# QUARTZ IN PROVENANCE EXAMINATION

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# ABSTRACT

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Since 1963, when Blatt and Christie published their work on the significance of undulatory extinction and polycrystallinity in quartz in provenance examination, much of sedimentary petrology has ignored quartz as being a useful indicator of source terranes. Recent developments by Basu et al (1974) have shown otherwise. Using recent and ancient sands of known parentage they have created four variable plots based on the type of extinction and polycrystallinity of quartz. This present study illustrates the usefulness of the Basu et al (1974) scheme. First generation, medium grained sandstones from the Pocahontas coal basin of West Virginia were evaluated and it was observed that quartz from plutonic, and low and high-rank metamorphic terranes were easily discernable.

Quartz luminescence and trace elements (titanium and manganese) were also tested as possible useful indicators of source. However, at this time these techniques are of questionable reliability.

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By

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# INTRODUCTION

This paper is a study of the quartz population in sandstones from the Pocahontas coal basin. With the aid of the petrographic microscope, the luminoscope, and the electron microprobe the writer will demonstrate the usefulness of quartz in provenance examination. This is the initial purpose of this thesis. Petrographic microscope analyses will provide information as to the utilization of undulatory extinction and polycrystallinity in quartz grains as a determination of rock type derivation. The luminoscope will provide information affecting the internal structure of the quartz crystal. The internal make up should reflect any deformation that has occurred during the history of the region of study. Electron microprobe examination of the elements titanium and manganese in quartz should reproduce results about the internal geochemistry of the mineral.

The second purpose of the investigation is to establish a correlation between changes in the quartz population with possible changes in source area. Ehrlich (1964) and more recently Davis and Ehrlich (1974) performed petrographic analyses in the Appalachian Basin proper which indicated that Carboniferous material wa s eroded from a southern source into the Black Warrior Basin of Alabama and from a southeastern uplift into the Pocahontas coal fields of West Virginia. These sources were located at a position normal to the present Appalachian fold belt, based on grain size and compositional variation within the sediment. Davis and Ehrlich (1974) assumed that the source remained constant during uplift. From this assumption it was postulated that the variation in mineral composition was a function of the variation in grain size away from the source. The source rock lithology was determined on the basis of the mineralogy in the Carboniferous sediment. The source location was determined by mineralogical trends and changes in grain size within the Pocahontas basin. Davis and Ehrlich (1974) illustrated that the maturity of the total mineralogy and the average quartz size within rocks of the same facies should change linearly away from the source. The source for these sediments according to Davis (1972) was composed of four different crustal assemblages. The parent rock was a granitic batholith which was underlain by migmatites and surrounded by low to medium grade metamorphic rocks. Covering the metamorphosed material were extrusive volcanics and sedimentary debris. These rock types were diagnosed by slight (5%) difference in the feldspar and rock fragment composition. For example, samples from the upper and lower portions of the Bear Wallow core may contain similar amounts of constituents (60% quartz, 10% feldspar, 30% "others"). These samples are then described as plutonic or volcanic-sedimentary assemblages depending upon the types of feldspars and rock fragments observed. Samples were obtained selectively throughout the basin and checked as to its mineralogical content. The bulk of the sediment, quartz, was neglected in previous studies as being "non-diagnostic" (mostly through the efforts of Blatt and Christie (1963)). Blatt and Christie (1963) based their results on an inability to correlate undulatory extinction and polycrystallinity in quartz with provenance. Since then Basu et al (1974) have established interesting comparisons and have shown quartz to be a reliable indicator of provenance. Basu et al (1974) based their conclusions upon the reliability of structural and stratigraphic interpretations of the basin of deposition with the degree of undulosity and polycrystallinity in quartz. Stratigraphy and sedimentation are important as folds, faults, and dipping strata may influence or alter the quartz crystal (Connolly, 1965). Immature first cycle clastics, to be useful provenance indicators, should not have undergone severe tectonic deformation or recrystallization. These processes would change the original crystal structure and thus provide misleading information as to the mineral parentage. Sediments from the Pocahontas basin are found in the Plateau region of the Appalachians and should have undergone lesser degrees of folding and faulting than the adjacent Valley and Ridge Province. Therefore, these sediments should contain valuable information concerning provenance.

The final purpose is to establish the trace elements titanium and manganese in quartz as a means for source rock examination. Dennen (1964, 1966, 1967a, 1967b) has done extensive work with trace element chemistry and found titanium to be the most sensitive element for distinguishing source areas. Dennen et al (1970) believed that trace element substitution in a mineral results from the direct interchange of those elements most abundant in the crystal melt. This is probably true. Since $Ti^{+4}$ is about one and a half times larger than silicon, it would not substitute for silicon and should be readily exsolved during metamorphism. If this is true then the micropobe should detect such changes within and around metamorphosed areas.

By applying the above methods of analysis the following questions can be asked: Is the quartz population of the sediment in the basin changing? It is likely that if the source rock is changing then some of the examinable characteristics of the quartz will also change.

## Area of Study

The area involved in this study is the Pocahontas coal basin of West Virginia and Virginia. According to Davis and Ehrlich (1974) the region is one of several Carboniferous basins which form the Appalachian Basin Proper. The Black Warrior basin and the Canadian Maritime Province are similar late Paleozoic depocenters (davis and Ehrlich, 1974).

The Pocahontas basin is bordered on the east and southeast by the Appalachian fold belt. The great majority of the sediments of the area are restricted to the Allegheny Plateau and are affected by the Appalachian orogeny to a lesser degree than those in the Valley and

Ridge Province. The basin is asymmetrical to the east and southeast. According to Davis (1972), the maximum thickness of the Carboniferous sediments in the basin rarely exceeds 3000 feet. The sediments are thickest in the southeast and thin towards the northwest (Galloway et al 1972). Although the stratigraphy of the basin is not well defined it is assumed that the outcrop strata in the northwestern portion of the area of deposition are Chesterian through Monongahellan in age, while the units in the southeast are mostly Lower Pottsville (White, 1903). Most of the sediments are low angle and flat lying detrital rocks which include several sedimentological facies. Periods of transgression and stable shorelines are indicated by these marine and transitional rocks (Englund, 1971). Three facies predominate the basin; they are as follows: 1. fluvial deltaic sands; 2. back barrier-lagoon facies; 3. barrier bar orthoquartzites (Davis and Ehrlich, 1974). The barrier bars are pure quartz sandstones underlain by offshore red and green shales. One of those shales, the Bluestone equivalent of the Mauch Chunk Group, was used as the lower limit for sampling as they were very easy beds to identify. The barrier bars are linear structures trending northeast to southwest (Ferm et al, 1965). Normal to and eastward from the orthoquartzite lenses are lobate sedimentary structures composed of immature graywacke sandstones and siltstones. Englund (1971) interprets these as fluvial and alluvial distributary channels of a major delta complex. The strata composed of interbedded siltstones, clays, and coals are from barrier, lagoonal and upper tidal flat environments.

The coal is quite thick, very abundant and highly economically minable. Of the major coal seams mined in the area of study, the Pittsburgh-Waynesburg, The Sewell, Pocahontas #3 and #4, Number 5 Block and Eagle Coals are probably the most well known (Davis, 1972). The stratigraphy appears to suggest a lateral sequence of deltaic and beach barrier facies prograding to the northwest.

Davis (1972) and Ehrlich (1964) believe that the eroded sediments are remnants of an east-west trending mountain chain (not unlike the Ouachita Mountains) rather than sands from different disturbances of the Appalachian orogeny. This paper is not to challenge the credibility of this concept, but to verify the type of source area which they discussed.

The samples observed were lithic, feldspathic lithic and sublithic sandstones averaging 1.5 - 2.0 ∅ in grain size. These medium grained sands contain various proportions of quartz, plagioclase, muscovite, chlorite and metamorphic, volcanic and sedimentary rock fragments. Depending upon the source of the rock, orthoclase, microline, perthitic and non-perthitic K-feldspar and biotite were also observed.

## A REVIEW OF QUARTZ IN PROVENANCE EXAMINATION

For a mineral to preserve information about its past that individual must be abundantly available in the sediment, mechanically durable to survive constant abrasion and transportation, and chemically stable as to not be dissolved by weathering. The mineral quartz fulfills these requirements and should contain a wealth of information concerning provenance examination. Quartz is the most abundant terrigenous mineral in sandstones and comprises 21% of the earth's crust from which it redistributes itself to an average of 30-65% in sandstones, 30% in shales, and 5% in carbonate rocks (Blatt, Middleton and Murray, 1972, p. 270). Much of this quartz is the result of reworked sediments originating from plutonic and metamorphic terranes. Volcanic and hydrothermal quartz, although not as common as plutonic quartz, is also an important constituent in provenance studies. Volcanism is associated with major tectonic movements which can cause increased erosion and sedimentation, and therefore, can play a major role as a sedimentary source.

Quartz is also one of the most durable common minerals. Most other minerals in sedimentary rocks exhibit softer and weaker features (i.e. cleavage planes). As other constituents become abraded and obliterated, quartz remains to become the dominant mineral in most sandstones.

Since quartz is an abundantly available, very durable and chemically stable mineral, which parts of the crystal should contain the most and easiest obtainable bits of information? The internal structure of the mineral should indicate the effects of the mechanical and chemical stability of each grain (Blatt and Christie, 1963; Blatt, 1967a; 1967b). The degree of undulatory extinction in quartz should reflect the strain history of the crystal. Undulose extinction is... "the amount of angular separation between the c-axis and different parts of the (quartz) crystal (Blatt, Middleton, and Murray, 1972, p. 271)." This wavy shadow is commonly thought to be the result of plastically deforming the crystal lattice by folding or faulting on the microscopic scale. Undulosity may also reflect upon the durability of the grain. Those grains which are monocrystalline and display undulose extinction are less mechanically stable than non-undulatory or straight extincting monocrystalline grains (Blatt, 1967b, p. 1035). It is also commonly thought that most quartz grains with non-undulatory extinction are from igneous origins. Those with strong wavy patterns are from metamorphic terranes.

## A History of Quartz in Provenance Studies

The polarizing microscopic work by Sorby in the late nineteenth century was the beginning of modern sedimentary petrology. Sorby (1877, 1880) was the first to describe and publish about the internal structure of quartz. He investigated grain shapes and sizes and tried to relate them to source area. For example, those quartz grains which were elongated in shape and polycrystalline in number were derived from metamorphic terranes whereas the monocrystalline and equidimensional varieties were determined to be of plutonic origin. Van Hise (1890) was slightly more sophisticated in his work and contributed to the study of quartz by being the first to describe undulatory extinction along with polycrystalline grains in the rock specimen. Van Hise tried to illustrate that undulatory extinction was the result of pressures which quartzose rocks underwent during low grade metamorphism. Rosenbusch in 1893 realized that undulatory extinction and polycrystalline grains were not restricted to metamorphic terranes but were also found in granitic plutons. Mackie (1896) was the first to describe and classify inclusions in quartz. This work along with observing extinction types later proved to be a valuable tool for others in their search for provenance. Although undulatory extinction, polycrystalline quartz and inclusions were used to infer source area, it was not until 1919 when Gilligan examined the Millstone Grit of Yorkshire that these properties became seriously used as indicators of source terranes. Sandstone petrology and its relationship to provenance remained at a standstill from the early 1920's to the early 1940's. Krynine (1940) revived this branch of geology when he combined Mackie's (1896) inclusion classification with Gilligan's (1919) work on undulatory extinction. The end result was a new "genetic" classification. Initially Krynine's (1940) ideas were based on seven polycrystalline and undulatory extinction types. In 1948 he revised his classification to include three types of igneous varieties, two species of metamorphic quartz, and a single example of both hydrothermal and volcanic quartz. The new system was based on the number of crystals per grain and crystal shape as well as the amount of undulatory extinction and inclusion varieties.

Tuttle (1952) and Gilbert (1954) revived Rosenbusch's (1893) ideas by illustrating that undulatory extinction need not be restricted to metamorphosed rocks but may also be found in igneous plutonic environments. By 1961, Folk had modified Krynine's ideas and created an "emperical classification" scheme . This is an objective system which assigns quartz grains to environments based on six types of undulatory extinction and grain morphology as well as four descriptive kinds of inclusions. Twenty-four arbitrary divisions which loosely correlate to Krynine's classification were created (Folk, 1961). Folk concluded that most non-undulatory quartz is of plutonic origin. Quartz grains which are strongly undulose originate almost entirely from gneises. Elongate polycrystalline quartz with straight extinction and bubble inclusions are hydrothermal and metamorphic. As one can see, quartz varieties, in many cases, are not limited to individual environments of formation. Folk also emphasized setting the boundary between non-undulose and strongly undulose quartz at $5^{\circ}$ of flat stage rotation. This decision terminated the arguments of Hubert (1960) and Andresen (1961). Hubert (1960) believed the boundary to be 25° while Andresen (1961) insisted that 30° be the correct distance of flat stage rotation. However, Blatt and Christie (1963) and Blatt (1967a; 1967b) denounced the use of the flat stage in undulosity determinations, as the actual angle of deviation from the c-axis is not demonstrated. They insisted that the universal stage be used in measuring the true angle of undulatory extinction. Since undulatory extinction and polycrystallinity occurs in many different environments, Blatt and others feel that quartz is not a reliable indicator of source terrane. Their results were based on the observation of mature and immature quartz as well as grusses from several different localities.

Connolly (1965) found that the different quartz varieties could be useful in provenance studies if the structure and stratigraphy of the area in question was known. Post depositional diagenesis, folding and faulting can effect the amount of undulatory grains in mature sandstones. Therefore, according to Connolly (1965), it is important that detailed studies of sandstone formations be performed prior to any use of quartz as a source indicator. The detailed studies should include information as to the vertical as well as lateral extent of the sand deposit.

Basu et al (1974) reevaluated Blatt and Christie (1963) ideas about the use of undulatory extinction and polycrystallinity in source rock examination. They observed more samples than the earlier (1963) study and limited their work to first generation immature detrital components from known source terranes. Universal and flat stage examinations were performed on each sample. The results were compared and found compatible with each other. Their observations revealed that in most cases the angle of extinction as determined on the flat stage was very near that obtained on the universal stage. Basu et al (1974) have determined that accurate provenance interpretations can be made on the flat stage. Their study incorporated the use of two types of undulatory extinction ($\leq 5^{o}$ rotation and $> 5^{o}$ rotation) and two varieties of polycrystalline quartz ($\leq 3$ and $> 3$ crystals per unit grain). These quartz characteristics can enable one to discern plutonic quartz from metamorphic quartz. Basu et al's (1974) study was limited to only the medium sand size fraction of first generation sandstones which have not undergone any severe post depositional tectonism or recrystallization. Blatt (1963; 1967a; 1967b) and others did not restrict the limitations of the samples and thus obtained nonproductive results. Also, Basu et al studied more samples in their limited range than did Blatt and Christie (1963).

## Other Useful Characteristics of Quartz

Until now most of the discussion about quartz has been limited to the undulosity and polycrystallinity of the grains. The mineral also has other characteristics which may prove helpful in determining the type of source terrane from which it originated.

Inclusions within the quartz crystal may help determine provenance. However, difficulty arises in correctly identifying the inclusion mineral as to its type and origin. For example, many common mineral inclusions (i.e. rutile) have multiple origins (Blatt, Middleton, and Murray, 1972). Folk (1961) classified inclusions into four categories. They are as follows: 1. abundant vacuoles; 2. needlelike minerals; 3. microlites; 4. few or no bubbles. Those specimens displaying abundant bubbles appear milky in reflected light. The bubble inclusions may be water, water and gas, or gas filled. This variety of inclusion may be indicative of vein quartz. Rutile and other needlelike mineral inclusions are not restricted to a single environment of formation. They may be produced in plutonic and metamorphic assemblages. Microlites are mineral inclusions other than the needlelike variety. They too are created in several environments. Vermicular chlorite is thought to originate in vein quartz. Those grains which contain few or no bubbles are common to all kinds of quartz. Katz et al (1970) demonstrated that linear planes of bubbles (called bubble trains) are healed fault boundaries within the crystal and may not be representative of a particular source rock. Also, if a grain is void of any inclusions and appears water clear, then the quartz may be volcanic in origin.

Dake (1921) and Feniak (1944) studied the relationship between quartz crystal size and plutonic and metamorphic origin. Coarse monocrystalline grains were thought to be of massive plutonic origin. Fine and very fine monocrystalline specimens were thought to be derived from schists. Silt size monocrystalline quartz was believed to be indicative of slate and phyllite origin.

The trace chemistry of quartz can vary between plutonic and metamorphic sources as was shown by Dennen (1964). One should be able to utilize these differences to obtain information as to the heritage of the eroded sediments. Iron, Magnesium, manganese, titanium, aluminum, calcium, and sodium are some of the more common trace elements found in quartz. Dennen (1964; 1967a; 1967b) has shown titanium to be the most interesting and possibly most indicative trace element because of its universal presence in all rock types. Titanium can not substitute directly with silicon in the $SiO_2$ lattice. Such a substitution should drastically deform the crystal because $Ti^{+4}$ is nearly twice the size of $Si^{+4}$ (Kuntz, 1936). The titanium for silicon replacement is common and should provide excellent information as to provenance, especially if the rocks have been subjected to different degrees of metamorphism (Kuntz, 1936). The application of the electron microprobe should be able to correlate changes in source with changes in trace element content.

Smith and Stenstrom (1965), Sipple (1968) and Sibley and Blatt (1974) have demonstrated the usefulness of quartz luminescence in sandstone petrology. Quartz can luminesce red or blue depending upon the trace chemistry within the crystal. The previously mentioned authors have demonstrated this technique's usefulness in observing diagenetic features as well as the internal structure of quartz. The present writer hopes to establish a correlation between quartz luminescence and provenance examination.

## QUARTZ VARIETIES

As previously noted in an earlier chapter, several petrologists (Krynine, 1946; Folk, 1961; Basu et al 1974...) have attempted to correlate quartz types with environments of formation. These were made on grain shape analyses, inclusion types, and grain extinction. Unfortunately, several common quartz varieties with those characteristics originate in many widely ranging source terranes. It is not uncommon to observe monocrystalline quartz with straight extinction, and a few bubble inclusions in plutonic, recrystallized, metamorphic or hydrothermal vein bodies (Blatt, Middleton, Murray, 1972, p. 276).

Some quartz crystals, however, do have identifiable characteristics obtained solely from an individual parent rock. These features, as well as the more common signs, will be described in the following paragraphs.

Quartz displays three very easily identifiable distinguishing characteristics. They are as follows: 1. polycrystallinity; 2. extinction varieties; 3. inclusion types within each grain. Folk (1965, p. 76) has shown that the first two categories are cyclic and compose the "quartz continuum" (Figure 1). To illustrate this, note that granitic quartz can originate as a monocrystalline grain with straight extinction. Upon increased pressure and temperature the grain can alter to a polycrystalline-undulatory metamorphic form. Vein quartz is often highly undulose due to stresses evolved

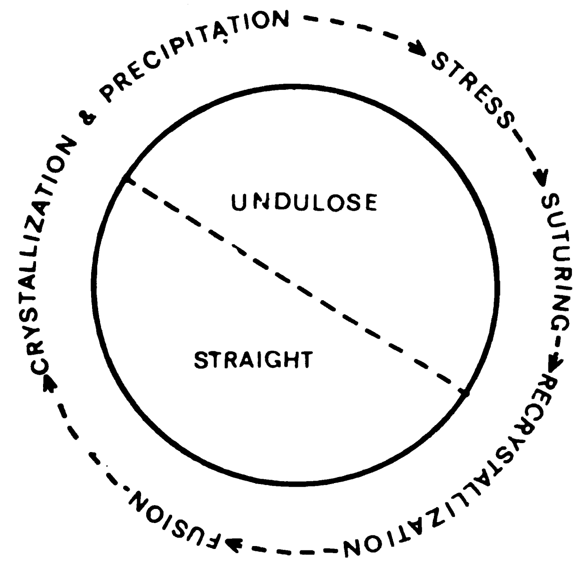



Figure 1 The Quartz Continuum (After Folk, 1965, p. 76)

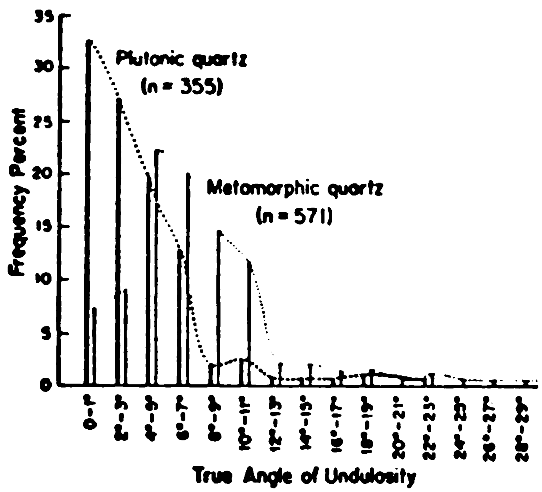



Figure 2 Histogram showing the distribution of true angles of undulosity in detrital quartz of plutonic and low-rank metamorphic parentage. Values based on univeral stage measurement. (After Basu et al, 1974)

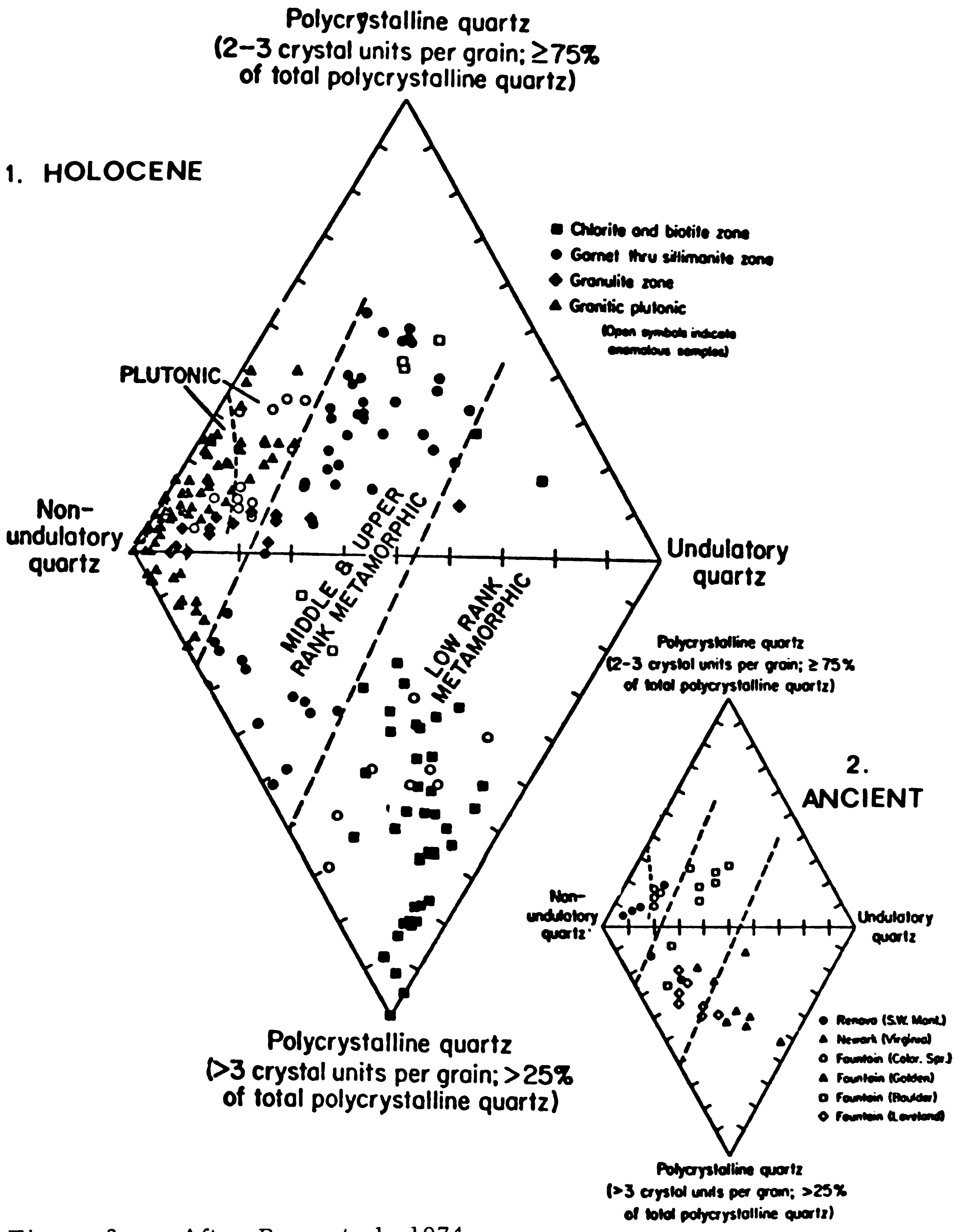



Figure 3 After Basu et al, 1974

as the quartz crystallizes in a confined area. Monocrystalline non-undulose quartz is also common in volcanic rocks. The continuum is a five step process which involves the crystallization, precipitation, and recrystallization of the mineral (Figure 1).

Basu et al (1974) recently studied over 200 samples including more than 8000 individual quartz grains from recent and ancient first generation sandstones of known parentage. The percentage of the above mentioned characteristics was determined for each sample. Undulose extinction observations on the universal stage were compared with that done on the flat stage. The results compared favorably 93% of the time, thus verifying the usefulness of quartz undulosity on the flat stage in provenance examination. The present author, therefore, incorporated this method as well as Folk's inclusion scheme to his inquiry about the Pocahontas coal field source terrane. The conclusions made by Basu et al (1974) enabled a diamond shaped, four-variable plot to be developed. This diagram (Figure 3) illustrates the capabilities of quartz as a source rock indicator.

<u>Polycrystalline Quartz</u>

Several petrologists (see previous chapter on History of Quartz in Provenance Study) have observed that most quartz varieties contain some polycrystalline grains. The same is true for undulatory and non-undulatory quartz; they are found in many source terranes. However, Basu et al (1974) found that plutonic quartz has fewer ( ≅13%)

polycrystalline grains than metamorphic quartz in the medium sand size range. Low grade metamorphic quartz is composed of 53% polycrystalline grains whereas the higher grade varieties contain 29% polycrystallinity. Of those specimens from plutonic and high grade metamorphic origin, it was observed that greater than 75% of the polycrystalline quartz contained three or fewer crystals. The crystals were subsequent in size and shape. Low grade metamorphic polycrystalline grains were multimodal in morphology, and were usually ( >75%) composed of more than three individuals. Although high grade metamorphic and plutonic quartz are similar in morphology, the different percentages of polycrystallinity in each is enough to distinguish the two. The type of grain boundary (sutured or non-crenulated) appears to play a very minor role in distinguishing plutonic from metamorphic quartz. Both varieties are displayed in each source.

## Monocrystalline Non-undulose Grains

Five degrees of extinction was selected as the boundary between undulose and straight extinction on the basis of the major changes in slope between histogram plots of plutonic and metamorphic frequency curves (Figure 2). Basu et al (1974) found monocrystalline and non-undulatory quartz to be most frequent ( $\approx$ 80%) in plutonic grains and slightly less plentiful in high rank metamorphic quartz (45-78%). Low grade metamorphic quartz contains the least amount of the single crystal-straight extinction variety.

## Monocrystalline Undulose Grains

Increased strain by structural deformation causes an increase in the degree of undulosity in quartz grains (Folk, 1965, p. 76). However, increasing the strain beyond the fracturing point may cause recrystallization and fusion of the deformed grain. Therefore, it is not uncommon to observe the greatest amount of undulatory quartz from low rank metamorphic terranes and a decreasing amount in high rank metamorphic and plutonic sources respectively. Basu et al (1974) verified this hypothesis.

## Inclusion Types

As previously mentioned, Folk (1965) derived four basic types of inclusions: 1. abundant bubbles; 2. needlelike minerals; 3. mineral inclusions other than needle-like; 4. and few vacuoles. The author used these inclusion types to enhance the results obtained from the Basu et al (1974) extinction scheme. Most varieties can be correlated with the few bubbles category (Blatt, Middleton, and Murray, 1972, p. 276). Bubbles are pockets of gas or liquid in the crystal lattice. Parallel planes of the vacuoles (called Bohm lamellae) are healed fracture zones. Nearly all sources contain quartz with few vacuoles. Needlelike inclusions are commonly found in metamorphic as well as plutonic terranes (Folk, 1965). One of the more common hairlike mineral inclusions is rutile, a common plutonic mineral. Microlites are mineral inclusions other than the hairlike specimens. They may include micas, feldspars, tourmaline, epidotes, as well as others. Metamorphic quartz is indicated by inclusions of sillimanite, chlorite and other micaceous minerals.

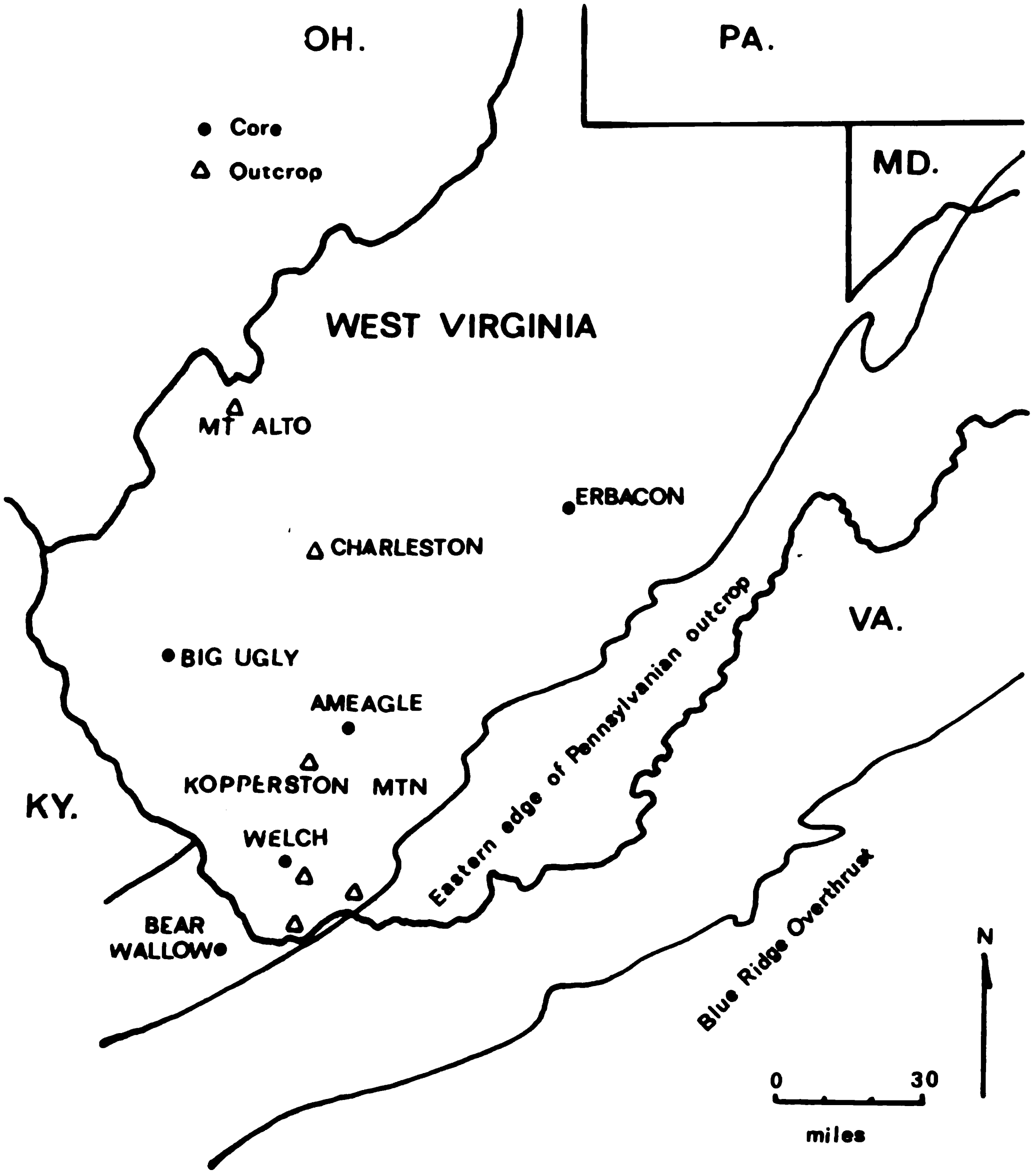
Vermicular chlorite is normally the rare microlite found in vein quartz (Folk, 1965). Abundant bubbles are probably the most characteristic diagnostic feature of vein quartz. These inclusions usually give hydrothermal quartz a "milky" appearance.

Volcanic quartz displays an unusual combination of a lack of inclusions along with a distinctive crystal shape. The crystal grows at very high temperatures and forms the unstable beta quartz. Upon cooling the crystalline magma below 573°C the beta variety inverts to the low temperature crystal (alpha quartz) (Blatt, Middleton, and Murray, 1972). The beta to alpha conversion may or may not reorient the crystal shape as many quartz grains in granite display the beta outline. According to Folk (1961), these crystals are monocrystalline, bypyramidal and hexagonal with straight edges and rounded corners. Occasionally, the edges are structurally corroded and show partially enclosed holes. Almost all specimens are non-undulatory and water clear.

# METHODS AND PROCEDURES

## Sampling Plan

Although carbonate rocks are found in the basin of study, only sandstones and conglomerates were collected for analyses. All facies within the basin were included in the collection. The original study by Davis (1972) was a determination of the mineralogy of the detrital components and its relationship to source area. This paper, because it is an extension of Davis' (1972) work, will employ her sets of samples. Rocks were obtained entirely from cores and recently exposed outcrops. It was important that the outcrops be fresh as not to destroy any unstable and immature components by weathering processes. Davis' (1972) samples included detrital sandstones from six cores provided by several coal and gas companies. The writer has utilized only three of those cores as the others were unavailable for examination. The sections used were from the Ameagle, Erbacon and Big Ugly cores. The Ameagle and Erbacon cores were obtained from the areas near towns bearing those names in West Virginia (Figure 4). The Big Ugly core was drilled and cut near Leets, West Virginia and named for the Big Ugly Public Hunting Area. (Davis, 1972, p. 85). Outcrops were used as vertical extensions of the cores. This was essential in correlating the stratigraphy of the area. The Kopperston Mountain samples were obtained from a hill




GEOGRAPHIC LOCATION OF CORE AND OUTCROP SAMPLES

Figure 4 (Modified after Davis, 1972, p. 8) along West Virginia Rt. 85 near Ameagle, West Virginia and the Mt. Alto rocks are from West Virginia Rt. 2 near Millwood, West Virginia (a town near the Ohio-West Virginia border) (Davis, 1972). These samples were later cut and made into thin sections. The original slides were labeled like the following example: E-13-6. The letter E designates the Erbacon core; the thirteenth sand body from the base; and the sixth sample taken within that sand. This procedure was repeated for all slides made from the cores and outcrops. Slides for this present study were recut from the same rocks but each sample was purposely chosen. The number of slides chosen was based on Davis' findings. Samples that showed the maximum, minimum and average quartz and "other" compositions were used and considered representative of the entire column. Approximately thirty thin sections were examined. Prior to gluing the slabs to the glass, the samples were recorded and renamed as to conceal their true identity. This procedure was to insure an honest and unbiased study of the detrital components. The thin sections were then analyzed with the aid of the petrographic microscope, the luminoscope and the electron microprobe.

## Petrographic Microscope Work

A leitz polarizing petrographic binocular microscope was used to determine the composition of the rocks in question. Each thin section was point counted a minimum of 400 grains during which 100 point intervals were used as a components percentage check. The rocks were then termed according to McBride's (1963) classification scheme. This was done by determining the percentages of quartz, feldspar, and "others" components within the rock slab. The "others" included rock fragments and all non-quartz or feldspar minerals (which included micas, pyroxenes, amphiboles, zircons and other "heavy minerals"). A few of the thin sections were etched with hydrofluoric acid. This process enabled the writer to better distinguish the untwinned feldspar and quartz.

Upon the conclusion of this process the writer then performed the re-evaluation of the quartz types involved. This was done by counting a minimum of 300 quartz grains per slide. These quartz fragments were classified as being non-undulatory, undulatory, polycrystalline with less than three crystals per grain and those with greater than three crystal units. All extinction angles were determined on a flat stage. Specimens which Folk (1961) would term semi-composite and composite were classified undulatory or polycrystalline based upon appearance. The highly fractured and "stressed" grains were called polycrystalline. The remainder were described as undulatory grains. These quartz grains were then plotted on a grid which is a modified version of the Folk (1961) and Basu et al (1974) classification schemes. The results of this work will be shown in a later chapter.

Upon the completion of quartz extinction determinations a third point count test was initiated. The percentage of inclusion types was

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was determined on the basis of 150 point counts per slide. Folk (1961) felt that if the inclusion types and extinction angles were known, provenance determination may be possible. The inclusions that were listed are as follows: abundant vacuoles (bubbles), rutile needles, microlites (mineral inclusion other than those with a needlelike appearance) and few bubbles.

## Luminoscope Determinations

The cathodoluminescence techniques are relatively new in sedimentary petrology. The instrument used is called the Nuclide Luminoscope and consists of a vacuum chamber, a high voltage control unit and a cold cathode electron gun. Samples are irradiated with an electron beam which excites electrons in the sample and causes luminescence. Those grains that luminesce are usually impure crystals in which the impurity acts as the luminescing center.

No special slide preparation other than polishing is necessary for the luminoscope work. All observations were made without the cover slips on the slides.

The luminoscope was used solely for the identification of quartz individuals. Quartz, because of impurities within its chemical and physical make up, can luminesce red, blue, or a mixture of the two, probably depending upon the percentage of the trace elements within. The trace element titanium is thought to cause some quartz varieties

to glow blue. The lack of this element produces redder specimens. Further discussion about the meaning of red versus blue quartz will be examined in a following chapter.

A minimum of 200 grains of quartz per slide were counted and determined to be red or blue. This process was repeated and checked three times. Upon completion of this step each thin section was again reviewed with the polarizing microscope in search of non-undulatory monocrystalline quartz grains. Thirty of these un-marred specimens were then marked, mapped, and drawn as to insure easy re-identification. These thirty grains were then restudied with the luminoscope and labeled red or blue.

Electron Microprobe

One of the purposes of this study is to use the electron microprobe to establish the occurrence of titanium and manganese in quartz as a reference standard for local provenance examination.

Because of the limited availability of the microprobe, the number of premarked slides to be observed was reduced from the original number to four. The slides that were chosen for observation are those which should have shown the maximum variation in Davis' (1972) source rock. Each thin section was placed in a similar orientation to that seen under the petrographic microscope. This was to insure a known location and identification for each of the thirty grains per slide. Each specimen was checked for the amount of manganese and titanium in counts per 20 seconds of time. Standards and background estimates for rutile and rhodocrosite were obtained prior to and following the analysis of the samples. The analysis was set to record data when the microprobe was set at 25 KV and .02 mA.

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# DISCUSSION AND RESULTS

## Petrography

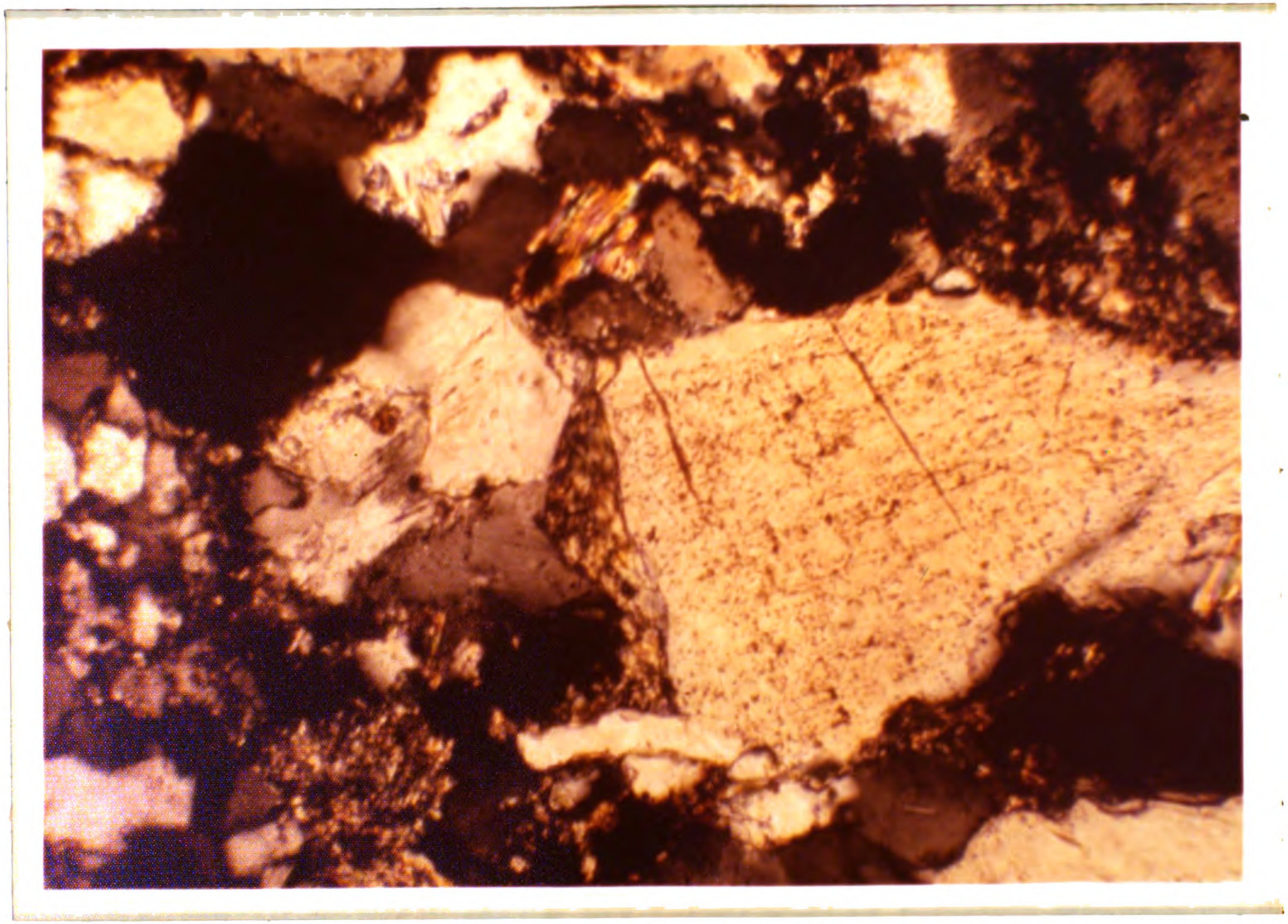
Each core was described petrographically as to the content of its mineralogy. This was done prior to any observation and discussion of quartz types. These results can be seen in Table 1 and are similar to those derived by Davis (1972). All reviewed samples within the cores were point counted to obtain the percentage of quartz, feldspar, and "other" constituents. This information was then plotted according to McBride (1963) and each slide was classified as to a sandstone type (Figure 6).

The majority of the petrographic work was concerned with the ability to distinguish a change in quartz population between different source terranes. The usefulness of this is to establish the different quartz types as reliable source indicators. At the time when the rocks were renamed two sets of slides were randomly duplicated and recorded. The purpose of this was to assure the reproducibility of the author's results. Slides L and F and K and M are from the same samples respectively. Figures 2 and 3 illustrate that the samples in question were unbiasedly plotted and classified in close approximation to each other. This indicates that the results were reproducible with some degree of accuracy.

The Basu et al (1974) classification of quartz and Folk's (1961) scheme for inclusions in quartz were followed. Percentages of the

| SAMPLES | Perthite | Orthoclase | Plagioclase | Microcline | Muscovite | Biotite | Chlorite | Quartz | Coal | V.R.F. | M.R.F. | Chert | Calcite | | Many Bubbles | Needles | Microlites | Few Bubbles | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Big Ugly** | | | | | | | | | | | | | | | | | | | |
| O; CH–6–3 | • | • | • | • | | | • | • | | | • | | | | – | c | b | a | |
| D; CH–4–3 | • | • | • | • | | | • | • | | | • | | | | d | c | b | a | |
| H; CH–3–2 | • | • | • | • | • | • | • | • | | • | • | • | • | | c | c | b | a | |
| A; CH–2–1 | • | • | • | • | • | • | • | • | • | | • | | | | – | – | b | a | |
| **Erbacon** | | | | | | | | | | | | | | | | | | | |
| C; E–13–6 | | • | • | • | • | • | | • | | • | • | • | | | d | c | b | a | |
| K&M; E–13–4 | | • | • | • | • | • | | • | • | • | • | • | | | a | c | d | b | |
| G; E–11–6 | | • | • | • | | | • | • | | • | • | • | | | c | c | b | a | |
| E; E–11–3 | | | • | | | | | • | | • | • | • | | | d | b | b | a | |
| R'; E–11–2 | | | • | | | | | • | | • | • | • | | | – | c | b | a | |
| Q; E–9–1 | | • | • | • | • | • | • | • | | • | • | • | | | c | d | b | a | |
| N; E–7–2 | | • | • | | • | • | • | • | • | • | • | • | | | b | c | d | a | |
| J; E–6–2 | | | • | | • | • | • | • | | | • | | | | – | – | b | a | |
| F&L; E–4–3 | | | • | | | | | • | • | • | • | • | | | d | b | b | a | |
| I; E–3–2 | | • | • | | • | • | | • | | • | • | • | | | – | – | b | a | |
| U; E–1–2 | | • | • | • | • | • | | • | | | • | | | | c | b | c | a | |
| B; E–1–1 | | • | | • | | | | • | | • | • | • | | | – | c | b | a | |
| **Ameagle** | | | | | | | | | | | | | | | | | | | |
| 3; R–9–3 | • | • | • | • | • | • | • | • | | | • | | | | – | c | b | a | |
| 2; R–5–1 | | • | • | | • | • | | • | | • | • | • | | | – | – | b | a | |
| 1; R–1–5 | | • | • | | • | • | • | • | • | • | • | • | | | d | c | b | a | |
| **Kopperston Mtn** | | | | | | | | | | | | | | | | | | | |
| 6; Kp–9 | • | • | • | • | • | • | • | • | | • | • | • | | | d | c | b | a | |
| 5; Kp–4 | • | • | • | | • | • | • | • | | • | • | • | | | d | b | c | a | |
| 4; Kp–1 | • | • | • | • | • | • | • | • | • | • | • | • | | | d | b | e | a | |
| **Mt Alto** | | | | | | | | | | | | | | | | | | | |
| 8; MA–5 | | • | • | | | • | • | • | | | • | | • | | – | b | – | a | |
| 7; MA–1 | | | • | | | • | • | • | | • | • | • | | | – | b | – | a | |

Table 1. Sample composition and variation



10 X

Figure 5. Observation of a typical thin section from the Pocahontas Coal Basin

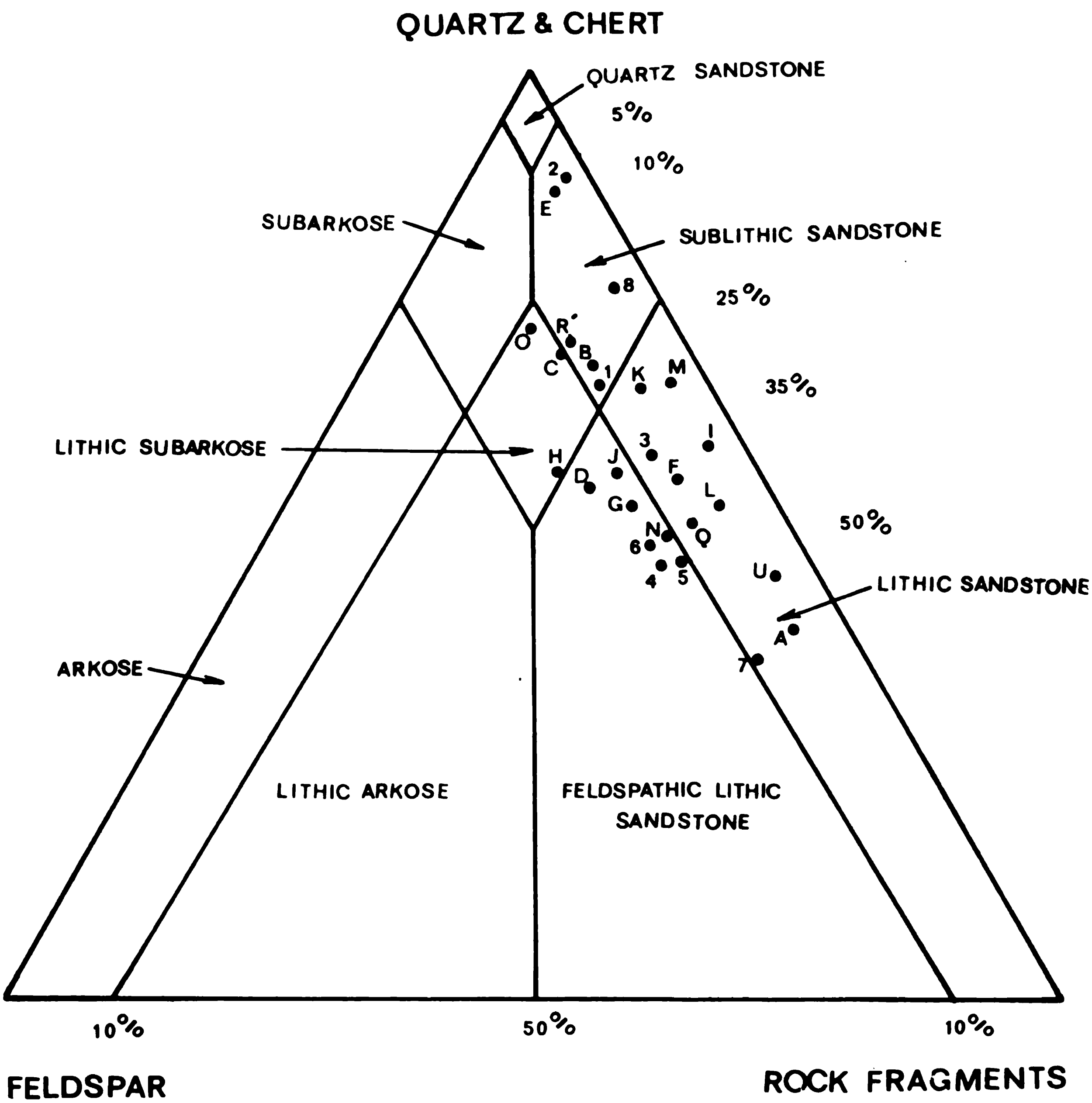


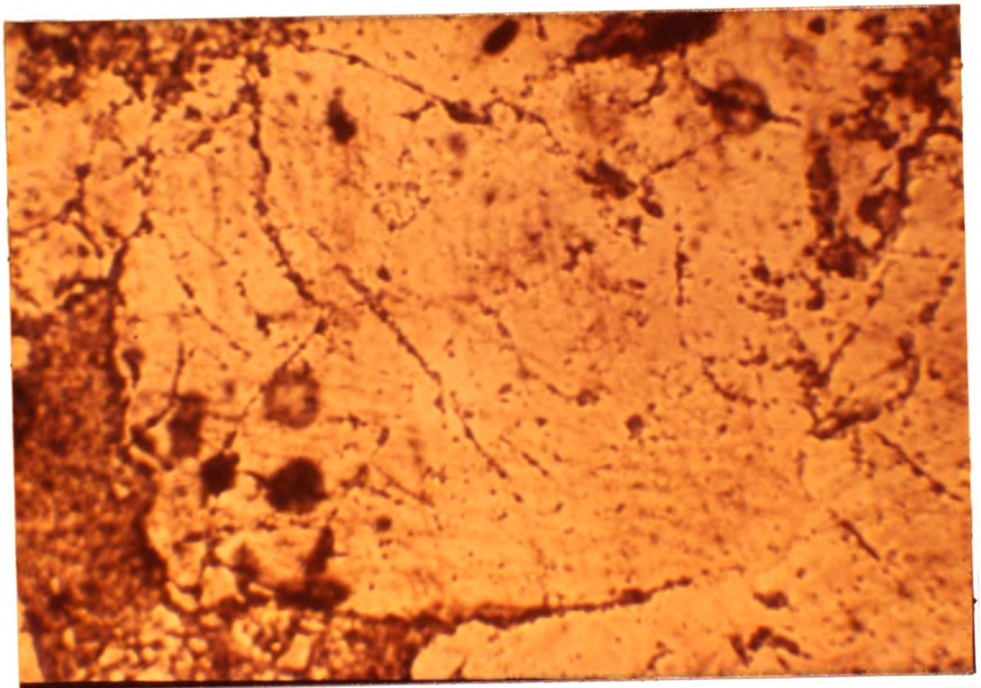

Figure 6 McBride's Classification of Sandstones

quartz types were determined and plotted (Figure 9). Five degrees of stage rotation was determined (by Basu et al, 1974) the boundary between undulose and straight extinction in monocrystalline quartz. Polycrystalline quartz was divided into two categories. The polycrystalline varieties with greater than three crystals per unit grain were separated from those grains containing fewer than three crystals. "Composite" quartz was also observed. Composite quartz appears to be a transitional grain between strongly (but irregularly) undulose quartz and polycrystalline quartz with "smeared" crystals (Figures 7 and 8). These specimens were divided into the undulose and polycrystalline varieties based upon the appearance which it more closely resembled. A second plot was performed totally classifying the composite quartz as polycrystalline. Both diagrams resulted in similar conclusions, as the amount of composite quartz was negligible when compared to the other varieties.

The results obtained from the plotted data closely, but not exactly, resembled that observed by Davis (1972) (Figure 9). All slides were described randomly, not stratigraphically, as to insure a non-biased interpretation of the data. Knowing that the stratigraphic interval would have influenced the results, Figure 9 shows the proximity of this author's conclusions to those produced by Davis (1972). Some samples produced unusual results. For example, R' is abnormal because Davis (1972) interpreted this slide

Figure 7a Quartz specimen as seen under uncrossed nicols.

Figure 7b The same quartz grain as seen under crossed nicols is illustrating a typical composite undulatory specimen.



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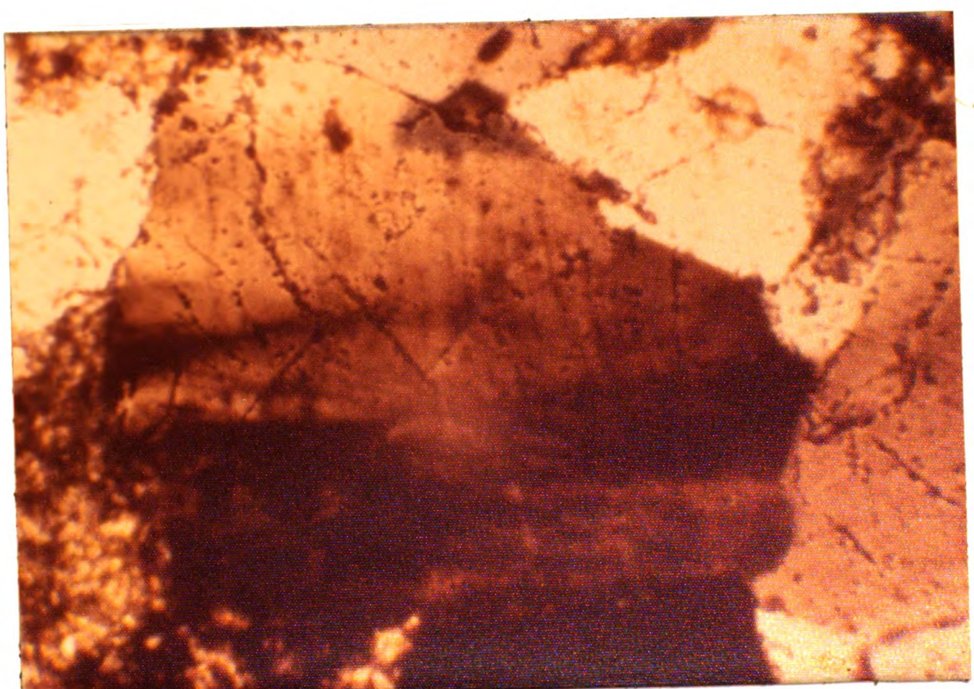

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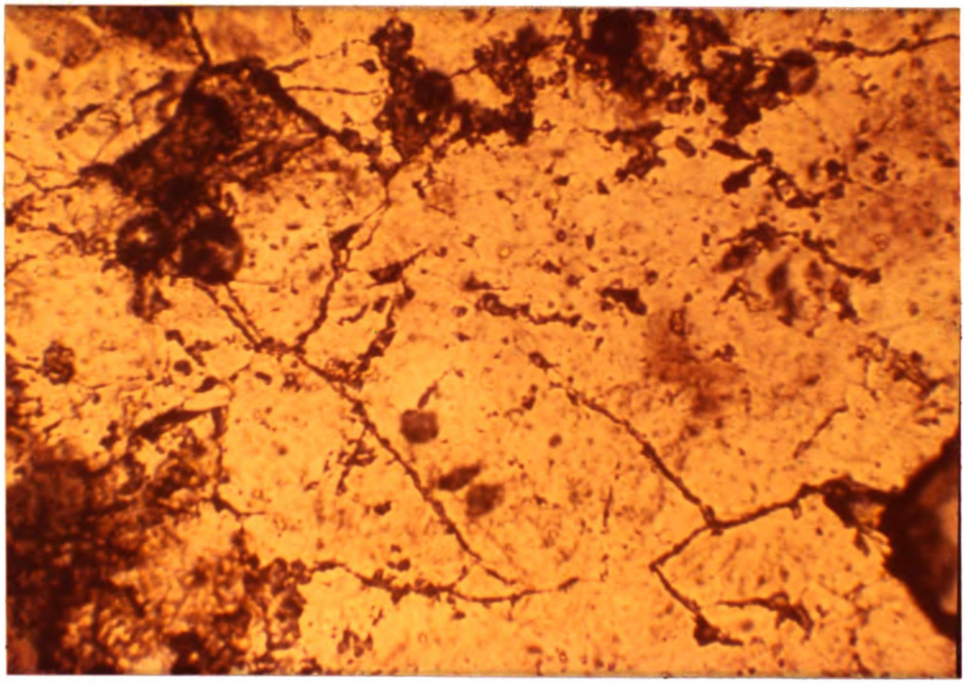
7B

Figure 8a Quartz specimen as observed under uncrossed nicols.

Figure 8b The same quartz as observed under crossed nicols. This specimen is of the composite polycrystalline variety.



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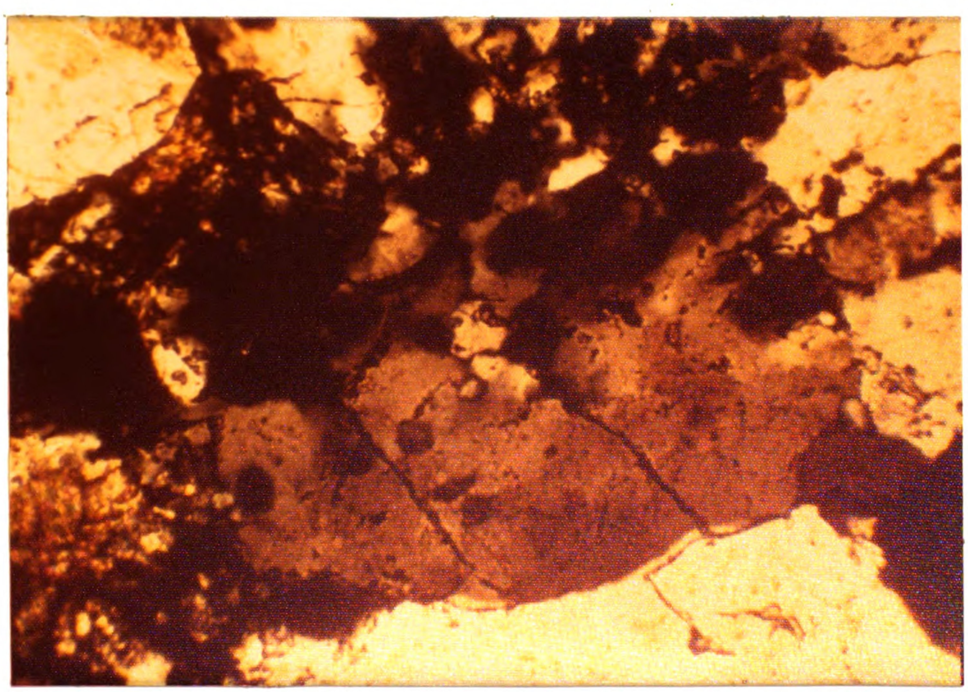

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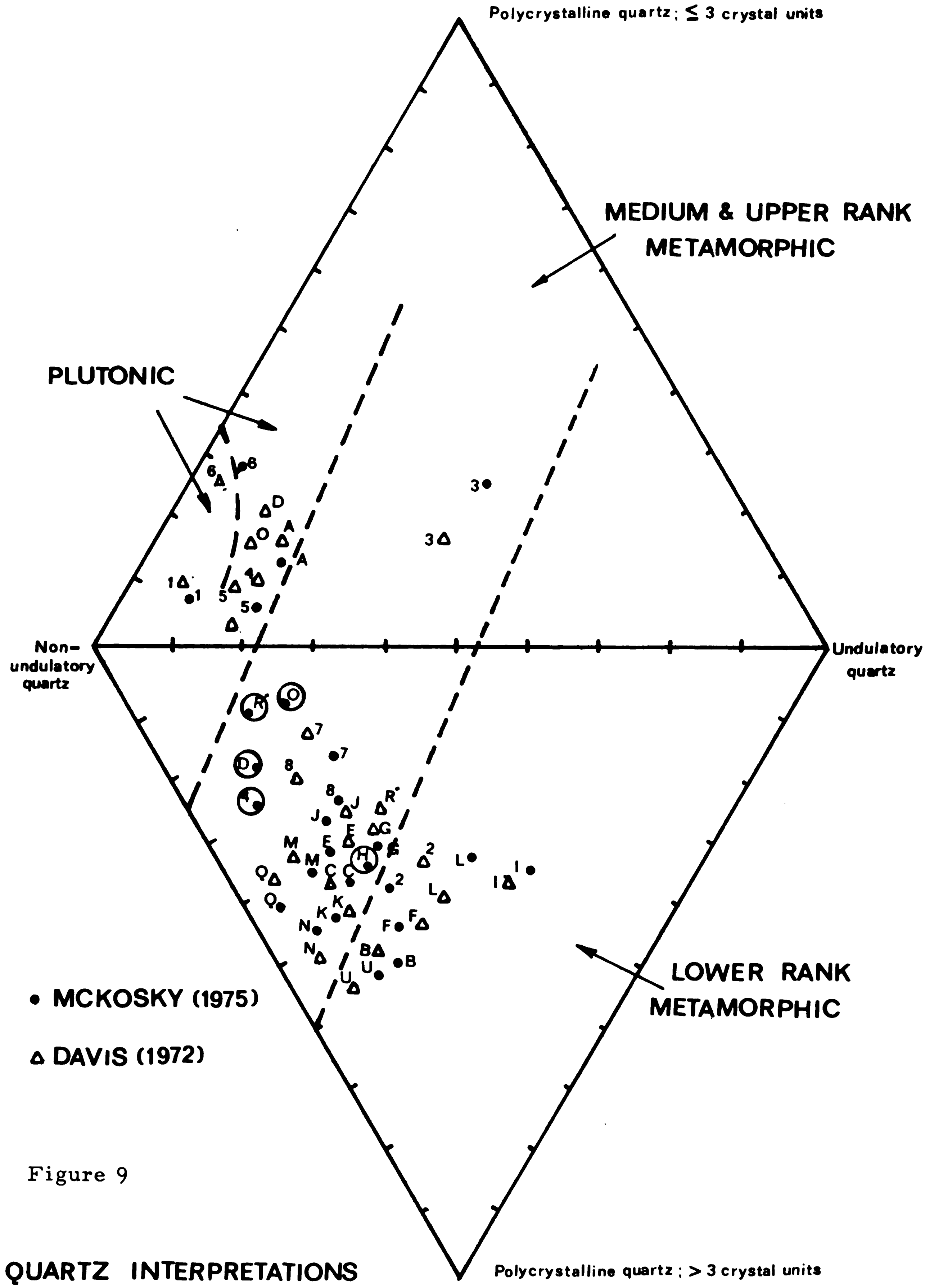


Figure 9

QUARTZ INTERPRETATIONS

as being lower-medium metamorphic. Samples above and below R' (E and Q) are in agreement with this grade of metamorphism. R' was interpreted as an upper metamorphic (and nearly plutonic) specimen.

Five of the 20 samples were anomalous. This number corresponds to a degree of accuracy less than which Basu et al (1974) said should be reproducible ( $\approx$ 93%). These errors or differences could be the result of an inability to correctly distinguish the exact boundary between the quartz varieties or in an error in the interpretation of Davis' (1972) source model. Basu et al (1974) readily admit to an indecision as to the precise location of the upper metamorphic-plutonic boundary in their diagram. Another possibility as to the erroneous conclusions may be reflected through incorrect interpretations made while observing the individual thin sections. Some samples have had grains plucked from the slide. This may have occasionally produced the questioned anomalies.

However, in most cases, the writer was easily able to discern lower, middle and upper metamorphic, as well as plutonic assemblages. These observations were in agreement with Davis' (1972) results (even though her conclusions were based upon the total mineralogical content). Although chert was found, quartz from volcanic-sedimentary rock fragments (described by Davis, 1972, as the lowermost assemblage in the cores) was not observed in this present study.

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Possibly this rock type was never present; at least in the cores which this author observed. Davis (1972, p. 41) describes the absence of the volcanic assemblage locally due to the... "destruction of the relatively soft fragments by a beach barrier environment, or by weathering and diagenesis." But I would expect to find some identifiable grains of crystal clear, beta-outline quartz.

It was intended by the writer that quartz inclusions should aid in the decision as to the source type. Unfortunately, most of the efforts were fruitless. As can be seen from Table 1 every slide observed exhibited "few vacuoles" as the most common type. This was to be expected as these inclusions are observed in all rock types. The amount of microlites observed was nearly useless as a determinant because the mineral type, in most cases, was not recorded. If they were known, better identification could have been made. The most disappointing aspect of the utilization of inclusions descriptions was in the difficulty to discern grains with abundant vacuoles from those with many bubble trains. If a volcanic assemblage was present it was hoped that the abundant vacuole category could reveal this.

Few diagenetic features were observed in any of the slides from the Pocahontas coal field. Calcite cement was only abundant in the sample MA5 from the Mt. Alto outcrop. Very few dust rings and secondary overgrowths were observed. New crystal faces and euhedral boundaries are rare in these sediments. The absence of secondary overgrowths and other diagenetic features is probably the result of the lack of porosity in the sandstones. If pressure-solution is the source of those diagenetic features then its absence may be explained by the following: 1. the rock is very dirty and composed of many rock fragments as well as other mineral constituents. Therefore, the quartz grains are separated and buffered from each other. This restricts any quartz to quartz interaction which could result in a silica solution; 2. since the rock is immature any silica in solution (perhaps from groundwater or another outside source) would be shared with and incorporated into the other silica rich minerals (i.e. feldspars) depriving quartz of the amount of silica needed to produce overgrowths; 3. even if enough silica may be present in solution to create the mentioned secondary features, the amount of remaining dirty components compacted around a quartz grain would inhibit any mobility and growth. Therefore, the lack of these diagenetic features indicates a very immature suite of sediments which have undergone rapid erosion, deposition and covering and have been subjected to little post depositional folding or faulting.

The effect of grain size upon the mineralogy of the rock was insignificant as was shown by Davis (1972). Grain size also does not affect the amount of polycrystalline quartz in the sediment Four samples of two different grain sizes ( 1 and 1.5 Ø) and polycrystalline content (10 and 40%) were studied. It was determined that those slides containing few versus many polycrystalline grains were approximately the same size. This illustrates that a decrease in the amount of polycrystalline quartz was not related to a reduction in grain size. In other words, the polycrystalline varieties were not broken down to form small monocrystalline grains in the medium sand range.

Luminoscope Work

Luminescence petrography is a relatively recent addition to sedimentary petrology and is still in its infancy. Relatively few workers (i.e. Smith and Stenstrom, 1965; Sipple, 1968; Sibley and Blatt, 1974 to name a few) have engaged in this field. Quartz may luminesce red, blue or a mixture of the two to form a brownish mottled specimen, reflecting the internal make-up of the grain. Without the aid of the luminoscope one is unable to distinguish these differences, as normal petrographic analysis will show these grains to be monocrystalline undulatory, nonundulatory and polycrystalline (Sipple, 1968). The quartz may or may not glow uniformly. It was believed by this writer that titanium produced the blue quartz and manganese made the other quartz grains glow red. Data to be discussed later from the microprobe suggests that these are probably

not the elements which cause the luminescence. In any effect, some trace elements are causing the different luminescence. Smith and Stenstrom (1965) have stated that blue luminescing quartz is produced at high temperatures. It is with this understanding that the writer did try to correlate the amount of tract element and color of the luminescence with possible changes in source terrane. Each slide was viewed under the electron beam of the luminoscope and determined to contain an estimated percentage of red and blue quartz. This was done by point counting each grain as it passed beneath the cross hairs of the microscope. The results were then analyzed by the means of the "t" statistic to see if any correlation could be made between rock type and luminescence percentage. Unfortunately, this was not possible. The "t" tests showed that no correlation between samples from the same sources, as well as from different sources, exists. No preferences between source terranes could be distinguished.

## Microprobe Analysis

The purpose of using the microprobe was to establish the occurrence of titanium and manganese in quartz as a reliable source indicator. If this was not possible it was then hoped that a change in titanium and/or manganese content within the samples would indicate a change in source area. That particular type of source area need not be known.

Dennen (1964, 1966) as previously stated, has done extensive work with the trace element chemistry within various rock types. In 1964 he revealed that titanium, because it is widely present in many different crustal assemblages, is the most distinctive trace element in quartz. Dennen (1964) observed great quantities (78%-96%) of the element in extrusive igneous and plutonic rocks. Titanium was less frequently ( <39%) found in metamorphic, vein and pegmatitic rocks. Also, Dennen et al (1970) traced the content of aluminum to temperatures of crystallization. Therefore, based on Dennen's concepts about titanium and Smith and Stenstrom's (1965) ideas about the temperature of formation of blue quartz, this author commenced his microprobe study of titanium and manganese.

As mentioned in an earlier chapter, each grain was observed with the microscope and the luminoscope, then mapped to insure the observation of non-undulose red or blue monocrystalline grains with the microscope. Extreme difficulty was encountered when comparing the mapped grains with those individuals as seen under the very high powered oculars of the microprobe. The process was very time consuming and difficult as the microprobe oculars are more powerful (by a few hundred times) than those used on the microscope. They also reproduced a mirror image of the initially observed specimens. Despite the difficulties encountered, each mapped non-undulose monocrystalline grain was observed and counts for Mn and Ti were taken on the microprobe. Aluminum was later counted to insure against the recording of feldspar grains.

Results for the titanium and manganese contents were averaged and then subtracted from the highest background for each element in the quartz standard. This procedure enabled the true content of each trace element to be obtained. Simple "t" statistics were performed upon this data, hoping that the results would be indicative of different source rocks. However, no correlations could be made as the titanium and manganese contents were different in rocks obtained from the same parentage. These results, although not discrediting the usefulness of trace elements in source terranes, have limited the reliability of Ti as a provenance indicator. Very recently Scotford (1975) has observed similar results questioning the usefulness of aluminum as an indicator of temperature of crystallization.

# CONCLUSIONS

Since 1963, when Blatt and Christie incorporated their study of the significance of undulatory extinction in quartz with provenance into the literature, much of sedimentary petrology has ignored quartz as a useful diagnostic indicator of source. Recent developments made by Basu et al (1974) have shown otherwise. Basu et al (1974) observed more samples in the medium sand size range than those studied by Blatt and Christie (1963) and found a close correlation between the type of source terrane and quartz variety. This present study has utilized the Basu et al (1974) technique in classifying quartz grains from known source terranes of the Pocahontas coal basin. Twenty-one of the 26 samples studied correlate with terranes derived by Davis (1972). Again, Davis (1972) obtained her results by reviewing the total mineralogy of the samples. Five samples--and possibly a sixth (A) because of its minute grain size--were anomallous either due to correlations made with erroneous data produced by Davis (1972) or more likely due to an uncertainty as to the exact location of the plutonic boundary on the Basu et al chart. Nevertheless, the ability of quartz to indicate changes in source as well as to accurately reveal the source type is a likely possibility. Quartz, therefore, should be a reliable indicator in provenance examination.

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The usefulness of the red and blue luminescence in quartz as a provenance indicator is very limited at this time. Although the history of this technique is very young, the future of this work appears to be more applicable to inferences about the internal structure of quartz rather than to the parentage of the grain.

The microprobe, in years to come, may also prove a valuable means for identifying source. This present study was done meticulously and yet produced negative results. I suggest that titanium and manganese are not the correct elements to be observed for future provenance examination.

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