THESIS

This is to certify that the

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PACKING, PRESSURE SOLUTION AND CEMENTATION
IN QUARTZ-RICH ARENITES

presented by

Douglas Gene Everse

has been accepted towards fulfillment
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[signature]
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PACKING, PRESSURE SOLUTION AND CEMENTATION IN QUARTZ-RICH ARENITES

By

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ABSTRACT

PACKING, PRESSURE SOLUTION AND CEMENTATION
IN QUARTZ-RICH ARENITES

By

Douglas Gene Everse

The inter-relationships of sandstone texture, composition, packing, pressure solution, cementation and maximum depth of burial have been determined for thirty-five quartz arenites, sublitharenites and litharenites from the Mid-Continent and Appalachian basin. Maximum depths of burial ranged from 170 meters to approximately 6,200 meters.

Three packing analyses were performed; one based on grain boundary intersections and two based on the arrangement of grain centers. The most useful measure of packing was the arrangement of grain centers as determined by Fourier analysis. Grain shape was found to be the most important parameter in the determination of packing.

Cathodo-luminescent microscopy was used to determine the amounts of silica cement and pressure solution. Minus-cement porosity is found to be less in the sublitharenites and litharenites than in the quartz arenites, presumably due to the plastic deformation of lithic fragments. Intergranular pressure solution is common in all of the samples but cannot account for most of the authigenic silica found. The relatively low amounts of pressure solution in the deeply buried samples can be interpreted to indicate that quartz cementation occurs at shallow depths of burial, or that relatively small volumes of cement retard further intergranular pressure solution.

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Finally, I wish to thank my wife, Georgia, for being more than a wife. She was computer operator, typist, lab technician and friend. She was the sounding board for an often discouraged grad student, but she would only give words to encourage in return. Without her patience

and encouragement, this thesis would not have been possible, and without her love, it would not have been worth it.

Douglas G. Everse
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INTRODUCTION

The purpose of this investigation is threefold: 1) an attempt has been made to evaluate the utility of several petrographic techniques as quantitative measures of packing in sandstones, 2) to determine the inter-relationships between packing, composition, texture, maximum depth of burial, pressure solution and silica cementation and 3) to use this information to determine the origin of silica cement in sandstones.

There are five fundamental properties of a sediment: 1) grain shape, 2) grain size, 3) composition, 4) orientation and 5) packing. Packing is the least understood of these properties, in part, due to difficulties in appropriate measurement techniques. In this study, two types of thin section packing analyses were investigated; one based on the number of grain boundary intersections along a random line (Kahn, 1956a), and two techniques based on the distribution of grain centers. In the latter technique, Fourier analysis has been used to describe the distribution of grain centers as well as a "degree-distance" plot suggested by Ramsay (1967, p. 195).

A packing arrangement in a sediment is the result of mechanical compaction under stress, pressure solution, grain breaking, grain rearrangements and plastic deformation. Experiments performed in this study were designed to determine the effects of sediment textures, mechanical compaction, pressure solution and cementation on grain packing. Also, these relationships between packing, composition, cementation, pressure solution and maximum depth of burial may be useful in determining the "timing" of cementation in sandstones. Blatt (1979) suggests that pressure solution plays a minor role in the process

of cementation because most cements occur at shallow depths of burial. Extensive quartz cementation, however, is common only in sandstones which have been deeply buried. Therefore, in this investigation, correlations were sought between maximum depth of burial and packing, pressure solution and quartz cement.

Grain shape, sorting and the percentage of ductile micas and rock fragments must effect the mechanisms of compaction in various sandstones (Hedberg, 1926; Athy, 1930; Waldschmidt, 1941; and Taylor, 1950). The effects of these variables, however, have only been expressed qualitatively or by the use of geometric packing analogs (Graton and Fraser, 1935: Tickell and Hiatt, 1938 and Beard and Weyl, 1973). In this study, some quantitative measurements of the effects of these variables were made possible.

PREVIOUS STUDIES

Many previous works on packing have been based on artificial compaction with the use of regular geometric arrays (eg. hexagonal, cubic, etc.), as analogs to natural packing (Fraser, 1935; Gaither, 1953 and Beard and Weyl, 1973). According to Fraser (1935) grain size, grain shape and sorting all modify the ideal conditions and control the porosity of unconsolidated deposits and upon compaction, solidification (cementation), appears to be the most important pore space reducer. Gaither (1953) and Beard and Weyl (1973) have also demonstrated the effects of grain shape and sorting on porosity in artificial samples. Sandstones in nature, however, do not display regular geometric arrays and these models are difficult to apply because they provide only gross approximations to relationships found in rocks.

There have been several quantitative studies of packing (Emery, 1954; Kahn, 1956 and Griffiths, 1961). These studies are based on grain boundary intersections along random lines. Results from this type of analysis are difficult to interpret when dealing with quartz cemented sandstones because of the often impossible task of differentiating cement from detrital grain.

Kahn (1956) used this method on three quartzites (the Tuscarora, Oriskany and Cuche), and determined their packing density and proximity. He found statistically significant differences between the formations and concluded that the Tuscarora formation showed the highest degree of packing. Does this represent a closer packing in the Tuscarora or a greater amount of authigenic silica? Perhaps the differences are due to grain size or shape variabilities. These questions are unresolvable because he did not distinguish detrital grains from their authigenic overgrowths due to the optically continuous nature of the cement and the lack of "dust ring" evidence.

The effects of intergranular pressure solution have also been widely studied. Many investigations (Weyl, 1959; Siever, 1962; Pittman and Lumsden, 1968 and others), have noted an increase in pressure solution with corresponding increases in clay content and have proposed several explanations for the association. Other studies have dealt with pressure solution as a pore reducing process (Rittenhouse, 1971a; Manus and Coogan, 1974; Sibley and Blatt, 1976; and Wilson and Sibley, 1978). Rittenhouse (1971a) used geometric analogs to determine theoretical pressure solution-porosity reduction ratios, while Sibley and Blatt (1976) and Wilson and Sibley (1978) looked at both theoretical and observed relationships to develop differing ratios. Manus and

Coogan (1974), however, looked at bulk volume loss and concluded that, "pressure solution may not be as common as generally thought".

The inter-relationship between pressure solution and quartz cementation has been studied in sandstones (Siever, 1959 and Sibley and Blatt, 1976). According to Siever (1959), pressure solution can account for most of the silica for cementation, while Sibley and Blatt (1976) concluded that pressure solution was not the major source for quartz cements. Other important relationships include an inverse relationship between the amount of plastically deforming material and pressure solution noted by Whisonant (1970), and Heald and Renton (1966) noticed that in impure sands, the degree of quartz cementation was proportional to quartz content.

SAMPLE COLLECTION AND PREPARATION

Thirty-five samples were collected from various tectonic settings in Wisconsin, Michigan, Ohio, Pennsylvania and West Virginia. The samples were chosen in order to provide sandstones of varying lithologies and maximum depths of burial. Artificial glass beads of different sizes and disaggregated sand samples were also used in this investigation.

Different formations were selected throughout the above-mentioned area of study. The formations ranged from Cambrian to Pennsylvanian in age and from near surface to 6,000 meters of maximum burial. Exact locations of sample sites are given in Appendix A.

Samples were impregnated with red-dyed, low viscosity epoxy resin (Minoura and Conley, 1971). Thin sections of each sample were cut perpendicular to bedding and four samples were also cut parallel. The thin sections were ground to thirty microns in thickness and then polished for cathodo-luminescent petrography.

Two techniques were performed on the artificial glass beads and disaggregated sand grains. The beads and grains were poured into several different containers. Some of the containers were tightly packed by shaking and tamping, while others were left unpacked after pouring. The beads and disaggregated sands were then impregnated with epoxy and thin sectioned.

DEPTH OF BURIAL

In order to relate compaction to the depth of the samples, it is necessary to determine the thickness of overlying stratigraphic units during the time of maximum burial. The calculated depths of burial for each sample presented in this section are maximum estimates taken from known stratigraphic unit thicknesses in or near the sample collection areas. An accurate estimation of the maximum depth of burial is difficult due to the unknown amounts of deposition and erosion in the sample collection areas. The depths provided in this section are rough estimates at best. The accuracy of the figures, however, is not what is of importance. What is important are the relative depths of burial experienced by each sample. Appendix B presents the maximum depths of burial calculated for each sample and the sources of this information.

Galesville (Cambrian)

The Galesville Sandstones used in this investigation were collected by T. V. Wilson in south-central Wisconsin. Considering the maximum stratigraphic thicknesses into the structural basins adjacent to this area, the maximum burial of this sandstone is estimated to be 900 meters (Wilson, 1977).

Grand River (Pennsylvanian)

Samples of the Grand River Formation Sands were collected from south-central Michigan. The thickness of the formation seen near the sample site is 100 meters. The maximum amount of sediment overburden witnessed in this part of the state is thought to be 70 meters (Lilienthal, 1978). The maximum depth estimate used in this study is a combination of the two figures above, approximately 170 meters.

Berea (Mississippian)

The Berea Sandstone is a channel sand that can have large variances in thickness. The samples collected were from northern Ohio, in a believed channel deposit, (Pepper, DeWitt and Demarest, 1954). There is no evidence of sediments younger than Mississippian, other than glacial drift in this area. A maximum depth of burial of 250 meters has been calculated at this site based on the thickness of the Mississippian sediments and on thicknesses of glacial drift in surrounding areas.

Pottsville (Pennsylvanian)

The Pottsville Sands were collected in southeastern Pennsylvania. Based on stratigraphic thicknesses determined by Schaffner (1963), a maximum depth estimate of 500 meters has been assigned for these samples.

Pocono (Mississippian)

Both of the Pocono samples were obtained in south-central Pennsylvania, east of the Pottsville samples. The total thickness of overlying sediment in this area of the state is larger because the sediments are from a deeper depositional basin located closer to the believed sediment source. (Edmunds, et. al., 1979). The maximum depth of burial in this area is 1,200 meters.

Keefer (Silurian)

The Keefer Sandstone was collected in south-central Pennsylvania, close to the Pocono samples site. The maximum depth of burial for the Keefer, based on stratigraphic thickness observations, is approximately 4,000 meters.

Tuscarora (Silurian)

The Tuscarora samples were collected by D. F. Sibley. The collection sites were in northeastern West Virginia and central Pennsylvania. The sandstones of West Virginia all lie within the same range of depths, 5,000 to 5,600 meters (Colton, 1970). The samples obtained from Pennsylvania are from a deeper sedimentary basin and range from 5,600 to 6,200 meters (Colton, 1970).

Oriskany (Devonian)

The Oriskany Sandstone samples were also obtained from northeastern West Virginia by D. F. Sibley. The Oriskany is a sandstone that was deposited during Colton's (1970) Silurian - Devonian Carbonate sequence. Its estimated depth in the stratigraphic column ranges from 4,300 to 5,000 meters.

West Virginia Sands (Pennsylvanian)

These assorted sandstones were collected by M. W. Davis in the Plateau Region of south-central West Virginia (Davis, 1972). The determined maximum depth of burial for these samples is 1,500 meters.

PETROGRAPHIC ANALYSES

Point Count Analysis

Three hundred point counts were made per thin section to estimate the percentages of quartz grains, clay, porosity and rock fragments. The sandstones were then classified, based on their compositions, according to McBride (1963). Table 1 supplies the formation name, age, sample number and classification of each sample used in this investigation. Exact compositions of the samples will be presented in the data section.

Cathodo-Luminescent Microscopy

Cathodo-luminescent microscopy was used to differentiate authigenic and detrital quartz (Sippel, 1968; Sibley and Blatt, 1976 and Wilson, 1977). Black and white photographs were taken of each thin section from three randomly chosen fields of view. Two photographs were taken for each field, one under transmitted light and the second under cathodo-luminescence. When compared, the transmitted and cathodo-luminescent photographs define the detrital grain-overgrowth boundaries.

Luminoscope photographs were taken on Kodak Tri-X pan black and white film (ASA 400), at five to ten minute exposures. The luminoscope was manufactured by the Nuclide Corporation, Model Number ELM2A-67. The beam was set at 14 kv and 0.6 to 0.8 ma.

The black and white negatives were projected on to graph paper that was adjusted to eliminate optical distortion. Detrital grain and

Table 1: Formation Names, Sample Numbers, Age and Classification of Sandstones Studied.

Stratigraphic Age	Formation Name	Sample Numbers	Classification
Cambrian	Galesville	F-G-1	Quartz Arenite
		G-1-7E	Quartz Arenite
		G-4-8E	Quartz Arenite
		G-6-6n	Quartz Arenite
		G-3-30E	Quartz Arenite
Silurian	Tuscarora	TS-4-SG	Sublitharenite
		TS-37-MG	Sublitharenite
		TS-5-NG	Sublitharenite
		TS-33-NG	Quartz Arenite
		TS-12-B	Quartz Arenite
		TS-16-B	Quartz Arenite
		TS-40-B	Quartz Arenite
Silurian	Keefer	F-K-1	Quartz Arenite
Devonian	Oriskany	OR-40	Quartz Arenite
		OR-41	Quartz Arenite
Mississippian	Berea	F-B-1	Sublitharenite
		F-B-2	Sublitharenite
Mississippian	Pocono	F-P-1	Litharenite
		F-P-2	Sublitharenite
Pennsylvanian	Pottsville	F-Pt-1	Sublitharenite
		F-Pt-2	Sublitharenite
Pennsylvanian	Grand River	F-LG-1	Quartz Arenite
		F-LG-2	Quartz Arenite
Pennsylvanian	West Virginia Sands	R-1-1	Sublitharenite
		R-1-2	Sublitharenite
		R-3-1	Sublitharenite
		RII4	Litharenite
		E-3-2	Litharenite

overgrowth margins were differentiated based on emission intensities and traced on the graph paper. Areas within the grains and overgrowths were determined by summing the number of points of intersection on the graph paper within their respective areas. The number of grains examined by this process varied between samples from 100 to 175 grains per thin section. The volumes of detrital quartz and overgrowths are proportional to the areas measured by point counting.

Percent intergranular pressure solution was estimated on luminescent photos by reconstructing rounded grain boundaries where penetration by adjacent grains has occurred and measuring the area of penetration by point counts on graph paper. The resulting estimate is somewhat subjective in that it requires the petrographer to reconstruct boundaries which have been destroyed by penetration of the two grains.

Sketching presolved grain boundaries and determining the percentages of pressure solution by point counts on graph paper should provide a maximum estimate of intergranular presolved quartz. Long grain contacts were considered presolved contacts, with the degree of penetration established by the shapes of the grains approaching the contact. Presolved grain areas were estimated liberally.

In a few samples (F-LG-1, F-LG-2 and F-K-1), a problem arose in the determination of detrital grain-overgrowth boundaries due to similar emitting intensities. This problem could result in slightly low estimates for overgrowth percentages and/or over-estimates of pressure solution in these samples. Cathodo-luminescence analysis was repeated on three thin sections to determine the precision of this type of analysis. A maximum error in reproducibility of 10 percent was found for the overgrowth percentages and up to 25 percent for the percent pressure solution. These proved to be within sampling error.

Textural Analysis

To test the effects of grain shape and sorting on the Fourier packing data, three samples were used. Sample 1A was made up of well-sorted, spherical glass beads, sample 1B was made of poorly-sorted, spherical glass beads, while Ottawa 1A was composed of well-sorted natural sand grains. All the samples were artificially packed by shaking and tamping and analyzed by the Fourier packing technique.

To evaluate the importance of grain shape in natural sands, Fourier grain shape analysis was performed on six samples (G-3-30E, G-4-8E, F-Pt-1, F-Pt-2, TS-5-NG, and TS-33-NG). This grain shape analysis works on the same principles as the Fourier Analysis used for packing (in Packing Analysis section), and is described in Ehrlich and Weinberg (1970).

In the natural sandstone samples, a size and size distribution analysis was conducted by thin section. The mean, median and sorting index calculations made by thin section observations were converted to sieve parameters for analysis. The conversion of the thin section calculations was accomplished by the use of Harrell and Eriksson's empirical conversion equations (1979).

POROSITY ANALYSIS

There is a problem in the precision of thin section analyses of porosity in sandstones (Wilson, 1977 and Halley, 1978). Wilson (1977) suggests that the use of thin section porosity determination techniques are inadequate when dealing with sands that are mineralogically complex or contain quantities of clay due to the increasing volume of micropore space. According to Halley (1978), estimating pore volumes in thin

section can be highly inaccurate due to the thickness of the slides and the "edge" effects. For this reason, porosities for fourteen samples were also determined by helium expansion--mercury emersion (HE--ME) performed by Core Laboratories, Incorporated. A t-test was performed between point count porosities and the helium expansion--mercury emersion porosities to test for differences between the two processes for the fourteen samples.

PACKING ANALYSIS BY PETROGRAPHIC TECHNIQUES

Fourier Analysis

Fourier analysis was used as a quantitative measure of packing. The procedure was to project a thin section image on a video screen and randomly select a grain. This grain then defined the center of an array. Surrounding grains, which make up the array, were defined as grains whose centers could be connected to the center grain by a straight line which does not intersect any other grains (Figure 1). Only Quartz grains and rock fragments were selected; clay and mica flakes were not used as defining grains. Figure 1 also demonstrates how the centers of the grains were plotted on an acetate overlay on the video screen. These plotted centers form the corners of a complex polyhedron.

Additional points (total = 12) were added to the array on straight lines connecting the original data points. This allowed for a more even distribution of data points and increased the number of harmonics which could be calculated without altering the shape of the polyhedron (Figure 2). The original and added data points were then digitized and put into x,y coordinates. The shape of the complex polyhedron, or array of centers, may then be estimated by Fourier analysis (Ehrlich and Weinberg, 1970).

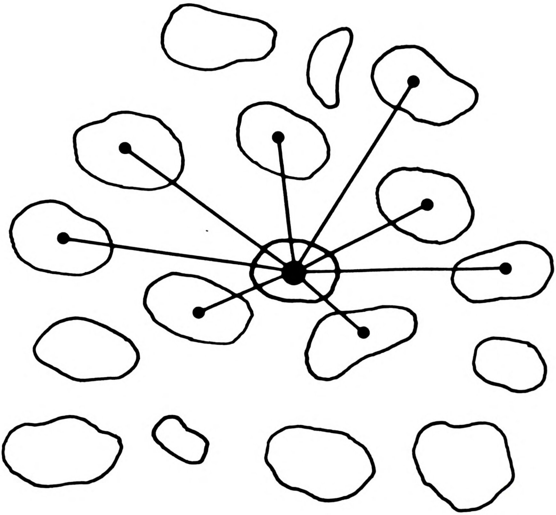


FIGURE 1 -- Definition of center grain and surrounding grains which form a packing array.

Fourier analysis expresses the radius from the center of the array to a given point as a function of the polar angle (Ø) and the sum of a series of sine and cosine wave amplitudes. The radius is expressed by a Fourier series:

$$R(0) - Ro + \sum_{n=1}^{\infty} Rn \cos (n\theta - \phi n)$$

where R(0) is the radius measured at polar angle (Ø), Ro is the average radius, n is the harmonic order, Rn the harmonic amplitude and on is the phase angle.

Fourier shape analysis resolves a complex polyhedron's two-dimensional shape into multiple shape components or harmonics, with each harmonic accounting for a specific contribution to the total shape. The sum of the harmonics can describe the polyhedron shape as precisely as desired.

With the origin at the center of the array, the "zeroth" harmonic is a centered circle with an area equal to the total grain area, the first harmonic describes the contribution of an offset circle, the second harmonic is a "figure eight", and the third, the contribution of a "trefoil". The n'th harmonic is characterized by a form with "n" nodes. Lower harmonics describe gross surface outlines and shapes, while the progressively higher harmonics show progressively finer surface textures.

To be able to compare all samples harmonic-by-harmonic, all amplitudes are normalized through division by the "zeroth" harmonic. Normalization makes shape comparisons independent of grain size and sets all "zeroth" harmonics equal to unity. The harmonics for a given Fourier series are both independent and uncorrelated. This permits the analysis of the differences in shape by comparing the differences in the n'th harmonic between two populations without regard for any of the other harmonics.

Fourier shape analysis was performed on each of the thin sections. Fifty grains were chosen at intervals large enough so that most of the area of the thin section was covered in the analysis. Duplicate analyses were performed on four samples to determine the precision of this method.

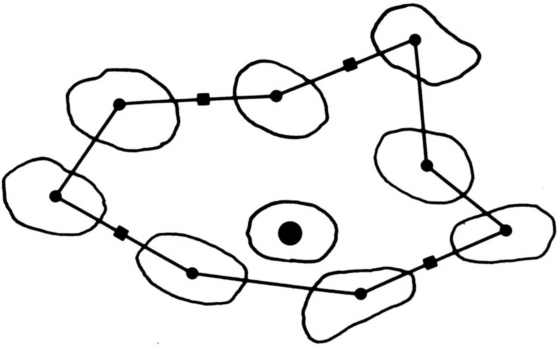
The centers of the grains forming each array were digitized, and the analysis computed by the program Fourier, written by Ehrlich and Weinberg (1970). Harmonics one through six were calculated for each thin section. Only the first six harmonics were used because the higher harmonics distinguish fine surface textures whose contributions are not important when dealing with packing array polyhedrons (Figure 2).

Harmonic mean and median amplitudes along with the standard deviation and coefficient of variance were calculated. A Kolomogrov-Smirnov D was also calculated to test for a normal distribution (Ehrlich and Weinberg, 1970). Computation of the program Fourier was accomplished with the use of the Cyber 750 computer system.

Due to the normalization of the harmonic amplitudes, two samples can be compared regardless of grain size or magnification. The harmonic amplitudes are non-normally distributed; therefore, the Mann-Whitney U-test, a non-parametric t-test, was used to test for differences in the n'th harmonic between samples.

Degree-Distance Analysis

A packing analysis similar to Fourier analysis, in that grain centers are utilized, was conducted on five samples: TS-40-B, TS-33-NG,



HARMONIC AMPLITUDES

1	2	3	4	5	6
0.0149	0.1557	0.0567	0.0394	0.0319	0.0348

FIGURE 2 -- Original and added data points connected to form a complex polyhedron with its associated harmonic amplitudes.

F-G-1, F-Pt-1 and F-Pt-2. The technique used is termed a "degree-distance" analysis by this author and is based on a method described in Ramsay (1967).

In this method, a line is drawn joining the centers of a randomly selected center grain with its adjacent grains. The distance (d) from center to center and the angle (a) from some known azimuth are calculated for each selected grain. In undeformed rocks, the plot of distance versus degrees should scatter along a mean line. Grains which have experienced pressure solution, however, are thought to plot in a definitely altered pattern, as suggested in Figure 3 (Ramsay, 1967).

Fifty grains, covering most of the slide, were picked as the center grain from which the degrees and distances to surrounding grains were measured. Measurements of distance and degrees were determined with the aid of acetate overlays on the projection of a thin section on a video screen. The measurements for each sample were then normalized through division by their mean grain size values, to allow for testing between samples with varying grain sizes.

The normalized data obtained by the "degree-distance" packing analysis was then statistically evaluated by a chi square test. A chi square test was chosen because of the non-parametric nature of the data.

Kahn's Method

A third packing analysis, based on grain boundary intersections along random lines, was performed on eight samples (G-4-8E, G-3-30E, TS-33-NG, TS-40-B, F-Pt-1, F-Pt-2, TS-5-NG and E-3-2). The procedure followed for this analysis is described in Kahn (1956a). In this technique, a packing proximity (Pp) and a packing density (Pd) are calculated from thin section observations.

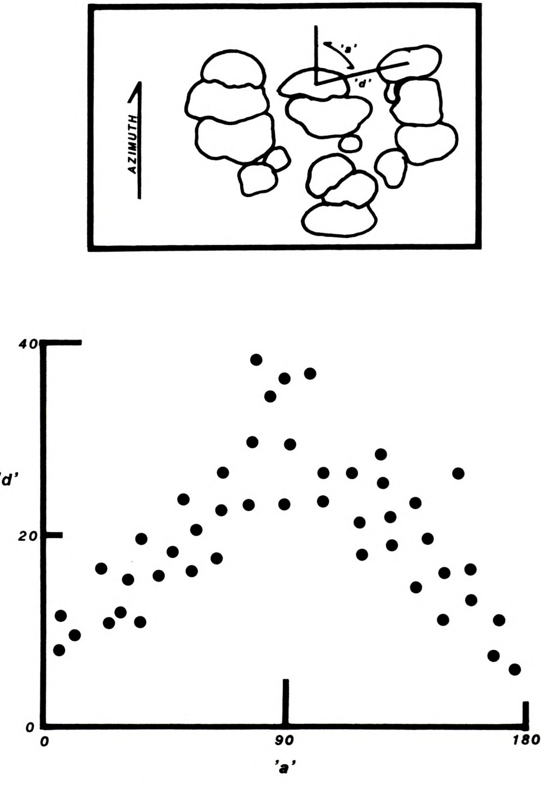


FIGURE 3 -- Determination of 'd' and 'a' with associated plot in a deformed rock by pressure solution (modified after Ramsay, 1967).

The packing promixity of a sandstone, as defined by Kahn, is a unit property and is expressed as the ratio of the number of grain to grain contacts to the total number of contacts:

$$Pp \frac{g}{n} = X\ 100$$

q = grain to grain contacts

n = total number of contacts

Packing density is an aggregate property which is an expression for the amount of space in a traverse occupied by grains:

$$Pd = \frac{m \sum_{i=1}^{n} gi}{t} \times 100$$

where (m) is a magnification correction term, (t) is the length of the traverse and the summation term is the sum of all the grain intercept values (gi) in the traverse.

Kahn's packing analysis was performed on eight samples chosen for their variability in amounts of cement and rock fragments. The packing proximities and packing densities calculated by this analysis are based on four random traverses per thin section. Random traverses were achieved by spinning the thin sections to obtain the traverse directions. Approximately two hundred boundary intersections were encountered per slide.

DATA

Porosity

Table 2 lists the results of both thin section and helium expansion--mercury emersion porosity determinations. The porosity values for the sublitharenites and litharenites do show statistical differences between the two processes probably due to the amount of micropore space

Table 2: Point Count Porosity Determinations versus HE--ME Calculations.

Quartz Arenites

Sample	Point Count Porosity	Core Lab Porosity (HE-ME)
G-3-30E	22.0	23.9
F-LG-1	27.0	25.8
F-LG-2	26.0	25.3
Data from Wilson (1977)		
outcrop two (n=12)	20.7	21.0
outcrop three (n=9)	21.1	24.2

t-test shows no difference between porosites for the above quartz arenites.

Sublitharenites-Litharenites

F-B-1	7.0	20.9
F-B-2	6.0	20.9
F-Pt-1	1.0	5.2
F-Pt-2	2.0	6.0
F-P-1	1.0	5.1
F-P-2	4.0	7.5
R-1-1	3.0	3.8
R-1-1	1.0	2.8
R-3-1	1.0	5.4
RII4	0.0	4.0
E-3-2	0 0	5.6

t-test produced differences between porosities for samples.

which goes undetected in thin section techniques, but is included in the HE--ME analysis. In quartz arenites, however, micropore space is minimized, and it has been demonstrated by Wilson (1977) and by the data in Table 2, that thin section determinations of porosity in quartz arenites produce adequate results.

Lithology

The data obtained through point counting, cathodo-luminescent petrography and helium expansion--mercury emersion analyses, are presented in Table 3. The amount of rock fragments and clay were taken from the point count analysis and the authigenic quartz and pressure solution values were obtained from cathodo-luminescence.

The porosity values for the samples in Table 3 were derived from the two methods. The quartz arenite porosites are based on thin section determinations while the sublitharenites and litharenite values are from HE--ME porosity calculations performed by Core Laboratories, Incorporated. No hand samples were available, however, for the HE--ME testing of three sublitharenites (TS-5-NG, TS-4-SG and TS-37-MG). The porosities for these samples were determined by point counting, but the values are so low that they were considered adequate.

Texture

The results of the various textural analyses are presented in Table 4. This table lists the second harmonic values from the grain shape analysis, which describes the grain shape elongation and the mean grain size and sorting index values.

Table 3: Petrographic Data

Sample	Det. Qtz.	Auth. Qtz.	Rock Frag.	Clay	Porosity	Minus-Cement Porosity	P. S.
F-G-1	74	18	1	3	4	22	3
G-1-7E	74	4	0	1	21	25	1
G-4-8E	75	2	3	2	18	20	2
G-6-6N	74	3	2	0	21	24	1
G-3-30E	73	2	2	1	22	24	3
F-G-1*	76	15	1	2	6	21	2
F-LG-1	65	2	3	3	27	29	1
F-LG-2	65	2	3	4	26	28	1
F-B-1	65	7	19	2	21	28	1
F-B-2	64	8	20	2	21	29	2
F-Pt-1	62	10	23	4	5	15	4
F-Pt-2	70	14	12	2	6	20	3
F-Pt-1*	67	6	24	2	5	11	3
F-Pt-2*	73	8	15	2	6	14	3
F-P-1	60	10	27	2	5	15	2
F-P-2	60	12	20	4	8	20	2
F-P-2*	59	12	23	3	8	20	2
F-K-1	75	17	4	5	1	18	6
TS-4-SG	72	8	16	3	(1)	(9)	5
TS-37-MG	70	10	18	2	(0)	(10)	2
TS-5-NG	72	11	14	3	(0)	(11)	4
TS-33-NG	75	20	1	2	2	22	3

Table 3: Petrographic Data, Continued

Sample	Det. Qtz.	Auth. Qtz.	Rock Frag.	Clay	Porosity	Minus-Cement Porosity	P. S.
FTS-12-B	68	24	0	4	4	28	5
TS-16-B	73	17	4	2	4	21	3
TS-40-B	73	15	4	7	1	16	14
OR-40	71	9	3	1	16	25	2
OR-41	72	11	4	1	12	23	3
R-1-1	73	13	8	3	4	17	3
R-1-2	75	8	12	4	3	11	5
R-3-1	71	7	18	3	5	12	2
RII4	56	5	38	1	4	9	2
E-3-2	56	6	37	1	6	12	3

() Only thin sections were available for porosity determination.

*Parallel

Note: Data from samples cut parallel to bedding were not used in the linear regression analyses.

Table 4: Grain Shape, Grain Size, and Size Distribution Data

Sample	Grain Shape Elongation (Second Harmonic)	Mean Grain 0 Size	Sorting Index
G-3-30E	.1911	2.4	0.51
G-4-8E	.1708	1.9	0.63
F-Pt-1	.1944	2.3	0.45
F-Pt-2	.1465	1.7	0.38
TS-5-NG	.1747	2.1	0.59
TS-33-NG	.1600	1.6	0.48

Packing

Kahn's packing analysis defines packing by the use of numerical values for packing proximity and packing density. Table 5 lists the packing proximities and packing densities calculated for the eight selected quartz arenites. The percentages of cement, minus-cement porosity and pressure solution, along with the packing second harmonic values for each sample are also listed for evaluation of this method.

The use of the "degree-distance" technique to define packing in sandstones, produces data which consist of a set of degree measurements from 1 to 180, along with their associated distance calculations from grain center to grain center. The data for all the samples (TS-33-NG, TS-40-B, F-G-1, F-Pt-1 and F-Pt-2), was statistically examined by a chi-square test and no samples demonstrated any differences at the 95 percent confidence level.

Fourier packing analysis defines a packing array in sandstones by the use of harmonics. Mean harmonic values for the first six harmonics for each sample are presented in Appendix C.

To test for differences in Fourier packing array shapes between samples, the Mann-Whitney U-test was performed on the second harmonic. The second harmonic was chosen to test for differences between samples because of its large contribution in defining the array shape, its variability between samples and its relatively low maximum percent error in reproducibility (Appendix C). Examination of the second harmonic was also selected because it is thought that with increased compaction and pressure solution, the packing array defined by the Fourier method should become more elongate and the second harmonic would express this relationship. Table 6 lists the samples compared and the results of the

Table 5: Kahn's Packing Analysis

Sample	Packing Proximity	Packing Density	Second Harmonic	% Cement	Minus-Cement % Porosity	% P. S.
G-4-8E	27.08	75.37	.1326	2	20	2
G-3-30E	57.64	81.77	.1668	2	24	3
TS-33-NG	83.05	94.95	.1311	20	22	3
TS-40-B	86.06	96.75	.1615	15	16	14
F-Pt-1	54.17	69.40	.1530	10	15	4
F-Pt-2	70.67	88.55	.1222	14	20	3
TS-5-NG	62.97	73.30	.1595	11	11	4
E-3-2	33.82	55.75	.1574	6	12	3

Mann-Whitney U-test on the second harmonic at a 95 percent confidence level. This data reveals that samples from the same formation are often different, while samples from different formations may be the same.

DATA ANALYSIS

Fourier Packing Data

In order to evaluate the usefulness of the Fourier second harmonic as an interpretive tool to the compaction processes which have acted upon the samples, a series of regression analyses were run. The mean second harmonics for each sample (Appendix C), were regressed against the depth of burial, pressure solution, percent quartz cement, minus-cement porosity, porosity and percent rock fragments (Table 3). No significant correlations were found.

Textural data were also regressed against the second harmonic for the six samples of Table 4. These regression analyses produced a positive correlation (r^2 = .72) between the Fourier Packing second harmonic and grain shape elongation. (Fourier grain shape second harmonic). Difficulties in determining actual grain shape in the well-cemented TS-33-NG sample could result in an erroneous correlation. A second regression analysis run without sample TS-33-NG, however, still yielded a significant correlation. The significance of regression analyses were determined by the use of a t-test at a 95 percent confidence level.

Linear regressions were also performed on the data to discover any relationships which may exist between variables and for purposes of interpreting the importance of various porosity reduction processes.

Table 6: Mann-Whitney U-test on the Second Harmonic

Samples Compared	2-Tailed P	Different or Same Population
TS-40-B - F-G-1	.2071	Same
TS-40-B - TS-12-B	.1744	Same
F-K-1 - F-G-1	.3977	Same
G-3-30E - G-4-8E	.0538	Same
OR-41 - TS-40-B	.1144	Same
G-3-30E - F-LG-2	.3102	Same
F-Pt-2 - F-B-1	.6867	Same
R-3-1 - E-3-2	.0682	Same
TS-4-SG - TS-37-MG	.1128	Same
OR-41 - OR-40	.6891	Same
F-P-1 - F-Pt-1	.2700	Same
TS-40-B - TS-33-NG	.0406	Different
TS-33-NG - TS-5-NG	.0393	Different
TS-33-NG - F-K-1	.0490	Different
G-3-30E - TS-33-NG	.0380	Different
F-Pt-1 - F-Pt-2	.0437	Different
TS-40-B - F-Pt-2	.0251	Different
F-B-2 - E-3-2	.0088	Different
F-Pt-1 - F-B-1	.0281	Different
G-3-30E - F-B-2	.0089	Different

Texture

To test how textural qualities may have influenced compaction in the samples studied, a set of linear regressions were run on grain size, grain shape and sorting (Table 4), against the other petrographic variables. None of these regression analyses provided any significant correlations between texture and the other variables.

Minus-Cement Porosity

A correlation value of $r^2 = .34$ was produced when the amount of minus-cement porosity was regressed against the percentage of rock fragments for each sample. This correlation is the result of an inverse relationship between the two variables. Another correlation ($r^2 = .45$) results from an inverse relationship between minus-cement porosity and pressure solution in the quartz arenite samples. No other significant correlations are exhibited between minus-cement porosity and the other petrographic data.

The plot of minus-cement porosity versus depth of burial shows a different type of relationship between samples. Although no linear relationship exists, a division of the samples into two distinct populations occurs. Figure 4 is the plot of minus-cement porosity with depth of burial, demonstrating the division of samples into a quartz arenite population and a sublitharenite-litharenite population, with the exceptions of the two Berea samples (F-B-1 and F-B-2) which fall within the quartz arenite area.

Cement

Regressions were performed to determine if linear relationships exist between the amount of silica cement and the other data. No

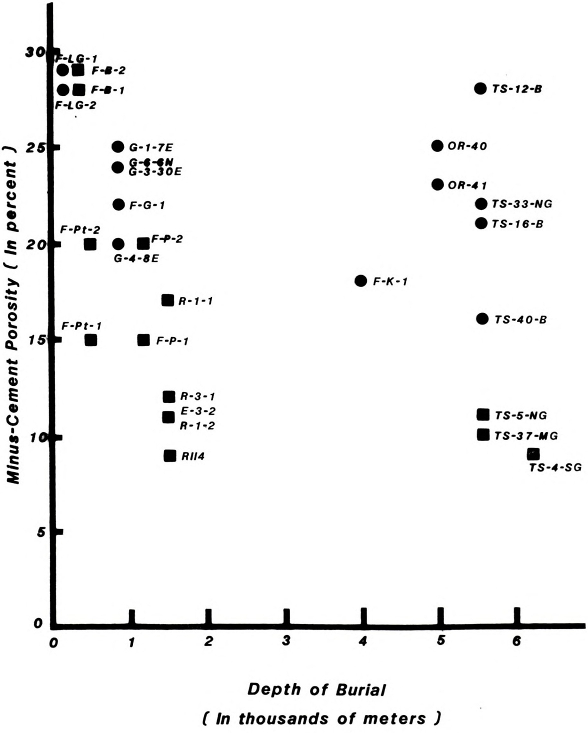


FIGURE 4 -- Plot of minus-cement porosity vs. depth of burial.

● QUARTZ ARENITES

■ SUBLITHARENITES & LITHARENITES

correlations were noted between percent cement and the other variables when the samples were considered as one population. Division of the samples, by lithology, into a quartz arenite group and a sublitharenite-litharenite group, did produce two linear relationships. A large inverse correlation (r^2 = .85) is seen in the regression between the amount of cement and porosity in quartz arenites. In the sublitharenite-litharenite group there is an inverse relationship with the amount of cement against percent rock fragments. The correlation value for this relationship is r^2 = .42, and although not as large, it is significant at the 95 percent confidence level by t-test.

Pressure Solution

Regression analyses run on pressure solution versus the other variables reveal two trends. There is a positive correlation (r^2 = .48) between pressure solution and the amount of clay and a positive correlation (r^2 = .24), also significant at the 95 percent confidence level, when the amount of pressure solution is regressed against the depth of burial. Removing the one very high pressure solution value (TS-40-B), produced a correlation coefficient of r^2 = .28. Figure 5 is a graph of the distribution of pressure solution with depth of burial.

EVALUATION OF PACKING ANALYSES

In this investigation, an attempt was made to establish a packing analyses that could be easily performed and provide the information needed for a quantitative reconstruction of compaction histories in ancient sandstones. Three different packing analyses were applied to the samples collected for this study. Two analyses were based on the

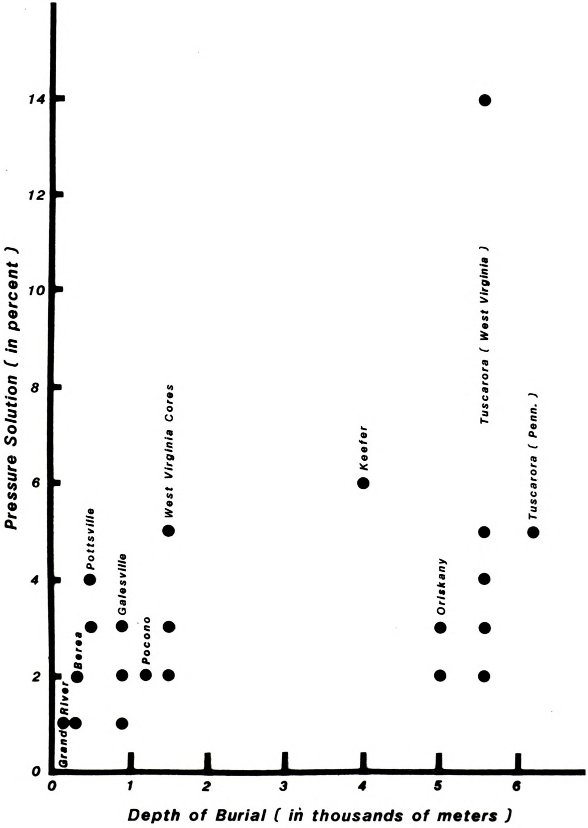


FIGURE 5 -- Plot of pressure solution vs. depth of burial.

arrangement of grain centers and the third, first discussed by Kahn (1956a), was based on grain boundary intersections. Kahn's packing analysis was run on eight samples of varying amounts of cement and rock fragments. On the basis of the packing proximity and packing density values derived through Kahn's method (Table 5), it would appear that the samples are widely varied in their degrees of packing. Samples TS-33-NG and TS-40-B have large packing proximity and packing density values which are statistically the same and indicate a tight packing arrangement. The lower values for samples G-4-8E and G-3-3E suggest a lesser degree of packing. The cement, minus-cement porosities and pressure solution percentages, associated with the packing data in Table 5, reveal discrepancies in the packing interpretations made from Kahn's analysis.

The minus-cement porosity and pressure solution percentages for sample TS-33-NG demonstrate that the degree of compaction this sample has experienced closely resembles that of samples G-4-8E and G-3-30E, not TS-40-B. The reason for this discrepancy between packing proximity and packing density determinations and the actual degree of packing, is that detrital grain-detrital grain, grain-cement and cement-cement boundaries are not differentiated. This is the inadequacy of Kahn's packing analysis when working with well-cemented sands.

To avoid the difficulties imposed by quartz overgrowths, two analyses, based on the arrangement of grain centers were employed. The first packing analysis, termed "degree-distance", was taken from a method proposed by Ramsay (1967). Using this method, no samples proved to be statistically different, rendering it inadequate as an analysis of packing.

Examination of packing by Fourier shape analysis also makes use of the arrangement of grain centers. The Fourier data consists of numerical values that are representative of packing forms witnessed in samples (Appendix C). Values of the second harmonic were used to test for differences between samples and, as demonstrated by the Mann-Whitney U-test results of Table 6, samples were found to be different at the 95 percent confidence level.

The value of Fourier data and the differences found between samples is questionable. Samples F-K-1 - F-G-1 and OR-41 - TS-40-B (Table 6) are statistically evaluated to be from the same population, yet the data shows that F-K-1 and F-G-1 are quite different in their maximum depth of burials and OR-41 and TS-40-B are very different in their amounts of pressure solution. Regression analyses run on the second harmonic values showed no correlations with depth of burial, minus-cement porosity, cement or pressure solution. The only significant correlation which exists with the packing second harmonic is a direct relationship with grain shape elongation ($r^2 = .72$).

The strong influence of grain shape on Fourier packing analysis is also demonstrated by the artificial, packed-perpendicular samples 1A and Ottawa 1A (Appendix C). Sample 1A was made up of well-sorted, spherical glass beads, while sample Ottawa 1A was composed of well-sorted, natural sand grains. Both samples were packed in the same manner and differed only in grain shape. The larger second harmonic of Ottawa 1A cannot be correlated to an increase in compaction, but as the correlation value $r^2 = .72$ demonstrates, increases in the second harmonic are due more to grain shape than any other factor. This relationship may explain the

discrepancies witnessed in the Mann-Whitney U-test results, but definitely limits Fourier's use as an interpretive tool to compaction processes.

POROSITY REDUCTION PROCESSES

Mechanical Compaction

Reduction in initial porosity begins shortly after burial by mechanical readjustment of grains into a more tightly-packed arrangement. Mechanical compaction is brought about by pressure from loading and tends to proceed until a stable grain frame-work is achieved, or until cementation by authigenic minerals makes intergranular movements impossible.

The maximum amount of compaction and/or minimum resulting porosities due to complete mechanical compaction vary considerably in response to the percentage of plastically deforming material, grain size, sorting and grain shape. The minimum porosity value established for tight packing of well-sorted and well-rounded, clean sands in laboratory experiments is approximately 36 percent (Gaither, 1953). Porosities as low as 33 percent were achieved by Wilson and Sibley (1978), on their experiments with Galesville sands. It is unlikely that mechanical compaction in nature could compact clean sands more effectively than was done in these experiments.

As described in Beard and Weyl (1973), sorting is the major textural control on pore space. Their studies revealed that poorly-sorted sands had less porosity (30.7%) than well-sorted sands (39.8%). Minor textural relationships were also found between porosity and grain shape. Tickell and Hiatt (1938) suggest that as angularity increases, so should pore space.

No correlations were found in this study, however, between grain size, shape or sorting textures and minus-cement porosities in quartz arenites or sublitharenite-litharenites. The lack of correlations suggests that most of the textural effects on porosity may be wiped out by later compaction processes; such as pressure solution or continued compaction due to ductile material.

Mechanical compaction in sublitharenites and litharenites plays a much larger role than it does in quartz arenites. Rittenhouse (1971b) measured, with artificial samples, the relationship between the percentage of ductile grains and reduction in pore space and thickness percents caused by compaction. His data demonstrates that the amount of compaction should increase significantly with increases in the proportion of ductile grains. The data obtained for the natural sandstones in this study, also show increased compaction and porosity loss with increases in the proportion of rock fragments. This is demonstrated in the relationship between samples F-Pt-1/F-Pt-2 and F-P-1/F-P-2 (Figure 5). In both cases the sample with the larger amount of rock fragments has the smaller porosity percentage, even though their maximum depths of burial are the same.

An inverse relationship exists between the minus-cement porosities and the amount of rock fragments ($r^2 = .34$). This relationship is due to the easily deformable nature of these rock fragments (mostly fine grain metamorphic and shales) under load as compared to the unyielding grains, such as quartz. The increased compaction in sublitharenites and litharenites with depth is shown by the lower minus-cement porosities found in these "dirty sands" (Figure 5).

Pressure Solution

In addition to mechanical grain adjustments, intergranular pressure solution has occured to some degree, in all of the samples. Pressure solution was entirely intergranular in nature, no styolitic developments were observed in the thin sections.

Siever (1959), has suggested that pressure solution is the major source of the quartz cement in the sandstones he studied. Recent investigations (Sibley and Blatt, 1976), however, have pointed out the inability of pressure solution to supply the quantities of silica needed to produce the amounts of cement seen in most sandstones. The data presented in Table 3 demonstrates that, on the average, pressure solution can only account for approximately one-third (36.7%) of the quartz cement present in the samples. This figure corresponds well with the results of Sibley and Blatt (1976), in which they also determined that one-third of the cement in the Tuscarora might have been derived from intergranular pressure solution. The bulk of the silica needed for cementation is not explained by pressure solution and must be derived from other sources.

The major variable influencing the amount of pressure solution observed in the samples, appears to be the quantity of clay. The correlation coefficient between percent pressure solution and percent clay for all samples is $r^2 = .48$, indicating an increase in pressure solution with increasing clay. This relationship has been observed by others (Weyl, 1959; Siever, 1962; Pittman and Lumsden, 1968 and Sibley and Blatt, 1976).

Several explanations have been proposed to explain the association of clay with pressure solution. Weyl (1959) suggests that clay promotes

pressure solution by enhancing diffusion of dissolved silica from grain boundaries to pore fluids. Pittman and Lumsden (1968) show that chlorite coatings inhibit quartz overgrowth formations which leads to increased pressure solution. Petrographic observations of the samples appear to show evidence for both processes. A correlation was also found between pressure solution and the maximum depth of burial (r^2 = .24) indicating the potential for pressure solution becomes greater with deeper burial.

The porosity reduction in quartz arenites due to intergranular pressure solution between grains was investigated by Rittenhouse (1971a). He presents a theoretical model where spheres, arranged in an orthorhombic lattice, were compacted due to "overburden" pressure. Volume decreases in the lattice result due to overlap or "solution" of the spheres at points of contact. The orthorhombic arrangement was chosen by Rittenhouse because of its close approximation to porosities observed in laboratory experiments (39.5%), and its contacts per grain (8), which is close to the 7.5 contacts per sphere achieved through random packing by Marvin (1939).

Minus-cement porosities for the quartz arenites studied (Table 3) average 21.8 percent, while the percent pressure solution is 3.4 percent. Assuming that the porosity before pressure solution was near 40 percent, there would be a 45 percent reduction in porosity due to 3.4 percent pressure solution. This pressure solution--porosity reduction ratio is much lower than that predicted by Rittenhouse's experiments and falls closer to the relationships predicted by Sibley and Blatt (1976) and Wilson and Sibley (1978). This is an important distinction, for if the relationship of pressure solution to porosity reduction suggested by

Sibley and Blatt (19676) is close to the natural relationship, then small amounts of pressure solution play a far more important role in porosity reduction than suggested by Rittenhouse (1971a).

Whisonant (1970) noted an inverse relationship between the amount of plastically deforming material and pressure solution. This relationship is also suggested by the pressure solution data of Table 3. The largest amounts of pressure solution were obtained in the quartz arenite samples (TS-40-B and F-K-1), with the average percent pressure solution being 3.4 percent in the quartz arenites and 2.7 percent in the sublitharenites and litharenites of comparable depths. Suggested reasons for these relationships are: 1) the stress from load is taken up by the plastically deforming material, 2) restriction of silica movement, and 3) there are less quartz grain-quartz grain contacts with increased amounts of deforming material.

Quartz Cementation

Quartz cementation in sublitharenites and litharenites can be a major pore reducing process. Often, sands in this group, however, are lithified by compaction alone, without noticeable introduction of chemical precipitates (Blatt, 1979). Heald and Renton (1966) noticed that in impure sands, the degree of quartz cementation was proportional to quartz content.

Cementation by quartz was observed, to some extent, in every sublitharenite and litharenite sample. An inverse relationship (r^2 = .42) was found however, between the amount of cement and the amount of rock fragments. This relationship is probably due to the lessening amounts of detrital quartz, which serve as both a source of silica and a

substrate for its precipitation, and restriction of silica movement caused by increased compaction with subsequent porosity reduction.

In quartz arenites, cementation is a major porosity reducing process, filling up to 40 percent of the rock volume. This quartz cement occurs most frequently as optically continuous overgrowths on detrital grains. The importance of cementation as a pore filling process is demonstrated by the large correlation coefficient (r^2 = .85) obtained when cementation is regressed against porosity. This is an inverse relationship with pore space decreasing as the amount of cement increases.

Sibley and Blatt (1976), obtained a negative correlation between authigenic quartz and pressure solution. In their samples they noted a lack of cement in the zones of intense pressure solution and concluded that the most intense pressure solution occurs in zones of the rock which were not lithified during earlier diagenesis. Areas which were cemented early in diagenesis would undergo less pressure solution because as cementation occurs, stresses become more homogeneously distributed throughout the rock, rather than being concentrated at grain boundaries. This relationship was also noticed in the Tuscarora quartz arenites of this study. Sample TS-40-B had the largest amount of intergranular pressure solution and also had the least amount of cement. In this sample, zones of intense pressure solution occurred in areas which showed very little or no cement. A correlation between quartz cement and pressure solution, between all the quartz arenites of this investigation, was not found. The reason for the lack of correlation is the presence of several samples which have small amounts of cement and low percentages of pressure solution. The fact that no

correlation exists between these quartz arenites does not discount the conclusions made by Sibley and Blatt (1976); although it is noted that the samples with little cement are the Galesville and Grand River, which were not deeply buried. It is possible that extensive pressure solution, in the samples with the low amounts of cement, could have been prohibited during the time of its maximum burial by high pore fluid pressures or by the presence of a cement, which has since gone to dissolution. If these uncemented sands were to be deeply buried today, they would undergo extensive pressure solution because of their lack of cement and subsequent concentration of pressures at grain boundaries.

The origin of quartz cement in quartz arenites remains a problem. The data in this study and previous studies, indicate that intergranular pressure solution is an inadequate source of authigenic silica. That being the case, the silica must be derived from stylolites within the formation or from external sources. Arguments which favor stylolites are: 1) that thorough silica cementation of quartz is more common in deeply buried sands (Lowry, 1976; Siever, 1959 and Heald and Renton, 1966) and 2) the difficulty of moving enough water through a formation from outside sources to account for quartz cements (Sibley and Blatt, 1976).

The problem with styolites as a major source of silica is that no one has demonstrated that they can provide the necessary amount of silica (Sibley and Blatt, 1976). Sibley and Blatt,(1979) suggest that most cementation occurs at relatively shallow depths of burial, where ground water flow rates are adequate to provide the necessary silica from external sources. The difficulty with this proposal is that large scale silica cementation is common only in formations which have been deeply buried.

The small amount of intergranular pressure solution observed in this study is consistent with the hypothesis that most cementation occurs at shallow depths of burial. Alternatively, it may indicate that a small amount of cement is enough to inhibit intergranular pressure solution.

CONCLUSIONS

1) The packing analyses performed in this study proved to be inadequate:
   a) Kahn's packing analysis produced data that results in misleading interpretations when working with well-cemented sandstones, due to the difficulty in distinguishing between detrital quartz grains and their overgrowths.
   b) Degree-Distance analysis did not show any statistical differences between the packing exhibited by the samples.
   c) Fourier packing analysis did produce differences between samples but the data is not useful as an interpretive tool of packing because its major influencing factor is grain shape.
2) The major porosity reduction process in sublitharenites and litharenites is mechanical compaction with minor amounts of pressure solution and cementation.
3) An inverse relationship exists between the amount of quartz cement observed in a sample and the amount of rock fragments.
4) Intergranular pressure solution in quartz arenites is a major pore reducing process which results in lower pressure solution--porosity reduction ratios than that demonstrated by Rittenhouses's (1971a) theoretical models.
5) A direct relationship is found that shows the amount of pressure solution increases with increasing amounts of clay.

6) Intense pressure solution occurs in areas of a rock which remain uncemented during diagenesis and the potential for increased pressure solution becomes larger with deeper burial.

7) Quartz cementation is a major porosity reducing process in the quartz arenites of this investigation.

8) The petrographic data of this study suggest that the precipitation of a quartz cement occurs at rather shallow depths of burial, or that small amounts of cement inhibit further intergranular pressure solution.

APPENDIX A

SAMPLING LOCATIONS

Galesville (Collected by T. V. Wilson)

All of the Galesville samples were collected at various outcrops in South Central Wisconsin. This sandstone was deposited around erosional remnants of the Baraboo Quartzite in the vicinity of Baraboo, Wisconsin.

Samples: F-G-1, G-1-7E, G-4-8E, G-6-6N, and G-3-30E.

Grand River

The Grand River Formation sands were collected near the town of Grand Ledge. Grand Ledge is located in Southern Michigan, in Eaton County.

Samples: F-LG-1 and F-LG-2.

Berea

The Berea Sandstone was obtained in the Buckeye Quarry near South Amherst, Ohio. South Amherst is located in Lorain, county in the North Central part of the state.

Samples: F-B-1 and F-B-2.

Pottsville

The Pottsville samples were collected on the Pennsylvania Turnpike in Westmoreland County, approximately 50 miles east of Pittsburg in Southeastern Pennsylvania. Sample 1 was taken near mile marker 87.2 and Sample 2 was taken at mile marker 84.8. Marker 84.8 is on the east flank of the Chestnut Ridge Anticline while 87.2 is on the west flank.

Samples: F-Pt-1 and F-Pt-2.

Pocono

Both Pocono samples were obtained approximately six miles east of Breezewood in Fulton county, Pennsylvania. Sample 1 and Sample 2 were collected at mile markers 168.3 aznd 169.6, respectively, off the Pennsylvania Turnpike in the South Central part of the state.

Samples: F-P-1 and F-P-2.

Keefer

The Keefer Sandstone was collected on the Pennsylvania Turnpike at the 183.7 mile marker. This location is also in Fulton County, in South Central Pennsylvania.

Samples: F-K-1.

Tuscarora (Collected by D. F. Sibley)

The Tuscarora Sands were obtained from various outcrops in West Virginia and Pennsylvania.

1) Susquehana Gap Pennsylvania - Sample: TS-4-SG
2) North Fork Gap West Virginia - Samples: TS-5-NG and TS-33-NG.
3) Baker West Virginia - Samples: TS-12-B, TS-16-B and TS-40-B.
4) Mills Gap West Virginia - Sampel: TS-37-MG.

Oriskany

The Oriskany samples were taken 1.9 miles east of Baker, West Virginia on Route 55.

Samples: OR-40 and OR-41.

Pennsylvanian

These samples consist of cores from wells located throughout the Appalachian Basin in Central West Virginia.

Samples: R-1-1, R-1-2, R-1-3, RII4 and E-3-2.

APPENDIX B

ESTIMATES OF MAXIMUM DEPTHS OF BURIAL

WITH REFERENCES

	Maximum Depth (In Meters)	Reference
Galesville		
Cambrian-Pennsylvanian	900 meters	Wilson (1977)
Grand River		
Pennsylvanian	100	Lilienthal (1978)
Younger Sediments	70	Lilienthal (1978)
	170 meters	
Berea		
Mississippian		
Berea	70	Pepper, et al (1954)
Sunbury	5	Collins (1979)
Cuyahoga	55	Collins (1979)
Maxville	60	Collins (1979)
	170 meters	
Pottsville		
Pennsylvanian		
Pottsville	60	Schaffner (1963)
Allegheny	70	Schaffner (1963)
Conemaugh	240	Schaffner (1963)
Mongahela	120	Schaffner (1963)
Washington	10	Schaffner (1963)
	500 meters	Schaffner (1963)
Pocono		
Mississippian		
Pocono	250	Edmunds, et al (1979)
Mauch Chunk	400	Edmunds, et al (1979)
Pennsylvanian		
Pottsville	60	Edmunds, et al (1979)
Allegheny	70	Edmunds, et al (1979)
Conemaugh	270	Edmunds, et al (1979)
Mongahela	150	Edmunds, et al (1979)
	1200 meters	

	Maximum Depth (In Meters)	Reference
Keefer		
Silurian		
Mifflintown and Bloomsburg	215	Pierce (1966)
Silurian-Devonian	800	Pierce (1966)
Acadian Clastics	1725	Pierce (1966)
Mississippian	690	Edmunds (1979)
Pennsylvanian	570	Edmunds (1979)
	4000 meters	
Tuscarora (Penn.)		
Silurian Clastics	430 - 460	Colton (1970)
Silurian Devonian	615 - 770	Colton (1970)
Devonian Clastics	2770 - 3070	Colton (1970)
Mississippian	860 - 950	Colton (1970)
Pennsylvanian	860 - 950	Colton (1970)
	6200 meters	
Tuscarora (W. Va.)		
Silurian Clastics	250 - 320	Colton (1970)
Silurian Devonian	550 - 630	Colton (1970)
Devonian Clastics	2770 - 3070	Colton (1970)
Mississippian	550 - 630	Colton (1970)
Pennsylvanian	800 - 950	Colton (1970)
	6500 meters	
West Virginia Sands (Pennsylvanian)		
Pocohontas	230	Arkle (1979)
New River	360	Arkle (1979)
Kanawha	710	Arkle (1979)
Charleston	100	Arkle (1979)
Conemauch	100	Arkle (1979)
	1500 meters	

APPENDIX C

FOURIER SHAPE ANALYSIS FOR PACKING

Artificial Samples

Samples		1st	2nd	3rd	4th	5th	6th
Unpacked	*1A	.0244	.1693	.1182	.0826	.0647	.0414
Unpacked	**1A	.0212	.1407	.1116	.0785	.0560	.0385
Unpacked	*1B	.0268	.1831	.1022	.0648	.0409	.0304
Unpacked	**1B 1)	.0239	.1484	.1054	.0763	.0506	.0381
	2)	.0225	.1429	.0930	.0630	.0432	.0318
Packed	*1A	.0239	.1428	.0974	.0570	.0401	.0305
Packed	**1A	.0193	.1497	.0879	.0604	.0378	.0294
Packed	*1B 1)	.0204	.1295	.0912	.0685	.0422	.0326
	2)	.0182	.1354	.0922	.0553	.0391	.0399
Packed	**1B	.0152	.1229	.0892	.0626	.0442	.0321
Unpacked Ottawa	**1A	.0141	.1424	.0811	.0471	.0317	.0343
Packed Ottawa	**1A	.0168	.1566	.0860	.0502	.0317	.0286

Natural Samples

Samples	1st	2nd	3rd	4th	5th	6th
Galesville						
F-G-1	.0135	.1365	.0675	.0481	.0415	.0295
G-1-7E	.0171	.1507	.0704	.0521	.0403	.0264
G-4-8E	.0158	.1326	.0751	.0523	.0484	.0277
G-6-6N	.0136	.1407	.0742	.0485	.0403	.0375
G-3-30E	.0183	.1668	.0783	.0626	.0429	.0338
*F-G-1	.0117	.0971	.0616	.0434	.0417	.0308
Grand River						
F-LG-1	.0184	.1456	.0715	.0502	.0420	.0292
F-LG-2	.0151	.1429	.0634	.0496	.0382	.0315
Berea						
F-B-1 (A)	.0135	.1198	.1688	.0496	.0399	.0354
F-B-1 (B)	.0135	.1190	.0684	.0494	.0404	.0361
F-B-1 (C)	.0127	.1285	.0536	.0511	.0382	.0316
F-B-2	.0169	.1200	.0642	.0405	.0380	.0314
Pottsville						
F-Pt-1	.0116	.1530	.0570	.0542	.0423	.0310
F-Pt-2	.0183	.1222	.0661	.0515	.0360	.0321
*F-Pt-1	.0112	.1326	.0459	.0559	.0412	.0321
*F-Pt-2	.0106	.1127	.0576	.0436	.0507	.0270

* Parallel
** Perpendicular

Artificial Samples

Samples	Harmonics 1st	2nd	3rd	4th	5th	6th
Pocono						
F-P-1	.0315	.1332	.0711	.0610	.0420	.0324
F-P-2	.0142	.1365	.0565	.0571	.0399	.0341
*F-P-2	.0104	.1071	.0582	.0526	.0301	.0302
Keefer						
F-K-1	.0157	.1562	.0601	.0584	.0349	.0337
Tuscarora						
TS-4-SG (A)	.0187	.1506	.0823	.0620	.0469	.0348
TS-4-SG (B)	.0187	.1501	.0823	.0621	.0467	.0352
TS-4-SG (C)	.0204	.1473	.0735	.0575	.0455	.0297
TS-5-NG (A)	.0153	.1583	.0775	.0588	.0419	.0330
TS-5-NG (B)	.0158.	.1595	.0616	.0567	.0377	.0317
TS-33-NG (A)	.0132	.1311	.0620	.0598	.0425	.0356
TS-33-NG (B)	.0137	.1202	.0655	.0539	.0442	.0304
TS-33-NG (C)	.0143	.1235	.0585	.0500	.0364	.0309
TS-12-B	.0125	.1334	.0592	.0513	.0405	.0301
TS-16-B	.0152	.1359	.0636	.0619	.0423	.0288
TS-40-B	.0156	.1615	.0624	.0546	.0433	.0315
TS-37-MG	.0214	.1196	.0725	.0571	.0404	.0331
Oriskany						
OR-40	.0142	.1240	.0633	.0495	.0444	.0274
OR-41	.0121	.1307	.0578	.0477	.0342	.0277
Pennsylvanian (From West Virginia)						
R-1-1	.0144	.1163	.0666	.0502	.0456	.0279
R-1-2	.0168.	.1337	.0717	.0497	.0400	.0324
R-3-1	.0123	.1264	.0605	.0504	.0398	.0348
RII4	.0136	.1390	.0775	.0531	.0414	.0290
E-3-2	.0215	.1574	.0704	.0619	.0431	.0329
Maximum % Error in Reproducibility	8.73	9.32	21.64	12.39	17.65	15.57

BIBLIOGRAPHY

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Athy, L. F., 1930, Density, Porosity and Compaction of Sedimentary Rocks: Amer. Assoc. Petrol. Geol. Bull., V. 14, pp. 1-24.

Arkle, T. Jr., et. al., 1979, The Mississippian and Pennsylvanian (Carboniferrous) Systems in the United States -- West Virginia and Maryland: U.S.G.S. Prof. Paper, 1110-A-L, 35 p.

Beard, D. C. and Weyl, P. K., 1973, Influence of Texture on Porosity and Permeability of Unconsolidated Sand: American Assoc. Petrol. Geol. Bull., V. 57, pp. 349-369.

Blatt, H., 1979, Diagenetic Processes in Sandstones: Soc. Econ. Paleo and Miner. Spec. Publ., No. 26.

Collins, H. R., 1979, The Mississippian and Pennsylvanian (carboniferrous) Systems in the United States -- Ohio U.S.G.S Prof. Paper, 110-A-L, 24p.

Colton, G. W., 1970, The Appalachian Basin -- Its Depositional Sequences and Their Geologic Relationships: Studies of Appalachian Geology: Central and Southern, Interscience Publishers, New York, pp. 5-47.

Edmunds, W. E. et. al., 1979, The Mississippian and Pennsylvanian (Carboniferrous) Systems in the United States -- Pennsylvania and New York: U.S.G.S. Prof. Paper, 1110-A-L, 33 p.

Ehrlich, R. and Weinberg, B., 1970, An Exact Method for Characterization of Grain Shape: Jour. Sed. Pet., V. 40, p. 205-212.

Emery, J. R., 1954, The Application of a Discriminant Function to a Problem in Petrography: Unpubl. M.S. Thesis, Penn. State, Univ., 120 p.

Fraser, H. J., 1935, Experimental Study of the Porosity and Permeability of Clastic Sediments: Jour. Geol. V. 43, p. 910-1010.

Gaither, A., 1953, A Study of Porosity and Grain Relationships in Experimental Sands: Jour. Sed. Pet., V. 23, pp. 180-195.

Graton, L. C. and Fraser, H. J., 1935, Systematic Packing of Spheres -- With Particular Relation to Porosity and Permeability: Jour. Geol., V. 43, p. 785-909.

Griffiths, J. C., 1961, Scientific Method in Analysis of Sediments: McGraw-Hill Book Co., New York, 508 p.

Halley, R. B., 1978, Estimating Pore and Cement Volumes in Thin Section: Jour. Sed. Pet., V. 48, pp. 642-650.

Harrel, J. A. and Eriksson, K. A., 1979, Empirical Conversion Equations for Thin Section and Sieve Derived Size Distribution Parameters: Jour. Sed. Pet., V. 49, p. 273-280.

Heald, M. T. and Renton, J. J., 1966, Experimental Study of Sandstone Cementation: Sed. Pet. V. 36, pp. 977-991.

Hedberg, H. D., 1926, The Effect of Gravitational Compaction on the Structure of Sedimentary Rocks: Am. Assoc. Petrol. Geol. Bull., V. 10, p. 1035-1072.

Kahn, J. S., 1956a, Analysis and Distribution of the Properties of Packing in Sand-Sized Sediments: 1) On the Measurement of Packing in Sandstones; Jour. Geol., V. 64, pp. 385-395.

------ 1956b, Analysis and Distribution of the Properties of Packing in Sand-Sized Sediments: 2) Distribution of the Packing Measurements and an Example of Packing Analysis: Jour. Geol., V. 64, pp. 578-606.

Lilienthal, R. T., 1978, Stratigraphic Cross-Sections of the Michigan Basin: Geol. Surv. Div., Mi. Dept. of Nat. Res., Rept. on Invest. 19, 89 plates, 36 p.

Lowry, W. D., 1956, Factors in Loss of Porosity by Quartzose Sandstones of Virginia: Am. Assoc. Petrol. Geol. Bull., V. 40, p. 489-500.

Manus, R. W. and Coogan, A. H., 1974, Bulk Volume Reduction and Pressure Solution Derived Cement: Jour. Sed. Pet., V. 44, p. 466-471.

Marvin, J. W., 1939, The Shape of Compressed Lead Shot and Its Relation to Cell Shape: Amer. Jour. Botany, V. 26 pp., 288-295.

McBride, E., 1963, A Classification of Sandstones: Jour. Sed. Pet., V. 33, p. 664-669.

Minoura, C. D. and Conley, N., 1971, Technique for Impregnating Porous Rock Samples with Low Viscosity Epoxy Resin: Jour. Sed. Pet., V. 41, p. 858-861.

Pepper, J. F., DeWitt, H. W., and Demarest, D. F., 1954, Geology of the Bedford Shale and Berea Sandstone in the Applachian: U.S.G.S. Prof. Paper, 259, 111p.

Pierce, K. L., 1966, Bedrock and Surficial Geology of the McConnelsburg Quadrangle, Pennsylvania: Penn. Geol. Surv., Atlas 109A, pp 1-111.

Pittman, E. D. and Lunsden, D. N., 1968, Relationship between Chlorite Coatings on Quartz Grains and Porosity, Spiro Sand, Oklahoma: Jour. Sed. Pet., V. 38, 668.

Ramsay, J. G., 1967, Folding and Fracturing of Rocks: McGraw-Hill Co., New York, 568 p.

Rittenhouse, G., 1971a, Pore-Space Reduction by Solution and Cementation: Amer. Assoc. of Petrol. Geol. Bull, V. 55, p. 80-91.

------ 1971b, Mechanical Compaction of Sands Containing Different Percentages of Ductile Grains: A Theoretical Approach: Amer. Assoc. Petrol. Geol. Bull., V. 55, p. 92-96.

Schaffner, M. N., 1963, Geology and Mineral Resources of the Donegal Quadrangle, Pennsylvania: Penn. Geol. Surv. Atlas 48. pp 1-66.

Sibley, D. F. and Blatt, H., 1976, Intergranular Pressure Solution and Cementation of the Tuscarora Orthoquartzite: Jour. Sed. Pet., V. 46, p. 881-896

Siever, R., 1959, Petrology and Geochemistry of Silica Cementation in some Pennsylvanian Sandstones: SEPM Spec. Publ. 7, p. 55-79.

Siever, R., 1962, Silica Solubility, 0^{o}c-200^{o}c, and the Diagenesis of Siliceous sediments: Jour. Geol., v. 70, p. 127-150.

Sippel, R. F., 1968, Sandstone Petrology, Evidence from Luminescense Petrography: Jour. Sed. Pet., V. 38, p. 530-554.

Taylor, J. M., 1950, Pore Space Reduction in Sandstones: Amer. Assoc. Petrol. Geol. Bull., V. 34, pp. 701-716.

Tickell, F. G. and Hiatt, W. N., 1938, Effect of Angularity of Grain on Porosity and Permeability of Unconsolidated Sands: Amer. Assoc. Petrol. Geol. Bull., V. 22, p. 1272-1274.

Waldschmidt, W. A., 1941, Cementing Materials in Sandstones and Their Probable Influence on Migration and Accumulation of Oil and Gas: Amer. Assoc. Petrol. Geol. Bull., V. 25, pp. 1839-1879.

Weyl, P. K., 1959, Pressure Solution and the Force of Crystallization -- A Phenomenological Theory: Jour. Geophys. Res., V. 64, p. 2001-2025.

Whisonant, R. C., 1970, Influence of Texture upon the Response of Detrital Quartz to Deformation and Sandstones: Jour. Sed. Pet., V. 40, p. 1018-1025.

Wilson, T. V., 1977, Porosity Reduction in a Cambrian Quartz Arenite Galesville Sandstone, South Central Wisconsin: Unpubl. M.S. Thesis, M.S.U. 77p.

Wilson, T. V. and Sibley, D. F., 1978, Pressure Solution and Porosity Reduction in a Shallow Buried Quartz Arenite: Amer. Assoc. of Petrol. Geol. Bull., V. 62, p. 2329-2334.