 60 cm) to thickly stratified (60 to 90 cm, Plate 3). The rare siltstone or shale beds interbedded within the quartzite beds are stratified (7-1/2 to 15 cm thick) and are restricted to the upper third of all sections (Figure 5).

Both massive and internally laminated beds occur. Lamination is more widespread than internal massiveness, (a few millimeters to a few centimeters thick) and appears to occur throughout the Snowden, except where disrupted by burrowing of marine organisms (Scolithus) or masked by pressure solution. The internal massiveness is probably a product of alteration, i.e., pressure solution. Graded bedding or imbricated fabrics are not present.

Crossbedding is the most common primary sedimentary structure (Plate 5). Again, pressure solution and burrowing of marine organisms (Scolithus) masks the presence of crossbedding. Where present, crossbedding is of the trough-festoon type and ranges from 7 to 13 cm in thickness.

The only fossil type found in the Snowden Member is the trace fossil Scolithus. Scolithus tubes occur elsewhere in other quartzite units within the Harpers and generally within the Antietam Formation (King, 1949; Bloomer and Werner, 1955; Schwab, 1971). Scolithus is interpreted as a trace fossil produced by a burrowing worm (Seilacher, 1967). Plate 6 shows the Scolithus tubes, the cylindrical structures 4 to 8 cm in diameter originating at the bedding surface and extending downward perpendicular to the bedding (Plate 7) for lengths up to 90 cm (Schwab, 1970). According to Seilacher (1967), Scolithus facies are characteristic of littoral sands in shallow water marine environments. Scolithus is confined to the upper third (top 900-1500 cm) of the Snowden Member.

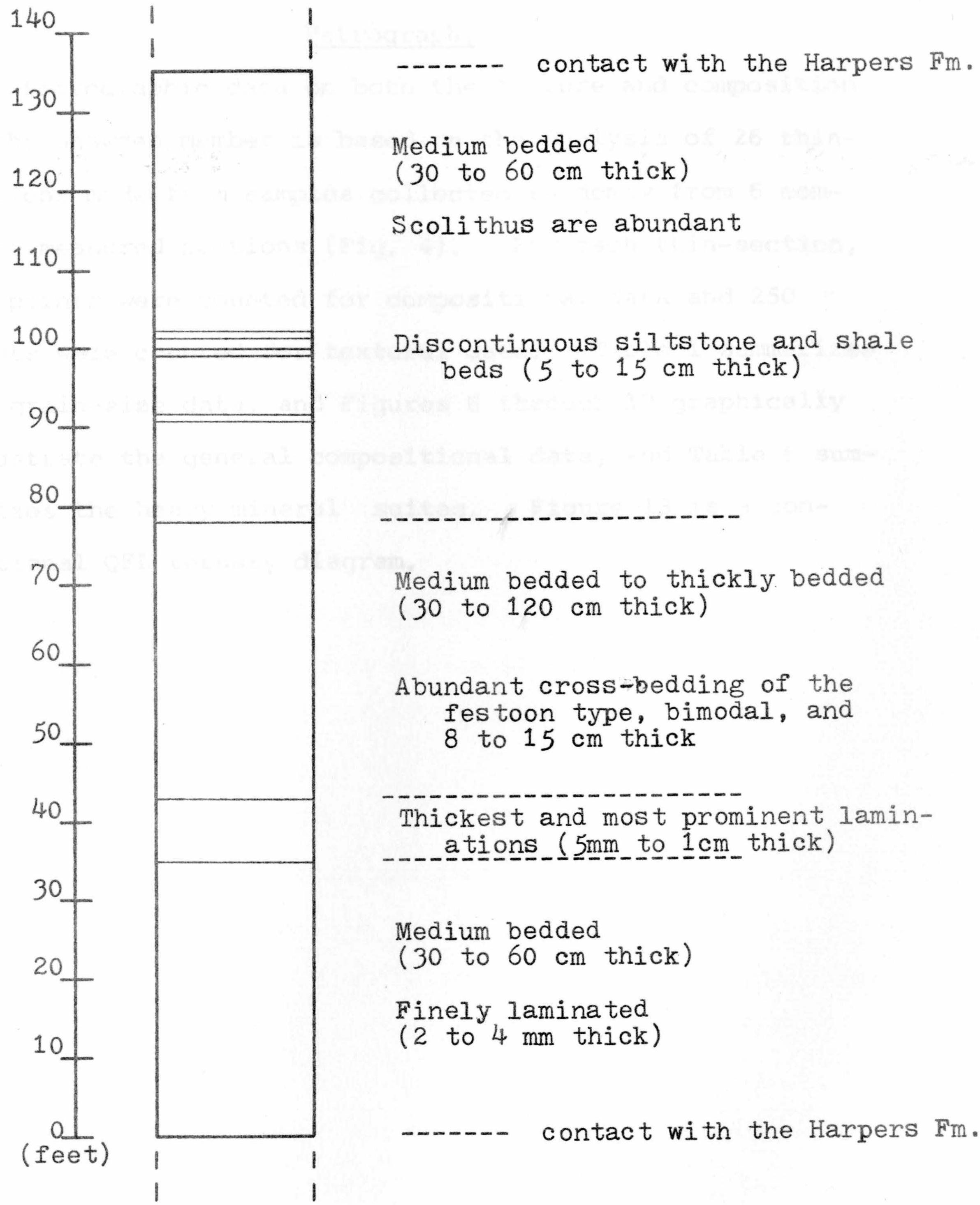


Fig. 5.- Simplified stratigraphic column of the Snowden Member from the type locality at Snowden, Virginia. Scolithus is confined to the upper third of the unit as are the siltstone and shale beds. Cross-bedding is most abundant in the middle third. The contacts with the Harpers Fm. are sharp.

Petrography

Petrographic data on both the texture and composition of the Snowden Member is based on the analysis of 26 thin-sections made from samples collected randomly from 6 complete measured sections (Fig. 4). For each thin-section, 500 points were counted for compositional data and 250 points were counted for textural data. Table 1 summarizes the grain-size data, and Figures 6 through 12 graphically illustrate the general compositional data, and Table 6 summarizes the heavy mineral suites. Figure 13 is a conventional QFL ternary diagram.

Texture

Grain size distribution was obtained by measuring the maximum grain diameter of 250 points for each of the 26 thin-sections. Grain size diameter in millimeters was converted to grain size in phi units, and appropriate grain size classes were assigned after Wentworth, 1922. Probability plots of total grain size distribution for each sample yielded raw phi 95, phi 84, phi 50, phi 16, and phi 5 values which were then converted to sieve size equivalents after Friedman, 1958: converted thin-section diameter = 0.3815 + 0.9027 (observed thin-section diameter). Values for phi mean, phi median, sorting, and skewness were calculated by the following equations (Folk, 1957):

phi mean = 1/2(phi 84 ± phi 16)

phi median = phi 50

sorting = 1/2(phi 84 - phi 16)

skewness = (phi mean - phi median) ÷ sorting

Table 1 summarizes the grain size distribution for each of the six sections and also presents statistical summaries of grain size distribution for the lower, middle, and upper third of the unit over the entire sample belt. Because the top third of the Balcony Falls, Pedlar Gap, and Vesuvius sections was covered, textural data for the top third was obtained from only the Snowden, Enchanted Creek, and Buena Vista sections. Figures 6, 7, 8, 9, and 10 plot the various statistical measures against one another and form the basis for the following discussion. Figures 11 and 12 are the summarized cumulative probability plots for the lower, middle, and upper third of the unit over the entire sample belt and for each of the six sections.

Figure 6, a graph of sorting vs. mean phi, indicates the boundaries between the different degrees of sorting (poorly sorted to very well sorted) and the different grain size classes (coarse sand to very fine sand). Each sample is plotted and labeled, and there is no obvious grouping or clustering of points. This lack of clustering would imply that although the sorting values range from moderate to very well sorted and the mean phi values range from medium to very fine sand, the unit is texturally homogeneous when the samples are graphed as a whole. Slight lateral and vertical trends are recognized, however, when the average of each section and the average of each stratigraphic third is plotted on the graph of sorting vs. mean phi (Fig. 7). Vertically, the trend is for the unit to become better sorted and finer grained upward. Horizontally, the trend is for the unit to become better sorted and finer grained from the Snowden section NE to the Buena Vista section, but from the Buena Vista section to the Vesuvius section, the trend is for the unit to become less sorted and coarser grained (resembling the texture of the Snowden and Balcony Falls sections). However, because these trends are only slight, especially when standard deviations are taken into account, the texture of the Snowden is strikingly homogeneous.

In a classic article on distinguishing dune, beach, and river sands on the basis of textural characteristics, Friedman, 1961, provides graphs of skewness vs. sorting for distinguishing beach sands from river sands and graphs of skewness vs. mean phi for distinguishing beach sands from dune sands. Figure 8 is a graph of skewness vs. sorting, and the dashed line represents the boundary (according to Friedman, 1961) between the beach sand field and the river sand field. Eighteen samples fall in the beach sand field and eight samples fall in the river sand field (70% beach sand). In a later study, Friedman (1968) demonstrated that breaking waves generate a back and forth flow of water which causes beach sands to be better sorted than river sands. Friedman also suggests that beach sand values tend to cluster around slightly positive to negative skewness while river sand values tend to be more spread out and more positively skewed (Fig. 8).

Figure 9 is a graph of skewness vs. mean phi, and the dashed line represents the boundary (according to Friedman, 1961) between the beach sand field and the dune sand field. Ten samples fall in the beach sand field and fourteen samples fall in the dune sand field (58% dune sand). Dune sands are usually characterized by a positive skewness and a somewhat finer grain size than beach sands (Blatt, 1980).

The positive skewness in dune sands arises from the trunication of the coarse tail of dune sands as wind is incapable of transporting the coarser particles. It is significant that 58% of the samples fall in the dune sand field. Perhaps to the degree to which we can rely on textural analysis for environmental determination, parts of the Snowden underwent deposition in a supra-tidal eolian environment as well as a deposition in an aqueous beach a bar environment.

Figure 10 is a graph of standard deviation vs. median phi. Such a graph has been used to distinguish sediments deposited by river processes from sediments deposited by wave processes (Stewart, 1958; Amaral and Pryor, 1977; Goldbery, 1980). Of particular interest is Goldbery's (1980) use of grain size data to interpret the depositional environment of the Pliocene Pleshet Formation, Beer Shera, Israel. Grain size data from the Snowden closely resembles grain size data from the Pleshet Formation on a graph of standard deviation vs. median phi (Fig. 10). Goldbery divides the Pleshet Formation into 6 units or facies. Unit 1, an upper shoreface facies, was deposited by river processes. Unit 2, an upper shore face to fore shore facies, was deposited by wave processes, and unit 4, a predominently foreshore facies with some upper shore face facies, plots in an area outside and below the area bounded by river and wave processes.

Data from the Snowden is subdivided into top, middle, and bottom thirds (Fig. 10). While bottom and top thirds tend to lie in the "wave process" field, middle thirds and some top and bottom thirds are not concentrated in any particular area. The best interpretation would be that during initial deposition (bottom third), both river and wave processes dominated. As deposition continued (middle third), no single process dominated, and the homogeneity of the grain-size distribution of the middle samples reflects this. As deposition was coming to an end (top third), wave processes tended to dominate generating better sorted and finer grained sediment.

SUMMARY OF GRAIN SIZE DATA

Section	# Samples	Mean	Standard Deviation	Mode	Sorting	Skewness
Snowden	3	1.85ϕ 0.28mm	0.47ϕ	1-2ϕ	0.53 mod.-well sorted	-0.004
Balcony Falls	3	1.43ϕ 0.37mm	0.35ϕ	1-2ϕ	0.61 mod. sorted	-0.03
Enchanted Creek	5	1.91ϕ 0.27mm	0.19ϕ	1-2ϕ	0.37 well sorted	-0.036
Pedlar Gap	6	1.47ϕ 0.36mm	0.56ϕ	1-2ϕ	0.45 well sorted	+0.04
Buena Vista	6	2.75ϕ 0.15mm	0.32ϕ	2-3ϕ	0.34 very well sorted	+0.015
Vesuvius	3	1.41ϕ 0.38mm	0.72ϕ	0-1ϕ	0.55 mod.-well sorted	+0.013
Top Third	3	2.23ϕ 0.21mm	0.29ϕ	2-3ϕ	0.35 very well sorted	-0.072
Middle Third	6	1.72ϕ 0.30mm	0.68ϕ	1-2ϕ	0.45 well sorted	+0.018
Bottom Third	6	1.77ϕ 0.29mm	0.46ϕ	1-2ϕ	0.49 well sorted	-0.017
Average from 6 sections		1.80ϕ 0.29mm	0.44ϕ	1-2ϕ	0.48 well sorted	-0.0003

Table 1.- Summary of grain size data from petrographic analysis.

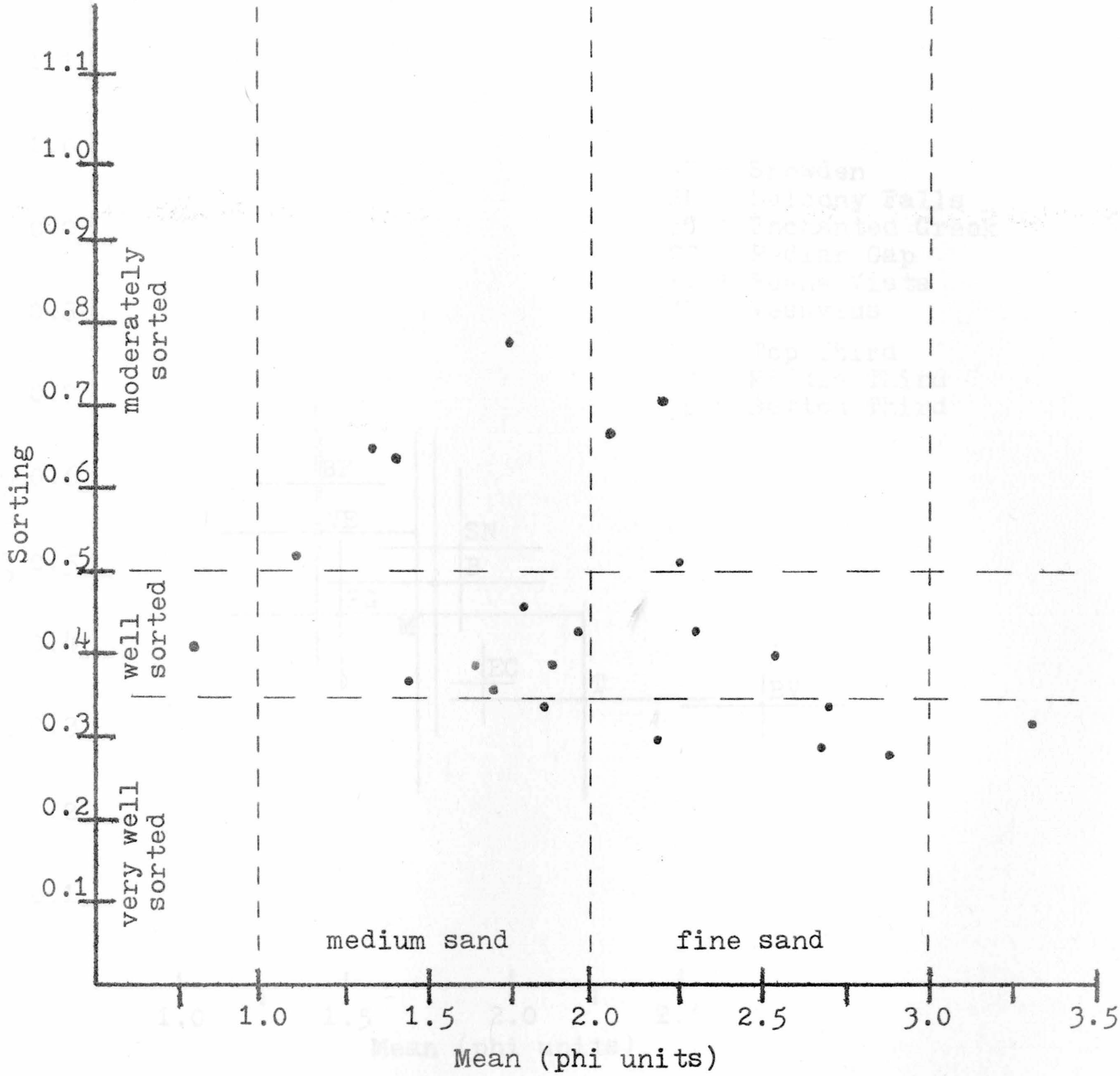


Fig. 6.- Sorting vs. mean phi: The mean and sorting values for all samples included in the textural analysis are graphed.

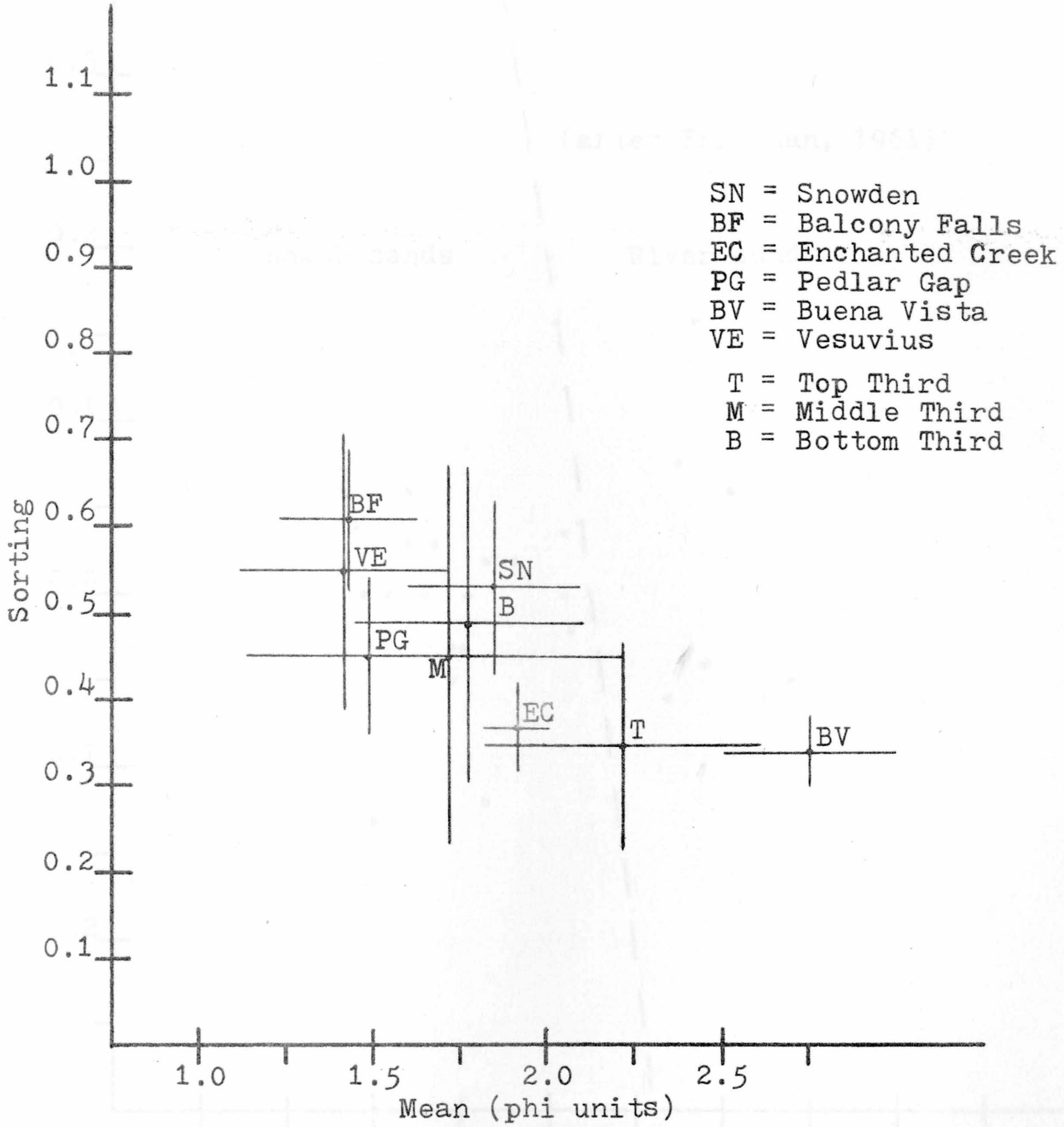


Fig. 7.- Sorting vs. mean phi: The average mean and sorting values for the six sections and the stratigraphic thirds are plotted. The standard deviation bars indicate the lack of real trends or variation in texture in the Snowden.

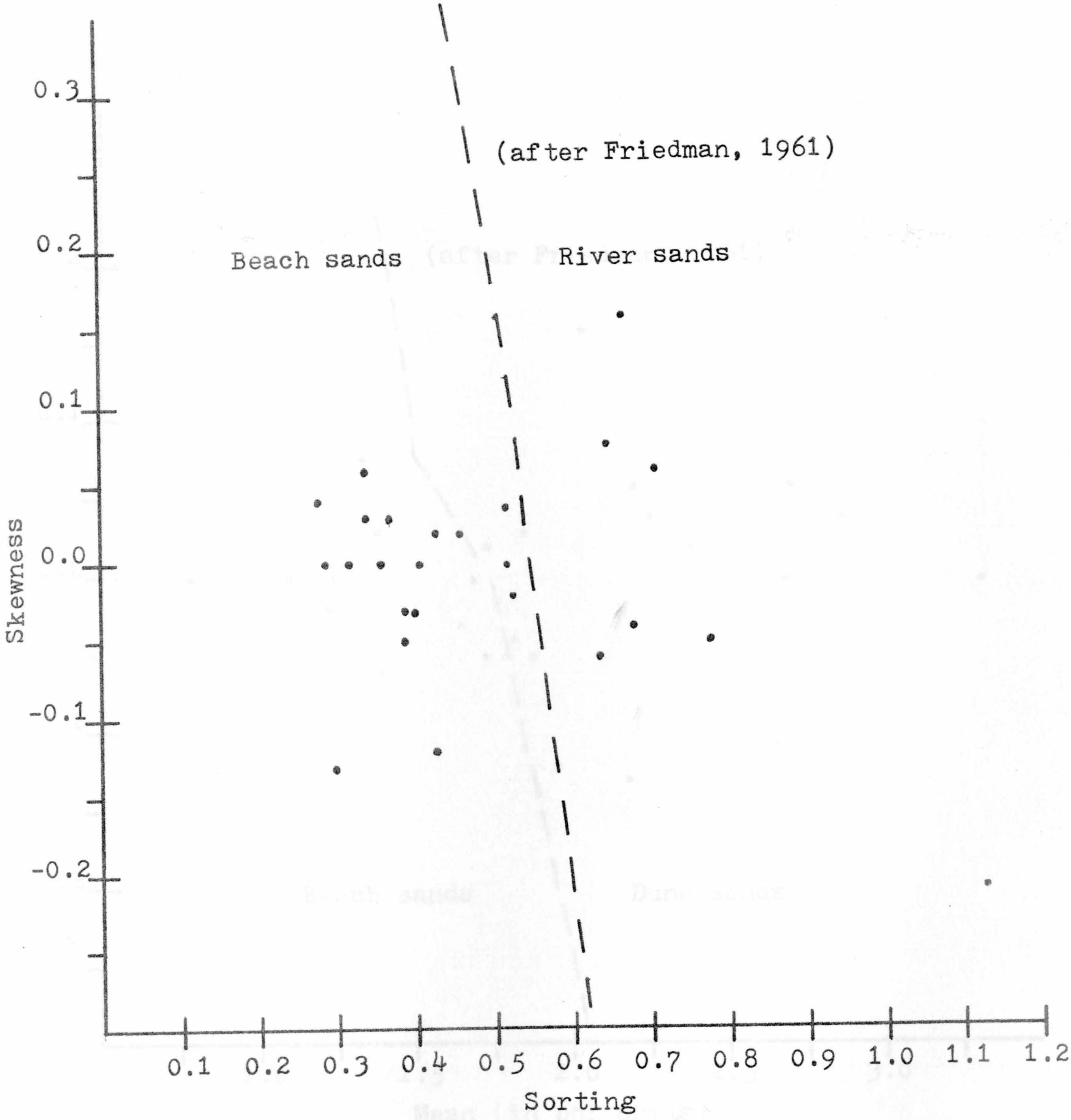


Fig.8.- Skewness vs. sorting: The dashed line represents the boundary between the beach sand field and the river sand field (Friedman, 1961).

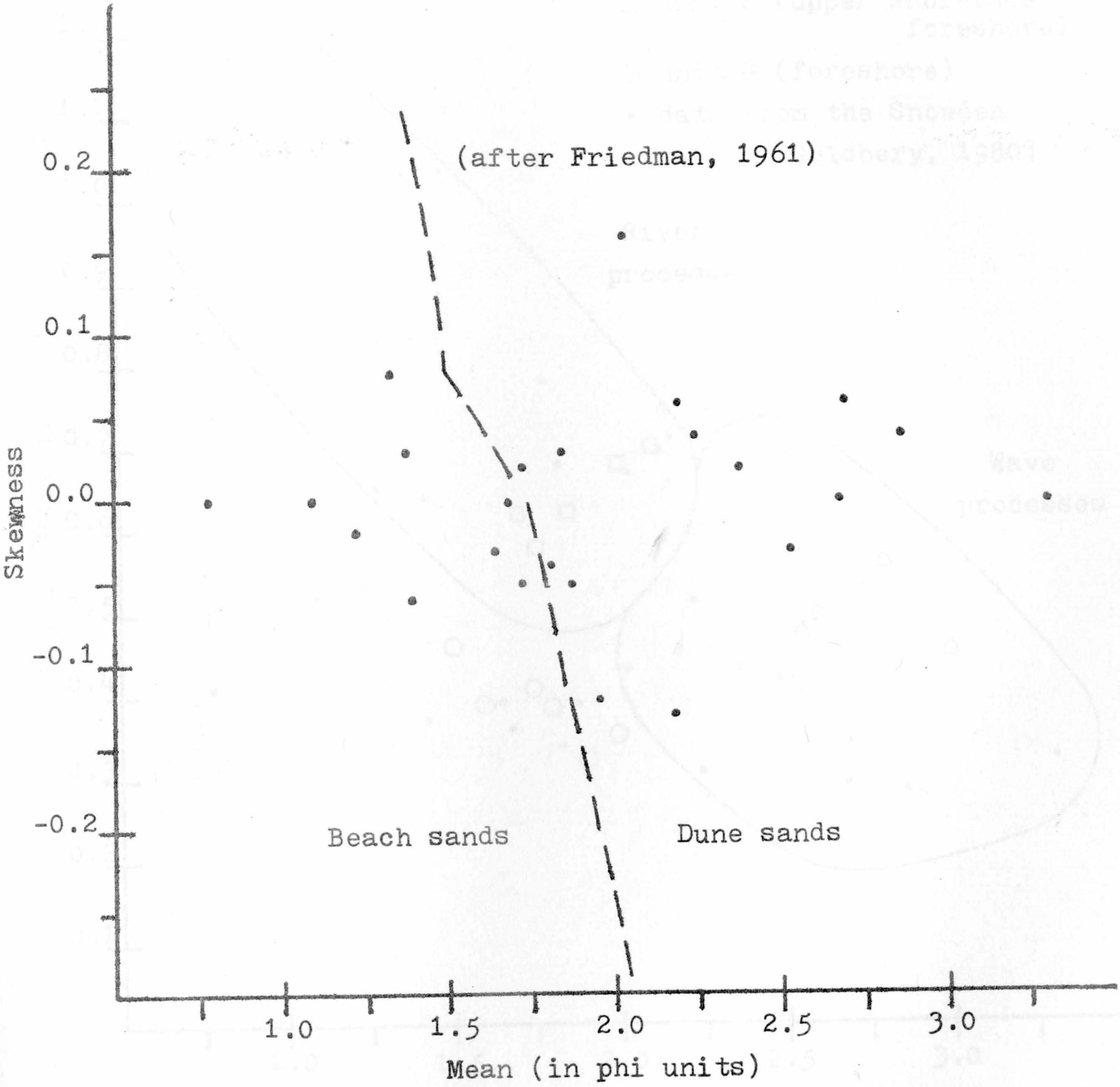


Fig. 9.- Skewness vs. mean phi: The dashed line represents the boundary between the beach sand field and the dune sand field (Friedman, 1961).

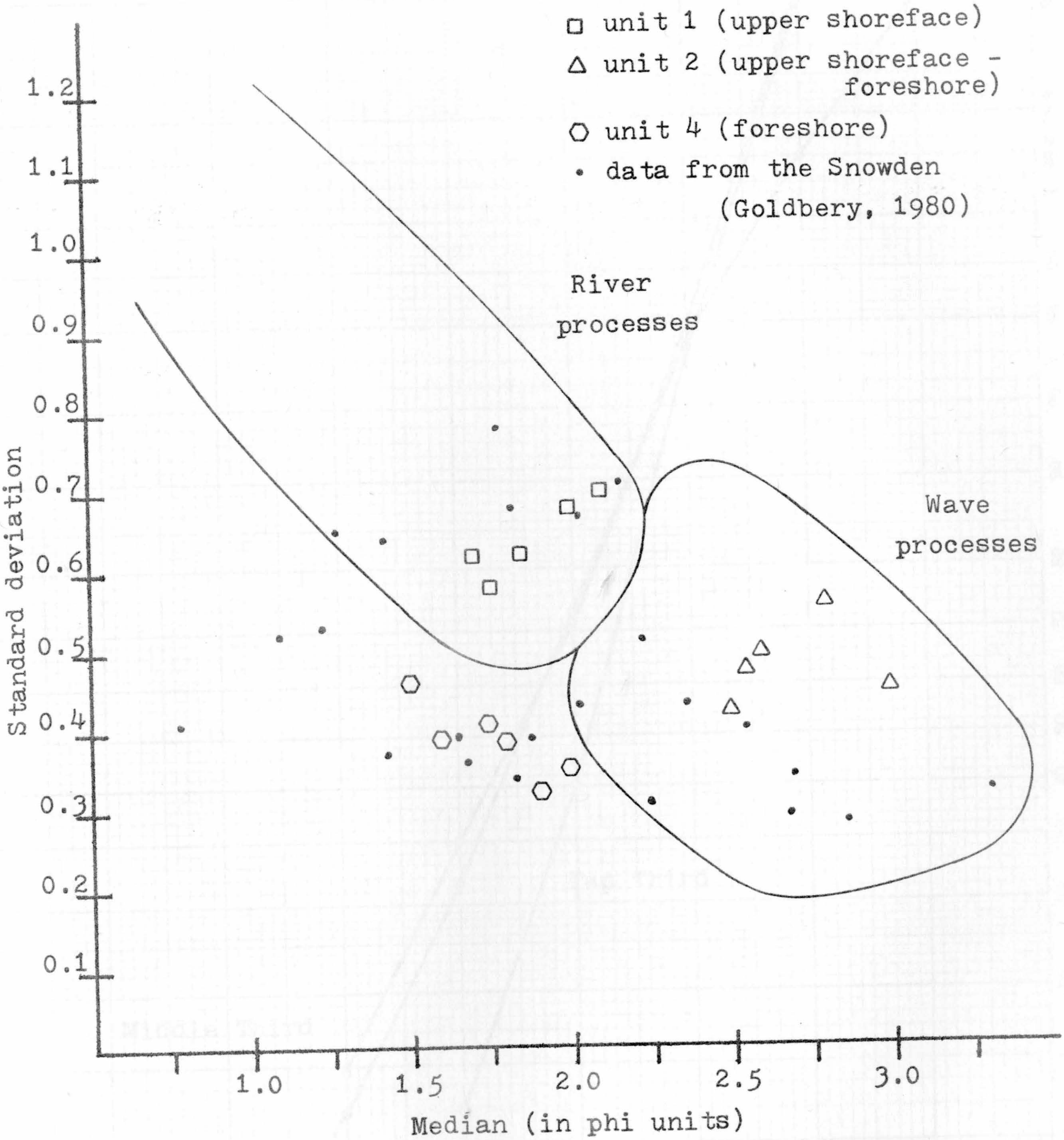


Fig. 10.- Standard deviation vs. median phi: The marked boundaries have been used to distinguish sediments deposited by river processes from sediments deposited by wave processes (Goldbery, 1980).

Fig. 11.- Cumulative probability plot for the stratigraphic thirds.

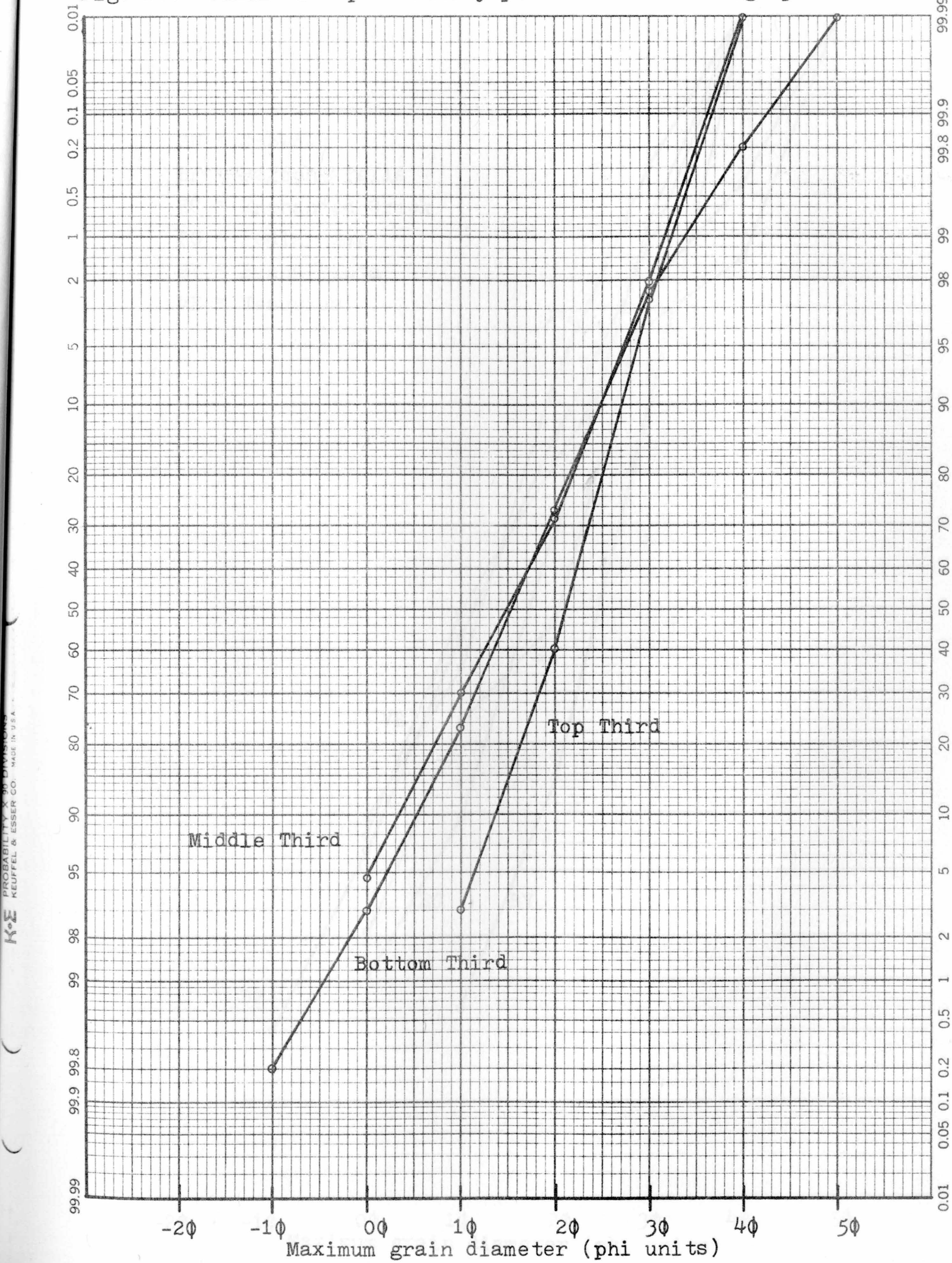
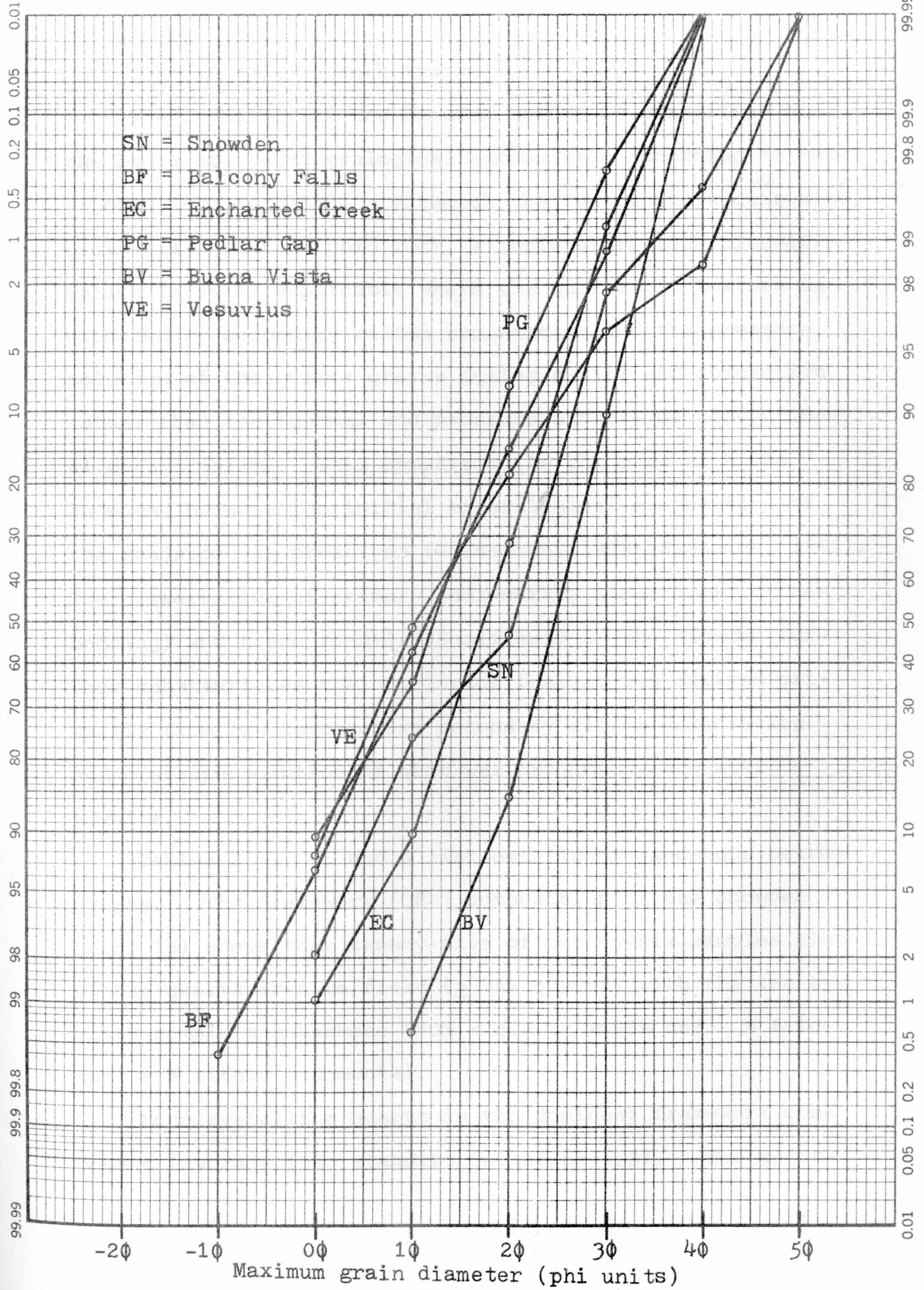


Fig. 12.- Cumulative probability plot for the six sections.



Bulk Mineralogy

The lithology of the Snowden Member is classified on the basis of its mineralogical composition according to Pettijohn (1973, p. 158). Although the Snowden is a quartzite, ordinarily a metamorphic rock, a sedimentary rock classification is still applicable where the quartzitic texture is produced by secondary silica cementation and the pressure solution of the quartz grains during burial and compaction rather than the thermal and pressure affects of conventional metamorphism. This appears to be the case with the Snowden, because the initial mineralogical composition of the sandstone is preserved (Pettijohn, 1973; Skolnick, 1965). The preservation of primary sedimentary structures (cross-bedding) and trace fossils (Scolithus) in the Snowden furthur substantiates the conclusion that it was derived primarily from low temperature secondary silica cementation and pressure solution of what was originally a quartz arenite.

Tables 2, 3, 4, and 5 list details of sandstone petrography. The framework (QFL) composition of the Snowden (Fig. 13) shows that twenty-five of twenty-six samples plot in the quartz arenite field ($\geq$ 95% quartz) with the twenty-sixth sample a subarkose (90% $<$ quartz $<$ 95% and % feldspar $>$ % lithic fragments).

Monocrystalline quartz is the dominant framework component (average 93%, standard deviation 1.3). The majority of the monocrystalline quartz grains exhibit undulatory extinction. The high percentage of undulatory quartz may be the result of post-depositional strain associated with the structurally deformed (folded and faulted) Hapers Formation (Connolly, 1965). Few abraded, authigenically overgrown grains were observed suggesting that the bulk of this material is first cycle. However, pressure solution may have erased some abraded secondary overgrown grains as original grain boundaries were destroyed. Nevertheless, even in samples least affected by pressure solution, the first cycle: multicycle quartz ratio is only 10% lower than average, and in no samples is the ratio less than 76:24.

Feldspar is the next most abundant framework component (average 2.1%, standard deviation 0.9). Potassium feldspar (microcline and orthoclase) occurs more often than plagioclase feldspar. Untwinned orthoclase was identified on the basis of optical properties and alteration (Scholle, 1979). Authigenic overgrowths are rare, and abraded overgrowths were not seen.

Lithic fragments are almost as abundant as feldspars (average 2.0%, standard deviation 0.8). The most common lithic fragment is polycrystalline quartz (80% of all lithic fragments are polycrystalline quartz). Seventy two percent of the polycrystalline quartz is composed of 6 or more crystals, and about half of the polycrystalline quartz clasts are composed of elongate crystals. Schist fragments are present, although not abundant (average 0.1%).

Detrital mica, rarely an abundant framework component, is typically muscovite (average 0.4%, standard deviation 0.1). Traces of biotite occur in one out of 26 samples. The heavy mineral suite (average 0.7%, standard deviation 0.1), listed in Table 6, includes epidote, tourmaline, apatite, zircon, magnetite, rutile, and sphene. Epidote and tourmaline are the most abundant (40% and 16% respectively of total heavy minerals). Epidote clasts are rounded to well rounded, and tourmaline clasts are angular to rounded.

Interstitial material, matrix and cement is rare (average 0.8% and 0.6%, standard deviation 0.1 and 0.1 respectively) because pressure solution has eliminated original intergranular pore spaces. In all cases, the cement is silicious and was probably derived through pressure solution as described by Pettijohn (1973, p. 424). The matrix component is more likely to be secondary than detrital because quartz arenites are deposited in environments capable of winnowing out matrix size clasts. Secondary matrix typically results from the disaggregation of lithic clasts or weathering of feldspars (Dickinson, 1970; Pettijohn, 1975). Locally, some secondary matrix may have been the result of shearing and recrystallization, and this is evident as some matrix exhibits an elongate fabric along a restricted planar section. The matrix is primarily composed of quartz with some feldspar and mica.

For the purpose of detecting possible lateral or vertical variations in compositions, the compositional data of the Snowden has been grouped laterally (along strike) in Tables 3 and 4 and vertically in Table 5. Along strike, the composition of the Snowden remains fairly homogeneous. There is a slight decrease in the amount of monocrystalline quartz and a slight increase in the amount of lithic fragments along strike to the northeast. The first cycle: multicycle quartz ratio decreases to the northeast, but petrographic analysis shows that samples to the northeast are least affected by pressure solution. Lack of pressure solution preserves original grain boundaries so that abraded overgrowths may be recognized. The heavy mineral suite remains generally homogeneous along strike. Epidote is the most common heavy mineral in 5 of the 6 sections. To the northeast there is a decrease in the amount of apatite and an increase in the amount of zircon (Table 6).

Vertically there are no significant differences in composition (Table 5). Monocrystalline quartz becomes slightly less abundant and total feldspar becomes slightly more abundant upward, but these changes in abundance are only on the order of one percent or less. Epidote remains the dominant heavy mineral in all cases, and tourmaline becomes slightly but insignificantly less abundant upward.

The lack of any significant vertical or lateral variation in composition coupled with the slight variation in texture (Table 1) is a striking feature of the Snowden. This overall compositional and textural homogeneity of the Snowden presumably reflects both the provenance and depositional environment of the sediment.

	Mean (percent)	Standard deviation	Range (low)	Range (high)
Quartz	93.4	1.3	89.6	97.2
1st cycle : multicycle	87:13		76:24	96:4
undulatory : nonund.	86:14		64:36	96:4
Microcline	0.5	0.2	0.0	1.4
Orthoclase	1.2	0.4	0.4	2.2
Plagioclase	0.4	0.2	0.0	1.6
Total Feldspar	2.1	0.9	0.6	3.6
Muscovite	0.4	0.1	0.0	1.0
Biotite	trace	---	0.0	trace
Total Mica	0.4	0.1	0.0	1.0
Chert	0.3	0.1	0.0	0.8
Polycrystalline Quartz	1.6	0.7	0.2	3.2
(≥6 crystals)	(72%)		(56%)	(88%)
(elongate crystals)	(51%)		(20%)	(76%)
Schist Fragments	0.1	0.1	0.0	0.6
Total Rock Fragments	2.0	0.8	0.4	3.6
Heavy Minerals	0.7	0.1	0.2	1.6
Silicious Cement	0.6	0.1	0.2	2.0
Matrix	0.8	0.1	0.0	2.8
Total	100.0			

Table 2.- Averages, standard deviations, and ranges of the results of petrographic analyses (26 samples).

	Snowden	Balcony Falls	Enchanted Creek
Quartz	94.6	93.9	93.1
1st cycle : multicycle	89:11	91:9	88:12
undulatory : nonund	88:12	87:13	79:21
Microcline	0.7	0.6	0.2
Orthoclase	1.1	1.6	0.9
Plagioclase	0.3	0.2	0.2
Total Feldspar	2.1	2.4	1.3
Muscovite	0.4	0.1	0.6
Biotite	---	---	0.1
Total Mica	0.4	0.1	0.7
Chert	0.3	0.2	0.7
Polycrystalline Quartz	0.8	1.5	1.9
(≥6 crystals)	(73%)	(77%)	(74%)
(elongate crystals)	(51%)	(50%)	(44%)
Schist Fragments	---	---	0.3
Total Rock Fragments	2.1	2.0	2.3
Heavy Minerals	0.6	0.7	0.5
Silicious Cement	0.8	0.4	1.2
Matrix	0.9	---	1.7
Total	100.0	100.0	100.0

Table 3.- Compositional data from petrographic analysis, grouped by mean percent for each section: Snowden, Balcony Falls, and Enchanted Creek sections.

	Pedlar Gap	Buena Vista	Vesuvius
Quartz	93.9	93.9	91.9
1st cycle : multicycle	89:11	87:13	80:20
undulatory : nonund.	86:14	87:13	87:13
Microcline	0.3	0.8	0.2
Orthoclase	0.9	0.7	1.7
Plagioclase	---	1.1	0.3
Total Feldspar	1.2	2.6	2.2
Muscovite	0.5	0.4	0.2
Biotite	---	---	---
Total Mica	0.5	0.4	0.2
Chert	0.4	0.1	0.1
Polycrystalline Quartz	1.7	1.9	1.9
(≥6 crystals)	(71%)	(60%)	(79%)
(elongate crystals)	(53%)	(57%)	(52%)
Schist Fragments	---	---	0.3
Total Rock Fragments	2.1	2.0	2.3
Heavy Minerals	0.6	0.7	0.5
Silicious Cement	0.8	0.4	1.2
Matrix	0.9	---	1.7
Total	100.0	100.0	100.0

Table 4.- Compositional data from petrographic analysis, grouped by mean percent for each section: Pedlar Gap, Buena Vista, and Vesuvius sections.

	Bottom Third	Middle Third	Top Third
Quartz	94.3	93.6	93.4
1st cycle : multicycle	87:13	85:15	91:9
undulatory : nonund.	87:13	81:19	83:17
Microcline	0.5	0.4	0.5
Orthoclase	1.0	1.0	1.1
Plagioclase	0.2	0.4	0.4
Total Feldspar	1.7	1.8	2.0
Muscovite	0.3	0.3	0.5
Biotite	---	---	0.1
Total Mica	0.3	0.3	0.6
Chert	0.2	0.5	0.3
Polycrystalline Quartz	1.3	1.8	1.6
(≥6 crystals)	(75%)	(73%)	(63%)
(elongate crystals)	(48%)	(49%)	(56%)
Schist Fragments	0.1	0.2	---
Total Rock Fragments	1.6	2.5	1.9
Heavy Minerals	0.6	0.4	1.0
Silicious Cement	0.7	0.8	0.4
Matrix	0.8	0.6	0.7
Total	100.0	100.0	100.0

Table 5.- Compositional data from petrographic analysis, grouped by mean percent for each stratigraphic third: bottom, middle, and top thirds.

Section	Heavy minerals: relative abundance in decreasing order of abundance
Snowden	epidote, apatite, tourmaline, rutile
Balcony Falls	epidote, magnetite, apatite, rutile, zircon
Enchanted Creek	epidote, tourmaline, magnetite, apatite, rutile, zircon
Pedlar Gap	tourmaline, apatite, epidote, zircon
Buena Vista	epidote, zircon, magnetite
Vesuvius	epidote, magnetite, sphene
Top Third	epidote, tourmaline, rutile, zircon, magnetite
Middle Third	epidote, tourmaline, apatite, rutile, zircon, magnetite, sphene
Bottom Third	epidote, apatite, zircon, tourmaline, rutile, magnetite

Total relative abundance based on actual point count:

epidote	= 40.3%
tourmaline	= 16.1%
apatite	= 14.5%
zircon	= 11.3%
magnetite	= 9.7%
rutile	= 6.5%
sphene	= 1.6%
	100.0%

Table 6.- Distribution and relative abundance of heavy mineral clasts.

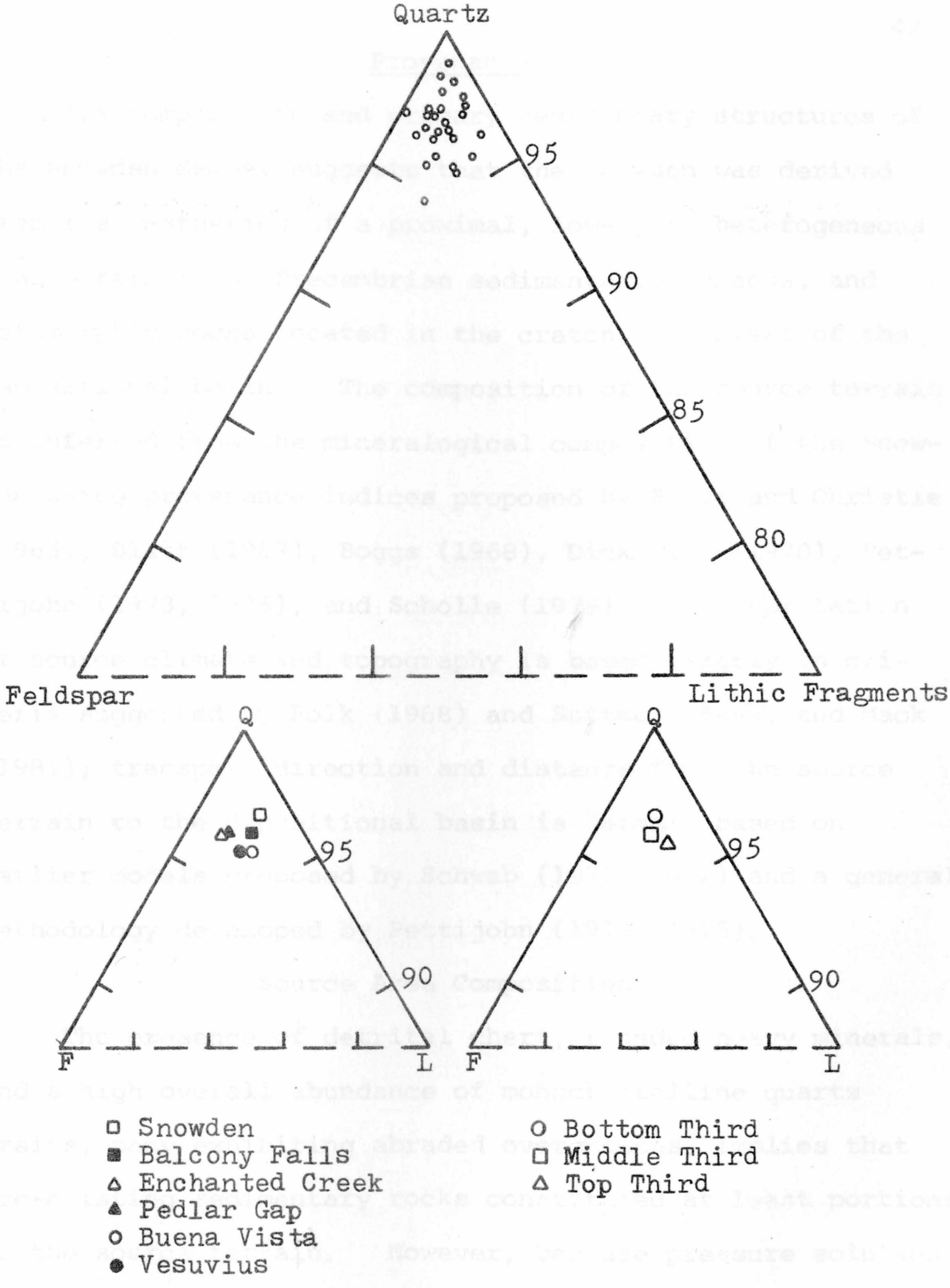


Fig. 13.- Compositional QFL diagrams: plots of individual samples, sectional averages, and stratigraphic third averages.

Provenance

The composition and primary sedimentary structures of the Snowden Member suggests that the Snowden was derived from the weathering of a proximal, low-lying heterogeneous source terrain of Precambrian sedimentary, igneous, and metamorphic rocks located in the craton, northwest of the depositional basin. The composition of the source terrain is inferred from the mineralogical composition of the Snowden using provenance indices proposed by Blatt and Christie (1963), Blatt (1967), Boggs (1968), Dickinson (1970), Pettijohn (1973, 1975), and Scholle (1979). Interpretation of source climate and topography is based largely on criteria suggested by Folk (1968) and Suttner, Basu, and Mack (1981); transport direction and distance from the source terrain to the depositional basin is largely based on earlier models proposed by Schwab (1971, 1972) and a general methodology developed by Pettijohn (1973, 1975).

Source Area Composition

The presence of detrital chert, rounded heavy minerals, and a high overall abundance of monocrystalline quartz grains, many exhibiting abraded overgrowths, implies that pre-existing sedimentary rocks constituted at least portions of the source terrain. However, because pressure solution makes it impossible to accurately determine the ratio of first cycle to multicycle quartz clasts, I cannot quantitatively estimate the overall abundance of sedimentary rocks in the source terrain. Even with extensive pressure solution, between 10 and 20% of the monocrystalline quartz clasts are at least second cycle. Consequently, substantial portions of the source terrain must have been sedimentary assemblages. The high overall abundance of orthoclase relative to microcline relative to plagioclase (Table 2) is also indicative of a sedimentary source terrain (Blatt, 1967).

The erosion of coarse-grained metamorphic rocks, particularly schist and gneiss, can also be inferred based on high overall abundance of polycrystalline quartz as well as the presence of schist fragments. Polycrystalline quartz may be derived both from igneous and metamorphic rocks. However, most (72%) of the polycrystalline quartz clasts consist of 6 or more quartz crystals, many (51%) of which are elongate cyrstals, characteristics typical of coarse-grained, foliated metamorphic rocks (Blatt and Christie, 1963; Blatt, 1967). Because fine-grained metamorphic rock fragments, particularly slate and phyllite, are generally preserved during weathering and transport (Boggs, 1968), their comparative absence relative to fragments of schist would suggest that the metamorphic terrain was predominantly composed of the deeper-seated, coarser-grained, foliated lithologies. This inference is compatable with the observation that epidote, the most common heavy mineral in the Snowden, is generally derived from high-grade metamorphic (gneissic) sources.

Plutonic rocks probably also occurred in the source area. This conclusion is suggested by much of the data. For example, approximately 86% of all monocrystalline quartz exhibits undulatory extinction, and the plagioclase/ total feldspar ratio is very low (average = 0.157). The erosion of acidic plutons (such as granite) characteristically produces such sediment presently (Blatt and Christie, 1963; Dickinson, 1970). Angular clasts of tourmaline, apatite, and magnetite also are generated by weathering a granitic source (Pettijohn, 1973).

The above lines of evidence suggesting that the source for the Snowden was a mixed terrane of high-grade metamorphic rocks (schists and gneisses) and acidic plutons, mantled by or including subordinate belts of sedimentary rocks, logically point to the underlying Blue Ridge Basement Complex as the most likely source for the unit. Werner (1966) described the local Virginia Blue Ridge Basement Complex in detail and defined three principle units: the Marshall Granite, the Lovingston Formation (granite-gneiss), and the Pedlar Formation (quartz monzonite). Of particular interest is the Pedlar Formation because it is partially composed of unakite (55% potassic feldspar, 25% epidote, and 20% quartz). The relative abundance of detrital epidote clasts in the Snowden would be explained by the presence of a source terrain partially rich in epidote. Clastic sediments of the Precambrian Swift Run Formation, which unconformably overlie the "deeply weathered surface of the Pedlar" (Werner, 1966, p. 11), were also included in the source terrain. In summary, the source terrain of the Snowden appears to be the dominent coarse-grained, low to high grade metamorphic and acidic igneous rocks of the Precambrian Basement Complex. Precambrian clastic sediments were evidently also eroded, but probably were less extensive in the source.

Climate and Relief

The climate of any source area controls the type of weathering (chemical vs. physical) and is ultimately responsible for the kind of detritus provided to the depositional basin. Therefore climate is a major factor in determining sandstone composition and must be taken into account in provenance studies. In a recent article on "Climate and the Origin of Quartz Arenites," Suttner, Basu, and Mack (1981) analyzed the mineralogical composition of Holocene fluvial sands derived from three distinct types of source terrains: 1) plutonic, 2) low-grade metamorphic, and 3) high-grade metamorphic. They compared the weathering products produced from such source rocks under two contrasting climates, arid and humid. Figure 14 summarizes their conclusions by plotting sandstone framework (QFL) and superimposing climatic bounding conditions. The composition of the sands were then quantiatively modified to "illustrate the effects of theoretical transport of 75 km followed by theoretical deposition in a shallow marine environment"(Suttner, Basu, and Mack, 1981, p. 1240). Figure 14 consists of the "adjusted" QFL diagrams drawn by Suttner et al. Figure 14a is a summary plot of just the medium sand fraction, and the compositional data from the Snowden plots in the metamorphic source field exposed to a humid climate. Figure 14b separates the various sources: plutonic source, low-grade metamorphic source, and high-grade metamorphic source. In all cases, regardless of the source composition, the data from the Snowden plots in the humid climate field. A humid climate would tend to promote the decomposition of feldspars and lithic fragments and promote the deposition of a cleaner, more quartz-rich, sandstone such as the Snowden.

The above analysis is based on a uniformitarian earth. That is, I assume that processes at work on the earth during the Cambrian were the same as those during the Holocene. In the case of weathering this is not necessarily true. Vegetation is a major factor in weathering as the presence of vegetation tends to reduce the degree of weathering. Because land plants were not present on the earth during the Cambrian, weathering during the Cambrian probably took place at a faster rate than it does today, during the Holocene. This is not to imply that a comparison of data from the Cambrian and the Holocene is unjustified. Rather, factors such as vegetation must be taken into account in studies based on a uniformitarian earth.

What relief did the source area most likely possess? According to Folk (1968), a source area of high relief exposed to a humid climate for a brief time will produce abundant angular, coarse-grained feldspar. On the other hand, a source area of low relief exposed to a humid climate (chemical weathering) for a prolonged time will produce little or no feldspar. Lack of abundant feldspar or lithic clasts in the Snowden would imply that the source area was of low relief and exposed to a humid climate. It should be mentioned, however, that lack of feldspar or lithic clasts could be explained by prolonged distance of transport or inheritance--the source terrain could have been lacking in these framework components to begin with. The fact that there is a significantly higher percentage of muscovite (o.4%) than biotite (trace) in the framework of the Snowden further suggests that the relief of the source area was low; sediments derived from source areas of low relief typically contain more grains of muscovite relative to biotite. The presence of angular clasts of magnetite, tourmaline, and some feldspars and resistent lithic clasts, would suggest that source terrain was proximal to the depositional basin.

Figure 15 is a paleocurrent map of the Chilhowee Group. The rose diagram from the Snowden Member is based on the orientation of 15 sets of cross-bedding azimuths measured at the Snowden section. Cross-bedding azimuths indicate a principal dispersal direction to the southeast (144°). Therefore, the source terrain for the Snowden was located to the northwest of the depositional basin. The reworking of sediment by longshore currents flowing northeast and southwest is inferred on the basis that numerous azimuths are oriented in this direction.

Tectonic Setting

A modern consensus exists that, "the key relations between provenance and basin are governed by plate tectonics, which thus ultimately controls the distribution of different types of sandstone (Dickinson, 1979, p. 2164)." Figure 16, a triangular QFL plot showing compositional distinctions believed to exist between sandstones derived from different tectonic provinces, is included to evaluate the sedimentary tectonic framework. In this type of diagram, polycrystalline quartz is conventionally grouped with monocrystalline quartz. Compositional data from the Snowden invariably plots in the "continental block provenance" or the "recycled orogen provenance". Sands derived from continental blocks are characterized by a high quartz content and a high ratio of K-feldspar to plagioclase (Dickinson, 1979). Such characteristics imply intense weathering on cratons (both shield and platform areas) with low relief. Crustal stability and slow erosion allows time for the reworking and cleaning of the sediment.

Recycled orogenic belts, located adjacent to the continental block, were also included in the source area. Recycled orogenic belts invariably mean source terrains composed of uplifted and structurally deformed strata and generation of multicycle sediments (Dickinson, 1979). In rare cases, while a unique combination of extreme conditions (climate, relief, and rate of sedimentation), may produce first-cycle quartz arenites (Suttner, Basu, and Mack, 1981), generally such sands are multicycle in origin. The overall compositional maturity of the Snowden (> 95% monocrystalline quartz grains) suggests a source terrain rich in monocrystalline quartz, and the best source for a high percentage of monocrystalline quartz is one that includes pre-existing quartz arenites. Then, the pre-existing quartz grains are merely re-cycled into younger sediments, the Snowden in our case.

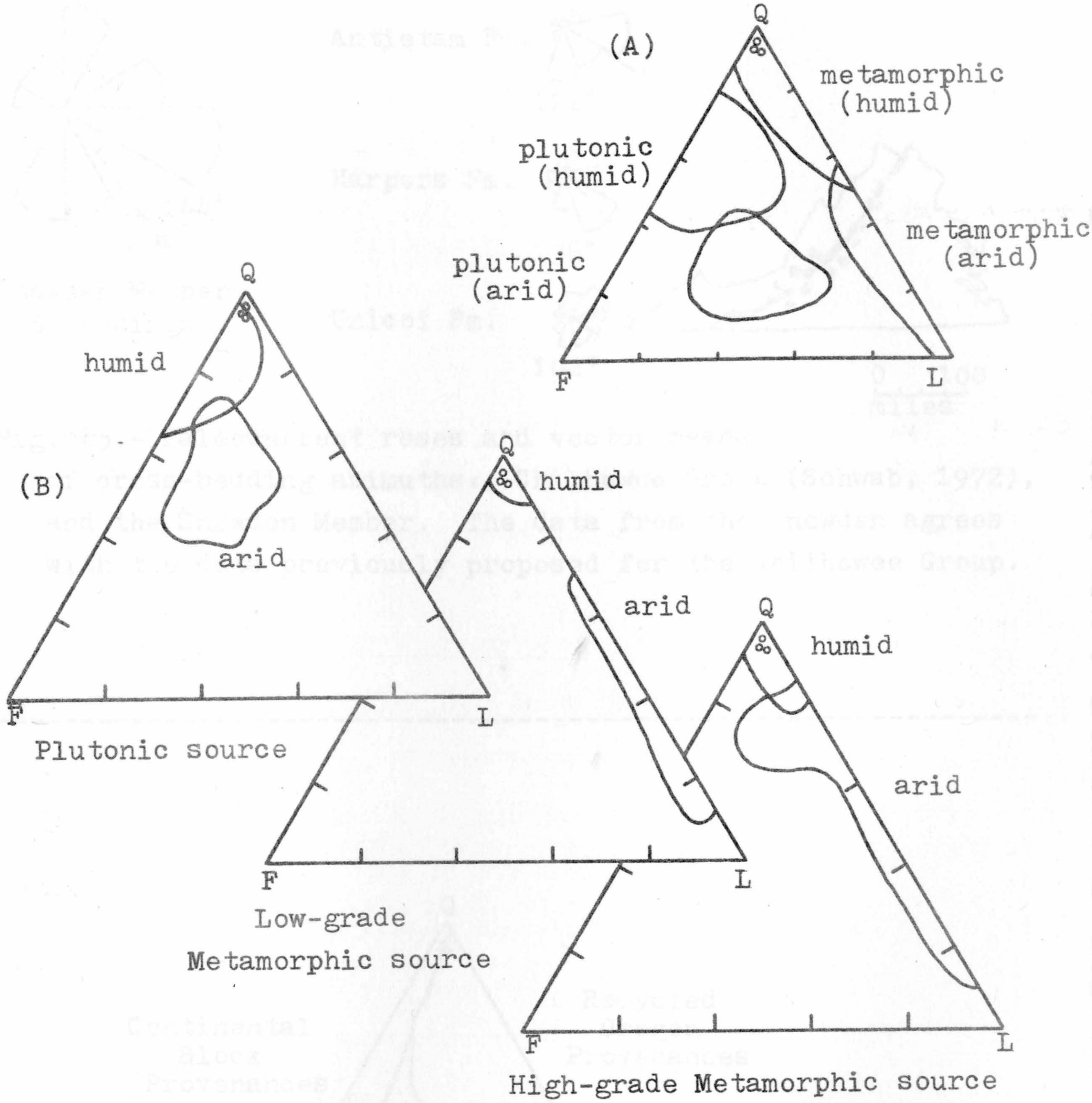


Fig. 14.- A) Climatic bounding conditions based on a study of Holocene fluvial sands derived from a number of different sources (Suttner et al., 1981). Data from the Snowden plots in the metamorphic source terrain in a humid climate.
B) Suttner et al. (1981) adjusted the climatic boundaries for shallow marine deposits, and they separated the various sources. Data from the Snowden invariably plots in the humid climate field regardless of the source composition.

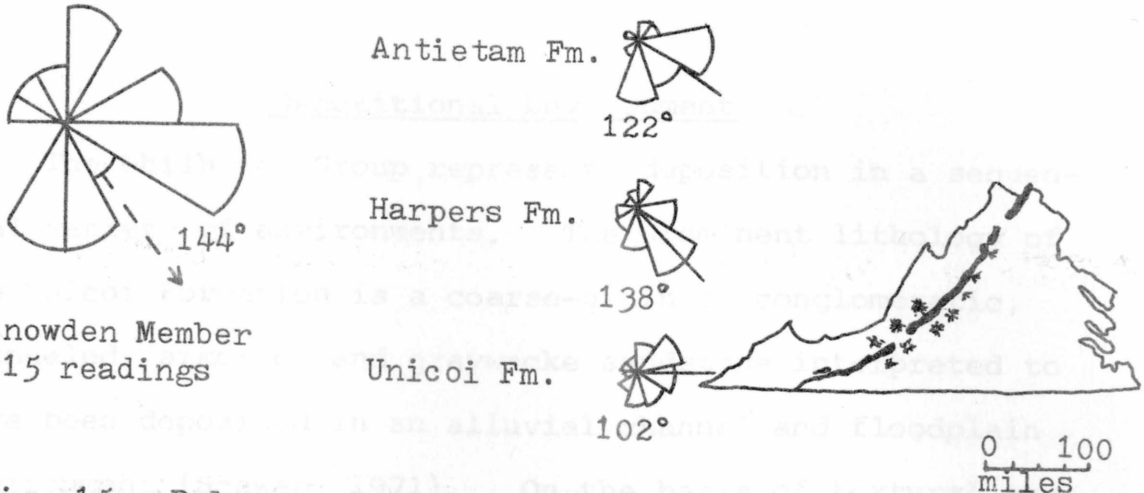


Fig. 15.- Paleocurrent roses and vector means of cross-bedding azimuths: Chilhowee Group (Schwab, 1972), and the Snowden Member. The data from the Snowden agrees with the data previously proposed for the Chilhowee Group.

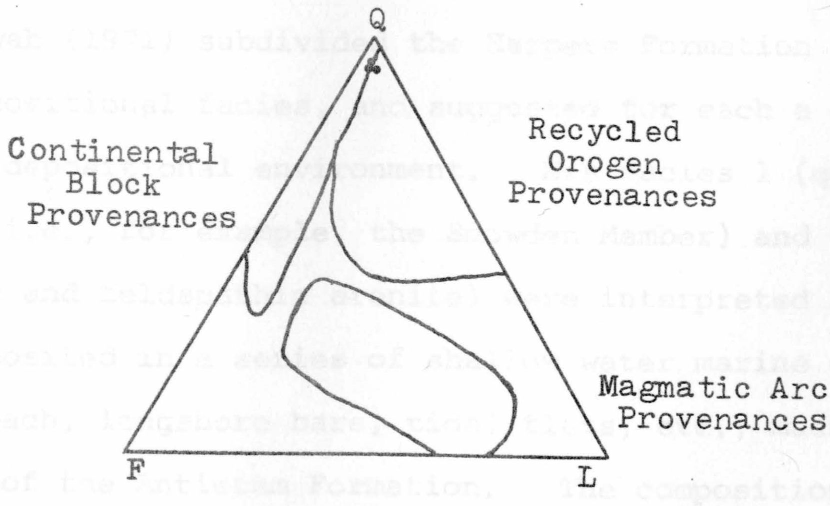


Fig. 16.- Triangular QFL plot showing mean framework modes for selected sandstone suites derived from different types of provenances (Dickinson, 1979).

Depositional Environment

The Chilhowee Group represents deposition in a sequential variety of environments. The prominent lithology of the Unicoi Formation is a coarse-grained, conglomeratic, channeled, arkosic, and graywacke sandstone interpreted to have been deposited in an alluvial channel and floodplain environment (Schwab, 1971). On the basis of textural and compositional maturity, abundant crossbedding, and a shallow marine fossil assemblage, a shallow marine suite of environments (beach, bar, and deltaic fringe) has been proposed for the Antietam Formation (Schwab, 1971). However, the Harpers Formation, the unit that "hosts" the Snowden, is composed of a much more heterogeneous suite of lithologies, and it is difficult to propose only a single depositional environment for the entire unit.

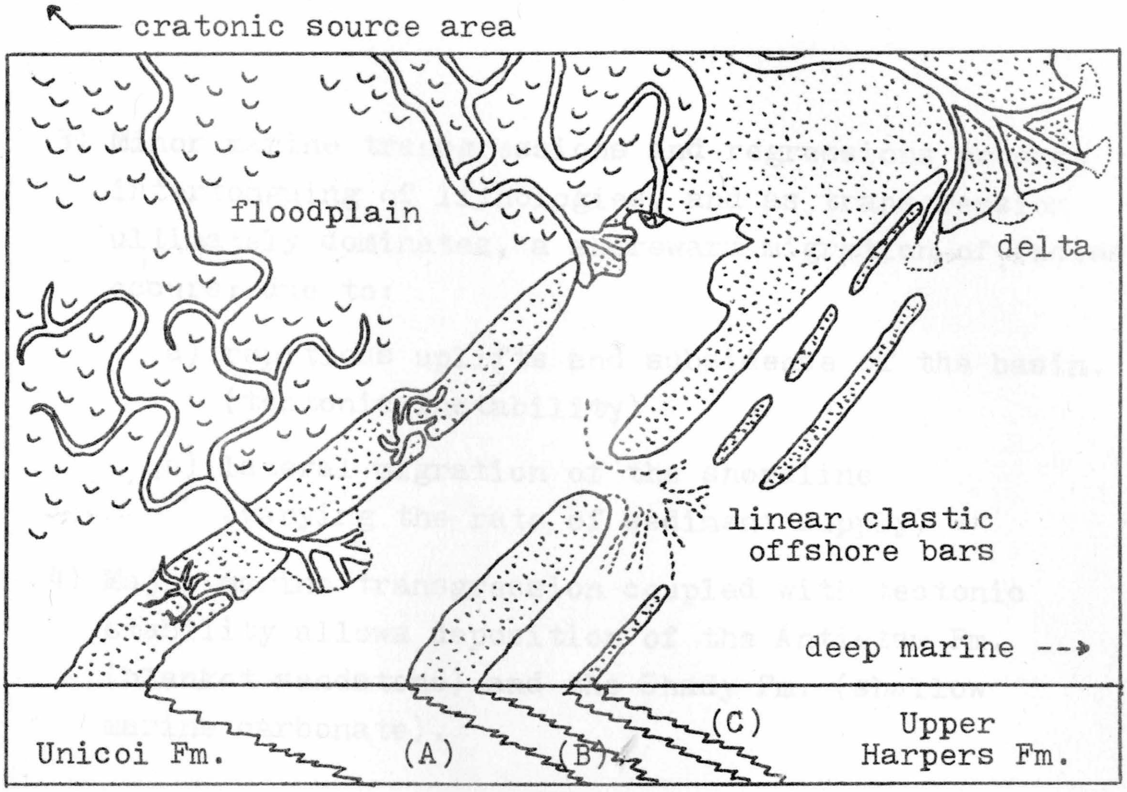
Schwab (1971) subdivided the Harpers Formation into four compositional facies, and suggested for each a contrasting depositional environment. His facies 1 (quartz arenite, i.e., for example, the Snowden Member) and facies 2 (lithic and feldspathic arenite) were interpreted as being deposited in a series of shallow water marine environments, beach, longshore bars, tidal flats, etc., much like the bulk of the Antietam Formation. The compositional variations were interpreted to be the result of differences in weathering, sediment supply, and rate of sedimentation. Conversely, facies 3 (wacke) and facies 4 (shale) were interpreted as deeper-water deltaic and/or turbidity current (fan?) deposits. This paper concentrates on defining, as specifically as possible, only the depositional environment of the Snowden Member (Schwab's facies 1). The interpretation is mainly based on analogies with shallow marine environments described by Pettijohn (1973), Selley (1978), and Reineck and Singh (1980).

The compositional and textural maturity of the Snowden Member (95% monocrystalline quartz in well rounded, well sorted grains) implies a shallow marine depositional environment. Shallow marine trace fossils, Scolithus, and shallow marine primary sedimentary structures, bimodal festoon crossbedding with low dips and slightly dipping laminations, suggests that re-working of sediments and final deposition occurred in a beach or offshore bar environment (Reineck-Singh, 1980). Although the burrowing of marine animals and the diagenetic effects of pressure solution have made it difficult to use primary sedimentary structures to "fingerprint" specific depositional environments (an objective that sedimentary structures alone rarely attain in any case), other characteristics of the Snowden suggest that deposition occurred in a linear clastic shoreline of an offshore barrier island or bar.

A modification of this depositional model is probably warranted. Adjacent to offshore islands or bars, marine currents are strong enough to rework deltaic sediments or other land detritus, sufficiently to generate quartz arenite deposits (Selley, 1978). Such deposits tend to contain: 1) concentrations of rounded heavy minerals (rounded clasts of epidote and other heavy minerals are common in the Snowden), 2) excellent sorting and a very high grain-matrix ratio (sediment of the Snowden is very well sorted and contains only secondary matrix), 3) bimodal crossbedding and marine burrows (the Snowden is characterized by these), 4) channeling, i.e., scour and fill (this is evident in the Snowden, Plate 5), 5) vertical increase in grain size (the grain size of the Snowden increases from the bottom third to the middle third, and the decrease in grain size from the middle third to the top third may be explained by minor marine transgressions because fine-grained siltstones and shales overlie the Snowden), 6) an elongate and linear sand body (this is the geometry of the Snowden), and 7) associated lithological types (laterally, the Snowden tends to separate terrestrial deposits of the Unicoi and lower Hapers from the deeper marine turbidite deposits of the Upper Harpers); (Pettijohn, 1973).

Figure 17 is an illustration of the proposed depositional environment of the Snowden Member. The depositional environments of the Unicoi and the Harpers Formations are incorporated in the illustration to stress lateral and vertical relationships.

In summary, the Snowden is characterized by a "beach sand" lithology and suite of primary sedimentary structures and trace fossils. On the basis of lateral lithological variations, geometry of the sedimentary body, and other characteristics mentioned above, the Snowden is interpreted to have been deposited in an offshore linear barrier island or bar during a period of time where the rate of influx of sediment was low enough to allow the reworking, compositional and textural maturing of sediment already present or slowly entering the depositional basin.



(A) Lower Harpers
(B) Snowden Member
(C) Other quartzose sandstones in the Harpers

Fig. 17.- Depositional model for the Snowden Member and the lower and middle Chilhowee Group. Based on a modern beach-shelf profile by Reineck and Singh (1980).

Summary

1) The Unicoi Fm. is interpreted as a continental, alluvial fan and floodplain deposit (Bloomer and Werner, 1955), and it was deposited northwest of the marine basin.

2) The Lower Harpers Fm., including the Snowden Member, is interpreted as a marine shelf deposit (slow subsidence of the basin, Schwab, 1971).

   The Upper Harpers Fm. is interpreted as a marine basin deposit, a turbidite (more rapid subsidence of the basin, Schwab, 1971).

3) Minor marine transgressions and regressions produce intertonguing of lithologies, and as transgression ultimately dominates, a shoreward migration of facies occurs; due to:

    a) repitious uplifts and subsidence of the basin. (tectonic instability)

    b) lateral migration of the shoreline. (varying the rate of sediment supply)

4) Major marine transgression coupled with tectonic stability allows deposition of the Antietam Fm. (blanket sandstone) and the Shady Fm. (shallow marine carbonate).

References

Amaral, E. J., and Pryor, W. A., 1977, Depositional environment of the St. Peter Sandstone deduced by textural analysis: Jour. Sed. Petrology, V. 47, p. 32-52.

Blatt, Harvey, 1967a, Original characteristics of clastic quartz grains: Jour. Sed. Petrology, V. 37, p. 401-424.

________, 1967b, Provenance determinations and recycling of sediments: Jour. Sed. Petrology, V. 37, p. 1031-1044.

________, and Christie, J. M., 1963, Undulatory extinction in quartz in igneous and metamorphic rocks and its significance in provenance studies of sedimentary rocks: Jour. Sed. Petrology, V. 33, p. 559-579.

________, Middleton, G., and Murray, R., 1980, Origin of sedimentary rocks, Englewood Cliffs: Prentice-Hall, Inc.

Bloomer, R. O., and Werner, H. J., 1955, Geology of the Blue Ridge region in central Virginia: Geol. Soc. America Bull., V. 66, p. 579-606.

Boggs, Sam Jr., 1968, Experimental study of rock fragments: Jour. Sed. Petrology, v. 38, p. 1326-1339.

Butts, Charles, 1940, Geology of the Appalachian Valley in Virginia, Geologic text and illustrations. Virginia Geol. Survey Bull. 42, 56 p., map.

Chen, Ping-Fan, 1977, Lower Paleozoic stratigraphy, tectonics, paleogeography, and oil/gas possibilities in the central Appalachians. West Virginia Geol. and Economic Survey, Investigation no. RI-26-1.

Connolly, J. R., 1965, The occurrence of polycrystallinity and undulatory extinction in quartz in sandstones: Jour. Sed. Petrology, v. 35, p. 116-135.

Dickinson, W. R., 1970, Interpreting detrital modes of graywacke and arkose: Jour. Sed. Petrology, v. 40, p. 695-707.

________, and Suczek, C. A., 1979, Plate tectonics and sandstone composition: Am. Assoc. Petroleum Geologists Bull., v. 63, p. 2164-2182.

Folk, R. L., 1968, Petrology of sedimentary rocks. Austin: Hemphill's Book Store.

Friedman, G. M., 1961, Distinction between dune, beach, and river sands from their textural characteristics: Jour. Sed. Petrology, v. 31, p. 514-529.

________, and Sanders, J.E., 1978, Principles of sedimentology. New York: Wiley and Sons.

Goldbery, Ron, 1980, Use of grain-size frequency data to interpret the depositional environment of the Pliocene Pleshet Formation, Beer Sheva, Israel: Jour. Sed. Petrology, v. 50, p. 843-856.

Keith, A., 1894, Geology of the Catoctin belt: U.S. Geol. Survey, 14th Ann. Report, part II, p. 285-395.

King, P. B., 1949, The base of the Cambrian in the southern Appalachians: Am. Jour. Sci., v. 247, p. 513-530.

Krumbein, W. C., and Pettijohn, F. J., 1938, Manual of sedimentary petrography. New York: Appleton-Century-Crofts, Inc.

Moorhouse, W.W., 1959, The study of rocks in thin section. New York: Harper and Row.

Page, H. G., 1955, Phi-millimeter conversion table: Jour. Sed. Petrology, v. 25, p. 285-292.

Pettijohn, F. J., 1975, Sedimentary rocks, 3rd ed. New York: Harper and Row.

________, Potter, P. E., and Siever, R., 1972, Sand and sandstone. New York: Springer-Verlag.

Potter, P. E., and Pettijohn, F. J., 1977, Paleocurrents and basin analysis, 2nd ed., New York: Springer-Verlag.

Reineck, H. E., and Singh, I. B., 1980, Depositional sedimentary environments, 2nd ed. Berlin: Springer-Verlag.

Scholle, P. A., 1979, A color guide to sandstones: Am. Assoc. Petroleum Geologists Memoir no. 28.

Schwab, F. L., 1970, Origin of the Antietam Formation (Late Precambrian? - Lower Cambrian), central Virginia: Jour. Sed. Petrology, v. 40, p. 354-366.

________, 1971, Harpers Formation, central Virginia: a sedimentary model: Jour. Sed. Petrology, v. 41, p. 139-149.

________, 1972, The Chilhowee Group and the late Precambrian-early Paleozoic sedimentary framework in the central and southern Appalachians: West Virginia Geol. and Economic Survey.

Seliacher, A., 1967, Bathymetry of trace fossils: Marine Geology, v. 5, p. 413-428.

Selley, R. C., 1980, Ancient sedimentary environments, 2nd ed. Ithaca: Cornell University Press.

Skolnick, H., 1965, The quartzite problem: Jour. Sed. Petrology, v. 35, p. 12-21.

Spencer, E. W., 1968, Geology of the Natural Bridge, Sugarloaf Mountain, Buchanan, and Arnold Valley Quadrangles, Virginia: Va. Division of Mineral Resources, report of investigations 13.

Suttner, L. J., Basu, A., and Mack, G. H., 1981, Climate and the origin of quartz arenites: Jour. Sed. Petrology, va. 51, p. 1235-1246.

Visher, G. S., 1969, Grain size distributions and depositional environments: Jour. Sed. Petrology, v. 39, p. 1074-1106.

Werner, H. J., 1966, Geology of the Vesuivius Quadrangle, Virginia: Va. Division of Mineral Resources, report of investigations no. 7.

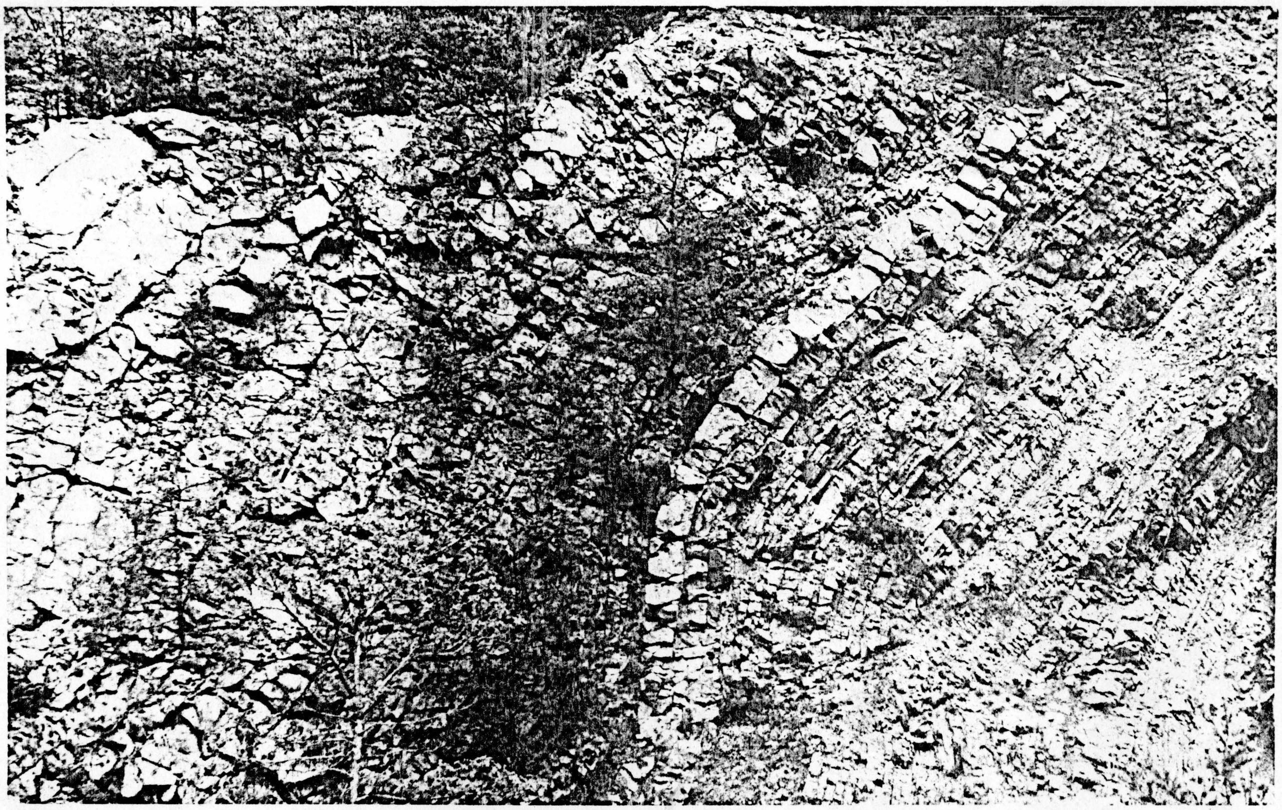


Plate 1.- Contact between the Snowden Member and the Harpers Fm. (Balcony Falls section).

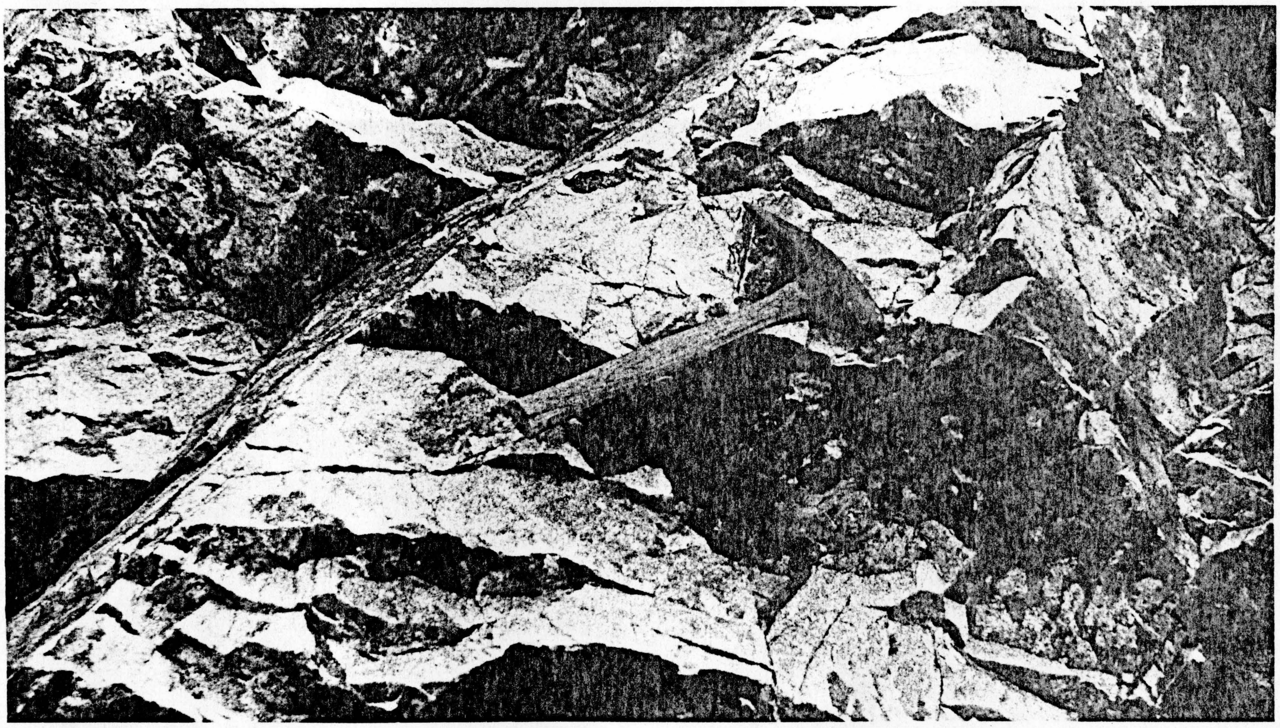


Plate 2.- A weathered surface of the Snowden is characterized by iron staining due to oxidation. The fresh surfaces are light colored and the weathered surfaces are dark (Vesuvius section).

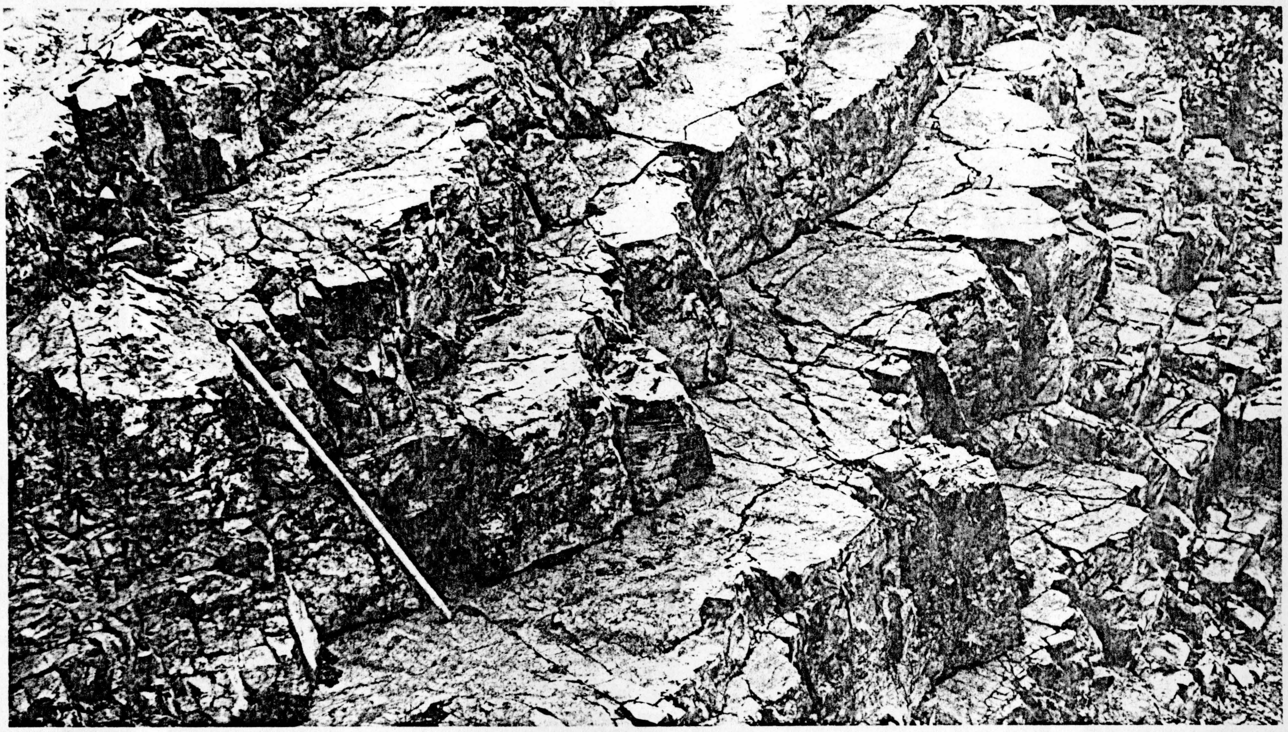


Plate 3.- The quartzite beds of the Snowden are uniform in thickness and laterally continuous. Bedding thickness ranges from 30 to 120 cm. The staff is 2 meters long (Vesuvius section).

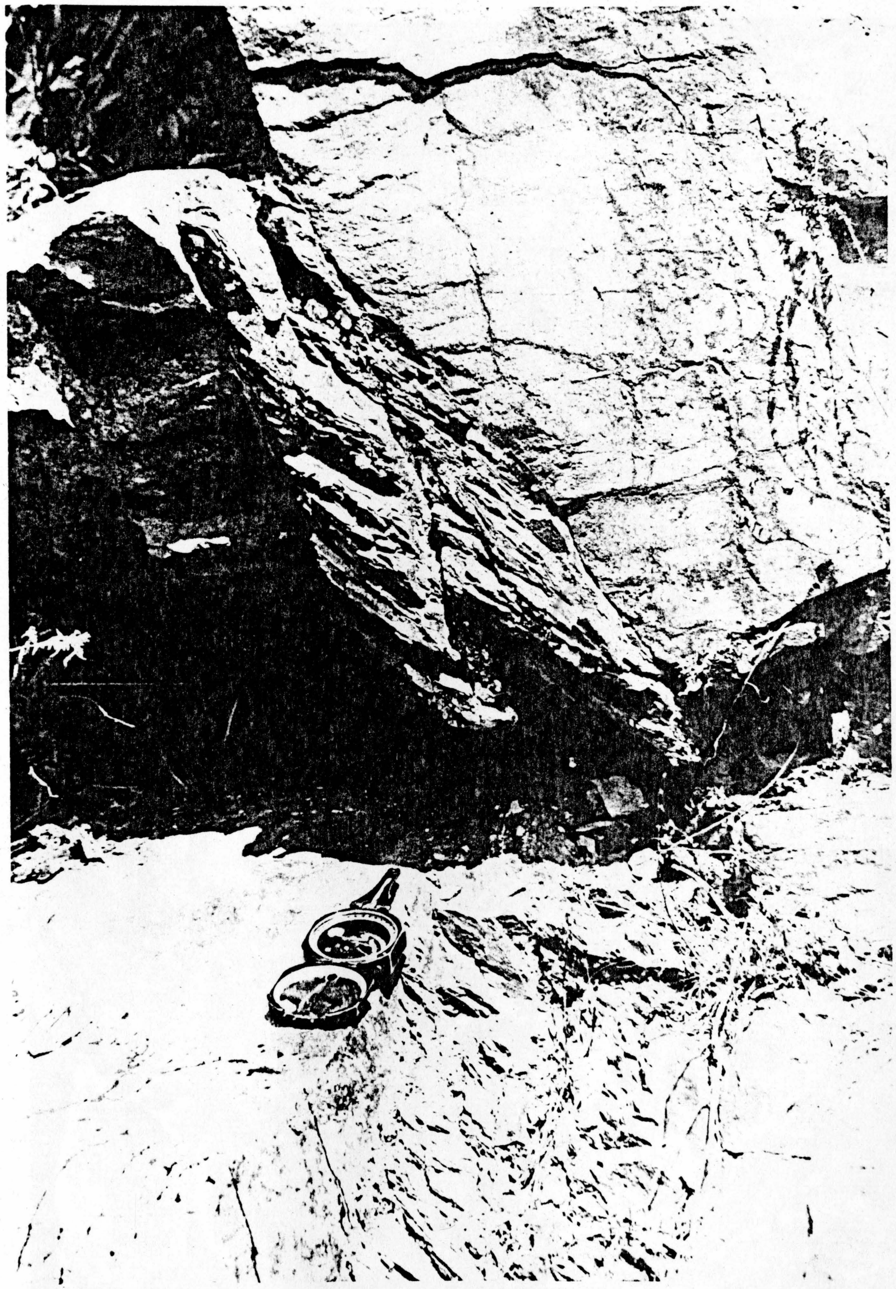
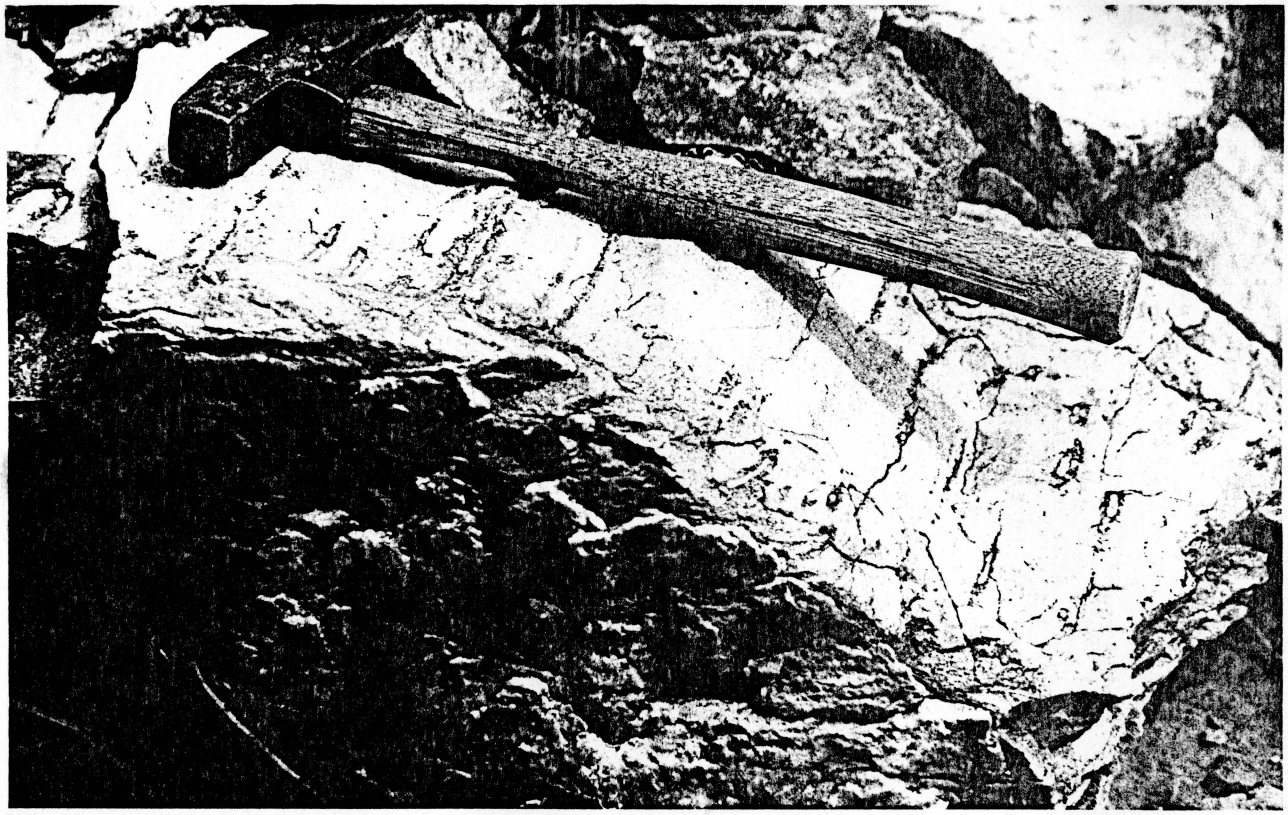


Plate 4.- Locally, discontinuous shale beds are interbedded with the quartzite beds of the Snowden. These shale beds are interpreted as being the result of channeling, ie. scouring and fill, during deposition. The discontinuous shale bed on the right is an example. Cleavage in the shale is oriented at an angle to the bedding surface of the quartzite beds (Snowden section).

Plate 5.- Cross-bedding in the Snowden is of the trough-festoon type and ranges from 7 to 15 cm in thickness (Snowden section).



Plates 6 & 7.- Scolithus tubes, the only fossil (trace fossil) found in the Snowden, are interpreted as worm burrows. These tubes are invariably oriented perpendicular to the bedding surface (Snowden section).