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ECONOMIC AND PETROGRAPHIC EVALUATION

OF GRAVEL RESOURCES IN SOUTHERN MICHIGAN

by

Norman E. Wingard

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ABSTRACT

ECONOMIC AND PETROGRAPHIC EVALUATION
OF GRAVEL RESOURCES IN SOUTHERN MICHIGAN

By

Norman E. Wingard

A pilot study of glacial gravels in Michigan was undertaken to determine petrographic variables to be related to the geology of the deposits and to their economic exploitation.

Samples were obtained over an area of approximately 17,000 square miles in southern and western Michigan in initial pilot and supplemental phases of the investigation.

The gravel deposits are classified genetically on the basis of the apparent dominant environment of deposition. This normally reflects the last cycle of deposition for much if not most of the material comprising the deposit.

An essentially homogeneous suite of lithologies is found in all samples. The relative quantities of various rock types vary within narrow limits but are systematic over large areas. These variations relate to the geometry of the bedrock outcrops relative to flow paths of glacial ice and glaciofluvial transportation. This systematic variation should allow approximate compositional estimates to be made for drift materials within the area. Certain lithologic types can be related to their bedrock source, whereas others, especially carbonates are often non-distinctive.

Distribution of materials in the deposits is apparently caused by

directional deviation of ice paths between different advances, changes of direction within individual ice masses, and dispersion of materials because of the mechanics of ice movement compounded by the effects of sediment re-cycling.

Particle size distribution indicates that even where strong directional orientation of the depositing medium is revealed by cross-bedding, no significant relationship exists between this orientation and the size distribution of materials.

Proglacial deposits display a slightly better mean sorting than ice contact deposits, however, the former are rarely well sorted. A wide range of overlap for sorting values between these categories is interpreted as largely caused by the effects of previous cycles of glacial and proglacial activity. Proglacial channel deposits contain the highest proportion of sand.

Physical characteristics of individual particles show generally low but consistent correlations.

The initial pilot phase, based on pebble counts, versus the supplemental phase using a pebble volume procedure shows that either method can be used to describe areal variations in the distribution of litholigic components; however, the relative volumes of components more clearly relate to the natural distributions and the procedure is more efficient.

Provenance and dispersal are basic considerations in the interpretation of the distribution of drift materials. Factors are location of bedrock outcrop or subcrop beneath the drift, structure and distribution of bedrock units, glacial lobation, associated moraines or morainal system, and the type of deposit based on morphology, structure, and relationships to other deposits.

Systematic regional variations in the composition of drift materials are best reflected by grouping all rock types into a three component system consisting of crystallines, clastics, and carbonates. A finer breakdown of the lithologic suite and other measured variables, including size frequency distribution and physical and chemical properties of individual components are needed only for local or detailed studies of individual gravel deposits.

Generally higher clastic content occurs in deposits related to the Saginaw Glacial Lobe than in those associated with the Lake Michigan Lobe, the reverse situation may occur, however.

Clastic to carbonate and crystalline to total sedimentary rock ratio maps provide complimentary interpretation of provenance and dispersal: Clastics relate principally to local sources of dilution, crystallines to residual concentrations produced by sedimentary re-cycling and multiple glaciations, and carbonates to a general background level produced by multiple peripheral sources.

Regional evaluation of the gravels is interpreted in terms of their engineering potential. Gravel quality which is dependent upon the amount of deleterious material present varies geographically as a consequence of the non-uniformity of natural interactions. Variations in lithologic content can be used to predict the range of petrographic characteristics relating to concrete aggregate suitability.

Material that constitutes good concrete aggregate is that which is chemically stable and physically sound when encased in portland cement and exposed to weathering. Deleterious rock types found in Michigan gravels are principally shale, chert, ferruginous clay concretions, friable sandstones, siltstones, and other rocks with planes of weakness. Physical and chemical durability may be influenced by coatings, or weathering.

Engineering tests on concrete made from the gravel samples show that chert and ferruginous concretions are the most harmful components in terms of freeze-thaw durability.

The percent of deleterious materials shows an expected inverse relationship to the bulk specific gravity of the aggregate and a direct relationship with percent absorption. No relationship was observed between deleterious content and flexural or compressive strength of the concrete.

Potential alkali reactivity of the aggregate indicates a probable relation to the percent of chert present.

The sum of the engineering tests on the aggregates suggests that heavy media separation should be sufficient for removing most deleterious components from the Michigan gravels. Over beneficiation can be avoided by following guidelines established by regional lithologic analysis of the gravel sources.

ACKNOWLEDGEMENTS

The project was carried out under the auspices of the Research Laboratory Section of the Michigan Department of State Highways as a Highway Planning and Research Project sponsored jointly by the Department and the Federal Bureau of Public Roads.

Thanks are due to the entire laboratory staff, many of whom contributed materially with patient participation in the laboratory work or with conversation and ideas. It is not possible to cite every person who contributed to one or more phases of the project. Several, however, do require special mention. They include M. G. Brown, who originated the project by proposing that aggregate source studies be done by the Department. Gordon Yettaw and B. P. Shah contributed substantially to the initial petrographic analysis. T. A. Herbert helped to develop the volume pebble analysis technique by working as field assistant and laboratory petrographer in the supplemental phase. Many of the ideas developed have been influenced by conversations with Mr. Herbert and by his critical review and comments on the manuscript.

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INTRODUCTION

The study was undertaken at the request of the Research Laboratory Section of the Michigan Department of State Highways. The need was expressed for more detailed knowledge of the glacier-related deposits of Michigan which serve as the principal source of aggregate materials for concrete construction.

The original stated objectives were:

1. "To develop a classification system for glacial aggregates based on geological history and origin.

2. "To determine the engineering properties of a representative number of glacial aggregates from various geological backgrounds.

3. "To determine if any correlations exist between goelogical background and engineering properties used for predicting performance of aggregates.

4. "To verify by experimental means whether reasonable prediction for performance of aggregates in pavements can be made by classifying the geological background of the aggregates."

The demand for low-cost aggregate materials for concrete structures and highways has been constantly increasing while the more readily available, high quality sources are being depleted. Michigan is the second largest producer of sand and gravel in the nation, with an annual production in 1966 of over 55 million tons, at the value of nearly 50 million dollars. Production figures for sand and gravel in Michigan for the 10 year period of 1957 through 1966 are given in Table 1.

TABLE 1

Sand and Gravel Production in Michigan from 1957 to 1966

Year	Million Short Tons	Value in Thousands of Dollars	Rank in U.S.
1957	41,838	35,144	2
1958	39,871	34,616	2
1959	48,052	41,193	2
1960	46,910	39,304	2
1961	54,603	47,790	2
1962	47,563	42,029	2
1963	50,458	43,433	2
1964	51,921	44,405	2
1965	53,168	47,176	2
1966	55,123	49,521	2

The over-riding purpose of the project is to establish the basis for a statewide survey of all gravel sources in Michigan. To implement the study, an area of Michigan was selected for investigation where heaviest use of aggregate occurs (excluding the Detroit metropolitan area) and, consequently, where the most critical need for detailed knowledge of the sources was felt. Initial work was focused around five metropolitan centers: Lansing, Jackson, Kalamazoo-Battle Creek, Grand Rapids, and Flint.

All known pits were visited and, where geologically representative samples were considered obtainable by hand shovelling techniques, were sampled. Generally between 600 and 1000 pounds of gravel were removed for laboratory analysis. Sampling was done by cutting vertical channels in as many exposure faces as possible, augmented by spot samples where channel samples could not be obtained.

Laboratory examination of the samples included petrographic determination of the pebbles, and specialized analyses of selected pebbles. Such special analysis included x-ray diffraction, thin section, and chemical. Engineering-type tests were performed on concrete specimens made from each sample in order to correlate potential engineering performance with geologic and petrographic variables.

Preliminary interpretation of the initial pilot data from 99 sources revealed the need to extend the geographic area of investigation. A supplemental study was done to test derived geological inferences and to develop and implement more effective field and laboratory techniques based on knowledge gained by the initial phase.

LOCATION AND EXTENT OF AREA

The initial study area spans approximately 7500 square miles constituting most of the central part of the southern quarter of Michigan's lower peninsula as shown by the solid line on Figure 1.

Selection of central southern Michigan for the study was based on the critical need for nearby sources of suitable materials for concrete aggregate. The size of the area was considered appropriate for a pilot study to determine the general relationship on a regional basis. The area is included between latitudes 42° and 43° 15' north and longitudes 83° 15' and 86° west. It comprises all or portions of 19 counties with Eaton County at its approximate center. The area contains and surrounds the five metropolitan areas of Lansing, Jackson, Battle Creek- Kalamazoo, Grand Rapids, and Flint. The supplemental study area is described on page 59.

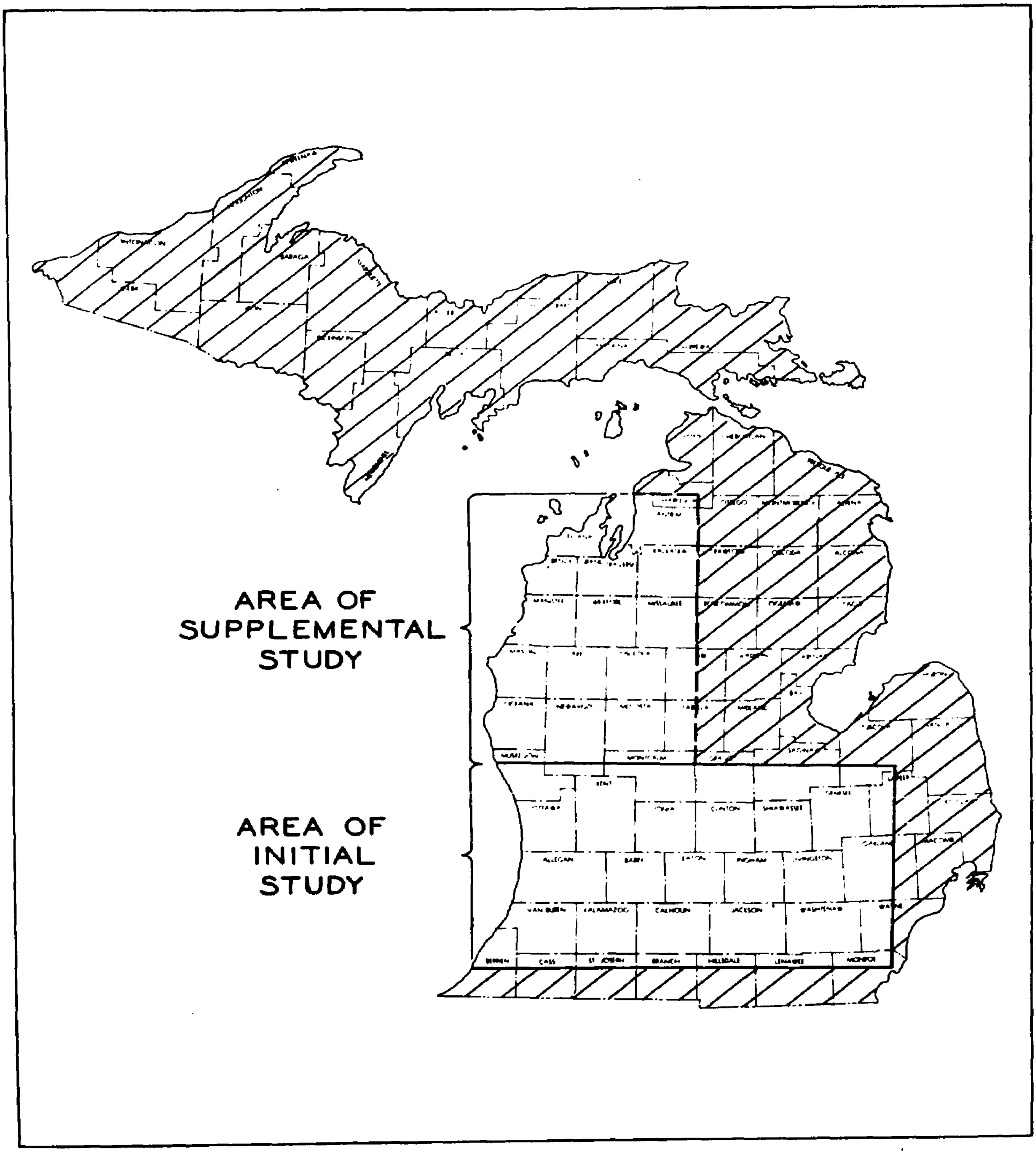

Figure 1. Index map showing location of study area.

GEOLOGY

Bedrock

The materials that make up the gravels and the other glacial deposits are derived entirely from the underlying bedrock over which the glaciers spread. In Michigan these materials were ground out of the rocks of the Michigan basin upstream from their place of deposition or were removed from the Canadian Shield area of Precambrian crystalline rocks in Canada. Figure 2 is a generalized geologic map of Michigan.

Pleistocene Geology of Michigan

The glacial features of the southern peninsula, developed during the Wisconsinan glacial stage, are related to three ice lobes which coalesced to form a continental ice sheet, at the time of maximum ice extent but were more or less distinct during advance and retreat. These were the Michigan or Lake Michigan Lobe which occupied the present Lake Michigan basin, the Saginaw Lobe which extended southwesterly from Saginaw Bay, and Huron-Erie Lobe which occupied the Lake Erie basin, the southern part of Lake Huron basin, and the portion of Ontario between the two basins.

Deposition of materials by ice and meltwater associated with one or more of these three lobes has produced a north-south succession of moraines. These are described in detail elsewhere (Leverett and Taylor, 1915). Moraines and

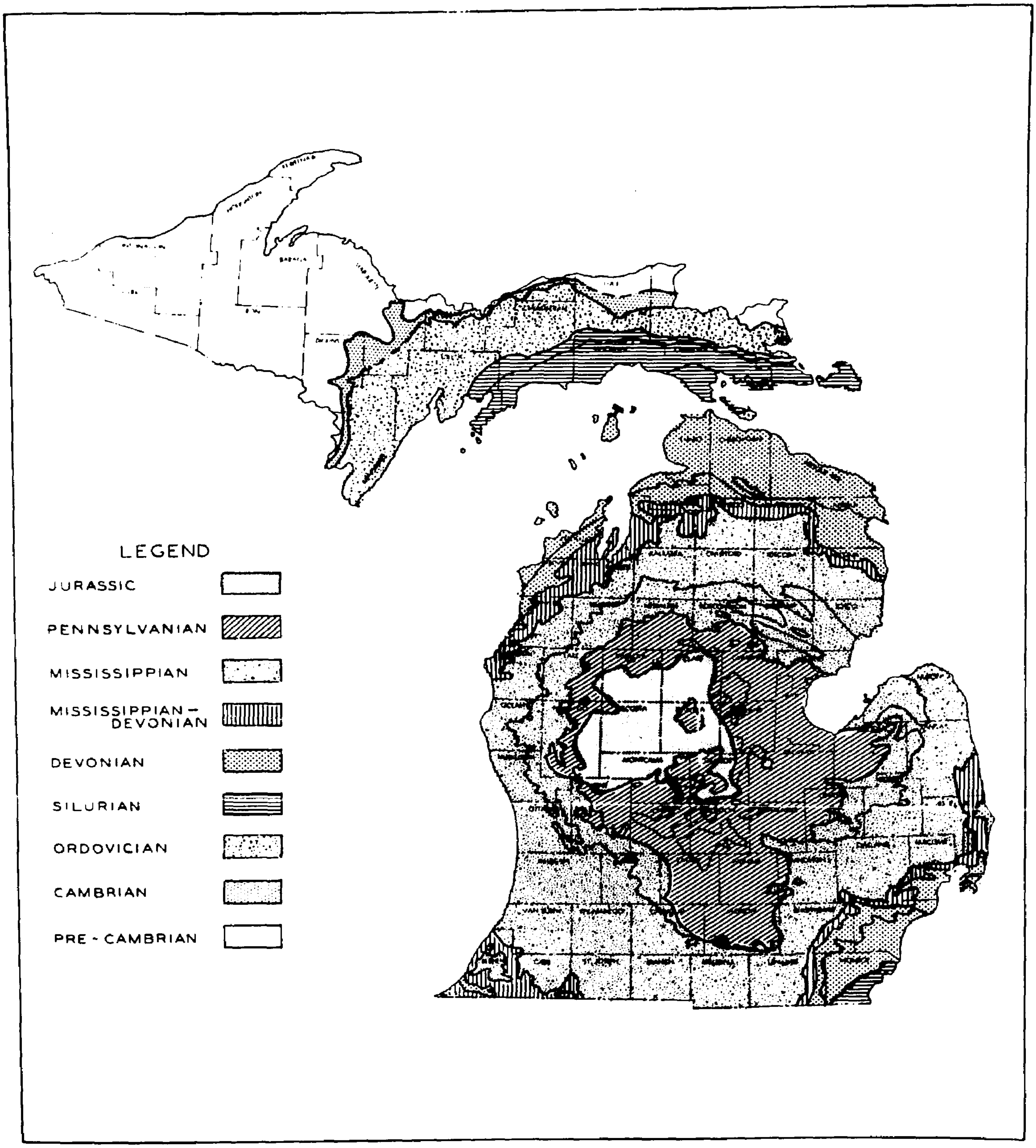

Figure 2. Geologic map of Michigan.

their associated outwash deposits in this principal study area can be seen in Figure 3.

To simplify discussion, these moraines were grouped by Leverett (1915) into morainic systems. The systems are groups of associated moraines of a given lobe or those with similar interlobate relationships.

Most of the major moraines of the southern half of the Lower Peninsula of Michigan are included in Leverett's Kalamazoo and Valparaiso morainic systems of the Lake Michigan Lobe, the Kalamazoo and Charlotte systems of the Saginaw Lobe, and the Mississinawa, Salamonie, Wabash, and Fort Wayne moraines of the Huron-Erie Lobe, and the interlobate belts between the Lake Michigan and Saginaw Lobes and between the Saginaw and Huron-Erie Lobes.

The more weakly developed moraines include the Sturgis and Tekonsha moraines, formed during recession of the Saginaw Lobe, but bordering all three lobes; the Lake Border Morainic System of the Lake Michigan Lobe, a series of weakly developed moraines in the Saginaw basin ; and the group of moraines between Huron and Erie basins including the Port Huron Morainic System, the Birmingham, Mt. Clemens, Emmett, etc. The Port Huron Moraine, however, is locally well developed and largely continuous along much of the eastern side of the Southern Peninsula (Leverett and Taylor, 1915).

A later re-advance by glacial ice is represented by the Valders Till. This largely consists of low, flat ground moraine composed of red till

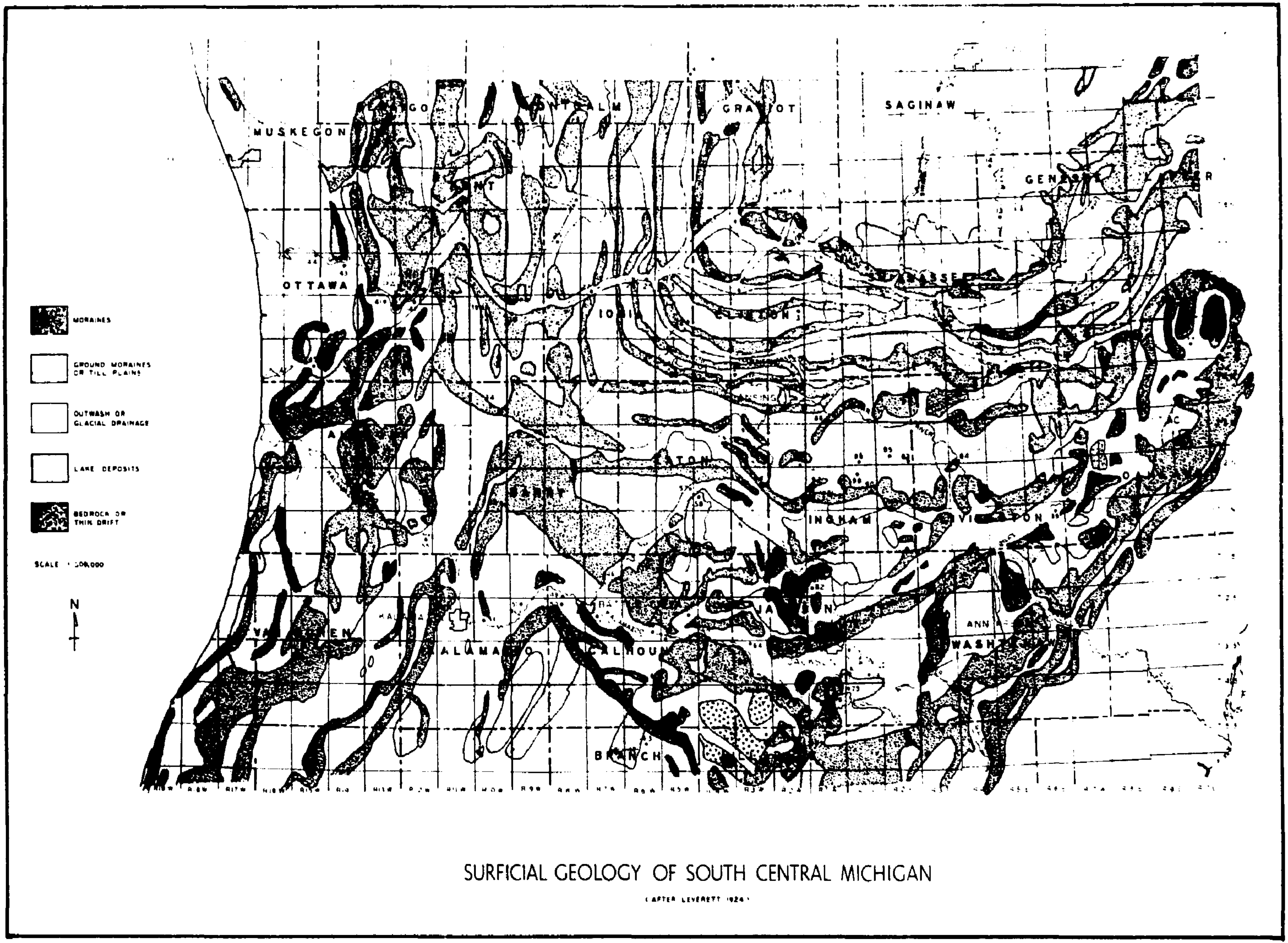

Figure 3. Glacial geology of south central Michigan.

bordering Lake Michigan to the north, (Melhorn, 1953).

Saginaw Lobe

The materials for the initial study were taken principally from Saginaw Lobe deposits and, in part, from the contiguous interlobate areas. A brief discussion is therefore, presented.

The central glacial lobe in southern lower Michigan, the Saginaw, moved southwestward from the Saginaw basin into Indiana. This lobe melted back while the Lake Michigan and Huron-Erie lobes still reached into Indiana. The relative weakness of the Saginaw Lobe as compared to its neighboring lobes was due to the fact that beyond the Saginaw basin the ice traversed across more elevated country. This resulted in less thickness and weaker development of the ice (Leverett and Taylor, 1915).

Several strong moraines developed in Michigan by the Saginaw Lobe ice. Leverett believed that prominant moraines could be formed by recession of this relatively small ice lobe because of increased load of drift material caused by the convergence of the three lobes. This load may, in fact, have been a factor in the weakness of movement of the Saginaw Lobe.

South of the Grand River Channel (occupied, in part, by the Maple River) the distribution of moraines has been greatly influenced by the relation of the Saginaw Lobe to the topography.

Descriptions of the individual moraines in this group can be found on pages 238 to 240 of U. S. Geological Survey Monograph 53.

Landforms versus Deposits

The most extensive glacial forms are recessional moraines, ground moraines or till plains, lake plains, and gravel or outwash plains. Recessional moraines mark positions of the glacier front subsequent to the building of the terminal or end moraine. These represent times when accretion of ice and melting were nearly balanced. These moraines may be land laid or water laid, depending on whether deposition was on land or in water ponded in front of the glacier.

Ground moraines or till plains lie between successive recessional moraines. They indicate areas where the receding glacier deposits its load of heterogeneous material without sorting. Locally till plains are reworked by melt waters.

Kames. A "kame" is an ice-contact feature. At least two principal methods of origin have been postulated (Flint, 1957, pp. 147-148). One method is the accumulation of debris on or in the surface of stagnant ice which later melts to leave this accumulation in a supposedly characteristic cone shape. The other is for a delta or outwash cone to be built in front of the ice. Later melting of the ice causes collapse on the side toward the ice and isolation of the remaining mound. In addition, "kames" may originate as crevasse fillings in the ice sheet. According to Sparks (1960), "Although these forms are recognizable when their initial shape is well preserved, they may degenerate slowly, through the action of erosion, to shapeless mounds of gravel, at which state it is very difficult to determine their origin." "Kames" thus, as with many other topographic features, are polygenetic. Their surface expression or landform does not necessarily represent any specific depositional environment.

Kettle Lakes. Kettles or kettle lakes are roughly circular depressions, frequently occurring on outwash plains, but sometimes found among moraines, or till plains, or elsewhere. They are traditionally regarded as having formed by melting of blocks of ice that have broken off of the main mass of the glacier during times of retreat and ablation. Ferris, et. al. (1954), offer an alternative to the classical ice block stranding hypothesis for the formation of kettle lakes in Oakland County, Michigan, which show a non-random areal distribution. The elevation of the major deeps in these lakes show a progressive deepening in a direction accordant with that of the slope of the bedrock topography. This consistency would not be likely from the random stranding of ice blocks. The lakes appear to occur over pre-glacial drainage lines with the elevation of their deeps corresponding to the surface of basal sands and gravels in the channel. The principal axes of the deeps in addition, correspond with the dominant frequencies of bedrock shear lineations (Kelly, 1936, p. 215). Pre-existing topographic lows, including drainage lines are left with "ice plugs" after the glacial ice has melted off the interfluves. The ice plugs are buried by the debris from melting ice from higher areas. Ice remaining in the lows may protect the depression from subsequent advances. Eventually the ice melts from the lows leaving depressions.

Outwash Plains. Outwash or gravel plains ideally are deposits with an internal sorting in which granular material predominates. These gravel deposits were laid down by braided meltwater streams that were overburdened with sediments.

Lake Beds. Lacustrine deposits or old lake beds are made up of clay or sands, either of which may be locally predominant. Lake beds are relatively flat, and in some places cover previous glacial or glaciofluvial deposits.

Deposits

The preceeding discussion of the more prominent glacially related landforms illustrates that similar topographic expressions may result from diverse origins. Similarly, materials deposited in two or more areas by identical or allied processes need not necessarily form surface expressions identifiable by present geomorphic terminology.

The materials of glacial and glaciofluvial deposits reflect the dynamic conditions at the time of deposition. The materials of the deposits must, then, be considered as components of a sedimentologic unit related to the dynamics.

Geomorphic terminology, which has long been used to describe glacial and associated surface features, cannot be used in a classification scheme for the materials composition of glacial and related deposits.

Geomorphology being the progency of "Physiography" is classically a descriptive study of surface features. The inherited terminology, useful in descriptive context, has no specific genetic significance. Many morphologic features are formed by a complex interaction of several dynamic processes, both depositional and erosional. The dynamics of sedimentation, on the other hand, are by far the dominant factors controlling the size frequency distribution of materials and as such must be used as the basis of classification.

Other factors which must then be taken into account in evaluating the deposit are: (1) provenance, source of the individual constituents: (2) dispersal; and (3) post-depositional processes such as solution, replacement, decomposition, disintegration, etc. which may affect the materials of the deposit to some degree.

Classification of Deposits

In order to sample and evaluate the complete spectrum of glaciofluvial materials it is necessary that a classification scheme be used that is based on the processes of sedimentation. Factors considered are depositional medium, such as glacial ice, melt water, etc. Field criteria used to recognize each class include primary sedimentary structures, geometry of the deposit, and texture of the material. Geomorphic terms for the associated topographic features are listed for each type of deposit as well as a mention of the structures which may be displayed. Table 2 lists the glacial and glacial-related types of deposits considered in the present study.

An attempt has been made to make the classification simple and straightforward. One of the project goals is to facilitate economic exploitation. In order to meet this goal the results must be interpretable to engineers and others interested in exploration of the materials, as well as to geologists.

Field criteria used to recognize geomorphic forms are the same characteristics widely recognized by glacial geologists and extensively described in the literature. Repetition here is outside the scope of the study, however,

TABLE 2

Classification of Glacial and Related Deposits

Genetic Type	Textures and Sedimentary Structures	Possible Associated Landform
(1) Glacial - includes all material deposited directly by glacial ice.	Till, no apparent stratification.	End moraines - including both terminal and recessional. Medial moraines Lateral moraines Ground moraines or till plains.
(2) Glaciofluvial morainal or morainal-ice contact	a. Water - laid drift, shows weakly developed stratification, may be discontinuous, often displays ice-shove features. b. Poorly sorted or clay-silt gravels.	Kame, Kame complex, and/or recessional moraine. Local "outwash" fan or cone, etc.
(3) Confined ice-contact	Poorly to moderately sorted gravels.	Eskers
(4) Glaciofluvial drainage channel (confined outwash	Moderately to well sorted gravels. Extensive cross bedding - foreset dips generally greater than in (5).	Confined drainage channels,"Spillways," valley trains, Kame terraces.
(5) Glaciofluvial outwash (unconfined outwash)	Moderately to well sorted gravels. Crossbedding at lower angles than in (4).	Outwash plains.

the reader is referred to Flint (1957), Thwaites (1956), Leverett (1902, 1917, 1929), Leverett and Taylor (1915), Lane (1907), Kneller (1964), Bretz (1955), Huxel and Petri (1965), and others.

Ideally a classification of deposits would have a genetic basis, reflect all compositional variations and be devoid of subjectivity in interpretation.

Most previous references to glacially related deposits have been geomorphically oriented. In many cases deposits and landform have been mistakenly considered identities. Since varying degrees of association exist between landform and deposit, ranging from complete to none, the degree of subjectivity involved in this type of interpretation is extremely high. This results in confusion and makes the practical applications of work so oriented extremely improbable.

A genetic classification of glacial and glacially related deposits has been used by Huxel and Petri (1965) in North Dakota. Their classification was devised to facilitate the study of local ground water hydrology; however, not surprisingly many of their "geohydrologic units" are similar or identical to the deposit types arrived at here. They recognized four types of glaciofluvial sediments, (A) valley outwash, (B) unconfined outwash, (C) ice-contact deposits, and (D) undifferentiated outwash.

In the present study "undifferentiated" deposit categories have been avoided in an attempt to make the results useable to persons having little or no geological training. Huxel and Petri describe their "undifferentiated outwash" as "thick and discontinuous... interbedded layers of clay, silts, sand, and gravel." Most of this would probably fit into the present classification under "morainal ice-contact" (b) poorly sorted clay or clay-silt gravels.

Most glacial and glaciofluvial deposits are complex. Only in relatively few cases have the processes of deposition been uniform sufficiently long that a gravel deposit could fit perfectly into one of the above categories. In many cases, two or even three of these implied modes of deposition may be reflected in one gravel source. The characteristics that appear to represent the dominant process of deposition have been used to select a depositional category.

Source of Materials

The lithologic analyses carried out here allow reasonably good inferences as to the bedrock sources and routes of glacial and fluvial transportation of much of the material making up the gravels. This knowledge is fundamental to the ultimate economic goal of predicting aggregate suitability on a regional basis.

All gravel sources studied in both the basic 99 source evaluation and the supplemental 133 sample study contain an essentially similar suite of lithologies. The principal distinguishable difference, is in the relative quantities of the various rock types rather than in wide variation in the suite itself.

The uniformity of this assemblage as found over the initial 19 county area and the area to the north sampled in the supplemental study is caused by the geometry of the bedrock outcrops relative to flow paths of glacial ice and glaciofluvial transportation.

The configuration of the Michigan basin is such that glacial advance from any direction passes over essentially the same series of outcropping formations. This caused the same essential suite of rocks to occur in all similarly deposited glacial or glaciofluvial sediments over the basin. The relative contributions from each formation differs in amounts proportional to the degree of angular concordance between the strike of the bedrock and the direction of glacial advance. Where direction of glacial movement became tangential to the strike of the rocks cropping out of the basin surface, the ice picked up the same type of rock material continuously along the course, forming a concentrated train of material down stream from that outcrop.

Figure 4 illustrates the inferred relation of glacier movement over the outcrop pattern of the basin. On the west side of the Lower Peninsula the direction of ice movement along the eastern edge of the Michigan ice lobe becomes tangential and nearly parallel in the strike of the basin rocks. This is reflected in the drift in Kalamazoo County and adjacent areas by concentration of sandstone and ferruginous concretions derived from the lower Marshall Sandstone and the Coldwater Shale.

Conversely, where the glacial advance was at right angles to the strike of the outcrop a much smaller amount of material was added to the ice, in proportion to the stratigraphic thickness of the outcropping lithologic unit. Where the ice passed over a stratigraphic sequence with a dominant lithology a high level of concentration is spread over a wide area. Such a high level occurs as a background concentration for carbonate rocks along the axis of the Saginaw Lobe (this study; Anderson, 1962). The ice deeply eroded as it passed

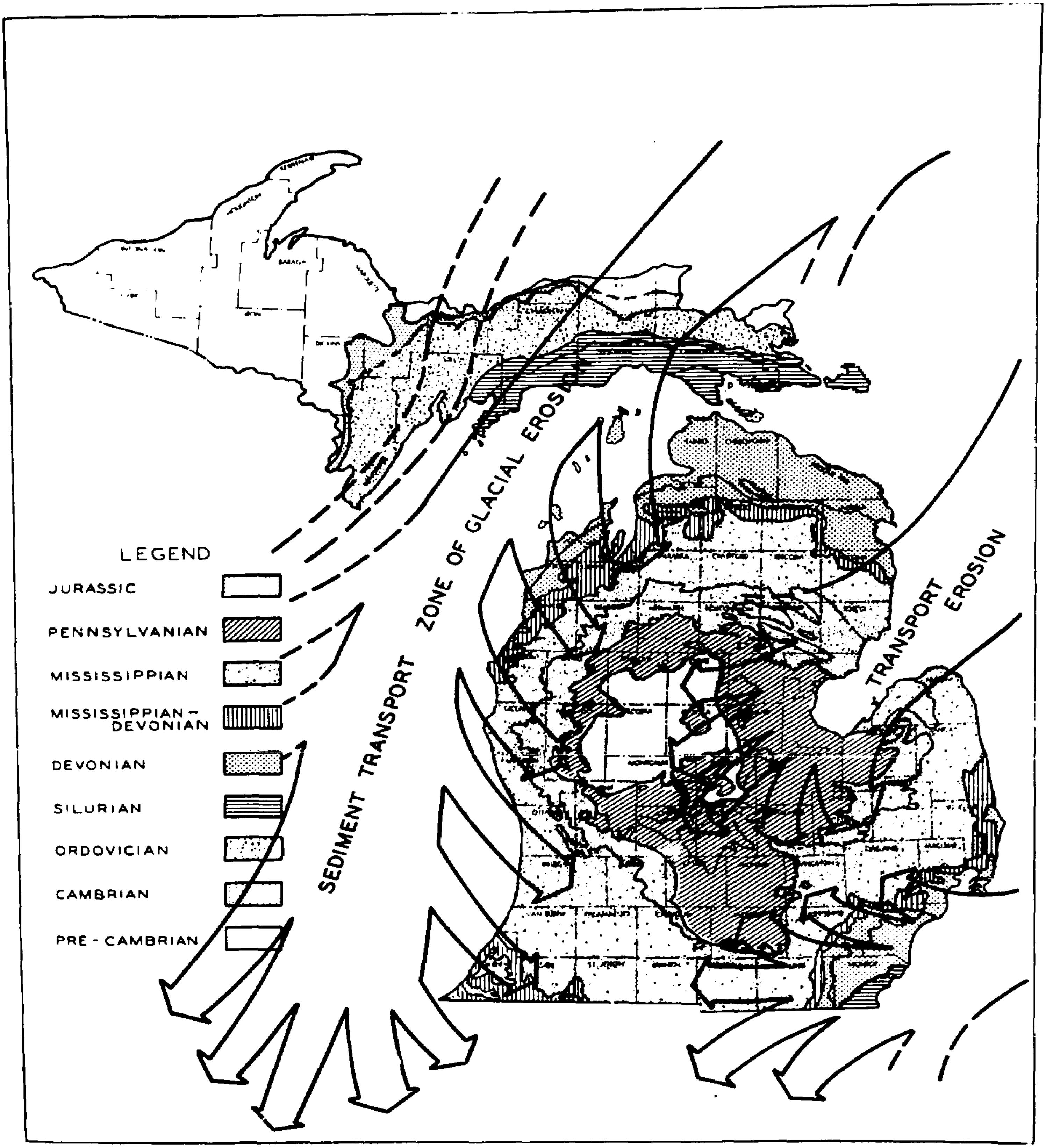

Figure 4. Inferred dispersal paths for glacially transported materials.

over the dolomite of the Niagaran Series that forms the escarpment separating Georgean Bay from Lake Huron. Although this did not supply all of carbonates found in deposits of this lobe it did contribute to a general rise in background level.

Most of the lithologies present in the gravel suite have been derived from the rocks of the part of the Michigan Basin that underlies the Lower Peninsula. Those which have been contributed from outside of this part of the basin are from bedrock sources in the Upper Peninsula and in Canada. With the exception of the Niagaran dolomites these rocks that are far-travelled are minor compared with those of local derivation. These far-travelled components constitute most of the igneous and metamorphic rock types from the Upper Peninsula of Michigan and from the shield area of Ontario.

Assignment of a pebble found in the gravel to a specific bedrock unit can be done only if the particle possesses distinctive identifying characteristics known to be associated with a stratigraphic unit. Many rock types found in the gravels are non-distinctive. This is especially true for carbonates, which can rarely be assigned to a specific unit. Sedimentary structures can rarely be observed in the particles and, generally, if vestiges of fossils remain, they are too badly abraided for specific identification. The same ambiguity holds for many other sedimentary rocks and igneous and metamorphic rocks as well. A shale, a basalt, or a quartzite pebble, to be assigned to a bedrock source unit must show some identifiable physical, chemical, or structural feature.

The rock types that are most frequently identifiable in terms of probable stratigraphic derivation are certain sandstones, some concretions, slates, schists, phaneritic igneous rocks, and any rocks containing petroliferous or carbonaceous matter.

Where the ice advanced over older drift that had been deposited by earlier ice or glaciofluvial action, the pre-existing drift was incorporated into the ice, thus greatly diluting the newly eroded first-cycle sediments. Any moraine and its associated proglacial deposit may thus be made up largely of second, third, and multicycled glacial sediment. Each minor advance and recession will have caused some erosion, transportation, and deposition of material.

Directional deviation of ice paths between different advances, changes of direction even within a single ice mass, and dispersion of materials due to the mechanics of ice movement compound the effects of sediment re-cycling to produce the distribution of materials found in the surficial deposits.

PROCEDURES

Preliminary Field Work

Initial field work consisted of reconnaissance of gravel exposure localities. Its purpose was twofold: (1) to observe the character of individual deposits so that a workable classification of glacial deposits could be established which would be amenable to the practical goal of the project, yet based on sound geologic principles, and (2) determine techniques for taking samples within the limits of available facilities which would satisfy the requirements of the proposed analysis.

During the early phase of the field work, measurements were made to determine the attitude of sedimentary structures in the gravel exposures. The strike and dip of foreset beds were measured in a number of exposures throughout the pits. The number of measurements was determined by the extent of exposure where the beds could be determined to be definitely in place. These were repeated throughout both the vertical and lateral extent of the exposure.

These measurements were then plotted as face poles on a Schmidt Stereographic Net. The distribution of points was determined by a point counting technique and the density of points falling on the plot was contoured. If a dominant direction of dip was evident from the plot, the perpendicular was taken as the average current direction.

Sampling

The sampling technique finally used for the bulk of the sampling was decided on the basis of the outcome of the study of the relationship of the mechanical distribution to sedimentary structures. The lack of correlation between the average current direction, even where strongly displayed, and the particle size distribution rendered it of no advantage to continue the time consuming procedure of measuring and plotting foreset bedding planes.

Since the purpose of the study was to characterize the gravel deposit, as a whole, an engineering type of sample was desirable. A sample that would best represent the deposit within the scope of time and equipment limitations was determined to consist of multiple channel samples where possible. Frequently it was necessary to offset the channel in order to obtain the complete vertical section.

Before sampling, all materials that had slumped over the face of the exposure were shovelled away in order to prepare a vertical face. The vertical extent of the exposure was increased by digging downward to a practical limit - either the water table or until caving prevented further progress. The entire vertical column was then sampled by using a pick-mattock and large sand scoop. A sample cross section of approximately six square inches was visually estimated and maintained during the sampling. Occasionally larger areas would cave-away under the impact of the pick-mattock but the excess material was not bagged.

This procedure was repeated from two to six times throughout the pit. The number of channel samples was determined by the amount of exposure present. In the initial phase 476 gravel pits were visited, of which 99 could be sampled by the manual methods employed. This type of sampling procedure is adequate only in active or recently active pits. In older exposures, where extensive slumping has occurred or vegetation has become established, samples could not be obtained in a reasonable length of time.

Mechanical Analysis

Particle size distribution was determined for the gravel fraction for all 99 samples to the intervals listed in Table 3.

TABLE 3

Sieve Size Grades for Gravel Analysis

Inches	Millimeters
2	50.8
2 - 1-1/2	50.8 - 38.1
1-1/2 - 1	38.1 - 25.4
1 - 3/4	25.4 - 19.0
3/4 - 5/8	19.0 - 16.0
5/8 - 1/2	16.0 - 12.7
1/2 - 3/8	12.7 - 9.51
3/8 - 3/16	9.51 - 4.76
<3/16	<4.76

A Gilson sieve shaker was used for the sieving. A minimum of five minutes was used for all samples.

Petrographic Analysis

The petrographic analysis of the gravel components consisted of a pebble count and various supplemental tests of physical and chemical characteristics on selected particles.

Its purpose was to determine the relative abundance of specific rock types and certain physical and chemical attributes of each that might bear some relationship to the geology of the deposits and engineering applications of the materials.

Principally, the petrographic examination was performed by means of a binocular microscope. The samples sieved during the mechanical analysis were re-sized into three grades:

1-1/2 - 1 1 - 3/4	1-1/2 - 3/4
3/4 - 5/8 5/8 - 1/2 1/2 - 3/8	3/4 - 3/8
3/8 - 3/16	3/8 - 3/16

The quantity in each was then reduced by splitting to approximately 150 pebbles for petrographic examination. Figure 5 shows the data sheet used to record the results of the petrographic analysis.

Although the > 1.50 inch particles were examined and recorded, the data were not used in the analyses since it was not possible to obtain 150 particles

Sample No. ______________ Size ________
Pit Name ______________________
Location ______________________

PETROGRAPHIC ANALYSIS DATA

Date ______________
Analyzed by ______________

No	Constituent	Sphericity			Weight			Specific Gravity	Absorption	Roundness	Surface Texture	Coatings				Fractures			Strength	Degree of Weathering			Organic Matter	Remarks
		a	b	c	Dry A	Sat. B	Sub. C			P		None	<1/3	>1/3	Composition	None	Few	Many		Fresh	Mod	Str		

Figure 5. Data sheet for initial petrographic analysis.

to maintain equal class size. The number of particles analyzed petrographically was 450 for each of 99 sources for a total of 45,550.

Each particle was evaluated in terms of the following variables:

1. lithology
2. shape (sphericity)
3. roundness
4. surface texture
5. coatings
6. fractures
7. strength
8. degree of weathering
9. organic matter
10. potentially alkali-reactive
11. presence of solubles or sulfides
12. potential base exchange

Sphericity (Shape). Methods of measuring and evaluating particle shape have been proposed by Wadell (1932, 1933), Krumbein (1941), Zingg (1935), Walz (1936), Marwick (1936), Schiel (1943), and others.

Wadell (1932) showed that the shape and roundness are geometrically distinct concepts. The shape being independent of the angularity or roundness of the edges or corners. Shape, fundamentally, measures the ratio of the surface area to the volume of a particle. Wadell defined sphericity as the cube root of the ratio of the volume of the particle and the volume of the circumscribing sphere:

$$\text{Sphericity} = \sqrt[3]{\frac{(\pi / 6)\ D^3}{(\pi / 6)\ A^3}}$$

where D is the nominal diameter of a particle and A is the long dimension of the particle which is equal to the diameter of a circumcribing sphere.

Krumbein (1941) showed that for most particles the nominal diameter, $D^3 = ABC$ where A = long axis, B = intermediate, and C = short axis of the particle, Therefore:

$$\text{Sphericity} = \sqrt[3]{\frac{(\pi\ /6)\ ABC}{(\pi\ /6)\ A^3}} = \sqrt[3]{\frac{BC}{A^2}}$$

The method used here was proposed by Krumbein. It requires only that the long, intermediate, and short diameters are measured and the sphericity is read from a chart or calculated directly. The sphericity is determined by two ratios between pairs of the diameters: the intermediate to long diameter and the short to intermediate diameter. This "intercept method" is based on comparison of the pebbles with a reference solid - a triaxial elipsoid. The three diameters of the pebble are defined as mutually perpendicular intercepts.

Average sphericity can be determined for any group by adding the component sphericities and dividing by the number of pebbles. For this study, a pebble caliper was constructed for the measurement of the three mutually perpendicular intercepts. This device was fashioned from the illustration shown by Krumbein (1941, p. 65). For a discussion of the method and technique of measurement, the reader is referred to Krumbein (1941, p. 66).

Roundness. Wadell's method of determining roundness requires determining the radius of the inscribed circle and the radii of the edges and corners of a projected image. The roundness is then determined as the ratio of the average radius of curvature to the radius of the inscribed circle. A much faster method which was used was that of Krumbein; wherein the roundness of each particle is visually compared with standard images of known roundness. The images were photographically reproduced from Krumbein's chart. Copies were made that were both enlarged and reduced by factors such that the image size was equivalent to the mean diameter for each size grade. Statistical studies of Krumbein's showed that average values for roundness obtained by this technique agree very closely with those obtained by the original method of Wadell. Continued checks, throughout the petrographic analysis, revealed that different workers continually gave similar and consistent values.

Lithologic Identification. After shape measurements and roundness were determined, lithologic identification of each pebble was made by breaking the pebble and observing it by means of a binocular microscope.

Lithologic Terminology. Before standardizing the lithologic terminology approximately 5000 pebbles were identified from 10 sources. Thin sections were made to aid in establishing identity of some of the finer grained rocks. In all, some 80 different rock terms including modifiers were recorded. A standard list of rock terms was then established which included all lithologies found in the gravels, plus several not yet found but thought possible to occur. This permitted a faster, more efficient identification of lithologies and eliminated the use of duplicate or redundant terminology. Table 4 is the list of rock nomenclature used for the remaining 89 samples.

Most of these are standard petrographic terms which can be found described in any petrographic reference book (Huang, 1962; Moorehouse, 1959; Krumbein and Pettijohn, 1938; Milner, 1962; Spock, 1953; Pettijohn, 1957). A few, however, are more specialized in usage and require explanation. These

TABLE 4

LITHOLOGIC TERMS

Igneous

Granite
Syenite
Granodiorite
Diorite
Gabbro
Peridotite
Dunite
Diabase

Felsite
Basalt
Amygdaloid

Pegmatite
Lamprophyre
Carbonatite

Sedimentary

Conglomerate
Breccia
Sandstone, graywacke
Sandstone, arkose
Sandstone, quartzitic
Siltstone
Calcareous siltstone
Shale

Crag
Till
Coal
Clay
Silt
Iron oxide (limonite, hematite, severely weathered ferruginous particles)
Ferruginous concretion (clay ironstone)

Limestone
Dolomitic limestone
Calcareous dolomite
Dolomite
Chalk
Chert, I, II, III, or IV
Chert, jasper
Cherty limestone

Metamorphic

Quartzite
Marble
Slate
Phyllite
Schist
Metagraywacke
Metaarkose

Minerals (state)

include crag, a natural concrete composed of gravel cemented together with calcium carbonate. The four categories of chert are visually distinct types described by Michaels, et. al, (1965) and intended to possess different properties affecting engineering usage.

Thin Sections. Thin sections were made and examined for a few selected pebbles which were representative of commonly recurring lithologies and for which identification was uncertain by megascopic means or binocular microscope.

Physical and Chemical Characteristics. Physical and chemical characteristics of each pebble were noted at the time of the lithologic identification. These include surface texture, presence or absence of coatings, fractures, strength, degree of weathering, presence or absence of organic material, or other contaminating substances which could be potentially harmful for use as concrete aggregate.

Surface Texture. A qualitative scale was used to describe the surface texture of each particle. Each textural class was assigned a number as follows:

0 - Smooth and Irregular	- Includes crystalline rocks. All smooth crystal faces and irregular edges and corners.
1 - Rough	- Very finely irregular surface.
2 - Slightly Rough	- Finely irregular surface.
3 - Slightly Polished	- Mostly sedimentary particles, slight stream rounding also characterized these particles.
4 - Polished	- Smooth surface on generally rounded particles.

5 - Smooth - Smooth surface that does not indicate polishing action.

6 - Chalky - Friable, etc.

Coatings. Coatings on particles were classified by both quantity and composition. It has been empirically determined that a particle with less than one-third of its area coated does not normally produce any deleterious effect for engineering purposes. The particles were, therefore, classed as those with (a) no coating, (b) coated on less than one-third of its area, and (c) coated on more than one-third of its area. The composition of the coating was also noted and classified as follows:

1. Friable or loosily bonded material
2. Gypsum
3. Opal, etc.
4. Silt or clay
5. $CaCO_3$ and $MgCO_3$
6. Manganese oxides
7. Iron oxides

Fractures. The severity of fracturing inherent in the particles was noted as none, few, or many. Any visible parting was considered as a fracture.

Strength. The technique used to judge relative strength was the traditionally accepted method of subjectively determining the degree of ease or difficulty with which the particle breaks under a hammer blow. The particles were rated as strong, moderate, or weak. This method, although useful, is not considered to be wholly adequate.

The unit of strength or durability coded for the computer data reduction program was a composite of the measured strength and the number of visible fractures or other planes of weakness.

Degree of Weathering. Each particle was determined to be fresh or unweathered, moderately, or strongly weathered.

Organic Matter. Petroliferous and carbonaceous matter were rated as being either present or absent.

Potentially Alkali Reactive, Presence of Solubles, Sulfides, or Potential Base Exchange. Particles for which the lithology and physical description accord with those known to be potentially chemically reactive were noted under the column Remarks.

Chemical Analysis

Carbonates. During the petrographic examination the carbonates were identified as limestone, dolomitic limestone, calcareous dolomite or dolomite by means of acid reaction and staining techniques. Alizarin red and ferric chloride were used to identify calcite. The alizarin red s produces a deep red stain on calcite but does not affect dolomite. Ferric chloride, similarly may be used to color calcite brown without affecting dolomite (Friedman, 1959). Dolomite or dolomitic limestones were recognized by a spot test involving p-nitrobenzene-azoresourcinal (Mann, 1955). When put into solution on the rock with dilute HCl, the organic dye is adsorbed by Mg $(OH)_2$ producing a distinctive blue color. The time that it takes for the blue color to appear is an indication of the amount of Mg present. A dolomite will produce the color within the first few seconds while the pebbles of intermediate composition will take several seconds. Almost any carbonate rock will produce the blue color after about one minute in solution.

Calcium and Magnesium Determinations of Carbonate Rocks. The calcium and magnesium determinations were made for carbonate pebbles selected from samples 1 through 50. Several pebbles were selected from each of the three classes of carbonate rocks identified by the binocular microscope and stain techniques, that is one or more identified as limestone, as dolomitic limestone or calcareous dolomite, and as dolomite.

The results were obtained by titration with ethylenediaminetetracetic acid disodium salt. Titration for calcium was performed at pH 12 with hydroxy naphthal blue indicator. During the procedure the magnesium was precipitated as hydroxide. The combined calcium and magnesium content was determined by a second titration at pH 10 with calmagite or eriochrome black T indicator. The magnesium content was determined as the difference between the two titrations. The results are reported in Appendix Table 12.

The chemical analyses were run on the carbonates: (1) to check on the accuracy of identification by staining and visual means, and (2) to determine what the range and average values were for the carbonates in the gravels.

The results shown in Table 12 were used to define the rock in terms of its oxide content. The number following the hyphen in Column 1 corresponds to the visual identification (1 - dolomite, 2 - intermediate, 3 - limestone). Data for the composition of carbonates is given by Pettijohn (1957) as listed in Table 5.

TABLE 5

Nomenclature of Sedimentary Calcitic and Dolomitic Carbonates
(After Pettijohn Table 80, p. 418)

Type	Percent Dolomite	Approx. MgO Equivalent %	Approx. $MgCO_3$ Equivalent %
Limestone			
High Calcium	0 to 10	0 to 1.1	0 to 2.3
Magnesium	0 to 10	1.1 to 2.1	2.3 to 4.4
Dolomitic Limestone	10 to 50	2.1 to 10.8	4.4 to 22.7
Calcitic Dolomite	50 to 90	10.8 to 19.5	22.7 to 41.0
Dolomite	90 to 100	19.5 to 21.6	41.0 to 45.4

The rock nomenclature determined from the chemical data is given in the last column of Table 12. Consistently high values for magnesium show substantial amounts of dolomite in all but one sample. Of the 159 powdered samples run, only one, A16-3, is a pure limestone. These results were not expected inasmuch as most carbonate rocks tend to occur near the end-members of the series. Even though the "average" limestone contains 7.90 percent MgO this value rarely occurs since most carbonate rocks contain either much more or much less magnesium. Most limestones, in fact, have less than 2 percent or over 19 percent MgO. An illustration of the general scarcity of intermediate carbonate rocks is found in a table given by Pettijohn (1957, p. 417) and reproduced here as Table 6.

TABLE 6

Relative Abundance of Limestone and Dolomite
(from Pettijohn, p. 417, 1957)

Percent Dolomite	Number of Samples
0 to 10	48
10 to 50	8
50 to 90	5
90 to 100	97

Three of the powders produced MgO exceeding 21.6 percent, the equivalent to 100 percent dolomite. Subsequent x-ray diffraction analysis on two of these for which sufficient powder was left over did not reveal the presence of magnesite or other magnesium-bearing minerals.

Standard samples of calcite and dolomite were run by the same procedure in order to determine if a systematic error might be causing the unexpectedly high Mg values. It was found that up to +5 percent could occur in the absolute values.

It is assumed that the relative values are correct and that the visual means of identification was essentially accurate. The MgO values, however, were systematically high by about 2 to 4 percent. A correction downward of 2 percent MgO would put all values into an expected range.

The greater numbers of carbonates of intermediate composition are partly due to the fact that with the exception of 16, 17, 18, and 38, more than one pebble was ground from each petrographic group, thereby, creating an average for the group.

Potential Alkali Reactivity

A chemical test, established by the American Society for Testing and Materials (ASTM C 289) was used to determine the potential alkali reactivity of each source of material in portland cement concrete. The method determined the potential reactivity by measuring the amount of dissolved silica and the reduction of alkalinity of a 1N NaOH solution allowed to react with powdered samples ground from the aggregate.

One thousand grams of material for each available size fraction were taken from each reserve sample. The material was crushed to < 1/4 inch in a jaw crusher and further reduced by means of a disc pulverizer to pass a #50 sieve. Powder passing the #50 and retained on a #100 sieve was tested.

The reaction procedure involves weighing the three replicate 25 g portions of the powder into specially made non-reactive, sealed reaction containers and adding 25 ml of NaOH solution. The powdered material is allowed to react with 1N sodium hydroxide for 24 hours at 80 C. Normally, three triplicate samples and a blank were run concurrently, requiring a total of 10 reaction containers.

The filtered solution obtained is used to determine the dissolved silica and reduction in alkalinity. Dissolved silica is determined gravimetrically as prescribed by the ASTM Manual (1964, p. 190-191). Dissolved silica is reported as: Sc = SiO_2 in millimoles per liter.

The reduction in alkalinity or basicity of the solution was obtained by titration. Reduction in alkalinity is reported in millimoles per liter = Rc.

Dissolved silica (Sc) is plotted on a logarithmic scale while reduction in alkalinity (Rc) is plotted along the arithmetic ordinate (Fig. 6). A curve drawn on the graph is an empirically determined dividing line between aggregates determined to be potentially alkaline reactive and those found to be innocuous. Those falling to the right of this line are likely to possess a deleterious degree of alkali reactivity. The presence of certain minerals may produce misleading interpretation. Iron and magnesium carbonates and magnesium silicates, or if soluble silicates are present, calcium carbonate may cause spurious increase in Rc and may cause an increase or decrease in Sc. This may affect the indication of potential reactivity of the marginal aggregates.

The major difficulty is interpreting the results of the extraneous decrease in alkalinity which results in the spurious increase in Rc, caused by dolomite or ferrous iron. According to Mielenz and Benton (1958) a quartz aggregate with 1 percent opal will be shown to be deleterious but in combination with dolomite may appear from the test to be innocuous due to precipitation of magnesium or iron hydroxide and increase of Rc. Mielenz and Benton cite as an example that if 2.5 percent opal were present the aggregate would appear definitely deleterious. Extraneous precipitation of hydroxide does not occur if the amount of reactive silica is high. With 5 percent or more of opal the bulk of the aggregate has no effect on Sc and Rc.

Final interpretation of the result is made in conjunction with the petrographic analysis and the freeze-thaw expansion tests (p. 86).

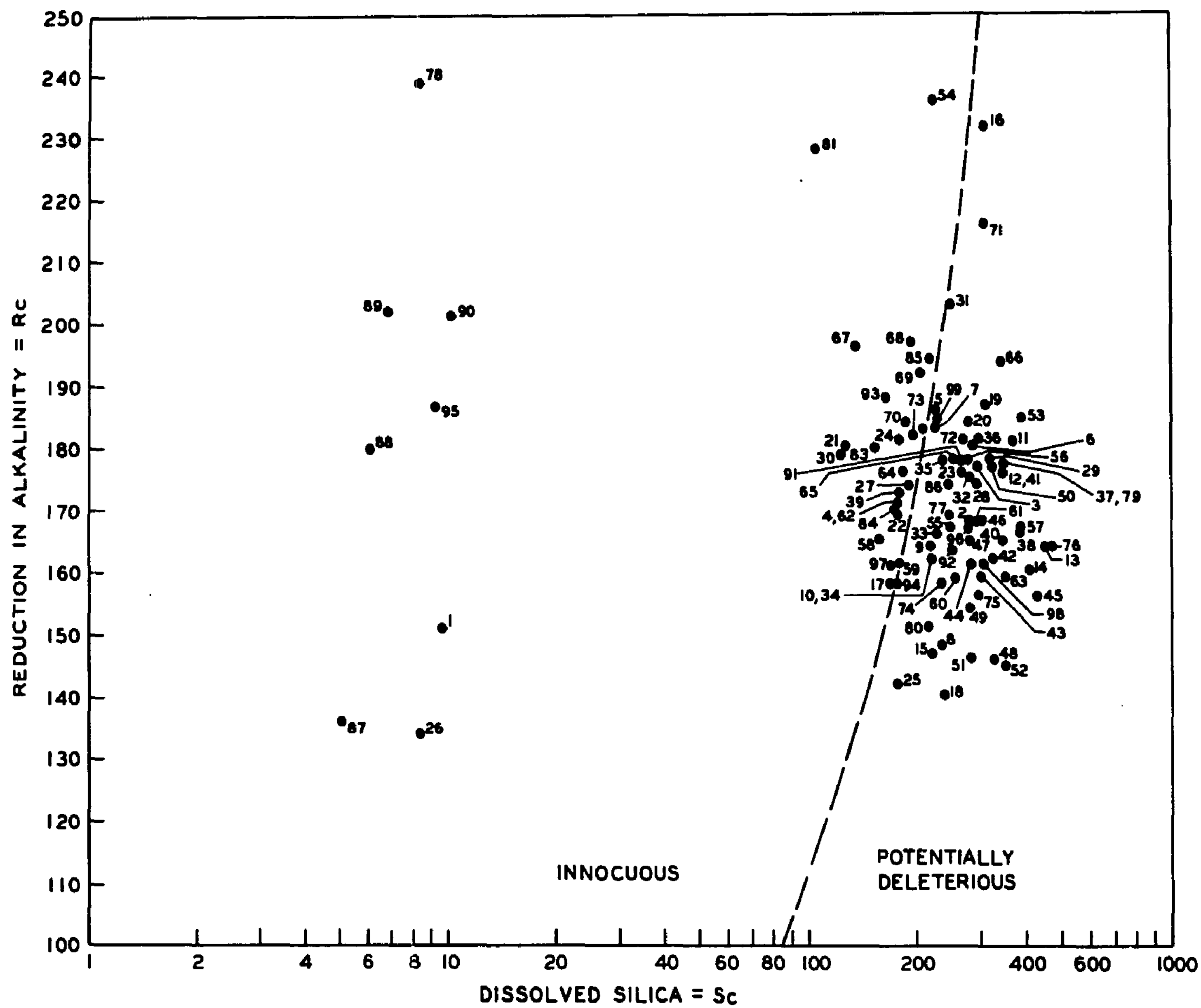

Figure 6. Potential alkali reactivity.

Engineering Tests of Concrete Beams

The procedures for the engineering tests relating to concrete beams and cylinders are given in detail in ASTM Standards. The appropriate standard is referred to in the discussion of the test results.

PETROLOGY OF GLACIAL GRAVELS

Form of Data

The data gathered together which collectively form the petrographic analysis consist of:

1. Field observations

2. Sieve analyses

3. Pebble counts and associated observations and measurements

4. Chemical analyses of carbonate particles

5. Tests of aggregate samples including specific gravity and percent absorption.

Analytical Procedure

Analysis of the petrographic data is carried out in two phases. Phase 1, the reduction of individual pit data and the calculation of variables for each sample independent of other samples. Phase 2 uses the generalized Phase 1 data to determine the between-pit variables.

Phase 1. The first phase is done by means of a computer oriented analysis consisting of two programs for the reduction of data and calculation of individual pit statistics.

Program "Percent"

A computer program was written to calculate percentages and means of all variables determined for each pit. These calculations are summarized on the data summary sheet (Table 11) and Tables 15 through 21.

Means were calculated independently for each rock type in each size grade and again for all particles in the sample with respect to sphericity, roundness, texture, physical durability, weathering and coatings. Means were calculated for the largest size only for specific gravity and absorption.

Percent calculations include the following: percentages of each rock type for the entire sample; percentages of particles of each rock type that fall into one of three degree categories (good, bad, indifferent) for the physical characteristics, i.e., physical durability, weathering, texture, and coatings; percentage of particles of all rock types for the entire sample that fall into one of the degree categories for the following characteristics: coatings, weathering, physical durability, organic matter, chemically reactive, potential base exchange, solubles and/or sulfides; percentage of potentially deleterious material (for engineering usage) in the sample. Zingg (1935) shape classes were also computed and the percentage of particles in each was determined.

Program "Least Squares"

This program calculated statistics for individual samples. It is basically a least squares analysis program designed to handle the available data. Output included: correlation coefficients, sums of variables, mean sums of variables, standard deviation of variables, sums of squares of variables, sums of squared deviations from the mean.

Phase 2. The second phase of the data analysis was to determine relationships between samples. The computer-oriented portion of this phase consists of:

(a) Factor analysis of lithologic distributions.

(b) Analysis of variance of physical and engineering variables.

Particle Size Analysis

Quartile Measures

Mechanical analysis data for the gravel fraction was used to construct curves for the cumulative size frequency distribution. The conventional method of constructing these curves for sand-sized materials is to plot the particle diameters on a logarithmic scale. Assuming a log-normal distribution for such sediments this technique symmetrizes the distribution. However, here we wish to deal with the coarse fraction of the distribution. For this purpose the curves are best plotted on an arithmetic rather than a logarithmic scale. The plots were chosen to give maximum expression to the data points. A sample curve is shown in Figure 7. Both the very coarse and the very fine ends of the distribution have been run off the scale of the graph in order to emphasize the spread of the central values. The first and third quartiles were picked and a sorting coefficient was calculated (Krumbein and Pettijohn, 1938).

The quartile measures, sorting coefficient, and arithmetic quartile deviations are all given in Tables 13 and 14. A sorting coefficient is intended to give a measure of the spread of the distribution. This is based on the ratio between two quartiles. A measure of the asymmetry or skewness may also be made by comparing the median value with an average of the first and third

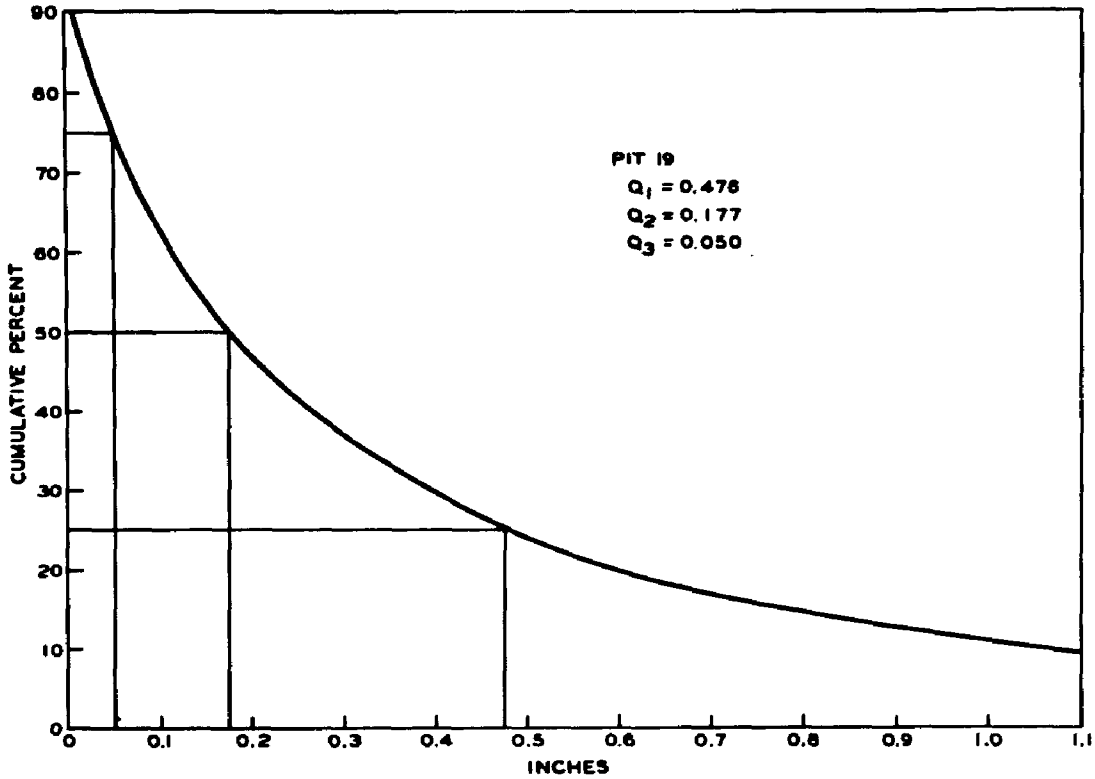

Figure 7. Sample cumulative size frequency distribution curve.

quartiles. Although similar calculations may be made from either arithmetic, geometric, or logarithmic distributions, the use of quartile measures has the advantage that they are confined to the central part of the frequency distribution and not subject to the influence of extreme particle sizes (Krumbein and Pettijohn, 1938).

<u>Sorting</u>

A perfectly sorted sediment has a sorting coefficient of 1.0. Values less than 2.5 are considered to be well sorted, 3.0 is normal and values exceeding 4.5 indicate poor sorting (Pettijohn, 1957 and Trask, 1932).

Values for the mean sorting coefficient for each of the deposit types considered are:

Morainal Ice Contact Deposits (Type 2)	4.72
Confined Ice Contact Deposits - Eskers (Type 3)	4.75
Proglacial Channel Deposits (Type 4)	4.20
Proglacial Fan and Delta Deposits (Type 5)	3.77

According to the criteria of Trask, both categories of ice contact deposits are poorly sorted and both categories of proglacial sediments are "normal" or moderately sorted. Individually, only two pits out of 99 are "well sorted," Nos. 44 and 71, with So values respectively of 2.24 and 1.84. These are both outwash deposits. No. 44 is on the Allendale Delta of the glacial Grand River Channel and No. 71 is an outwash plain or delta in Jackson County possibly associated with glacial Raisin River drainage. Fifteen of the outwash deposits exceed So of 4.5 and would be considered "poorly sorted."

The So in a general way reflects the degree of reworking by fluvial processes. The compound nature of glacial and glaciofluvial deposits brought about by the fact that each deposit is the result of the interaction of more than a single episode of glacial or fluvial activity appears to be reflected by the sorting displayed by the individual deposits. Some of these, classified as morainal, may possess a higher degree of sorting (lower So value) than some of those classed by their morphology as outwash or proglacial. The recycling of materials by later episodes creates a complexity precluding the direct relationship of morphology and sorting or any other single petrographic characteristic. The fact that the mean So for proglacial deposits is lower (better sorted) than the mean for ice contact deposits indicates that the last episode, the one by which their position in the classification is determined, is the most important single influence on sorting. However, the range of values for individual pits shows that the previous histories of the material is very important in determining the degree of sorting.

Physical Characteristics of Particles

Following is a description and discussion of the measured physical properties of individual particles from the 99 samples. Significant variability of these characteristics is discussed in connection with each variable. Relationships between the various characteristics among samples are presented at the end of the section.

Roundness. Maximum and minimum roundness for a size range from .3454 for size 1 sample #6 and .6852 for Size 1 sample #40 (Table 18). Both of these sample sites are confined outwash (Gp #4). Mean maximum and minimum roundness for all sizes are respectively, .3820 and .6642 for the same two pits. The standard deviation for roundness for all sizes ranges from a low of .0865 for pit #56 and a high of .1481 for pit #12. Pit #56 is a morainal deposit (Gp. 2) and #12 is a confined outwash or valley train.

Sphericity. Mean sphericity for each pit ranges from .7137 for pit #51 to .7859 for pit #5 (Table 15). There is no apparent relation to deposit type, source of materials, or other depositional variable. Similarly, sphericity does not bear any measureable relationship to particle size.

Standard deviations of sphericity for each size grade are consistently low for all pits with the highest being 0.34 for pit #5. This is the pit with the highest mean sphericity for all particles. The largest and smallest size grades have the highest sphericities (.816 and .808, respectively) and size 2 (intermediate) is average. This, however, is not a general relationship.

Correlation coefficients for sphericity - size are normally distributed for 99 pits and have both their mean and median values at -.04. Sphericity does not vary appreciably between rock types.

Surface Texture. Mean values of surface textural measurements are used as an index for variations. Values are given in Table 17. Surface textural variations show some correlation with other physical variables, especially weathering, specific gravity, roundness, and physical durability. It does not correlate with sphericity and shows no apparent variation with size.

Correlation of surface texture with other physical parameters occurs because of common characteristics of certain lithologies such as friable standstones, dense cherts and limestones, etc. Stream action often produces a polish on certain types of rocks although some may round but not polish. The data show that certain rocks tend to cluster in a given surface textural group and others scatter widely through several of the catégories.

Surface textural values averaged from each pit show little variation. Neither different geomorphological affiliations of deposits nor sedimentological parameters are reflected by any consistent surface textural differences.

Weathering. The degree of weathering of rock particles results from action of post-depositional processes. Mean values are given in Table 16.

Weathering appears to display no selective effect relative to particle size. There is no apparent overall increase or decrease in the degree of weathering with changing particle size. Although the degree of weathering influences the physical durability, it does not appear to be the basic causal factor in the durability - size relationships. These are discussed under the heading "Physical Durability."

Specific Gravity. Specific gravity is a fundamental engineering property of concrete aggregate. Mean specific gravity for each lithologic group over all 99 deposits is listed in Table 7. These data are consistent with previously known values for lithologies and present no new findings. No systematic variation between deposits was determined.

TABLE 7

Mean Specific Gravity for Each Rock Type

Lithology	Specific Gravity
Phaneritic Acid Igneous	2.6877
Phaneritic Intermediate Igneous	2.9173
Phaneritic Basic Igneous	2.9901
Micro-Phaneritic Igneous	2.8263
Aphanitic Acid Igneous	2.7224
Aphanitic Basic Igneous	2.8623
Pegmatite	2.6318
Sandstone	2.2988
Siltstone	2.2588
Calcareous Siltstone	2.0291
Shale	2.5274
Crag	2.1983
Coal	2.3710
Clay	2.1303
Iron Oxide	2.1120
Ferruginous Concretions	2.5802
Limestone	2.5685
Dolomitic Limestone	2.7531
Dolomite	2.7368
Chalk	1.9392
Chert	2.5036
Non-Foliated Metamorphic	2.6713
Foliated Metamorphic	2.6984
Others	2.7934

Percent Absorption. Since absorption is inversely related to specific gravity its relationships to other variables and to deposits are similar. Means for specific gravity and absorption are given in Tables 20 and 21.

Physical Durability. Physical durability is a measure of the physical character of the rock that correlates with other expressions of physical condition, including specific gravity, absorption, and weathering. A low but nonetheless statistically valid correlation also occurs between physical durability and surface texture.

There is no apparent difference in the durability of the three size grades. Table 19 lists the mean values for durability. This mean, as with surface texture and degree of weathering, is an index value determined by the average number of particles falling into various discrete classes.

Chemical Characteristics of Particles

The chemical nature of the individual gravel particles may affect the engineering quality of the gravel and is discussed in the section on engineering usage. The petrology of the gravel itself is best evaluated by lithologic composition which in turn reflects the chemistry of individual constituents.

Relationships between Petrographic Variables

Correlation coefficients were computed for all combinations of petrographic variables for each pit. For almost every combination of variables, the range of coefficients is quite wide. To determine if the coefficient values were meaningful or simply randomly distributed, the ranked coefficients for certain combinations were plotted for all 99r's on probability graph paper. A straight line with a mean or median value of 0 would result if the distribution of r's were random. If, however, the distribution of r's were non-random, the curve would be skewed either right or left, depending on whether the correlation were positive or negative. Skewness of the curve indicates true correlation. Spurious high or low correlations can be disregarded and the median value used as the actual degree of correlation for all 99 deposits.

Tables 8, 9 and 10 list the combinations of variables plotted. All are more or less normal and the degree of skewness is shown by the mean and median value.

TABLE 8

Median Correlation Between Pairs of Variables for 99 r's - Size 1 (1-1/2" - 3/4")

	SPECIFIC GRAVITY	ABSORPTION	LITHOLOGY	SPHERICITY	TEXTURE	ROUNDNESS	WEATHERING	PHYSICAL DURABILITY
Specific Gravity	---							
Absorption	-.76	---						
Lithology	-.02	-.02	---					
Sphericity	.03	-.07	.02	---				
Texture	.11	.04	.09	.02	---			
Roundness	-.06	.09	0	.10	.18	---		
Weathering	-.27	.34	-.06	-.06	-.11	-.01	---	
Physical Durability	-.38	.37	-.12	-.06	-.15	-.01	.40	---

TABLE 9

Median Correlation Between Variables For 99 r's
Size 2 (3/4" - 3/8")

	LITHOLOGY	SPHERICITY	TEXTURE	ROUNDNESS	WEATHERING	PHYSICAL DURABILITY
Lithology	---					
Sphericity	.02	---				
Texture	.05	-.02	---			
Roundness	.01	.07	.37	---		
Weathering	-.08	-.03	-.07	.02	---	
Physical Durability	-.13	-.06	-.11	-.05	.47	---

TABLE 10

Median Correlation Between Variables For 99 r's
Size 3 (3/8" - 3/16")

	LITHOLOGY	SPHERICITY	TEXTURE	ROUNDNESS	WEATHERING	PHYSICAL DURABILITY
Lithology	---					
Sphericity	.03	---				
Texture	.11	-.03	---			
Roundness	.03	.07	-.36	---		
Weathering	-.09	-.03	-.12	0	---	
Physical Durability	-.15	-.02	-.13	-.15	.28	---

For particles of the largest size grade (1-1/2" to 3/4"), the highest correlations are specific gravity and absorption. These predictably show strong negative correlation. The median correlation for all particles measured is -.76. Physical durability is significantly correlated with both specific gravity and absorption. The signs on these may be confusing because of the coding used for physical durability, which ranks the most durable as 1 and the least as 3. High specific gravity, then, and high durability (low code number) occur together and, therefore, create a negative coefficient. High absorption occurs with low durability (high code number) and creates a positive coefficient.

Durability and weathering also show a highly significant correlation. The positive r here again indicates that the more weathered particles are the less durable. Specific gravity and absorption also are affected by the degree of weathering of the particles. Durability and surface texture show a lower but nonetheless consistent correlation. Other relationships between petrographic variables that are less pronounced but still consistently present are surface texture with roundness and weathering and sphericity with roundness.

Lithology does not show strong relation to any of the other variables. This, no doubt, is due to the large number of rock types present in the suite. The relationships shown, however, are consistent throughout all 99 deposits.

The correlation of lithology with physical durability is strongest while surface texture and weathering show some association. It is interesting to note that no apparent relationship exists between rock type and roundness.

In the two smaller size grades, similar relationships are found between variables. Contrasts are cited as follows: Surface texture and roundness are more closely related then in the larger size class. Roundness and durability show a higher contrast in the smallest size (3/8" to 3/16"). The negative sign indicates that the more round appear slightly more durable on the whole for this size. This may be due to planes of weakness or other physical elements producing a relatively more marked reduction in roundness of small particles. This is an inherent problem in the measurement of roundness based on the number of "corners."

Distribution of Lithologies

Several analytical techniques were used to describe and analyze the areal variation of the lithologic suite. The percentage composition of diagnostically significant rock types as well as various combinations were plotted on areal maps. Much of the interpretation of this data has application in engineering usage of the materials and will be discussed in this connection. The geological significance is discussed later in this section.

Within Individual Samples. The distribution of rock types in each gravel pit sampled is represented in Table 11.

Roundness, sphericity, texture, coatings, physical durability, weathering and chemical durability are discussed in general under "Petrography" and need not be described for each pit. The data are presented in Tables 12 through 21. Between pit relationships will be discussed in the next section.

Between Samples. The consistency of the lithologic suite between samples was mentioned earlier in the discussion of sources of materials. The general content of this suite is given in the discussion of the petrographic analysis, p. 61-71.

Factors in the present distribution of materials in the gravels are, (1) bedrock sources and their distribution and exposure to glacial and related erosion, (2) distance and direction of transport, (3) mode of transport (ice, ice and water, water) and deposition, and (4) post depositional alteration of the deposited materials by either chemical or physical means.

Interaction between each of these factors and the relative importance of each determines the final properties of each lithology at each site. These, however, are fundamental physical parameters which are basic to any deposit but not easily resolved to specific sample sites. Rather an empirical analysis of these factors is used to explain the lithologic distribution in terms of local areal parameters.

Factors (1) and (2) have been discussed under "Source of Materials" p. 17-21, while (3) mode of transport and deposition is beyond the scope of this study. The specific effects of the interaction of water and ice transport within the region of study is taken into account subsequently, p. 61-71.

Post depositional changes principally effect the solution or precipitation of soluble minerals and salts. Precipitation of $CaCO_3$ occurs along exposed faces of coarse strata which serve as channels of ground water migration. This produces the material referred to as crag. In several of these same deposits incipient alteration of feldspars in the contained rocks is producing the deposition of minute needle-like clay coatings on the pebbles. Oxidation has caused the partial or complete disintegration of some particles containing ferrous carbonates and of some basic and intermediate igneous rocks. Diorites in some cases are decomposed to the point of physical disintegration. Leaching of carbonates, common in glacial tills in some areas,does not appear to be important in the gravel deposits.

A series of factor analyses was performed in an effort to further classify the 99 sources of gravels and to obtain a clear relationship of these deposits to the known geology of the region.

Basically, factor analysis is an analytical procedure used to reduce the number of variables and to delineate new and fewer independent underlying factors. The intercorrelations among the variables constitute the basic data for factor analysis. The procedure searches the correlation coefficients for relationships, groups, similar variables, and then derives a hypothetical factor specific to each group.

The most frequently used option for extracting factors is the principal-factor solution. Using this technique a first factor is extracted which accounts for the largest proportion of variation in the observed measures. A second independent factor is then determined that accounts for a maximum of the residual variation. The process is continued until the total variation is explained.

The factor pattern that has been determined is then usually mathematically rotated to arrive at a simpler structure or pattern and the most meaningful positions for the factors. The rotated solutions may provide a basis for the construction of a model to explain the initial variation or serve for other interpretation.

Factor analysis, then, is essentially a sophisticated data reduction technique. Thorough treatment of factor analysis can be found in Cattell (1952) and Harmon (1960). The computer program used in this study is described in "Factor A: Principal Components and Orthogonal Rotation," Technical Report No. 34, Computer Institute for Social Services Research, Michigan State University.

Lithologic data fed into the factor analysis routine were arranged into categories which would permit assignment of individual samples into similarity categories by means of the maximum factor loadings derived by verimax rotation. Eight different sets of input data were used for separate runs. These include both ranked lithologic data and actual percentage values compiled into four different grouping schemes.

The use of both ranked and actual percentage data provides a check on the possibility that small fluctuations in the percentage data might alter the loadings and mask the gross relationships. On the other hand, the degree to which one lithologic group differed from another might be more geologically significant than the simple fact that one is more abundant than another.

The first set of data analyzed by the factor analysis routine consisted of 17 lithologies. These were selected from the 24 groups included in the petrographic analysis by omission of seven low frequency members whose presence or absence was likely to be random or follow a Poisson distribution.

Four sets of output were obtained for both the ranked and the percentage data input. Separate solutions individually resolved the variations in the data into two, three, four, and five factors on the basis of the maximum rotated factor loadings.

Similar sets of solutions were obtained for the subsequent factor analyses based on the data reorganized into fewer variables. The seven variable input yielded up to five rotated factor loadings, the four variable analysis supplied two and three way loadings and the three variable analysis loaded two ways.

Each solution to the factor analysis when plotted on a map of the area shows the areal distribution of samples that fall into the assigned factor categories.

Only those solutions that appeared to yield something of significance to the geology of the deposits or engineering usage of the materials is discussed below under "Inferences" p. 61.

Supplemental Study of Lithologic Distribution

The lithologic results of the above pilot study prescribed that a new set of experimental data should be gathered and examined. The purpose of the new phase was three-fold: (1) to develop and implement a more efficient procedure for sampling drift materials (potential aggregate sources for economic projects) to determine large scale areal variability. (2) Extend the geographic area of investigation to test derived inferences regarding areal variability of the lithologic suite. (3) Gather additional information to verify and expand the inferences regarding the effects of glacial dispersion and other geological parameters.

Volume Pebble Analysis. Inferences both of geological and economic significance are drawn from the distribution of materials in the drift.

The areal distribution of the quality characteristics of the material for highway or construction aggregate is interpreted and thereby made more predictable by means of the reconstruction of the flow paths of glacial ice, the resulting dispersal patterns for the materials, their provenance, and the dynamic factors controlling deposition and reworking. The quality of natural materials for use as aggregate is a function of the relative amounts of the differing components measured by volume rather than numbers of pebbles. This has been documented by studies of freeze-thaw resistance of concrete and other durability studies made by the Michigan Department of State Highways Research Laboratory and other agencies. Larger particles have been clearly shown to be more harmful than small, if they are subject to expansion or disintegration when enclosed in concrete.

Similarly relative quantities of differing materials in a glaciofluvial deposit are more directly interpretable in terms of provenance, transportation, deposition and post depositional history in terms of volume rather than numbers of pebbles.

A size range of particles or glacial drift containing the greatest variability in lithologic content was determined by Anderson (1962) to be between 1/2 and one inch diameters. Although the present study shows no consistent relationship between size and lithology, the use of this size range for the analysis of the materials has the advantage of eliminating any possible spurious size effects, and greatly facilitates the sampling procedure.

The use of volume sampling for sedimentological analysis provides a number of advantages over the traditional pebble counting technique. These include smaller sample size, elimination of multiple size grading, speed, and simplified data handling. An analytical result can be obtained consisting of fewer elements which is more readily explained in terms of the genetic history of the deposit.

Location and Extent of Expanded Area of Study. The area covered for the supplemental study is shown by the broken line on the index map (Fig. 1). It extends the original study area to include practically all of the western half of the Southern Peninsula of Michigan. The extended area covers approximately 9000 square miles.

Sampling Procedure. A single sample from the 1/2-in. to 1-in. pebble population was obtained from each of 138 townships in the western half of the Lower Peninsula. The samples were taken from field exposures in gravel pits or other man made excavations. Gravel pits were preferred locations for sampling because of the additional sedimentological data available, but where pits were not present road cuts or any other suitable exposures were sampled. Many pits had fresh vertical exposures, in which case the sample consisted of an integrated composite of grab samples or a vertical channel from all gravel strata present. Where exposure was absent a lag sample was obtained from the pebbles exposed at the surface. These lag samples were subsequently found to be unsuitable and were eliminated from the analysis. The 1/2-in. to 1-in. pebbles were separated by hand sieving through square mesh screens and 8 to 10 pounds were bagged for laboratory analysis.

Laboratory Procedure

Preliminary Handling

In the laboratory the samples were first washed to remove clay lumps and fine material adhering to the pebbles. The washed pebbles were then placed in a 2000 ml beaker to obtain an approximate initial volume. The pebbles were agitated in the beaker to obtain maximum packing and more pebbles were added to bring the level to 2000 ml mark. For this procedure the beaker was initially filled with water which was allowed to spill out as it was displaced by the pebbles. This helped to protect the beaker from breakage during filling and reduced friction between pebbles to aid packing.

Lithologic Separation

The two-liter volume of pebbles was then separated into ten lithologic groups: (1) extrusive igneous, (2) intrusive igneous, (3) foliated metamorphic, (4) non-foliated metamorphic, (5) carbonate, (6) siliceous sediment (chert), (7) sandstone, (8) shale and siltstone, (9) ferruginous clay concretions, and (10) others.

This simplified classification was employed so that rapid visual identification would be possible. Each category is based on easily visible criteria yet retains all significant elements necessary for the interpretation of the geologic origin of the materials for the purpose of regional evaluation as well as retaining identity of deleterious components for engineering usage. A binocular microscope, giving magnifications of seven to 30 times was used for particles when identity was questionable by naked eye observation.

The volume of each lithologic category was determined by weighing all of the pebbles in each group, first in air, and then in water. The weight difference is equal to the volume in cubic centimeters. Weight data and volume were recorded in tabular form to facilitate transfer of the data to punch cards for statistical treatment.

Inferences from Analysis of Lithologic Distribution

The areal variation in the lithologic suite is probably the most geologically significant factor in the interpretation of the Pleistocene geology of the region. Basic considerations in the areal interpretation of the distribution of drift materials are provenance and dispersal. Factors that might enter into the interpretation are: bedrock outcrop or subcrop beneath the drift, structure and distribution of bedrock units (Fig. 2), glacial lobation, associated moraine or morainic system, and the type of deposit base on morphology, structure, and relationships to other glacially related deposits. Interpretation of the percentage distribution was attempted relative to the bedrock and the surficial geology.

The factor analysis (p. 57)based on the original 99 samples initiated the interpretive phase of the lithologic analysis.

The general outcome of the factor analyses was that when more than three variables are used the outcome is difficult to interpret meaningfully and that when the data are reduced to a simple classification the factor analysis becomes transparent and unnecessary since this simplified data are more easily interpreted directly. The need for intricate statistical manipulation of the data is thus obviated. Reducing the complexity of the analysis has the advantage of allowing the investigator to see clearly the natural variation in the composition of the materials directly reflected in a useful result.

The interpretation of the factor analyses brought the investigation full cycle, from an extensive lithologic breakdown of the gravel samples, requiring a complex statistical analysis, to a highly simplified rock classification consisting of only the most basic lithologic categories: crystallines, clastics, and carbonates. When the distribution of sample sites is adequately dense and covers a sufficiently large area, this simple tripartite classification reflects most clearly the areal distribution of materials in terms of the geological agencies responsible. More specifically, the distribution of drift materials can be related to lines of glacial and proglacial dispersion.

Figures 8 and 9 are 100 percent triangles. They represent the distribution of the three lithologic categories. Each corner of the triangle represents 100 percent crystalline, clastic, or carbonate components. Each sample is represented by one point. The diagrams illustrate the relationships between lithologies in the drift mentioned earlier; although internally heterogeneous, that is containing a large assemblage of rock types, this assemblage is uniform over the entire area. A cliche sometimes applied to this situation is "homogeneous in its heterogeniety." This is shown by the tight clustering of points. A very small range of composition exists in terms of possible values. This means that any inferences to be made from the lithologic variability in gravels, must be made on the basis of relatively subtle variation in broadly defined lithologic categories.

The above findings indicate that significant regional variations in the composition of the gravels are best reflected by gross lithology.

The fine breakdown of the lithologic suite and other measured variables, including size frequency distribution and physical and chemical properties of individual components serve best for local or detailed studies of individual gravel deposits.

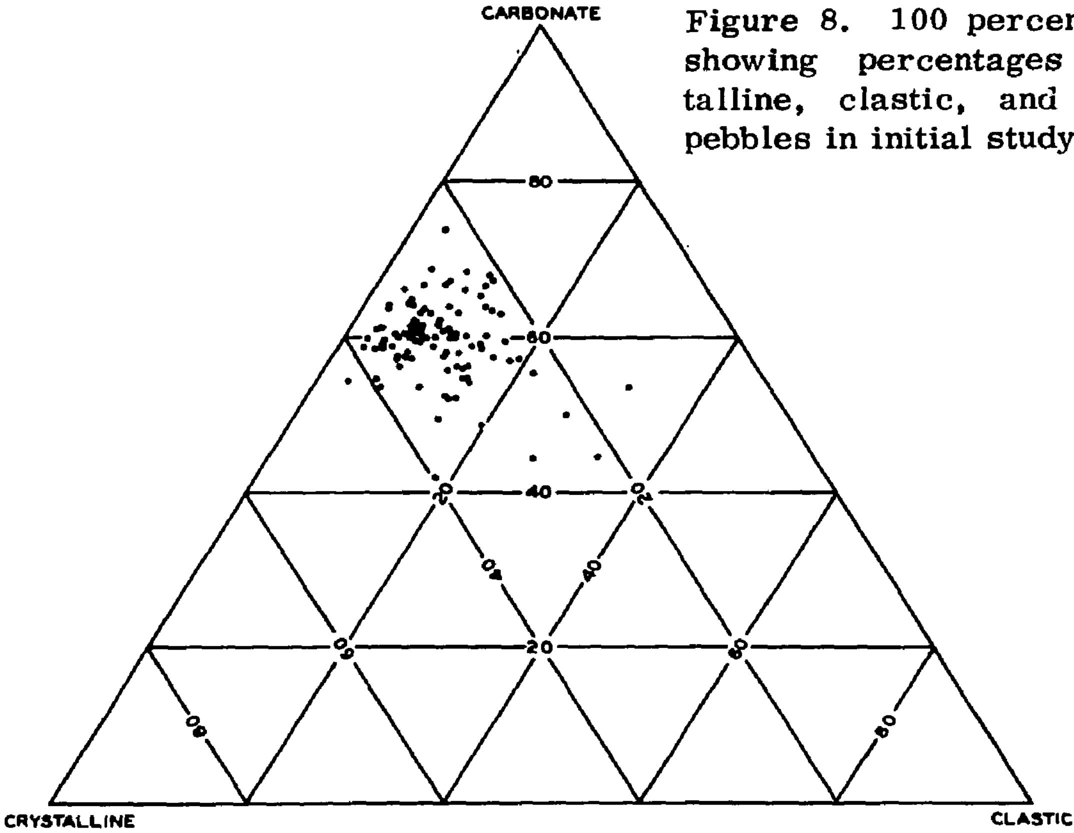

Figure 8. 100 percent diagram showing percentages of crystalline, clastic, and carbonate pebbles in initial study area.

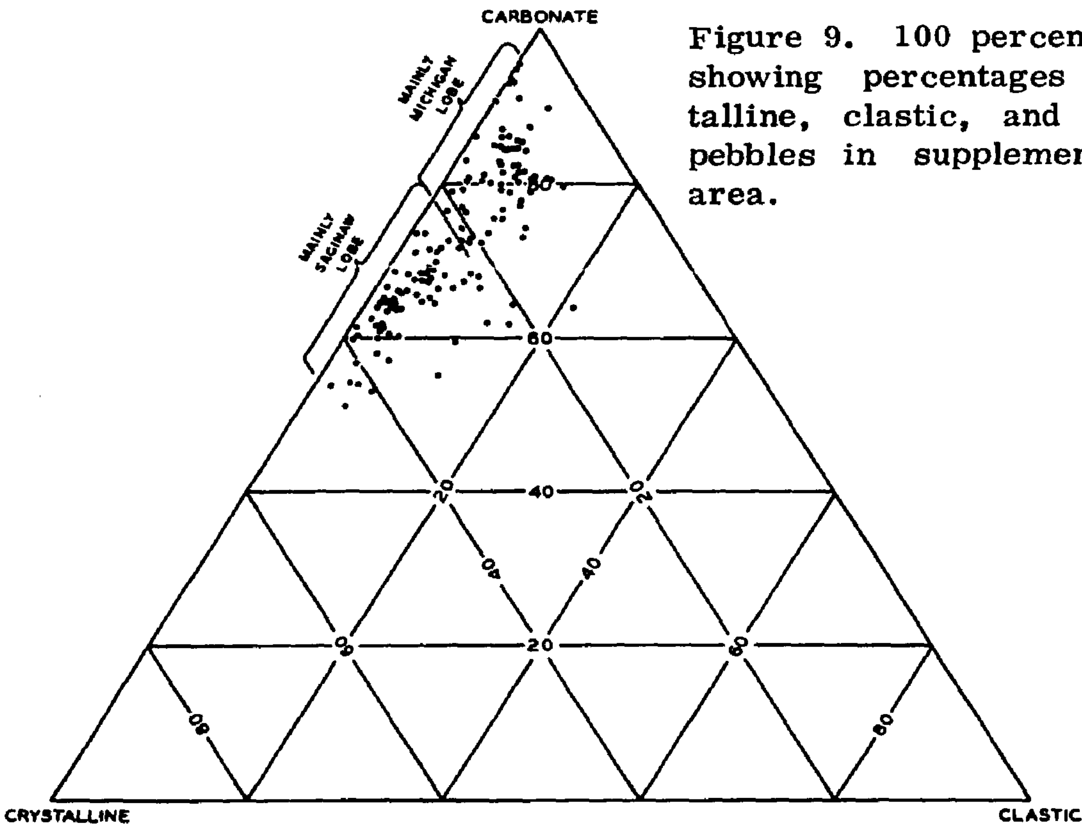

Figure 9. 100 percent diagram showing percentages of crystalline, clastic, and carbonate pebbles in supplemental study area.

The initial 99 deposits, principally in the Saginaw Lobe clustered around 60 percent carbonate with all but five containing less than 5 percent clastic rocks (Fig. 8). A nearly identical clustering of points occurs again for the supplemental samples taken from the same lobe (Fig. 9). Somewhat higher carbonate values generally relate to Michigan Lobe deposits, however, an indefinite range of overlap occurs such that a randomly chosen sample from a Saginaw Lobe deposit may have a higher proportion of carbonate than certain Michigan Lobe samples.

Percentages of the major rock categories for all 232 samples were plotted on areal maps that also show rock outcrop. These are included as Figures 10, 11, and 12. These maps are descriptive of the distribution of materials and interpretive in themselves. However, facies interpretation is facilitated by considering the areal distribution of the ratios of (a) clastic to carbonate rocks, and (b) crystalline to sedimentary rocks.

The lithologic ratio maps (Figs. 13 and 14) were superimposed over a map showing areas of thin drift and outcrop for the expanded study area. Data again include all 232 samples.

Figure 13 shows the ratio of clastic to carbonate rocks. Increasing sizes of circles represent increasing clastic-carbonate ratio. Sample sites where no appreciable clastics occur are unmarked.

The distribution of ratio values forms a complex pattern. A contour map of the distribution would appear unduly complicated and would more likely confuse than aid the interpretation. The circle-point plot, however, shows only the actual distribution of relative values and is easily interpreted in terms of

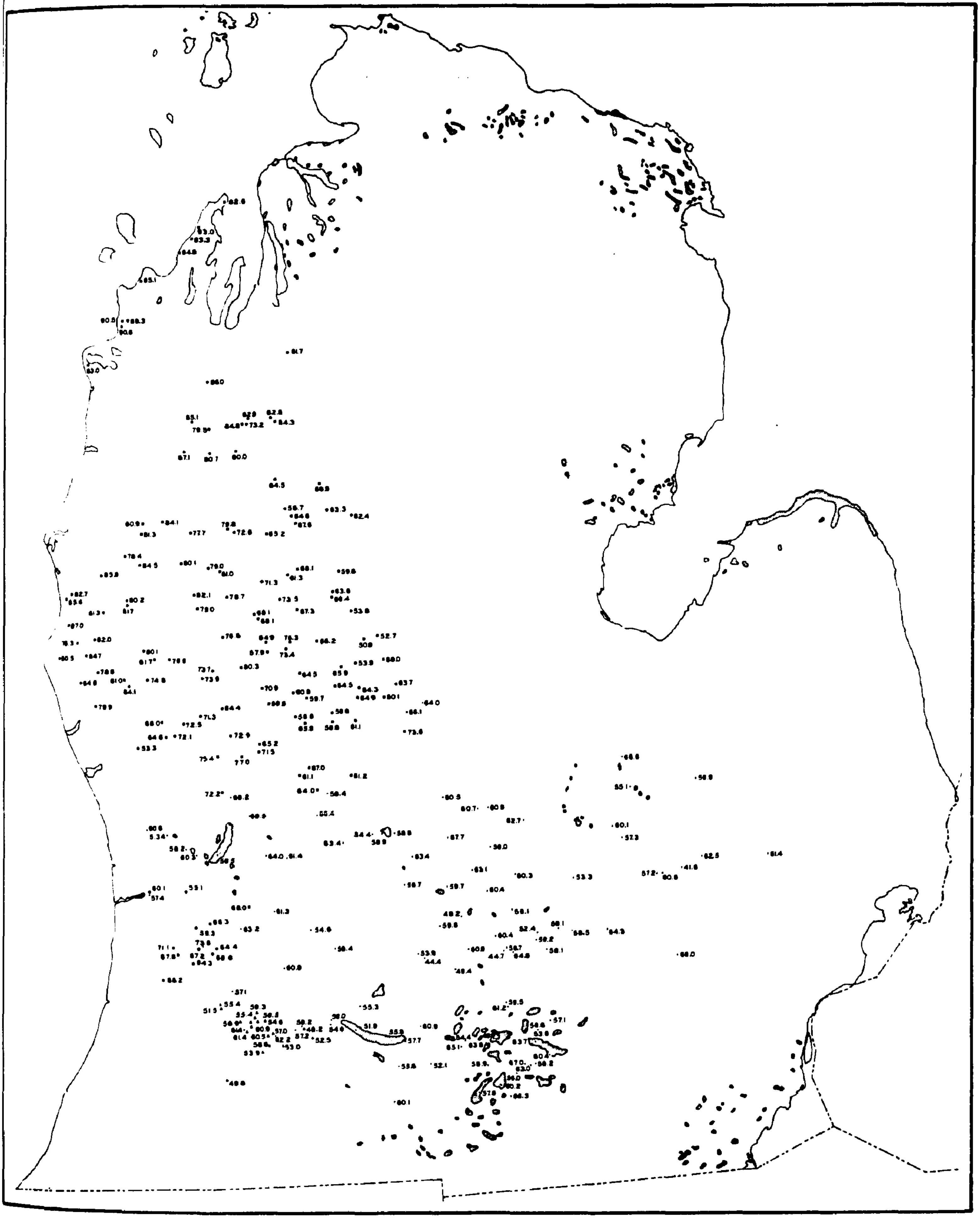

Figure 10. Percent carbonate rocks.

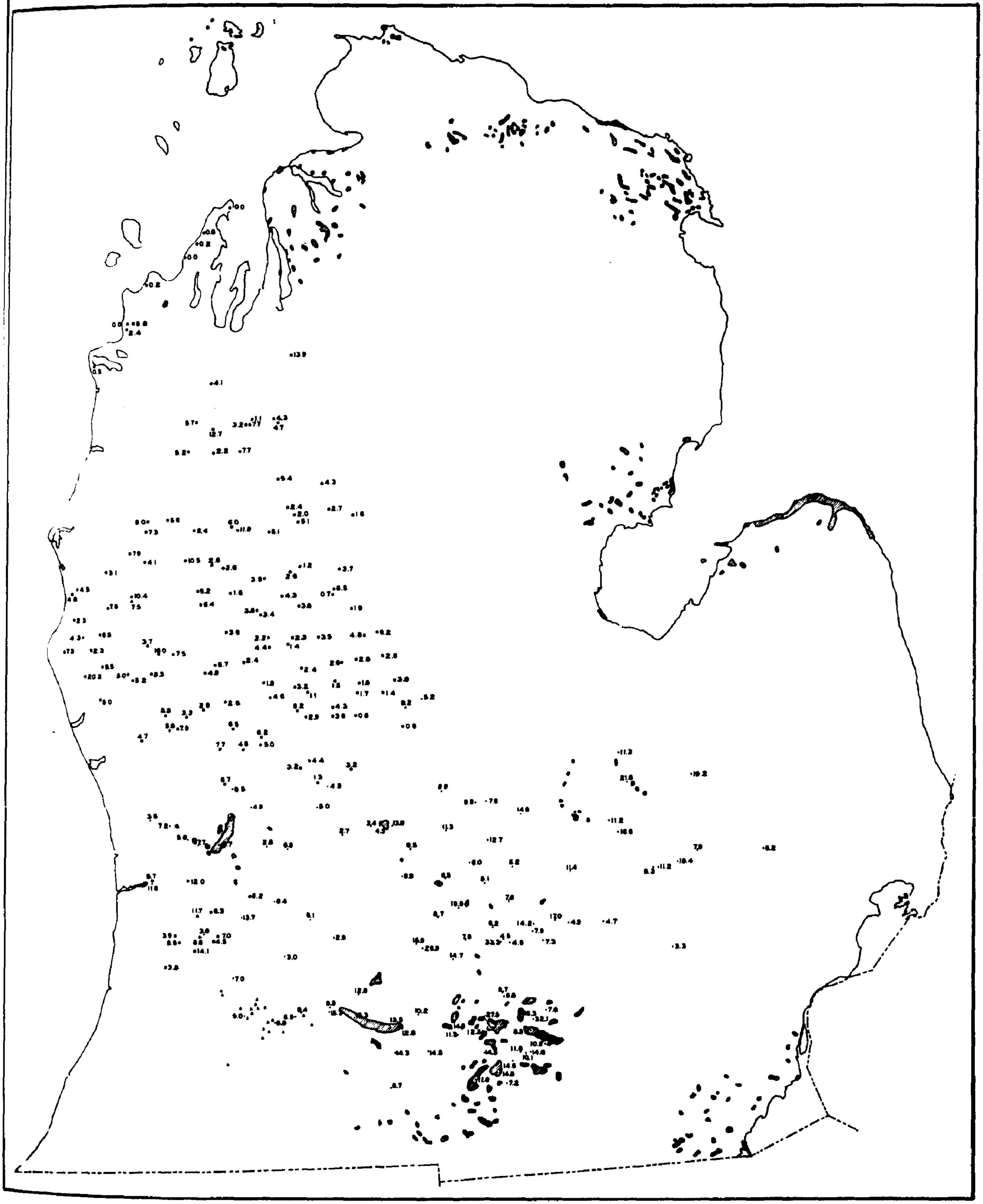

Figure 11. Percent clastic rocks.

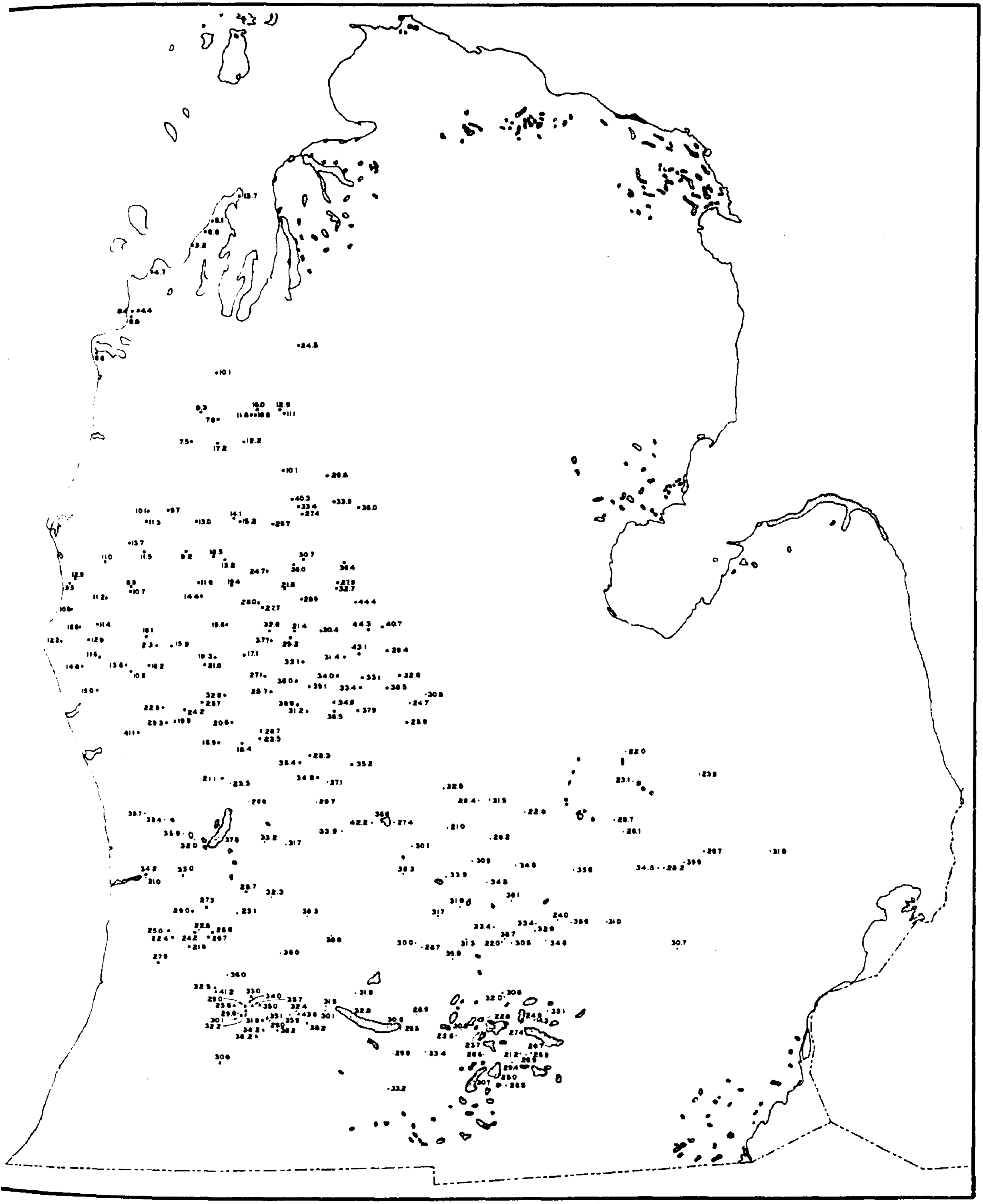

Figure 12. Percent crystalline rocks.

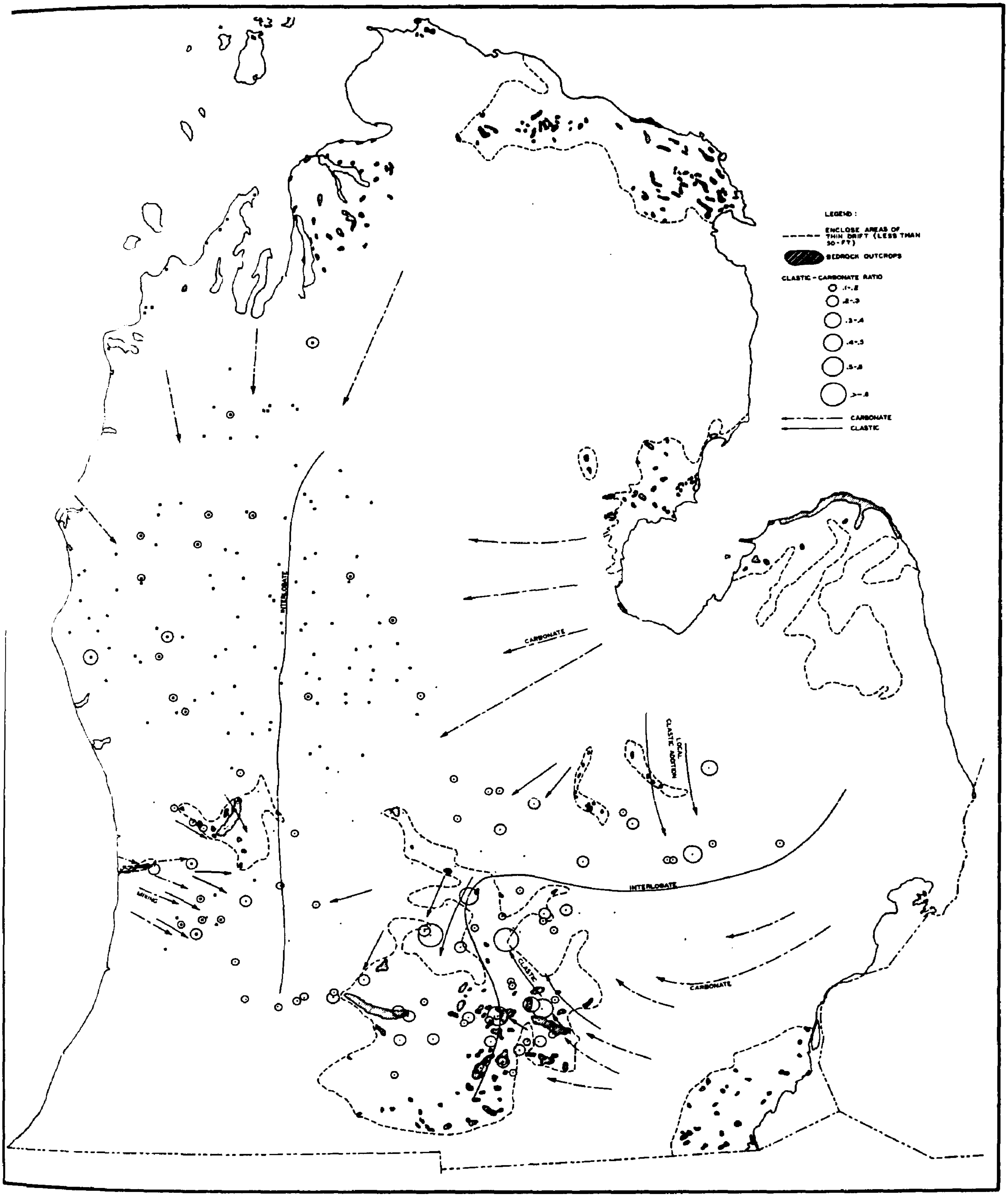

Figure 13. Clastic/carbonate ratio map.

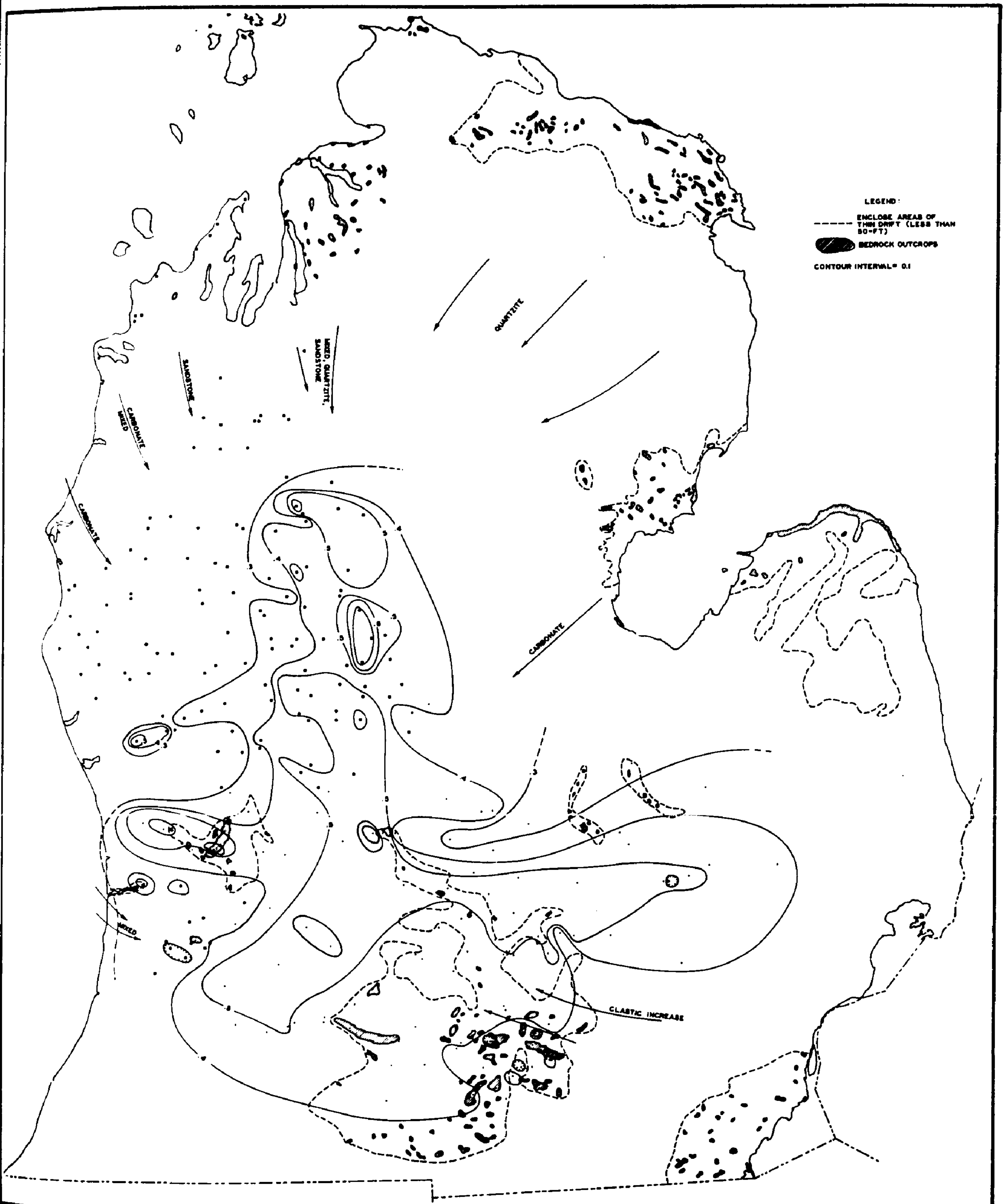

Figure 14. Crystalline/sedimentary ratio map.

the several elements involved in the transportation and deposition of the materials.

Drift materials being carried into the central part of southern Michigan on the northwest, east and southeast, are shown by the arrows on the map to have a generally high relative carbonate content. These materials are derived from known sources and provide expected values. A few circled points in the north of the area derive their clastic content from Keweenawan and Cambrian sandstones that crop out along the south shore of Lake Superior. In the south of the area the apparently spotty distribution of higher clastic areas is explained by the dispersal pattern of Figure 4 relative to the distribution of areas of thin drift and subcrop or outcrop.

Figure 14 is a plot of the ratio of crystalline rocks to sedimentary rocks. The crystalline/sedimentary ratio is more consistent in its areal spread than the clastic/carbonate ratio. This permits the conventional contouring of the data. Interpretation is consistent with that of the clastic/carbonate distribution discussed above.

The highest crystalline concentrations occur in a Y-shaped pattern that lies just inside the interlobate zones on the Saginaw Lobe side. Rather than relating to the areas of local bedrock as on the previous map, the crystalline high is best explained as resulting from residual materials left over from earlier cycles of glaciation; possibly even pre-Wisconsinan. Leverett (1915) ascribed native copper in the drift in Lower Michigan and Ohio to have come from the northwest. Later workers (Horsberg and Anderson, 1956, and Anderson, 1962) regard earlier glacial movement to have advanced along topographic lows, following a generally north to south path parallel to the axes of the present great lakes. Either way crystalline rocks would be carried in from the Lake Superior region or crystalline areas east of there. The present pattern has resulted from re-working of the older drift by glacial and related fluvial agents concommitant with the bringing in of large quantities of carbonates by later glacial episodes. Intermediate values of the crystalline/sediment ratio outside of the central high owe their pattern to local influences of mixing by generally inward radially moving ice and outward flowing meltwaters. Local reductions in the crystalline/sediment ratio that create the irregular pattern on the south side of the eastern limb of the crystalline high are caused by the clastic addition from local sources. The depression over Allegan County, on the southwest results from mixing in of Mississippian and Pennsylvanian shales and sandstones removed from the east side of the Lake Michigan basin.

The patterns of transportation and dispersal suggested here provide the framework to estimate the gross lithologic content anywhere within the area. Knowing the deleterious components that occur in association with each of the three basic lithologies will permit an estimate of percent of deleterious materials to be expected at any specific site along with the approximate physical and chemical properites of the anticipated deleterious component. Accuracy of this prediction will be based largely on that of the presently existing published descriptions of the source rocks and on detailed descriptive studies suggested here to be carried out on certain bedrock formations. (See suggestions for further research, p. 104).

APPLICATION TO ENGINEERING USAGE OF AGGREGATE MATERIALS

Application of Petrographic Analysis to Source Exploration and Evaluation

The following considerations relevant to engineering usage of gravels are based on petrographic and geologic data and findings presented above. The lithologic composition and size grading of Michigan glacial gravels results from the complex interaction of multiple geologic causes including intensity and duration of erosion, transportation, and subsequent weathering of the component materials, their sources, directions of glacial movement, effects of mixing by repeated glacial movements, interspersed with repeated periods of further mixing and deposition by flowing melt waters from the ice.

Gravel quality which is dependent upon size grading and the amount of deleterious material present varies geographically as a consequence of the non-uniformity of these natural interactions.

Variations in the lithologic content resulting from these interactions are of several scales of magnitude. The large-scale variations are those concerned here. These variations can be used to predict the range of petrographic characteristics relating to concrete aggregate suitability from sources within the study area. Smaller scale variability in the petrographic character of gravel sources must still be evaluated by individual producers.

Material that constitutes good concrete aggregate is that which is chemically stable and physically sound when encased in portland cement and subjected to atmospheric weathering. The relevant physiochemical properties are determined by means of petrographic analysis.

Techniques outlined by Mather and Mather (1950) and Mielenz (1946) provide a general basis for aggregate petrography. Modification of basic procedures will generally lead to the most effective procedure for characterizing the deposits in a specific source.

Regional evaluation as performed here provides the following information that can be directly applied to the prediction of expected aggregate quality within the study area:

1. General lithologic content of gravel.
2. Approximate proportion of deleterious rock types.
3. Nature of deleterious rock types.

The relationships between the more finely detailed petrographic variables determined in the pilot phase of this study are drawn from a sample population that statistically approaches infinty and are taken over an area sufficiently large (7500 square miles) that they can be assumed to extend to glacial gravels throughout Michigan. This background of information, when coupled with the regional lithologic variations as determined by the methods of the supplemental phase, can provide a complete basis of prediction of regional trends of aggregate quality. As already pointed out, specific sites or pits, however, still require their own detailed analysis. Grading characteristics, in particular, have no predictability over large areas.

Factors Relating to Aggregate Suitability

The suitability of an aggregate depends on both its physical and chemical soundness. Much literature has been amassed that describes these characteristics in detail (see references) and they need only be touched on here.

Basically deleterious particles can be regarded as either physically or chemically harmful, however, a particle may be both physically unsound and chemically reactive. Sedimentary formations in Michigan contribute these doubly harmful materials to gravels in the form of shale, chert and ferruginous clay concretions. Other physically unsound materials consist of friable sandstones, siltstones, and certain other rock types that tend to split or break along planes of weakness. Crystalline rock sources in the Northern Peninsula or Canada provide foliated metamorphic and certain igneous rocks that are physically non-durable due to chemical weathering or posses deleterious shape characteristics.

Coatings

Coatings on aggregate particles may be either physically or chemically deleterious or innocuous. Clay, silt, fine sand or small pebbles cemented to particle surfaces, if not firmly bound to the particle, may reduce cement-aggregate bonding. In the gravels analyzed here the cementing agents are either carbonates or oxides and are not excessively water soluble or reactive in concrete. Sulfates and other water soluble materials are known as encrusting or cementing agents in some areas and where they occur are chemically deleterious. If weakly or poorly bonded encrustations or chemically reactive coatings occur in large quantities the flexural strength and durability of the concrete may be reduced.

Weathering

Extensive weathering of certain rock types that are chemically unstable under atmospheric conditions may produce aggregate particles that are physically non-durable. Some carbonates, siltstones, shales and basic igneous rocks may be altered by weathering processes involving organic acids, frost action, and solution by percolating ground water. Weathered particles are characterized by low density or crumbly surface texture. Residual products of weathering including clay minerals, oxides, sulfates, and carbonate may or may not be deleterious. Some rock types produce deleterious alteration products during weathering whereas others may become only partially granulated with little chemical alteration. The effect of weathering on durability of a particle in concrete must be separately evaluated for each rock type contained in the aggregate.

The most common physically non-durable or weathered particles are strongly weathered igneous and metamorphic rocks, leached carbonate rocks, shales, and iron oxides.

Shape

Shale, slate and foliated metamorphic rock types are often considered deleterious because of their concrete mix characteristics. They produce a harsh mix which requires excess water to make it workable. In addition, disc or rod shapes may reflect internal weaknesses such as fractures or laminations. These shapes are measured as Zingg classes I and IV (see petrographic analysis and Appendix).

Other Physical Weaknesses

Laminations, fractures, and schistocity of aggregate particles such as schist, slate, shale, siltstone, gneiss, and some limestone provide planes of weakness that may lead to failure of concrete by increased susceptibility to chemical and mechanical attack.

Soft or friable particles such as friable sandstone, shale, siltstone and weathered crystallines are undesirable because of low strength, elasticity and abrasion resistance. Rocks with weakly bonded hard grains such as some sandstones may be distinguished from those with weakly bonded soft grains. The former may not be as harmful as the latter if not abundant.

Several easily identifiable rock types have undesirable pore characteristics. These include some types of chert, ferruginous concretions, shale, and siltstones. These rocks contain interconnected voids of less than four to five microns that produce high capillarity but drain at hydrostatic pressures in excess of the tensile strength of the concrete. Absorbed water not expelled during the freezing cycle expands and if the particle is near the surface of a pavement causes a popout. If such particles are deeply embedded in the pavement and if the pavement is subjected to heavy traffic the entire slab may disrupt.

Chemical Durability

Some rocks are subject to expansive chemical reaction. The most common problem is the "alkali-aggregate" or "alkali-silica" reaction. Here, rocks with free silica react with the alkali present in the cement to produce silicate gels in the concrete. These gels generate hydrostatic pressure which may disrupt or otherwise deteriorate the concrete. In Michigan rocks found to contain free silica are relatively few in variety and generally consist of cherts, or cherty limestones, siliceous shales and phylites.

A second alkali reaction called the "alkali-carbonate" reaction has been found to cause extensive damage to concrete in certain neighboring states and Canada. Careful examination of carbonates was made in this study to determine if certain long-term road failure could be linked to this cause.

The reaction is produced only by very fine grained argillaceous carbonate rocks of intermediate composition (calcareous dolomites or dolomitic limestones) that display indistinct laminations. Aggregate particles of this exact description were not found in any of the analyzed samples. Rocks approximating this description were subjected to special x-ray and chemical analysis to determine clay content and were examined after incorporation in concrete beams. No indication was found to suggest that this problem occurs in Michigan aggregates.

Other potential chemical reactions include base exchange reactions by zeolites and clay minerals, decomposition by sulfide minerals that would produce sulfuric acid, and solution of water soluble minerals such as chlorides and sulfates. None of these reactive materials is present to any significant degree in any of the analyzed samples.

Organic matter present in aggregate particles will inhibit hydration of portland cement or produce abnormal hydration products which will decrease the strength or durability of the concrete. Such harmful material consists of carbonaceous material like coal or woody materials and petroliferous or bituminous matter disseminated in the rock.

Engineering Test Results

Of the original 99 samples, sufficient material remained after the petrographic examination for engineering testing. First vacuum absorption and bulk specific gravity determinations were made (ASTM C 127). Three each 3 by 4 by 16 in. concrete beams and four each 4 by 8 in. concrete cylinders were then made from the aggregate using a 5.5 sack concrete and 5 percent air entrainment. After 14 days moist curing at 100 percent relative humidity the beams were subjected to a rapid freezing and thawing procedure. Failure was indicated by means of a sonic modulus. Seventy percent of the pretest value was considered to represent failure. The test procedure is described in detail in American Society for Testing and Materials Standards C 291-61 and C 215-60. Each beam was then tested for flexural strength with third point loading (ASTM C 78-59). The 4 in. cylinders were tested for compressive strength after 28 days of moist curing. Potential alkali reactivity of the 99 individual samples was also determined by chemical tests (ASTM C 289) described on page 37 . The results are plotted on Figure 6.

Scatter diagrams were plotted to determine relationships between (1) the individual potentially deleterious types of material and the engineering test results (Figs. 15 through 18) and (2) the total potentially deleterious rock types and the same engineering tests (Fig. 19).

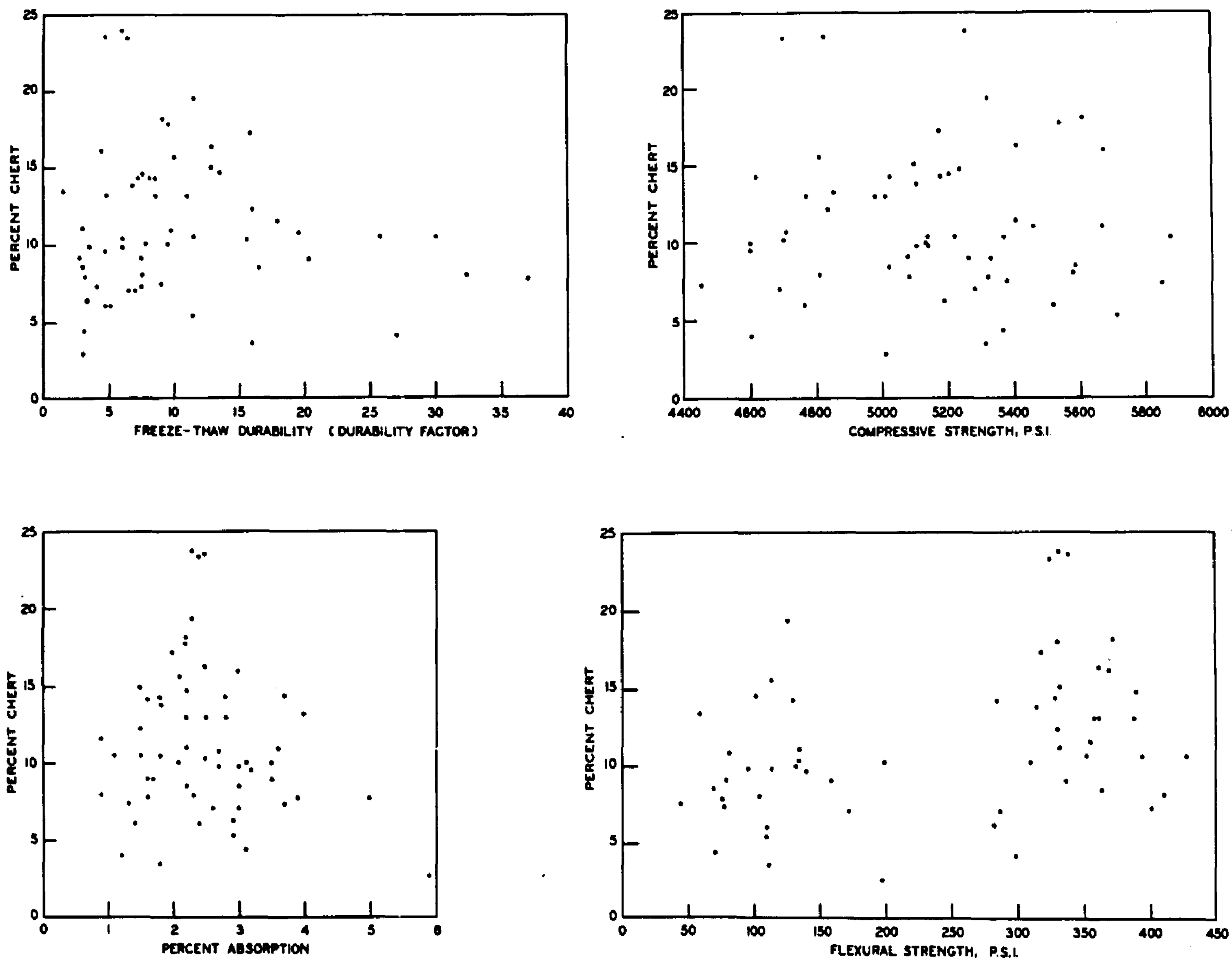

Figure 15. Scatter diagrams of percent chert vs. engineering test results.

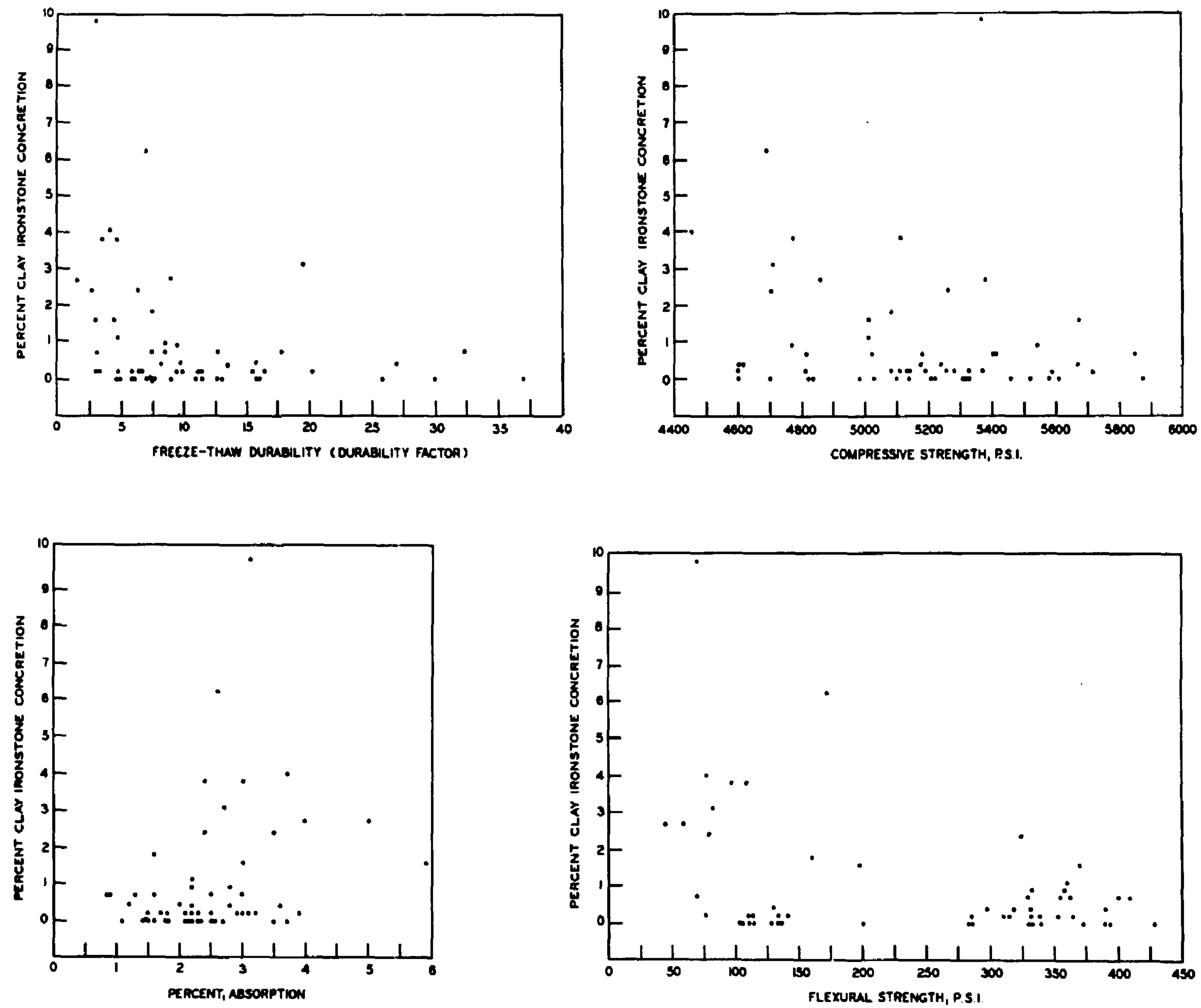

Figure 16. Scatter diagrams of percent ferruginous concretions vs. engineering test results.

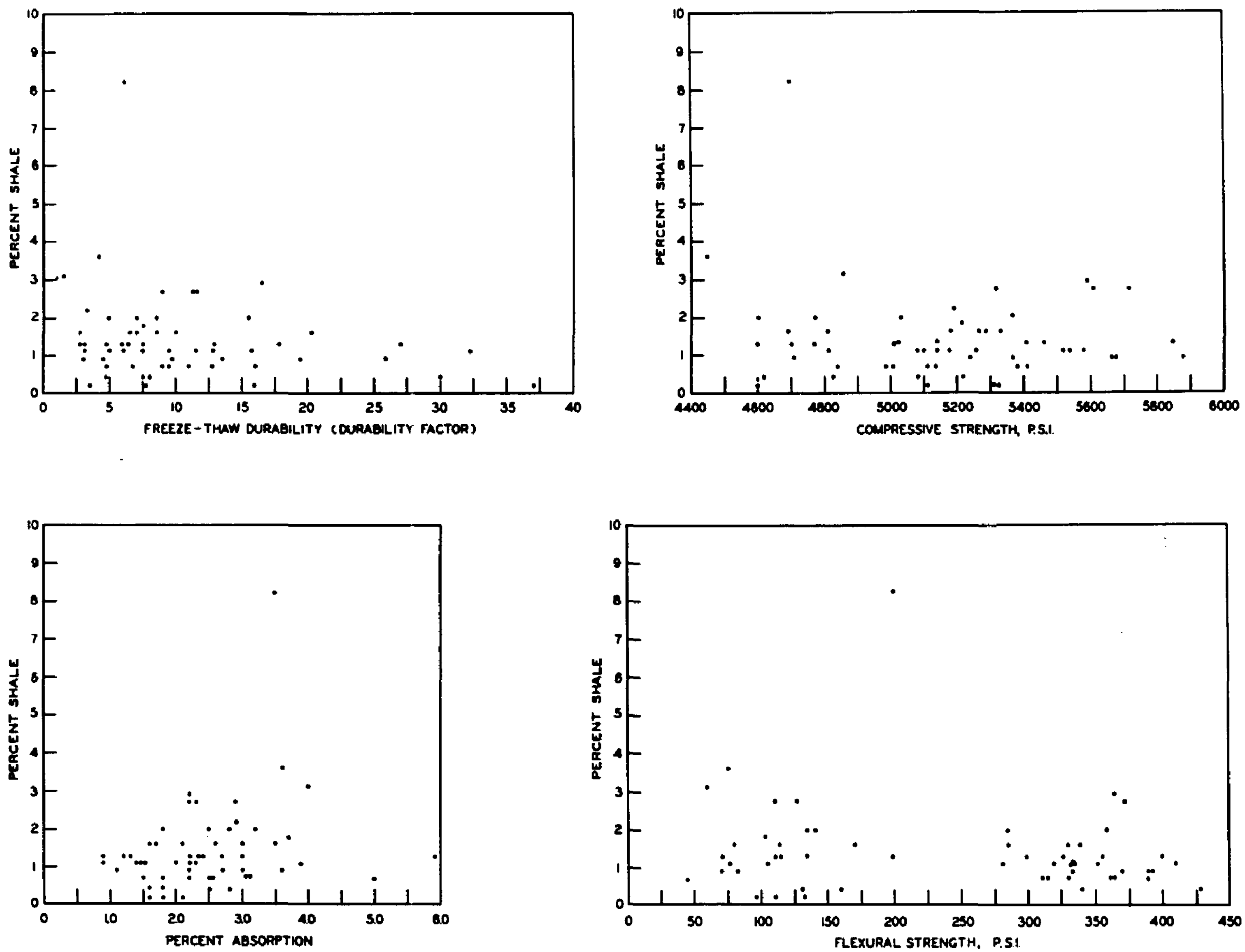

Figure 17. Scatter diagrams of percent shale vs. engineering test results.

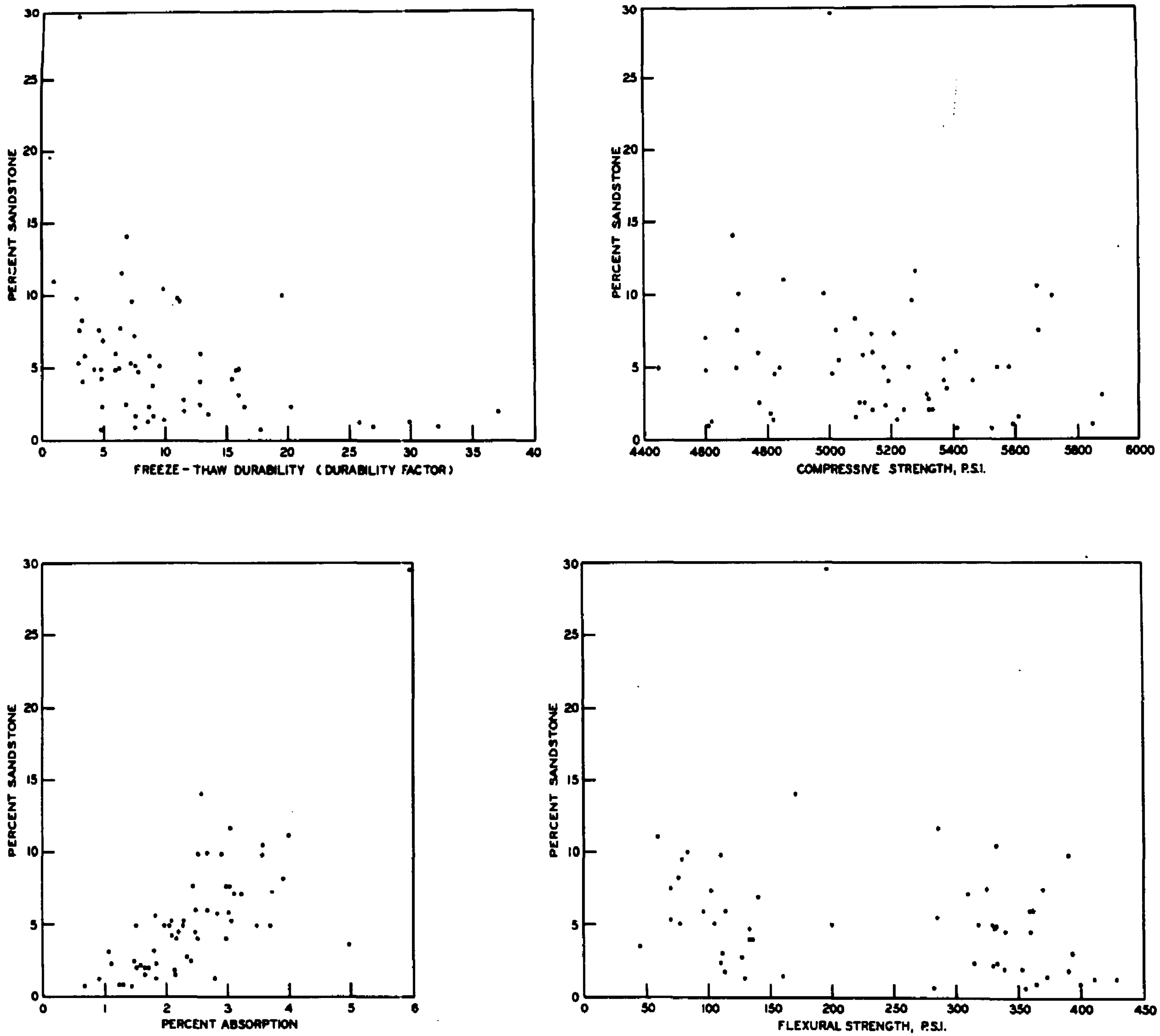

Figure 18. Scatter diagrams of percent sadnstone vs. engineering test results.

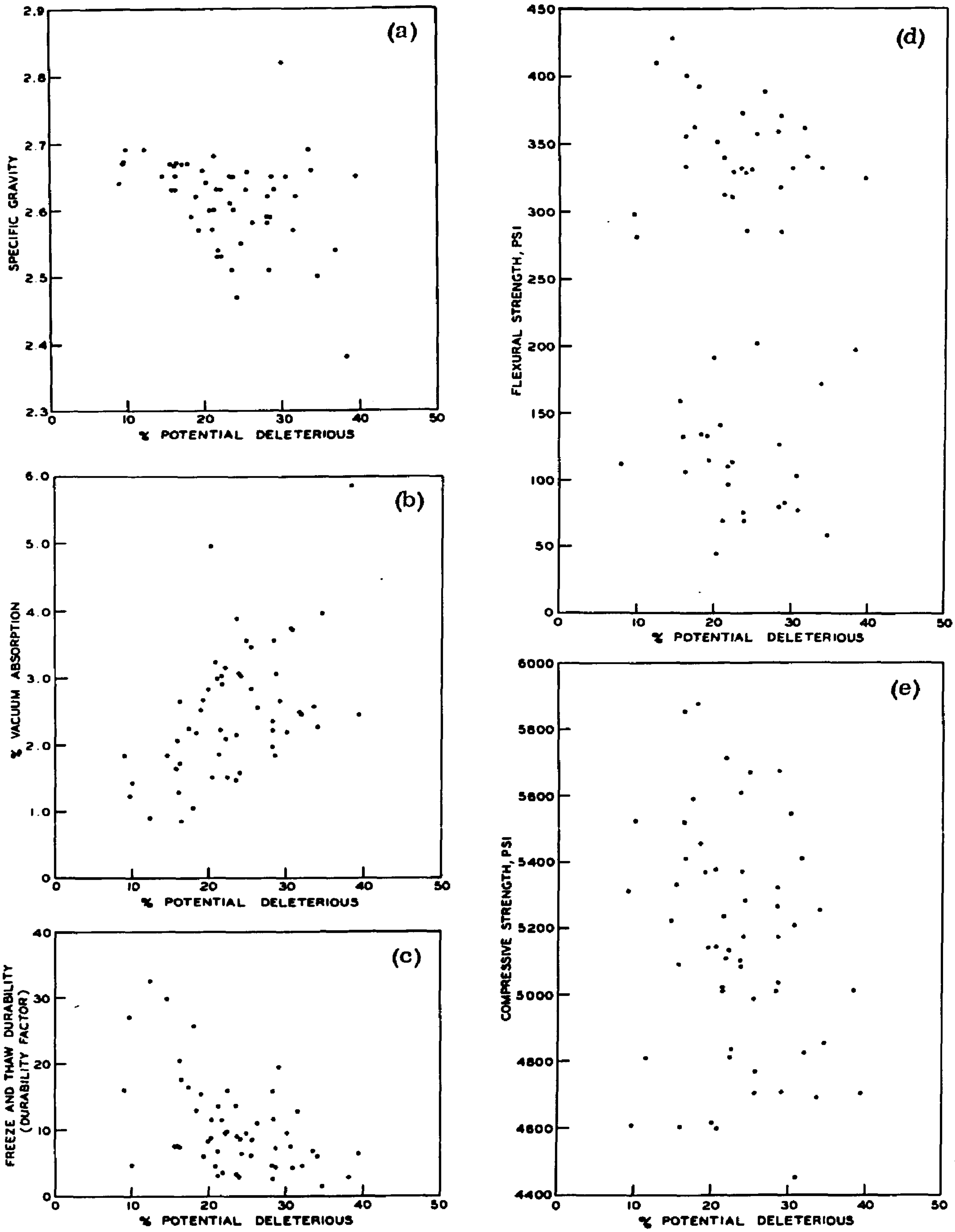

Figure 19. Scatter diagrams of total potential deleterious vs. engineering test results.

Diagrams for the four most abundant potentially deleterious rock types; chert, sandstone, shale, and ferruginous concretions are plotted against the various test results in Figures 15, 16, 17 and 18.

Although trends can be recognized from this set of diagrams, the fact that some samples have relatively few particles of a particular deleterious type creates a certain amount of extraneous scatter that tends to cloud the interpretation. Combining the individual potentially deleterious types reduces this scatter. The percent of potentially deleterious material of Figure 19 was calculated by combining the percentages of sandstone, siltstone, calcareous siltstone, shale, iron oxide, ferruginous concretions and chert. These percentages are plotted against the engineering test results. Discussion is presented below.

Bulk Specific Gravity versus Percent Potential Deleterious, Figure 19 (a).

A general inverse relationship is observed between specific gravity and percent potential deleterious. This is an expected result and, in fact, heavy media separation depends upon this established relationship.

A few points in the upper right of the diagram represent samples containing high concentrations of chert and ferruginous concretions. Specific gravity determined for individual particles of chert and ferruginous concretions during the petrographic examination indicate that both of these deleterious types have a wide range of values. In most cases, however, they can be removed by heavy media separation. The overall range of specific gravity for chert is 2.30 to 2.68. For ferruginous concretions the range is 1.7 to 3.4.

Vacuum Absorption versus Percent Potential Deleterious, Figure 19 (b).

This diagram indicates a direct relation between high absorption and high deleterious content. This is in agreement with current aggregate specifications which limit the amount of soft particles (high absorption, low specific gravity) in processed material. The gravel used to make the test beams and cylinders was bank run (untreated), therefore the content of porous material was high. The highest absorption occurs in samples with as much as 40 percent sandstone, shale, siltstone, and chert. These same samples when incorporated in test beams produced early freeze-thaw failure and low flexural strength.

Freeze and Thaw Durability versus Percent Potential Deleterious, Figure 19 (c).

A durability factor was calculated for each of the test beams by the method of ASTM Standard C 291. The sonic moduli of the beams are measured at regular intervals in the freeze-thaw cycling. When the modulus of a beam reaches 70 percent of the original value the beams are removed from testing.

The scatter diagram shows a grouping in the area greater than 17 percent potential deleterious material and a durability factor of 17 which is equal to 73 freeze-thaw cycles. Of the 56 samples 75 percent fall within the boundaries of this area.

Several factors that are not tested here may influence failure in the beams. They include the size of the test beam (the 3 by 4 by 16-in. standard beam was used in this study), the maximum size of the aggregate (1 in. maximum used in the present study) and the specific deleterious rock types causing failure. The interaction of these variables is being examined by further testing at the present time.

Flexural Strength (psi) versus Percent Potential Deleterious, Figure 19 (d).

The flexural strength was tested after the beams had been subjected to freeze-thaw testing. The grouping of points on the scatter plot indicates that almost half the beams disrupted internally causing significant weakening. These beams had values from 40 - 200 psi. The remaining beams had significantly less internal disruption and their values ranged from 275 - 425 psi.

The scattered values for flexural strength relative to the percent of potentially deleterious materials does not indicate any significant correlation.

28 Day Compressive Strength versus Percent Potential Deleterious, Figure 19 (e).

Four inch cylinders were tested for compressive strength after 28 days of moist curing. No relation between compressive strength and the amount of potentially deleterious material is apparent.

Potential Alkali Reactivity, Dissolved Silica, versus Reduction in Alkalinity, Figure 6.

Figure 6 is a plot of the dissolved silica (Sc) on a logarithimic scale versus the reduction in alkalinity on an arithmetic scale. An empirically derived curve on the graph represents the dividing line between potentially deleterious and innocuous aggregate (ASTM C 289).

The data points fall in two groups, one divided by the curve on the right, and the other a dispersed group of eight points on the left.

When this data is examined in conjunction with the petrographic results a general relation with the chert content is suggested. The amount of chert present on the innocuous side is less than on the potentially deleterious side, but this relation is not absolute. Much scatter is present since relatively high and low values fall on either side of the curve. This is probably caused by the presence of several types of chert found in the glacial gravel. Until a positive basis of distinction of innocuous versus deleterious chert types is developed this method will be of limited value.

Deleterious Constitutents and Beneficiation of Michigan Glacial Gravel

The bulk of the gravel aggregate produced and used in highway construction in southern Lower Michigan is upgraded by heavy media separation (HMS) of the lighter, deleterious particles from the sound material. Various methods of beneficiation and their applications are not within the scope of the present discussion, however, mention is made of the application of HMS to specific problem areas in southern Lower Michigan.

Examination of the glacial gravel has shown that the distribution of deleterious rock types to be quite variable but predictable within certain limits. The presence of certain deleterious rock types such as chert, shale, ferruginous concretions, and sandstone are found in definite dispersal patterns. This means that glacial flow paths between the original source rock and the point of deposition may be reconstructed to aid in gravel source evaluation. The lithologic composition of the glacial drift was controlled by the directions of ice movement, the bedrock over which the ice moved and the nature of the depositional media. Sampling of gravel pits and other exposures of drift has yielded data which when plotted on State-wide maps position these flow paths and dispersal patterns (Figs. 4, 10-14, 20-22). These data may then be applied to cases in which specific deleterious types must be eliminated.

Heavy media separation will almost always produce acceptable material using a specific gravity of from 2.55 to 2.60. However, where the distribution of deleterious types is known this high a gravity liquid may not be needed and "over benefication" will increase the cost of the aggregate. In the case of new deposits preliminary, local quality evaluation using the regional information gained in this study may identify areas of low deleterious content which may reduce the overall beneficiation costs. Where ferruginous concretions are abundant even a 2.60 gravity will not remove all deleterious particles. In this case special beneficiation techniques may have to be used.

The problem in areas with specific deleterious rock types is discussed below.

Sandstone and Ferruginous Concretions in Gravel Sources of Calhoun, Eaton, Ingham and Jackson Counties

The glacial gravels in the four county areas of Calhoun, Eaton, Ingham and Jackson counties, have particularly high concentrations of friable sandstone and ferruginous concretions. The source for the sandstone and some of the Fe-concretions is the lower Marshall Sandstone of Mississippian age. The remainder of the Fe-concretions are attributed to the Coldwater Shale. Areas of outcrop for these formations can be determined from Figure 2 and the various percentage maps. The percentage of sandstone ranges from 5 percent to 25 percent while the percentage of concretions ranges from less than 1.0 percent to 10 percent. The range of abundance of these materials is largely controlled by the proximity of outcrop locations to the gravel pit locations.

To meet specifications for highway aggregate gravel from low quality sources, such as may occur in this four county area, must be upgraded by beneficiation. Heavy media separation (HMS) of the lighter deleterious particles is the most common method. Ferruginous concretions, however, may not yield to heavy media separation even with a liquid of gravity 2.6. The concretions often have remanent siderite ($FeCO_3$) cores with a 3.8 specific gravity. All ferruginous concretions have varying amounts of limonite (Fe_2O_3, S.G. 3.6-4.0). This occurs as a weathering product of the iron carbonate. Further weathering in a subaerial environment may reduce parts of the Fe-concretion to an "iron bearing clay." This is the term most prevalent in engineering literature. Statistical data obtained in the present study indicate that over fifty percent of the relatively unweathered Fe-concretions have a specific gravity greater than 2.6. Broken and weathered Fe-concretions may have densities as low as 1.7 while the unweathered, intact ones may have values up to 3.4. Locating a gravel pit in an area with a high proportion of concretions may be frustrating for the producer because of rejection of processed material and for the contractor who may not meet construction schedules due to lack of suitable aggregate. Early freeze-thaw failure of even recent pavements because of Fe-concretions indicates that the problem may be present even after HMS processing.

Careful selection of new sources in this four county area may yield gravel which contains fewer Fe-concretions thus making it more profitable to produce specification material. Highest percentages of ferruginous concretions occur in southern Ingham and eastern Jackson counties (Fig. 20). Friable sandstone which may be deleterious has a similar but more widespread distribution. Exploration for new gravel sources in western Jackson, Calhoun and southern

Figure 20. Map of percent ferruginous concretions.

Eaton counties should reduce the percentage of Fe-concretions. A reduction of the total Fe-concretions will yield gravel with low gravity deleterious materials which can be removed with a heavy media liquid of from 2.50 to 2.55 specific gravity.

High Chert Content in Areas of Oakland, Genesee, Shiawassee, and Livingston Counties and the Kalamazoo, Calhoun County Area.

Two areas in southern Lower Michigan with an unusually high chert content in the gravel deposits can be observed in Figure 21. The petrographic data from fourteen gravel pits in the Oakland, Genesee, Shiawassee and Livingston County area shows ten pits with a chert content greater than 14 percent. One pit had 27.8 percent chert present. In the Kalamazoo, Calhoun county area seven pits have values greater than 16.2 percent. The range in value is from 16.2 percent to 23.8 percent. The mean for this area is 19.4 percent.

The area of Oakland, Genesee, Shiawassee and Livingston counties lies entirely with the boundaries of the Saginaw Glacial Lobe. The deposits in this area are a result of erosion and deposition by glacial ice fanning outward from the northeast-southwest axis of Saginaw Bay and its southwestward continuation. Glacial erosion took place on the exposed bedrock which flanks Saginaw Bay (Fig. 4). The cherty Bayport Limestone (Upper Mississippian age) is found in outcrop in these areas. The locally high concentrations of chert in the pits of this area are largely due to the proximity of the chert bearing Bayport Formation. The regional chert level in the Saginaw glacial lobe deposits is approximately ten percent. This indicates that possibly as much as 15 percent of the total chert was derived from local Bayport outcrops only a few miles

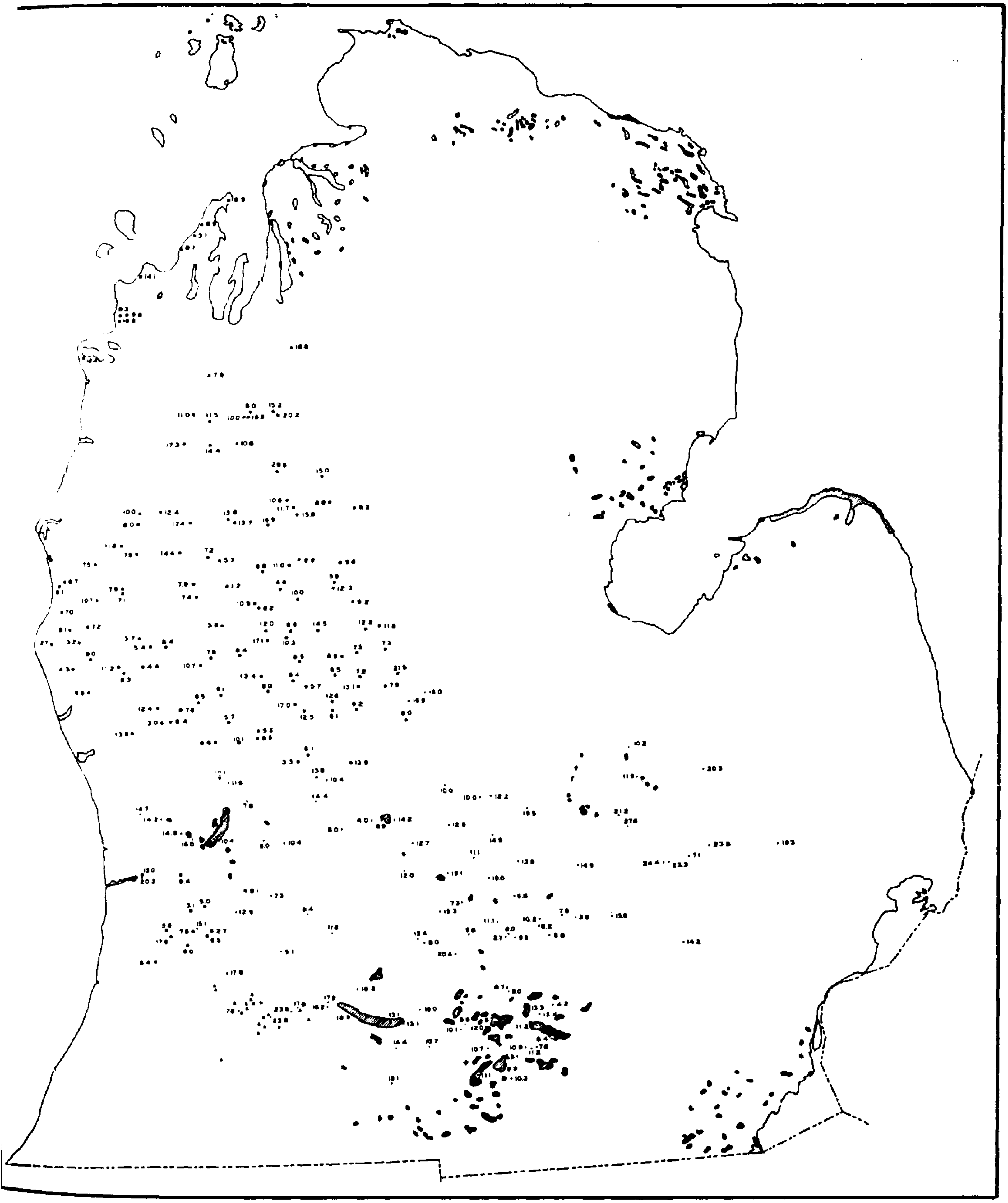

Figure 21. Map of percent chert.

away. The background chert level of 10 percent is probably due to glacial erosion from the Lake Huron basin which is underlain by a thick sequence of limestone and dolomite much of which is chert bearing. The Traverse Group of formations and the Dundee Limestone formation of the Onondaga Group also appear to have contributed chert to the glacial gravel.

Chert percentages in the Kalamazoo, Calhoun county area range from 16.2 percent to 23.8 percent. This high concentration of chert is probably caused by residual enrichment due to fluvial breakdown of the weaker rock types. The gravel pits samples all lie along the Kalamazoo River which during deglaciation was a torrential meltwater stream. Meltwater from both the Saginaw and Lake Michigan glacial lobes had outlets via the glacial Kalamazoo River system. This produced an environment which eliminated most of the weak clastic rock types and thus increased the overall percentage of the more resistant chert.

The original source formations for the chert found in Lake Michigan glacial lobe deposits are stratigraphically correlative with the formations which supplied the chert in the Saginaw Lobe deposits. These include most of the chert bearing Devonian age carbonates and the Upper Mississippian Bayport Limestone (Fig. 2). Chert values for most of the Lake Michigan Lobe deposits are fairly uniform except where fluvial enrichment has taken place. This is explained by the fact that most of the carbonate (and chert) was derived from Lake Michigan basin outcrops which occur over a large area. This explains the dispersed background chert levels for the entire State that range from between 4 percent to 8 percent depending upon the proximity of the original source rocks.

Some of the more porous cherts that are low in specific gravity are easily removed by heavy media liquids. The range in specific gravities is from 2.0 to 2.7 depending upon the type of chert. No definitive criteria have yet been determined to distinguish the deleterious chert types from the non-deleterious. The generally low chert levels, however, pose few problems since HMS beneficiation will remove most of the chert which in most areas is not critical.

Ferruginous Concretions and Shale Content in Allegan and Ottawa Counties.

Ferruginous concretion and shale levels are abnormally high in eleven samples from Allegan and Ottawa counties. This problem also extends to the south into VanBuren County beyond the limits of the present sampling.

The high levels of ferruginous concretions range from 1.4 percent to 10.8 percent. The mean value is approximately 6.0 percent. High values such as these pose the same benefication problems discussed for the Ingham, Jackson, Eaton, and Calhoun county area .

The original source for the Fe-concretions in this area is the Coldwater Shale which directly underlies the glacial drift. The Coldwater also contributed shale pebbles which occur in abnormally high concentrations throughout the area. The shale, however, readily yields to HMS due to its low specific gravity.

The values for both Fe-concretions and shale are given below:

Sample Number	Shale	Fe-Concretions
1-14	2.1%	2.7%
2-12	2.9	3.5
2-13	6.2	10.8
2-14	4.9	---
3-12	0.5	9.8
3-13	2.0	10.4
3-13 (2)	4.0	5.9
3-14	2.7	5.8
4-11	0.5	2.5
4-12	3.1	5.4
5-13	4.7	1.4
5-15	0.6	1.4

From inspection of the data it is inferred that small scale fluctuations in the hydraulics of the local depositional environments are largely responsible for gravel quality in the area. High shale values indicate a less vigorous fluvial environment while low shale values indicate more intense fluvial activity. This means that beneficiation can be reduced by locating new gravel pits along the major drainage channels wherever possible.

Total Deleterious

The net effect of all potentially deleterious components is shown by the map of percent total deleterious (Fig. 22). The distribution of values on this map reflects the sum of the specific deleterious types discussed above. Areas of high values relate to a considerable degree to the distribution of chert since this component is the most frequent single deleterious type. Soft and friable clastic rocks, however, increase the total deleterious content significantly in the southern part of the area.

Exploration for Gravel Aggregate

Exploration for gravel can be viewed as to separate phases: location and evaluation. Exploration generally centers around existing streams or stream channels where quantities of gravel are usually abundant. Because fluvial action often increases the quality by removing the soft or deleterious particles, these areas provide high quality aggregate. On the other hand, glacial drift that was deposited directly by melting ice or meltwater streams which flowed from the receding ice masses often contains poor quality materials because of high concentrations of soft particles.

Exploration for gravel in a glaciated terrane is somewhat more difficult than in non-glacial areas because the surface forms may be nondistinctive and local pockets of gravel may form, rather than broad, channelled deposits. Identification of glacial deposits which may contain gravel on the other hand,

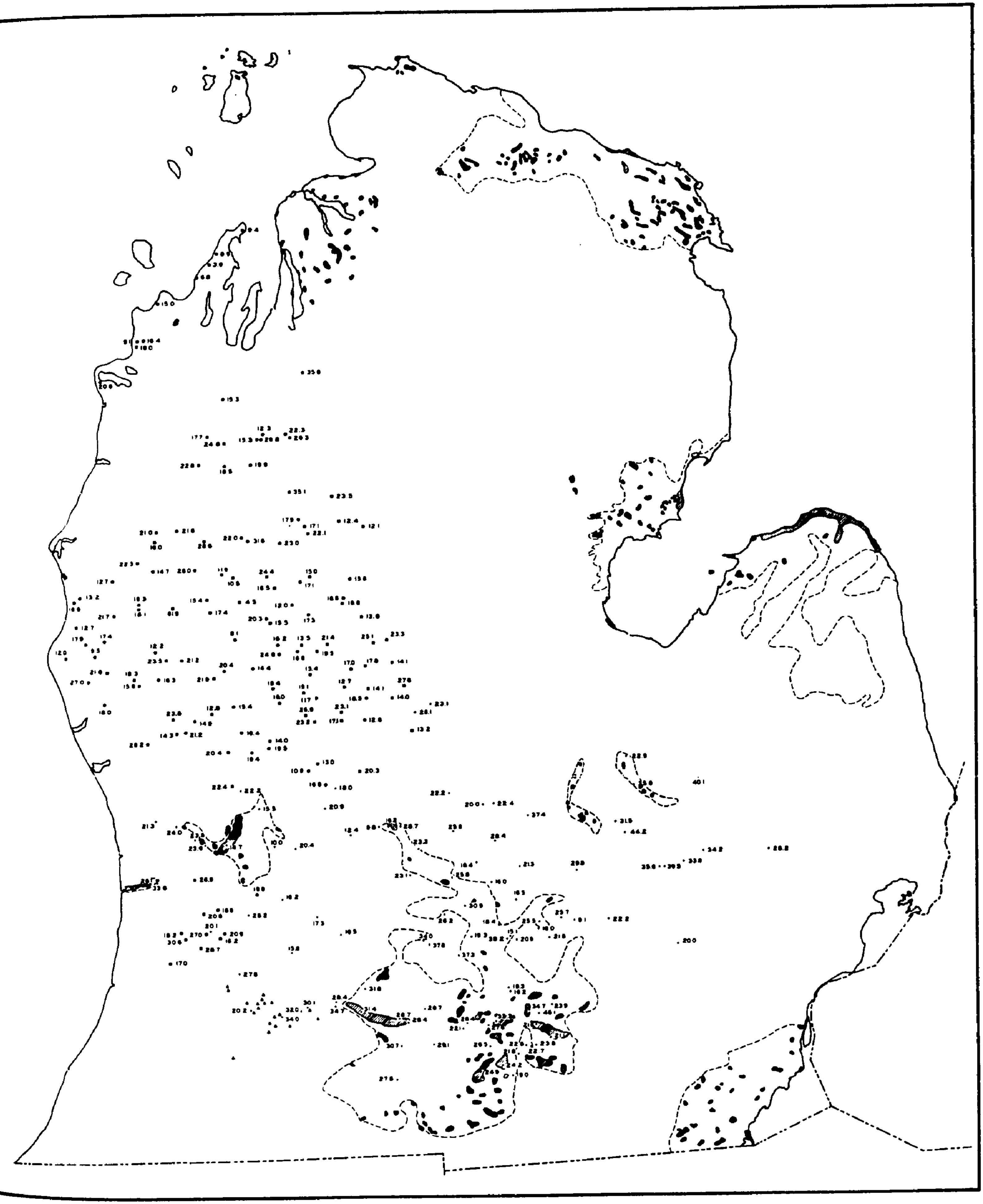

Figure 22. Map of percent total deleterious.

may be aided by the fact that some features are topographically positive and may have a recognizable "morphology." Surficial geology maps, topographic maps, aerial photographs and soil maps aid in the location of likely source areas. Surficial geology maps in glaciated regions will show areas of outwash (deposits water laid at the ice margins, hence "washed out") that contain the bulk of the gravel and sand. Topographic maps and aerial photos at a larger scale will show other features which locally may be of significance.

Evaluation

Once a gravel deposit is located it must be examined and evaluated more fully. The horizontal and vertical extent, the grading and the quality of material present are all factors which must be considered if the deposit is to be developed and operated profitably. Test pits or bore holes must be excavated to establish the size and variations within the deposit. The spacing of the excavations is determined by the amount of information desired. Samples must be taken at both vertical and horizontal intervals to assess the amount of useable material present, being careful to insure that the samples are representative. Gravel quality is determined by separating a portion of the sieved material for petrographic examination. Petrographic analysis of glacial gravel in Michigan will show varying amounts of deleterious particles both locally and regionally.

Normally engineering sampling is for the purpose of measuring lateral variation only. For this purpose a composite sample is desirable. Usually vertical channel samples are best. Vertical variability in the materials of a glacial gravel deposit, however, does exist and can be measured and evaluated. In this case, separate horizons should be separately sampled and examined. This type of sampling might be of benefit to take advantage of natural sorting action in deposits where a major change in the depositional media or source of materials has occurred during the time of its accumulation.

Gravel Petrography Applied to Exploration for Aggregate

The petrographer will play an increasing role in gravel exploration as the supply of good quality aggregate diminishes. Certain areas of Michigan have unusual problems with regard to deleteri ous rock types which may be solved by critical petrographic examination.

Samples for petrographic examination can be obtained by field personnel and returned to the Laboratory or the petrographer can sample and examine the material on-site.

Most exploration involves sampling material from test pits and bore holes. When the petrographic examination is made in the field, a large area can be evaluated in a short time. Excavation equipment can be moved immediately to a new site determined by the test results obtained from the preceding site. The on-site evaluation is, therefore, more economical since drilling crews can operate at maximum efficiency in terms of the petrographic information gained.

The grading of material present in a deposit usually can be determined approximately by visual estimation in the field. Samples from a fresh working cut can be sieved for more specific information if the quality of the gravel is acceptable enough to warrant further exploration.

The technical equipment needed for field petrographic examination is easily transported to the job site. The equipment includes a selection of sieves to separate the coarse aggregate, sorting cans, a variable power binocular microscope and a quantity of water for washing samples.

The actual petrographic identification may be undertaken in either of two ways. The first is the standard ASTM Method of relating the frequency of lithologies on a count basis. This method requires additional sieving and selection of 200 pebbles in each size grade. The second method is by the volume pebble analysis as developed in the present study (p. 59). The method relates the frequency of individual rock types (or grouping of rocks) by comparing their volume to an original volume of material. The volume determinations can be made by water displacement or by using Archimedes principle.

Lithologic identification needs only to provide efficient data for the economic purpose. Michigan glacial gravels contain a wide variety of rock types, however, the significant deleterious types are easily identifiable.

The composition and physical characteristics of deleterious components are determined in early exploratory evaluation. After a pit is established, continuing quality control evaluation can be maintained by a simplified classification of materials requiring only recognition of the deleterious rock types.

The deleterious suite has one member, the ferruginous concretion, which requires additional care on the part of the petrographer. Fe-concretions have a range in specific gravity from 1.5 to 3.5 depending upon their internal composition. The Fe-concretion, where found in abundance, must be treated by heavy media separation at a high gravity of 2.60 to insure elimination. Often the Fe-concretion will be non-uniformly distributed throughout a deposit. This means that close attention must be paid to areas of high concentration during the exploration phase of pit development so that economic operation can be maintained during production.

CONCLUSIONS

1. A classification of gravel deposits which can be used for economic evaluation is based on the visual appearance of the materials in the field. Associated landform is of secondary importance.

2. Mechanical analysis indicates that mean sorting of the gravel deposits differs slightly between ice-contact and proglacial deposits, with the proglacial deposits being better sorted. This is primarily caused by higher sand content in the proglacial deposits.

3. Physical characteristics of individual particles display low but consistent correlations, however, do not serve to differentiate samples on any basis of classification.

4. Lithologic analysis supplies the definitive criteria for aggregate source evaluation. An essentially uniform assemblage of rock types occurs over the entire area of southern and western Lower Michigan. The general uniformity of the suite is interpreted as largely caused by mixing because of recycling of materials during multiple phases of glaciation and glaciofluvial reworking.

Significant regional variations inthe composition of the gravels are reflected by gross lithology. A three component system consisting of crystalline, clastic, and carbonate rocks, relates to processes of transportation and deposition. A lithofacies type of analytical approach centered on these components is interpreted in terms of the final dispersal of the materials. A more detailed breakdown of the lithologic suite, size frequency distribution, and physical and chemical properties of individual components are useful for local or detailed studies of individual gravel deposits.

5. Lithologic analysis provides a basis for prediction of regional trends of aggregate quality. Variations in gross lithology relate directly to amounts of physically and chemically unsound materials. Engineering test results of the materials, in turn, indicate that the expected regional levels of deleterious particles can, in most cases, be removed by heavy media separation.

6. A few specific deleterious rock types can usually be cited as the major aggregate problem for general geographic regions. The lithologic analysis supplies sufficient information to explore for best sources to minimize the deleterious materials and to make recommendations for beneficiation.

7. Petrographic evaluation of aggregate sources for exploration or other purposes can be effectively done in the field with a small amount of equipment by the volume pebble technique.

SUGGESTIONS FOR FURTHER RESEARCH

The volume pebble analysis system of lithologic analysis must be applied to the remaining areas of the State. In this way the integrated picture will be established of the geologic history and processes that distributed the glacial materials. This will enable the range of aggregate quality to be estimated on a State-wide basis.

Detailed small area studies for aggregate source evaluations are necessary where specific information is sought in conjunction with production. Since it was not the purpose of this report to characterize specific sources, this aspect has only been mentioned, but is not developed here.

Further insight with the specific quality characteristics of aggregate materials in the gravels will be gained by detailed and systematic study of the bedrock units from which they were derived by the glacial and related processes. Most important of these to be studied are the carbonates of Mississippian age and the clastic formations of Pennsylvanian age.

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APPENDIX

TABLE 11
GENERAL DATA SUMMARY SHEET
FOR INITIAL 99 SAMPLES

PIT NUMBER	TYPE OF DEPOSIT	LOBE	SAMPLE WEIGHT	PHANERITIC ACID IGNEOUS	PHANERITIC INTERMEDIATE IGNEOUS	PHANERITIC BASIC IGNEOUS	MICRO-PHANERITIC IGNEOUS	APHANITIC ACID IGNEOUS	APHANITIC BASIC IGNEOUS	PEGMATITE	SANDSTONE	SILTSTONE	CALCAREOUS SILTSTONE	SHALE	CRAG	COAL	CLAY	IRON OXIDE	CLAY IRONSTONE CONCRETION	LIMESTONE	DOLOMITIC LIMESTONE	DOLOMITE	CHALK	CHERT	NON-FOLIATED METAMORPHIC	FOLIATED METAMORPHIC	OTHERS	ORGANIC MATERIAL	POTENTIALLY ALKALINE REACTIVE	SOLUBLES, SULFIDES	POTENTIAL BASE EXCHANGE	PHYSICAL DURABILITY 1	PHYSICAL DURABILITY 2
				PERCENT																													
1	Ice Contact	Sag.	219570	5.78	4.00	2.44	2.22	3.11	1.78	0	2.44	1.33	0.22	0.67	0	0	0.44	1.78	0.22	21.78	17.56	6.00	0	13.78	11.78	2.67	0	4.22	1.56	0.67	0	39.78	59.
2	Ice Contact	Sag.	112183	8.89	1.11	0	0	0	9.78	0	2.89	1.11	0	1.56	0	0	0.89	0	0	21.56	8.22	10.67	0	19.11	12.89	1.11	0.22	4.89	0	0.44	0	14.89	70.
3	Unconfined Outwash	Sag.	101337	5.56	0.89	0	0.67	0.67	8.67	0	7.56	2.22	0	1.56	0	0	1.33	0.44	0.22	20.44	13.11	10.22	0	14.89	9.56	2.00	0	3.78	0	0.22	0	21.11	66.
4	Unconfined Outwash	Sag.	161494	9.11	0.67	0	1.33	0	10.44	0.22	5.78	2.67	0.44	1.78	0	0.67	0	0	2.67	14.89	14.67	7.11	0	14.89	11.11	1.56	0	4.89	0	0.44	0	18.00	69.
5	Confined Outwash	Sag.	197751	11.33	0.22	0.22	0.22	0	9.33	0.44	9.78	1.33	0.44	1.56	0	0.22	1.11	0.22	2.44	14.67	8.44	4.22	0	20.44	11.56	1.33	0.44	3.78	0	0.44	0	27.78	56.
6	Confined Outwash	Sag.	165710	3.98	0.31	0.31	0.92	0	8.26	0	6.12	5.20	0.92	1.83	0	0	2.45	0	0.31	15.90	6.42	7.34	0	27.83	10.09	2.14	0	4.28	0	0.31	0	23.24	55.
7	Confined Outwash	Sag.	90348	4.25	0	0.45	1.12	0	9.62	0.45	3.80	2.91	1.12	0.67	0	0	2.68	0	0.22	21.92	11.63	5.15	0	21.25	11.19	1.57	0	4.47	0	0.67	0	29.75	59.
8	Ice Contact	Sag.	116678	6.44	0.22	0.44	0.89	0.22	8.22	0.49	4.00	1.56	0.89	1.11	0	0	0.67	0	0.67	15.56	11.11	5.56	0	24.44	14.00	2.89	0.22	4.44	0	0.44	0	36.44	56.
9	Ice Contact	Sag.	219736	4.22	1.11	0.22	1.56	0	4.89	0.22	7.56	0.44	0.44	1.33	0	0.44	1.11	0	2.44	19.11	13.33	2.89	0	23.33	9.11	4.00	0.22	5.33	0.44	1.33	0	48.89	40.
10	Confined Outwash	Sag.	222914	5.33	1.11	1.33	2.22	1.11	6.89	0	14.00	0.89	0.67	1.56	0	0.22	0	0	0.22	11.78	14.67	5.11	0	7.11	15.78	3.33	0.67	4.00	0.22	0.89	0	42.89	35.
11	Confined Outwash	S-H I	109687	5.11	0	0	1.78	1.11	4.89	0.22	5.56	0.89	0	1.33	0	0	0	0	0.22	14.44	20.22	3.33	0	22.78	13.78	2.44	0.89	3.11	0.22	0.67	0	50.89	41.
12	Confined Outwash	S-H I	81040	6.87	0.27	0	1.37	1.65	2.75	0	12.36	2.75	0.27	2.20	0.27	0	1.37	0.27	0.27	23.63	9.89	2.47	0	20.33	8.79	1.92	0.27	2.75	0.27	0	0	39.01	42.
13	Unconfined Outwash	Sag.	151636	5.77	1.28	0	0.32	0.64	2.88	0.32	11.54	5.45	0	3.21	0	0.32	0.96	1.60	0.32	26.00	11.22	3.21	0.64	11.86	8.01	3.21	0.64	2.24	0	0.32	0	43.27	38.
14	Unconfined Outwash	Sag.	197944	6.74	0	0.54	2.43	1.35	3.23	0	4.85	2.43	0.81	2.43	0	0	0.54	1.35	0.27	38.27	10.78	5.93	0	10.24	5.39	1.89	0.54	2.16	0.27	0.27	0	46.90	43.
15	Unconfined Outwash	Sag.	187648	4.89	1.11	2.44	3.11	0.89	7.33	0.22	4.89	0.89	0.67	0.67	0	0	0.44	0.89	0	24.67	15.11	6.22	0	13.22	8.00	3.11	0.22	5.11	0.44	1.78	0	59.11	32.
16	Confined Outwash	Sag.	189772	3.02	0.82	0	2.75	1.10	3.02	0	11.54	0.27	0	1.65	0	0.55	1.10	0	0.55	26.37	12.64	3.30	0	19.51	7.69	3.85	0.27	3.57	0	0	0	55.77	32.
17	Confined Outwash	Sag.	140740	5.57	0.67	0.89	1.78	0.67	6.24	0.22	3.12	2.00	0.67	1.56	0	0.22	7.45	0	0.45	27.17	13.36	9.13	0.45	10.02	10.91	2.23	0.22	4.23	0.22	0.45	0	53.01	34.
18	Confined Outwash	Sag.	153452	6.89	0.22	0.67	4.22	2.89	5.56	0.22	3.78	1.33	1.11	0.67	0	0	0	0	0.44	25.33	20.67	3.33	0.89	10.00	8.89	4.89	0	1.33	0	0	0	39.33	52.
19	Ice Contact	Sag.	642168	3.76	0.67	0	2.89	0.44	6.44	0.44	3.78	2.00	0.89	1.33	0	0	1.11	0	1.11	28.67	13.78	6.00	0	16.89	6.67	3.11	0	1.78	0.44	0	0	49.78	37.
20	Ice Contact	Sag.	112592	5.78	0	0	4.00	0.67	7.33	0	2.22	0.22	0.22	1.56	0	0	0.89	0	0.89	28.00	13.33	6.00	0	16.00	6.67	2.00	0.22	3.78	0.22	0.22	0	42.00	33.
21	Ice Contact	Sag.	207932	5.56	0.22	0.44	3.56	0.22	5.56	0.22	5.56	1.78	2.67	2.00	0	0	1.78	0	0	23.33	16.89	4.22	0	14.22	9.11	2.44	0.22	2.44	0	0	0	49.33	37.
22	Confined Outwash	Sag.	215196	5.56	0	1.11	4.44	1.11	4.00	0.22	1.78	1.33	0.22	2.67	0	0	0.44	0	0.89	25.78	19.33	5.11	0	12.67	9.56	3.78	0	3.56	0	0.44	0	31.78	39.
23	Confined Outwash	Sag.	133476	6.89	0.67	1.11	2.67	0.67	6.67	0.44	2.47	1.56	1.33	0.44	0	0	0.89	0	0.44	22.44	10.44	3.33	0	12.00	12.22	4.67	0.44	1.78	0	0.44	0	43.11	40.
24	Confined Outwash	Sag.	240164	2.89	0.67	0	3.56	1.56	2.89	0.22	5.78	2.00	0	2.00	0	0	1.33	0.67	0.89	34.89	12.44	6.44	0	12.89	6.89	2.00	0	2.44	0.89	0	0	50.67	35.
25	Confined Outwash	Sag.	228362	6.44	2.22	1.33	2.22	1.56	12.00	0.22	2.00	0.67	0.22	1.56	0	0	0	1.11	0.22	33.56	11.56	4.00	0	8.89	7.33	2.67	0.22	2.22	0.44	0	0.22	59.11	34.
26	Confined Outwash	Sag.	227000	10.89	2.89	2.89	0	4.44	11.56	0	0.89	1.11	0	1.33	0	0	0	0	0.44	42.44	4.44	2.22	0.22	4.00	6.67	2.00	1.56	0.67	0	0.44	0	60.89	23.
27	Confined Outwash	Sag.	212472	6.22	2.22	0.89	0	1.78	14.00	0	1.33	0.22	0	1.11	0	0	0	0.22	0.67	38.78	10.22	6.67	0	8.00	7.33	1.11	0.22	1.78	0	0	0	72.00	23.
28	Unconfined Outwash	Sag.	216104	7.33	1.56	1.33	1.38	2.22	9.33	0	3.11	0.44	0	0.89	0	0	0	0	0	28.89	12.67	6.00	0	10.44	10.67	3.11	0.67	1.56	0	0.22	0	66.56	32.
29	Unconfined Outwash	Sag.	199760	8.00	1.11	0.22	0.44	1.11	8.22	0	2.67	0.67	0.22	1.11	0	0	0.22	0.44	0.22	35.78	10.67	4.44	0	14.44	7.56	1.56	0.89	1.56	0	0.44	0	57.78	32.
30	Confined Outwash	L-S I	233356	7.78	0.89	0	1.33	1.56	4.44	0.44	2.00	0.22	2.44	0.22	0	0	0	0.44	0	31.33	21.56	7.33	0	7.78	7.11	2.89	0.22	1.33	0.22	0.22	0	46.44	43.
31	Unconfined Outwash	L-S I	119656	6.00	0.67	0	1.56	0.67	5.11	0	2.67	1.33	2.67	0.67	0.22	0	0.89	0.89	1.11	32.00	16.22	5.56	0	11.56	4.44	2.22	0.67	2.00	0	0	0	45.22	45.
32	Ice Contact	Sag.	276940	6.24	1.54	0.45	1.56	4.01	8.00	0.22	0.67	0.22	0.67	1.34	0	0	0	0.22	0.67	27.84	13.14	5.12	0	11.58	12.03	1.34	0.45	1.78	0	0	0	45.45	46.
33	Confined Outwash	Sag.	310082	6.67	1.56	0.67	1.78	4.44	6.67	0	1.11	0.44	1.56	2.89	0	0	0	0.22	0.22	33.33	9.33	2.67	0	8.44	14.22	2.67	1.11	2.00	0	0.22	0	43.56	46.
34	Ice Contact	L-S I	140740	4.44	1.54	0.22	1.78	4.00	4.67	0.44	0.89	0.89	2.67	1.33	0	0.22	0.44	1.11	0.67	27.56	15.78	8.89	0.22	7.33	8.00	2.44	0.44	2.44	0.44	0.22	0	53.11	38.
35	Ice Contact	L-S I	371372	8.00	1.78	0.89	0.67	5.11	8.11	0	1.56	0.22	0.67	0.44	0.67	0	0	2.00	1.78	22.67	19.33	7.11	0	9.11	4.89	2.00	0	1.56	0	0	0	53.11	37.
36	Ice Contact	L-S I	294646	8.00	1.11	0.22	0.89	2.89	3.56	0.67	4.44	1.78	6.22	0.67	0.22	0	0.22	1.11	1.11	24.44	13.56	10.22	0.44	12.89	4.00	1.11	0.22	1.33	0	0.44	0	46.89	34.
37	Ice Contact	L. Mich	103966	6.93	0.50	0.25	0.50	1.24	3.22	0	1.73	0.50	0.25	0.99	1.73	0	0	1.73	0.50	27.97	20.79	6.19	0.25	15.10	6.17	0.99	0.50	2.48	0	0	0	39.11	48.
38	Confined Outwash	----	336414	6.22	1.11	0.67	0.44	4.00	5.11	0	2.00	0.89	2.89	1.11	0	0	0	0.22	0.22	25.11	18.22	7.33	0	10.44	11.11	2.89	0	3.56	0	0.44	0	67.33	25.
39	Unconfined Outwash	----	181600	8.00	1.78	0.67	1.33	3.11	8.00	0	0.67	0	0.89	1.11	1.56	0	0	1.56	0	43.33	7.33	5.11	0	6.00	7.78	1.33	0.44	0.67	0	0.22	0	52.67	39.
40	Confined Outwash	----	261050	12.67	1.11	1.56	1.11	1.56	6.67	0.44	1.33	0.22	0.67	0.44	0	0	0	0.44	0	34.67	9.78	4.22	0	10.44	10.89	1.56	0.22	0.89	0.22	0.22	0	54.44	37.
41	Confined Outwash	----	190226	10.00	1.33	1.33	1.11	2.89	5.11	0	1.56	0.22	1.56	0.67	0	0	0	0.22	0	34.00	14.89	4.89	0	16.00	10.00	1.56	0.67	1.56	0.22	0.44	0.22	60.11	34.
42	Unconfined Outwash	----	300094	11.11	1.11	0.44	0.44	2.89	4.67	0	2.44	0.44	1.78	1.11	0	0	0	0	0	26.89	10.67	5.56	0	14.89	12.22	2.89	0.44	2.00	0	0.44	0.22	74.44	21.
43	Unconfined Outwash	----	337442	11.56	0.89	1.33	0.67	2.00	3.78	0	2.22	0.22	2.89	1.56	0	0	0.22	0.22	0.67	18.67	21.56	7.78	0.22	14.22	16.22	2.22	0.89	1.78	0	0.22	0.22	62.22	28.
44	Unconfined Outwash	----	223022	12.22	0.89	0.67	0.67	2.44	4.44	0.22	1.78	0.22	0.67	0.89	0	0	0	0.44	0.44	34.00	8.00	2.89	0	14.67	10.89	2.67	0.89	3.33	0	0.22	0	73.56	21.
45	Unconfined Outwash	----	172974	8.97	0.61	0.31	2.75	1.53	2.14	0.31	4.28	2.14	3.36	1.53	0	0.31	0	1.53	0.61	26.91	6.73	2.14	0	29.10	12.23	1.53	0	2.45	0	0	0	33.94	40.
46	Ice Contact	Sag.	208386	5.56	2.00	1.11	2.22	2.22	2.44	0.22	6.00	0.89	5.11	0.67	0	0	0	0.22	0.67	23.56	11.56	3.33	0	16.22	13.56	2.22	0.22	2.00	0.67	0.67	0	54.00	30.
47	Confined Outwash	Sag.	198988	7.11	0.44	2.00	0.67	1.11	2.00	0	11.11	1.56	2.22	0.22	0	0	0	0.22	0.67	22.00	8.44	2.00	0	18.89	17.33	1.78	0.22	1.11	0	0	0	46.98	39.
48	Confined Outwash	Sag.	150274	4.45	1.34	2.00	1.34	1.11	2.23	0	8.91	1.34	1.56	1.56	0	0	0	0.22	0.67	27.39	11.36	3.12	0	13.14	16.26	1.56	0.22	0.45	0	0	0	61.16	25.
49	Confined Outwash	Sag.	197944	4.92	1.56	0.89	2.68	0.89	2.01	0.22	4.91	1.12	2.23	1.12	0	0	0	0.22	0.45	32.14	6.70	2.01	0	17.19	14.51	1.34	0.89	0.67	0.45	0	0	58.48	32.
50	Confined Outwash	Sag.	179330	4.00	0.89	0.67	0.22	3.11	1.56	0	9.11	1.33	3.78	0.89	0	0.22	0	0	0	21.56	12.22	2.00	0	15.22	16.00	1.33	0.89	1.11	0.22	1.33	0	51.89	32.
51	Unconfined Outwash	Sag.	137582	7.33	0.89	1.56	1.78	0.67	2.00	0	5.11	1.33	0.67	1.11	0	0.22	0	0.44	0.89	27.33	10.00	2.67	0	17.78	14.00	3.33	0.89	0.89	0.44	2.00	0	57.33	30.
52	Unconfined Outwash	Sag.	181146	8.67	0.22	3.56	0.67	1.56	0.89	0	4.44	0.44	1.56	0.44	0.22	0	0	0	0	12.67	16.89	2.00	0	23.56	16.67	1.56	0	0.22	0.44	0.22	0	62.00	23.
53	Confined Outwash	L-S I	246068	4.00	0.22	2.22	0.67	1.56	1.56	0	4.89	1.78	0.89	1.11	0.22	0	0	0	0.22	14.22	20.00	3.56	0	22.78	15.11	1.33	0.67	0.44	0	0.44	0	61.11	24.
54	Unconfined Outwash	L. Mich	221098	8.22	2.00	0.67	1.11	0.44	2.00	0	3.56	0.22	2.67	0.67	11.56	0	0	0.89	2.67	30.22	4.89	6.78	0	7.56	6.00	2.89	0	1.56	0	0	0	52.22	34.
55	Unconfined Outwash	L-S I	189232	7.11	0.89	1.33	1.78	1.11	1.56	0.22	2.00	1.11	2.89	0.89	0.67	0	0	0	0	34.00	13.33	1.33	0	17.76	18.67	2.89	0.44	0.22	0	0.89	0	46.67	19.
56	Ice Contact	Sag.	186862	7.78	0.89	0.89	2.44	0.22	1.56	0.22	6.44	1.11	0.89	0.22	0	0	0	0	0.22	27.56	12.89	3.56	0	15.33	15.56	2.00	0.22	1.78	0.44	0.67	0	52.67	37.
57	Confined Outwash	Sag	208840	8.44	1.11	0.67	1.33	0.44	2.00	0	12.00	0.89	1.78	0.89	0	0	0.22	0	0	26.00	8.44	2.67	0	16.44	16.00	2.00	0.67	1.56	0.22	0.89	0	39.11	39.
58	Unconfined Outwash	Sag.	187992	3.33	0	2.44	1.56	1.56	2.89	0.22	23.33	2.22	0.22	0	0	0	0.22	1.11	1.56	20.22	4.89	1.78	0	6.00	13.33	2.44	0.67	2.44	0	1.11	0	60.44	17.
59	Unconfined Outwash	Sag.	219736	4.44	1.78	1.33	0.89	2.00	3.33	0	8.78	0.44	1.56	0.67	0	0	0	2.22	0	32.00	5.78	3.11	0	13.11	14.00	0.89	0.67	1.11	0	1.11	0	61.76	26.
60	Confined Outwash	Sag.	220644	7.56	2.00	0.89	0.22	0.89	0.89	0	7.56	0.89	0.67	0.89	0	0	0	0.44	1.56	20.89	8.67	4.00	0	16.00	14.67	1.11	0.22	0.22	0.44	0	0	49.11	34.
61	Unconfined Outwash	Sag.	207932	4.44	1.78	1.78	0.89	2.67	2.89	0	7.33	3.56	1.33	1.78	0	0	0	0.67	0	26.38	9.78	4.22	0	14.44	13.67	2.22	0.67	2.22	0.67	0	0	54.44	31.
62	Ice Contact	Sag.	204754	5.33	3.78	1.11	0.44	3.33	2.00	0	10.00	1.56	1.33	0.89	0	0.22	0	1.56	3.11	34.67	1.56	2.67	0	10.87	14.22	1.56	0	1.11	0.22	0.22	0	60.56	16.
63	Unconfined Outwash	Sag.	129844	7.11	2.22	0.44	1.11	1.56	3.11	0	1.78	1.11	1.11	2.67	0	0	0	0.44	0.22	30.00	7.33	3.11	0	19.11	15.56	1.78	0.22	1.11	1.78	0	0	27.78	50.44
64	Ice Contact	Sag.	266498	4.22	2.89	0.22	0.44	2.22	3.33	0	9.56	1.11	1.78	1.56	0.67	0	0	2.22	2.44	30.89	4.67	6.00	0	8.89	12.67	3.11	0.22	1.78	0.67	0.22	0	56.78	31.11
65	Confined Outwash	Sag.	292842	7.61	0.67	1.34	0.22	1.12	1.12	0	7.16	1.12	1.79	0.67	0	0.22	0.45	0.45	0.22	38.48	12.75	3.13	0	10.07	10.07	1.12	0.22	1.57	1.34	0	0.67	51.01	30.87
66	Confined Outwash	Sag.	272400	9.18	0.51	0.77	0.51	1.28	1.53	0	10.46	1.79	1.28	0.77	0	0.77	0	0.51	0	31.63	11.73	4.08	0	10.71	10.97	1.53	0	2.30	0	0	0	54.99	22.79
67	Glacial	Sag.	143918	3.56	1.56	1.11	0.89	2.00	2.22	0	11.78	2.00	3.11	4.22	0.44	0.44	0.22	1.33	4.00	25.11	14.89	2.89	0	4.67	9.56	1.56	0.44	4.89	0	0.67	0	48.89	30.00
68	Ice Contact	Sag.	94432	3.56	2.00	0	0.67	2.23	2.23	0	8.02	0.22	1.56	1.78	4.01	0.22	0	1.11	1.78	34.74	7.80	4.68	0	12.03	9.13	2.23	0	2.45	0.22	0.45	0	57.02	27.84
69	Unconfined Outwash	Sag.	236534	8.00	1.33	1.33	0	4.22	0.44	0	11.56	0.89	0.67	1.56	0	0	0	0.22	0.21	23.56	20.22	1.11	0	6.89	7.11	2.44	0.22	6.78	1.11	0	0	47.22	30.00
70	Unconfined Outwash	Sag.	200596	5.78	2.22	1.11	0.89	3.11	1.33	0	10.44	0.22	0	0.89	0	0	0	0.22	0.44	26.89	13.78	5.33	0	11.11	14.22	1.78	0.22	2.89	0.44	0	0	63.11	29.78
71	Unconfined Outwash	Sag.	275578	4.23	1.04	1.04	0.52	4.42	0.78	0	5.97	0.26	0.78	1.82	0.26	0	0	0.26	0	35.32	14.29	2.86	0	11.17	11.69	1.56	0	2.34	0.78	0.26	0	76.62	12.99
72	Ice Contact	Sag.	156638	8.63	1.52	0.25	0.76	2.28	0.51	0	9.39	0.25	0.28	1.78	0	0	0	0.76	0	29.70	22.34	3.55	0	10.91	6.86	0.25	0	5.08	1.52	0	0	58.12	20.42
73	Ice Contact	Sag.	266028	8.69	2.89	1.11	1.33	2.67	0.22	0	9.78	1.33	0.44	2.67	0	0.22	0	2.00	0.22	33.11	11.56	4.67	0	5.33	9.56	2.00	0	3.33	0.22	0.22	0	68.22	17.22
74	Confined Ice Contact	Sag.	221098	4.67	3.33	0.22	0.89	2.44	0.44	0	7.56	0.67	0.89	1.33	1.33	0	0.22	0.44	0.67	30.00	15.33	5.11	0	8.44	12.44	1.56	0	3.11	0	0.22	0	66.67	22.44
75	Confined Ice Contact	Sag.	222248	5.79	2.00	0.22	1.11	2.90	0.67	0	8.24	1.34	3.78	1.11	1.34	0	0	0.67	0.22	30.51	14.92	3.56	0	7.80	12.25	1.34	0.22	3.56	0	0.45	0	67.71	18.71
76	Confined Outwash	Sag.	133022	4.32	1.17	0.94	1.17	2.81	0.70	0	6.56	0.47	1.87	1.17	0	0	0	0	0	31.15	17.80	2.81	0	11.24	12.41	1.41	0	2.81	0	0	0	67.21	21.78
77	Ice Contact	Sag.	301456	6.25	1.79	1.12	1.56	4.28	0.45	0	4.02	0.22	0.67	2.01	0	0	0.22	0.22	0.22	27.90	27.01	0.67	0	10.27	7.37	1.56	0.22	4.46	0.22	0	0	72.00	22.02
78	Ice Contact	Sag.	210292	5.11	2.22	0.44	0.22	3.11	1.11	0	11.11	1.11	1.78	3.11	0.44	0.22	0	2.89	2.67	23.54	13.54	2.67	0	13.33	9.54	1.56	0.22	3.33	0	0.67	0	43.11	37.84
79	Ice Contact	Sag.	161170	3.42	0.53	0	0.53	0.53	0.26	0	27.11	0.53	1.58	2.11	0	0.79	0	0.53	1.06	30.53	5.00	2.42	0	13.42	8.42	0.26	0	2.11	0	0	0	51.32	30.00
80	Ice Contact	Sag.	185686	7.37	2.01	0.89	1.12	5.13	1.34	0.22	5.36	0	0.22	0.89	0	0	0.22	4.34	9.02	23.21	17.86	3.78	0	4.24	0.71	3.35	0	4.02	0	1.12	0	66.52	19.64
81	Confined Ice Contact	Sag.	107598	10.22	1.56	1.56	0.67	4.22	0.89	0	8.00	0.44	0.22	0.89	0	0.44	0	0.89	0.44	25.56	21.11	3.11	0	6.67	10.44	0.67	0	1.78	0.44	0.22	0	72.44	19.33
82	Ice Contact	Sag.	306450	6.00	3.11	0.44	0.89	3.11	0.67	0	5.11	0.44	0	1.11	0	0.67	0	1.11	0	27.33	34.22	0.44	0	6.00	13.56	1.56	0.22	3.78	0	1.33	0	70.44	20.89
83	Confined Ice Contact	Sag.	446282	11.56	1.33	1.33	3.78	4.00	0.67	0	3.11	0.89	0.67	0.22	0	0	0	0.44	0	25.33	29.11	0.22	0	3.56	11.11	0.67	0	3.33	0	0.89	0	77.78	17.78
84	Confined Outwash	Sag.	257872	8.22	1.33	0.89	1.11	3.33	2.22	0	1.78	0.67	0.67	1.56	0	0	0	0.22	0.22	28.44	17.78	2.22	0	15.56	12.00	1.78	0	3.78	0.44	0	0	46.11	44.00
85	Confined Ice Contact	Sag.	175344	5.07	0.60	0.60	0.60	3.20	0	0	5.07	0.80	1.79	5.06	0.20	0	0	0.80	0.30	33.13	15.83	1.49	0	7.76	11.94	0.90	0	6.57	0	0.90	0	67.76	20.20
86	Ice Contact	Sag.	219282	10.90	3.63	0.48	2.18	3.15	1.45	0	5.57	0.73	0.73	0.73	0	0.72	0	0	0	20.82	25.42	2.60	0	6.78	12.11	1.94	0	2.16	0	0.48	0	49.88	40.19
87	Ice Contact	Sag.	291468	4.07	1.56	0.22	0.67	1.89	0.22	0	29.56	0	1.11	1.33	0.44	0	0	1.33	1.56	18.89	21.33	0	0	2.67	6.89	2.00	0.67	2.44	0	1.33	0	44.67	22.67
88	Confined Ice Contact	Sag.	332782	7.78	2.22	0.44	2.89	4.44	2.22	0	4.00	0.67	0.89	2.22	0	0	0	1.78	0.22	30.67	28.00	3.11	0	6.22	10.44	1.78	0	2.89	0	0	0	49.22	40.67
89	Confined Ice Contact	Sag.	218374	7.78	1.78	0.44	2.44	4.00	1.11	0	4.89	0.67	0.22	0.22	0	0.89	0	0.67	0	20.44	17.78	3.11	0	10.22	14.00	1.33	0	3.11	0	0.22	0	40.22	42.44
90	Confined Ice Contact	Sag.	288290	7.56	2.22	0.89	1.78	2.22	4.22	0	5.78	0.44	0.22	0.22	0	0	0	2.89	3.78	16.44	22.67	4.22	0	9.78	11.11	1.56	0	3.56	0.22	1.56	0	44.22	44.22
91	Confined Ice Contact	Sag.	300078	9.11	1.33	0.22	2.44	2.89	0.44	0	6.89	0	0.44	2.00	0	0	0	0.44	0.22	27.56	22.67	1.33	0	9.56	10.67	1.78	0	2.67	0	0.22	0	46.11	42.00
92	Confined Ice Contact	Sag.	238380	11.33	5.11	1.56	3.33	3.56	0.67	0	2.44	0.22	0.22	1.33	0	0	0	3.56	3.78	17.56	27.33	1.56	0	6.00	9.11	1.11	0.22	2.67	0.22	1.11	0	46.22	44.22
93	Confined Ice Contact	Sag.	272400	10.22	2.44	0	2.22	2.67	1.78	0	4.00	0.22	1.33	0.67	0	0	0	0	0	21.56	26.22	1.33	0	11.11	12.89	1.11	0.22	2.22	0.22	0.22	0	42.00	40.78
94	Ice Contact	Sag.	300476	6.89	2.00	1.11	1.78	4.00	1.78	0	6.00	0.22	0.22	1.33	0	0	0	0.22	0	34.44	24.00	2.44	0	9.78	11.78	1.78	0.22	5.78	0.67	0.44	0	40.67	46.67
95	Ice Contact	Sag.	362774	8.89	3.56	0.89	1.78	2.89	0.44	0	4.89	2.22	7.33	3.56	0.22	0	0.67	1.78	4.00	17.33	16.00	2.07	0	7.33	10.00	1.60	0	1.56	0.22	0.22	0	34.00	49.56
96	Unconfined Outwash	Sag.	272064	10.44	4.00	0	1.56	2.89	1.33	0	4.67	0.22	0	0.22	0	0.22	0	0	0	21.56	26.44	2.22	0	10.00	12.22	0.89	0	2.22	0	0.89	0	44.22	50.67
97	Confined Outwash	Sag.	288641	10.44	2.00	0.44	2.00	2.89	1.56	0.22	4.00	0.67	0	1.33	0	0	0	0.44	0	24.00	24.67	2.89	0	11.11	9.78	1.33	0.22	4.44	0.67	0.89	0	33.78	58.00
98	Unconfined Outwash	S-H I	290106	9.11	1.33	0.88	2.67	2.44	2.22	0	1.33	1.56	0	0.44	0	0	0	0	0.44	22.44	24.44	4.44	0	16.22	9.78	2.00	0.22	2.00	0.00	0.44	0	52.00	44.22
99	Unconfined Outwash		457176	10.00	1.33	0.44	1.33	2.44	3.33	0	2.67	0.00	0	2.07	0	0.22	0	0	0	17.78	19.11	5.56	0	19.33	10.22	2.67	0	4.22	1.56	0.67	0	40.00	32.22

PERCENT		CLAY IRONSTONE CONCRETION	[illegible]
PERCENT		LIMESTONE	[illegible]
PERCENT		DOLOMITIC LIMESTONE	[illegible]
PERCENT		DOLOMITE	[illegible]
PERCENT		CHALK	[illegible]
PERCENT		CHERT	[illegible]
PERCENT		NON-FOLIATED METAMORPHIC	[illegible]
PERCENT		FOLIATED METAMORPHIC	[illegible]
PERCENT		OTHERS	[illegible]
PERCENT		ORGANIC MATERIAL	[illegible]
PERCENT		POTENTIALLY ALKALINE REACTIVE	[illegible]
PERCENT		SOLUBLES, SULFIDES	[illegible]
PERCENT		POTENTIAL BASE EXCHANGE	[illegible]
PERCENT	PHYSICAL DURABILITY	1	[illegible]
PERCENT	PHYSICAL DURABILITY	2	[illegible]
PERCENT	PHYSICAL DURABILITY	3	[illegible]
PERCENT	DEGREE OF WEATHERING	1	[illegible]
PERCENT	DEGREE OF WEATHERING	2	[illegible]
PERCENT	DEGREE OF WEATHERING	3	[illegible]
PERCENT	COATINGS	1	[illegible]
PERCENT	COATINGS	2	[illegible]
PERCENT	COATINGS	3	[illegible]
PERCENT	ZINGG CLASS, PERCENT	I DISC SHAPED	[illegible]
PERCENT	ZINGG CLASS, PERCENT	II SPHERICAL	[illegible]
PERCENT	ZINGG CLASS, PERCENT	III BLADED	[illegible]
PERCENT	ZINGG CLASS, PERCENT	IV ROD SHAPED	[illegible]
		PERCENT CLASSES I + IV	[illegible]
		PERCENT TOTAL DELETERIOUS	[illegible]
PIT MEAN		SPHERICITY	[illegible]
PIT MEAN		ROUNDNESS	[illegible]
PIT MEAN		TEXTURE	[illegible]
PIT MEAN		COATING	[illegible]
PIT MEAN		PHYSICAL DURABILITY	[illegible]
PIT MEAN		WEATHERING	[illegible]
		AGGREGATE SPECIFIC GRAVITY	[illegible]
		AGGREGATE PERCENT ABSORPTION	[illegible]
		FREEZE-THAW DURABILITY	[illegible]
		FLEXURAL STRENGTH, P.S.I.	[illegible]
		COMPRESSIVE STRENGTH, P.S.I.	[illegible]

TABLE 12
CHEMICAL TEST DATA

Sample No.	CaO, percent	MgO, percent	Name
1-1	26.9	16.5	Calcitic Dolomite
1-2	30.3	15.4	Calcitic Dolomite
1-3	35.8	12.9	Calcitic Dolomite
2-1	29.2	21.6	Dolomite
2-2	38.8	7.7	Dolomitic Limestone
2-3	43.1	4.2	Dolomitic Limestone
3-1	30.2	16.1	Calcitic Dolomite
3-2	36.9	9.8	Dolomitic Limestone
3-3	47.3	1.8	Magnesian Limestone
4-1	29.7	20.0	Dolomite
4-2	28.3	16.3	Calcitic Dolomite
4-3	42.8	8.0	Dolomitic Limestone
5-1	20.5	11.6	Calcitic Dolomite
5-2	32.8	6.6	Dolomitic Limestone
5-3	44.3	5.4	Dolomitic Limestone
6-1	29.8	20.4	Dolomite
6-2	32.1	18.3	Calcitic Dolomite
6-3	45.6	3.1	Dolomitic Limestone
7-1	27.1	18.7	Calcitic Dolomite
7-2	27.6	6.7	Dolomitic Limestone
7-3	42.4	5.8	Dolomitic Limestone
8-1	29.8	21.2	Dolomite
8-2	31.2	19.1	Calcitic Dolomite
8-3	37.3	7.2	Dolomitic Limestone
9-1	27.4	22.6	Dolomite
9-2	29.0	20.0	Dolomite
9-3	38.9	9.8	Dolomitic Limestone
10-1	28.1	20.7	Dolomite
10-2	28.4	19.1	Calcitic Dolomite
10-3	33.4	4.2	Dolomitic Limestone
11-1	30.0	20.1	Dolomite
11-2	31.5	16.4	Calcitic Dolomite
11-3	36.7	7.3	Dolomitic Limestone
12-1	29.5	21.8	Dolomite
12-2	30.3	14.1	Calcitic Dolomite
12-3	48.1	2.6	Dolomitic Limestone
13-1	12.8	9.1	Dolomitic Limestone
13-2	29.8	19.3	Calcitic Dolomite
13-3	35.6	5.6	Dolomitic Limestone
14-1	27.4	19.3	Calcitic Dolomite
14-2	34.4	13.9	Calcitic Dolomite
14-3	46.9	3.4	Dolomitic Limestone
15-1	27.9	20.4	Dolomite
15-2	30.4	18.7	Calcitic Dolomite
15-3	43.7	5.5	Dolomitic Limestone
16-1	26.6	16.3	Calcitic Dolomite
16-2	30.9	14.0	Calcitic Dolomite
16-3	31.5	11.4	Calcitic Dolomite
17-1	26.7	19.4	Calcitic Dolomite
17-2	28.6	18.8	Calcitic Dolomite
17-3	36.4	8.1	Dolomitic Limestone
18-1	29.4	22.0	Dolomite
18-2	27.0	20.7	Dolomite
18-3	41.9	7.5	Dolomitic Limestone
19-1	26.7	19.2	Calcitic Dolomite
19-2	28.3	17.9	Calcitic Dolomite
19-3	36.7	12.4	Calcitic Dolomite
20-1	27.9	22.5	Dolomite
20-2	27.1	20.1	Dolomite
20-3	47.9	4.0	Dolomitic Limestone
21-1	30.0	20.0	Dolomite
21-2	31.2	14.5	Calcitic Dolomite
21-3	42.3	6.2	Dolomitic Limestone
22-1	29.8	19.4	Calcitic Dolomite
22-2	27.8	21.0	Dolomite
22-3	41.0	4.4	Dolomitic Limestone
23-1	26.6	19.8	Dolomite
23-2	29.1	20.4	Dolomite
23-3	43.2	6.7	Dolomitic Limestone
24-1	27.0	19.1	Calcitic Dolomite
24-2	25.6	18.6	Calcitic Dolomite
24-3	37.4	12.1	Calcitic Dolomite
25-1	29.1	19.6	Dolomite
25-2	29.8	19.9	Dolomite
25-3	40.7	9.7	Dolomitic Limestone
26-1	29.9	21.2	Dolomite
26-2	24.8	16.8	Calcitic Dolomite
26-3	31.1	15.8	Calcitic Dolomite
27-1	30.5	21.1	Dolomite
27-2	27.4	18.8	Calcitic Dolomite
27-3	33.8	12.2	Calcitic Dolomite
28-1	29.3	20.8	Dolomite
28-2	29.7	19.2	Calcitic Dolomite
28-3	38.4	7.2	Dolomitic Limestone
29-1	28.0	20.6	Dolomite
29-2	29.0	19.8	Dolomite
29-3	46.6	3.9	Dolomitic Limestone
30-1	29.8	20.8	Dolomite
30-2	30.1	19.5	Calcitic Dolomite
30-3	41.0	9.9	Dolomitic Limestone
31-1	30.4	21.2	Dolomite
31-2	28.7	19.3	Calcitic Dolomite
31-3	36.1	11.6	Calcitic Dolomite
32-1	30.7	20.2	Dolomite
32-2	28.6	19.6	Dolomite
32-3	37.1	8.6	Dolomitic Limestone
33-1	29.4	20.4	Dolomite
33-2	28.2	17.9	Dolomite
33-3	30.3	8.6	Dolomitic Limestone
34-1	29.0	19.6	Dolomite
34-2	27.3	18.7	Calcitic Dolomite
34-3	36.7	8.0	Dolomitic Limestone
35-1	29.5	20.6	Dolomite
35-2	31.7	17.6	Calcitic Dolomite
35-3	36.5	7.0	Dolomitic Limestone
36-1	21.8	14.3	Calcitic Dolomite
36-2	29.0	19.4	Calcitic Dolomite
36-3	50.3	2.3	Dolomitic Limestone
37-1	29.6	20.1	Dolomite
37-2	30.9	21.0	Dolomite
37-3	38.4	10.1	Dolomitic Limestone
38-1	29.8	20.5	Dolomite
38-2	27.6	19.1	Calcitic Dolomite
38-3	13.1	6.9	Dolomitic Limestone
39-1	30.0	22.0	Dolomite
39-2	31.8	20.6	Dolomite
39-3	34.0	11.0	Calcitic Dolomite
40-1	30.7	20.9	Dolomite
40-2	26.5	17.9	Calcitic Dolomite
40-3	33.1	12.5	Calcitic Dolomite
41-1	27.6	18.2	Calcitic Dolomite
41-2	30.1	19.2	Calcitic Dolomite
41-3	32.9	10.2	Dolomitic Limestone
42-1	30.0	20.2	Dolomite
42-2	24.3	16.9	Calcitic Dolomite
42-3	32.9	11.9	Calcitic Dolomite
43-1	30.6	20.4	Dolomite
43-2	27.9	18.0	Calcitic Dolomite
43-3	37.1	11.8	Calcitic Dolomite
44-1	26.9	18.3	Calcitic Dolomite
44-2	31.3	19.1	Calcitic Dolomite
44-3	34.0	12.1	Calcitic Dolomite
45-1	26.7	18.2	Calcitic Dolomite
45-2	25.2	16.2	Calcitic Dolomite
45-3	32.7	8.5	Dolomitic Limestone
46-1	29.8	20.3	Dolomite
46-2	29.6	19.7	Dolomite
46-3	38.9	7.0	Dolomitic Limestone
47-1	30.3	21.3	Dolomite
47-2	31.1	21.1	Dolomite
47-3	47.8	2.8	Dolomitic Limestone
48-1	31.3	20.8	Dolomite
48-2	30.5	21.5	Dolomite
48-3	44.4	5.1	Dolomitic Limestone
49-1	30.5	21.1	Dolomite
49-2	28.9	19.3	Calcitic Dolomite
49-3	36.9	5.0	Dolomitic Limestone
50-1	30.1	20.7	Dolomite
50-2	30.2	20.3	Dolomite
50-3	43.4	5.9	Dolomitic Limestone
A 16-1	29.6	20.4	Dolomite
A 16-2	28.2	19.8	Dolomite
A 16-3	54.5	0.9	High Calcium Limestone
A 17-1	29.8	20.1	Dolomite
A 17-2	28.8	14.7	Calcitic Dolomite
A 17-3	29.5	20.3	Dolomite
A 18-1	30.7	21.3	Dolomite
A 18-2	30.5	21.7	Dolomite
A 18-3	33.5	2.4	Dolomitic Limestone

TABLE 13
SUMMARY OF SIZE DATA

Type 2 (Ice Contact)

Pit No.	M_a	M_d	S_o
1	.255	.073	5.02
2	.257	.125	2.94
8	.324	.149	2.91
9	.368	.155	4.13
19	.372	.177	3.08
20	.304	.113	3.81
21	.288	.087	4.10
32	.481	.209	3.06
34	.635	.302	2.75
35	.774	.334	4.23
36	.260	.036	5.15
37	.160	.027	5.11
46	.586	.182	3.99
55	.385	.074	5.77
56	.382	.202	2.69
62	.625	.194	4.23
64	.682	.147	4.16
68	.492	.095	5.63
72	.218	.080	3.02
73	.296	.259	5.27
77	.463	.035	8.09
78	.767	.374	3.66
79	.162	.015	8.94
80	.511	.120	6.09
82	.251	.040	10.07
86	.210	.040	4.34
87	.710	.230	5.19
94	.346	.090	3.37
95	.666	.171	6.14
T	12.229	4.135	136.94
$\bar{X}$	0.422	0.143	4.72
	N = 29		

Type 3 (Confined Ice Contact)

Pit No.	M_a	M_d	S_o
74	.494	.155	4.20
75	.520	.173	3.60
81	.372	.065	7.83
83	.355	.062	5.52
85	.130	.010	8.12
88	.460	.165	3.66
89	.391	.109	4.07
90	.579	.135	4.86
91	.253	.075	3.64
92	.412	.140	2.89
93	.246	.064	3.91
T	4.212	1.153	52.30
$\bar{X}$	0.383	0.105	4.75
		N = 11	

Type 4 (Confined Outwash)

Pit No.	M_a	M_d	S_o
5	.305	.080	3.24
6	.823	.010	3.46
7	.259	.130	2.48
10	.542	.189	5.44
11	.186	.044	2.91
12	.813	.018	3.39
16	.142	.016	2.79
17	.312	.114	3.51
18	.272	.154	3.22
22	.208	.059	4.32
23	.296	.136	2.89
24	.264	.102	4.09
25	.426	.176	4.25
26	.564	.269	4.66
27	.495	.158	4.50
30	.487	.204	4.91
33	.348	.051	4.11
38	.476	.262	2.69
40	.500	.270	2.98
41	.322	.154	3.11
42	.293	.165	2.92
43	.274	.160	3.09
44	.325	.228	2.24
45	.120	.219	4.12
47	.279	.086	4.61
48	.334	.268	4.86
49	.449	.126	4.27
50	.256	.265	5.16
53	.311	.089	4.22
59	.172	.230	6.23
60	.413	.143	3.24
65	.383	.055	5.40
66	.184	.025	10.05
76	.284	.040	9.89
84	.343	.110	3.79
97	.256	.081	4.32
T	12.716	4.086	151.36
$\bar{X}$	0.353	0.113	4.20
		N = 36	

Type 5 (Unconfined Outwash)

Pit No.	M_a	M_d	S_o
3	.101	.010	2.88
4	.232	.056	3.69
13	.070	.013	3.00
14	.128	.054	3.13
15	.293	.117	3.05
28	.349	.130	4.08
29	.195	.035	4.48
31	.556	.239	3.72
39	.696	.255	4.22
51	.640	.155	4.32
52	.335	.191	2.55
54	.750	.276	4.36
58	.288	.075	4.70
59	.436	.112	5.51
61	.332	.209	3.46
63	.230	.092	3.03
69	.307	.065	4.70
70	.362	.079	3.32
71	.158	.055	1.84
96	.277	.083	3.91
98	.312	.065	4.60
99	.485	.110	4.46
T	7.532	2.476	83.01
$\bar{X}$	0.342	0.112	3.77
		N = 22	

M_a = Arithmatic mean diameter

M_d = Quartile median diameter

S_o = Sorting coefficient

TABLE 14
QUARTILE MEASURES FOR SIZE FREQUENCY ANALYSIS

Pit No.	Type Deposit[1]	Q_1	Q_2	Q_3	$\frac{Q_1}{Q_3}$	Sort. Coeff. $\frac{Q_1}{Q_3}$	Quart. Dev. Arith. $\frac{Q_2 - Q_3}{2}$
1	2	0.328	0.073	0.013	25.23	5.02	0.1 x 57
2	2	0.348	0.125	0.040	8.70	2.94	0.1 x 54
3	4	0.058	0.010	0.007	8.29	2.88	0.026
4	4	0.218	0.056	0.016	13.62	3.69	0.101
5	3	0.272	0.080	0.026	10.46	3.24	0.123
6	3	0.048	0.010	0.004	12.00	3.46	0.022
7	3	0.309	0.130	0.050	6.18	2.48	0.129
8	2	0.399	0.149	0.047	8.44	2.91	0.176
9	2	0.528	0.155	0.031	17.03	4.13	0.248
10	3	0.740	0.189	0.025	29.60	5.49	0.351
11	3	0.152	0.044	0.018	8.44	2.91	0.031
12	3	0.069	0.018	0.006	11.50	3.39	0.031
13	4	0.072	0.013	0.008	9.00	3.00	0.032
14	4	0.157	0.054	0.016	9.81	3.13	0.070
15	4	0.345	0.117	0.037	9.32	3.05	0.154
16	3	0.078	0.016	0.010	7.80	2.79	0.034
17	3	0.357	0.114	0.029	12.31	3.22	0.164
18	3	0.406	0.154	0.039	10.41	3.22	0.183
19	2	0.476	0.177	0.050	9.52	3.08	0.208
20	2	0.364	0.113	0.025	14.56	3.81	0.169
21	2	0.336	0.087	0.020	16.80	4.10	0.158
22	3	0.224	0.059	0.012	18.67	4.32	0.106
23	3	0.374	0.136	0.045	8.31	2.89	0.164
24	3	0.370	0.102	0.022	16.82	4.09	0.174
25	3	0.598	0.176	0.033	18.12	4.25	0.282
26	3	0.823	0.269	0.038	21.66	4.66	0.392
27	3	0.650	0.158	0.032	20.31	4.50	0.309
28	4	0.386	0.130	0.023	16.78	4.08	0.181
29	4	0.181	0.035	0.009	20.11	4.48	0.086
30	3	0.701	0.204	0.029	24.17	4.91	0.336
31	4	0.733	0.239	0.053	13.83	3.72	0.340
32	2	0.601	0.209	0.064	9.39	3.06	0.268
33	3	0.169	0.051	0.010	16.90	4.11	0.079
34	2	0.824	0.302	0.109	7.56	2.75	0.357
35	2	1.075	0.334	0.060	17.92	4.23	0.507
36	2	0.186	0.036	0.007	26.57	5.15	0.089
37	2	0.131	0.027	0.005	26.20	5.11	0.063
38	3	0.600	0.262	0.083	7.23	2.69	0.258
39	4	0.893	0.255	0.050	17.86	4.22	0.421
40	3	0.708	0.270	0.080	8.85	2.98	0.314
41	3	0.425	0.154	0.044	9.66	3.11	0.190
42	3	0.427	0.165	0.050	8.54	2.92	0.188
43	3	0.400	0.160	0.042	9.52	3.09	0.179
44	3	0.475	0.226	0.095	5.00	2.24	0.190
45	3	0.068	0.019	0.004	17.00	4.12	0.032
46	2	0.685	0.182	0.014	21.29	4.61	0.142
47	3	0.298	0.086	0.014	21.29	4.61	0.142
48	3	0.283	0.068	0.012	23.58	4.86	0.135
49	3	0.457	0.126	0.025	18.28	4.27	0.216
50	3	0.240	0.065	0.009	26.67	5.16	0.115
51	4	0.616	0.155	0.033	18.67	4.32	0.291
52	4	0.435	0.191	0.067	6.49	2.55	0.184
53	3	0.321	0.089	0.018	17.83	4.22	0.151
54	4	1.065	0.276	0.056	19.02	4.36	0.504
55	2	0.333	0.074	0.010	33.30	5.77	0.161
56	2	0.515	0.202	0.071	7.25	2.69	0.222
57	3	0.155	0.030	0.004	38.75	6.23	0.075
58	4	0.287	0.075	0.013	22.08	4.70	0.137
59	4	0.486	0.112	0.016	30.37	5.51	0.235
60	3	0.669	0.209	0.056	11.95	3.24	0.181
61	4	0.669	0.209	0.056	11.95	3.46	0.306
62	2	0.788	0.194	0.044	17.91	4.23	0.372
63	4	0.266	0.092	0.029	9.17	3.03	0.118
64	2	0.863	0.147	0.050	17.26	4.16	0.406
65	3	0.321	0.055	0.011	29.18	5.40	0.155
66	3	0.110	0.025	0.001	110.00	10.05	0.054
67	1	0.542	0.153	0.050	13.55	3.68	0.251
68	2	0.476	0.095	0.015	31.73	5.63	0.230
69	4	0.265	0.065	0.012	22.08	4.70	0.126
70	4	0.254	0.079	0.023	11.04	3.32	0.115
71	4	0.102	0.055	0.030	3.40	1.84	0.036
72	2	0.228	0.080	0.025	9.12	3.02	0.101
73	2	0.259	0.061	0.009	28.78	5.27	0.125
74	6	0.531	0.155	0.030	17.70	4.20	0.250
75	6	0.545	0.173	0.042	12.98	3.60	0.251
76	3	0.198	0.040	0.002	98.00	9.89	0.097
77	2	0.196	0.035	0.003	65.33	8.09	0.096
78	2	1.072	0.374	0.080	13.40	3.66	0.496
79	2	0.080	0.015	0.001	80.00	8.94	0.039
80	2	0.557	0.120	0.015	37.13	6.09	0.271
81	6	0.306	0.065	0.005	61.20	7.83	0.150
82	2	0.229	0.040	0.002	114.50	10.07	0.113
83	6	0.305	0.062	0.010	30.50	5.52	0.147
84	3	0.360	0.110	0.025	14.40	3.79	0.167
85	6	0.066	0.010	0.001	66.00	8.12	0.032
86	2	0.151	0.040	0.008	18.87	4.34	0.071
87	2	0.972	0.230	0.036	27.00	5.19	0.468
88	6	0.496	0.165	0.037	13.41	3.66	0.229
89	6	0.415	0.109	0.025	16.60	4.07	0.195
90	6	0.590	0.135	0.025	23.60	4.86	0.282
91	6	0.265	0.075	0.020	13.25	3.64	0.122
92	6	0.394	0.140	0.047	8.38	2.89	0.173
93	6	0.233	0.064	0.015	15.53	3.91	0.109
94	2	0.284	0.090	0.025	11.36	3.37	0.129
95	2	0.795	0.171	0.021	37.86	6.14	0.387
96	4	0.273	0.083	0.018	15.17	3.91	0.127
97	3	0.280	0.081	0.015	18.67	4.32	0.132
98	4	0.253	0.065	0.012	21.08	4.60	0.120
99	4	0.496	0.110	0.025	19.84	4.46	0.235

1. Glacial
2. Glacio-fluv. Ice Contact
3. Confined Outwash
4. Outwash Delta or Plain
5. Glacio-lacustrine
6. Eskers

TABLE 15
MEAN SPHERICITY FOR ALL ROCK TYPES BY SIZE GRADE

Pit No.	Deposit Type	$\bar{X}$ All Sizes (1-1/2 to 3/16 in.)	$\bar{X}$ Size 1 (1-1/2 to 3/4 in.)	$\bar{X}$ Size 2 (3/4 to 3/8 in.)	$\bar{X}$ Size 3 (3/8 to 3/16 in.)
1	IC	.7283	.7312	.7325	.7210
2	IC	.7525	----	.7418	.7385
3	UO	.7570	.8039	.7517	.7413
4	UO	.7803	.8205	.7631	.7483
5	CO	.7859	.8158	.7433	.8077
6	CO	.7574	.8612	.7450	.7408
7	CO	.7682	.7714	.7541	.7793
8	IC	.7528	.7508	.7564	.7475
9	IC	.7420	.7326	.7527	.7403
10	CO	.7317	.7454	.7249	.7295
11	CO	.7462	.7541	.7387	.7467
12	CO	.7387	.7530	.7263	.7430
13	UO	.7334	.7736	.7343	.7291
14	UO	.7322	.7346	.7341	.7300
15	UO	.7607	.7598	.7843	.7379
16	CO	.7496	.7141	.7542	.7598
17	CO	.7403	.7385	.7490	.7310
18	CO	.7335	.7527	.7410	.7068
19	IC	.7432	.7552	.7331	.7435
20	IC	.7478	.7490	.7563	.7381
21	IC	.7622	.7717	.7586	.7548
22	CO	.7568	.7569	.7690	.7452
23	CO	.7507	.7540	.7501	.7479
24	CO	.7444	.7447	.7434	.7435
25	CO	.7329	.7383	.7372	.7231
26	CO	.7309	.7350	.7395	.7179
27	CO	.7431	.7377	.7369	.7546
28	UO	.7451	.7567	.7387	.7398
29	UO	.7325	.7339	.7211	.7426
30	CO	.7381	.7403	.7292	.7455
31	UO	.7537	.7511	.7604	.7494
32	IC	.7377	.7440	.7337	.7355
33	CO	.7396	.7481	.7352	.7354
34	IC	.7538	.7510	.7560	.7547
35	IC	.7493	.7422	.7472	.7586
36	IC	.7490	.7500	.7494	.7480
37	IC	.7528	.7485	.7591	.7495
38	CO	.7488	.7523	.7459	.7488
39	UO	.7527	.7484	.7526	.7571
40	CO	.7474	.7515	.7435	.7471
41	CO	.7486	.7593	.7383	.7476
42	UO	.7393	.7281	.7382	.7517
43	UO	.7581	.7637	.7518	.7577
44	UO	.7411	.7496	.7360	.7375
45	UO	.7322	.7293	.7265	.7393
46	IC	.7400	.7488	.7480	.7243
47	CO	.7419	.7483	.7471	.7317
48	CO	.7203	.7400	.7179	.7029
49	CO	.7291	.7333	.7293	.7252
50	CO	.7147	.7286	.7203	.6954
51	UO	.7137	.7174	.7173	.7073
52	UO	.7210	.7513	.7210	.6910
53	CO	.7144	.7371	.7236	.6874
54	UO	.7131	.7281	.7207	.6898
55	UO	.7248	.7517	.7297	.6930
56	IC	.7443	.7591	.7425	.7311
57	CO	.7444	.7362	.7545	.7425
58	UO	.7266	.7326	.7431	.7040
59	UO	.7427	.7456	.7598	.7226
60	CO	.7555	.7597	.7551	.7515
61	UO	.7400	.7565	.7206	.7435
62	IC	.7366	.7368	.7631	.7098
63	UO	.7332	.7437	.7462	.7116
64	IC	.7366	.7446	.7671	.6986
65	CO	.7620	.7510	.7444	.7904
66	CO	.7725	.7443	.7542	.8084
67	G	.7474	.7346	.7413	.7705
68	IC	.7680	.7630	.7678	.7737
69	UO	.7500	.7493	.7487	.7608
70	UO	.7491	.7479	.7407	.7586
71	UO	.7676	.7734	.7661	.7671
72	IC	.7691	.7417	.7677	.7896
73	IC	.7530	.7411	.7558	.7621
74	CIC	.7636	.7734	.7567	.7606
75	CIC	.7617	.7640	.7653	.7557
76	CO	.7571	.7548	.7604	.7549
77	IC	.7645	.7672	.7660	.7603
78	IC	.7517	.7479	.7523	.7599
79	IC	.7483	.7537	.7448	.7490
80	CO	.7400	.7389	.7260	.7549
81	CIC	.7583	.7521	.7544	.7685
82	IC	.7559	.7457	.7574	.7646
83	CIC	.7604	.7762	.7551	.7499
84	CO	.7535	.7597	.7458	.7551
85	CIC	.7416	.7452	.7416	.7443
86	IC	.7538	.7629	.7514	.7494
87	IC	.7735	.7709	.7603	.7735
88	CIC	.7481	.7486	.7325	.7630
89	CIC	.7465	.7655	.7649	.7366
90	CIC	.7487	.7386	.7650	.7495
91	CIC	.7528	.7607	.7454	.7574
92	CIC	.7384	.7365	.7327	.7469
93	CIC	.7347	.7521	.7426	.7091
94	IC	.7447	.7489	.7550	.7303
95	IC	.7153	.7430	.7192	.6852
96	UO	.7257	.7347	.7424	.7000
97	CO	.7399	.7614	.7515	.7062
98	UO	.7237	.7324	.7345	.7040
99	UO	.7365	.7523	.7296	.7278

TABLE 16
MEAN DEGREE OF WEATHERING FOR ALL ROCK TYPES BY SIZE GRADE

Pit No.	Deposit Type	$\bar{X}$ All Sizes (1-1/2 to 3/16 in.)	$\bar{X}$ Size 1 (1-1/2 to 3/16 in.)	$\bar{X}$ Size 2 (3/4 to 3/8 in.)	$\bar{X}$ Size 3 (3/8 to 3/16 in.)
1	IC	1.618	1.544	1.593	1.7200
2	IC	1.955	----	1.966	1.940
3	UO	1.864	1.769	1.920	1.827
4	UO	1.896	1.922	1.907	1.800
5	CO	1.822	1.803	1.813	1.8267
6	CO	1.825	1.727	1.826	1.826
7	CO	1.736	1.757	1.786	1.626
8	IC	1.780	1.777	1.767	1.800
9	IC	1.813	1.875	1.713	1.813
10	CO	1.804	1.607	1.920	1.827
11	CO	1.6933	1.753	1.793	1.553
12	CO	1.629	1.661	1.600	1.633
13	UO	1.448	1.846	1.604	1.260
14	UO	1.589	1.768	1.863	1.235
15	UO	1.497	1.6600	1.540	1.289
16	CO	1.623	1.714	1.546	1.666
17	CO	1.484	1.608	1.380	1.442
18	CO	1.751	1.733	1.833	1.687
19	IC	1.731	1.884	1.593	1.727
20	IC	1.484	1.493	1.6200	1.340
21	IC	1.662	1.746	1.547	1.727
22	CO	1.611	1.555	1.827	1.433
23	CO	1.673	1.893	1.420	1.707
24	CO	1.489	1.514	1.480	1.453
25	CO	1.416	1.600	1.393	1.253
26	CO	1.342	1.483	1.260	1.287
27	CO	1.253	1.260	1.267	1.233
28	UO	1.313	1.573	1.220	1.147
29	UO	1.418	1.333	1.807	1.113
30	CO	1.413	1.544	1.500	1.187
31	UO	1.431	1.503	1.373	1.420
32	IC	1.440	1.320	1.420	1.580
33	CO	1.402	1.473	1.433	1.300
34	IC	1.347	1.412	1.380	1.253
35	IC	1.382	1.433	1.407	1.307
36	IC	1.462	1.604	1.260	1.527
37	IC	1.369	1.442	1.400	1.287
38	CO	1.300	1.374	1.327	1.167
39	UO	1.227	1.307	1.220	1.153
40	CO	1.262	1.349	1.160	1.280
41	CO	1.251	1.356	1.253	1.140
42	UO	1.184	1.293	1.107	1.153
43	UO	1.247	1.260	1.300	1.187
44	UO	1.372	1.280	1.2-3	1.624
45	UO	1.547	1.440	1.473	1.633
46	IC	1.374	1.408	1.456	1.260
47	IC	1.358	1.404	1.329	1.353
48	CO	1.281	1.260	1.302	1.280
49	CO	1.430	1.497	1.483	1.300
50	CO	1.365	1.218	1.373	1.507
51	UO	1.371	1.419	1.313	1.360
52	UO	1.316	1.279	1.327	1.333
53	CO	1.322	1.404	1.253	1.300
54	UO	1.471	1.550	1.593	1.273
55	UO	1.336	1.473	1.167	1.367
56	IC	1.342	1.338	1.320	1.353
57	CO	1.407	1.293	1.413	1.513
58	UO	1.409	1.300	1.473	1.453
59	UO	1.309	1.253	1.440	1.233
60	CO	1.436	1.347	1.627	1.333
61	UO	1.419	1.540	1.315	1.395
62	IC	1.473	1.533	1.533	1.333
63	UO	1.451	1.412	1.453	1.487
64	IC	1.447	1.520	1.520	1.287
65	CO	1.325	1.327	1.299	1.349
66	CO	1.320	1.359	1.400	1.215
67	G	1.460	1.731	1.340	1.287
68	IC	1.456	1.687	1.327	1.347
69	UO	1.307	1.486	1.180	1.111
70	UO	1.316	1.080	1.373	1.493
71	UO	1.314	1.512	1.133	1.380
72	IC	1.320	1.531	1.351	1.153
73	IC	1.316	1.573	1.193	1.180
74	CIC	1.277	1.459	1.233	1.128
75	CIC	1.408	1.711	1.433	1.080
76	CO	1.253	1.339	1.053	1.383
77	IC	1.152	1.073	1.060	1.324
78	IC	1.567	1.486	1.673	1.527
79	IC	1.474	1.662	1.333	1.513
80	CO	1.396	1.528	1.460	1.207
81	CIC	1.236	1.160	1.147	1.400
82	IC	1.247	1.349	1.147	1.253
83	CIC	1.138	1.100	1.140	1.173
84	CO	1.349	1.400	1.153	1.493
85	CIC	1.373	1.333	1.467	1.267
86	IC	1.228	1.342	1.233	1.127
87	IC	1.5400	1.660	1.460	1.487
88	CIC	1.273	1.211	1.280	1.327
89	CIC	1.356	1.338	1.247	1.407
90	CIC	1.478	1.395	1.520	1.500
91	CIC	1.478	1.301	1.407	1.700
92	CIC	1.349	1.510	1.313	1.227
93	CIC	1.300	1.443	1.207	1.253
94	IC	1.307	1.407	1.160	1.353
95	IC	1.473	1.481	1.393	1.413
96	UO	1.256	1.407	1.113	1.247
97	CO	1.416	1.624	1.153	1.467
98	UO	1.436	1.467	1.447	1.393
99	UO	1.533	1.553	1.527	1.520

TABLE 17
MEAN SURFACE TEXTURE FOR ALL ROCK TYPES BY SIZE GRADE

Pit No.	Deposit Type	$\bar{X}$ All Sizes (1-1/2 to 3/16 in.)	$\bar{X}$ Size 1 (1-1/2 to 3/16 in.)	$\bar{X}$ Size 2 (3/4 to 3/8 in.)	$\bar{X}$ Size 3 (3/8 to 3/16 in.)
1	IC	2.340	2.1678	2.38	2.4467
2	IC	3.524	----	3.420	3.400
3	UO	3.082	3.064	3.207	2.907
4	UO	3.162	3.512	3.107	2.993
5	CO	3.371	3.622	3.287	3.240
6	CO	2.935	2.818	2.986	2.913
7	CO	3.174	3.028	3.173	2.133
8	IC	3.291	3.571	3.327	3.033
9	IC	3.222	3.479	3.080	3.227
10	CO	2.600	2.574	1.780	3.347
11	CO	2.700	2.164	3.087	2.860
12	CO	2.360	2.387	2.046	2.646
13	UO	2.439	2.384	2.342	2.540
14	UO	2.233	2.029	1.966	2.584
15	UO	2.846	3.180	2.233	3.128
16	CO	2.489	2.047	2.980	2.186
17	CO	2.705	2.622	2.627	2.885
18	CO	2.184	2.087	2.113	2.353
19	IC	2.713	2.068	3.173	2.893
20	IC	2.858	3.053	2.347	3.173
21	IC	2.449	2.127	3.027	2.227
22	CO	2.747	3.102	2.213	2.927
23	CO	2.642	2.053	3.207	2.667
24	CO	2.600	2.331	2.873	2.613
25	CO	2.993	2.540	3.187	3.253
26	CO	2.840	3.517	2.440	2.560
27	CO	3.093	3.700	2.240	3.340
28	UO	2.820	2.807	3.260	2.393
29	UO	2.471	3.040	2.280	2.093
30	CO	2.393	2.204	2.447	2.540
31	UO	2.636	2.403	3.213	2.300
32	IC	2.822	3.273	2.573	2.620
33	CO	2.698	2.667	2.273	3.153
34	IC	2.936	2.804	3.300	2.707
35	IC	2.993	3.200	2.767	3.013
36	IC	2.671	2.497	2.787	2.707
37	IC	2.589	2.413	2.773	2.527
38	CO	3.284	3.669	3.273	2.940
39	UO	2.511	2.660	2.633	2.240
40	CO	2.996	2.597	2.793	3.593
41	CO	2.929	2.678	3.200	2.907
42	UO	3.073	3.720	2.561	2.933
43	UO	2.707	2.685	2.473	2.947
44	UO	3.494	3.840	3.840	2.798
45	UO	2.761	2.800	2.833	2.640
46	IC	2.530	2.803	2.141	2.620
47	CO	2.995	2.465	2.906	3.487
48	CO	3.091	2.660	2.953	3.660
49	CO	2.846	3.624	2.409	2.487
50	CO	3.051	3.282	2.867	3.007
51	UO	2.978	2.919	3.453	2.540
52	UO	2.993	2.986	3.153	2.853
53	CO	2.889	2.829	2.933	2.900
54	UO	2.784	2.718	3.340	2.287
55	UO	2.867	3.180	2.627	2.793
56	IC	2.647	2.453	2.407	3.060
57	CO	2.547	3.020	2.200	2.420
58	UO	3.507	2.813	3.347	3.360
59	UO	3.060	3.093	3.733	2.353
60	CO	2.969	2.707	2.660	3.540
61	UO	3.104	3.633	2.725	2.904
62	IC	3.516	3.647	3.540	3.360
63	UO	2.838	2.797	2.813	2.907
64	IC	3.387	3.723	3.567	2.860
65	CO	3.229	2.913	3.299	3.477
66	CO	3.138	2.641	3.547	3.027
67	G	3.269	3.696	2.753	3.360
68	IC	3.233	3.510	2.720	3.467
69	UO	2.908	2.493	3.293	3.028
70	UO	3.360	3.627	3.560	2.893
71	UO	3.452	3.512	3.387	3.480
72	IC	2.693	2.719	2.453	2.913
73	IC	3.044	3.700	2.793	2.640
74	CIC	3.149	3.662	2.580	3.208
75	CIC	3.283	3.477	3.567	2.807
76	CO	3.110	2.748	3.160	3.369
77	IC	3.085	3.080	3.280	2.890
78	IC	2.893	2.431	3.400	2.860
79	IC	2.855	2.987	2.473	3.167
80	CO	2.563	2.514	2.553	2.620
81	CIC	2.680	2.540	2.873	2.627
82	IC	2.451	2.658	2.253	2.440
83	CIC	2.464	2.520	2.507	2.367
84	CO	2.593	2.467	2.640	2.673
85	CIC	2.788	2.067	3.153	2.513
86	IC	2.220	2.225	2.267	2.187
87	IC	2.044	1.830	2.073	2.173
88	CIC	2.653	2.680	2.373	2.920
89	CIC	2.449	2.168	2.473	2.700
90	CIC	2.371	1.864	2.733	2.473
91	CIC	2.193	2.089	2.267	2.173
92	CIC	2.253	2.503	2.107	2.153
93	CIC	2.009	2.101	1.880	2.047
94	IC	2.149	2.053	1.973	2.420
95	IC	1.858	2.085	1.780	1.553
96	UO	2.298	2.653	2.107	2.133
97	CO	1.802	2.221	1.200	1.993
98	UO	3.169	2.927	3.253	3.327
99	UO	2.740	2.567	2.780	2.873

TABLE 18
MEAN ROUNDNESS FOR ALL ROCK TYPES BY SIZE GRADE

Pit No.	Deposit Type	$\bar{X}$ All Sizes (1-1/2 to 3/16 in.)	$\bar{X}$ Size 1 (1-1/2 to 3/16 in.)	$\bar{X}$ Size 2 (3/4 to 3/8 in.)	$\bar{X}$ Size 3 (3/8 to 3/16 in.)	Pit No.	Deposit Type	$\bar{X}$ All Sizes (1-1/2 to 3/16 in.)	$\bar{X}$ Size 1 (1-1/2 to 3/16 in.)	$\bar{X}$ Size 2 (3/4 to 3/8 in.)	$\bar{X}$ Size 3 (3/8 to 3/16 in.)
1	IC	.5600	.5463	.5733	.5593	51	UO	.6251	.6182	.6213	.6360
2	IC	.4549	----	.4640	.4400	52	UO	.6451	.6531	.6467	.6360
3	UO	.4593	.5051	.4507	.4480	53	CO	.6296	.6288	.6380	.6220
4	UO	.4382	.4729	.4327	.4093	54	UO	.5749	.5691	.5927	.5627
5	CO	.4498	.4787	.4413	.4353	55	UO	.6356	.6480	.6347	.6240
6	CO	.3820	.3454	.3800	.3880	56	IC	.6002	.6000	.6200	.5807
7	CO	.4331	.4457	.4526	.4073	57	CO	.6233	.6193	.6300	.6207
8	IC	.4584	.4928	.4513	.4407	58	UO	.6000	.6013	.6013	.5973
9	IC	.4984	.5167	.5107	.4800	59	UO	.6562	.6653	.6453	.6580
10	CO	.5442	.6115	.5667	.4787	60	CO	.6329	.6513	.6300	.6167
11	CO	.5669	.5938	.5373	.5706	61	UO	.6286	.6100	.6537	.6202
12	CO	.5192	.4758	.5867	.4693	62	IC	.6189	.6340	.6180	.6047
13	UO	.4923	.4231	.4725	.5120	63	UO	.6500	.6514	.6580	.6393
14	UO	.5452	.5449	.5678	.5248	64	IC	.6111	.6007	.6220	.6100
15	UO	.5744	.5033	.6500	.5698	65	CO	.6484	.6453	.6449	.6550
16	CO	.5398	.6127	.5427	.5966	66	CO	.6519	.6511	.6640	.6403
17	CO	.5203	.5301	.5720	.4617	67	G	.5956	.6076	.5987	.5827
18	CO	.5733	.5940	.5680	.5580	68	IC	.5798	.5660	.5980	.5747
19	IC	.4571	.5383	.4380	.3960	69	UO	.5824	.5838	.5820	.5778
20	IC	.4729	.4360	.5520	.4307	70	UO	.5904	.6020	.5727	.5967
21	IC	.4774	.5077	.4193	.4940	71	UO	.5982	.6095	.6100	.5807
22	CO	.4529	.4232	.5373	.3953	72	IC	.5914	.5771	.5959	.5960
23	CO	.5124	.5273	.4407	.5693	73	IC	.6216	.6173	.6493	.5980
24	CO	.4538	.5257	.4113	.4200	74	CIC	.6263	.6622	.6007	.6174
25	CO	.5149	.5627	.4793	.5027	75	CIC	.5568	.5483	.5413	.5807
26	CO	.5333	.4993	.5700	.5320	76	CO	.5836	.6134	.6207	.5201
27	CO	.5180	.5227	.5700	.4613	77	IC	.6052	.5960	.6140	.6055
28	UO	.5598	.5993	.5000	.5800	78	IC	.5393	.5632	.5187	.5407
29	UO	.5109	.4367	.5520	.5440	79	IC	.5403	.5225	.5873	.5027
30	CO	.5744	.5333	.5840	.6060	80	CO	.5707	.5549	.5720	.5847
31	UO	.4942	.4893	.4313	.5627	81	CIC	.6033	.6133	.6167	.5800
32	IC	.5513	.5127	.6047	.5367	82	IC	.5907	.5904	.6053	.5753
33	CO	.5349	.5787	.5787	.4473	83	CIC	.5880	.5893	.5980	.5767
34	IC	.5336	.5905	.4707	.5387	84	CO	.5900	.5973	.5827	.5900
35	IC	.5378	.5140	.5700	.5293	85	CIC	.5233	.5467	.4853	.5553
36	IC	.5420	.6040	.5200	.5007	86	IC	.5390	.5613	.5353	.5247
37	IC	.5589	.5846	.5493	.5507	87	IC	.5507	.5653	.5400	.5467
38	CO	.5591	.6137	.5587	.5167	88	CIC	.5840	.5776	.5707	.6047
39	UO	.6082	.6220	.6313	.5713	89	CIC	.5824	.5954	.5613	.5847
40	CO	.6642	.6852	.6860	.6207	90	CIC	.5708	.5551	.5780	.5793
41	CO	.6491	.6732	.6313	.6433	91	CIC	.5871	.5692	.5807	.6127
42	UO	.6620	.6327	.6780	.6753	92	CIC	.5700	.5463	.5833	.5807
43	UO	.6591	.6438	.6727	.6600	93	CIC	.5709	.5725	.5700	.5700
44	UO	.6517	.6427	.6553	.6570	94	IC	.5682	.5827	.5467	.5753
45	UO	.6223	.6000	.6173	.6313	95	IC	.5469	.5884	.5480	.5033
46	IC	.6038	.6143	.6087	.5887	96	UO	.5918	.6247	.5733	.5773
47	CO	.6213	.6365	.6208	.6133	97	CO	.5302	.5530	.5140	.5247
48	CO	.6414	.6493	.6369	.6380	98	UO	.6456	.6560	.6453	.6353
49	CO	.6350	.6456	.6302	.6300	99	UO	.6193	.6200	.6307	.6073
50	CO	.6385	.6309	.6373	.6473						

TABLE 19
MEAN DURABILITY FOR ALL ROCK TYPES BY SIZE GRADE

Pit No.	Deposit Type	$\bar{X}$ All Sizes (1-1/2 to 3/16 in.)	$\bar{X}$ Size 1 (1-1/2 to 3/16 in.)	$\bar{X}$ Size 2 (3/4 to 3/8 in.)	$\bar{X}$ Size 3 (3/8 to 3/16 in.)	Pit No.	Deposit Type	$\bar{X}$ All Sizes (1-1/2 to 3/16 in.)	$\bar{X}$ Size 1 (1-1/2 to 3/16 in.)	$\bar{X}$ Size 2 (3/4 to 3/8 in.)	$\bar{X}$ Size 3 (3/8 to 3/16 in.)
1	IC	1.809	1.886	1.827	1.707	51	UO	1.551	1.892	1.280	1.467
2	IC	1.922	----	1.973	1.893	52	UO	1.529	1.592	1.647	1.360
3	UO	1.9156	1.769	1.973	1.887	53	CO	1.529	1.575	1.593	1.400
4	UO	1.947	1.891	2.013	1.867	54	UO	1.711	1.953	1.567	1.620
5	CO	1.876	1.850	1.820	1.927	55	UO	1.431	1.727	1.393	1.173
6	CO	1.951	1.818	1.920	1.993	56	IC	1.573	1.939	1.527	1.253
7	CO	1.812	1.671	1.853	1.773	57	CO	1.820	1.840	1.787	1.833
8	IC	1.707	1.741	1.693	1.640	58	UO	1.618	1.840	1.500	1.513
9	UO	1.620	1.573	1.560	1.593	59	UO	1.511	1.613	1.400	1.520
10	CO	1.789	1.836	1.807	1.693	60	CO	1.673	1.813	1.927	1.280
11	CO	1.571	1.548	1.553	1.613	61	UO	1.598	1.567	1.705	1.500
12	CO	1.783	1.629	1.886	1.726	62	IC	1.420	1.533	1.400	1.327
13	UO	1.746	1.692	1.932	1.566	63	UO	1.740	1.736	1.847	1.640
14	UO	1.633	1.812	1.623	1.577	64	IC	1.573	1.520	1.533	1.647
15	UO	1.490	1.433	1.493	1.544	65	CO	1.670	1.853	1.673	1.483
16	CO	1.563	1.730	1.420	1.633	66	CO	1.662	2.098	1.347	1.711
17	CO	1.589	1.497	1.753	1.477	67	G	1.782	1.690	2.047	1.580
18	CO	1.687	1.753	1.613	1.693	68	IC	1.582	1.592	1.780	1.373
19	IC	1.631	1.712	1.580	1.600	69	UO	1.690	2.007	1.393	1.639
20	IC	1.431	1.373	1.607	1.313	70	UO	1.440	1.353	1.320	1.647
21	IC	1.638	1.655	1.600	1.607	71	UO	1.338	1.369	1.320	1.327
22	CO	1.567	1.548	1.707	1.420	72	IC	1.546	1.937	1.574	1.267
23	CO	1.671	1.860	1.500	1.653	73	IC	1.462	1.633	1.287	1.467
24	CO	1.633	1.791	1.600	1.493	74	CIC	1.444	1.500	1.500	1.322
25	CO	1.476	1.607	1.447	1.373	75	CIC	1.459	1.530	1.440	1.407
26	CO	1.389	1.408	1.440	1.320	76	CO	1.438	1.693	1.233	1.423
27	CO	1.322	1.313	1.360	1.293	77	IC	1.316	1.200	1.147	1.610
28	UO	1.369	1.640	1.220	1.247	78	IC	1.762	2.021	1.553	1.680
29	UO	1.518	1.353	1.953	1.247	79	IC	1.774	2.000	1.807	1.620
30	CO	1.633	1.809	1.733	1.347	80	CO	1.468	1.931	1.400	1.093
31	UO	1.656	1.785	1.400	1.780	81	CIC	1.358	1.287	1.273	1.513
32	IC	1.627	1.307	1.773	1.800	82	IC	1.382	1.808	1.213	1.140
33	CO	1.669	1.773	1.787	1.447	83	CIC	1.267	1.533	1.187	1.080
34	IC	1.556	1.730	1.460	1.480	84	CO	1.658	1.787	1.593	1.593
35	IC	1.556	1.453	1.560	1.653	85	CIC	1.442	1.833	1.440	1.313
36	IC	1.722	1.826	1.673	1.660	86	IC	1.600	1.982	1.527	1.373
37	IC	1.738	1.913	1.607	1.747	87	IC	1.880	2.184	2.013	1.427
38	CO	1.398	1.367	1.427	1.307	88	CIC	1.607	1.527	1.693	1.593
39	UO	1.553	1.687	1.513	1.460	89	CIC	1.771	1.815	1.607	1.747
40	CO	1.500	1.705	1.353	1.440	90	CIC	1.662	1.612	1.720	1.633
41	UO	1.476	1.698	1.420	1.307	91	CIC	1.678	1.726	1.713	1.560
42	UO	1.302	1.267	1.487	1.153	92	CIC	1.651	1.940	1.727	1.280
43	UO	1.467	1.603	1.600	1.213	93	CIC	1.662	1.879	1.633	1.473
44	UO	1.316	1.327	1.167	1.456	94	IC	1.700	1.887	1.653	1.560
45	UO	1.841	2.080	1.807	1.820	95	IC	1.824	1.839	1.920	1.640
46	IC	1.572	1.755	1.685	1.280	96	UO	1.609	1.780	1.613	1.433
47	CO	1.751	2.079	1.872	1.380	97	CO	1.744	1.960	1.700	1.573
48	CO	1.526	1.780	1.503	1.293	98	UO	1.518	1.633	1.493	1.427
49	CO	1.501	1.416	1.691	1.387	99	UO	1.660	1.733	1.907	1.540
50	CO	1.639	1.638	1.607	1.673						

TABLE 20
MEAN ABSORPTION

Pit No.	Deposit Type	$\overline{X}$ Size 1 (1-1/2 to 3/16 in.)	Pit No.	Deposit Type	$\overline{X}$ Size 1 (1-1/2 to 3/16 in.)
1	IC	1.389	51	UO	2.252
2	IC	----	52	UO	1.742
3	UO	1.843	53	CO	1.559
4	UO	1.766	54	UO	3.944
5	CO	2.003	55	UO	2.281
6	CO	1.193	56	IC	1.802
7	CO	1.202	57	CO	2.740
8	IC	1.578	58	UO	3.569
9	IC	2.291	59	UO	2.220
10	CO	2.210	60	CO	2.209
11	CO	1.994	61	UO	3.492
12	CO	4.957	62	IC	2.446
13	UO	3.917	63	UO	2.554
14	UO	2.642	64	IC	3.684
15	UO	1.554	65	CO	2.793
16	CO	3.178	66	CO	2.649
17	CO	1.776	67	G	3.922
18	CO	1.658	68	IC	3.638
19	IC	2.337	69	UO	3.804
20	IC	1.[illegible]22	70	UO	3.505
21	IC	1.412	71	UO	3.103
22	CO	1.595	72	IC	3.136
23	CO	1.809	73	IC	3.135
24	CO	2.302	74	CIC	2.463
25	CO	1.325	75	CIC	3.510
26	CO	1.553	76	CO	2.422
27	CO	1.610	77	IC	1.903
28	UO	.686	78	IC	3.353
29	UO	2.055	79	IC	4.210
30	CO	1.527	80	CO	2.422
31	UO	2.772	81	CIC	1.718
32	IC	1.405	82	IC	1.884
33	CO	1.187	83	CIC	1.499
34	IC	1.882	84	CO	1.482
35	IC	1.720	85	CIC	3.653
36	IC	3.104	86	IC	1.880
37	IC	2.365	87	IC	4.631
38	CO	1.708	88	CIC	1.527
39	UO	1.924	89	CIC	1.492
40	CO	1.649	90	CIC	2.233
41	CO	1.425	91	CIC	1.878
42	UO	1.271	92	CIC	2.386
43	UO	1.565	93	CIC	11.456
44	UO	1.723	94	IC	4.391
45	UO	4.849	95	IC	1.286
46	IC	2.344	96	UO	1.169
47	CO	2.248	97	CO	1.6888
48	CO	1.894	98	UO	1.132
49	CO	1.908	99	UO	1.884
50	CO	1.905			

TABLE 21
MEAN SPECIFIC GRAVITY

Pit No.	Deposit Type	$\overline{X}$ Size 1 (1-1/2 to 3/16 in.)	Pit No.	Deposit Type	$\overline{X}$ Size 1 (1-1/2 to 3/16 in.)
1	IC	2.685	51	UO	2.816
2	IC	----	52	UO	2.617
3	UO	2.669	53	CO	2.658
4	UO	2.666	54	UO	2.537
4	CO	2.637	55	UO	2.605
6	CO	2.672	56	IC	2.558
7	CO	2.689	57	CO	2.535
8	IC	2.674	58	UO	2.370
9	IC	2.650	59	UO	2.577
10	CO	2.690	60	CO	2.588
11	CO	2.589	61	UO	2.539
12	CO	2.450	62	IC	2.625
13	UO	2.401	63	UO	2.543
14	UO	2.541	64	IC	2.507
15	UO	2.631	65	CO	2.533
16	CO	2.500	66	CO	2.549
17	CO	2.630	67	G	2.539
18	CO	2.614	68	IC	2.542
19	IC	2.584	69	UO	2.469
20	IC	2.700	70	UO	2.549
21	IC	2.653	71	UO	2.532
22	CO	2.636	72	IC	2.472
23	CO	2.628	73	IC	2.534
24	CO	2.573	74	CIC	2.567
25	CO	2.651	75	CIC	2.511
26	CO	2.666	76	CO	2.572
27	CO	2.695	77	IC	2.618
28	UO	2.700	78	IC	2.503
29	UO	2.558	79	IC	2.363
30	CO	2.638	80	CO	2.647
31	UO	2.615	81	CIC	2.623
32	IC	2.674	82	IC	2.628
33	CO	2.686	83	CIC	2.639
34	IC	2.685	84	CO	2.626
35	IC	2.690	85	CIC	2.487
36	IC	2.582	86	IC	2.617
37	IC	2.598	87	IC	2.384
38	CO	2.643	88	CIC	2.662
39	UO	2.687	89	CIC	2.633
40	CO	2.653	90	CIC	2.627
41	CO	2.650	91	CIC	2.600
42	UO	2.614	92	CIC	2.733
43	UO	2.601	93	CIC	2.651
44	UO	2.592	94	IC	2.567
45	UO	2.375	95	IC	2.654
46	IC	2.571	96	UO	2.633
47	CO	2.548	97	CO	2.594
48	CO	2.613	98	UO	2.665
44	CO	2.590	99	UO	2.620
50	CO	2.591			