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COLLEGE OF MINERAL INDUSTRIES

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FLOOD PLAIN SEDIMENTS OF HALFMOON CREEK, PENNSYLVANIA

by
Alan A. Adler and Laurence H. Lattman

ABSTRACT

The sediments underlying part of the flood plain of Halfmoon Creek, Pennsylvania were studied by taking auger samples from holes spaced fifteen feet apart on a square grid. The topography of the flood plain was mapped with a contour interval of 0.2 feet.

Three basic sediment types are distinguished: A1 which contains more than 55 per cent clay and silt, and no gravel; A2 which contains less than 55 per cent clay and silt, and no gravel; and B which contains gravel. Lateral accretion is composed of gravel (type B) overlain by sediment type A2, and overbank deposits are composed of sediment types A1 and A2. The finest overbank deposits (vertical accretion) occur in topographic lows on the flood plain. The amount and coarseness of the gravel increases toward the bottom of the valley fill and toward the valley sides.

Although there is a continuous gradation from gravel to the finest sediment, lateral accretion can be distinguished from overbank deposition except for the sandy sediment type A2. Lateral accretion comprises about two-thirds of the volume of the flood plain sediments.

INTRODUCTION

Several recent studies of flood plain sediments (Happ, Rittenhouse, and Dobson, 1940; Jahns, 1947; Wolman and Leopold, 1957) have dealt with the problem of distinguishing lateral accretion from overbank deposition. Wolman and Leopold have summarized the problem and the attendant disagreement as to the relative importance of each in valley fill. It is the primary purpose of the present study to determine whether particle size is a valid criterion for distinguishing lateral accretion from overbank deposition. To achieve this purpose the sediments of a small segment of a flood plain were sampled and studied in great detail.

In order to study the relation of the flood plain topography to present overbank deposition, a topographic map with a contour interval of 0.2 feet was made of a selected segment of the flood plain. The sediments in this segment were sampled by auger (1.5 inch diameter soil auger). The auger holes were spaced fifteen feet apart and put down until the auger encountered impenetrable material, a very coarse gravel. From every auger hole a sample was collected consisting of each three inches penetrated. Some of these samples were sieved and all were described in the field.

It was a secondary purpose of the study to ascertain the distribution of gravel in the stream deposits, and any relationships among gravel size, amount, and position.

![Figure 1: Location Map](image)

DRAINAGE BASIN OF HALFMOON CREEK

The drainage basin of Halfmoon Creek is in the Ridge and Valley section of the Folded Appalachian Province (Figure 1) and is shown on the Philipsburg, Bellefonte, and Tyrone topographic quadrangles. The segment of the flood plain studied in detail centers at latitude 40° 43' 15"N, longitude 78° 02' 30"W, Centre County, Pennsylvania.

Within the drainage basin, the topographic grain trends approximately N 45° E. The drainage basin upstream from the study area occupies 16.2 square miles, has a maximum relief of approximately 750 feet, a local relief of about 250 feet, and an average hillslope of about 300 feet per mile except in the headwaters on Bald Eagle Mountain. The stream density (total stream length in miles divided by drainage area in square miles) is 1.2.

Upper Cambrian to Lower Silurian rocks crop out within the drainage basin. These rocks
are limestones, dolomites, shales, graywacke, and quartzite. At the study area the stream is in the Cambrian Gatesburg dolomite, which upon weathering, develops a thick sandy residuum.

The drainage basin lies on the northwest flank of the Marengo syncline (Butts, et. al., 1939). Dips are nearly vertical in the headwaters of Halfmoon Creek, and horizontal to gently southeast throughout the remainder of the drainage basin.

Metereological data from The Pennsylvania State University approximately ten miles northeast of the study area indicate an annual rainfall of forty-one inches rather evenly distributed throughout the year. The seasonal precipitation is 17.5 inches during the fall and winter, and 23.5 inches during the spring and summer. The highest weekly precipitation, which occurred once in thirty years, is 6.4 inches.

Less than one-fifth of the drainage basin is devoted to farming, and the remainder is pasture and forest. The flood plain is entirely in pasture and has been so for at least the last fifty years. The area was probably first deforested about 150 years ago.

HALFMOON CREEK

Halfmoon Creek heads on the southeast slope of Bald Eagle Mountain, the northwesternmost ridge of the Appalachian Mountains, and flows about five miles to the study area. In these five miles the stream receives eight tributaries with a combined length of approximately fourteen miles. From its head the stream flows southwest parallel to the regional strike for three miles with an average gradient of about seventy feet per mile. The stream then flows south-southeastward for approximately two miles with an average gradient of about twenty-five feet per mile, to the study area.

Within the study area the stream has an average gradient along the talweg1 (Figure 3) of twenty-eight feet per mile (0.0053 foot per foot), an average width of about ten feet, and the bed of the channel averages 2.5 feet below the adjacent banks (Figure 2). The sinuosity ratio (stream length divided by airline distance) in the study area is 1.12. Bankfull stage is about two feet above the mean height of the bed.

Halfmoon Creek is out of its banks at least once and commonly several times every spring.

1Talweg (or talweg) — a line joining the deepest parts of a stream channel.
In the spring of 1959 due to an ice jam, the overbank water was about three feet over the flood plain (oral communication, Mr. C. M. Walker).

Halfmoon Creek is probably a degrading stream. The very coarse gravel that could not be penetrated by the auger is generally six inches to two feet below the bed of the stream as mapped, and hence probably well within the depth of scour of Halfmoon Creek in flood (Inglis, 1949). The gravel is probably of Pleistocene age and acts as "bedrock" as discussed below.

METHODS OF STUDY

Mapping and Sampling.

The topography of the flood plain in the study area (Figure 2) was mapped by alidade at a scale of one inch equals thirty feet and a contour interval of 0.2 feet. Stations were occupied on a square grid whose intersections were fifteen feet apart. This grid is indicated on Figures 2 and 5 by A1, A2, A3, ..., B1, B2, B3, ... The talweg was mapped independently (Figure 3).

At each intersection on the grid an auger hole was put down until penetration was stopped by very coarse gravel. A total of 584 auger holes were made. Samples were taken with the auger. The top six inches of material in each auger hole was discarded because this is the probable maximum depth of disturbance by cattle. The material from six inches to one foot depth was collected as a sample, and the remainder of the samples from each auger hole consisted of each three inches penetrated. A field description of each sample was recorded as described below.

Analysis of Samples.

Laboratory Analysis:

All samples from forty auger holes were sieved. These samples were oven-dried at 105° F., disaggregated by mortar and rubber pestle, and sieved on a tapping machine for five minutes. Sieves used were U. S. Standard Sieves, numbers 10, 35, 60, 230, and pan. The sediment size terms used to classify samples studied in the laboratory follow the Wentworth (1922) scale, except that all material larger than two millimeters in diameter was called gravel.

The auger holes whose samples were sieved are indicated by letters on Figures 2 and 5. Histograms of samples from nine auger holes are shown on Figure 4.

Field Analysis:

Material was termed gravel in the field if it was over two millimeters in diameter as determined by visual comparison with particles known to be of this diameter. Sand was identified by rubbing the specimen between fingers. If discrete particles were felt, they were identified as sand, if they were less than two millimeters in diameter. Clay was identified by rolling sample between fingers to obtain a thread less than one-eighth inch in diameter. If such a thread was obtained, the specimen was recorded as containing clay. It was then tested between the teeth to determine if silt was present. Silt occurred in all clay samples.

Classification of Sediments.

From laboratory and field analyses a classi-
fication of the sediments was constructed (Table I). Sediment type A by definition contained no gravel. The presence of any gravel places the sediment in type B. Sediment type A1 which contains more than 55 per cent clay and silt usually contains no material coarser than medium sand, although a few samples contained up to 2 per cent coarse sand which could not be detected in the field. Most commonly, sediment type A2 which has less than 55 per cent clay and silt, and no gravel, has most material in the very fine sand to fine sand range (Figure 4). The arbitrary value of 55 per cent clay and silt was used to differentiate sediment types A1 and A2 because of the association of sand, which could be detected easily in the field, with material containing less than 55 per cent clay and silt (A2). Material containing more than 55 per cent clay and silt (A1) very rarely contained sand which could be detected in the field. Hence the differentiation of A1 and A2 could be attained by field examination.

Occasionally, a thin lens of gravel occurred in a sampling unit of fine material. Because of the presence of a small amount of gravel, such a sample would be classified as type B1, rather than type A (see, for example, auger hole DD, Figure 4). These discrepancies might have been removed by a more detailed classification or a smaller sampling unit, but in light of the purpose of the study and the analytical methods used, the classification given in Table I was considered sufficiently detailed.
TABLE I  
Classification of Sediments

<table>
<thead>
<tr>
<th>Sediment Type</th>
<th>Laboratory Description</th>
<th>Field Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A₁</td>
<td>More than 55 per cent clay and silt, no gravel</td>
<td>Predominantly clay and silt, no gravel or obvious sand</td>
</tr>
<tr>
<td>A₂</td>
<td>Less than 55 per cent clay and silt, no gravel</td>
<td>Contains sand, clay and silt, no gravel</td>
</tr>
<tr>
<td>A₁₋₂</td>
<td>Not used</td>
<td>No gravel, cannot be differentiated into A₁ or A₂</td>
</tr>
<tr>
<td>B₁</td>
<td>Trace to 10 per cent gravel</td>
<td>Not used</td>
</tr>
<tr>
<td>B₂</td>
<td>10 per cent to 20 per cent gravel</td>
<td>Not used</td>
</tr>
<tr>
<td>B₁₋₂</td>
<td>Not used</td>
<td>Trace to 20 per cent gravel</td>
</tr>
<tr>
<td>B₂</td>
<td>More than 20 per cent gravel</td>
<td>More than 20 per cent gravel</td>
</tr>
</tbody>
</table>

Comparison of Laboratory and Field Analyses

A total of 351 samples from forty scattered auger holes were sieved. A field analysis of these samples had already been made. From the field and laboratory analyses samples were classified according to Table I and a comparison made of the agreement between the two methods of analysis. Of seventy-seven samples classified type A₁ in the field, seventy were classified type A₁ in the laboratory. Fifty-six samples were classified type A₂ in the field and all but seven of these were similarly classified in the laboratory. Sediments containing gravel (type B) show about the same correlation between analyses. Agreement between field and laboratory classification was found for about 90 per cent of the samples compared. Because of this agreement between laboratory and field analyses of forty auger holes, the remainder of the auger holes were analyzed only in the field.

FLOOD PLAIN OF HALFMOON CREEK

Physiography.

The flood plain in the study area is about four hundred feet wide and sharply bounded by relatively steep colluvial slopes (Figure 2). On the northeast side a ploughed ridge at the base of the colluvial slope prevented sampling to the extreme edge of the flood plain. The maximum local relief is 1.4 feet and the total relief is about four feet.

The most striking topographic features of the flood plain (Figure 2) are two flood plain channels, one on either side of the stream. The

PLATE 1A: VIEW WEST ALONG HALF MOON CREEK  
CAMERA STATION IS AT A17-841 OF FIGURE 2. THE STREAM IS IN HIGH-WATER STAGE AND IS FLOWING TOWARD OBSERVER. NOTE SLUMPING OF SOD AT UNDERCUT BANK, AND THE GRAVEL AT THE SURFACE ON THE DOWNSTREAM (NEAR) END OF POINT BAR.

PLATE 1B: VIEW NORTH ACROSS POINT BAR  
CAMERA STATION IS A1+10-86 OF FIGURE 2. THE STREAM IS FLOWING TOWARD THE RIGHT. SEDIMENT TYPE A₁ (SANDY MATERIAL) IS AT THE SURFACE OF THE POINT BAR, EXCEPT AT THE LOWER RIGHT WHERE GRAVEL IS AT THE SURFACE.
channels slope down the valley and their beds have irregular elevations. Both are marked by conspicuous topographic lows along their courses, some of which are shown at A4-B11, A9-B18, A15-B6, A17-B17, of Figure 2. The relief of the bottom of the flood plain channels may be as great as one foot. The southern channel has tributaries (A4-B7, A9-B24, Figure 2) which exhibit a dendritic pattern. The northern channel gradually disappears in the relief of the flood plain and the southern channel debouches into Halfmoon Creek. There are several smaller channels of similar nature (A13-B37, Figure 2).

The flood plain channels, the relief of the flood plain is generally low (less than one foot), rolling, and irregular. Two tongues of colluvium project onto the flood plain (A20-B2, A3-B38, Figure 2).

Several steep banks occur (A20-B38, Figure 2), some of which are associated with flood plain channels (A15-B6, Figure 2). All point bars on the inside of the stream bends show the characteristic steep to vertical banks on the upstream side and gentle slope downstream (A12-B1, A12-B16, A16-B27, A17-B37, Figure 2). The undercut banks on the outside of the stream bends are capped by silt which slumps into the stream when sufficiently undercut (Plate 1a).

**Base of Valley Fill.**

All augering was stopped by very coarse gravel which apparently underlies the entire study area. The gravel was sampled by digging pits and was found to consist of cobbles and boulders over eight inches and up to sixteen inches in diameter. The top of this gravel deposit is irregular with a relief of about four feet (Figure 6) and the gravel is far coarser than anything now seen to be transported by Halfmoon Creek and probably acts as "bedrock" underlying the flood plain.

The gravel may be of Pleistocene age, because it is the same size as talus of probable periglacial origin found on slopes in the headwaters of Halfmoon Creek. It is considered that only sediments overlying this coarse gravel are related to modern deposition by the stream.

The surface of the coarse gravel (Figure 6) is low on the sides and high in the center of the flood plain. The lows approximately underlie the flood plain channels and have a shape which suggests that they are old stream channels. Halfmoon Creek may have cut the channels in the coarse gravel when it occupied former courses marked by the flood plain channels. The present stream position overlies a discontinuous group of topographic highs on the surface of the coarse gravel. A cross section through the flood plain would show "bedrock" higher in the center than on either side, a fact that has been reported by several other investigators (Wolman and Leopold, 1957).

**Sediments.**

The uppermost six inches of sediments underlying the flood plain were disturbed by cattle and not studied in detail. Most samples of this material were predominantly clay and silt (sediment type A1), but some contained notable amounts of sand (sediment type A2). In places, gravel (sediment types B) was exposed at the surface.

Fine sediments (type A1) in general, form the upper one foot of material sampled in the auger holes (Figure 5) except at the point bars, where sediment type A2 containing more sand than type A1, is at the surface (NN and adjacent logs, and X, Z, and adjacent logs of Figure 5; Plate 1b). Sediment type A1 is variable, consisting of material containing from 55 per cent clay and silt to 90 per cent clay and silt (sample from 1.00 to 1.25 feet, log AA, Figure 4). The finest material of type A1 is found beneath the topographic lows in the bottoms of the flood plain channels (AA of Figures 2 and 4). Locally, type A1 is quite thick (A21-B27 and A17-B19, Figure 5).

Sediment type B (gravel) generally occurs toward the bottom of the valley fill, and the amount of gravel in the sample usually increases downward in the auger holes (Figure 5). The amount of gravel also increases close to the valley sides. Locally, thick gravel is found near the center of the flood plain (A8-B11, A8-B13, A6-B11, Figure 5). On the downstream side of point bars, gravel generally is found at the surface (Plate 1a and 1b) and forms the dominant material in auger holes (A12-B5, Z of Figure 5) Subangular to subrounded gravel underlies the
LEGEND

<table>
<thead>
<tr>
<th>A1</th>
<th>CLAY AND SILT CONTENT &gt; 55%</th>
</tr>
</thead>
<tbody>
<tr>
<td>A12</td>
<td>UNDIFFERENTIATED A1 AND A2</td>
</tr>
<tr>
<td>A2</td>
<td>CLAY AND SILT CONTENT &lt; 55%</td>
</tr>
<tr>
<td>B1</td>
<td>GRAVEL CONTENT - TRACE TO 10%</td>
</tr>
<tr>
<td>B12</td>
<td>UNDIFFERENTIATED B1 AND B2</td>
</tr>
<tr>
<td>B2</td>
<td>GRAVEL CONTENT - 10 TO 20%</td>
</tr>
<tr>
<td>B3</td>
<td>GRAVEL CONTENT &gt; 20%</td>
</tr>
<tr>
<td>S</td>
<td>GRAVEL TOO COARSE TO SAMPLE</td>
</tr>
</tbody>
</table>

FIGURE 5: LOGS OF AUGER HOLE
NOTE: GRID IS 3.6 FEET ABOVE LOWEST POINT ON STREAM BED. CROSSES ON LOGS INDICATE INTERSECTIONS OF LOGS AND GRID. UPPER 0.5 FEET OF ALL LOGS (DISTURBED LAYER) NOT SHOWN.
colluvial tongues extending from the valley sides onto the flood plain (A18-B1, C of Figure 5, and B of Figure 4 and 5). This is in contrast with the predominantly surrounded gravel in the stream bed.

It was not practical to correlate sediments between logs (Figure 5) because the position of sediment types vary widely from auger hole to auger hole.

RELATIONSHIPS OF SEDIMENT TYPES TO PHYSIOGRAPHIC FEATURES OF THE FLOOD PLAIN

In order to establish possible relationships between sediment type and physiographic features of the flood plain, samples from nine selected auger holes were sieved and studied in detail (Figure 4). These auger holes were located in point bars, flood plain channels, colluvial tongues, and other recognized landforms.

Point Bars.

Point bars are formed by deposition of lateral accretion (Happ, Rittenhouse and Dobson, 1940; Fisk, 1947; Wolman and Leopold, 1957). Wolman and Leopold noted the heterogeneity of point bar deposition. They found finer material near the surface overlying coarser material, and noted eddies at the downstream side of the point bar which localized deposition of fine material. These investigators stated that it was difficult to distinguish the fine material deposited as lateral accretion, from that deposited as overbank deposition. The present study generally supports that conclusion.
The point bar centered around A12-B3 of Figure 2 was studied in greatest detail. Auger hole NN (Figure 2, 4, and 5) is near the point of maximum curvature of the point bar. This auger hole (Figure 4) shows sandy material (sediment type A2) at the top (Plate 1b) overlying gravel (sediment type B) of variable textural composition. Other auger holes on the point bar (A12-B2, A11-B4 of Figure 5) show type A2 at the top and one auger hole in a small depression on this point bar (A11-B3 of Figure 5) contains a small amount of sediment type A1 overlying type A2. At the downstream end of the point bar, gravel is at the surface (A12-B5 of Figure 5; Plate 1b). Point bars at A11-B10, A12-B16 of Figures 2 and 5 show similar sediment types and distribution. Only one local occurrence of fine sediment (type A1) is found on the point bars. Sediment type A1 occurs primarily on the flood plain behind the active point bar deposition.

It is concluded that fine sediment (type A1) is not normally deposited as lateral accretion, although a small pocket was found in one topographic low on a point bar. The finest material deposited as lateral accretion is type A2.

**Flood Plain Channels.**

The flood plain channels are underlain by heterogeneous sediments and contain the finest material deposited on the flood plain. This finest material, which may contain up to 90 per cent clay and silt, appears to be deposited in the topographic lows in the channels (AA of Figures 2 and 4). Coarse material (type B) may locally be near the surface in these channels (V of Figures 2 and 5). Sediment type A2 and the coarser fraction of type A1 are also present.

**Colluvial Tongues.**

The colluvial tongues are underlain predominantly by gravel (sediment type B), much of which does not appear to be of alluvial origin (B of Figures 4 and 5, C of Figure 5). It was not found possible to distinguish readily alluvial from colluvial material in these tongues. Small amounts of fine alluvial material seem to overlie and interfinger with the coarser colluvium and alluvium in the tongues (F, C, A21-B5 of Figure 5).

**Other Landforms of the Flood Plain.**

A possible natural levee at A13-B21 of Figures 2 and 5 contains primarily fine material of types A1 and A2 (GG of Figures 4 and 5). The material becomes coarser downward and none of the very fine sediment such as is found in the lows in the flood plain channels is present.

Elsewhere the flood plain sediments show typical heterogeneity (JJ, A, LL, and DD of Figures 4 and 5) but in general become coarser downward. Interlayering of fine material and gravel is common.

**GENESIS OF SEDIMENT TYPES**

There is a transition among the sediment types used in the present classification. However, certain distinctions appear valid. The following evidence is adduced to support the distinctions made below:

1. There is almost no material of type A1 associated with the present point bar deposition (lateral accretion).
2. The fine material (type A1) occurs as a thin, sometimes discontinuous, veneer at the surface of the flood plain. Locally, type A1 may be several feet thick.
3. The finest material of type A1 (containing 70 to 90 per cent clay and silt) usually occurs in the topographic lows in the flood plain channels. This material shows an alternate increase and decrease of sand in vertical section (AA of Figure 4).
4. Sediment type A2 occurs at the top of point bars and locally in flood plain channels, but is not usually found at the surface of the flood plain.

From these facts it is concluded that type A1 is overbank deposition and that the finest material of type A1 (70 to 90 per cent clay and silt) is vertical accretion deposited from standing water in topographic lows after floods recede. In this connection Mr. C. M. Walker, owner of the property, reports that the most common annual flood is less than one foot deep on the flood plain and that standing water may remain in the topographic lows for extended periods. During these floods, when the downvalley flow is slow, a coarser fraction of sediment type A1 (55 to 70 per cent clay and silt) is deposited over the flood plain.

Sediment type A2 is deposited on top of point bars and forms part of the lateral accretion. It is also deposited locally in flood plain channels during uncommon, high, fast-flowing floods. One such flood, about three feet deep over the stream banks, occurred in the spring of 1959.
after the field work for this study was done. This flood deposited sandy material (type A₂) locally in flood plain channels (Plate 2). Thus sediment type A₂ may be of lateral accretion or overbank origin and, when of overbank origin, is apparently localized in deposition.

Gravel deposits (sediment types B) are the result of lateral accretion. The point bars of Halfmoon Creek have the gravel concentrated on the downstream side (Plates 1a and 1b). The reason for this is not understood. Perhaps the gravel is deposited on the downstream side because the talweg (and hence probably the thread of maximum current) swings toward the point bar near the downstream end (see Figure 3, especially the point bar farthest upstream). The approach of the talweg to the point bar at the downstream end could bring coarser material to this position.

The coarsest gravels in the flood plain are found in the bed of Halfmoon Creek (lag gravels of Happ, et al., op. cit.) and low in the valley fill near the edges of the flood plain. Stringers of gravel are found throughout the valley fill (sample from 2.0 to 2.25 feet, log AA, Figure 4).

**EFFECT OF FLOOD PLAIN SEDIMENTS ON STREAM ACTIVITY**

*Distribution of Gravel (Sediment Type B)*

The topography on the surface of the gravel deposits is shown in Figure 7 (compare with Figure 6). The surface is irregular and has a relief of about five feet. There is a reflection of the channels in the underlying coarse gravel ("bedrock") in the weakly developed lows on the surface of the flood plain gravel. The present stream overlies a gentle high on the gravel surface. In the northern corner of the map (Figure 7) there is a suggestion of a buried gravel bar and adjacent swale.

In some bore holes, particularly in the lows on either side of the stream (e.g., A4, B12 and A6, B9) there is no sediment type B. The discontinuous nature of the gravel or lateral accretion suggests that the stream may change position by avulsion⁠¹ as well as by continuous migration. The absence of continuous lateral migration would account for the local absence of gravel.

**Distribution of Fine Sediments**

A comparison of Figures 2 and 6 suggests that topographic lows in the bedrock may have been cut when Halfmoon Creek followed courses indicated by the flood plain channels. The flood plain channels in turn, receive the finest sediment deposited (vertical accretion). Fisk (1947) suggested that fine sediments (clays) were difficult for the Mississippi river to erode and hence exerted an effect on that stream's position. All of this suggests that the present position of Halfmoon Creek, which overlies topographic highs on the bedrock surface, may be strongly influenced by the fine sediments accumulating in the flood plain channels. By this hypothesis, the stream would be constrained to flow near the center of the flood plain because of fine sediments accumulating in flood plain channels which are former stream courses abandoned by avulsion.

**SUMMARY AND CONCLUSIONS**

There is a continuous gradation in size from coarsest to finest material in the valley fill. Except for sediment type A₂ which may be deposited as lateral accretion or overbank deposition, the genesis of the sediments may be distinguished by particle size.

Lateral accretion of Halfmoon Creek consists of gravel (sediment type B) near the bottom and sandy material toward the top. The sandy ma-

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¹avulsion—the process by which a stream suddenly changes its position by meander, by cut off or by breaking through its banks.
material on top of the lateral accretion (point bar) is indistinguishable from coarser material of overbank origin which is deposited locally on the flood plain by exceptional, high floods. Fine material (type A), also of overbank origin is deposited during the more usual quiet floods as a veneer on the flood plain surface. The finest sediments of overbank origin settle from stagnant water in the enclosed topographic lows in the flood plain, which are commonly found in beds of flood plain channels.

Gravel is concentrated in the lower part of the valley fill and is generally thickest close to the valley sides. Any procedure for sampling a flood plain for gravel as a construction material should take account of this distribution.

In the part of the flood plain studied, lateral accretion accounts for approximately two-thirds of the volume of valley fill.

ACKNOWLEDGMENTS

The writers are grateful to Drs. MacKenzie L. Keith and Luna B. Leopold who read the manuscript and offered numerous helpful suggestions. Mr. C. M. Walker of Stormstown, Pennsylvania allowed free access to his property and gave helpful information on the recent history of Halfmoon Creek.

FIGURE 7: TOPOGRAPHY ON TOP OF SEDIMENT TYPE B (GRAVEL). ZERO CONTOUR IS TWO FEET BELOW ZERO CONTOUR OF FIGURE 2.
COMMERCIAL POSSIBILITIES OF SOME CAMBRIAN AND ORDOVICIAN LIMESTONES
AND DOLOMITES IN BLAIR AND CENTRE COUNTIES, PENNSYLVANIA

by
Richard R. Thompson

ABSTRACT

Exposures of the Middle Cambrian Pleasant Hill limestone, the Stacy and Ore Hill members of the Upper Cambrian Gatesburg formation, and parts of the Lower Ordovician Larke dolomite and Stonehenge limestone were sampled systematically at localities in Blair and Centre Counties, Pennsylvania.

The chemical analyses indicate that the Ore Hill member of the Gatesburg formation and the upper part of the Pleasant Hill beds would be satisfactory for use as metallurgical flux stone as well as for manufacture of portland cement, if blended with shale from nearby exposures. The Ore Hill member also would qualify for the manufacture of lime for bottle glass and for magnesian lime that would be acceptable for soil stabilization and structural purposes. The Ore Hill member could be used for production of agricultural lime where a high magnesium content is desirable, and the Pleasant Hill might similarly be used where a high calcium content is needed. The Larke and Stonehenge formations and other parts of the Gatesburg formation are unacceptable or marginal for the above-described uses.

The Ore Hill member seems especially deserving of further investigation for commercial use; it is quite pure and occurs over extensive areas in central Pennsylvania. Further investigation should include diamond drilling as well as analyses of samples from other localities.

PURPOSE AND SCOPE

The present paper, dealing with the Cambrian Pleasant Hill and Gatesburg formations and the Lower Ordovician Larke and Stonehenge formations is the second in a series of reports intended to provide information about the chemical characteristics and commercial possibilities of Cambro-Ordovician limestones and dolomites in central Pennsylvania (see Swartz and Thompson, 1958). To obtain this information, samples were collected systematically from localities in Blair and Centre Counties. Each sample was analysed for non-ignited acid insoluble residue, and nine composite samples were analysed for SiO₂, Al₂O₃, Fe₂O₃ and CaO by X-ray fluorescence, and for MgO by a wet chemical method.

Results of the study are reported in three parts. Part I is concerned with sampled parts of the Pleasant Hill limestone and Gatesburg dolomite, and Part II with the Larke dolomite and Stonehenge limestone. Part III is a discussion of the methods of analysis.

PART I. THE MIDDLE CAMBRIAN PLEASANT HILL LIMESTONE AND THE UPPER CAMBRIAN GATESBURG FORMATION

CHARACTERISTICS AND OCCURRENCE

The Pleasant Hill limestone of Middle Cambrian age was named by Butts (1918) from exposures in a quarry at Pleasant Hill Church about one mile northwest of Henrietta, Blair County, Pennsylvania. Butts redescribed the section in 1945 and divided the formation into a lower 400 feet of thin-layered, argillaceous, sandy and micaceous limestone with some calcareous shale, and an upper 200 feet of thick-bedded, fine-grained dark gray limestone. Wilson (1952) measured the upper 350 feet of the Pleasant Hill limestone at a section near Williamsburg, Pennsylvania, and reported that the upper 190 feet at that locality are relatively pure limestone without the sandy, silty and shaly layers that occur in the lower part of the formation.

The Gatesburg dolomite of Upper Cambrian age was named by E. S. Moore (Butts, 1918) from exposures at Gatesburg Ridge, Centre County, Pennsylvania, and subsequently was divided into four members by Butts (1918). Later work by Butts and Moore (1936), Butts et al (1938) and Butts (1945) provided general descriptions of the members; Krynine (1946) and Wilson (1952) additionally included the Mines dolomite as the uppermost member of the formation. Wilson also described stratigraphic changes of the Gatesburg formation from central Pennsylvania to central Maryland, and included in his paper a complete list of references to earlier reports which had contributed to understanding of the Gatesburg in those areas.

The general stratigraphic positions of the Pleasant Hill and Gatesburg formations in the Nittany Valley - Morrison Cove region are as follows:
FIGURE 1: AREAL DISTRIBUTION AND SAMPLED LOCALITIES OF PLEASANT HILL AND GATESBURG FORMATIONS, BLAIR COUNTY, PENNSYLVANIA. AREAL GEOLOGY AFTER BUTTS (1945).
LOWER ORDOVICIAN

Stonehenge limestone – Larke dolomite, 200-600 feet.

UPPER CAMBRIAN

Gatesburg formation, 1700 to 1800 feet, divided into following members:
Mines dolomite member, 250 feet, with oolitic chert.
Upper sandy dolomite member, 650-700 feet.
Ore Hill member, 200 feet, thin-bedded limestones in southern Blair County; massive, dark, coarsely crystalline dolomite in northern Blair County.
Lower sandy dolomite member, 400 feet.
Stacy dolomite member, 200-400 feet.
Warrior limestone, 1350 feet of alternating dark, platy, fine-grained to aphanitic limestone, generally oolitic and fossiliferous, algal stromatolites, and dark aphanitic dolomite.

MIDDLE CAMBRIAN

Pleasant Hill limestone, about 200 feet of thick-bedded, fine-grained limestone above, underlain by 400 feet of thin-bedded, argillaceous, sandy, and micaceous limestone with some calcareous shale. Thickness, 600 feet.

LOWER CAMBRIAN

Waynesboro formation (?), 200 feet or more of green and red shale above; sandstone, quartzite and conglomerate below.

The geographic distributions of the belts of outcrop of the Pleasant Hill and Gatesburg formations in Blair County, Pennsylvania, are illustrated in Figure 1. The belts trend northeast-southwest and generally are bordered on the northwestern sides by thrust faults. Structure sections A-A’ and B-B’ (Figure 2), drawn in the positions located in Figure 1, show the subsurface disposition of the Gatesburg formation near Birmingham and Ore Hill, respectively. In both sections, the Stacy member is represented by a double-line pattern drawn perpendicular to the rock layers, whereas a triple-line designation is used for the Ore Hill member. Near Birmingham, at the location of section A-A’, the Ore Hill member is completely exposed where the Gatesburg is brought to the surface adjacent to a thrust fault which truncates most of the Stacy member. Near Ore Hill, at the location of section B-B’, the Ore Hill member is exposed in a slightly overturned anticlinal fold, which is not eroded deeply enough to uncover the Stacy member.

The Pleasant Hill limestone crops out north of Henrietta (section C-C’, Figure 2), where it and the Waynesboro formation have been brought to the surface by a thrust fault. The upper part of the formation is removed at that locality by a second thrust fault. Owing to the structural complexity of the area, detailed geological investigation would be needed for selection of quarry sites.

Wilson (1952) has shown in some detail that the Ore Hill member changes from limestone in the southern part of Blair County to dolomite in the northern part. He divided the exposed beds at Birmingham into an upper portion that contains 22 feet of finely-crystalline dolomite with undulating silty laminae, in contrast to a lower portion, 141 feet thick, of massive, coarsely-crystalline, dark gray dolomite.

The writer further subdivides the lower 141 of the Ore Hill member at Birmingham into an upper 60-foot unit (Unit II) of vugular, coarsely-crystalline dolomite, underlain by a lower, non-vuggy unit (Unit I) with a few undulating argillaceous laminae and partings. This subdivision is in accordance with the distinctly different percentages of impurities shown by chemical analyses of the two units: Unit II averages 1.5 per cent non-ignited acid insoluble residue whereas Unit I averages 5.8 per cent.

SAMPLING AND ANALYSIS

Samples for preliminary chemical evaluation of the Ore Hill member of the Gatesburg formation were collected from two localities in Blair County: (1) from exposures at the type section in a quarry 300 yards northeast of the intersection of Pennsylvania State Highway 686 and a road leading eastward to Ore Hill Station in Bloomfield Township, and (2) from exposures near Birmingham at about four miles east of Tyrone, along the northern side of the highway leading from Tyrone to Union Furnace. The upper part of the Stacy member was sampled
FIGURE 2. STRUCTURE SECTIONS THROUGH SAMPLED LOCALITIES. LOCATIONS OF SECTIONS ARE INDICATED IN FIGURE 1. Gatesburg contain interbeds of orthoquartzite up to several feet in thickness and generally spaced from five feet to twenty-five feet apart; therefore those members were not sampled for analysis. The Mines dolomite member also was not sampled because it contains beds of siliceous oolite and layers of chert, which are spaced too closely together to provide any continuous 50-foot thickness of dolomite that might be satisfactory for exploitation.

Analyses of the samples were performed in two stages, as described in Part III of this paper.

CHEMICAL CHARACTERISTICS OF THE PLEASANT HILL LIMESTONE

Chemical characteristics of samples from the Pleasant Hill limestone at Pleasant Hill Church,
Blair County, are summarized in Figure 3.

The exact stratigraphic position of the sequence sampled at Pleasant Hill Church was not established, due to lack of adjacent exposures of overlying and underlying beds. Thicknesses indicated at the left of Figure 3, represent distances above the lowermost bed exposed in the quarry which was sampled. A covered interval of 70 feet occurs between the two sampled portions. Stratigraphically higher layers are shown in Figure 3 in the higher parts of the column.

The gross lithology of the rock is indicated in the columnar section in Figure 3. Short horizontal lines to the left of the column show the stratigraphic positions of the samples which were taken in the field.

Chemical data are plotted to the right of the columnar section. Points along the graph show the per cent of non-ignited acid insoluble residue (N.A.I.R.) for the individual samples.
Brackets enclose portions of the column from which samples were combined for X-ray analyses for silica, alumina, ferric oxide and calcium oxide, and for wet chemical analyses of magnesium oxide, sulfur and phosphorus.

The variable chemical character of the Pleasant Hill rock sequence at Pleasant Hill Church is illustrated in Figure 3 by the graph of per cent N.A.I.R. The diagram shows that the same general variability persists in both the lower 40 feet and upper 40 feet of the rock.

As is shown in Figure 3 and in Table III, the upper 40-foot interval is relatively pure limestone and contains on the average 1.7 per cent SiO₂, 2.1 per cent Al₂O₃, 0.3 per cent Fe₂O₃, 2.6 per cent MgO and 49.7 per cent CaO. The limestone of the lower 40-foot interval is less pure.

According to Wilson (1952), the Pleasant Hill beds exposed at Pleasant Hill Church resemble lithologically the upper, relatively pure, 190-foot thickness of Pleasant Hill beds exposed in a section near Williamsburg, Pennsylvania. Chemical analysis of samples from the Williamsburg section would add useful information about the quality of the upper part of the Pleasant Hill formation.

COMMERCIAL POSSIBILITIES OF THE PLEASANT HILL LIMESTONE

The upper beds of the sampled portion of the Pleasant Hill limestone, extending from 110 feet to 148 feet (Figure 3), are suitable for use as metallurgical flux stone, for manufacture of high calcium agricultural lime and for manufacture of Portland cement, for which shale could be obtained from nearby exposures of the Reedsville formation.

The lower beds of the Pleasant Hill limestone, which extend from zero to 40 feet (Figure 3), contain somewhat higher percentages of silica, alumina and iron and are marginal for use as flux stone, but would qualify for manufacture of Portland cement and agricultural lime.

Because of limited exposures of the Pleasant Hill beds, further investigation by diamond drilling will be needed for evaluation of commercial possibilities.

CHEMICAL CHARACTERISTICS OF THE ORE HILL MEMBER OF THE GATESBURG FORMATION

Chemical characteristics of the limestone facies of the Ore Hill member at Ore Hill, Pennsylvania, and of the dolomite facies of the Ore Hill member at Birmingham, Pennsylvania, are shown in Figure 4 which is similar in design to Figure 3.

In the Birmingham section (Figure 4), the two uppermost samples represent the basal part of the upper Ore Hill dolomite as defined by Wilson (1952), and both contain more than ten per cent N.A.I.R. In sharp contrast, samples from Unit II are characterized by low percentages of N.A.I.R. A second marked change in percentage of N.A.I.R. occurs at about minus 60 feet at the contact between Unit I and Unit II; the average per cent N.A.I.R. increases there from 1.5 per cent in the lower part of Unit II to 5.8 per cent in the upper part of Unit I. Unit I extends downward to minus 130 feet where it grades into the underlying finely-crystalline dolomite which is marked at the top by a thin zone of chert nodules, one to two inches in maximum diameter.

More complete composite chemical analyses of the Ore Hill member at Birmingham, shown to the right of the N.A.I.R. graph in Figure 4 as well as in Table IV, indicate the dolomitic character of the entire rock sequence. The lower 30 feet of Unit II, which contains 0.9 per cent SiO₂, 0.4 per cent Al₂O₃, 0.3 per cent Fe₂O₃, 32.2 per cent CaO and 21.4 per cent MgO, is chemically the purest portion. The upper 30 feet of Unit II shows an increase in impurities to 1.6 per cent SiO₂, 0.8 per cent Al₂O₃ and 0.4 per cent Fe₂O₃.

<table>
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<th>Thickness intervals above lowermost exposed bed in quarry</th>
<th>SiO₂ (per cent)</th>
<th>Al₂O₃ (per cent)</th>
<th>Fe₂O₃ (per cent)</th>
<th>CaO (per cent)</th>
<th>MgO (per cent)</th>
<th>S (per cent)</th>
<th>P₂O₅ (per cent)</th>
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<td>150 to 110 feet</td>
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<td>Concealed interval</td>
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<tr>
<td>40 to Zero feet</td>
<td>2.59</td>
<td>2.74</td>
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<td>47.92</td>
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<tr>
<td>Zero to 150 feet (Average)</td>
<td>2.16</td>
<td>2.42</td>
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<td>48.83</td>
<td>2.68</td>
<td>0.75</td>
<td>&lt;0.020</td>
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</table>
Unit I shows a marked increase in percentage of impurities and a slight decrease in CaO in comparison with Unit II. The average chemical composition of Unit I is SiO₂ 3.2 per cent, Al₂O₃ 1.2 per cent, Fe₂O₃ 0.5 per cent, CaO 30.3 per cent, and MgO 20.4 per cent.

Average determinations, weighted by thickness, of the Ore Hill member at Birmingham are listed in Table IV and show that Unit II contains 1.2 per cent SiO₂, 0.6 per cent Al₂O₃, 0.4 per cent Fe₂O₃, 32.2 per cent CaO and 21.1 per cent MgO. In contrast to the low-impurity beds of the Ore Hill member at the Birmingham section, preliminary analyses of samples from the Ore Hill member at Ore Hill, Pennsylvania, show an average of 7.99 per cent N.A.I.R. for 40 feet of exposure. The high N.A.I.R. values do not justify complete chemical analysis of the rock exposed there.

According to Wilson (1952), exposures of the Ore Hill member at Ore Hill, correlate with lower beds of the Ore Hill at Birmingham, but, as indicated by question marks in Figure 4, exact relations between the two sections shown are not yet firmly established.

COMMERCIAL POSSIBILITIES OF THE ORE HILL MEMBER OF THE GATESBURG FORMATION

The dolomite beds of Unit II, as defined at the Birmingham section, might be considered for metallurgical flux stone and for manufacture of agricultural lime where a high magnesium content is desired. If selectively quarried, the lower 30 feet of Unit II could qualify for the manufacture of a special lime to be used in bottle glass, as well as for manufacture of magnesium lime which would be acceptable for soil stabilization and for structural purposes.

The dolomite beds of Unit I contain larger percentages of impurities and separately would be useful only for high magnesian agricultural lime. However, Unit I and Unit II combined together might have commercial potential as blast furnace flux.

The upper Ore Hill dolomite sampled at Birmingham and the limestone beds sampled at Ore Hill have no commercial chemical use at the present time.

In future investigation of the Ore Hill member, sampling and analysis should be undertaken of limestone beds in southern Blair County that are considered to be lateral equivalents of the dolomite beds of Unit II.

PART II. THE LOWER ORDOVICIAN LARKE DOLOMITE AND STONEHENGE LIMESTONE

STRATIGRAPHY AND OCCURRENCE

The Larke dolomite was named by Butts (1918) from 250 feet of "thick-beded, coarse, steely-blue dolomite" exposed near Larke, three miles south of Williamsburg, Blair County, Pennsylvania. According to Butts (1945), the absence of chert in the Larke dolomite distinguishes it from the Mines dolomite below and the Nittany dolomite above.

The Stonehenge limestone was named by Stose (1909) from exposures near the village of Stonehenge two miles east of Chambersburg, Franklin County, Pennsylvania. Stose divided the Stonehenge at the type locality into an upper 225 feet of light to dark gray limestone containing sandy laminae and numerous beds of edge-wise conglomerate, and a lower 260 feet of dark to very light gray massive limestone characterized by Ophiolela complanata and other fossils.

Butts (1945) considered the Stonehenge to be Ordovician, and younger than the Larke,

| TABLE IV |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Chemical Analyses of the Ore Hill Member of the Gatesburg Formation as Sampled at Birmingham, Pennsylvania |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
|                  | Suso | Al₂O₃ | Fe₂O₃ | CaO  | MgO  | S   | P₂O₅ |
| UNIT II          |      |      |      |      |      |     |      |
| Zero feet to -30 feet | 1.60 | 0.85 | 0.41 | 32.17 | 20.90 | 0.013 | 0.014 |
| -30 feet to -60 feet | 0.87 | 0.36 | 0.31 | 32.17 | 21.40 | 0.012 | Trace |
| UNIT I           |      |      |      |      |      |     |      |
| -60 feet to -128 feet | 3.20 | 1.16 | 0.53 | 30.30 | 20.40 | 0.017 | 0.020 |
| Weighted average: |      |      |      |      |      |     |      |
| Zero feet to -128 feet | 2.22 | 0.88 | 0.45 | 31.24 | 20.78 | 0.014 | <0.020 |

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**MINGHAM, PENNSYLVANIA**

**DOLomite FACIES**

**ANALYSES**

<table>
<thead>
<tr>
<th>% N.A.I.R.</th>
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<th>15</th>
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</table>

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<th>X-RAY FLUORESCENCE</th>
<th>WET CHEMICAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>Al₂O₃</td>
</tr>
<tr>
<td>%</td>
<td>%</td>
</tr>
</tbody>
</table>

1. 60  0.65  0.41  32.17  20.90

2. 0.87  0.36  0.31  32.17  21.40

3. 3.20  1.16  0.53  30.30  20.40

shaly laminae

hy crystalline laminae

hy crystalline nodules

**JRG FORMATION AS SAMPLED AT ORE**

**FIGURE 1.**

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FIGURE 5: DISTRIBUTION OF STONEHENGE LIMESTONE (Oa) AND LARKE DOLOMITE (Olw) IN BLAIR COUNTY AND PARTS OF CENTRE COUNTY, PENNSYLVANIA. SAMPLED LOCALITIES ARE MARKED BY CIRCLED NUMERALS. AREAL GEOLOGY AFTER BUTTS (1945) AND BUTTS ET AL. (1939).
which he considered to be uppermost Cambrian in age.

Contrary to the views of Butts and previous workers, Prouty (1954) suggested that the two formations are equivalent in age and are facies of each other because (1) the Larke and Stonehenge formations occur in the same stratigraphic position, (2) they do not both occur in the same areas, (3) numerous beds of edgewise conglomerate occur in both formations, and (4) the Larke contains dolomitized “ghosts” of sedimentary structures. Donaldson (1959) divided the calcitic Stonehenge facies of the Bellefonte area in Centre County, Pennsylvania, into five lithologic members and, with the aid of paleontologic evidence, traced the members southwestward into the dolomitic Larke facies, and thus provided substantial proof for the age equivalency of the two formations.

Both Prouty and Donaldson conclude that although the Larke and Stonehenge formations are age equivalents, they constitute lithologically different rock bodies and should be mapped separately.

In their respective areas, the Stonehenge and Larke formations each occur below the Nittany dolomite, and above the Mines dolomite, as follows:

**LOWER ORDOVICIAN**

Axemann limestone, 150 feet, thin-bedded, moderately fossiliferous.
Nittany dolomite, 100 feet, thick-bedded, in part cherty.
Stonehenge limestone, 400 feet of limestone north of the Little Juniata River; Larke dolomite, 250 feet of dolomite south of the Little Juniata River.

**UPPER CAMBRIAN**

Mines dolomite, 250 feet, with beds of oolitic chert.
Gatesburg dolomite, 1750 feet, with numerous sandy beds in part.

The surface distribution of rocks of the Larke and Stonehenge formations in parts of Blair and Centre Counties is shown in Figure 5, after areal geologic maps published by Butts (1939, 1945). In general, the outcrop patterns of the Larke and Stonehenge formations trend northeast to southwest and occur in the central portions of subordinate anticlines within the Nittany arch. (See Butts, 1939, 1945, for structural details.) Numerous faults truncate the formations, giving the outcrop patterns a discontinuous appearance.

Structure section A-A' (Figure 6) is drawn through the Roaring Spring locality. Samples from the upper 80 feet of exposed Larke beds were found to contain low percentages of N.A.I.R. The Larke dolomite is represented in Figure 6 by a pattern of triple-lines which extend diagonally between the top and bottom of the bed. The Larke crops out near the crest of an anticline which is overturned slightly toward the northwest; the angle of dip on the northwestern side of the anticline is very steep compared to the dip on the southeastern side. If the Larke dolomite were to be exploited in the Roaring Spring area, consideration should be given to the attitude of the beds as well as to a more detailed
plan of sampling and chemical analysis than is given in this paper.

**SAMPLING AND ANALYSIS**

Samples for preliminary commercial evaluation of the Larke dolomite were taken from exposures at Williamsburg and near Roaring Spring, in Blair County. Beds of the uppermost 70 feet of the Larke dolomite were sampled at the eastern edge of Williamsburg, part way up the hill along an unmarked road that leads from Williamsburg to Huntingdon. Sampling extended from the lowermost exposure along the road to the base of the overlying Nittany dolomite, which is in gradational contact with the Larke. Beds of the lowermost 180 feet of the Larke were sampled at an exposure about one mile south of Roaring Spring on the eastern side of the road leading from Roaring Spring to Ore Hill. The section was sampled upward from a six-inch cherty bed which, according to Donaldson (1959), marks the base of the Larke.

The Stonehenge limestone was sampled at a well-exposed outcrop located about three-fourths of a mile northwest of Birmingham on the northern side of the Little Juniata River and Highway 350. The exposure is almost directly north of the mouth of Honest Hollow. At the Birmingham section the Stonehenge beds are intricately folded. The lower 170 feet were sampled upward from a six-inch chert layer which marks the top of the Mines dolomite at that locality.

Locations of the Birmingham, Williamsburg and Roaring Spring localities are designated by circled numerals 1, 2, and 3, respectively, in Figure 5.

Samples from all three localities were taken at a stratigraphic interval of two feet where possible. The samples were analyzed according to procedures described in Part III of this report.

**CHEMICAL CHARACTERISTICS**

Chemical characteristics of sampled portions of the Larke dolomite and Stonehenge limestone in Blair and Centre Counties are summarized in Figure 7. Stratigraphic thicknesses are shown to the left of the columns, and represent distances above the base of the formation. The datum at the top of Figure 7 represents the top of the Larke and Stonehenge formations. It is placed in the indicated position on the basis of thicknesses reported by Butts (1945) for the Larke exposures, and the thickness of the Stonehenge measured by the writer at the Birmingham section.

The rock types shown in the geologic columns in Figure 7 are explained in the legend. Sample positions are indicated to the left of the columns by short horizontal lines. Each point on the N.A.I.R. percentage graphs, at the right of the geologic columns, corresponds to a sample position at the left of the columns. The bracket to the right of the N.A.I.R. graph for the Roaring Spring section encloses Unit II, the portion of the section that was combined into a composite sample for analysis.

The sampled portion of the Larke dolomite at Roaring Spring is divisible into two units on the basis of lithologic as well as chemical characteristics. Unit I extends from zero feet to 100 feet above the base of the formation and contains numerous types of dolomite, among the most prominent of which are edgewise conglomerates, cross-laminated dolomites, and massive, coarsely-crystalline dolomites. Unit II extends from 100 feet to 180 feet above the base and is composed of coarsely crystalline, medium gray dolomite in one-foot beds which contain an abundance of dolomite-filled vugs and are cut by numerous dolomite-filled fractures.

Of the two units, Unit II is the purer chemically. It contains an average of 3.4 percent N.A.I.R., and is shown by X-ray fluorescence analysis to contain 3.2 percent SiO₂, 0.5 percent Al₂O₃, 0.3 percent Fe₂O₃, and 30.9 percent CaO, and by wet chemical analyses to contain 21.1 percent MgO, 0.013 percent sulfur and 0.017 percent P₂O₅. Unit I contains an average of 15.3 percent N.A.I.R. and therefore was not analysed in more detail.

In contrast to the low percentages of N.A.I.R. in samples from Unit II at Roaring Spring, samples from the uppermost 70 feet of the Larke dolomite exposed at Williamsburg contain an average of 7.3 percent N.A.I.R., and hence were not further analysed.

Samples from the lowermost 170 feet of Stonehenge limestone exposed at Birmingham contain an average of 12.9 percent N.A.I.R., and the general appearance of the N.A.I.R. graph seems similar to the graph for Unit I at Roaring Spring.

In general, the upper part of the sampled portion of the Larke is purer chemically than
FIGURE 7: CHEMICAL AND LITHOLOGIC CHARACTERISTICS OF LARKE DOLOMITE AND STONEHENGE LIMESTONE IN ROARING SPRING, WILLIAMSBURG AND BIRMINGHAM, PENNSYLVANIA. SAMPLED LOCALITIES ARE LOCATED BY CIRCLED FIGURE 5.
the lower part. It is possible, however, that the low percentages of N.A.I.R. in samples from Unit II at Roaring Spring are not representative of the upper part of the Larke and Stonehenge formations in other areas, because the abundance of secondary dolomite-filled fractures could have reduced the original percentage of N.A.I.R. in the samples. If this is the case, perhaps the slightly higher N.A.I.R. percentages from the uppermost 70 feet of Larke at Williamsburg are more truly representative of the upper part of the Larke.

On the other hand, Unit II, with its low N.A.I.R. percentage, may be laterally continuous into other areas. If this is the case, perhaps the stratigraphically higher beds exposed at Williamsburg should be considered as Unit III, a higher unit above Unit II at Roaring Spring. Because the upper beds of the Stonehenge limestone were not sampled at Birmingham and are unexposed at Williamsburg, a solution to this problem, which has an important bearing on whether the Larke-Stonehenge beds are commercially useful, is not provided in the present report. Further sampling and analysis of the upper beds of the Larke-Stonehenge within the area might provide more conclusive evidence.

COMMERCIAL POSSIBILITIES

The dolomites of Unit II at the Roaring Spring exposure of the Larke formation could be used commercially for manufacture of agricultural lime and perhaps should be considered for blast furnace flux. Calculation of available tonnages of the low-impurity dolomites of Unit II depend in part on whether the dolomite-filled fractures persist into the areas surrounding the Roaring Spring locality.

The intensely fractured dolomites of Unit II in the Larke at Roaring Spring may be a local occurrence, and exploration in central Pennsylvania for other occurrences of low-impurity dolomite at the stratigraphic position of Unit II might be futile or costly.

The high percentages of N.A.I.R. in other sampled portions of the Larke dolomite and Stonehenge limestone render those parts unsatisfactory for commercial chemical use.

PART III. METHODS OF ANALYSIS
INTRODUCTION

Analyses were performed in two stages. In the first stage, a portion of each sample was analysed for percentage of insoluble residue by the method described by Thompson (1958), in which the residue is not ignited. Determinations by this method are listed as non-ignited acid insoluble residue (N.A.I.R.) in place of acid insoluble residue (A.I.) which implies ignited residues. In the second stage of analysis, sequences of samples containing low percentages of N.A.I.R. were combined into composite samples which in turn were analysed for SiO₂, Al₂O₃, Fe₂O₃ and CaO by X-ray fluorescence and for MgO by wet chemical analysis, according to procedures described below.

X-RAY FLUORESCENCE ANALYSIS

Standard samples for calibration of the X-ray method were selected from previously analysed Cambro-Ordovician limestones and dolomites of central Pennsylvania so that the approximate range in percentage of each constituent in the rock sequence was represented. The standard samples, as well as the unknown samples, were crushed in a jaw crusher to chips about one-fourth of an inch in maximum dimension. The chips were mixed thoroughly, ground to minus 250 mesh in a disc mill, and mixed again. Portions of the samples to be analysed by X-ray fluorescence were packed in plastic slide holders. Sample preparations and packings were made by a single operator.

The X-ray counts for all determined elements were made on a General Electric XRD-5 X-ray spectrometer. Each X-ray count reported represents an average of two consecutive readings, minus the background count. Each count for alumina, iron and calcium was taken over a period of 40 seconds, whereas silica was counted for 100 seconds. Machine settings used for obtaining the X-ray counts of each element are shown in Table V.

In addition to replicates of the X-ray analyses, each standard sample was analysed twice by wet chemical methods to provide a basis for consideration of error in the wet chemical determinations.

CALIBRATION CURVES AND ESTIMATION OF CHEMICAL VALUES

Several statistical procedures can be applied for calculation of calibration curves for X-ray
TABLE V
Machine settings of the X-ray fluorescence spectrometer used in analyses of SiO₂, Al₂O₃, Fe₂O₃ and CaO.

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<thead>
<tr>
<th></th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>Fe₂O₃</th>
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<td>LiF</td>
</tr>
<tr>
<td>Peak angle</td>
<td>108°</td>
<td>142.6°</td>
<td>57.5°</td>
<td>113.15°</td>
</tr>
<tr>
<td>Background angle</td>
<td>104°</td>
<td>136.6°</td>
<td>50.5°</td>
<td>108.15°</td>
</tr>
</tbody>
</table>

fluorescence data. Of these, the method of least squares, described by Dixon and Massey (1951), and the method of grouping, described by Bartlett (1949), appear to be the most useful. The most commonly employed of the two procedures is the method of least squares which is designed for the determination of linear regression curves of the type \( Y = a + bx \). This procedure is appropriate where values of the independent variable (X) are assumed to be measured without error. In the present work, both the chemical analyses and the X-ray counts are subject to error in measurement and the calculation of the calibration lines by the method of least squares is inappropriate, unless one can demonstrate that

![Calibration Curves](image)

**FIGURE 8: CALIBRATION CURVES FOR Al₂O₃, Fe₂O₃, CaO AND SiO₂.**
the error in the chemical analyses is negligible in comparison to the error involved in the X-ray counts. The grouping method for calculation of linear regression lines, as described by Bartlett (1949), considers both variables to be subject to error in measurement.

For comparative purposes, the calibration lines used in the present report were calculated by both the method of least squares and the method of grouping. Lines determined by the two methods for each analysed constituent are shown in Figure 8 where lines determined by the grouping method are solid, and lines determined by the method of least squares are dashed. Where the two lines coincide at the scale of the diagrams, as is true in most cases, only the solid line is recorded. Formulae for the lines are recorded in Table VI.

The formulae calculated by the grouping method of Bartlett (1949) were used for estimating the percentages of each unknown constituent in the unknown samples. Percentages were estimated by substituting the determined X-ray counts for Y in the formula, and solving for X.

The calibration curves generally are reproducible if run on the same day; it is desirable to redetermine the calibration curves if samples are to be analysed on different days.

Precision

The precision of determining the calibration curves, and therefore of estimating unknown values from the curves, ultimately depends on the precision with which the standard samples were analysed by both wet chemical methods and by X-ray fluorescence. A representation of the precision involved in these determinations is shown in Figure 8. Points representing the X-ray and wet chemical analyses of the standard samples are indicated by larger dots. Smaller dots along horizontal or vertical lines through the larger dots indicate the precision with which the determinations were made. Where smaller dots are absent, analyses were reported with such precision that smaller dots representing replicate analyses would fall within the diameter of the larger dots. Perusal of Figure 8 shows that in most cases the error involved in both methods of analysis is negligible, except for analyses of the higher alumina values shown in Figure 8A.

Calculation of the precision of the estimation of unknown values from the calibration curves presents another problem. In general, linear regression analysis is designed for predicting a dependent Y value from an independent X value. More commonly, however, we wish to predict in the reverse direction, which in terms of the present work means that we wish to predict the percentage of chemical constituent (X value) from a specific number of X-ray counts (Y value). The variance involved in the procedure is derived by Bennett and Franklin (1954, pp. 231-2). It also is possible to calculate confidence limits around the predicted X value by using Student’s “t” test as described by Bennett and Franklin (1954, pp. 228-30). The confidence limits calculated by this method are unique for each predicted value and can not be used in defining the error in predicting other values. Bennett and Franklin show that the confidence limits for the predicted X values become larger with increasing departure from the mean value of X.

In order to obtain an approximation of the error involved in the estimation of SiO₂, Fe₂O₃, Al₂O₃, and CaO by X-ray fluorescence analysis, confidence limits were calculated at the 95 percent level of probability for three predicted values of each constituent. Inasmuch as the confidence limits theoretically increase toward the extremities of the calibration curve, an attempt was made to select one predicted value from the lower extremity of each calibration curve, one from near the middle of the curve and one from the upper extremity of the curve. These confidence intervals suggest an order of magnitude for confidence limits around values predicted from other parts of the curves.
The confidence limits at the 95 percent level of probability for three estimated values of each constituent determined by X-ray fluorescence are shown in Table VII. The confidence limits indicate that for a method of rapid quantitative analysis, percentages of Fe₂O₃ and SiO₂ are measured with fairly good precision, whereas the estimates of Al₂O₃ and CaO are less satisfactory.

Inasmuch as the CaO values show the largest confidence intervals, six unknown samples were analysed for CaO by both wet chemical procedures and by X-ray fluorescence in order to compare the results of the two methods. The comparison of these analyses is shown in Table VIII. Only in the case of sample No. 2 does the gravimetric wet chemical analysis (29.5 percent) fall outside the confidence limits placed around the X-ray value (31.6 percent). Lack of agreement may result partly from the fact that the upper linear counting limit of the X-ray counter was inadvertently exceeded in the CaO determinations.

**TABLE VIII**
Comparison of CaO determinations made by X-ray fluorescence and gravimetric wet chemical analyses.

<table>
<thead>
<tr>
<th>Sample</th>
<th>% CaO, X-ray fluorescence</th>
<th>% CaO, gravimetric wet chemical</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>31.0</td>
<td>29.5</td>
</tr>
<tr>
<td>2</td>
<td>31.6</td>
<td>29.5</td>
</tr>
<tr>
<td>3</td>
<td>31.1</td>
<td>29.0</td>
</tr>
<tr>
<td>4</td>
<td>49.8</td>
<td>49.8</td>
</tr>
<tr>
<td>5</td>
<td>50.5</td>
<td>50.6</td>
</tr>
<tr>
<td>6</td>
<td>30.4</td>
<td>29.6</td>
</tr>
</tbody>
</table>

In summary, the precision of the X-ray analyses reported herein is fairly good for Fe₂O₃, Al₂O₃, and SiO₂, but is less satisfactory for CaO. The precision of the analyses might be improved by (1) greater care in the homogenization and packing of samples, (2) using a longer counting time or a fixed number of counts for most of the X-ray determinations, (3) using a larger number of samples and more replications of analyses in establishing the calibration curves, and (4) using internal standards. However, any of these modifications would increase the time of analysis. According to the present analytical procedures, about 30 unknown samples can easily be analysed for SiO₂, Al₂O₃, Fe₂O₃, and CaO in less than four normal working days, including the preparation of the samples. Excluding the initial investment for the X-ray spectrometer, a single sample can be analysed for these four constituents for less than three dollars per sample, as compared to more than 40 dollars per sample and a considerably longer period of time for analysis by conventional wet chemical methods.

**WET CHEMICAL ANALYSES**

A rapid wet chemical method for the determination of MgO was developed by A. M. Bystrom from methods described by Shapiro and Brannock (1956) and by Patton and Reeder (1956). A sample is ignited and washed into a beaker, evaporated to dryness, baked, and then dissolved in hydrochloric acid. The acid insoluble portion is recovered by filtration, and the solution is filtered directly into a volumetric

**TABLE VII**
Confidence limits at the 95 percent level of probability around values estimated by X-ray fluorescence analysis.

<table>
<thead>
<tr>
<th>X-ray Counts (Y)</th>
<th>Lower Limit</th>
<th>% Chemical Constituent (X)</th>
<th>Upper Limit</th>
<th>X-ray Counts (Y)</th>
<th>Lower Limit</th>
<th>% Chemical Constituent (X)</th>
<th>Upper Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>161</td>
<td>1.67</td>
<td>2.16</td>
<td>2.65</td>
<td>319</td>
<td>3.73</td>
<td>4.18</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>58</td>
<td>0.00</td>
<td>0.12</td>
<td>1.01</td>
<td>66</td>
<td>0.04</td>
<td>0.58</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>417</td>
<td>0.00</td>
<td>0.15</td>
<td>0.34</td>
<td>1359</td>
<td>0.21</td>
<td>0.40</td>
</tr>
<tr>
<td>CaO</td>
<td>71017</td>
<td>26.42</td>
<td>28.60</td>
<td>30.78</td>
<td>124398</td>
<td>46.15</td>
<td>47.90</td>
</tr>
</tbody>
</table>
flask. Ammonia is added to the volumetric flask to precipitate iron and alumina from the solution, and MgO is determined colorimetrically by the method of Patton and Reeder (1956).

Replicate analyses of MgO in a limestone sample by the above-described method provided the results tabulated in Table IX.

<table>
<thead>
<tr>
<th>Sample</th>
<th>MgO %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>2.4</td>
</tr>
<tr>
<td>1b</td>
<td>2.8</td>
</tr>
<tr>
<td>1c</td>
<td>2.7</td>
</tr>
<tr>
<td>1d</td>
<td>2.7</td>
</tr>
</tbody>
</table>

ACKNOWLEDGMENTS

The writer wishes to thank Dr. F. M. Swartz, who supervised the work, and Dr. E. G. Williams, who critically reviewed parts of the manuscript. Dr. A. C. Donaldson aided in the location of some of the exposures, and W. B. Wigginton assisted in sampling. The X-ray fluorescence analyses were performed by Mrs. C. Malloy, and the MgO analyses by Dr. A. M. Bystrom. Analyses for sulfur and phosphorus were made by Martha Bailey under the direction of C. O. Ingamells.

REFERENCES

Bartlett, M. S. (1949), "Fitting a straight line when both variables are subject to error," Biometrics, Vol. 5, pp. 207-212.


THE APPLICATION OF STATISTICAL METHODS IN PROSPECTING FOR HIGH-ALUMINA CLAY

by
E. G. Williams and J. C. Griffiths

INTRODUCTION

In a recent study in Western Pennsylvania, Williams (1960) found certain, consistent relationships between the stratigraphy of Pottsville sandstones (basal Pennsylvanian) and the occurrence of associated high-alumina clays. The important stratigraphic relationship, shown in figure 1, is that high-alumina clay occurs only in areas where the Upper Connoquenessing sandstone is absent. The important, qualitative, petrographic relations are that in clay-bearing areas as compared to barren areas, the upper five feet of the Lower Connoquenessing sandstone contains larger amounts of quartz and rounded tourmaline. Williams postulated that the occurrence of high-alumina clay was controlled by the development of topographic highs during late Lower Connoquenessing time.

The purpose of this paper is to refine and further develop petrographic criteria for locating topographic highs and related high-alumina clay deposits. Because the clays are of main concern here, the terms “clay bearing” and “non-clay bearing” will be used to delimit the sampling areas or populations.

Twenty four samples were obtained from the upper five feet of the Lower Connoquenessing sandstone (see fig. 1 for stratigraphic position of samples.) Twelve samples from seven localities were obtained in clay-bearing areas, and twelve from eight localities in the non-clay bearing areas. The samples were disaggregated by repeated heating and quenching in water. The size, shape and roundness of twenty grains per sample of both quartz and tourmaline were measured. The degree to which these variables were effective in classifying an area as clay or non-clay bearing was determined by statistical analysis, using Student’s “t” test for differences between means and discriminant functions for multi-variable comparisons.

METHODS OF ANALYSIS

All measurements were made on loose grains mounted on thermoplastic rods and projected on a screen. Rods were used in order to obtain the
TABLE 1
Analysis of Variance for Tourmaline Roundness

<table>
<thead>
<tr>
<th>Source of Variation</th>
<th>Degrees of Freedom</th>
<th>Sum of Squares</th>
<th>Mean Square</th>
<th>Variance Ratio (F)</th>
<th>Variance Components</th>
<th>Variance Components X 10^6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Populations</td>
<td>1</td>
<td>0.70</td>
<td>0.700</td>
<td>9.33*</td>
<td>0.01042</td>
<td>10.42</td>
</tr>
<tr>
<td>Samples of Populations</td>
<td>4</td>
<td>0.30</td>
<td>0.075</td>
<td>7.50*</td>
<td>0.00345</td>
<td>3.45</td>
</tr>
<tr>
<td>Rods of Samples</td>
<td>6</td>
<td>0.06</td>
<td>0.010</td>
<td>1.33</td>
<td>0.00025</td>
<td>0.25</td>
</tr>
<tr>
<td>Groups of Grains on Rods</td>
<td>12</td>
<td>0.09</td>
<td>0.008</td>
<td>0.58</td>
<td>-0.00112</td>
<td>-1.121</td>
</tr>
<tr>
<td>Grains of Groups</td>
<td>96</td>
<td>1.26</td>
<td>0.013</td>
<td></td>
<td>0.01310</td>
<td>13.10</td>
</tr>
</tbody>
</table>

1Negative values are indicative of zero contributions.

TABLE 2
Analysis of Variance for "a" Axis of Quartz

<table>
<thead>
<tr>
<th>Source of Variation</th>
<th>Degrees of Freedom</th>
<th>Sum of Squares</th>
<th>Mean Square</th>
<th>Variance Ratio (F)</th>
<th>Variance Components</th>
<th>Variance Components X 10^6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Populations</td>
<td>1</td>
<td>4.4491</td>
<td>4.4491</td>
<td>7.229</td>
<td>0.062</td>
<td>6.20</td>
</tr>
<tr>
<td>Samples of Populations</td>
<td>4</td>
<td>2.4614</td>
<td>0.6154</td>
<td>0.849</td>
<td>-0.0055</td>
<td>-0.55</td>
</tr>
<tr>
<td>Rods of Samples</td>
<td>6</td>
<td>4.3486</td>
<td>0.7248</td>
<td>3.67*</td>
<td>0.0528</td>
<td>5.28</td>
</tr>
<tr>
<td>Groups of Grains on Rods</td>
<td>12</td>
<td>2.3657</td>
<td>0.1971</td>
<td>0.895</td>
<td>-0.0046</td>
<td>-0.46</td>
</tr>
<tr>
<td>Grains of Groups</td>
<td>96</td>
<td>21.1439</td>
<td>0.2202</td>
<td></td>
<td>0.2202</td>
<td>22.02</td>
</tr>
</tbody>
</table>

*Significant at 5% level.

maximum and minimum projection areas. (Hulbe, 1955).

Five measurements were made on each grain; the long axis (a = X_l); the intermediate axis (b = X_i); the short axis (c = X_s); perimeter (X_p) and roundness (X_r). The axes are measured in millimeters by techniques discussed by Griffiths (1959), and converted to phi units according to the transformation, $e = 2^{-9}$, (Krumbein, 1938). Roundness is estimated by visual comparison charts, (Krumbein, 1941).

In order to evaluate the sources of sampling variation, which would be useful in planning future experiments, a hierarchical or nested sampling design was used. Each sample of tourmaline and quartz was split into sub-samples of 30 to 50 grains which were then mounted on rods. Two groups of five grains each were randomly selected from each rod. A total of 240 quartz and 240 tourmaline grains were obtained from each of the two populations, making a grand total of 980 grains.

The efficiency of the nested sampling design for the "a" axis of quartz and the roundness of tourmaline was tested by components of variance analysis (Snedecor, 1956). Three samples were randomly selected from each population. The analyses, tables 1 and 2, show that for both measurements the components of variance are largest at the population and grain levels. This would suggest that the subsampling into rods and groups could be eliminated without loss of information. In performing the discriminant analysis, it is legitimate to combine all samples within populations, since the sample component of variance is small.

ANALYSIS OF DATA

General Statement—The principle problem is to determine quantitatively which attribute or group of attributes of the sandstone are useful in distinguishing clay bearing areas from barren ones. Summary statistics for all measured variables are given in table 3. Two statistical tests are utilized in evaluating the usefulness of the variables; Student's "t" and the discriminant function. The former tests the significance of mean differences of a single variable, whereas the latter tests the degree to which all the variables are discriminating between the two populations.

Tests of Mean Differences—Table 4 shows the
TABLE 3
Size, Shape and Roundness of Quartz and Tourmaline

<table>
<thead>
<tr>
<th>Population</th>
<th>Mineral</th>
<th>Axis</th>
<th>X</th>
<th>s²</th>
<th>s</th>
<th>√b₁</th>
<th>bₙ</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay</td>
<td>Quartz</td>
<td>a</td>
<td>1.445</td>
<td>0.276344</td>
<td>0.525</td>
<td>0.150</td>
<td>3.000</td>
<td>240</td>
</tr>
<tr>
<td></td>
<td></td>
<td>b</td>
<td>1.821</td>
<td>0.249777</td>
<td>0.500</td>
<td>0.230</td>
<td>3.032</td>
<td>240</td>
</tr>
<tr>
<td></td>
<td></td>
<td>c</td>
<td>2.182</td>
<td>0.277951</td>
<td>0.527</td>
<td>0.210</td>
<td>2.911</td>
<td>240</td>
</tr>
<tr>
<td>Non-clay</td>
<td>Quartz</td>
<td>a</td>
<td>1.638</td>
<td>0.234404</td>
<td>0.484</td>
<td>0.031</td>
<td>2.616</td>
<td>240</td>
</tr>
<tr>
<td></td>
<td></td>
<td>b</td>
<td>2.016</td>
<td>0.247980</td>
<td>0.498</td>
<td>0.033</td>
<td>3.513</td>
<td>240</td>
</tr>
<tr>
<td></td>
<td></td>
<td>c</td>
<td>2.366</td>
<td>0.249095</td>
<td>0.499</td>
<td>0.049</td>
<td>3.125</td>
<td>240</td>
</tr>
<tr>
<td>Clay</td>
<td>Tourmaline</td>
<td>a</td>
<td>1.903</td>
<td>0.177711</td>
<td>0.422</td>
<td>0.252*</td>
<td>3.111</td>
<td>240</td>
</tr>
<tr>
<td></td>
<td></td>
<td>b</td>
<td>2.346</td>
<td>0.150650</td>
<td>0.388</td>
<td>0.114</td>
<td>2.853</td>
<td>240</td>
</tr>
<tr>
<td></td>
<td></td>
<td>c</td>
<td>2.680</td>
<td>0.160700</td>
<td>0.401</td>
<td>0.432**</td>
<td>3.326</td>
<td>240</td>
</tr>
<tr>
<td>Non-clay</td>
<td>Tourmaline</td>
<td>a</td>
<td>1.920</td>
<td>0.116986</td>
<td>0.342</td>
<td>0.140</td>
<td>3.183</td>
<td>240</td>
</tr>
<tr>
<td></td>
<td></td>
<td>b</td>
<td>2.338</td>
<td>0.110589</td>
<td>0.333</td>
<td>0.118</td>
<td>3.214</td>
<td>240</td>
</tr>
<tr>
<td></td>
<td></td>
<td>c</td>
<td>2.689</td>
<td>0.156505</td>
<td>0.396</td>
<td>0.319*</td>
<td>3.292</td>
<td>240</td>
</tr>
<tr>
<td>Clay</td>
<td>Quartz</td>
<td>R</td>
<td>0.299</td>
<td>0.009999</td>
<td>0.100</td>
<td>0.392**</td>
<td>2.862</td>
<td>240</td>
</tr>
<tr>
<td>Non-clay</td>
<td></td>
<td>R</td>
<td>0.265</td>
<td>0.010787</td>
<td>0.104</td>
<td>0.390*</td>
<td>2.660</td>
<td>240</td>
</tr>
<tr>
<td>Clay</td>
<td>Tourmaline</td>
<td>R</td>
<td>0.470</td>
<td>0.018549</td>
<td>0.136</td>
<td>0.095</td>
<td>3.079</td>
<td>240</td>
</tr>
<tr>
<td>Non-clay</td>
<td></td>
<td>R</td>
<td>0.342</td>
<td>0.011854</td>
<td>0.109</td>
<td>0.658**</td>
<td>5.047**</td>
<td>240</td>
</tr>
</tbody>
</table>

*Significant at the 5% level
**Significant at the 1% level
X = Arithmetic mean
√b₁ = Skewness (asymmetry)
s = Standard deviation
bₙ = Kurtosis (peakedness)
n = Number of grains

t = Student’s t = difference of means
standard error of difference

TABLE 4
Significance Tests for Means and Variances

<table>
<thead>
<tr>
<th></th>
<th>Clay</th>
<th>Non-Clay</th>
<th>F</th>
<th>t</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz &quot;a&quot; axis</td>
<td>1.445 0.525 1.638 0.484</td>
<td>1.18NS 4.20**</td>
<td>240</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quartz Roundness</td>
<td>0.299 0.100 0.265 0.104</td>
<td>1.08NS 3.62**</td>
<td>240</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tourmaline Roundness</td>
<td>0.470 0.136 0.342 0.109</td>
<td>1.56** 3.66**</td>
<td>240</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tourmaline &quot;a&quot; axis</td>
<td>1.903 0.422 1.920 0.342</td>
<td>1.52** 0.49NS</td>
<td>240</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

TABLE 5
Confidence Limits and Divide Points

<table>
<thead>
<tr>
<th></th>
<th>X</th>
<th>95% Conf. Limits</th>
<th>Divide Pt.</th>
<th>No. Grains</th>
<th>No. Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lower</td>
<td>Upper</td>
<td>Divide Pt.</td>
<td>No. Grains</td>
<td>No. Samples</td>
</tr>
<tr>
<td>Quartz &quot;a&quot; axis</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clay</td>
<td>1.445</td>
<td>1.231 1.677</td>
<td>1.50</td>
<td>20</td>
<td>12</td>
</tr>
<tr>
<td>Non-Clay</td>
<td>1.638</td>
<td>1.423 1.853</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quartz Roundness</td>
<td>0.299</td>
<td>0.255 0.343</td>
<td>0.28</td>
<td>20</td>
<td>12</td>
</tr>
<tr>
<td>Non-Clay</td>
<td>0.265</td>
<td>0.219 0.301</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tourmaline Roundness</td>
<td>0.470</td>
<td>0.410 0.530</td>
<td>0.40</td>
<td>20</td>
<td>12</td>
</tr>
<tr>
<td>Non-Clay</td>
<td>0.342</td>
<td>0.294 0.390</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

31
results of the significance tests of mean difference for the "a" axis (long axis) and roundness of both quartz and tourmaline: only the "a" axis of tourmaline is not significant. The variance ratio (F) is significant for tourmaline roundness, which indicates that the comparison of means is not completely valid. However, by changing the sampling plan to include more samples and fewer grains per sample (12 samples and 20 grains per sample) the variance can be made more homogeneous and the "t" test of means can then be used.

Table 5 gives the 95% confidence limits and divide points (intersection of two distributions) for the statistically significant variables. The confidence intervals have been calculated using 20 grains per sample. For tourmaline roundness, the confidence limits do not overlap the divide point, whereas there is considerable overlap for quartz "a" axis and roundness. It would appear therefore that if it is desirable to attempt to distinguish clay areas from barren ones on the basis of single variables, tourmaline roundness offers the best possibility.

DISCRIMINANT ANALYSIS OF QUARTZ GRAIN MEASUREMENTS

240 grains from each of the two environments were measured and the sums of squares and products were calculated by computer. The 5 x 5 covariance matrix augmented by the mean differences was inverted to find the discriminant equation:

\[ Z = 0.103X_1 + 0.114X_2 + 0.009X_3 + 0.048X_4 - 0.083X_5 \]

where Z is the discriminating index and X_1 to X_5 represent the three axes, the perimeter and the roundness respectively of the quartz grains. This equation was tested for significance by analysis of variance (Fisher, 1948) in Table 6.

| TABLE 6 |
| Analysis of Variance Test of Discriminant Index for Quartz Grain Measurements |
| Source of Variation | Degrees of Freedom | Sum of Squares | Mean Square | Variance Ratio (F) |
| Discriminant | 5 | 225.743 | 45.149 | 704.9** |
| Residual Error | 234 | 14.257 | 0.064 |
| Total | 239 | 240.00 |

It is quite obvious that the equation will discriminate between the two environments. We may now test whether all the measurements are necessary and, as it was suspected that X_5 and X_4 were not playing an important role, these were isolated by computing the discriminant for X_5, X_1, and X_2 in that order. The extended test is shown in Table 7.

| TABLE 7 |
| Analysis of Variance Testing the Additional Contribution of X_5, X_1, X_2 to the Discriminating Equation |
| Source of Variation | Degrees of Freedom | Sum of Squares | Mean Square | Variance Ratio (F) |
| Discriminant X_5 | 5 | 225.743 | 45.149 | 704.9** |
| Discriminant X_5, X_1 | 3 | 225.720 | 75.240 | 1175.6** |
| Discriminant X_5, X_1, X_2 | 2 | 0.023 | 0.0115 | <1 |
| Residual | 234 | 14.257 | 0.064 |
| Total | 239 | 240.00 |

Since the mean square for X_5, X_1 is less than that for the residual mean square these two variates are not contributing effectively to discrimination.

We may also ask whether X_5 is contributing effectively to the remaining three variates (X_5, X_1, X_2) and this test is performed in Table 8.

| TABLE 8 |
| Test to Determine Whether X_5 is Contributing to the Discriminant Using Only X_1 and X_2 |
| Source of Variation | Degrees of Freedom | Sum of Squares | Mean Square | Variance Ratio (F) |
| Discriminant X_5, X_1 | 3 | 225.720 | 75.240 | 250.80** |
| Discriminant X_5, X_1, X_2 | 2 | 219.577 | 109.788 | 3659.6** |
| Diff. X_5 | 1 | 6.143 | 6.143 | 204.77** |
| Residual | 476 | 14.280 | 0.030 |
| Total | 479 | 240.00 |

From this test it can be seen that X_5 (roundness) and X_1 (long "a" axis in phi units) are the major contributors and that X_2 (the intermediate "b" axis in phi units) is contributing a significant extra amount to the discriminant.

The contributions may also be estimated from the magnitude of the multiple correlation coefficient (R^2) as follows:

\[ R^2 = 0.9405 \]

although X_2 is contributing a significant additional amount, it could be omitted without serious loss.

The discrimination equation of the three variates is:

\[ Z = -0.083X_5 + 0.108X_1 + 0.084X_2 \]

and this would be the most informative equation for use with quartz grain measurements.
Using only the first two measurements the equation becomes:

\[ Z = 0.182X_1 - 0.083X_5 \]

**Discriminant Analysis of Tourmaline Grain Measurements**

Following the same program for the measurements on tourmaline yields the equation:

\[ Z = 2.437X_1 - 1.585X_2 - 0.367X_3 + 2.175X_4 + 17.814X_5 \]

The accompanying analysis of variance is illustrated in table 9.

**TABLE 9**

<table>
<thead>
<tr>
<th>Source of Variation</th>
<th>Degrees of Freedom</th>
<th>Sum of Squares</th>
<th>Mean Square</th>
<th>Variance Ratio (F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discriminant</td>
<td>X₁,X₂</td>
<td>230.5891</td>
<td>47.9178</td>
<td>552.7**</td>
</tr>
<tr>
<td>Residual</td>
<td>474</td>
<td>0.4109</td>
<td>0.0867</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>479</td>
<td>240.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

When the variables \( X_3, X_4 \) are omitted the amount accounted for by the discriminant increases slightly; upon testing \( X_3 \) and \( X_1 \) in this order it is found that \( X_2 \) is the sole contributor and the equation using roundness \( (X_3) \) of tourmaline is adequate to perform the discrimination and the addition of axial measures or perimeter is pointless. The equation is:

\[ Z = 17.387X_3 \]

In practice either two measures on quartz (roundness and long "a" axis) or a single measure of roundness of tourmaline is adequate to separate the two populations. It is a matter of convenience which of the two is used. If tourmaline is selected then the discriminant reduces to a simple "r" test among the means. (see table 4).

**APPLICATION OF TECHNIQUES**

**General Statement**

The successful application of the techniques presented here for clay prospecting depends upon three geological factors; 1) the degree of association between high-alumina clay and topographic highs (or the criteria used in defining the latter if the existence of such features is doubted); 2) the degree of association between absence of clay and the absence of topographic highs, and 3) the degree to which the samples analyzed represent the upper five feet of the Lower Connoquenessing sandstone in all clay and non-clay bearing areas.

The third assumption is believed to be fulfilled because the samples were obtained from all known, important high alumina clay areas and adjacent barren areas in western Pennsylvania. Williams (1960) found that the association in factor (2) was invariant, that is, high alumina clay was never found in areas where topographic highs or their defining criteria were absent. The association in factor (1) was not invariant, that is, high-alumina clay did not occur everywhere (or blanket) the topographic highs. Therefore, Williams argued that topographic highs were a necessary but not entirely sufficient condition for the formation of the clay. Thus the discriminant equations can only predict "potentially favorable" areas for the occurrence of clay.

**Discriminant Analysis**

The discriminant equations provide a means for distinguishing between "potentially favorable" and unfavorable areas for the occurrence of high-alumina Mercer clay. This is done by first substituting the population means of all significantly contributing variables into the appropriate discriminant equations. The variables for quartz are the "a" and "b" axes and roundness and for tourmaline, the roundness. The values obtained ("Z" indices) are those most characteristic of the two populations. The "Z" index which best separates the two populations (clay vs. non-clay) is obtained by substituting the mean of the combined populations into the appropriate discriminant equation. The several "Z" values for quartz and tourmaline are shown in table 10. Thus, a sample or samples whose "Z" index for quartz is less than 3.666 will be classified as occurring in an area "potentially favorable" for the occurrence of high-alumina clay, whereas those greater than 3.666 will be classified as occurring in a barren area. A similar procedure could be used with tourmaline. However, it is suggested that analyses of the mean roundness of tourmaline would be a simpler procedure. (see table 4).

**TABLE 10**

<table>
<thead>
<tr>
<th>Characteristic &quot;Z&quot; Indices for Quartz and Tourmaline in Clay and Non-Clay Bearing Areas</th>
<th>TOURMALINE</th>
<th>QUARTZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z</td>
<td>Z x 12*</td>
<td>Z</td>
</tr>
<tr>
<td>Clay Area</td>
<td>0.284</td>
<td>3.425</td>
</tr>
<tr>
<td>Combined</td>
<td>0.304</td>
<td>3.666</td>
</tr>
<tr>
<td>Non-Clay Area</td>
<td>0.324</td>
<td>3.907</td>
</tr>
</tbody>
</table>

*Z value obtained by making X₁ (roundness) equal to unity.

**Sampling**

For exploration procedures, the sampling
and measurement techniques do not need to be as complex as those employed here. Because the components of variance at all sampling levels, (except grains) were relatively low, no sub-sampling is necessary. About 20 representative (random) grains from each hand specimen would be sufficient. Furthermore, mounting the grains on plastic rods is unnecessary, since all significant variables can be measured on the maximum projection areas (rods are used to obtain the minimum projection area). The grains can be sprinkled on glass slides and measurements made under the petrographic microscope.

Since both quartz and tourmaline will discriminate equally well, the analytical procedure depends upon the time available and the desired precision: Obviously, the use of both minerals would give the greatest reliability of classification. The use of quartz alone would involve less time because it doesn’t have to be concentrated as does tourmaline.

In prospecting for high-alumina Mercer clay using the previously discussed techniques, samples should be obtained from the upper five feet of the Lower Conomoquenessing sandstone, which can easily be recognized by its color and mineral composition (Williams, 1960). If quartz is used, measurements of the critical variables are made for each sample and the means substituted in the discriminant equations. The samples can then be classified by the resulting "Z" index. If samples from a relatively large number of localities are obtained, then "Z" values can be plotted on a map and contoured. Areas enclosed by the critical "Z" value (3.666) would then be ones "potentially favorable" for the occurrence of high-alumina clay.

If tourmaline is used, the mean roundness is computed and plotted directly on the map. The map is then contoured and areas in which the roundness is greater than 0.40 would be classified as potentially favorable for the occurrence of the high-alumina clay.

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REFERENCES


