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THE LITHOSTRATIGRAPHY OF THE BRASSFIELD FORMATION (LOWER SILURIAN) IN THE CINCINNATI ARCH AREA

A dissertation submitted to

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DOCTOR OF PHILOSOPHY

1967

by

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I hereby recommend that the thesis prepared under my supervision by Edward O'Donnell

entitled The Lithostratigraphy of the Brassfield Formation (Lower Silurian) in the Cincinnati Arch Area

be accepted as fulfilling this part of the requirements for the degree of Doctor of Philosophy

Approved by:

Form 668—Grad. School—1M—8-64

CONTENTS

ABSTRACT

The Brassfield Formation is a time transgressive unit of Middle to Late Llandovery age (B_1?-C_3). It is recognized in Ohio, Indiana, Kentucky, Tennessee, and Arkansas and is correlative with the Sexton Creek Limestone and Kankakee Dolomite of the Illinois Basin, Tuscarora Formation of the Appalachian Basin, and the Medina Group and the lower part of the Clinton Group of New York.

This study is focused on the Cincinnati Arch Area, that is, southwestern Ohio, southeastern Indiana, and central Kentucky and it is primarily a lithostratigraphic study with the intention of attempting to reconstruct the paleogeography of that area in Early Silurian time. Forty-six sections were measured around the Cincinnati Arch. Samples were collected and analyzed as to their dolomite content, insoluble residues, mineralogy, and fabric.

As an outgrowth of this study the following units of the Brassfield are recognized:

(1) Belfast Member

(2) Lower massive Member

(3) Upper thin bedded Member

(4) Noland Member

Within these members five microfacies are recognized:

I Crinoid-bryozoan biosparite

II Biogenic dolomite

III Medium crystalline dolomite

IV Hematitic-biosparite

V Dolomitic biomicrite

Microfacies I and IV appear to indicate high energy environments although in ecologic details they are different and microfacies V presumably indicates a low energy environment. Microfacies II probably represents both high and low energy conditions which suggests that dolomitization was independent of lithologic control. Recrystallization has been so extensive in microfacies III that it is impossible to speculate on the energy of the environment.

Conodont and brachiopod evidence indicates that the Brassfield was deposited first in central Kentucky, and as time progressed the Brassfield was later deposited in southwestern Ohio and southeastern Indiana. It appears that initially water conditions in central Kentucky, and the southern part of southwestern Ohio were relatively deep, and probably represent the lower limits of the photic zone. Chert and glauconite were formed in what were probably the deepest water sediments. Brassfield waters were probably never deep in the northern portion of southwestern Ohio and southeastern Indiana and probably represent a shallow water high energy environment. Gradually the sea became shallower in east central Kentucky and probably retreated from southern Ohio and southern Indiana, resulting in a change of facies in central Kentucky and in a disconformity between the

Brassfield and Dayton Formations in Ohio. Deposition was more or less continuous in east central Kentucky and the Dayton Formation is considered to be correlative with the Waco Dolomite tongue of the Brassfield. The hematite-rich beds seem to have formed at this time when sea level was low in what was probably a shallow water, near shore environment.

There is no evidence for the existance of the Cincinnati Arch in Early Silurian time. The lithology and thickness of the Brassfield is apparently unrelated to the present Arch. Anomalies such as a higher clastic percent on the east side of the present Arch can better be explained as the result of proximity to source area rather than the Arch acting as a barrier to sedimentation.

As an outgrowth of this study the following nomenclature changes are proposed:

(1) The Brassfield "limestone" of Foerste (1906) be recognized as the Brassfield Formation.

(2) The Crab Orchard "group" of Foerste (1935) is better evaluated as the Crab Orchard Formation.

(3) The names Alger Formation, Indian Fields Formation, and Estill Shale of the Crab Orchard "group" are highly local expressions and little is gained by continuing to employ these designations regionally.

(4) The Noland "Formation" of the Crab Orchard "group" is best evaluated as a member within the Brassfield Formation.

INTRODUCTION

Statement of Purpose

This investigation of the Brassfield Formation has as its principal goal the study of the lithostratigraphy with the intention of attempting to reconstruct the paleogeography of southwestern Ohio, southeastern Indiana, and central Kentucky during Early Silurian (Llandovery) time. To do this it was necessary to:

(1) Decipher the lithofacies relationships of the Brassfield Formation and to relate them to faunal zones of this area as established by Berry and Boucot (manuscript in preparation) and by Rexroad (1967, in press).

(2) Relate where possible the Brassfield to the sediments of the Appalachian, Michigan, and Illinois Basins.

As an outgrowth of this study, a nomenclatural change is proposed. The Brassfield is redefined to encompass the Noland "Formation" of Rexroad _et al_ (1965). The Noland is reduced from formation rank in the Crab Orchard Group to member rank in the Brassfield Formation, and the Crab Orchard "Group" is reduced to formation rank.

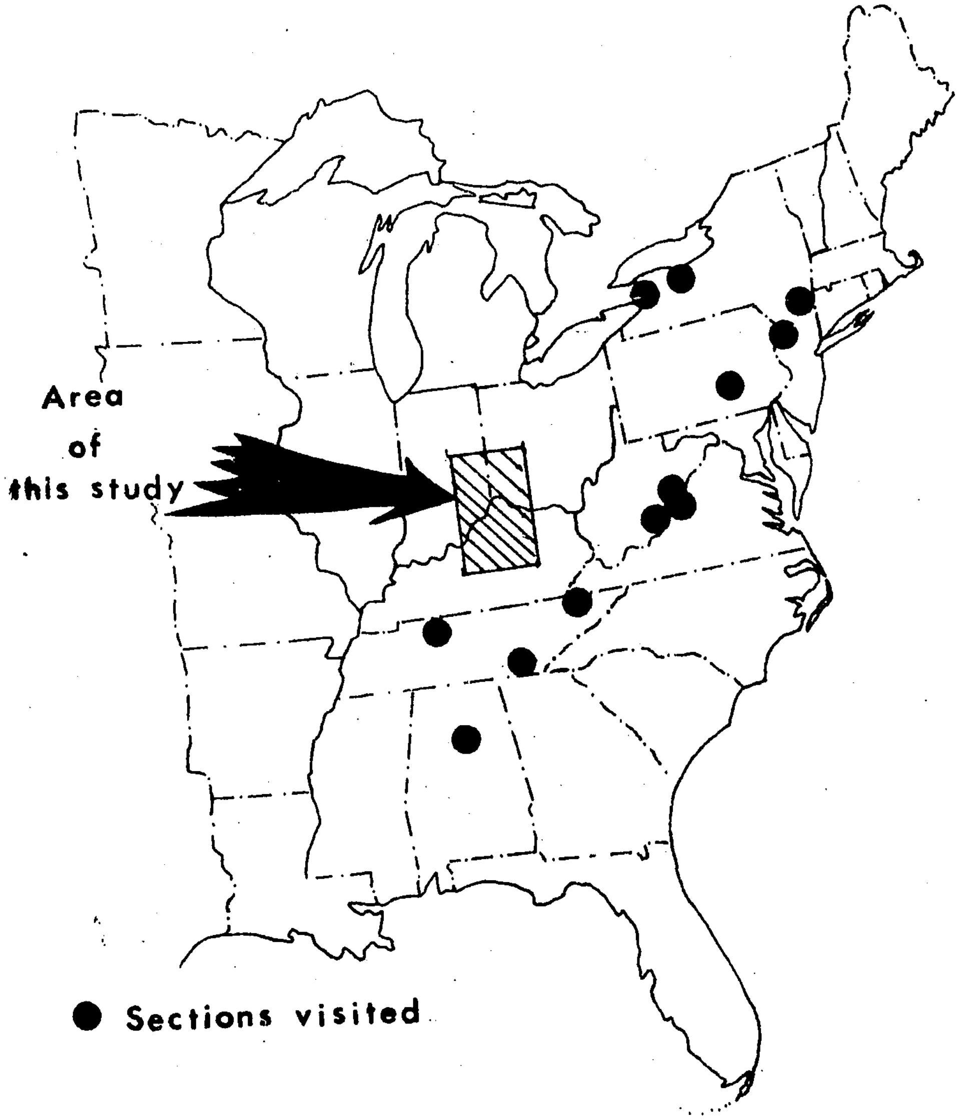


Fig. 1

Acknowledgements

Thanks go to all the people who have helped in this thesis. Among them are Dr. Hans J. Hofmann of the Canadian Geological Survey who originally suggested a problem and under whose direction the work was initiated. Dr. Wayne A. Pryor of the University served as a subsequent advisor and supervised the completion of the problem. Drs. Kenneth E. Caster, Warren D. Huff, William F. Jenks, Frank L. Koucky, Leonard Larsen, and John Warren of the University of Cincinnati read the manuscript and offered many helpful suggestions. I also benefited from conversations in the field with Messers Roy Kepferle, John Peck, Warren Peterson, George Simmons, and Gordon Weir, all of the United States Geological Survey's Kentucky mapping program. Dr. Carl Rexroad of the Indiana Geological Survey generously discussed his work on the Brassfield and made available a copy of his unpublished manuscript on the "Stratigraphy and Conodont Paleontology of the Brassfield (Silurian) in the Cincinnati Arch Area". In a like manner Dr. Arthur J. Boucot of the California Institute of Technology made available an unpublished manuscript on the "Silurian of North America" by Berry and Boucot. Thanks also go to Mr. Philip A. Ziegler who helped much in this study as a field assistant, to Miss Duck Hee Lee who aided in the making of the thin sections, and to Mrs. Elizabeth K. Dalve who drafted figs. 3, 6, 7, 8, 9, 10, 37, 38, and 39, under the author's supervision. Field and travel expenses were provided by a grant from the Ohio Academy of Science and the Fenneman Fund of the University of Cincinnati. Finally I want to thank my parents Mr. and Mrs. Edward A. O'Donnell who made possible my college education.

Fig. 2. Structure contour map showing the location of the area of this study with respect to the principal structural units of Ohio and Indiana. Structure contours on top of the Trenton Group. Contour interval is 500 feet. (Modified from Green, 1957).

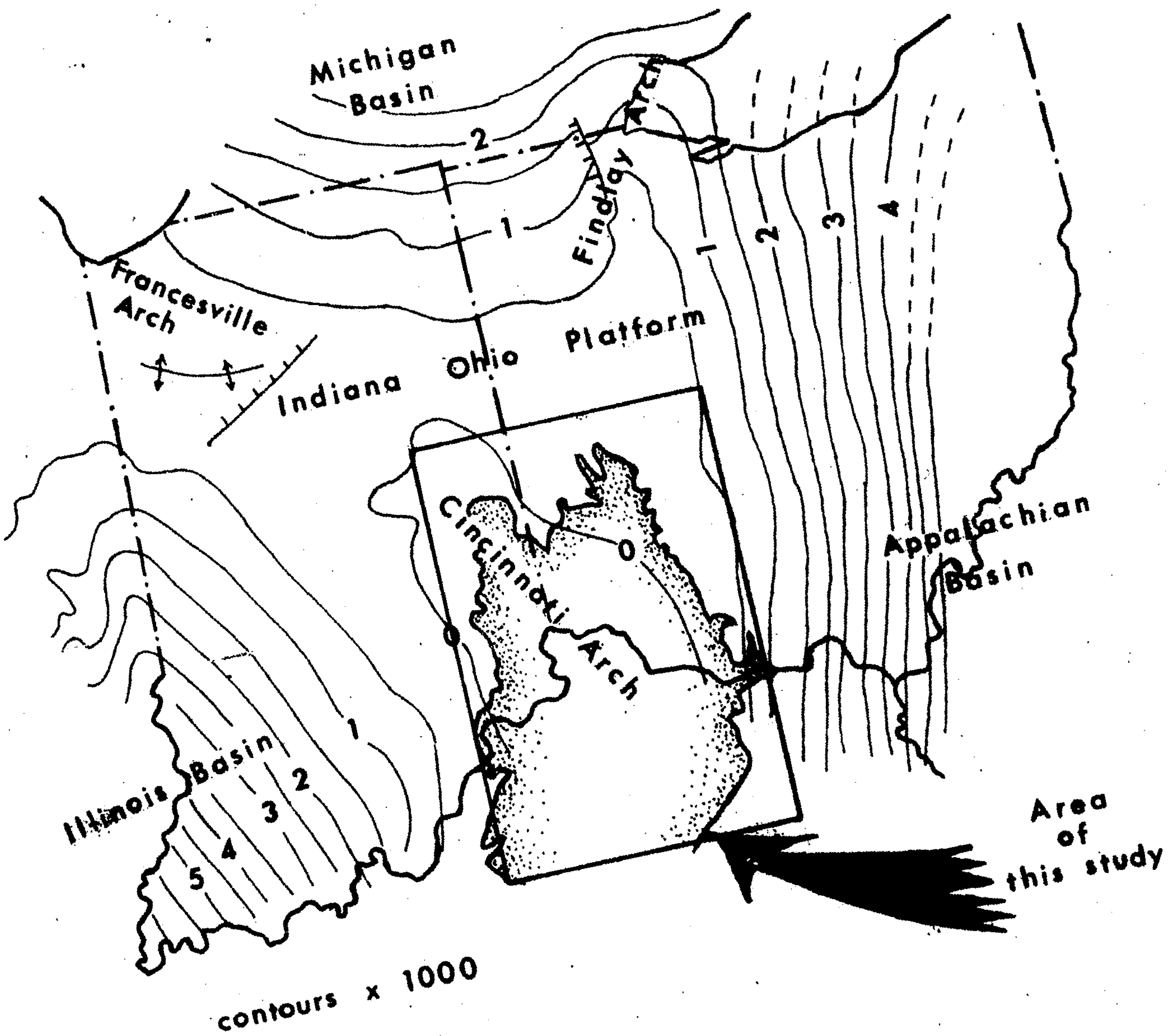

Michigan Basin
Findlay Arch
Francesville Arch
Indiana Ohio Platform
Cincinnati Arch
Appalachian Basin
Illinois Basin
Area of this study
contours x 1000
0
1
2
3
4
5

Fig. 2

Regional Structure

The Cincinnati Arch is the dominant regional structure in the area of this study (fig. 2). It is best described as a platform-like structure located between the Illinois, Michigan, and Appalachian Basins. Dip of the rocks is very slight. According to Green (1961, p. 184) in northeastern Indiana it is only $1/3^{\circ}$ toward the Michigan Basin; 175 miles to the southwest it is $1/3^{\circ}$ toward the Illinois Basin; and between these two areas there is no dip as high as $1/3^{\circ}$. Between Indianapolis, Indiana, and Columbus, Ohio, a distance of 160 miles, there is no dip as much as $1/4^{\circ}$. Although the Arch may have existed as a positive area and influenced sedimentation during some intervals of geologic time, there appears to be no evidence of its existence in Early Silurian time when the Brassfield Formation was deposited.

Method of Investigation

GENERAL STATEMENT: This study is based primarily on 46 sections measured around the Cincinnati Arch. The sections were carefully sampled. About 630 samples were collected and analyzed as outlined below (see fig. 4). Also, for purposes of comparison, classical Silurian exposures were visited in New York, New Jersey, Pennsylvania, West Virginia, Virginia, Tennessee, and Alabama (fig. 1).

MEASURED SECTIONS: Forty-six sections were measured around the Cincinnati Arch by means of a tape measure, hand level, meter stick, and Brunton Compass (fig. 3). Three of the sections, Tollesboro, Kentucky (Section 40), Jacksonville, Ohio (Section 42), and Loudon, Ohio (Section 43), were measured in part by hand level and then checked by photogrammetric means. This was done because of the inaccessability of the exposure. The sections studied are no more than 28 miles apart at the maximum (Sections 22-26) and no closer than a quarter mile at the minimum (Sections 14-15). The average distance between sections is approximately 15 miles. Where possible, sections with a good upper and lower contacts were chosen, but this was not possible in all cases.

SAMPLING: An average of fifteen samples of the Brassfield and underlying and overlying units were taken from each locality. They were carefully selected to

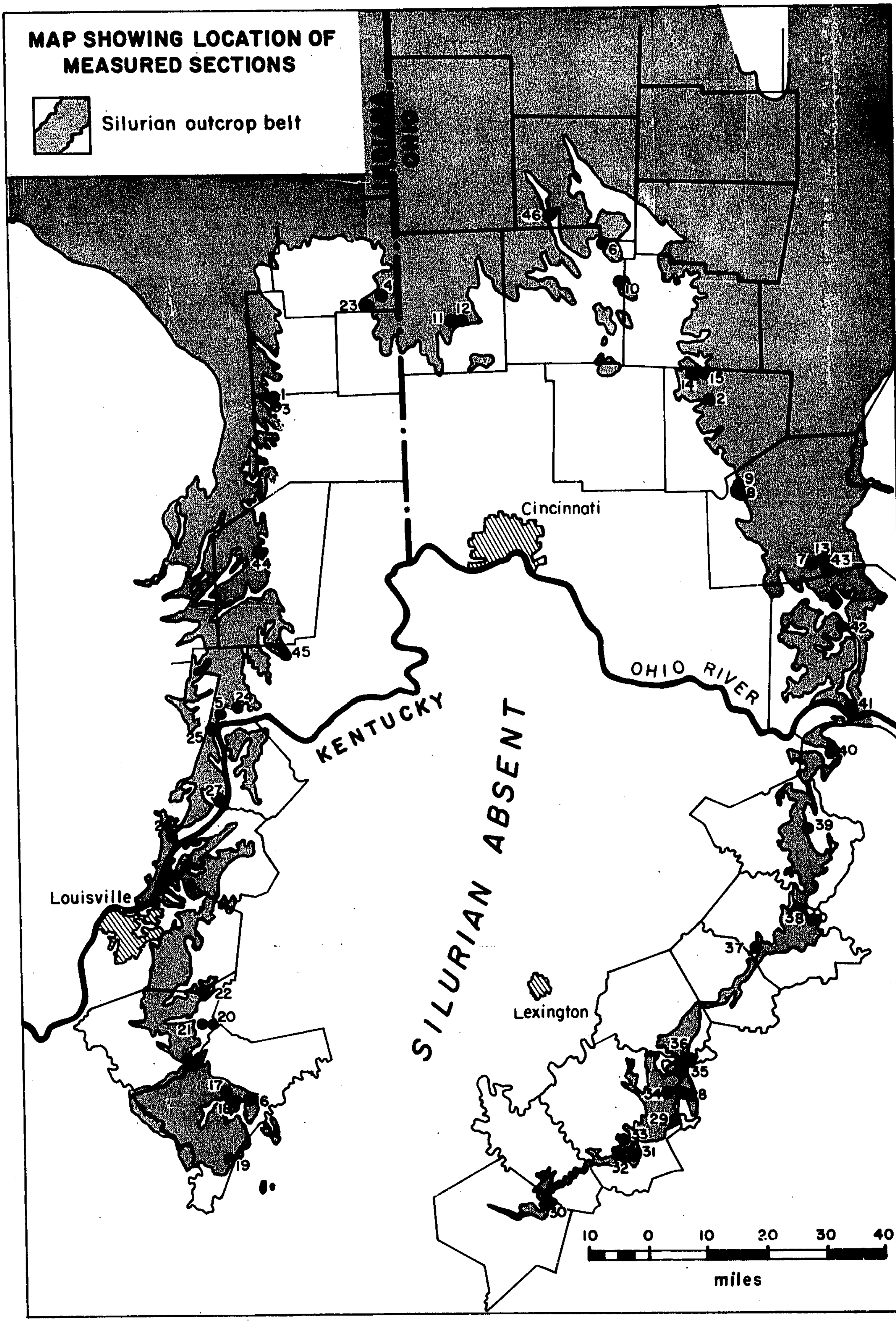

MAP SHOWING LOCATION OF MEASURED SECTIONS
Silurian outcrop belt
OHIO
Cincinnati
OHIO RIVER
KENTUCKY
SILURIAN ABSENT
Louisville
Lexington
10 0 10 20 30 40
miles

Fig. 3

represent each lithic unit and were spaced no more than one meter apart. The interval sampled was carefully described. The greatest number of samples was taken at stratigraphic boundaries, such as the break between the Upper Ordovician and the Brassfield, where the samples have been taken every 10 centimeters for the first half meter.

ACID TREATMENT: All samples were subjected to leaching by 0.5 normal hydrochloric acid. About 20 grams of material was used. Weighing of the sample before and after acid digestion was done on a Sartorius "Kilomat" balance which could be read accurately to the hundredth of a gram. The weight percent of insoluble material following acid digestion was calculated to two decimal points. Acid digestion was allowed to procede until the reaction of HCl and the carbonate ceased. The sample was washed three times with distilled water and then allowed to dry overnight at 70°C. It was hoped that the weight percent of insoluble material would serve as an index of rock purity.

About 50 select samples, weighing about 0.5 kg. each, were dissolved in 0.1 Normal acetic acid if they were limestone or 0.1 Normal HCl if they were dolomite. This was done to recover any insoluble material. Clay minerals were recovered after washing by decantation. Heavy minerals were removed by acetylene tetrabromide.

Processing of Samples

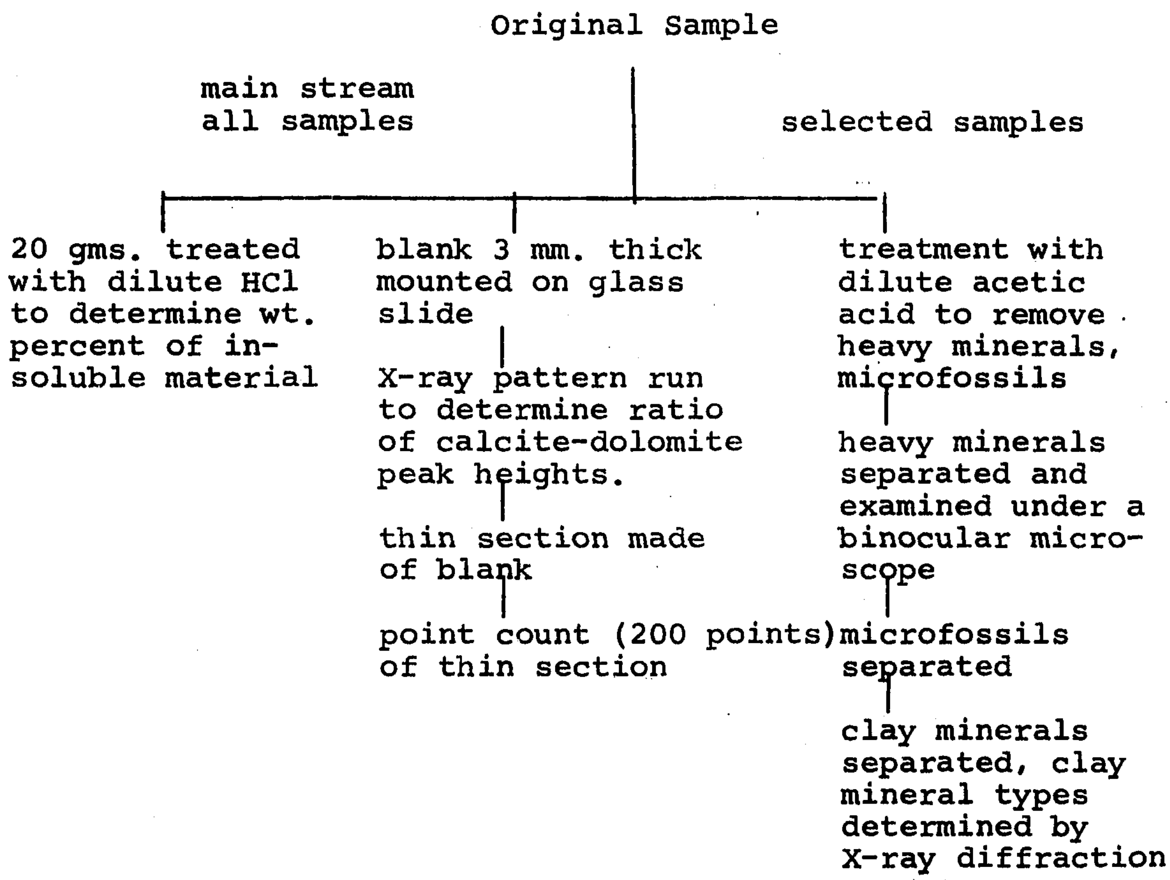


Fig. 4. Flow scheme for processing of samples.

X-RAY TREATMENT OF CARBONATES: Thin section blanks 3 mm. thick, polished with a #400 grit, were irradiated on a General Electric XRD-5 X-ray Diffraction unit, using Ni filtered Copper Kα radiation (λ = 1.5418 Å). A 3° medium resolution beam slit, medium resolution collimator, and a 0.1 inch detector slit scanning at 2° per minute constituted the geometric set up of the X-ray diffractometer. By using a medium resolution slit, better than 2/3 of the slide was exposed to the X-ray beam, thereby averaging-out its' effect. The samples were run from 25° 2θ to 32° 2θ to pick up the 3.34 Å quartz peak, the 3.03 Å calcite peak, and the 2.88 Å dolomite peak.

The method of calculating the percent of calcite and dolomite was based on the curve prepared by Tennant and Berger (1957, p. 26). The validity of this curve was checked by using artificially prepared powdered mixtures of calcite and dolomite mounted on glass slides, and the resulting curve was almost identical with Tennant and Berger's curve. Thin section blanks were used in the actual analyses of the dolomite content of the rocks for two reasons. One was a contamination problem from the grinding vessel, and the other more important problem was in securing a proper mixture of the ground rock powder. When the mixing was incomplete the results were not reproducible. Checking of weight losses in pre-weighed samples subjected to acid leaching (dilute acetic acid preferentially attacks calcite rather than dolomite) showed anomalous results. Frequently the X-ray data would indicate a variance of $\pm$ 20% from the percent dolomite indicated by the acid leaching. Therefore it was felt that the use of thin section blanks polished smooth would give semi-quantitative results. Cross-checking by selective acid leaching and point counts under the petrographic microscope has verified this.

X-RAY TREATMENT OF SHALES: The shale samples were soaked in beakers of distilled water for approximately 10 hours and were disaggregated with a Branson model S-75 ultrasonic sonifier for 2-3 minutes. The sonifier provided a source of high intensity ultrasonic energy which disintegrated the samples leaving a suspension of clay and silt sized material. After waiting 20 hours to allow the coarsest fraction to settle, the upper one centimeter of the suspension (4μ size or less) was removed by pipette and allowed to settle on a 27 x 46 mm glass slide which resulted in an oriented sample. The slide was then dried at room temperature.

The prepared slides were irradiated in the same manner as the thin section blanks, the only difference being that these samples were irradiated from a 2 θ of 2° to 2 θ = 28°. All of the significant clay mineral peaks, as well as those of many common impurities fall within this range. Identification of the clay minerals is based on the methods outlined in Warshaw and Roy (1961). Illite was identified on the basis of X-ray diffraction of their (ool) spacings with the first order peak at about 10 Å. The chlorites were identified by their 14 Å basal spacing. The 7 Å and 3.5 Å peaks which are common to both chlorite and kaolinite create a problem in their identification. To distinguish between them, acid treatment (warm HCl destroys chlorite), the presence of the third order chlorite peak (4.7 Å), and heat treatment (1 hour at 600° C destroys the kaolinite structure), were utilized.

THIN-SECTION ANALYSIS: About 450 thin sections were made, irradiated, and examined with the petrographic microscope. Each sample collected was thin sectioned except for a few soft clay shale samples. X-ray diffraction analysis, as outlined in the previous section, was to determine the calcite-dolomite content of the carbonates. Point counts were made for each thin section based on 200 counts per slide. For purposes of classifying Folk's Classification of Carbonate Rocks was used (Folk, 1962, p. 70). Each rock was subdivided into its allochemical and orthochemical components as follows:

Allochems
- intraclasts
- oölites
- pellets
- fossils

Orthochems
- sparry calcite
- microcrystalline calcite

Miscellaneous
- dolomite
- quartz
- rock fragments
- clay
- non-calcareous fossils
- pyrite
- glauconite

Recognition of allochems as opposed to orthochems usually presented little problem. With respect to allochems the Brassfield consists almost exclusively of intraclasts and fossil fragments. The term intraclast is used in the same sense as Folk uses it, that is, a transported coherent carbonate sediment derived from within the sedimentary basin. Recognizing fossils per se generally is not difficult. Subdividing them as to type is another problem however. The most readily recognizable ones fell into three groups: (1) crinoid plates and columnals, (2) bryozoa, (3) brachiopod and pelecypod shell fragments (see figs. 28-36). Examination of the acid insoluble residues shows the presence of sponge spicules, arenaceous foraminifera and conodonts. In no instance, do they comprise as much as 1% of the volume of a sample, which would explain their apparent absence from the thin sections.

Sparry calcite and micrite were differentiated on the basis of size and appearance. Fine crystalline calcite less than 4 microns in size, which commonly had a "murky" appearance, was classified as micrite. The larger, clear, crystalline calcite usually occurs as a pore filling cement and was referred to as spar or sparry calcite.

Crystal and grain dimensional parameters were measured for purposes of comparison and to establish the hydrodynamic regime in which the Brassfield was deposited. Maximum and median grain or crystal size was calculated by a micrometer eyepiece that had been calibrated against a special Leitz microscopic 2 mm. scale which had been divided into 200 parts. Median grain size was computed by measuring 11 consecutive grains or orthochems in recrystallized rocks. When arranged in order of magnitude the middle digit (the sixth one in this case) is the median. Admittedly this is a small statistical population but only semi-quantitative results were desired for comparative purposes. Textural maturity was estimated by a visual comparison of the thin sections with diagrams in Folk (1962, p. 76).

STRATIGRAPHY

Brassfield Formation

HISTORICAL BACKGROUND: The Brassfield Formation was named the Brassfield "limestone" by Foerste in 1906 (p. 10, 27). Historically it has been recognized as a distinctive lithologic body for over 130 years. The Brassfield approximates the "Flinty Limestone" of Locke (1838, p. 239) in Adams County, Ohio. Owen in 1857 was apparently the first to append the name Clinton to the oölitic iron ore bed and associated "limestones" (dolomites) capping the Cincinnatian Series in Kentucky. Orton (1871, p. 145) was the first to refer to the Brassfield as "Clinton" in Ohio. According to Cummings (1922, p. 445) the Brassfield was not generally recognized in Indiana as being distinct from the underlying or overlying rocks until Prof. A. H. Young sent a collection of fossils from the salmon colored limestone near Hanover, Indiana to Foerste suggesting that the fauna was of Clinton character. Foerste (1896) subsequently published a paper on the "Clinton" of Ohio and Indiana. S. A. Miller in 1892 (p. 611) stated that he was unable to find any evidence of the existence of the Clinton or Medina in Indiana. Foerste recognized very early that the Brassfield was not exactly equivalent to the New York Clinton. Foerste (1896, p. 189) wrote that:

> "...Although I have been accustomed to call the Ohio formation the Clinton, yet

> I should be willing to recognize the fact that the identity is not very marked, by giving it a name of its own, for instance, the Montgomery formation, on account of its typical development in Montgomery County in Ohio"...

However the name Montgomery was preoccupied and Foerste chose not to continue using it. Foerste (1904, p. 340) later said that:

> "...the Clinton of Ohio, Indiana, and Kentucky, appears to have attained the stage of development equivalent to the Clinton of New York, below the lenses, but does not contain such species as *Pentamerus oblongus*, *Atrypa reticularis*, *Spirifer radiatus*, *S. niagarensis*, which in the west begin their existence in The Osgood bed."

In 1906 Foerste (p. 10) proposed the name Brassfield Limestone for the beds along the Louisville and Atlantic Railroad cut between Brassfield and Panola in Madison County, east central Kentucky. Foerste (1906, p. 177) notes that this is "...the most carefully measured section in this vicinity." His description of it is as follows:

Black shale

Brownish rock belonging to the Duffin layer

appearing brecciated	1 ft. 6 in.
Devonian limestone, more brown than the underlying layer of limestone with a few fossils	4 ft.
Blue argillaceous Devonian limestone	1 ft. 6 in.
Lulbegrud clay	15 ft.
Thin layers of limestone	2 ft.
Oldham limestone, consisting of thicker layers with comparatively little clay intercalated. Stricklandinia occurs at top.	9 ft.
Elkins limestone interbedded with more clay.	3 ft. 4 in.
Plum Creek clay	3 ft. 3 in.
Thin clayey limestone interbedded with clay, also belonging to the Plum Creek horizon.	1 ft. 10 in.
Massive limestone with Whitfieldella. The top, for a distance of 6 to 9 inches is oölitic.	2 ft. 6 in.
More frequently bedded part of Brassfield limestone, with large crinoid beads at the top (Clinton).	12 ft. 3 in.
Very massive limestone at base of Brassfield limestone	6 ft.
Ordovician	

Foerste (1906, pp. 27-29) went on to say that:

"The lower part of the Brassfield limestone usually consists of one or several rather thick and massive appearing layers, while the middle and upper part consist of more numerous, thinner bedded layers, toward the top of the section these limestones ofen are interbedded with thin layers of clay...

The massive layers, at the base, usually are unfossiliferous, even on close examination. They do not weather to as deep a rusty-yellowish brown as the thinner layers of the Brassfield limestone. Frequently they have a more argillaceous appearance than the thinner layers, and their color, when freshly exposed is more bluish...It has been noticed that in some areas the total thickness of these massive layers seems to vary considerably, while the thickness of the entire Brassfield section, in the same area is fairly constant. In most cases only the lower part of the Brassfield limestone has a massive appearance, while in others almost the entire section has this massive character.

The overlying parts of the Brassfield limestone are too thin bedded and irregular to be of value for any purpose except crushed rock. In the lower part of the thin bedded section, the limestone layers are likely to be separated by thin layers of clay. In the upper part of the Brassfield section, these layers of clay are likely to be thicker, but not sufficiently to predominate over the limestones. Farther northward, from Montgomery County, in Kentucky, to Highland County, in Ohio, the relative quantity of clay in the upper part of the Brassfield section increases. Northwest of Highland County, however, clay occurs only at the very top of the Brassfield section, and at many localities is absent. It is the upper, thinner bedded part of the Brassfield limestone which is fossiliferous. Most of the fossils occur at the top of the section."

In the same paper Foerste (p. 35) commented on the relation of the formation to the New York Clinton:

"...The identification of the Brassfield limestone of Kentucky, and its northern extension in Ohio and Indiana, in former years, with the Clinton limestone of New York, rests rather upon a somewhat similar facies of the two faunas, and upon the general absence of the more

> typical species of the Rochester shale fauna of New York in these limestones at the base of the Silurian in Ohio, Indiana, and Kentucky, than upon the presence of any considerable number of species common to both areas. On closer inspection, the fauna of the Brassfield limestone of Ohio, Indiana, and Kentucky appears to differ sufficiently from the fauna of the Clinton limestone of New York to warrant the assumption of the presence of some sort of barrier between the two areas".

It was several years before Foerste's name "Brassfield" for the "Clinton" of Ohio, Indiana, and Kentucky, won general acceptance. Schuchert, (1910, p. 489), and Schuchert and Twenhofel (1910, pp. 704-710) referred to the Brassfield as the "Ohio Clinton" and stated that it was below the typical Clinton of New York and the name Clinton persisted in the Indiana Reports until 1916 (Culbertson, pp. 226-227).

Schuchert in 1913 (p. 107) proposed the name Cataract formation for a sequence of fossiliferous limestones, shales, and dolomites, in southern Ontario which had been called Clinton. According to Schuchert these rocks lay below the Medina Group of New York. Williams (1914, p. 40) stated that "...the Medina sandstones of Niagara Gorge

(125 feet thick) are represented farther north by dolomite and shale (Cataract formation)". Kindle (1914, p. 918) concurred with Williams, and he reported that "...Examination by the writer of a number of sections holding this (Cataract) fauna, in connection with a review of the Niagara section, has convinced him that all of the terranes associated with the Cataract fauna are represented in the Medina of the Niagara section".

Schuchert (1914, p. 294) amended his view regarding the stratigraphic position of the Cataract and conceded that: "...the typical Medina formation shades through lateral alteration into the typical Cataract." He also (*ibid*.) regarded "...the Medina, Cataract and Brassfield as correlates of one another", but he did not mean to imply that "...each one is wholly equivalent of any other. Each formation invades eastern North America from a different direction and each one has its own peculiar faunal assemblage".

THICKNESS AND AREAL DISTRIBUTION: The Brassfield is a wide spread stratigraphic unit and is recognized as such in Ohio, Indiana, Kentucky, Illinois, Tennessee, and Arkansas (Swartz *et al*., 1942). Around the Cincinnati Arch it crops out in an arcuate pattern (fig. 3). In the central and southern part of the map, which coincides with the Cincinnati Arch, Silurian rocks are absent because of post-Middle Silurian pre-Middle Devonian erosion. It is very likely that the Brassfield extended across the Arch. Remnants of it have been found in the central area at several places. Foerste (1935, p. 169) reported finding 15.5 feet of Brassfield on Scrubgrass Creek near Mitchellsburg, Kentucky. The top bed of this exposure, according to Foerste, contained "Stricklandinia triplesiana" (Microcardinalia triplesiana), and "undetermined species of Whitfieldella" (Cryptothyrella), and "...the large crinoid beads so characteristic of the top of the Brassfield all along the eastern side of the Cincinnati Anticline in Ohio and Kentucky". The Scrubgrass Creek occurrence of the Brassfield is by no means the only one in the central part of the Arch. Foerste (1935, p. 125) cites its presence also at Jeptha Knob, six miles southeast of Shelbyville, Kentucky but gives no details as to its thickness here.

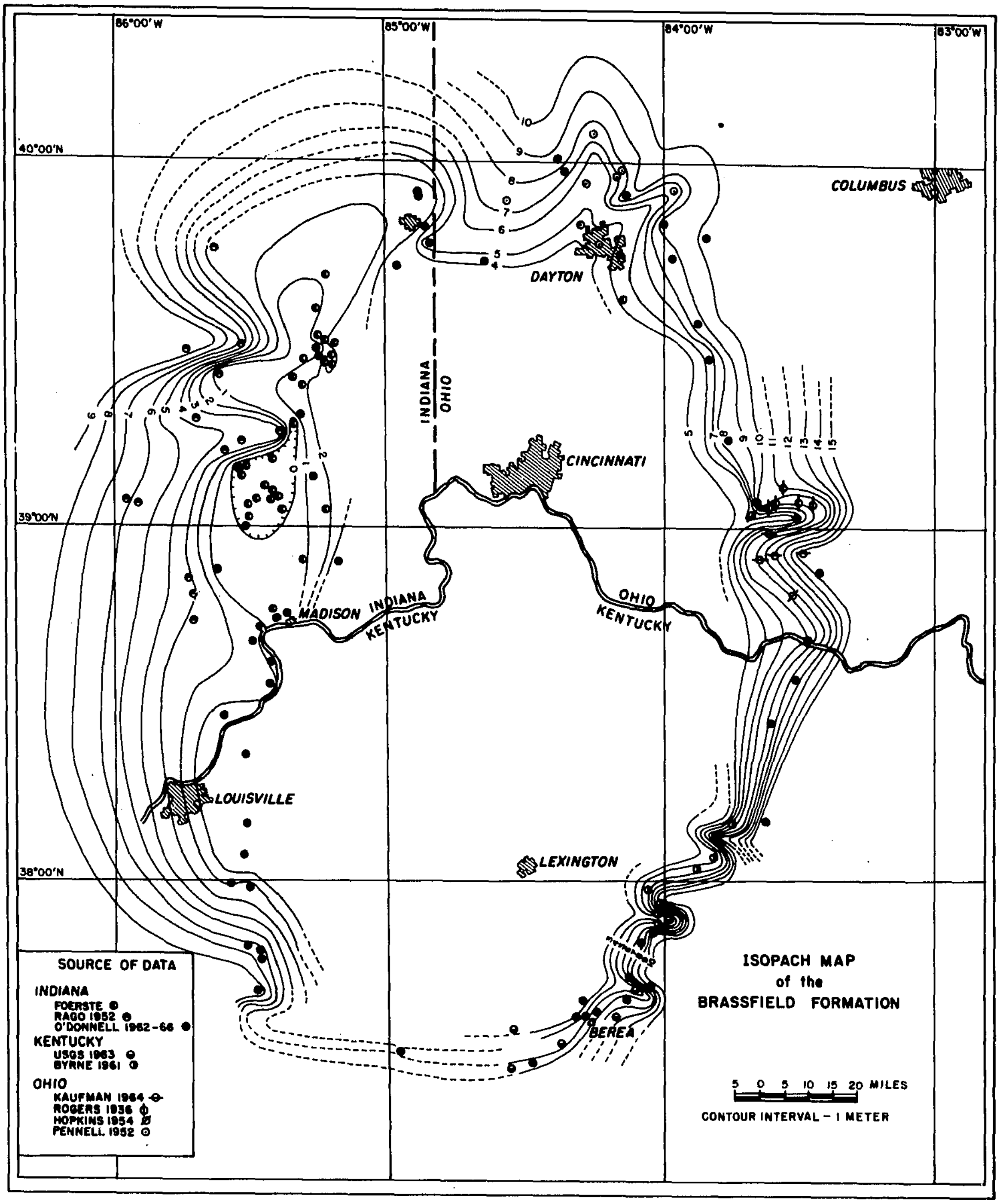
An Isopach map of the Brassfield Formation was constructed for the area encompassing the margins of the Cincinnati Arch (fig. 6). Data was compiled from the 46 measured sections of this study, two well cores of O'Donnell (1963), plus information garnered from the literature which is indicated on the Isopach Map. Complete sections were used as much as possible for the Isopach map and incomplete sections were used only for reference to give an indication of minimum thickness. The interval from the Belfast "Limestone" through the Waco "Limestone" was used in preparing the map.

The Brassfield is thickest on the east side of the Arch especially in east central Kentucky where it approaches 15 meters in thickness. It gradually diminishes northward. At West Milton, Ohio, it is 8.03 meters thick, at Lewisburg, Ohio 6.63 m., and at Elkhorn Falls, Indiana 4.42 m. The Brassfield continues to diminish in thickness in a southwesterly direction until it is entirely absent in an area including parts of Ripley, Jennings, and Decatur Counties, Indiana. South of Batesville, Indiana, the Brassfield is scarcely more than one meter thick. One exception is at Cross Plains, Indiana where the Brassfield measures 3.10+ meters. The Brassfield remains thin in Trimble and Oldham Counties, Kentucky and then increases in thickness in Nelson and Marion Counties to as much as 8.64 m. at Bardstown. The Brassfield is not exposed south of Nelson County until exposures in northern Tennessee are reached.

Examination of the Isopach Map shows a general thinning of the Brassfield towards the Arch. It should be held in mind in this discussion that the Brassfield is not very thick in terms of lithologic bodies and rarely exceeds 15 meters. It is thicker on the east side of the Cincinnati Arch partly because more clastic detritus has been introduced from the east. However even where the shales which make up the Noland Member are absent, north of Highland County, Ohio, the Brassfield is still 8-10 meters thick. On the west side of the Arch the Brassfield is 7-8 meters thick near Bardstown and the outlier at Scrubgrass Creek is almost 5 meters thick. Going north from Bardstown, Kentucky, the Brassfield rapidly thins. From the southern part of Jefferson County, Kentucky north to Laruel, Franklin County, Indiana, the Brassfield rarely exceeds 1.5 meters in thickness. Throughout Indiana in subsurface the Brassfield averages 2-3 meters except in the north where it thickens to over 30 meters as it approaches the Michigan Basin.

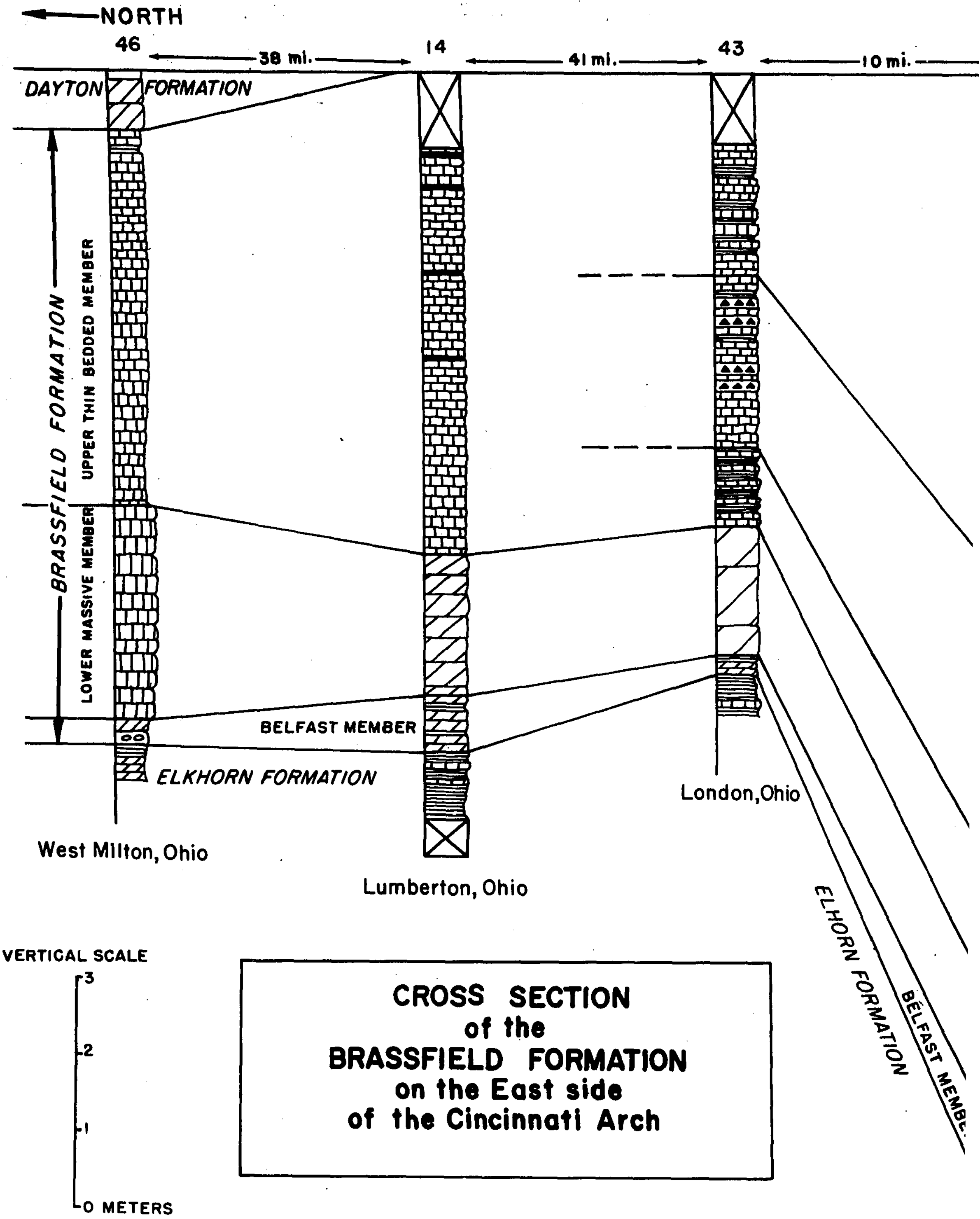
The Isopach contours make an irregular lobate pattern in east central Kentucky. Their irregular pattern is attributed, in part, to the abundance of data points for this region. However this same area has a higher percent of clastic materials (fig. 10), a fact which tends to negate the idea that the lobes are due solely to more abundant data. At first examination, their pattern suggests small deltas, but they are 50 miles beyond the limit of Rittenhouse's "Clinton Sands", which tends to exclude that possibility. Rather than representing small deltas, the lobes may have been caused by submarine erosion, or they may be the result of submarine topography. Carbonate deposition may have been favored by slightly higher banks closer to wave base. Clay and silt would settle in lower areas resulting in the accumulation of different sediment types at different rates.

GEOLOGIC CROSS-SECTIONS: Two north-south cross sections were drawn for the east and the west side of the Cincinnati Arch (figs. 7 and 8). The cross sections show the four named members of the Brassfield. The Belfast

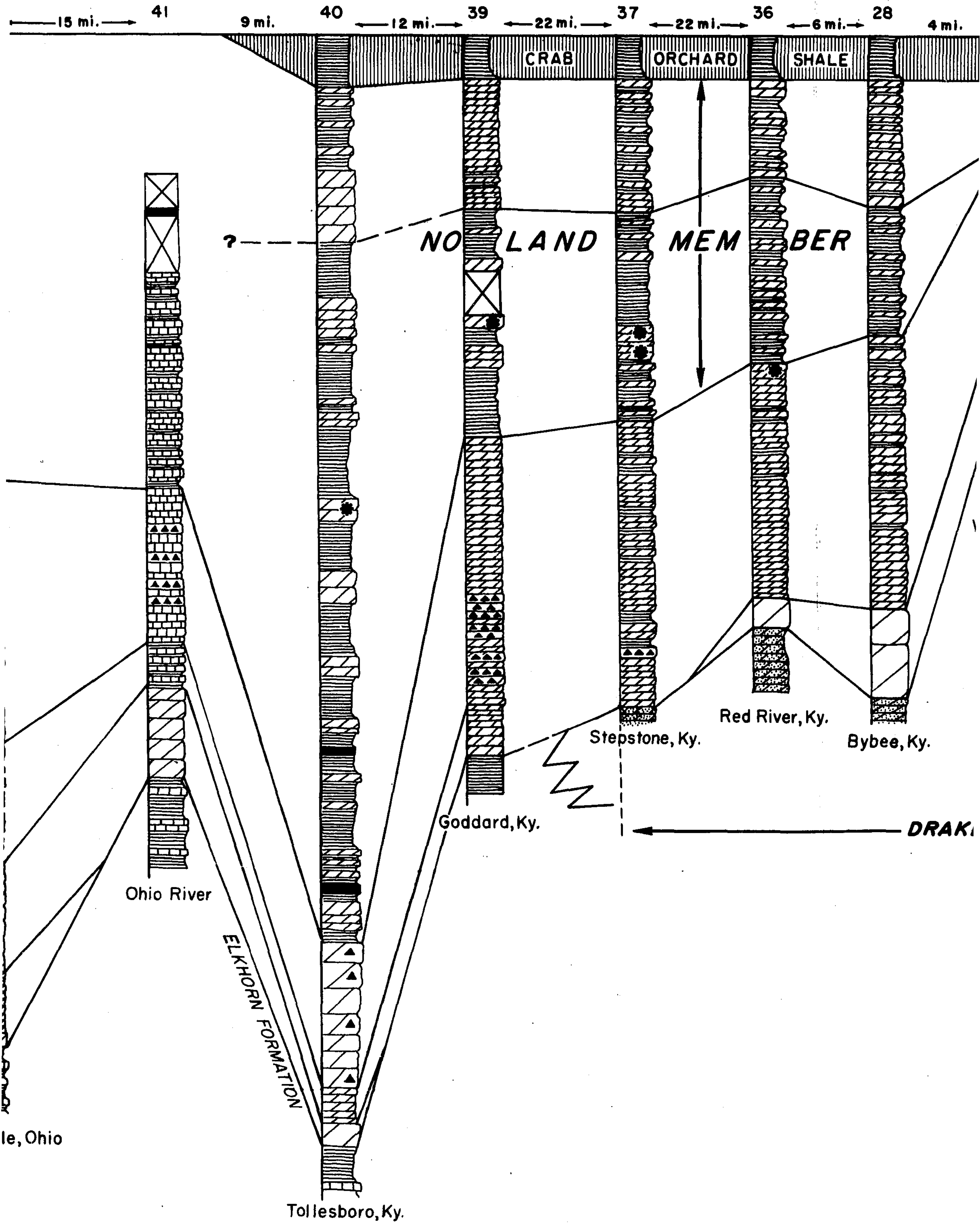


86°00'W
85°00'W
84°00'W
83°00'W
40°00'N
39°00'N
38°00'N
COLUMBUS
DAYTON
INDIANA
OHIO
CINCINNATI
MADISON
INDIANA
KENTUCKY
OHIO
KENTUCKY
LOUISVILLE
LEXINGTON
BEREA
SOURCE OF DATA
INDIANA
FOERSTE
RAGO 1952
O'DONNELL 1962-66
KENTUCKY
USGS 1963
BYRNE 1961
OHIO
KAUFMAN 1964
ROGERS 1936
HOPKINS 1954
PENNELL 1952
ISOPACH MAP
of the
BRASSFIELD FORMATION
5 0 5 10 15 20 MILES
CONTOUR INTERVAL - 1 METER

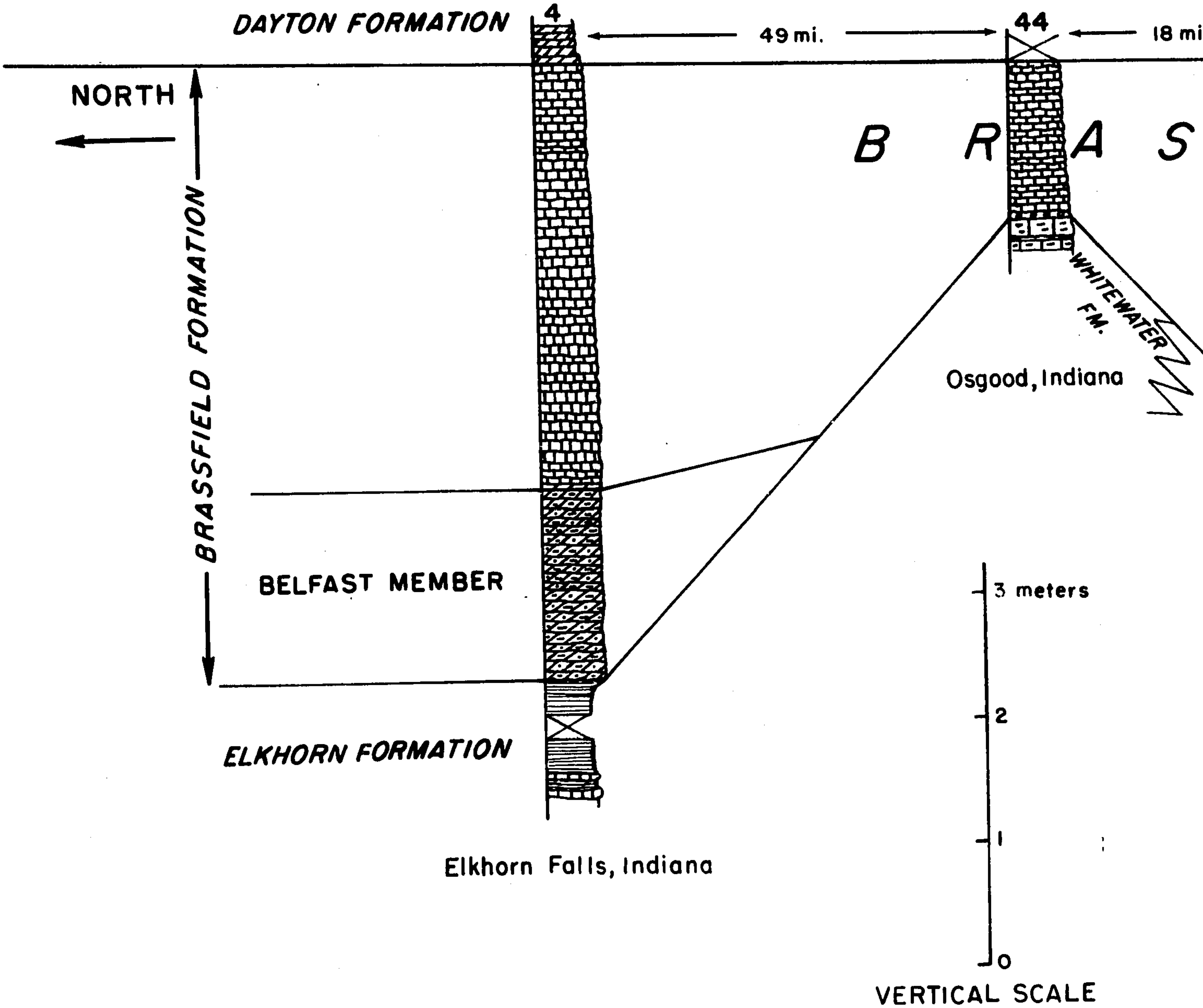
Fig. 6


NORTH
46
38 mi.
14
41 mi.
43
10 mi.
DAYTON FORMATION
BRASSFIELD FORMATION
UPPER THIN BEDDED MEMBER
LOWER MASSIVE MEMBER
BELFAST MEMBER
ELKHORN FORMATION
West Milton, Ohio
Lumberton, Ohio
London, Ohio
ELHORN FORMATION
BELFAST MEMBE
VERTICAL SCALE
3
2
1
0 METERS
CROSS SECTION
of the
BRASSFIELD FORMATION
on the East side
of the Cincinnati Arch

J



15 mi.
41
9 mi.
40
12 mi.
39
22 mi.
37
22 mi.
36
6 mi.
28
4 mi.
CRAB
ORCHARD
SHALE
?
NO LAND
MEM BER
Ohio River
ELKHORN FORMATION
le, Ohio
Tollesboro, Ky.
Goddard, Ky.
Stepstone, Ky.
Red River, Ky.
Bybee, Ky.
DRAK


DAYTON FORMATION
4
49 mi.
44
18 mi
NORTH
BRASSFIELD FORMATION
B R A S
WHITEWATER FM.
Osgood, Indiana
BELFAST MEMBER
ELKHORN FORMATION
Elkhorn Falls, Indiana
3 meters
2
1
0
VERTICAL SCALE

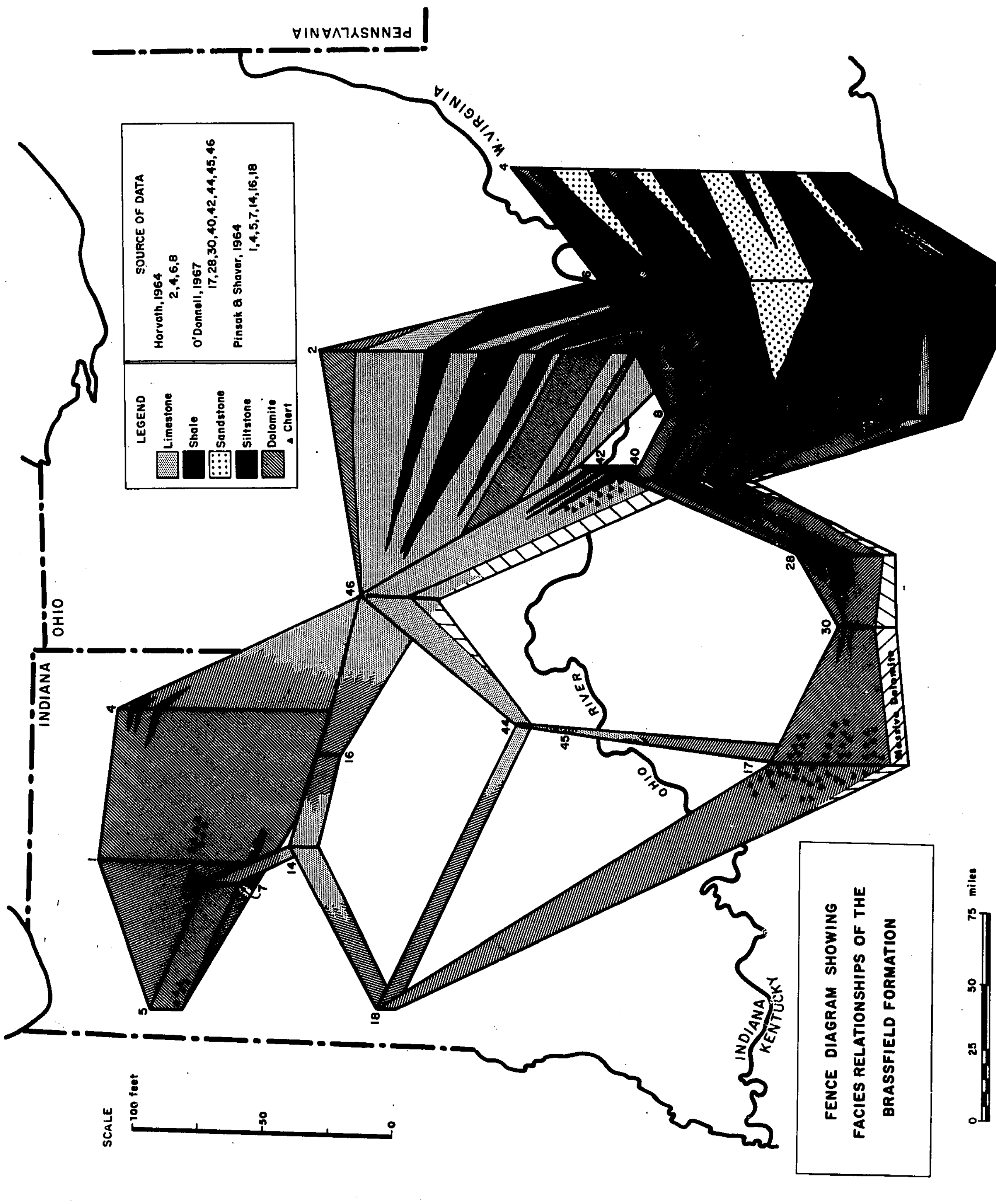
Member is found from Elkhorn Falls in Wayne County, Indiana (Section 4) north to Troy, Miami County, Ohio (Foerste 1935, p. 148), and as far south as West Union, Adams County, Ohio (ibid.). The Lower massively bedded Brassfield can be recognized from Elkhorn Falls (Section 4), as far south as Tollesboro, Lewis County, Kentucky (Section 40). It reappears in Estill County, Kentucky, along the Red River (Section 36) and can be traced south to Crab Orchard, Lincoln County, Kentucky. It is present in west central Kentucky from Bardstown, Nelson County, (Sections 16, 17, 18) to New Hope, Nelson County (Section 19). The Upper thin bedded Member, the most characteristic aspect of the Brassfield, is present in all sections of this study. The Noland Member is found in east central Kentucky, Adams, and the southern part of Highland County, Ohio. It can be traced into the Upper thin bedded Member as one goes further north. The Noland represents an extension of clastic material derived from the Appalachian Basin, and it can be traced into the clastics of the Tuscarora Formation (Perry, 1962, and Horvath, 1964).

FENCE DIAGRAM: A fence diagram (fig. 9) was constructed using eight sections from this study which were supplemented with subsurface data from Indiana, eastern Ohio, eastern Kentucky, and West Virginia. The stratigraphic interval represented included the Belfast through the Noland Member of the Brassfield. The projection was

was so oriented as to stress the relationship between the Brassfield and the sediments of the Michigan and Appalachian Basins. In this way it overlaps the Clastic Percent Map, the Cross-sections, and Isopach Map.

It can be readily seen in the Fence Diagram that in going westward from Pennsylvania and West Virginia, the sandstones, siltstones, and shales which make up the Tuscarora Formation, thin considerably and grade into the carbonates which constitute the bulk of the Brassfield Formation. Going south from the Michigan Basin, dolomites and shales of the Cataract Group also thin and the shale disappears on the west side of the Cincinnati Arch. However it should be noted that there is some question as to the thickness of the rocks which have been called "Brassfield" in the northern part of Indiana. Pinsak and Shaver (1964, p. 75;77) report thicknesses of 60 feet and 89 feet for wells number 1 and 4 respectively. Rexroad (personal communication) thinks that the Brassfield is only 10 to 12 feet thick in this area. There is a possibility that Pinsak and Shaver may have included part of the pre-Silurian rocks such as the Manitoulin Dolomite and Cabot Head Shale in the Brassfield.

In terms of lithology, the Brassfield is dolomitic south of the Ohio River on both sides of the Cincinnati Arch but to the north, along the outcrop belt, the rocks are more calcareous. In subsurface in Indiana the Brassfield is a



FENCE DIAGRAM SHOWING
FACIES RELATIONSHIPS OF THE
BRASSFIELD FORMATION
LEGEND
Limestone
Shale
Sandstone
Siltstone
Dolomite
▲ Chert
SOURCE OF DATA
Horvath, 1964
2,4,6,8
O'Donnell, 1967
17,28,30,40,42,44,45,46
Pinsak & Shaver, 1964
1,4,5,7,14,16,18
PENNSYLVANIA
W. VIRGINIA
OHIO
INDIANA
OHIO RIVER
INDIANA
KENTUCKY
SCALE
100 feet
50
0
0
25
50
75 miles

Fig. 9

dolomite with only local occurrences of limestone. Chert is found in a northeast-southwest belt extending across the Arch and it is found locally in central Indiana.

CLASTIC PERCENT MAP: A clastic percent map (fig. 10) was prepared in a similar fashion to the Isopach Map. The measured sections of this study were supplemented with subsurface data from the literature. The interval from the Belfast through the Waco "Limestone" was included in the Brassfield. The Clastic percent was computed according to the formula:

$$\text{Clastic } \% = \frac{\text{sandstone} + \text{shale}}{\text{limestone} + \text{dolomite}}$$

Examination of the Clastic Percent map shows a northeast-southwest trend of the clastic percent contours. The clastic content of the Brassfield is highest along the southeast margin of the Cincinnati Arch in Kentucky. The thick shales which comprise the Noland Member of the Brassfield begin to disappear northeast of Adams County, Ohio and Crab Orchard, Kentucky. There are several lobate structures present all located on the east side of the Cincinnati Arch. As was suggested in the discussion of the Isopach Map the "lobes" probably represent pro-delta fronts of material being transported from the southeast.

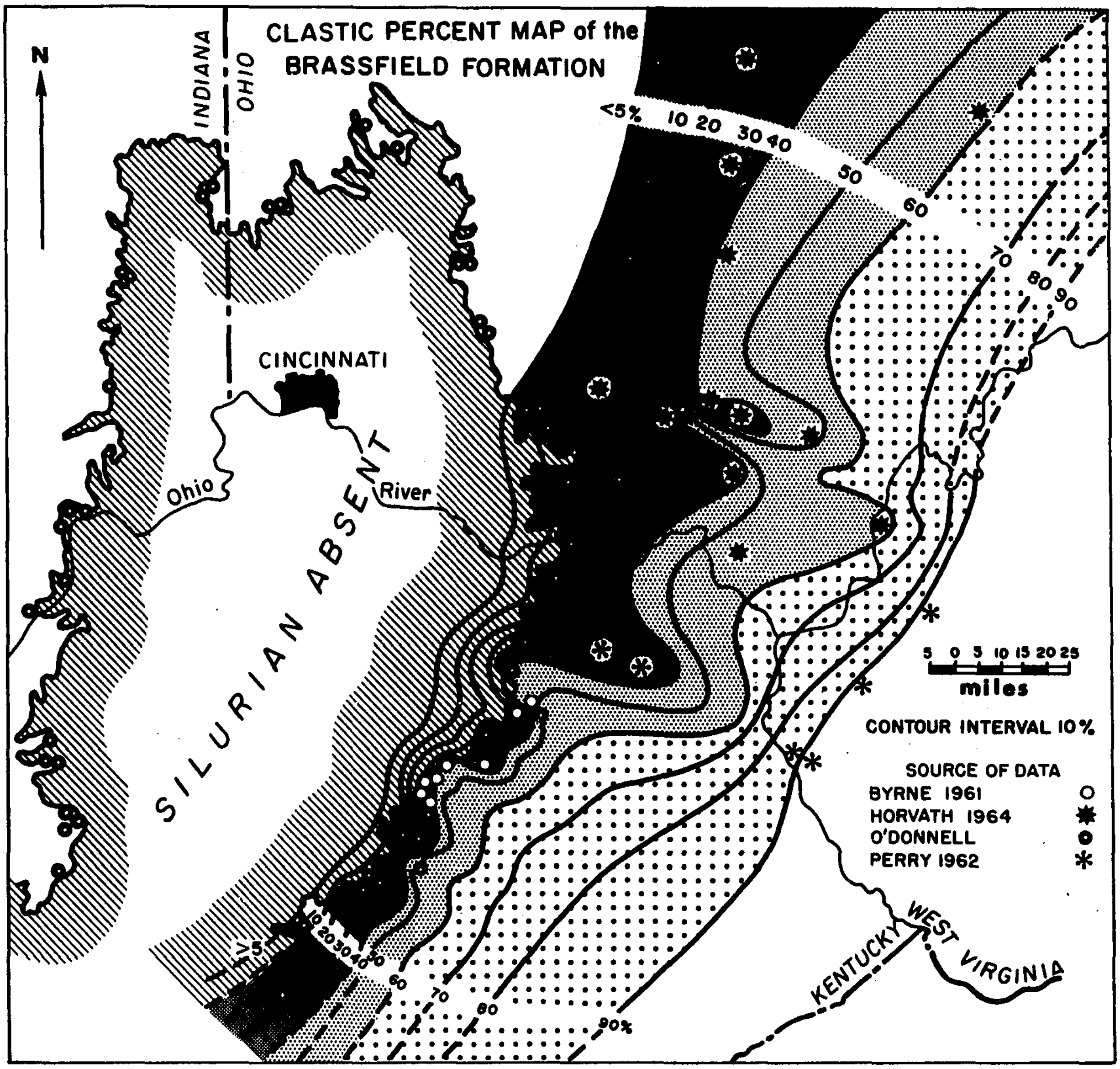

CLASTIC PERCENT MAP of the BRASSFIELD FORMATION
N
INDIANA
OHIO
CINCINNATI
Ohio
River
SILURIAN ABSENT
<5%
10 20 30 40
50
60
70
80
90
90%
5 0 5 10 15 20 25
miles
CONTOUR INTERVAL 10%
SOURCE OF DATA
BYRNE 1961
HORVATH 1964
O'DONNELL
PERRY 1962
KENTUCKY
WEST VIRGINIA

Fig. 10

LITHOFACIES MAP: The Brassfield Formation of the Ohio, Indiana, and Kentucky area consists of three lithologic suites: (1) a limestone suite, (2) a dolomite suite, (3) a terrigenous suite in which the sediments are derived primarily from detrital or terrigenous material. A lithofacies map (fig. 11) was constructed using the data from the Cross sections, the Fence Diagram, and the Clastic Percent Map. The "type" Brassfield is representative of the dolomite suite. Most of what has been called Brassfield in southwestern Ohio and Indiana is from the limestone suite. The Noland Member of the Brassfield although of marine origin contains a high percentage of clay and silt probably of detrital origin. It grades eastward into the clastics of the Tuscarora Formation and the Medina Group of western New York.

Figure 11 shows the plot of three lithologic suites. On figure 11 it can be seen that there is no relationship between the present day Cincinnati Arch and the lithologic suites. The limestone and dolomite suites cross the Arch from east to west at the approximate position of the Ohio River. The belt of clastic material strikes northeast-southwest and does not parallel the Arch but is oblique to it. There is a possibility that the Cincinnati Arch may have served as a barrier to the influx of clastics from the east but the general absence of clastics in southwestern Ohio, southeastern Indiana, and west central Kentucky

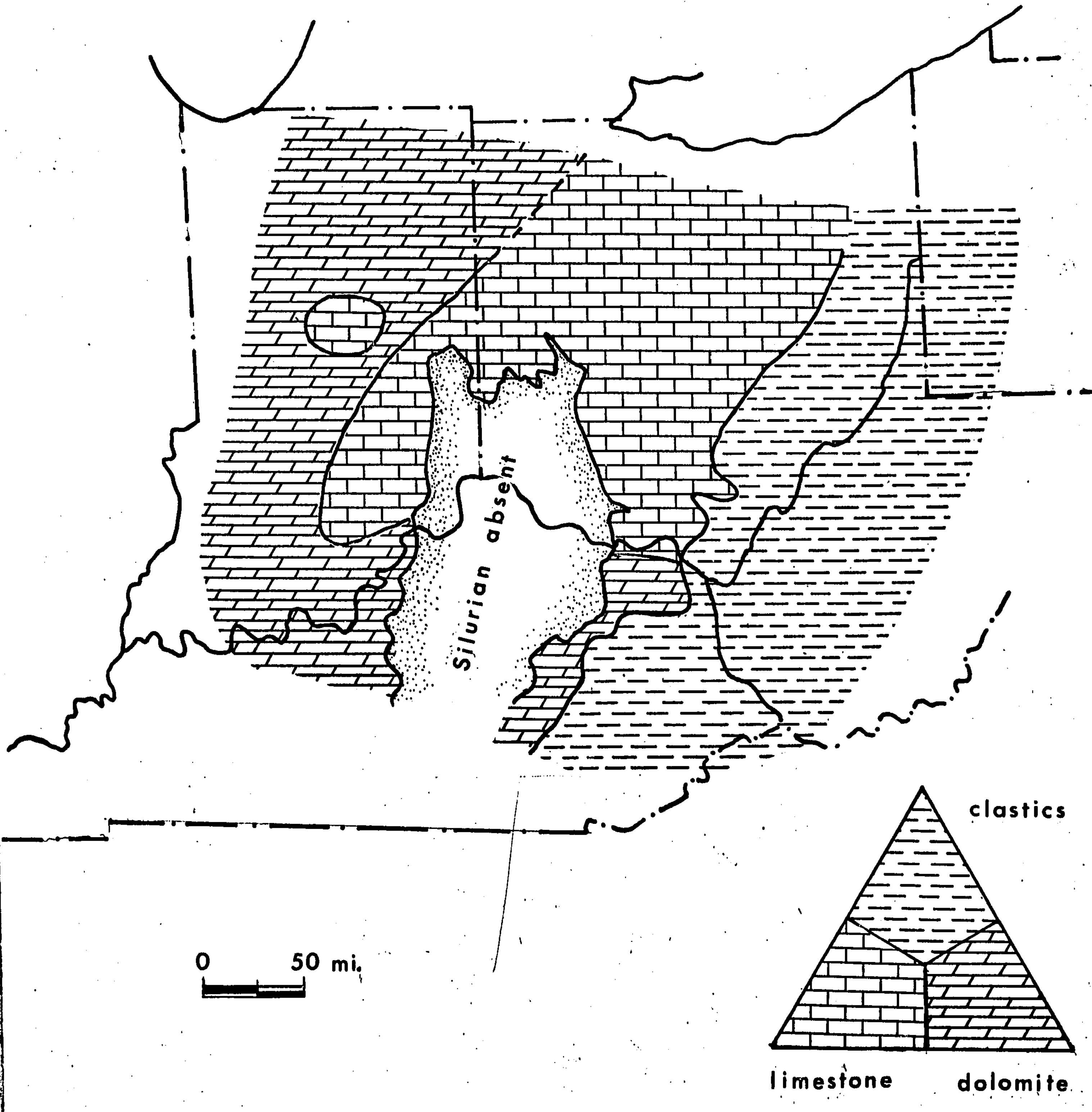


Fig. 11. Lithofacies map of the Brassfield Formation in Indiana, Kentucky, and Ohio.

probably reflects distance from a source area.

BEDDING CHARACTERISTICS: The bedding of the Brassfield is variable. Frequently at the base of the unit, in Kentucky and southwestern Ohio, is a single massive dolomite bed ranging from 50 to 200 cm thick. Several of these beds may be present reaching an aggregate thickness of over 300 cm. Occasionally the dolomite beds will weather to reveal laminae less than one centimeter thick. Primarily because of the laminae and of the rather constant thickness of the beds in outcrop, they are interpreted as representing quiet water sedimentation.

In Kentucky and southwestern Ohio the massive dolomite bed(s) is/are overlain by more thinly bedded limestones or dolomites which range from 2-100 cm thick but generally average about 20 cm. Although individual beds may vary considerably in thickness, with respect to each other, each one usually maintains a fairly constant thickness in outcrop. These beds are also interpreted as representing a low energy environment of quiet water sedimentation.

The uppermost part of the Brassfield usually consists of irregularly bedded calcarenites and dolarenites ranging from 2-40 cm thick (figs. 14, 16). They are discontinuous and cannot be traced for more than several tens of meters in outcrop. They are commonly cross-laminated and probably represent a moderately high energy environment.

PALEONTOLOGY: It was beyond the scope of this study to undertake a detailed paleontological study. The Brassfield contains a diverse marine fauna (Table I). For faunal lists the interested reader is referred to Bassler (1915), Butts (1927), Culbertson (1916), Foerste (1893, 1901, 1906, 1917, 1919, 1923, 1931, and 1935), Manning (1933), Mound (1961), and Rexroad (1967).

Table I

Number of species reported in the Brassfield Formation in Kentucky and Ohio

(Foerste, 1931)

Fossil group	Type Brassfield	Noland Member	
		Oldham tongue	Waco tongue
brachiopods	34	8	9
bryozoans	27	4	2
cephalopods	22		
corals	13	7	19
echinoderms	6		
gastropods	17		2
graptolites	2		
hydrozoans	2		
ostracods	1	1	1
pelecypods	9		
trilobites	14	2	3

Most of the faunal collections in Kentucky and southwestern Ohio apparently came from the fossiliferous upper few feet of the formation. For example, Foerste in his 1906 paper (pp. 30-33) cited nine locations where he collected fossils during his study of the Brassfield of east-central Kentucky. At eight of these sites he collected from the uppermost fossiliferous part of the Brassfield. Only at Abbott's Mill, south of Indian Fields in Clark County "...In the lower part of this section"... Foerste identified _Cyclonema daytonensis_, _Leptaena rhomboidalis_, and _Clathropora frondosa_, Foerste (1906, p. 32, 185). Only one of these, _Clathropora frondosa_, has been considered stratigraphically important, being confined to "Clinton" age rocks (Bassler, 1953, p. 136).

LITHOLOGIC CHARACTER: The Brassfield formation is exposed over a very large area encompassing tens of thousands of square miles. It is remarkable that it is recognizeable over so great an area (Swartz, 1942). For example the Brassfield exposed near West Milton, Miami County, Ohio is almost indistinguishable from the Brassfield in Jasper, Marion County, Tennessee except for the presence of chert in it at the latter place. This represents a straight line distance of 375 miles!

To generalize about the Brassfield's lithology is almost impossible. What is true of one locality is not true of another. Figs. 7 and 8 summarize the gross lithologic changes within the Brassfield around the Cincinnati Arch. For purpose of discussion the Brassfield will be subdivided into four parts, which are listed in descending stratigraphic order and will be described in the sections to follow.

(4) Noland Member which is a shaly facies of the Upper Brassfield and will be accorded member rank in this study. The Noland Member can be further subdivided:

(d) Waco Dolomite tongue
(c) Lulbegrud Shale lentil
(b) Oldham Dolomite tongue
(a) Plum Creek Shale lentil

(3) Upper thinly or irregularly bedded Brassfield which will be alternately referred to as the Upper Brassfield or the Upper thin(ly) bedded Brassfield.

(2) Lower massively bedded Brassfield which will alternately be referred to as the Lower Massive Brassfield.

(1) Belfast Member which will encompass the Centerville Shale as a lentil.

Locally the Brassfield can be subdivided into many more informal units as is the case in Adams and Highland Counties, Ohio and Lewis County, Kentucky. As many as six informal members can be recognized there: (see figs. 17, 18, 19 and 21)

(6) Noland Member
(5) Upper thinly bedded Brassfield
(4) Upper Massively bedded Brassfield
(3) Lower thinly bedded Brassfield
(2) Lower Massively bedded Brassfield
(1) Belfast Member

(1) The Belfast member was named as the Belfast Bed by Foerste in 1896 for generally unfossiliferous massive and argillaceous bluish limestones (dolomites?) in places clayey

shale 1-2 meters thick, exposed in Highland and Adams Counties, Ohio. For many years the Belfast was regarded as the top bed of the Richmond group (Foerste 1931, p. 184) until it was learned that could be traced laterally into typical Brassfield strata (ibid.). The Belfast has few fossils beyond some conodonts and scolecodonts. Foerste found the brachiopod Platystrophia daytonensis in both the Belfast and the Brassfield.

As recognized in this study, the Belfast consists of thin bedded greenish gray (5GY 6/1) to light olive gray (5Y 6/1) argillaceous dolomites which weather to a pale yellowish brown (10YR 6/2). The beds are thin and of more or less constant thickness. They range from 2-10 cm. thick. Occasionally the Belfast is interbedded with a grayish-yellow-green (5GY 7/2) clay-shale lenses which range from 0.25 to 2 cm. thick. It is recognizable from West Union, Adams County, Ohio north to Troy, Miami County, Ohio, and as far west as Elkhorn Falls (section 4), in Wayne County, Indiana.

Foerste (1931, pp. 184-185) reported that an indurated clay shale 2½ feet thick had been found beneath the Brassfield during the excavation of a drainage ditch for a now flooded quarry 1 mile northeast of Centerville, Ohio. He named this the Centerville formation. Foerste found a fauna which included the brachiopod genera Schuchertella, Brachyprion, and Cryptothyrella which led him to correlate it with the Edgewood limestone of Illinois. Aside from its type locality the Centerville has been recognized at West Union and Lawshe, Ohio. It appears to be of limited areal extent and may be a local phase of the Belfast.

(2) Lower Massive Brassfield at the type locality, in Kentucky, is essentially a single massive bed of medium crystalline dolomite 188 cm. thick but differential weathering on vertical joint surfaces shows finer internal bedding, with beds 1-10 cm. thick. No fossils were observed and it is usually barren. The massively-bedded Brassfield is a persistent unit found on both sides of the arch. (See figs. 7 and 8). In the southern outcrop area it is dolomitic and to the north near Dayton, Ohio it is a partially dolomitized crinoidal biosparite. Thickness is variable even within a single outcrop (see fig. 23). On the east side of the Arch the massively-bedded Brassfield is absent from Owingsville, Kentucky north to Tollesboro, Kentucky. To the west of the Arch it is missing south of Elkhorn Falls, Indiana to Bardstown, Kentucky, where it reappears and can be traced southward to New Hope, Kentucky (fig. 8).

Rexroad et. al (1965) in their study of the Silurian of East Central Kentucky equate the Lower massively-bedded Brassfield with the Belfast "bed". This is rejected here, for even when the Belfast is present it is overlain by a massive dolomite bed 1-2 meters thick. Rexroad reported that the conodonts of the Lower massive Brassfield are equivalent to those of the upper Edgewood limestone in Illinois. This will be discussed in the section on the age of the Brassfield.

(3) Upper thinly bedded Brassfield at the type locality consists of thin irregular medium crystalline biogenic dolomite beds 2-25 cm. thick, with thin shaly partings. Large serrated and crenulate crinoid columnals and poorly preserved brachiopod molds, probably Cryptothyrella, are found in a bed 30 cm. below the top of this unit. Fossils are restricted almost exclusively to the top one meter of this unit. Total thickness at the type locality is 455 cm.

The bed containing the large crinoid columnals is generally referred to as the "Bead Bed"(George Simmons, personal communication, 1964). The name "Bead Bed" is probably derived from the colloquial expressions of "fairey beads" and "Indian beads" which are used to describe crinoid columnals. The columnals are quite large ranging from 0.5 to 2.5 cm. in diameter (see fig. 12). Geographically the beds are found on the east side of the Cincinnati Arch from Dayton, Ohio to Birmingham, Alabama with the exception of one reported occurrence at Scrub Grass Creek near Mitchellsburg, Kentucky. The "Bead Bed" is usually found close to the top of the Brassfield as defined by Foerste (1906, p. 36) and has been used as a physical marker to delineate the top of the Brassfield. Field mapping by the U. S. Geological Survey in Kentucky (personal communication George Simmons, 1964) indicates that the "Bead Bed" is not the infallible marker to the top of the Brassfield. Indeed at several localities it falls either within or above a shale sequence referred to as the Plum Creek or even the Lulbegrud shale. This is the case at Section 37, Interstate 64 and Sugar Grove Church, Bath County, Kentucky, and at Section 40, Tollesboro, Kentucky (fig. 18). The use of the "Bead Bed" as a stratigraphic marker is in question.

On the east side of the Cincinnati Arch nodular and bedded chert is found in the thinly bedded member from the northern part of Highland County, Ohio as far south as Owingsville, Kentucky. Going from north to south the chert is found progressively lower in the section (fig. 7). On the west side of the Arch chert is found from Bardstown, Kentucky south to Raywick, Kentucky. The chert is a replacement type (see figs. 14, 15, 16) and it replaces dolomite as well as fossil fragments. It is closely associated with pelletoidal glauconite. Some nodules contain pyrite. Rago (1952) and Freeman (1951) studying the Brassfield in subsurface used the presence of chert as a criteria for its recognition. Pinsak and Shaver (1964) rejected this for the chert also occurs in the overlying Laurel and Salamonie Formations. Much of what has been identified as Brassfield in subsurface because of chert is likely to be

Laurel or Salamonie.

Irregular, thin beds of hematite ranging from 2-100 cm. thick are found towards the top of the thin bedded Brassfield and in the Noland Member. The hematite beds are restricted to the east side of the Cincinnati Arch from Lumberton, Ohio to Owingsville, Kentucky. Hematite has replaced and infiltrated fossil fragments in these beds and they are referred to colloquially as "fossil ores". The hematite beds have been mined locally and have been used as an iron ore because of their low amount of impurities, high iron content, and for their high limestone content. The limestone served as a fluxing agent and these "fossil ores" were self fluxing. Unfortunately they were too thin and soon "played-out". It was the presence of hematite (Newberry, 1873, p. 62), fossil content (Orton, 1871, p. 148), and stratigraphic position (ibid.), which led the early workers to correlate the hematite beds and associated crinoidal limestones with the Clinton of New York. Foerste (1906, p. 35), although he too equated these rocks with the Clinton of New York, noted that "...the fauna of the Brassfield limestone of Ohio, Indiana, and Kentucky, appears to differ sufficiently from the fauna of the Clinton limestone of New York to warrant the assumption of the presence of some sort of barrier between the two areas." The Brassfield actually represents a facies of the iron ores of the Clinton Group which began on the craton in Lower Llandovery time (Brassfield) and transgressed time as it migrated eastward into the miogeosyncline in New York, West Virginia, Virginia, Tennessee, and Alabama by Late Llandovery and Wenlock time.

(4) Noland Member--In east central Kentucky, Foerste's Brassfield is overlain by a sequence of unfossiliferous shales, the lower part of which is interbedded with fossiliferous dolomites. Linney in 1882 (fide Foerste 1935, p. 127) called this the Crab Orchard shales group. Foerste recognized (1906, p. 10) two "limestone" horizons, the Oldham and the Waco, towards the base of the Crab Orchard shales. The shales intervening between the Brassfield and Oldham were named by him the Plum Creek (ibid.) and the shale between the Oldham and Waco was called the Lulbegrud (ibid.). Foerste recognized the Plum Creek-Oldham-Lulbegrud-Waco sequence from Berea in Madison County north to Bath County.

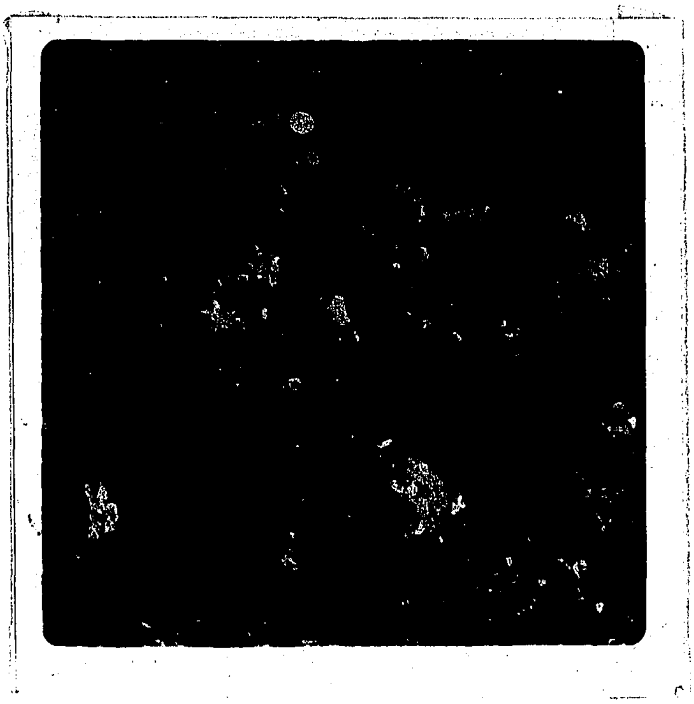
In his 1906 paper on the Silurian, Devonian, and Irvine formations of Kentucky, Foerste apparently considered the Crab Orchard to be of group rank, in the modern usage of the word, although it is listed as a formation (p. 10). The Plum Creek and Oldham were assigned to the Indian Fields (formation?) and the Lulbegrud-Waco to the Alger (formation?) as members. Foerste called the uppermost shale member of the Alger the Estill Clay. These beds are all illustrated in the 1906 paper; and the reader is referred to figures 2, 3, 4, 5, 7. They are all gradational with one another. For example the upper two meters of the Brassfield at the type locality becomes shalier toward the top and is 90% dolomite, 10% shale. The Plum Creek consists of 258 cm. of interbedded shale (80%) and dolomite (20%). The dolomite content increases toward the top of the unit. The Oldham Limestone is composed of 316 cm. of interbedded dolomite and shale. The lower one meter consists of 75% dolomite, 25% shale. The upper two meters are 30% dolomite, 70% shale.

Rexroad et al. (1965) proposed the name Noland Formation to include the rocks from the top of the Brassfield ("Bead Bed") to the base of the Estill Shale. The Noland encompasses the Plum Creek Shale, Oldham "Limestone", Lulbegrud Shale, and Waco "Limestone" from Lincoln County northeastward to Bath County, Kentucky. From Bath County to Adams County, Ohio recognition of the members is uncertain but the overall sequence of shales and dolomites can be traced into the upper thinly bedded Brassfield in Ohio (fig. 7). As the shale content of the rocks decreases the dolomite content decreases too. Rexroad et al. (1965) assigned the Noland Formation and the Estill Shale to the Crab Orchard Group. Since the Oldham-Waco appear to be part of the main carbonate body of the Brassfield and the Plum Creek-Lulbegrud shales appear to represent shale lentils between carbonates, they are here accorded the rank of tongues and lentils within the Noland member of the Brassfield.

This assignment is supported by the conodont work of Rexroad *et al*. The Brassfield (up to the "Bead Bed"), the Plum Creek, Oldham, Lulbegrud, and Waco all fall within Otto Walliser's conodont Zone I named for the Llandovery sequence in the Carnic Alps. The Estill Shale has Zone II and Zone III conodonts in its lower parts but none of the forms which characterize Zone II. From this Rexroad concluded (1965, p. 2) that Zone II is missing and that there is a hiatus between the Estill and the Noland. Rexroad (1967, personal communication) has since found Zone II conodonts in "the upper part of the Waco" and a zone between the Brassfield and the Osgood. Also Boucot (in Rexroad *et al*., 1965) says that *Microcardinalia* is a good guide to the upper Llandovery (C_3). It is found in both the Oldham and the top of the Brassfield near Dayton, Ohio thus, establishing a time equivalency between the two.

Fig. 12. The "Bead Bed" 172 cm below the top of the Brassfield Formation at Section 34, Waco, Kentucky. A quarter in the top center of the photo gives some indication as to the large size of the crinoid columnals which make up the Bead Bed.

Fig. 13. Basal conglomerate in the Lower massive Brassfield. The large cobbles were derived from the underlying Drakes Formation which is out of sight beneath the hat. Section 31, Berea, Kentucky.



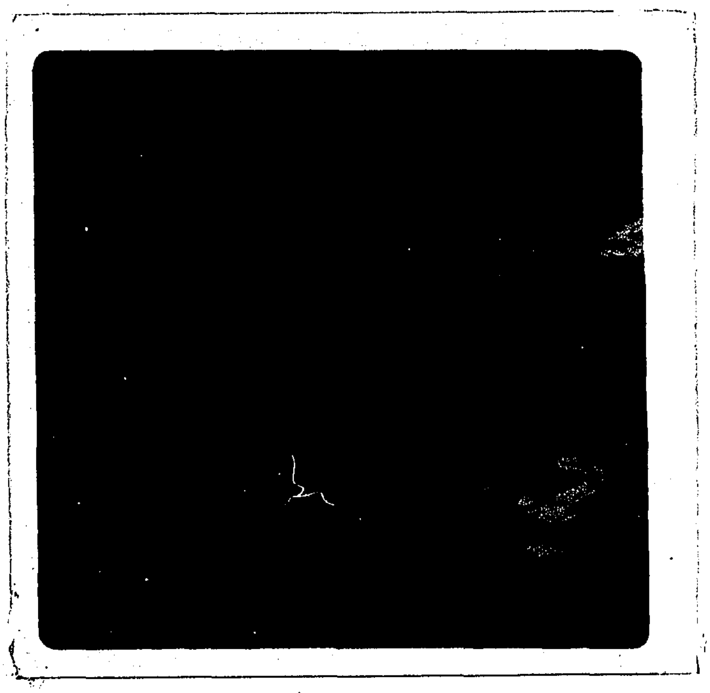
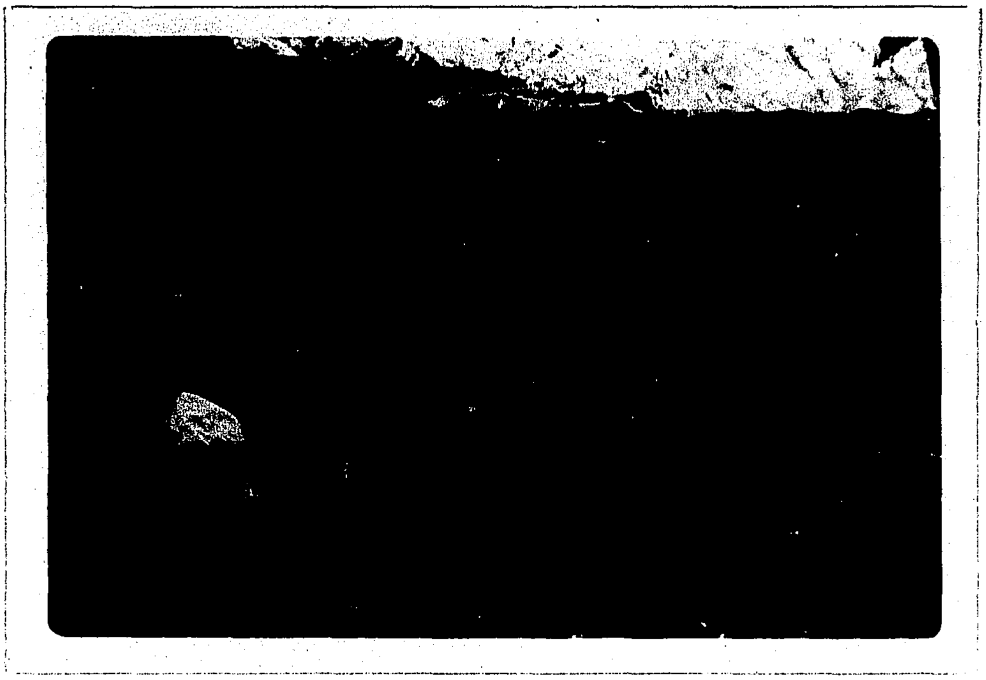


Fig. 14. Cross laminated part of the Upper thinly bedded member of the Brassfield Formation at Section 10, the Wright Brothers Memorial, Fairborn, Ohio. (Hat in picture for scale.)

Fig. 15. Intraformational conglomerate from the massively bedded chert zone 7 meters above the base of the Brassfield Formation at Section 42, Jacksonville, Ohio. The cobbles are Brassfield material which has been eroded and redeposited within the formation.



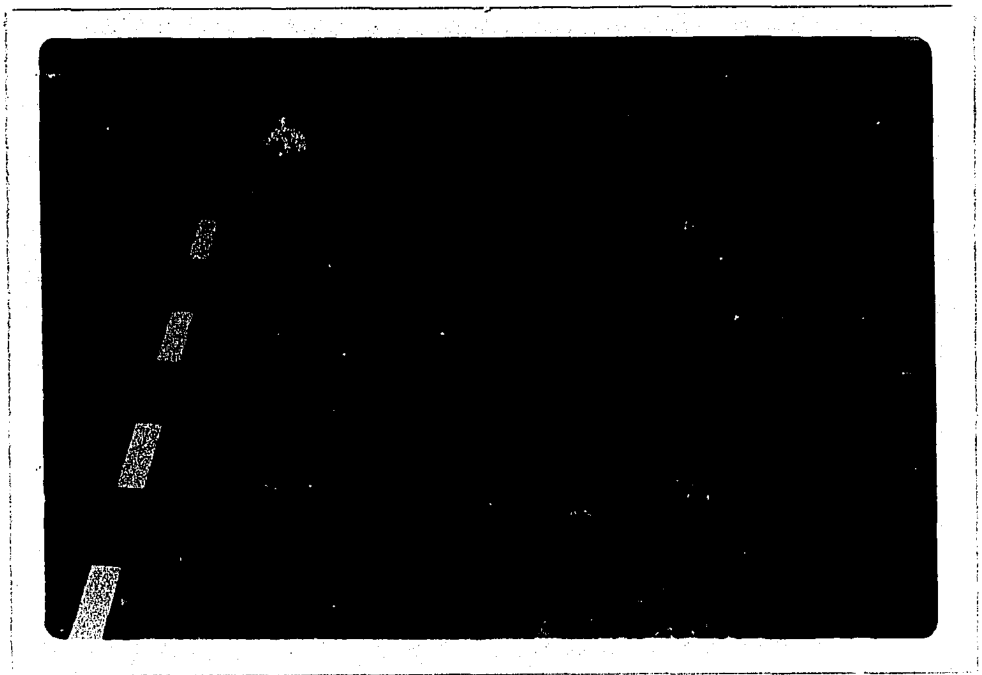
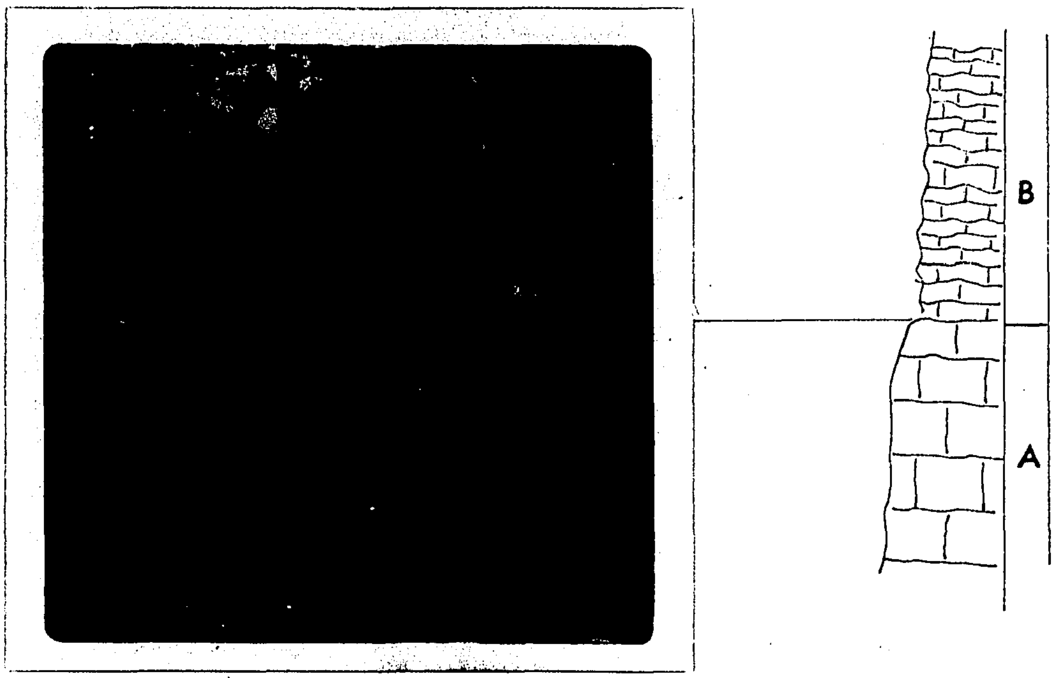


Fig. 16. An exposure of the Lower massively bedded Brassfield (A) and the Upper thinly bedded Brassfield (B) near Eaton, Ohio (Section 11).

Fig. 17. Exposure of the Brassfield Formation at Section 41, Loudon, Ohio. Two formal members (A, E) and three informal members (B, C, D) can be recognized here: (A) Belfast Member, (B) thinly laminated, massively bedded dolomite, (C) thin bedded limestone and shale, (D) massively bedded limestone with glauconite rich chert beds, (E) Noland Member which consists of thinly bedded limestone and shale. Compare with figs. 18, 19, 21.


B
A

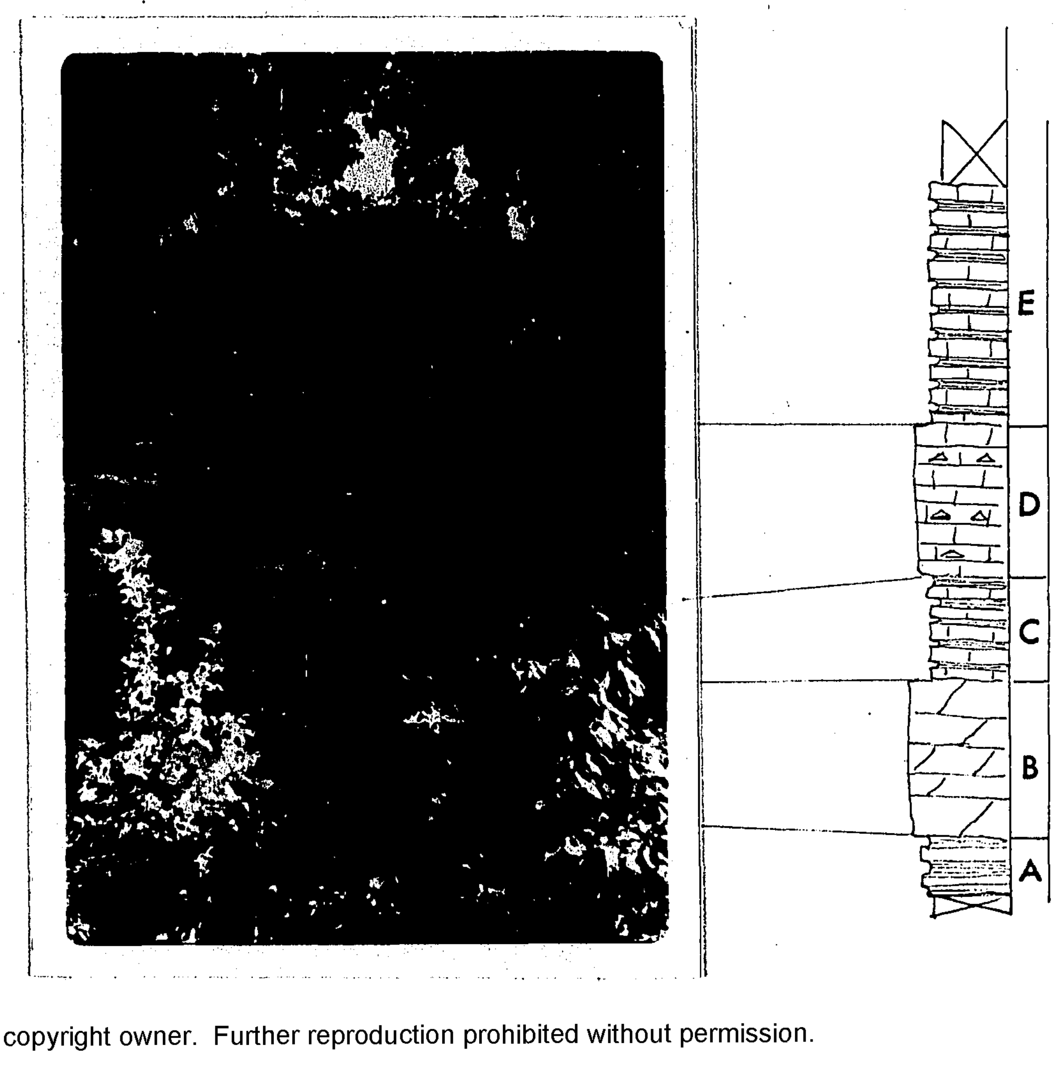
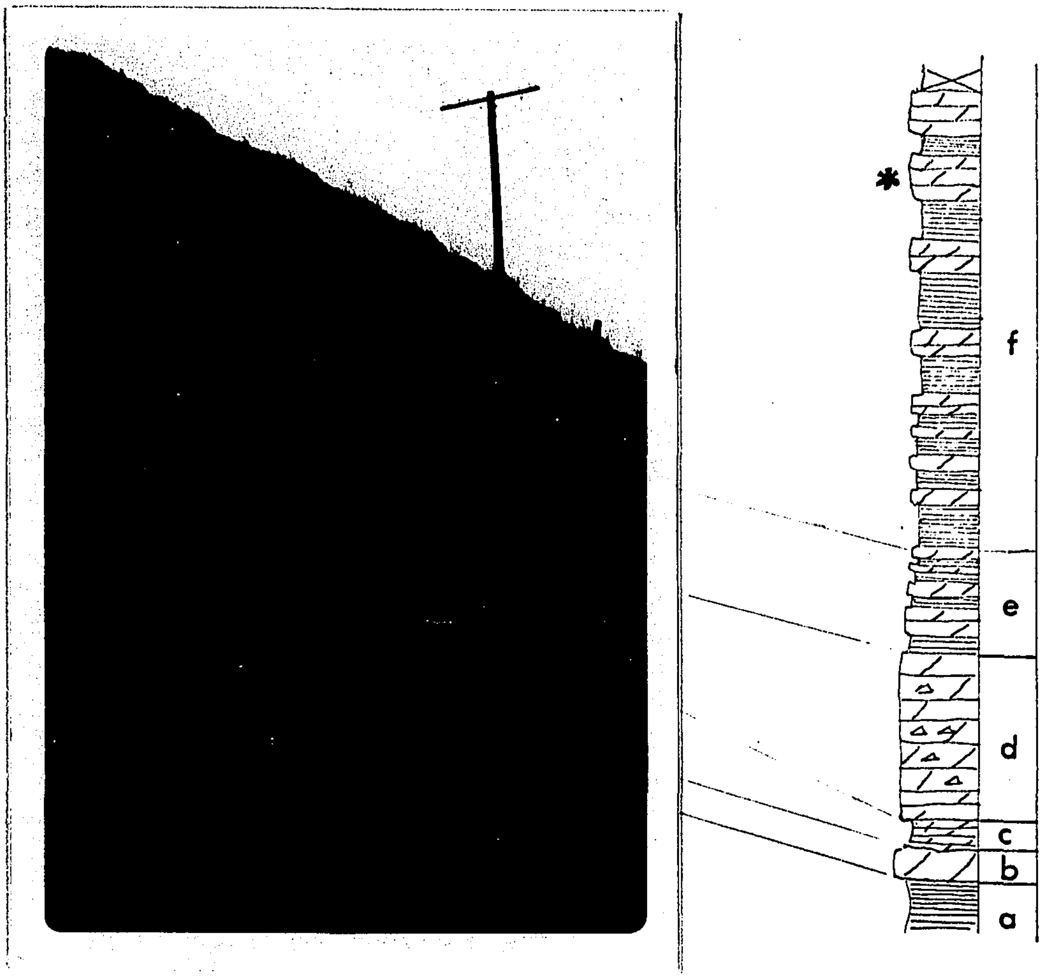

E
D
C
B
A

Fig. 18. An exposure of the Elkhorn and Brassfield Formations near Tollesboro, Kentucky (Section 40). One formally named (F) and four informally named members (B, C, D, E) of the Brassfield are present: (A) Elkhorn Formation, (B) Lower massively bedded member, (C) thin bedded dolomite and shale, (D) Upper massively bedded dolomite with shale, (E) upper thinly bedded dolomite and shale, (F) Noland Member. Compare with figs. 17, 19, 21.

Fig. 19. Exposure of the Elkhorn and Brassfield Formations in a roadcut about 1 mile southwest of Jacksonville, Ohio (Section 42). One formally named (g) and six informally named units (B, C, D, E, F) of the Brassfield are present: (A) Elkhorn Formation, (B) Lower massively bedded member, (C) thinly bedded dolomite and shale, (D) massively bedded dolomite, (E) thinly bedded limestone and shale (F) massively bedded limestone containing glauconitic chert, (G) Noland Member which consists of thinly bedded limestone and shale. Compare with figs. 17, 18, 21.



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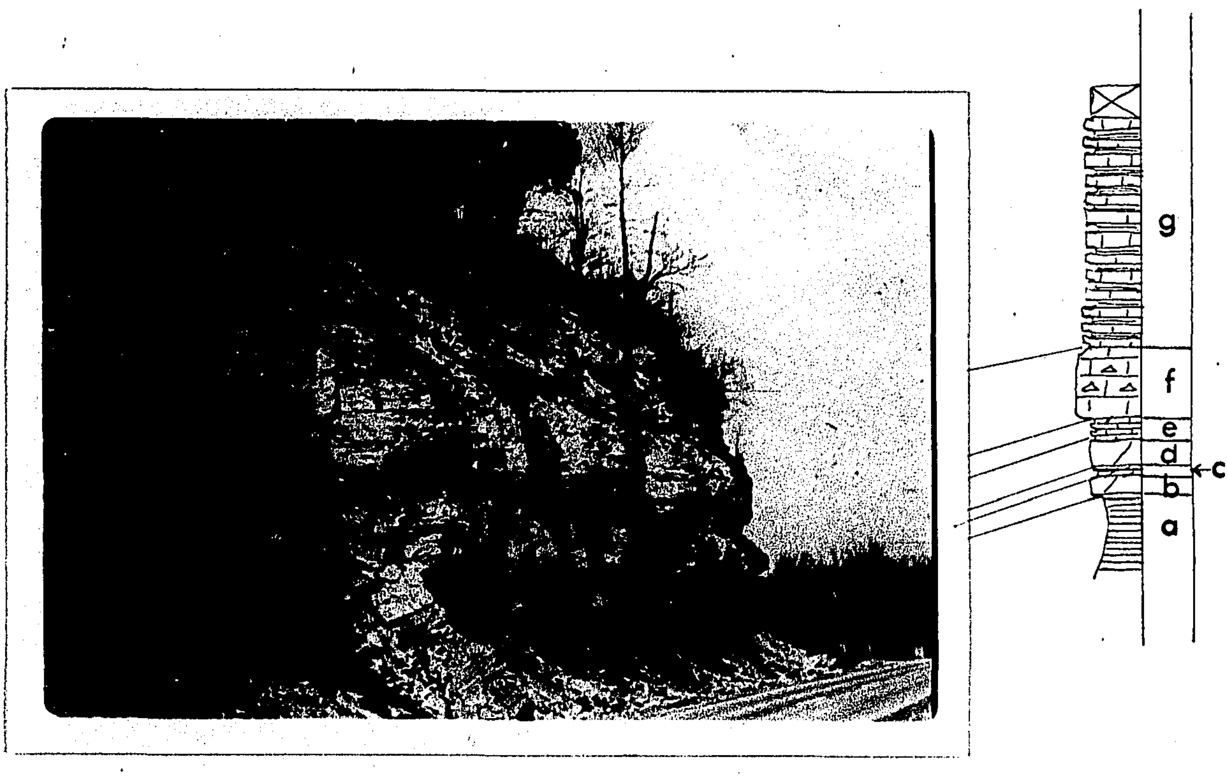
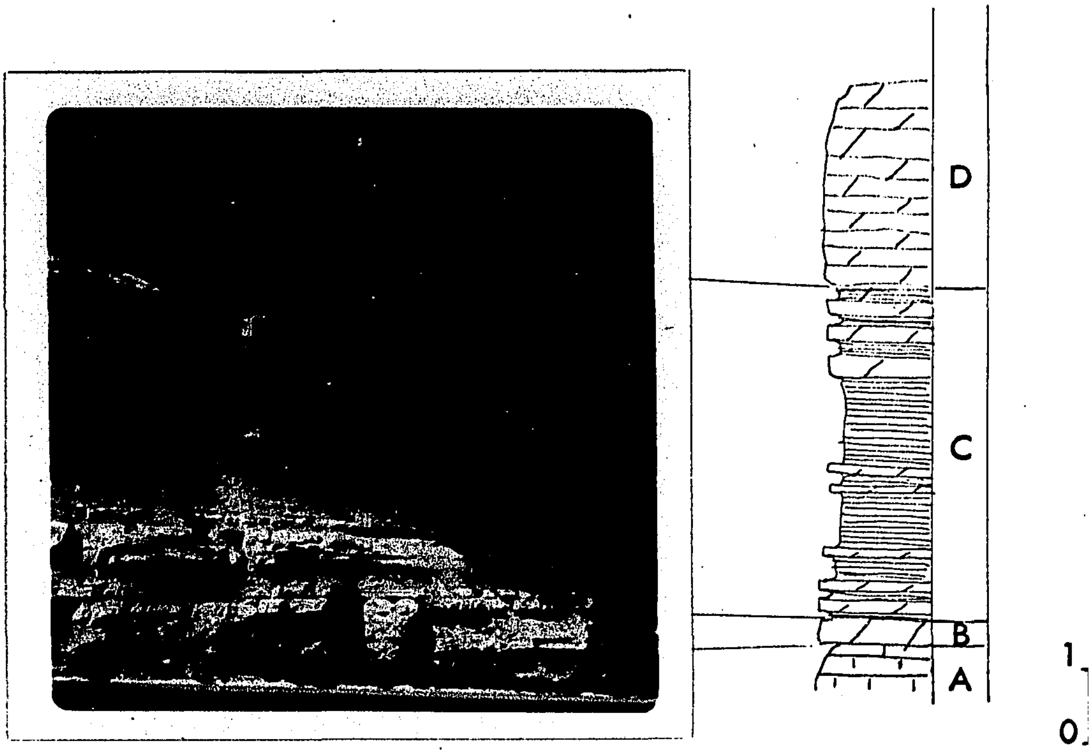


3
0

Fig. 20. Exposure of Whitewater (A), Brassfield (B), Osgood (C), and Laurel (D) Formations on Powerhouse Road (Section 5) near Madison, Indiana.

Fig. 21. Exposure of the Elkhorn (A) and Brassfield Formations (B, C, D, E) on U. S. Rt. 52 at the mouth of Ohio Brush Creek (Section 41). One formally named member (E) and three informally named members of the Brassfield are present: (B) Lower massively bedded member, (C) thinly laminated limestone and shale, (D) massively bedded limestone containing chert beds, (E) the Noland Member which consists of limestone and shale with at least one hematite bed 12 cm thick about 9 meters above the base of the Brassfield. (Meter stick in lower right part of the photo for scale).


D
C
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1
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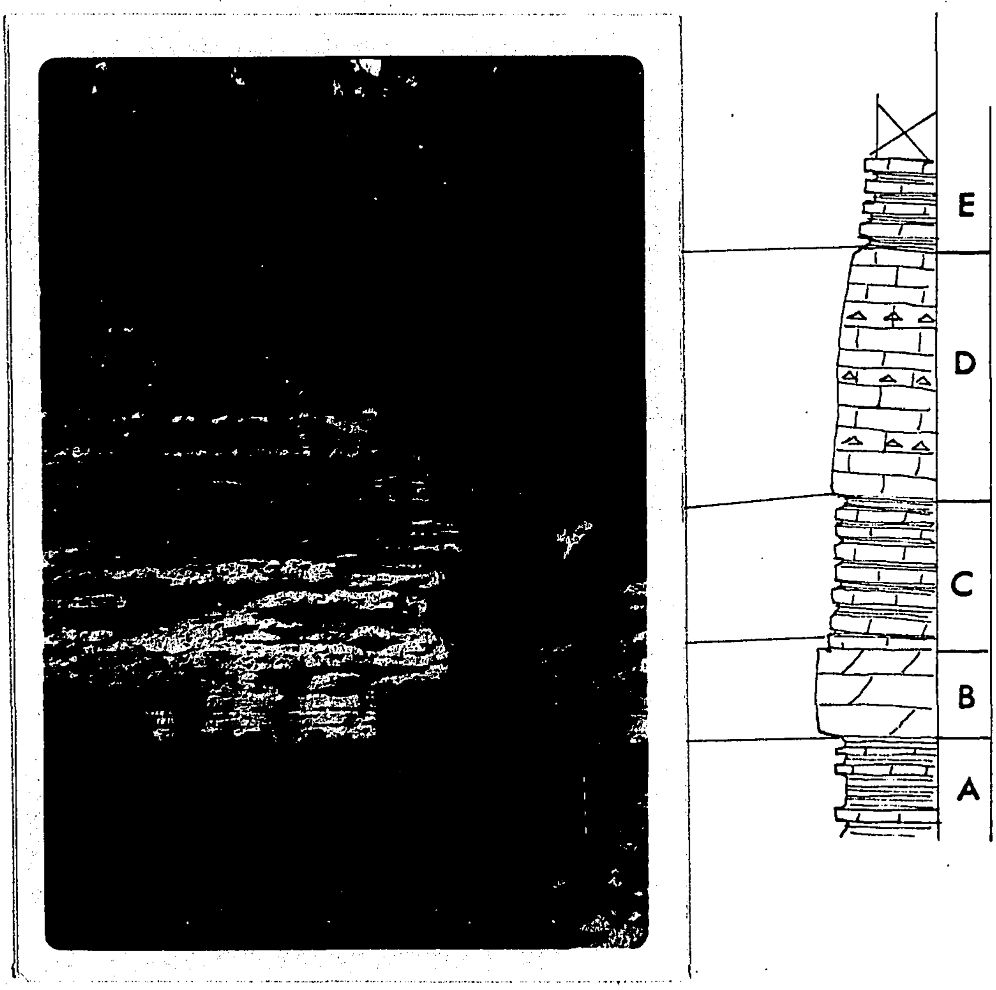
E
D
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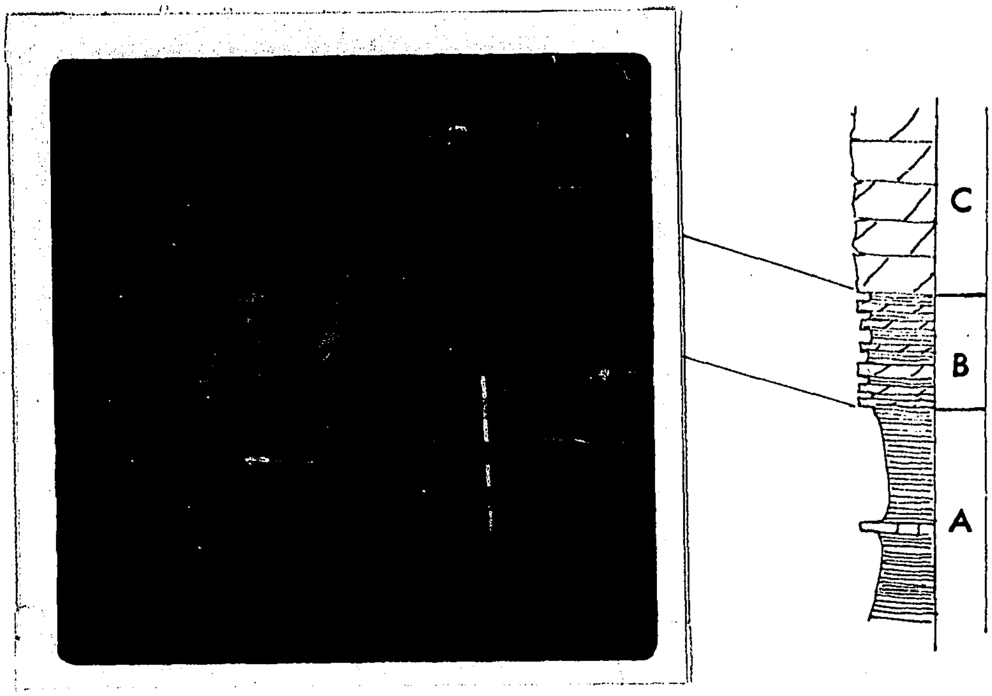
Fig. 22. Exposure of the Elkhorn (A) and Brassfield Formations (B, C) at Section 15, Lumberton, Ohio. Two members of the Brassfield are visible in the upper part of the photo: (B) Belfast Member, and the Lower massively bedded member (C). (Meter stick for scale).

Fig. 23. Contact of the Drakes (A) and Brassfield Formations (B, C) on I-75 near Berea, Kentucky (Section 32). The Lower massively bedded Brassfield (B) thins from 86 cm at the left side of the photo to 27 cm on the right. It is overlain by the Upper thinly bedded Brassfield (C). (Meter stick for scale).


C
B
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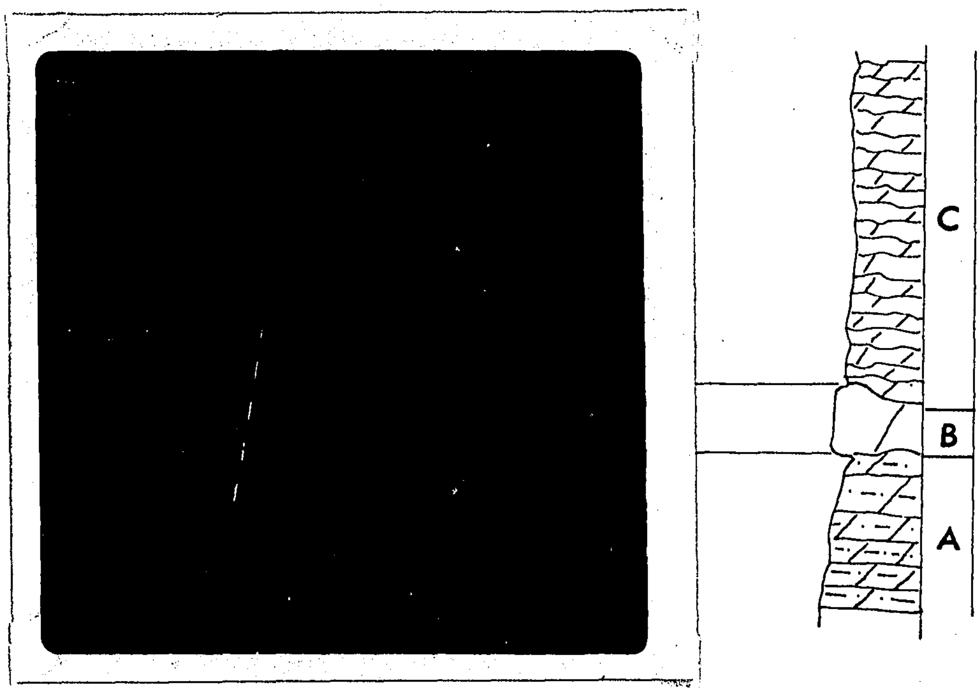
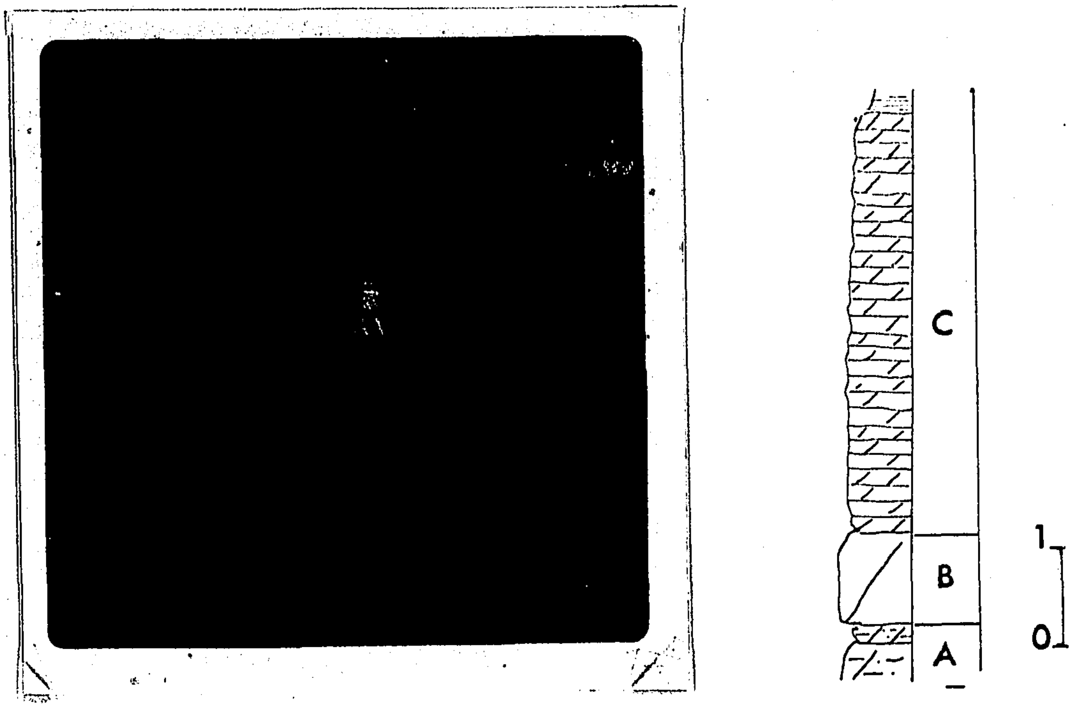
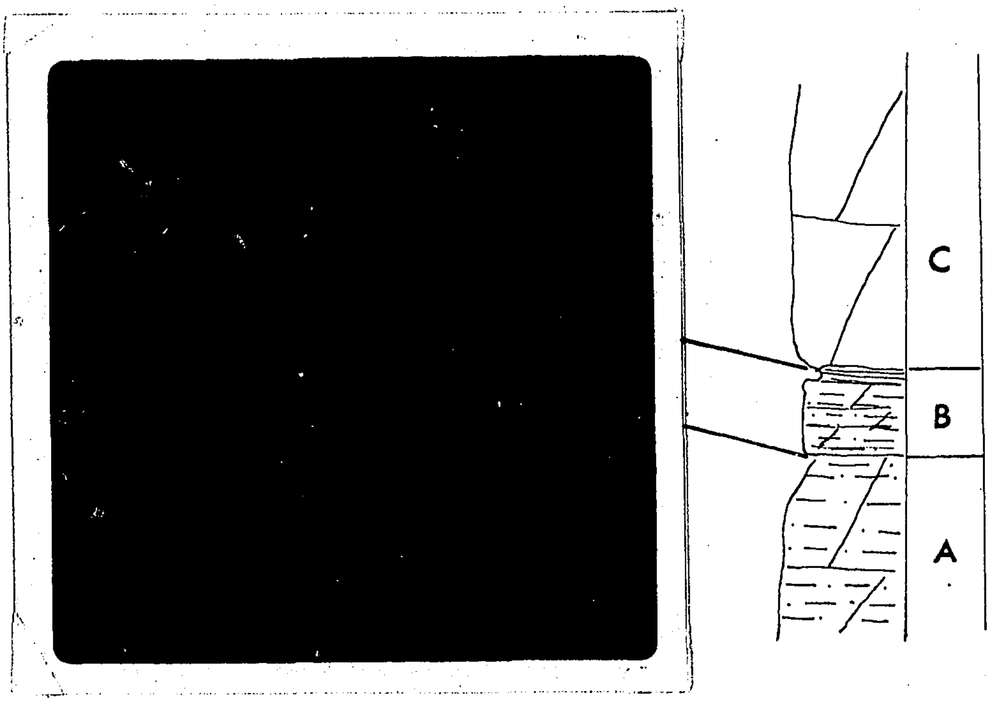

C
B
A

Fig. 24. Contact of the Saluda (A) and Brassfield Formations (B, C) on the Kentucky Blue Grass Parkway near Bardstown, Kentucky (Section 16). The contact between the Lower massively bedded Brassfield (B) and the Upper thinly bedded Brassfield (C) is marked by a distinctive change in color.

Fig. 25. Detail of the above photo showing the contact of the Saluda (A, B) and the Brassfield Formations at Section 16. (B) is the "Hitz Bed" which is a thinly laminated silty dolomite which serves as a marker for the top of the Saluda.


C
B
A
1
0


C
B
A

Dayton Formation

The Dayton Formation is typically a dense, medium crystalline biogenic dolomite which ranges in thickness from 0.5 to 4 meters. Bedding is regular, in contrast to the irregularly bedded upper part of the Brassfield. Most beds range from 5-10 cm. thick. Some nodular chert is present in the Dayton in the vicinity of Richmond, Indiana. The Dayton was named by Orton in 1871 (p. 297) for strata exposed near Dayton, Ohio.

In its northern exposures, contact with the underlying Brassfield is sharp. Bowman reported (1956) that the Dayton Formation truncates cross bedding in the Upper Brassfield in Highland County, Ohio thus indicating a pre-Dayton erosional interval in Ohio. The Dayton begins to lose its identity south of Highland and Adams Counties, Ohio, and it can be traced into the Noland Member of the Brassfield. The upper contact of the Dayton with the Crab Orchard Shale is sharp in Highland and Adams Counties. To the north near Dayton and Centerville the upper Dayton becomes more argillaceous and the upper carbonate layers are interbedded with thin shale layers. Going to the southwest in Indiana the Dayton can be traced into the shales and carbonates of the Osgood Formation.

The Dayton's fauna is sparse east of the Miami River in Montgomery, Miami, Clark, and Greene Counties, Ohio. Foerste (1935, p. 138) reported finding isolated specimens of Favosites, orthocerone cephalopods, and one specimen of Pentamerus, possibly Pentamerus peeblesensis near Dayton. South of Wilmington, Ohio corals become prominent. Pentamerus peeblesensis is common locally. It was the presence of Pentamerus peeblesensis which led Foerste to provisionally correlate the Dayton with the Wolcott Limestone of New York.

Although the Dayton can be traced into the Noland Member of the Brassfield and it occupies the stratigraphic position of the Waco Tongue, it will be accorded formational rank north of the Ohio River in this study. South of the River the upper contact of the Noland is gradational with the Crab Orchard Shale, while north of it, this contact is quite sharp.

Crab Orchard Formation

The Crab Orchard Formation was named by Linney in 1882 for a series of light green and reddish brown clay shales in Garrard and Lincoln Counties, Kentucky. Foerste (1906, p. 10) divided the Crab Orchard "division" into the Alger and Indian Fields Formations. These two formations were further subdivided into the Plum Creek Clay, Oldham Limestone, Lulbegrud Clay, Waco Limestone, and Estill Shale. Foerste (1906, p. 62) himself conceded that:

> "...From a lithological standpoint, this grouping of strata is perhaps not as natural as one in which the entire Silurian section of east-central Kentucky would be divided into two great divisions, consisting of a great lower division including chiefly limestone, but also one considerable clay deposit, and of a great upper division, consisting almost entirely of clay. In this case the lower division would include the Brassfield, Plum Creek, and Oldham beds, while the upper division would include all of the Alger Formation..."

Foerste was trying to establish stratigraphic equivalency of the Kentucky section with the Silurian of Ohio. The Brassfield of Kentucky was the same as the rocks called Clinton in Ohio. The Crab Orchard was correlated with the Niagara Shale in Ohio. The Dayton Limestone formed the basal part of the Niagara Shale and Foerste believed it to be the same as the Oldham of Kentucky. Foerste called the great mass of clays overlying the Oldham, the Alger Formation, and the carbonates and shales directly over the Brassfield, the Indian Fields Formation.

Since these divisions are not, strictly speaking, natural rock stratigraphic divisions, it is proposed here that the Crab Orchard be redefined and referred to as the Crab Orchard Formation. The lower part is considered to be a member of the Brassfield Formation, that is, the Noland Member, and it would include the Plum Creek, Oldham, Lulbegrud, and Waco horizons. This would leave only the Estill Shale in the Crab Orchard "Division". Since the name Crab Orchard has priority the name Estill Shale should be dropped.

Osgood Formation

The Osgood Formation was named by Foerste (1896, pp. 191-192) for the strata underlying the Laurel "Limestone" and overlying the Clinton Limestone (Brassfield) (fig. 20). The type area is at Osgood, Ripley County, Indiana. The Osgood is a widespread unit and has been recognized from Missouri to Tennessee. Foerste (1935, pp. 164-165) recognized four members in southeastern Indiana which are listed here in descending order:

Upper Osgood Shale	2-5'
Osgood Limestone	3-5'
Lower Osgood Clay	3-16'
Basal limestone	8"-32"

The basal limestone may be a phase of the Dayton Formation and the upper shaly part of the Osgood probably represents the Crab Orchard lithosome. The Dayton grades up into shales which can be traced southwest into the Osgood in Indiana and southeast into the Crab Orchard of Kentucky.

South of the Ohio River the Osgood section thickens and the shales become more prominent. Near Bardstown, Kentucky it consists of about 35 feet (section not measured) of pale olive (10Y 6/2) and dusky red (5R 3/4) clay shales. Lithologically the Crab Orchard Shale, on the east side of the Cincinnati Arch, is very similar to the Osgood. At College Hill, Madison County, Kentucky, the Crab Orchard of approximately 50 feet (not measured) of pale olive

(10Y 6/2) shales which become dusky red (5R 3/40) toward the top. The two rock bodies differ in that the upper contact of the Brassfield with the Crab Orchard is gradational whereas it is quite sharp with the Osgood.

Foerste (1931, p. 177), in listing the Osgood fauna, noted that it consists of 44 species of cystids, 9 crinoids, 31 bryozoans, 22 brachipods, 6 corals, 4 gastropods, 3 trilobites, and 1 cephalopod. Most striking, according to Foreste, is the number of species of cystids. Out of 44 species 38 were originally described as belonging to the genus Holocystites. All of the crinoids except 1 belong to the genus Stephanocrinus. Foerste (1931, p. 178) found a close correspondance between the fauna of the Osgood and Rochester Shale (Upper Clinton) of New York. Of the 31 bryozoans found in the Osgood of Indiana, 29 also occur in New York. On this basis Foerste correlated the Osgood with the Rochester.

Summary of Nomenclature Changes

The following nomenclatural changes are proposed. Justification is given in the text:

1. The Brassfield "limestone" be recognized as the Brassfield Formation. At the type locality and much of Kentucky it is dolomitic, so the lithologic designation is a misnomer. Furthermore the Brassfield as amended in this study includes extensive shale beds.

2. The Crab Orchard "group" of Foerste (1935) is better evaluated as the Crab Orchard Formation, and that the Alger Formation, Indian Fields Formations and the Estill Shale of the Crab Orchard "group" are highly local expressions and little is gained by continuing to employ these designations regionally.

3. The Noland Formation of the Crab Orchard "group" is best evaluated as a member within the Brassfield Formation. It consists of interbedded shales, dolomites, and limestones which have been called the Plum Creek Shale, Oldham Limestone (Dolomite), Lulbegrud Clay, and Waco Limestone (Dolomite). It is recommended that they be reassigned as lentils (the shales) and tongues (the dolomites) of the Noland Member.

4. The Dayton "Limestone" is better referred to as the Dayton Formation because of its dominantly dolomitic character.

PETROGRAPHY AND MINERALOGY

Microfacies Analysis

The microfacies analysis is based on point counts of approximately 450 slides. Five major microfacies are recognizeable:

I Crinoidal-bryozoan biosparite

II Biogenic dolomite

III Medium crystalline dolomite

IV Hematitic biosparite

V Dolomitic-biomicrite

MICROFACIES I: The crinoidal-bryozoan biosparite facies, is typical of the undolomitized part of the Brassfield (figs. 26-30) in Ohio, Indiana, and Kentucky. It consists of moderately well sorted coarse calcarenites and calcirudites. A ternary plot of the allochems versus the matrix was prepared for sections 1, 2, 3, 4, 6, 7, 8, 10, 14, 41, and 43 and four of them are reproduced here (fig. 38). The great bulk of the samples fell along the line joining sparry calcite with the allochems. Most of the allochems were crinoid plates and columnals with lesser but significant numbers of bryozoa (fig. 27). The high number of crinoid fragments is probably a function of sorting and preservation. Their hydrodynamic properties are such that they are susceptible to comparatively little abrasion. Also in terms of the number of particles, a single crinoid upon death would produce 20 to 100 plates and 50 or more columnals. A brachiopod or bryozoan would produce little more than a dozen fragments at best.

Median grain size of the allochems is 0.08 Ø. This was calculated by plotting the sizes of the allochems on a cumulative percent graph using class intervals of 1 Ø unit each. This was based on a population of 116 thin sections made from the rocks collected at the above localities. The inclusive graphical standard deviation is 0.98 Ø and it was calculated by the formula:

$$\sigma I = \frac{\text{Ø}84 - \text{Ø}16}{4} + \frac{\text{Ø}95 - \text{Ø}5}{6.6} \quad \text{(Folk, 1962)}$$

According to Folk's sorting classes Microfacies I would be a well sorted calcarenite. In a comparison of this microfacies with Folk's plot (1962, p. 79) of mean size (Ø 50) versus soring (σI) for the sediment samples of Isla Perez, Alacran reef, Microfacies I fell within the "field" of the submerged as opposed to the beach samples.

The bedding of Microfacies I is usually thin and irregular. Current ripples and cross-lamination are common. Considering this and the degree of soring, Microfacies I probably represents a shallow water, high energy environment. Waves and currents sorted the fossil fragments, breaking them up in the process. Cementation could have resulted from intrastratal solutions or by exposure to subaerial weathering in which there would be partial leaching of the

$CaCO_3$ and deposition of it as sparry calcite in the pore spaces. The latter process is operative today on Bermuda. The Bermuda "Eolianites" are used commercially as a building material. They are soft and friable when fresh. They can be readily quarried and cut with an ordinary saw. The cut blocks are exposed to the atmosphere for several months. The $CaCO_3$ on their surface is leached and redeposited in the pore space of the blocks forming a very effective natural cement.

MICROFACIES II: The biogenic dolomite facies, is typical of most of the Brassfield dolomites as well as the Dayton Formation (figs. 26, and 31-33). Where there is extensive recrystallization and crystal growth they are very difficult to see. Recognition is best brought about by adjusting the microscope's diaphragm for maximum contrast and covering the source of illumination with tissue paper to make the lighting more diffuse. Usually there were too few fossil ghosts in a given thin section to compute the average grain size, but the maximum grain size was noted. It ranged from 0.50 mm to 7.5 mm.

Where recrystallization is not too great this microfacies resembles Microfacies I. Most likely it began with parent material similar to that of Microfacies I. Crinoid, bryozoan, and shell fragments were cemented by sparry calcite. At some time following cementation there was a lowering of sea level causing these rocks to fall into a zone in which they would be acted upon by hypersaline brines (see section on origin of dolomite).

MICROFACIES III: The medium crystalline dolomite facies, differs from Microfacies II in that it contains no recognizeable fossils (fig. 34) and is of more limited areal extent. It appears to be limited to portions of the Lower massive Brassfield south of the Ohio River especially where it is thinly laminated. Because of the thin laminae and the massive bedding it is thought to represent a quiet water environment in which there is slow accumulation of calcium carbonate. Bottom muds in this environment may have consisted of micrite and aragonite. Dolomitization may have been brought about, shortly after deposition, by the same mechanism which produced the dolomites in Microfacies II except that recrystallization has been more extensive.

MICROFACIES IV: The hematitic biosparite microfacies is restricted to the east side of the Cincinnati Arch from Greene County, Ohio to Bath County, Kentucky. The hematite is found in irregular, thin limestone or dolomite beds ranging from 2-100 cm. thick. These beds occur close to the top of the thin bedded Brassfield or within the Noland Member. Chert beds and hematite are not found in all outcrops together but when they are both present, the hematite occupies a higher stratigraphic position.

The rocks of the hematitic biosparite microfacies are well sorted, coarse calcarenites, crinoidal-bryozoan biosparites. They are ripple marked and cross-laminated indicating that they were deposited in a high energy environment. The hematite replaces, fills, and coats bioclasts (figs. 35; 43-48). X-ray diffraction analysis of the hematite-biosparite microfacies samples from Sections 14, 38, and 41, and thin section analysis of these samples indicate that they contain primarily hematite with minor amounts of pyrite. Some of the hematite has weathered to limonite. This can be observed in hand specimen and thin section. Glauconite and chamosite are apparently absent for they were not detected by either X-ray diffraction of thin section analysis.

Alling (1947, p. 995) stated that the Clinton type ores are of two types: one is a "fossil ore" in which the hematite fills and/or replaces bioclasts; the other is an "oölitic ore" in which a nucleus is surrounded by layers of hematite, chamosite, and glauconite. The Brassfield hematite beds are primarily of the "fossil ore" type although they do contain some "oölites".

Allochems in the rocks of Microfacies IV are cemented by clear sparry calcite thus indicating that replacement took place prior to cementation. The genesis of the iron ores will be considered later.

MICROFACIES V: The dolomitic biomicrite microfacies, coincides with the Belfast Member of the Brassfield. It is found north of the Ohio River from West Union, Adams County, Ohio, north to Troy, Miami County, Ohio, and as far west as Richmond, Wayne County, Indiana. It consists of poorly sorted, thin regularly bedded calcisiltites and calcilutites which are sometimes interbedded with shale (fig. 22). When shale is present it diminishes towards the top of the Belfast. Dolomite content of these beds ranges from less that 5% at Section 12 to greater than 50% at Sections 7, 14, 15, 42, and 43. The insoluble residue content of these beds is consistently higher than the overlying beds as is shown in Table II.

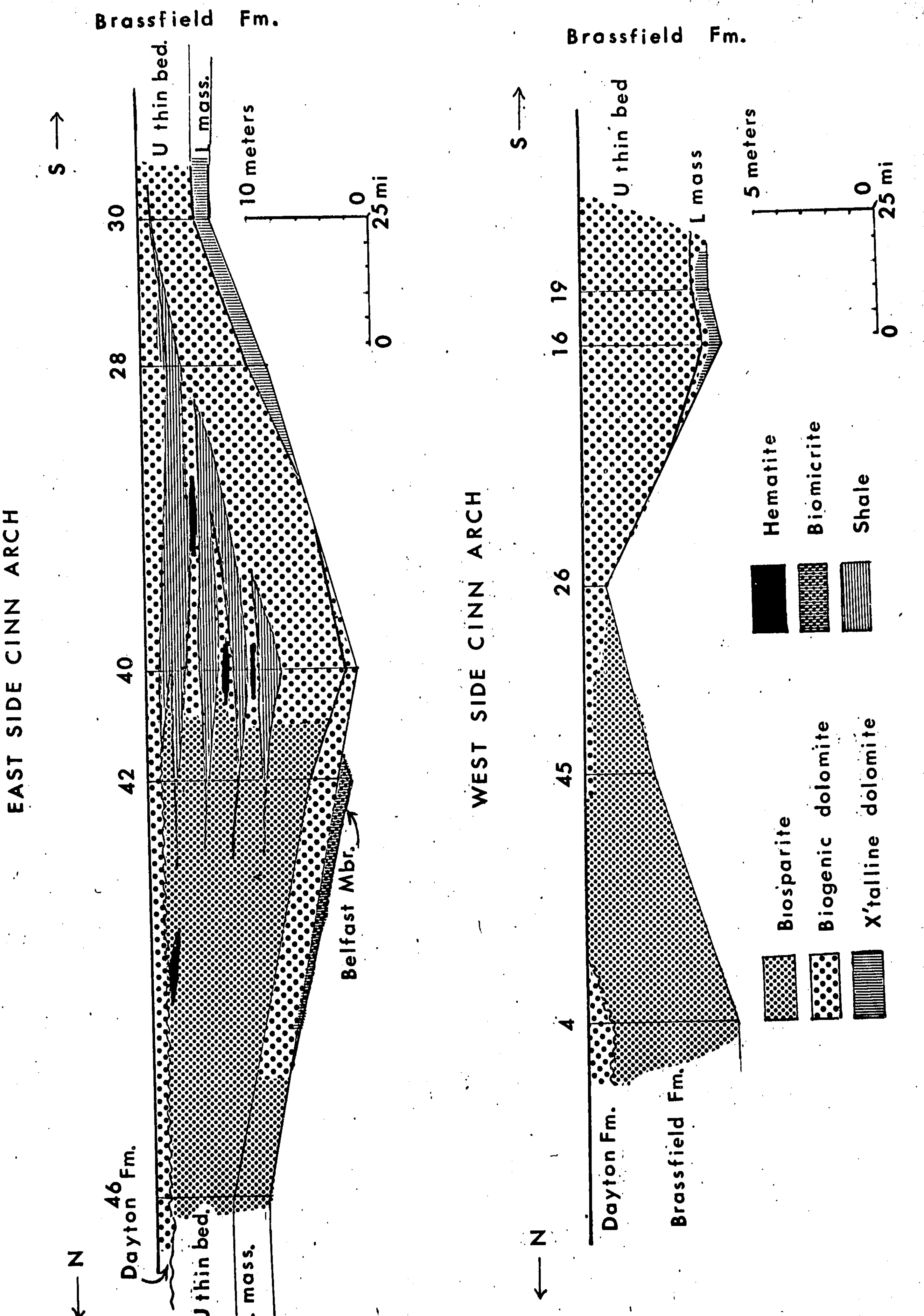
Table II

Section #	Wt. % Insoluble Residue Belfast Member	Wt. % Insoluble Residue Brassfield Fm. less the Belfast Member
7	11.11%	9.24%
12	9.34	2.05
14	25.26	7.69
42	27.11	12.23
43	23.79	7.41

Fossils are common to rare in Microfacies V depending on the degree of dolomitization (figs. 36, 37). Generally shell fragments predominate over bryozoans and crinoid columnals. Microfacies V represents a lower energy environment than the other four microfacies just described. Terrigenous detritus is highest in this microfacies indicating turbid waters, or a long period of slow carbonate deposition with a more or less constant, slow influx of terrigenous material.

Fig. 26. (Top)
North-south cross section of the Brassfield Formation on the east side of the Cincinnati Arch showing the relationship between the microfacies and the various members of the Brassfield.

(Bottom)
North-south cross section of the Brassfield Formation on the west side of the Cincinnati Arch showing the relationship between the microfacies and the various members of the Brassfield.


EAST SIDE CINN ARCH
Brassfield Fm.
U thin bed
L mass.
S →
10 meters
0
0
25 mi
30
28
40
42
46
Dayton Fm.
U thin bed
L mass.
Belfast Mbr.
← N
WEST SIDE CINN ARCH
Brassfield Fm.
U thin bed
L mass
S →
5 meters
0
0
25 mi
16
19
26
45
4
Dayton Fm.
Brassfield Fm.
← N
Hematite
Biomicrite
Shale
Biosparite
Biogenic dolomite
X'talline dolomite

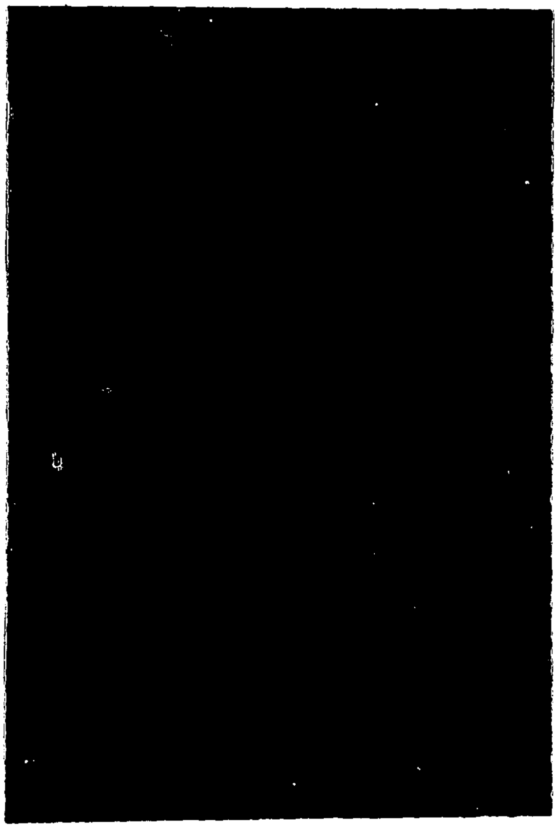
Microfacies I

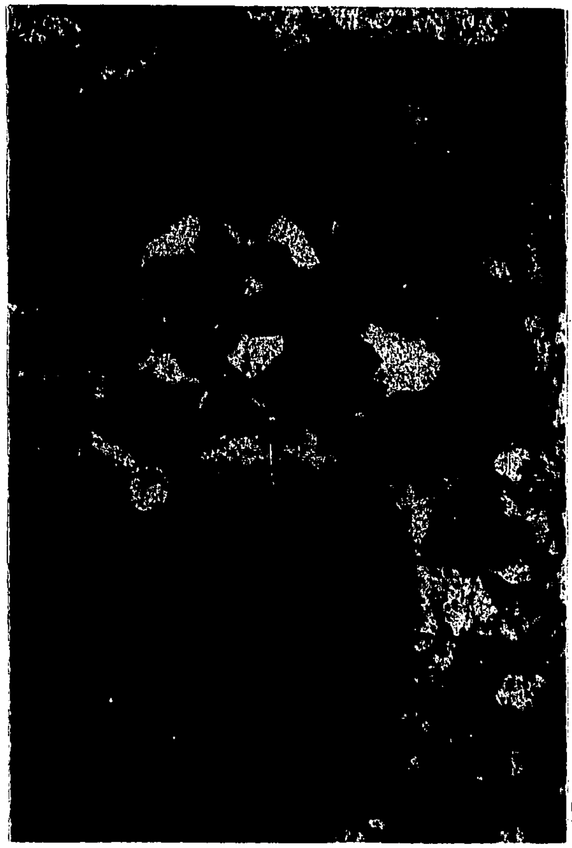
Fig. 27. Photomicrograph (40X) of the Lower Massive Brassfield 82-93 cm. above the Elkhorn Formation at Section 11, Eaton, Ohio. The Brassfield in this photo is a fine calcirudite, biomicrudite, exhibiting partial replacement of the micrite and a bryozoan by dolomite rhombs.

Fig. 28. Photomicrograph (40X) of the Upper thin bedded Brassfield at Section 12, Easton, Ohio. This sample is characteristic of the Upper Brassfield which consists of coarse calcarenites, fine calcirudites, crinoidal biosparites and biosparrudites.

Fig. 29. Photomicrograph (40X) of the Lower Massive Brassfield 195-205 cm. above the Elkhorn Formation at Section 42, Jacksonville, Ohio. The dark crinoid plate in the center of the field is replaced by glauconite.

Fig. 30. Photomicrograph (40X) of the Upper thin bedded Brassfield 185-188 cm. above the Elkhorn Formation at Section 11, Eaton, Ohio showing partial replacement of fossil fragments and sparry calcite by dolomite rhombs.



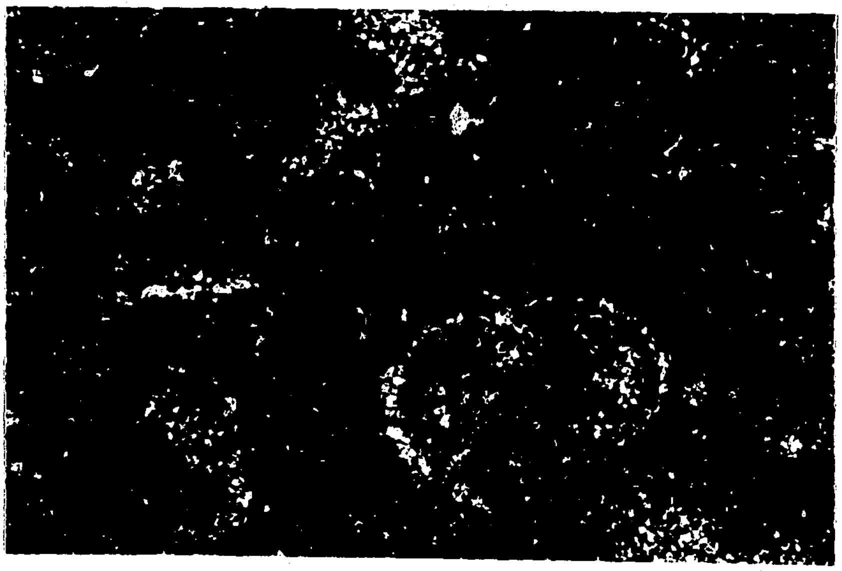


Microfacies II

Fig. 31. Photomicrograph (40X) of the Dayton Formation at Section 46, West Milton, Ohio, showing fossil ghosts in a fine crystalline dolomite.

Fig. 32. Photomicrograph (40X) of the Waco Dolomite at Section 39, Goddard, Kentucky, showing a crinoid plate replaced by dolomite.

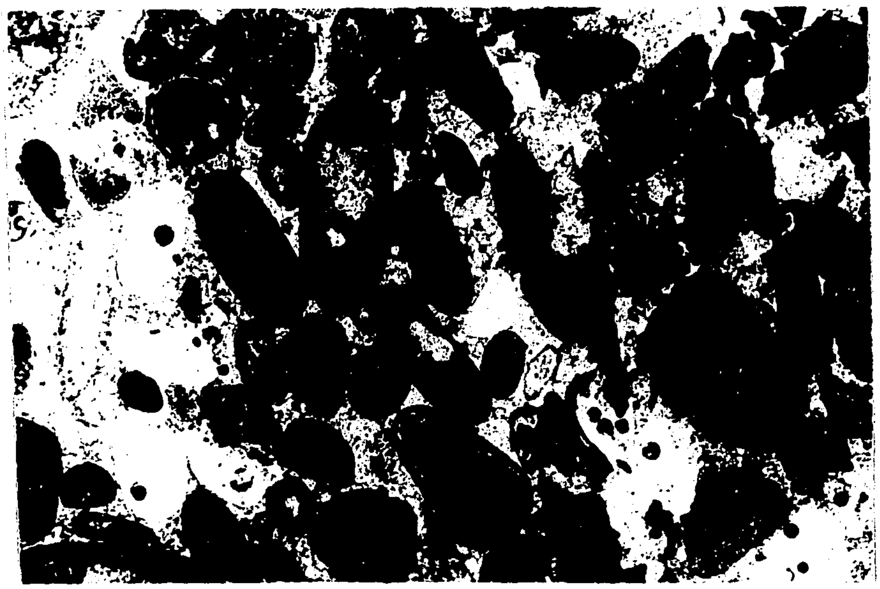
Fig. 33. Photomicrograph (40X) of the Osgood Formation 30-35 cm. above the Brassfield Formation at Section 1, Laurel, Indiana, showing fossil ghosts.



Microfacies III and IV

Fig. 34. Photomicrograph (40X) of the Lower Massive Brassfield 1-4 cm above the Drakes Formation at Section 28, Bybee, Kentucky, showing a medium crystalline dolomite devoid of fossils. (Microfacies III).

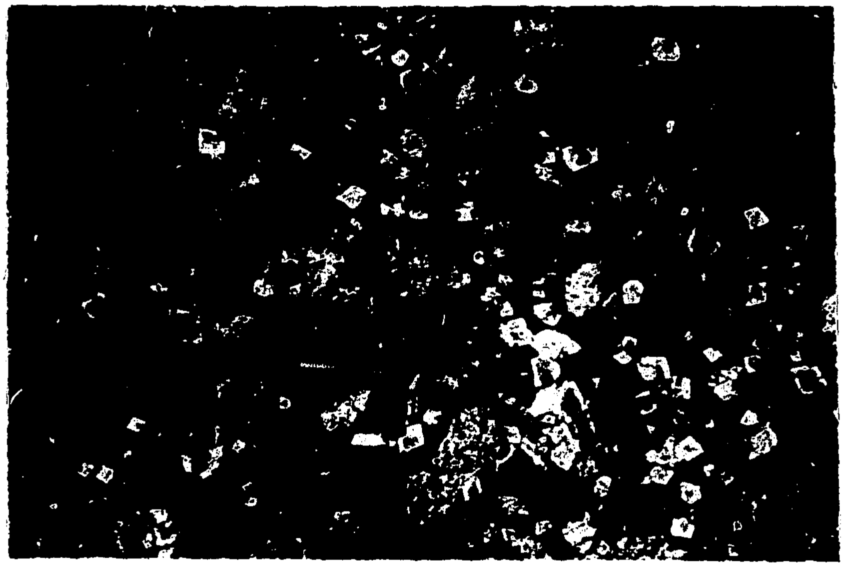
Fig. 35. Photomicrograph (40X) of the hematitic Brassfield 817-827 cm. above the Elkhorn Formation at Section 14, Lumberton, Ohio. The photo shows a coarse calcarenite, crinoidal biosparite, in which porous crinoid plates have been filled and surrounded by hematite. The rounded oval shape suggests chemical accretion of the hematite and the probability of subaequeous agitation prior to cementation. (Microfacies IV).

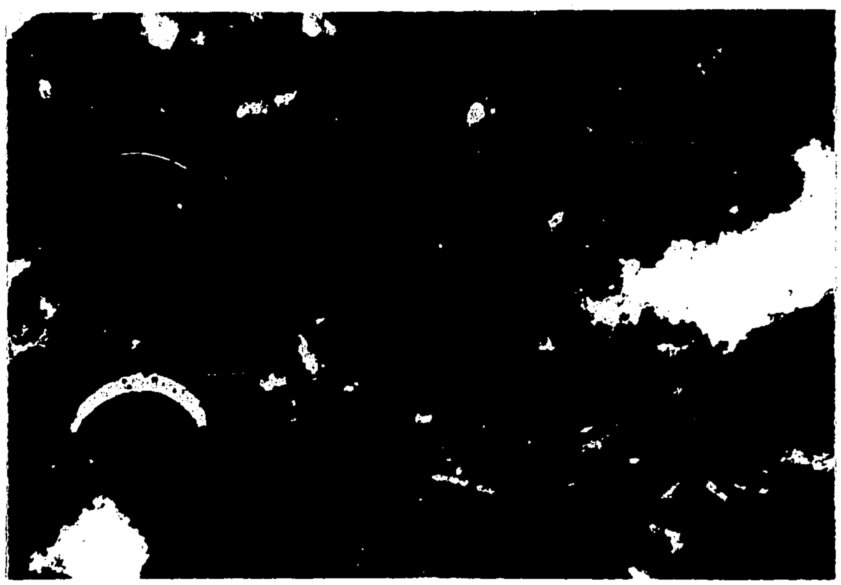


Microfacies V

Fig. 36. Photomicrograph (40X) of the Belfast Member of the Brassfield 23-25 cm. above the Elkhorn Formation at Section 12, Eaton, Ohio. At this locality the Belfast is a slightly dolomitic biomicrite. Compare with the sample illustrated below.

Fig. 37. Photomicrograph (40X) of the Belfast Member of the Brassfield 43-45 cm. above the Elkhorn Formation at Section 12, Eaton, Ohio. This sample has a lower dolomite (5% vs. 26%) and allochem content than the specimen shown in Fig. 36.





Thin Section Data

Point counts were made of all thin sections. The following characteristics were noted:

(1) Lithic components

(2) Size of allochemical components

(3) Mineralogy

(4) Rock fabric

LITHIC COMPONENTS: Allochems, sparry calcite cement, and microcrystalline calicite matrix (micrite), were observed primarily in the area north of the Ohio River (section 41) on the east side of the Cincinnati Arch, and north of Mt. Washington, Kentucky (Section 22) on the west side. To the south of the Ohio River and Mt. Washington, dolomitization had destroyed most allochems, sparry calcite, and micrite. This can be seen in fig. 39 by comparing the plot of the median size of the allochems versus the median percent of dolomite. Where the rocks are greater than 45-50% dolomite it was impossible to make accurate counts of the allochems, sparry calcite, and micrite. The allochems were subdivided into intraclasts and bioclasts. The bioclasts could be further divided into three components: crinoid plates and columnals, bryozoans, and shell fragments, which included brachiopod, trilobite and ostracod fragments. Volumetrically the crinoid and bryozoans were far more important than the shell fragments. Two ternary diagrams were prepared for the east side, and two for the west side of the Cincinnati Arch (fig. 38). Because of recrystallization, only Sections 2, 7, 8, 9, 14, 41, 42, and 43 were plotted for the east side and Sections 1, 3, 6, 10, 11, and 12 were plotted for the west. The three poles for the diagrams at the top of fig. 38 are for allochems, sparry calcite, and micrite, while in the diagrams at the bottom of the Plate they are for crinoids, bryozoans, and shell fragments. Data from the east side of the Cincinnati Arch is plotted on the right side of the Plate and data from the west side of the Arch is on the left. Contrasting the type of bioclasts between the east and west sides of the Arch it can be seen from fig. 38 that the points occupy slightly different areas. Those of the east are closer to the line joining the crinoid-bryozoan poles and are biased towards the crinoid end of the line. Samples from the west of the Arch are concentrated yet closer to the crinoid pole but they have a slightly higher shell fragment content. The plot of the allochems versus the sparry calcite cement and the microcrystalline matrix shows most points along the line joining the allochems and sparry calcite, close to the allochem pole. Five of the samples from Section 12, Eaton, Ohio, from the west side of the Arch, fall close to the micrite pole. These samples are from the Belfast Member of the Brassfield. The same thing can be seen on the east side of the Arch where three samples from Section 7, Belfast, Ohio, fall close to the micrite pole.

SIZE OF ALLOCHEMICAL COMPONENTS: The maximum and median size of the allochemical components was measured and plotted on fig. 39. Recrystallization and dolomitization destroyed most of the allochems south of the Ohio River, although occasionally fossil ghosts can be recognized. Usually the ghosts are so few in a given section that only a maximum size can be measured. Admittedly the maximum size, as measured in thin section, is always less than the true maximum size if for no other reason than the fact that the apparent size is a function of the orientation of the section. Furthermore even the choice of the section was selective in that rarely did it cross the largest allochem in the hand specimen. Maximum size was plotted for purposes of comparison. The greatest size encountered in thin section was 31 mm. at Section 10, the Wright Brothers Memorial, Fairborn, Ohio. Where the rocks have been dolomitized, in Kentucky, maximum size is less than in Ohio. Other than this, no particular pattern is discernible. With regard to the median size, the Brassfield could be characterized as a coarse calcarenite (Folk, 1962, p. 74) although particle size ranged from 0.3 mm. (medium calcarenite) to 1.2 mm. (fine calcirudite). No particular pattern could be discerned with regard to the median size and it should be emphasized here that the size of the allochems was extremely variable in a given outcrop or even thin section.

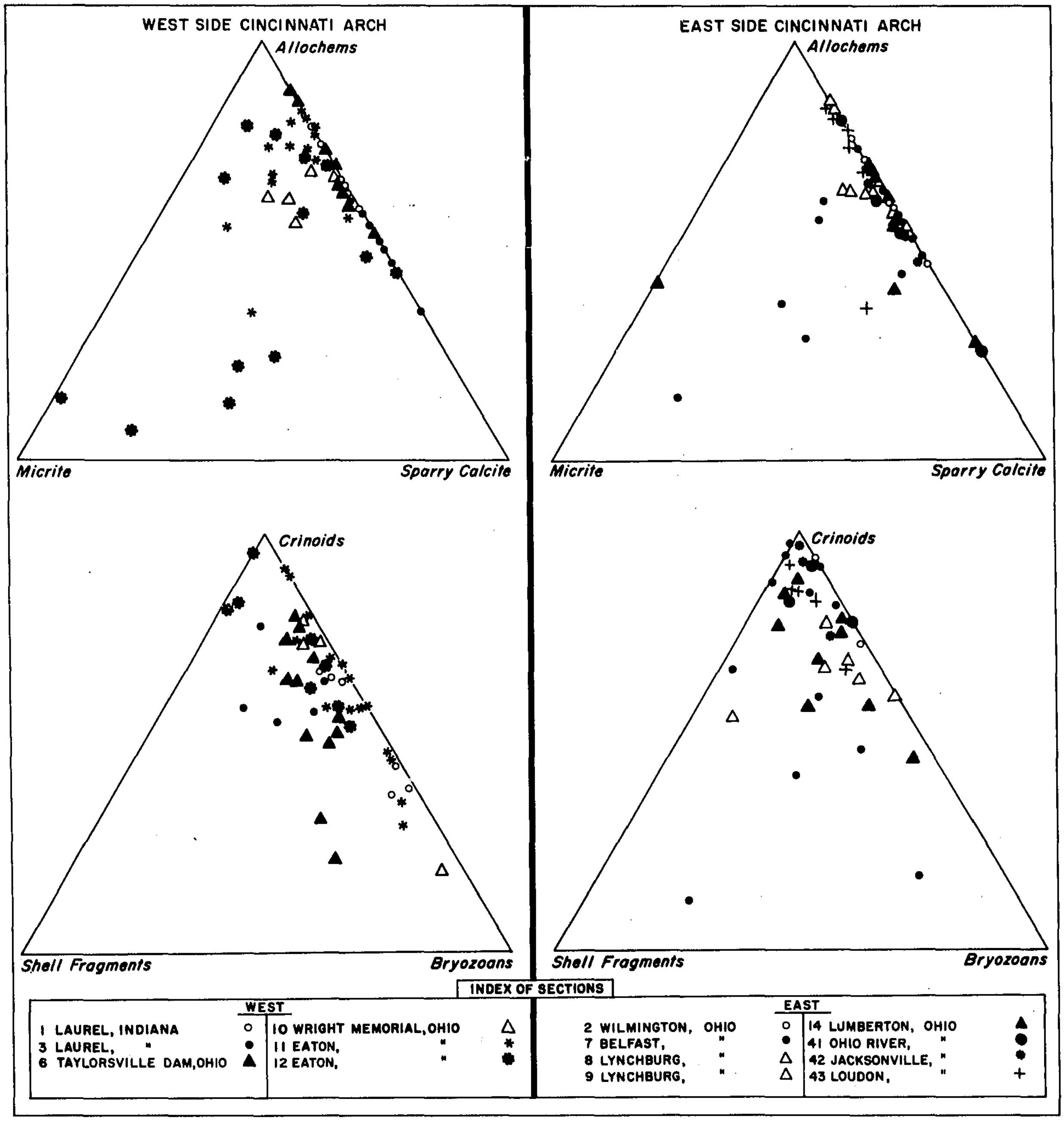

WEST SIDE CINCINNATI ARCH
Allochems
Micrite
Sparry Calcite
EAST SIDE CINCINNATI ARCH
Allochems
Micrite
Sparry Calcite
Crinoids
Shell Fragments
Bryozoans
Crinoids
Shell Fragments
Bryozoans
INDEX OF SECTIONS
WEST
1 LAUREL, INDIANA
3 LAUREL, "
6 TAYLORSVILLE DAM, OHIO
10 WRIGHT MEMORIAL, OHIO
11 EATON, "
12 EATON, "
EAST
2 WILMINGTON, OHIO
7 BELFAST, "
8 LYNCHBURG, "
9 LYNCHBURG, "
14 LUMBERTON, OHIO
41 OHIO RIVER, "
42 JACKSONVILLE, "
43 LOUDON, "

Fig. 38

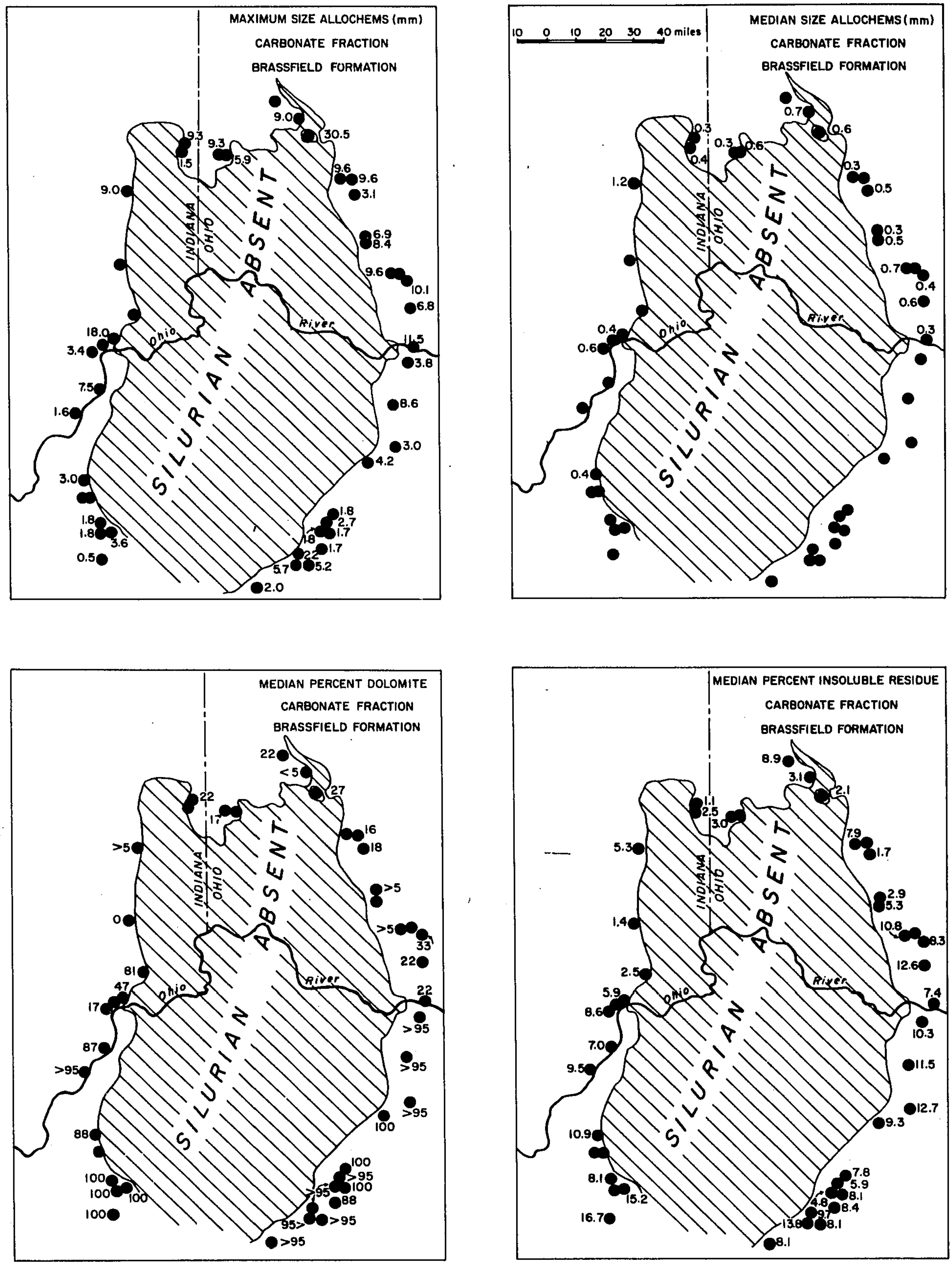

MAXIMUM SIZE ALLOCHEMS (mm)
CARBONATE FRACTION
BRASSFIELD FORMATION
MEDIAN SIZE ALLOCHEMS (mm)
CARBONATE FRACTION
BRASSFIELD FORMATION
10 0 10 20 30 40 miles
MEDIAN PERCENT DOLOMITE
CARBONATE FRACTION
BRASSFIELD FORMATION
MEDIAN PERCENT INSOLUBLE RESIDUE
CARBONATE FRACTION
BRASSFIELD FORMATION
INDIANA
OHIO
SILURIAN ABSENT
Ohio
River

Fig. 39

Mineralogy

CALCITE-DOLOMITE: The dolomite content of the rocks, in this study, was determined by X-ray diffraction, and by the petrographic microscope. Polished rock slabs were acid etched by immersing them in 1 normal hydrochloric acid for 2-3 minutes to see whether or not dolomitization had been selective. In the more northern outcrops dolomitization followed, very crudely, the bedding whereas south of the Ohio River, dolomitization was random.

The dolomite occurs in two forms. One form consists of well formed rhombs (fig. 27), and the other is as a replacement of fossil fragments, in which the original shell structure is sometimes well preserved (fig. 33). At times dolomite rhombs replace the bioclasts, and fossil ghosts are common in many of the dolomitic samples. Dolomitization has been greatest south of the Ohio River as can be seen on fig. 39 where the carbonate rocks are composed of more than 88% dolomite.

QUARTZ: Quartz is of minor importance in terms of the bulk volume of the Brassfield although it is an important constituent of most insoluble residues particularly on the east side of the Cincinnati Arch, south of Highland County, Ohio and on the west side south of Mt. Washington, Kentucky (Section 22). The quartz is of two varieties: detrital quartz, and euhedral quartz which is probably authigenic. Butterman (1961, p. 19), in his

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studies of the Silurian insoluble residues in southwestern Ohio, found most of the quartz to be of silt size. This was verified by a survey of the insoluble residues from sections 1, 2, 3, 5, 6, 7, 10, 11, 12, 14, 16, 18, 24, 25, 27, 31, 34, 35, and 36. The silt size grains are anhedral and angular. Some of Butterman's sections contained trace amounts of very fine to medium sand size quartz (ibid., p. 20). He found the smaller grains to be angular, but the larger ones were subangular to subround and in some instances polished. Doubly terminated quartz crystals are occasionally found in trace amounts. These crystals, when viewed under crossed nicols, show secondary enlargement around detrital quartz grains. These enlargements are in optical continuity with the detrital grains. In a few of the crystals there is no evidence of a nucleus, and the crystal appears to be authigenic.

CHERT: The chert is present as a fossil replacement material, and is chalcedonic or quartzose. It is white (N9) to yellowish gray (5Y 8/1) in color. The chert occurs as discrete nodules which are usually concentrated along bedding planes, as beds, and as small particles randomly distributed throughout the section. As was mentioned earlier, the chert is found progressively higher in the Brassfield as one goes from south to north, on the east side of the Cincinnati Arch. The chert is present as a fossil replacement material, or as a fibrous chalcedonic type which occurs as sand size fragments. The chert less frequently occurs as drusy irregular masses, stick-like forms which encrust pyrite crystals, radiating needle-like forms, and irregular powdery masses.

PYRITE: Pyrite is another important constituent of the insoluble residues. Like quartz it represents only a small percent of the bulk volume of the carbonate rocks but it is found in about 3/4 of the insoluble residues in amounts ranging from traces to over 95%. It commonly occurs as crystal aggregates, individual octahedra, and pyritohedra. Less commonly it occurs as individual cubes, dolomoldic masses, fossil replacements, and rod-like aggregates.

The crystal aggregates are irregular in shape. The crystal forms of the individuals composing the aggregates are generally octahedra and occasionally cubes and pyritohedra. Generally a single aggregate is made up of crystals of one form, but in some a combination of forms is present.

HEMATITE AND LIMONITE: Hematite is restricted to the "hematite beds" on the east side of the Arch. It commonly occurs as fossil replacements and as oölites (figs. 43-48). The oölites are either solid or are hematitic shells and range in size from 0.10 to 1.7 mm. The replaced forms consist almost exclusively of crinoid plates and columnals, and bryozoa.

Limonite occurs in many of the residues as an alteration product of hematite, pyrite, or glauconite. Sometimes it is found replacing fossil fragments but this is probably due to the oxidation and hydration of hematite, pyrite, or glauconite which originally replaced the fossil fragments.

GLAUCONITE: Two distinct classifications have been drawn up for the term glauconite. The earlier one is based on color and morphology. Mineralogists have set up another classification scheme based on chemical composition and structure. Burst (1958, p. 311) discusses the historical development of the two classification schemes for "glauconite". Following Burst (ibid.) the word glauconite will be used as a field term to describe greenish pellets and fossil casts, while the term "glauconite" is applied to monomineralic material in which a definite micaceous structure exists.

Glauconite is present in more than half of the insoluble residues examined. It is present as elongate pellets, semi-spheroidal, and free form bodies (ibid., p. 314). The elongate pellets are similar in form to fecal pellets. Some of the free form bodies resemble clay agglomerates, and some of the glauconite definitely represents cavity fillings.

Glauconite pellets were hand separated from crushed rock samples of sections 16, 18, 40, and 42, and were compared with glauconite from the Crab Orchard Formation collected at Section 39. Oriented samples were prepared and they were examined by X-ray diffraction and they consisted of poorly crystalline disordered material.

Miscellaneous--Hopkins (1954, pp. 30-32) reported finding feldspar, sphalerite, fluorite, celestite, brownish green tourmaline, marcasite, zircons, muscovite, and biotite. They are usually present in only trace amounts. In addition to these, I found small, very well rounded pink garnets at Sections 2, 6, and 25.

Insoluble Residue

It was recognized early in this study that the Brassfield had a higher insoluble residue content in Kentucky than in Ohio and Indiana. This reflects proximity to a source area. To compare the insoluble content of these rocks, ternary diagrams were prepared with calcite, dolomite, and the weight percent of insoluble residue plotted at the three apices. The area around the Cincinnati Arch was divided into four quadrants. Two were located on each side of the Arch. The Ohio River served as a north-south boundary on the east side of the Arch but the boundary on the west side of the Arch was arbitrarily placed about 10 miles north of the Ohio River to emphasize lithosomal differences. The quadrants are numbered in a clockwise fashion beginning with the northeast quadrant.

A ternary diagram was prepared for each area. The samples were plotted and can be seen in fig. 40. Most of the points plotted formed more or less natural groups close to either the calcite or dolomite pole. The median value for the percent dolomite and the percent of insoluble residue was calculated and is summarized on Table III.

TABLE III

Quadrant	% Dolomite	Wt. % Insoluble residue
I (Lower Brassfield)	57%	12%
(Upper Brassfield	18	7
II (Lower Brassfield)	95%	26%
(Upper Brassfield)	95	8
III	87%	8%
IV	5%	3%

Quadrant I is located on the east side of the Cincinnati Arch and extends from Dayton, Ohio to the Ohio River. Two prominent fields are present on the ternary diagram. The Lower massive Brassfield plots close to the dolomite pole while the Upper Brassfield plots near the calcite pole. The insoluble residue content of the Lower Brassfield is almost twice that of the Upper Brassfield but it is less than half as much as in the Lower Brassfield in Quadrant II. The insoluble residue of the Upper Brassfield is only 1% greater than the Upper Brassfield north of the Ohio River but it is the same as found in the Upper Brassfield in Quadrant III on the west side of the Cincinnati Arch.

Quadrant II extends from Tollesboro, Kentucky to Crab Orchard, Kentucky. Dolomite content of these rocks is in excess of 95%. The Lower massive Brassfield has over three times as much insoluble material as the Upper Brassfield but the insoluble content of the Upper Brassfield is approximately the same as in Quadrants I and III.

Quadrant III extends from Cross Plains, Indiana (Section 45) south to Bardstown, Kentucky. The rocks all plot close to the dolomite pole, and are similar to the dolomites on the east side of the Arch except for a slightly lower dolomite content. The Lower Brassfield was only recognized in 4 of the 18 sections measured on the west side of the Cincinnati Arch, so Quadrants III and IV were not subdivided as were Quadrants I and II. In Quadrant III the Brassfield is primarily a dolomite and it becomes more calcareous towards the Ohio River. The insoluble residue content is the same here as on the east side of the Cincinnati Arch.

Quadrant IV is on the west side of the Cincinnati Arch and it extends from Richmond, Indiana to Osgood, Indiana. The rocks of this quadrant are the least dolomitized and the cleanest of the four quadrants. Lithologically they are closest to the Upper Brassfield found in Quadrant I. The low insoluble residue content probably is due to the fact that they were the farthest removed from a source of terrigenous material which lay to the east.

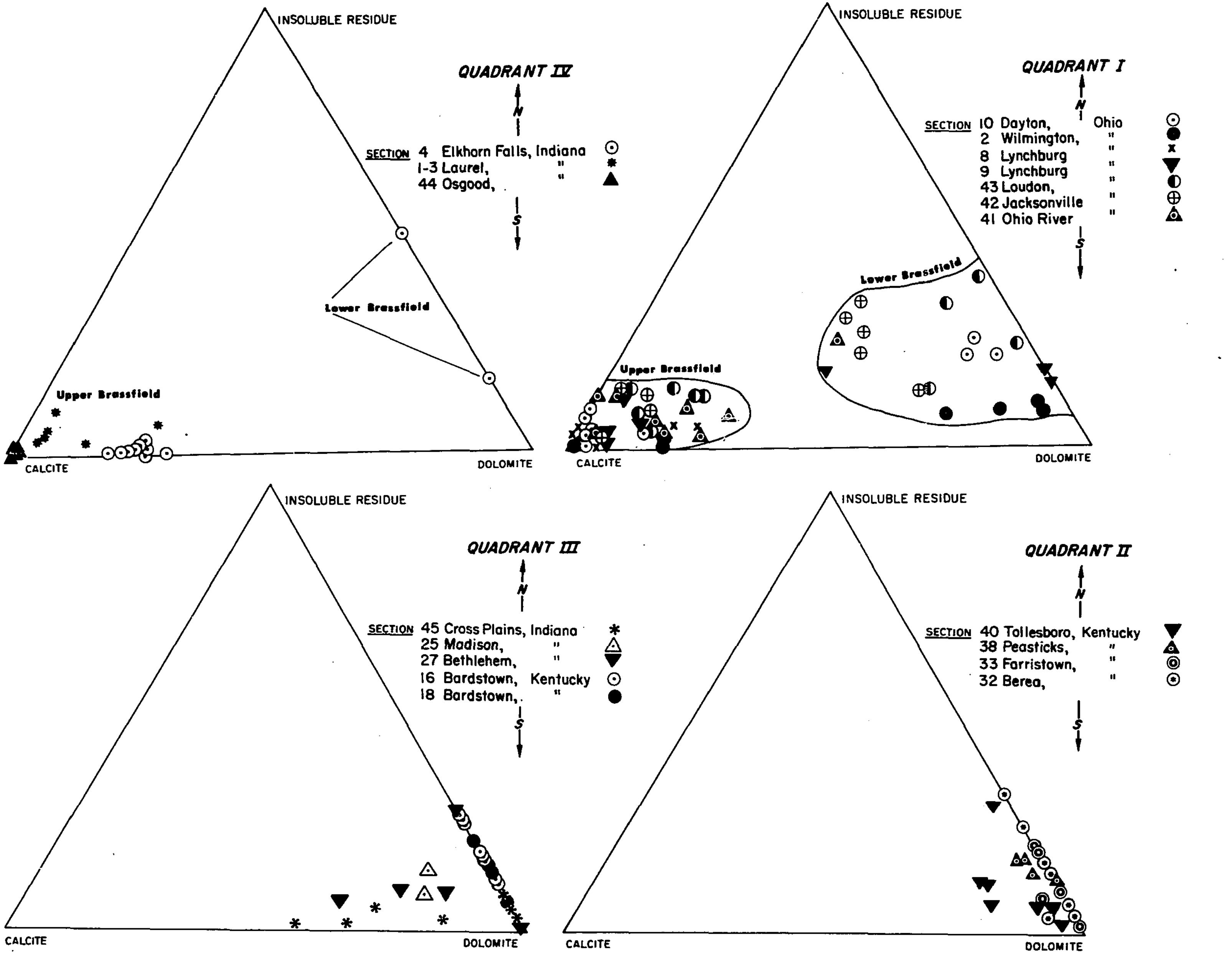

INSOLUBLE RESIDUE
QUADRANT IV
N
S
SECTION 4 Elkhorn Falls, Indiana
1-3 Laurel, "
44 Osgood, "
Lower Brassfield
Upper Brassfield
CALCITE
DOLOMITE
INSOLUBLE RESIDUE
QUADRANT I
N
S
SECTION 10 Dayton, Ohio
2 Wilmington, "
8 Lynchburg "
9 Lynchburg "
43 Loudon, "
42 Jacksonville "
41 Ohio River "
Lower Brassfield
Upper Brassfield
CALCITE
DOLOMITE
INSOLUBLE RESIDUE
QUADRANT III
N
S
SECTION 45 Cross Plains, Indiana
25 Madison, "
27 Bethlehem, "
16 Bardstown, Kentucky
18 Bardstown, "
CALCITE
DOLOMITE
INSOLUBLE RESIDUE
QUADRANT II
N
S
SECTION 40 Tollesboro, Kentucky
38 Peasticks, "
33 Farristown, "
32 Berea, "
CALCITE
DOLOMITE

Fig. 40

Clay Mineralogy

Results of the clay mineral analysis are summarized in Table IV. These analyses represent material which was derived from discrete "shale" beds and do not represent the clay size material found in the carbonate rocks. The distribution of clays in fig. 41 shows a geographic restriction of chlorite and kaolinite to the east side of the Cincinnati Arch with the exception of trace amounts of chlorite in the Osgood Formation in Nelson County in west central Kentucky. Ehlers and Hoover (1961, p. 234) report that kaolinite is present in negligible amounts in the northern parts of southwestern Ohio but increases towards the southern portion of southwestern Ohio and this was verified by this study.

In an environmental interpretation based on clay mineralogy consideration must be given as to whether or not clay suites reflect the source area, or are a product of diagenesis in the depositional basin. Grim (1953) concludes that climate, topography, pH of solutions, the prevalence of oxidizing and reducing conditions, and parent material in the source area have considerable control in the formation of clay minerals. Keller (1956, p. 2689) cautions that when drawing environmental inferences from a rock or mineral concerning its origin, the rock or mineral may not have been formed where it now is found. Keller maintains that clay minerals are products of parent materials responding to the energy present in the reaction under which they were formed, and that in the genesis of some minerals

Clay Mineralogy

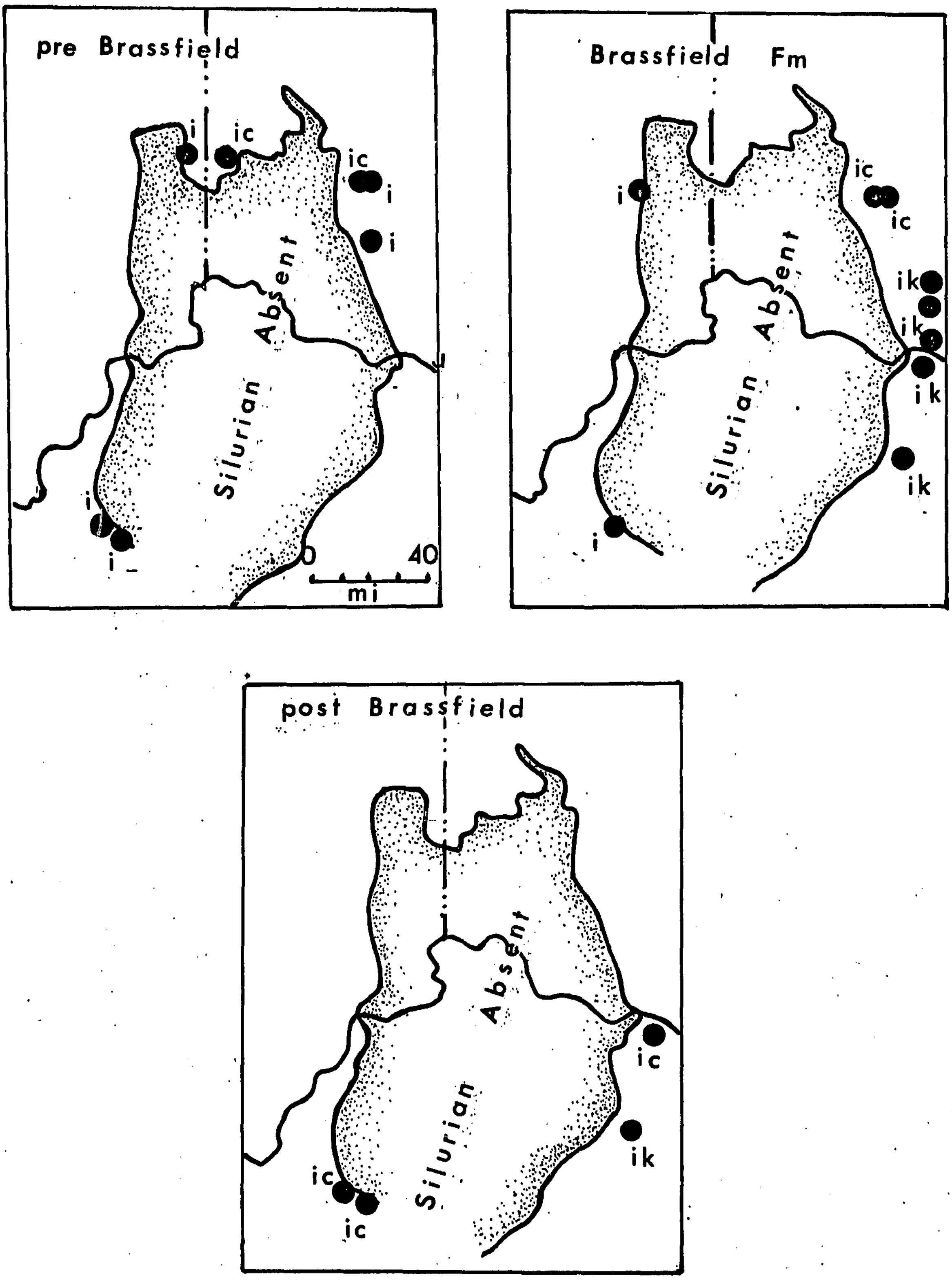


Fig. 41

LEGEND: i=illite, c=chlorite, k=kaolinite;

Table IV Clay Mineral Data

Stratigraphic Unit	Sample Number	Interval	Illite	Kaolinite	Chlorite
Upper Ordovician Elkhorn Formation (Stratigraphic interval in cm below the Brassfield)	4-3*	52-59	x		
	4-4	43-48	x		
	4-5	12-16	x		
	4-6	0-3	x		
	9-1	100-105	x		x
	9-2	95-100	x		x
	9-3	0-20	x		x
	12-1	28-30	x		x
	12-3	13-15	x		x
	12-4	10-13	x		x
	12-5	8-10	x		x
	12-6	6-8	x		x
	12-7	0-2	x		x
	14-1	17-18	x		x
	14-2	8-11	x		x
	14-3	4-6	x		x
	14-4	3-4	x		x
	14-5	0-2	x		x
	15-1	0-3	x		x
Saluda Formation (stratigraphic interval in cm below the Brassfield)	16-1	0-4	x		
	18-5	0-2	x		
SILURIAN					
Brassfield Formation (stratigraphic interval in cm above the Ordovician)	2-3	38-42	x		x
	3-7	108-118	x		
	3-11	30-52	x		
	3-13	6-10	x		
	17-1	596-609	x		

Table IV continued

Stratigraphic Unit	Sample Number	Interval	Illite	Kaolinite	Chlorite
(Belfast Member)	15-3	40-44	X		X
Brassfield Fm. (Noland Mbr.)	41-10	764-769	93%	7%	
	42-12	1060-1065	88	12	
	42-13	1292-1295	92	8	
	43-10	476-480	91	9	
	43-12	531-534	86	14	
	40-13	1080-1085	83	17	
	40-16	1365-1370	87	13	
(Plum Creek Shale)	47-3	580-585	90	10	
Osgood Formation (stratigraphic interval in cm above the Brassfield	16-26	75-85	x		trace
	16-27	70-72	x		trace
	18-24	90-92	x		
	18-25	50-53	x		trace
Crab Orchard Fm.	40-18	0-2	x		x
	47-5	75-80	91	9	

* First set of digits represents the Section number (see fig. 3), which is followed by a dash and the second set of digits represents the sample number within the section.

the effect of parent material is dominant, but in others the controlling factor is environment. Milne and Earley (1958, p. 328) in their studies of recent sediments from the northeastern part of the Gulf of Mexico noted that the clay mineral assemblage of an area is dependent largely on the character of the source area. Weaver (1959) reviewed the clay mineral data on sediments and he concluded that the clay minerals in Recent marine mudstones are primarily detrital in origin and reflect the composition of the source area. In the marine environment many of the degraded clays are reconstituted by adsorbing cations between the layers, but Weaver goes on to say that it has not been demonstrated as to whether or not there is any more vigorous alteration of the detrital clays in a marine environment. In a study of the deep sea sediments of the Atlantic Ocean, Pierre Biscaye (1965, p. 803) found that most recent Atlantic Ocean deep sea clays are detritus from the continents and he concluded that the formation of minerals in situ on the ocean bottom is relatively unimportant in the Atlantic Ocean.

The abundance of detrital illite in sediments may be explained by the high concentration of micas in many rock types, the widespread abundance of illite in many soils, and their relative resistance to chemical weathering (Jackson et al., 1948, p. 1239-1240; Goldich, 1938; Reiche, 1950, p. 55). Chlorite occurs as a widespread primary constituent of rocks (low grade metamorphics and many shales) and as a product of weathering and the weathering of other clay minerals such as illite (Jackson, 1959, p. 136; Quigley and Martin, 1963). Jackson *et al.* (1948, p. 1238) include chlorite with the most easily weathered silicates and expect it in dominant amounts only in certain kinds of youthful soils derived from basic rocks. The mineral is more prevalent in soils at higher latitudes where weathering is less intense (Biscaye, 1965, p. 812). An acid environment is commonly believed to be a prerequiste for the formation of kaolinite. Keller (1956, p. 2701) notes that for the formation of kaolinite there must have been excess of hydrogen ion and removal of calcium, iron, sodium, and potassium. Kaolinite has the highest alumina to silica ratio of the clay minerals and its formation is promoted if the weathering processes tend to remove silica in solution thereby enriching the residue in alumina. So then the formation of kaolinite is favored by an acid environment in which the bases and combined silica are removed in solution. This is especially characteristic of moist terrestrial conditions. Weaver (1958, p. 259) observed that kaolinite is most common in continental and nearshore sediments. Alkaline marine waters favor the formation of illite, for here potassium and calcium ions are retained and there is little excess hydrogen ion.

It therefore appears that the clays in the Brassfield Formation are detrital and that they are derived from a source area in the southeast. This would explain the restriction of kaolinite and chlorite to the east side of the Cincinnati Arch. This study shows that kaolinite and chlorite are generally mutually exclusive of each other, although Ehlers and Hoover (1961, p. 233) found that one may be found in trace amounts when the other is an important constituent of a given sample. The chlorite is probably derived from the weathering of basic igneous rocks and low grade metamorphic rocks. Kaolinite probably represents a higher degree of chemical weathering in which the soluble bases and combined silica are removed in solution in an acidic environment. The probability of the clays being derived from a souce area to the southeast is indicated by the increasing kaolinite content of the shales and the higher clastic percent of the Brassfield in that direction (see fig. 10).

The possibility of there being a relationship between the chlorite in the shales and the dolomite content of the carbonate rocks was considered. The chlorite could serve as a source of magnesium for dolomitization, in which case the shales in association with the dolomites should be deficient in dolomite and enriched with illite and kaolinite.

However no such relationship was found. For example the upper part of the Elkhorn and the lower part of the Brassfield at Sections 2, 14, and 15 in Clinton County, Ohio are dolomitic but the associated shales contained appreciable amounts of chlorite. Conversely, the Brassfield at Section 3 in Franklin County, Indiana consists of 100% limestone but no chlorite.

DISCUSSION

Age of the Brassfield

The Brassfield Formation is a time transgressive unit of Early Silurian (Llandovery) Age. Berry and Boucot (manuscript in preparation) advocate the use of the European series names, that is, Llandovery, Wenlock, and Ludlow, for Lower, Middle, and Upper Silurian, rocks of North America. The New York Section has served as the Standard Silurian Section for North America but according to Berry and Boucot (ibid.) "...most of the New York Silurian lacks zonally diagnostic graptolites or brachiopods ...The New York Section is mainly a series of knotty, largely unsolved problems in Silurian stratigraphy rather than a standard for correlation...the standard European sections can be used with far more ease and accuracy than the New York section, and we recommend that this continue."

Berry and Boucot have subdivided the Llandovery following Jones' (1925) lithologic units for the Llandovery District supplemented by Williams (1951) study of the brachiopods. For the Early Llandovery the subdivisions are A_1 through A_5, for the Middle Llandovery B_1 through B_3, and for the Late Llandovery C_1 through C_6.

According to Berry and Boucot, three of the brachiopods found in the Brassfield are useful for stratigraphic zonation:

(1) Cryptothyrella (synonym: Whitfieldella) ranges

from the Ordovician to a C_1 or C_2 (Early-Late Llandovery). Cryptothyrella subquadrata and C. quadrangularis are usually found in the upper part of the type Brassfield in association with the "Bead Bed" or slightly above it.

(2) Platymerella is provisionally correlated by Berry and Boucot (ibid.) with the B_1-C_2 zone. Platymerella is found in the lower part of the Kankakee, Sexton Creek, and Brassfield Formations (ibid.). Platymerella occurs in about the same stratigraphic position as Virginiana with which it is closely related. The chief difference between them is that Platymerella is subequally biconvex in profile whereas Virginiana has a much greater degree of convexity in the pedicle valve than in the brachial valve (ibid.). Berry and Boucot suggest that the differences between the two brachiopods may be the result of ecologic controls.

(3) Microcardinalia ranges in age from C_3 to C_5. The C_3 zone is characterized by the presence of Microcardinalia and Triplesia. In the mid-continent Microcardinalia does not range above the C_3 interval (Boucot, written communication, 1967). Microcardinalia is found in the Noland Member of the Brassfield. Rexroad et al. (1965, p. 12) state that "...Its (Microcardinalia norwoodi) occurrence is considered to be physically distinctive of the top of the Oldham in this area" (east central Kentucky). However Rexroad et al. (1965, p. 12) report that the related species M. triplesiana is found at the top of the Brassfield, in

association with the "Bead Bed", on the Veterans Administration Center Grounds in Dayton, Ohio. Rexroad _et al_. (1965, p. 13) interpret this as indicating the time transgressive nature of the Brassfield. It was deposited in east central Kentucky before being laid down at Dayton, Ohio.

Recently conodonts have been used for Silurian zonation in Europe by Walliser (1962, 1964). In a preliminary paper, based on work in the Cellon area of the Carnic Alps, Walliser (1962) outlined seven informal horizons (Bereich I - VII) for the Llandovery through Skala interval. In 1964, Walliser retained Bereich I but proposed ten formal zones to replace Bereiche II-VII. By means of samples collected in the Bohemian basin, Walliser (1964, p. 95-101) has related some of the conodont zones to the graptolite zones (fig. 42).

Rexroad and Richard (1965) have been able to recognize Walliser's conodont zones in the Silurian rocks of the Niagara Gorge in New York; and Rexroad (1967, in press) has also recognized them in the Brassfield Formation.

Rexroad (_ibid_.) has identified 74 species of conodonts in the type Brassfield of the Cincinnati Arch Area. Forty species of _Hindeodella_ are represented in Rexroad's collections but six of the species are represented by so few specimens that Rexroad is not sure of whether or not they are indigenous to the Brassfield. Only 27 of the 34 remaining species are named and seven of these are new species. Rexroad found that Paltodus consulatus, Drepanodus suberectus, and Spathognathodus oldhamensis are almost completely absent in southeastern Indiana, whereas they are present on the east side of the Arch from Dayton, Ohio to Berea, Kentucky (O'Donnell Section 31). Moreover, from the Ohio River southward, Rexroad (ibid.) found these three species and Panderodus unicostatus serratus progressively higher in the section. At the type section of the Brassfield and Oldham, (O'Donnell Section 29) all three are rare in the Brassfield, but all except D? suberectus are abundant in the Plum Creek Shale and in the Oldham (1967, manuscript in preparation). Rexroad maintains that this suggests stratigraphic control and that the Brassfield is progressively younger to the north and northwest.

Rexroad (ibid.) notes an anomaly in the conodont fauna of the "Bead Bed" from the Brassfield's type section (O'Donnell Section 29) north to Tollesboro, Kentucky (O'Donnell Section 40). There is a greater abundance of Icriodina and fewer specimens of Panderodus than found in most other beds. In the overlying Plum Creek Shale the relationship of these two species to each other and to the remaining species closely parallels their relationship below the "Bead Bed" (ibid.), although, according to Rexroad (ibid.) the total aspect of the Plum Creek fauna, in this area, differs from that of the type Brassfield. The megafauna and lithology of the "Bead Bed" is sufficiently different from the rest of the Brassfield to suggest to Rexroad (ibid.) that the conodont anomaly in the "Bead Bed" is the result of environmental control.

As it is presently understood, the Brassfield falls within Walliser's Bereich I and possibly part of the celloni Zone (Rexroad, 1967, personal communication). Rexroad has found a thin, medium crystalline biogenic dolomite between the Brassfield and Osgood Formations in west central Kentucky and adjacent parts of Indiana. This dolomite ranges from about 10 cm. to 1 meter thick and contains celloni Zone conodonts. Rexroad is tentatively assigning this unnamed dolomite to the Brassfield. Since his 1965 paper, Rexroad (1967, personal communication) has found celloni Zone conodonts on the east side of the Cincinnati Arch in the upper part of the Waco Dolomite where it is interbedded with the shales of the Crab Orchard Formation and in the lower part of the Crab Orchard Formation from northern Bath County, Kentucky to northern Adams County, Ohio. The greatest part of the Brassfield, including the Noland Member, still falls within Bereich I.

Walliser subdivided Bereich I into two subdivisions that are distinguished by the presence of Icriodina in the upper part and by its absence from the lower part. According to Rexroad (1967, in press) Icriodina is found throughout the Brassfield although it is not present throughout the Belfast Member in all sections. (Rexroad's use of the term Belfast coincides with the generally accepted useage of that name in southwestern Ohio, but in Indiana and Kentucky it would coincide with the term Lower massive Brassfield as proposed in this report.) Therefore, the base of the Brassfield must nearly coincide with the base of the upper part of Bereich I. Bergstrom has written to Rexroad (*ibid*.) stating that he has found conodonts in Sweden in association with graptolites representative of the *Monograptus sedgwicki* Zone (21). Rexroad says that these conodonts are either high Berich I forms or low *celloni* Zone forms but in either case they are post-Brassfield and post-Noland in age. Thus the conodont evidence indicates that the top of the Brassfield is below graptolite Zone 21. Ross (1962, p. 1385) reported finding graptolites of the *Diplograptus modestus* subzone of the *Akidograptus acuminatus* Zone (16), in the lower part of the Edgewood Dolomite about 45 feet below the zone of *Platymerella manniensis.* Berry has examined Ross' collection (Berry and Boucot, manuscript in preparation) and notes the presence of *Climacograptus* cf. *medius*, *C*. cf. *rectangularis*, *C*. cf. *scalaris* var. *normalis*, which *Diplograptus* ? indicate an age within the span of the graptolite zones 16-19. Rexroad (1967, in press) considers the Edgewood conondonts to be younger than the Brassfield, and equates them with the *Orthograptus vesiculosus* (17) zone. Thus the approximate limits of the Brassfield, based on conodonts, are from Orthograptus vesiculosus (17) through Monograptus convolutus (20) and possibly M. sedgwicki (21) graptolite zones (see fig. 42).

Correlation of the Brassfield with the standard Silurian subdivisions of Great Britain by means of conodonts with respect to the graptolite zones, and by brachiopods with respect to the graptolite zones, according to Rexroad (1967, in press), cannot be successfully reconciled on the basis of present knowledge. Boucot (1967, written communication) states that, at present, they do not know the exact position of the Virgiana/Platymerella bearing beds in terms of the Standard Silurian sequence, and that "...they should be somewhere between the Lower Llandovery and about the end of C_2 but could be any or all parts of this rather large time interval." Microcardinalia in association with Triplesia is indicative of the C_3 zone. Walliser (1964, p. 94) however shows the upper celloni and lower amorphognathoides conodont zones in this position. On the basis of the Platymerella and Microcardinalia, the Brassfield represent any part or all of the interval from the Monograptus gregarius Zone to the M. crispus Zone (19-23 inclusive). Thus the brachiopods indicate that the Brassfield is younger than do the conodonts when compared with graptolites (see fig. 42).

Absolute age determinations have been done on glauconite in the Brassfield yielding an age of 410 million years (Hurley et al., 1960, p. 1804). The sample came from the Brassfield in Adams County, Ohio. Unfortunately no other stratigraphic information is available for this sample. Kulp (1961, p. 1516) in his geologic time scale used this date for the Silurian System.

Correlation of the Brassfield

The correlation chart (fig. 42) and the discussion which follows is based primarily upon the work of Berry and Boucot (manuscript in prepartation), with the exceptions noted below. The Brassfield is modified herein to include the Noland Member, the name Estill Shale has been dropped, and the Crab Orchard reduced to formation rank. The Belfast Member seems better restricted to the rocks in Southwestern Ohio rather than applied more widely as has been attempted by Rexroad et.al. (1965). The reasons for doing this have been outlined in the Stratigraphy Section.

According to Berry and Boucot, Savage's use of the term Brassfield, in his papers on the geology of Missouri and Illinois, includes both the pre-C_3 zone of Platymerella and the C_3 zone of Microcardinalia. The Microcardinalia zone is, in places, underlain by strata containing Pentamerus oblongus. Savage assigned all the Silurian pre-Platymerella zone beds, as well as the Brassfield and its equivalents, the Sexton Creek Limestone and the Kankakee Dolomite, to the Alexandrian Series.

Foerste's use of the term Brassfield also included the Platymerella and Microcardinalia zone beds, although they may be locally absent. The type Brassfield, located in the area between Lincoln and Bath County, Kentucky contains Cryptothyrella but has not yet yielded Platymerella. To the north in Adams County, Ohio, Platymerella has been found in strata which have been identified as Brassfield (Foerste, 1935, p. 188). In this area Microcardinalia is found in the Oldham tongue above the type Brassfield; but in Ohio it is found at the top of the Brassfield in association with the "Bead Bed:. To Berry and Boucot this indicates the diachronous nature of the Brassfield. It is older in east central Kentucky than in Ohio and western Kentucky.

In Ontario, on Manitoulin Island and on the Bruce Peninsula, the Brassfield is probably equivalent to the Dyer Bay Formation which contains Virginiana (Bolton, 1957, p. 36). Traditionally the Brassfield has been correlated with the Manitoulin Dolomite and Cabot Head Shale (see section on STRATIGRAPHY). However Berry and Boucot have examined the brachiopods of both formations and have concluded that the Manitoulin is of pre-C_3 age because of the complete absence in the Manitoulin of Cyrtia, Eospirifer, Chilidiopsis, Atrypa "reticularis", Eocoelia cf. intermedia, and Resserella elegantula. The presence of Fardenia, Zygospiraella planoconvexa, and Dolerorthis indicates an Early Llandovery age. The Cabot Head is relatively unfossiliferous but again the brachiopods suggest an Early Llandovery age.

The Medina Group of New York (Power Glen Shale, Grimsby Sandstone, and Thorold Sandstone) has not yet yielded fossils useful for correlation purposes. Berry and Boucot assign it a pre-C_3 age because of its stratigraphic position below the Clinton Group, and above the Queenston Formation. Rittenhouse (1949) has traced the Brassfield in subsurface into the Medina Group in northeastern Ohio and western Pennsylvania.

To the south, in the folded Appalachians, the Brassfield has been traced, in subsurface, by Perry (1962) and Horvath (1964) into the Tuscarora Formation. According to Berry and Boucot, the Tuscarora does not contain diagnostic fossils but its gradational relationship with the overlying Rose Hill Formation indicates that the Tuscarora is of Early Silurian age. The Rose Hill is of Late Llandovery age and ranges from C_3-C_6. Berry and Boucot believe that the portion of the Rose Hill formation containing *Eocoelia* cf. *intermedia* and "an unnamed younger form" is of C_3-C_5 age, whereas the upper part containing *E. sulcata* is of C_6 age.

In summary then, the Brassfield seems to be correlative, in part, with rocks which have been assigned to the Medina Group and Lower Clinton Group in the Appalachian Basin, the Cataract Group of the Michigan Basin, and the Alexander Group of the Illinois Basin.

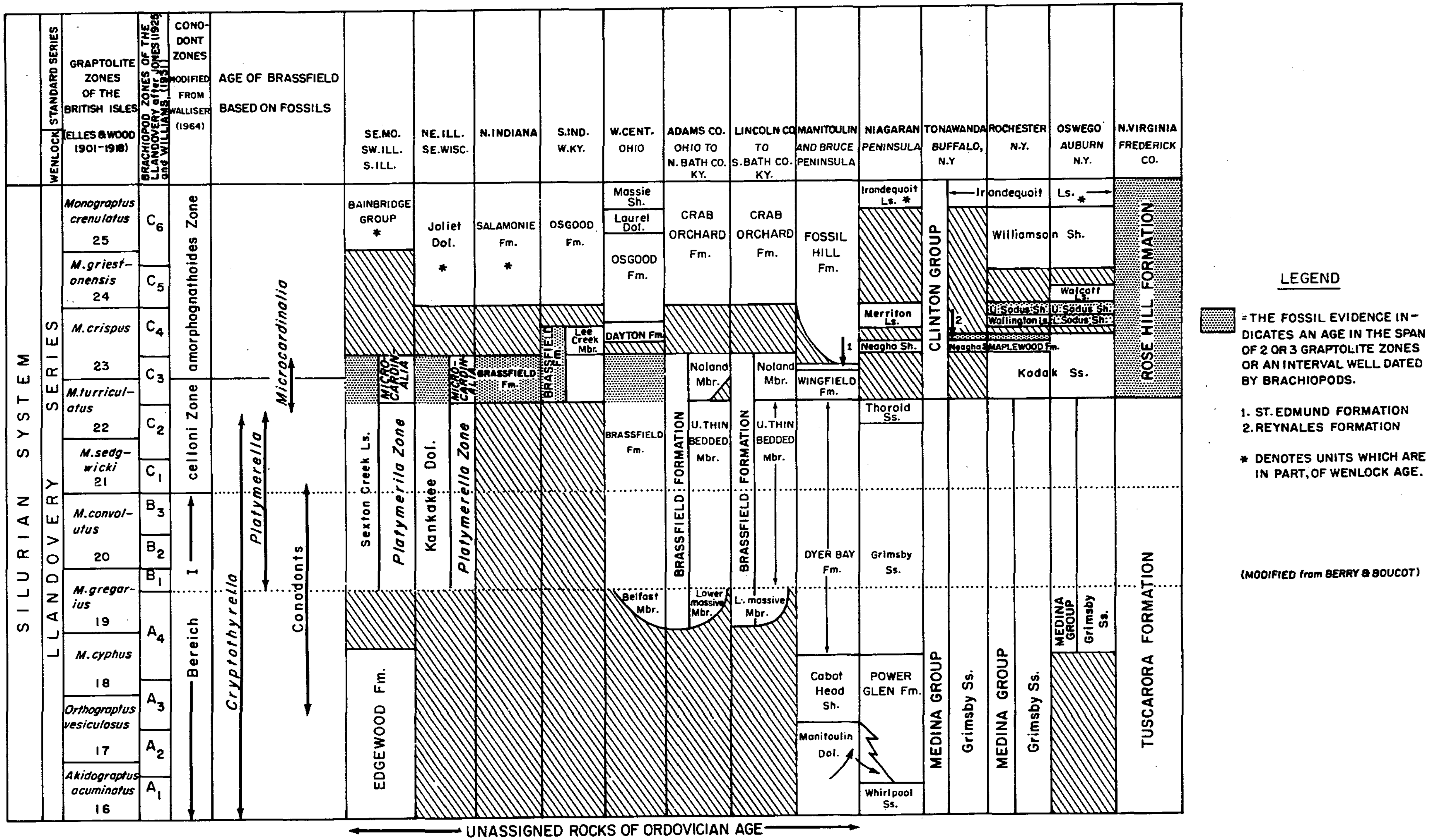

SILURIAN SYSTEM
LLANDOVERY SERIES
WENLOCK
STANDARD SERIES
GRAPTOLITE ZONES OF THE BRITISH ISLES (ELLES & WOOD 1901-1918)
BRACHIOPOD ZONES OF THE LLANDOVERY after JONES (1925) and WILLIAMS (1951)
CONODONT ZONES MODIFIED FROM WALLISER (1964)
AGE OF BRASSFIELD BASED ON FOSSILS
SE.MO. SW.ILL. S.ILL.
NE.ILL. SE.WISC.
N.INDIANA
S.IND. W.KY.
W.CENT. OHIO
ADAMS CO. OHIO TO N. BATH CO. KY.
LINCOLN CO TO S.BATH CO. KY.
MANITOULIN AND BRUCE PENINSULA
NIAGARAN PENINSULA
TONAWANDA BUFFALO, N.Y
ROCHESTER N.Y.
OSWEGO AUBURN N.Y.
N.VIRGINIA FREDERICK CO.
Monograptus crenulatus 25
M.griestonensis 24
M.crispus 23
M.turriculatus 22
M.sedgwicki 21
M.convolutus 20
M.gregarius 19
M.cyphus 18
Orthograptus vesiculosus 17
Akidograptus acuminatus 16
C6
C5
C4
C3
C2
C1
B3
B2
B1
A4
A3
A2
A1
amorphognathoides Zone
celloni Zone
Bereich I
Microcardinalia
Platymerella
Cryptothyrella
Conodonts
BAINBRIDGE GROUP *
Joliet Dol. *
SALAMONIE Fm. *
OSGOOD Fm.
Massie Sh.
Laurel Dol.
OSGOOD Fm.
CRAB ORCHARD Fm.
CRAB ORCHARD Fm.
FOSSIL HILL Fm.
Irondequoit Ls. *
Irondequoit Ls. *
Williamson Sh.
Walcott
U.Sodus Sh.
U.Sodus Sh.
Wallington Ls.
L.Sodus Sh.
Merriton Ls.
Neagha Sh.
Neagha Sh.
MAPLEWOOD Fm.
Kodak Ss.
CLINTON GROUP
ROSE HILL FORMATION
MICROCARDINALIA
MICROCARDINALIA
BRASSFIELD Fm.
BRASSFIELD Fm.
Lee Creek Mbr.
DAYTON Fm.
Noland Mbr.
Noland Mbr.
WINGFIELD Fm.
Thorold Ss.
1
2
Sexton Creek Ls.
Platymerella Zone
Kankakee Dol.
Platymerella Zone
BRASSFIELD Fm.
BRASSFIELD FORMATION
U.THIN BEDDED Mbr.
BRASSFIELD FORMATION
U.THIN BEDDED Mbr.
DYER BAY Fm.
Grimsby Ss.
Belfast Mbr.
Lower massive Mbr.
L. massive Mbr.
MEDINA GROUP
Grimsby Ss.
EDGEWOOD Fm.
Cabot Head Sh.
POWER GLEN Fm.
Manitoulin Dol.
Whirlpool Ss.
MEDINA GROUP
Grimsby Ss.
MEDINA GROUP
Grimsby Ss.
TUSCARORA FORMATION
UNASSIGNED ROCKS OF ORDOVICIAN AGE
LEGEND
= THE FOSSIL EVIDENCE INDICATES AN AGE IN THE SPAN OF 2 OR 3 GRAPTOLITE ZONES OR AN INTERVAL WELL DATED BY BRACHIOPODS.
1. ST. EDMUND FORMATION
2. REYNALES FORMATION
* DENOTES UNITS WHICH ARE IN PART, OF WENLOCK AGE.
(MODIFIED from BERRY & BOUCOT)

Fig. 42

Origin of the Iron Ore

The hematite beds of the Brassfield are a facies of the Clinton iron ores of Early Silurian age. The iron ore facies began on the craton in Middle Llandovery time (Brassfield) and migrated eastward toward the miogeosyncline by Late Llandovery time (Clinton). The Clinton ores are very extensive and can be traced from New York State to Alabana along the strike of the Appalachians (Clark and Stearn, 1960, p. 106). According to Alling (1947, p. 995), the Clinton ores are of two types. One is an oölitic type which consists of fossil fragments or quartz surrounded by layers of hematite, chamosite, and glaucomite. The other is a "fossil ore" in which fossil fragments are replaced and coated with hematite (fig. 50). The Brassfield fits into the latter category. The Brassfield "iron ore" contains hematite which has been partly altered to limonite. Pyrite is present but not common. No glauconite or chamosite was observed in thin section. X-ray diffraction of samples from the hematite beds at Sections 14, 38, and 41 indicated primarily hematite and minor amounts of pyrite.

The iron for the hematite could come from a variety of sources. The Brassfield has abundant glauconite disseminated throughout it. Entire beds of it are common towards the top of the unit. The hematite always occurs above the glauconite beds. Pyrite is also common throughout the unit but is usually rare in the hematite-rich beds. The iron could be derived from the glauconite and pyrite by oxidation and/or the deep chemical weathering of an adjacent land mass.

Eh-pH appears to be the controlling mechanism in the deposition of iron. The hydrogen ion concentration in an aqueous media controls precipitation while the redox potential controls the oxidation state of the iron, hence the mineral type formed. Modern streams have an average pH of 7 as compared with the ocean which has a pH of about 8.3 (Mason, 1960, p. 158). Their iron content is approximately 1.0 ppm while the iron content of marine water is about 0.008 ppm (ibid. p. 159). The important point here is that in the modern marine environment iron is not accumulating but it is being removed in some fashion. This can be brought about by removal by organisms, oxidation and hydrolysis, loss of carbon dioxide or by reaction with sea bottom colloidal silica and clay yielding a gel that adsorbs potassium from sea water to form glauconite or similar reactions to form chamosite.

Once the iron has entered the sea diagenetic processes begin. A series of complex reactions take place depending on the Eh and pH conditions. Alling (1947) in his study of the Clinton ores of New York postulated the formation of collophane followed by hydrotroilite and chamosite. Hydrotroilite altered to marcasite and then pyrite. Glauconite was probably forming synchronously with the hydrotroilite. Subsequently the iron bearing compounds were oxidized and under the proper Eh-pH conditions formed hematite.

All indications point to a shallow marine environment for the Brassfield's "fossil ores". Beds are generally thin and irregular in thickness. They range from 2-100 cm. thick. They are cross-laminated and contain broken fossil fragments which have been surrounded, infiltrated, and replaced by hematite. The conditions which produced the iron rich zones probably began with a gradual offlap of the sea to the west from the miogeosyncline in upper Brassfield time. Clastic material flowed out across the carbonate banks which made up the lower Brassfield. Changes of sea level caused by crustal warping, seasonal tidal fluctuations, and eustatic processes, probably caused the shoreline to shift repeatedly. Parts of the Appalachian landmass were exposed to weathering at this time (Yeakel, 1962, p. 1535). Chemical breakdown of iron bearing rocks would be brought about by physical and chemical weathering processes; however there is no reason to believe that weathering processes were the same in east central North America, in Lower Silurian time, as they are today. For one thing the land was void of plant life as known today. Some primative plants such as the psilophytes and club mosses (Kay, 1965, p. 666) are found in rocks as old as Cambrian (?) but there is no indication as to how extensively the land areas were covered by these plants, as well as algae and lichens. Plant cover would inhibit physical weathering and erosion but the plants produce organic acids which would facilitate chemical weathering.

Another point to consider is whether the climate in east central North America was the same in Silurian time as it is today. George Bain (1966) has reconstructed ancient climatic zones for the earth using paleomagnetic evidence and physical data such as evaporites, reefs, carbonate bodies, and paleosols. Bain drew a series of maps based on these criteria. The one for the Silurian (ibid. V-22) shows eastern North America falling within 10° of the equator. Bain characterizes the climate of this area as consisting of the savannah and tropical rain-forest type.

Rocks exposed to tropical weathering conditions, with abundant moisture could produce laterites provided there was little or no relief. Because of a general lack of deep rooted plants, if there were any relief physical weathering would take place before the chemical breakdown of the rocks could take place. Under lateritic conditions iron, silica, and aluminum, would be selectively leached from the rocks depending on the pH. They would be transported to the ocean where a change in pH would cause flocculation. The iron and aluminum probably interact with amorphous silica on the sea floor to form chamosite and glauconite. Under reducing conditions the iron would form hydrotroilite, marcasite, and pyrite. The Brassfield sea bottom contained a prolific fauna which was broken up by wave action, sorted, and redeposited. Crinoid plates, columnals, and bryozoa because of their hydraulic characteristics were least abraded and are the best preserved in the rocks.

The thin section analysis showed some of the glauconite filling porous crinoid plates (fig. 46, 49). The same phenonemon was observed in the hematite beds but in this case the filling material was hematite not glauconite (figs. 47, 48, 50). There is a possibility that the glauconite has been oxidized to hematite but this would require the removal of silica. Many of the fossil fragments exhibit rounding and abrasion. The fragment itself may be angular but the outline is usually oval. What has happened is that some of the hematite has surrounded and partially replaced the fossil fragments. Newell, Purdy, and Imbrie (1960) in their study of Bahamian oölitic sands found that the greatest bulk of oölites are forming in shallow well agitated waters at depths less than 5 feet. Considering the Brassfield "oölites" they probably began as fossil fragments either filled or replaced by glauconite or limonite. A lowering of sea level exposing the glauconite, pyrite, and chamosite, may have caused them to become oxidized. Rivers flowing from landmasses to the east were introducing iron into a shallow sea either supersaturated or close to saturation with iron. The change of pH from river water (7) to marine water (8.3) would cause the precipitation of the iron on an iron rich nucleus, that is, the limonite and glauconite in the fossil fragments. Water turbulence would lift the grains into suspension. So long as the bioclasts remain on the substrate where waters are undersaturated with respect to iron, oölite grain growth will not occur. With continual agitation the bioclasts were coated with hematite.

In summary then, the hematite beds in the Brassfield are found towards the top of the unit usually in association with shale beds. Bedding is irregular, ripple marks and cross-lamination are present. All evidence points to the hematite beds being formed in a shallow water, high energy environment. The actual formation of the hematite probably followed a four step process:

(1) Formation of glauconite, pyrite, and chamosite in a normal marine environment. Some of the glauconite and chamosite filled the fossil fragments.

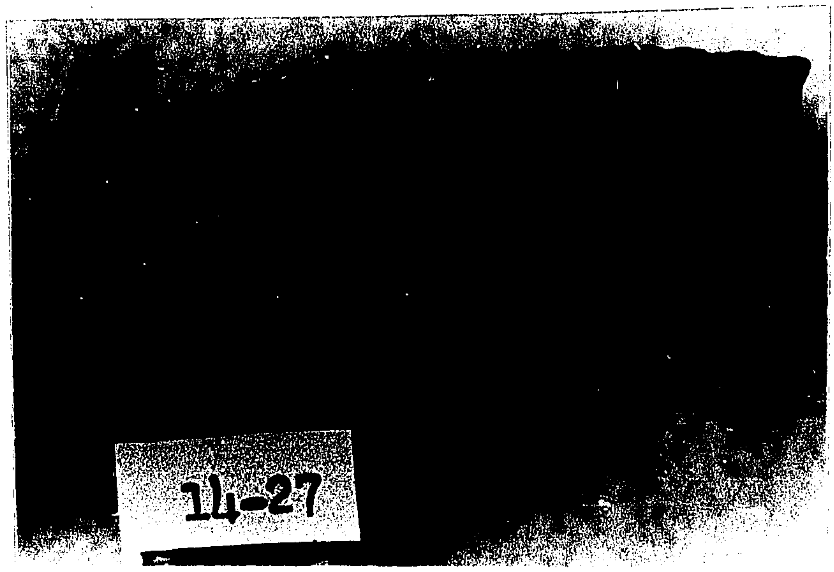
(2) A lowering of sea level by crustal warping, eustatic processes or seasonal tidal fluctuations resulted in a shift of the shore line, in this case further west. The pyrite, glauconite, and chamosite were oxidized. Some of it went into solution. Rivers rich in iron reaching the sea would become supersaturated with respect to iron as the pH became more alkaline.

(3) Iron would precipitate probably as hematite on iron rich nuclei (the bioclasts) or it might infiltrate porous skeletal fragments, or replace some of the bioclasts. This took place in high energy wave worked areas such as tidal channels.

(4) Cementation was the final stage.

Fig. 43. Polished section (1.75X) of the hematite rich portion of the Upper thin bedded Brassfield at Section 14, Lumberton, Ohio. Petrographically this is a poorly sorted, fine calcirudite, crinoidal biosparrudite.

Fig. 44. Polished section (1.75X) of the contact between the hematitic and non-hematitic beds of the Upper thin bedded Brassfield at Section 14, Lumberton, Ohio. The hematite lamina and the limestone lamina are both fine calcirudites, crinoidal biosparrudites. In the hematitic one however, some of the crinoid fragments have been replaced and infiltrated by hematite.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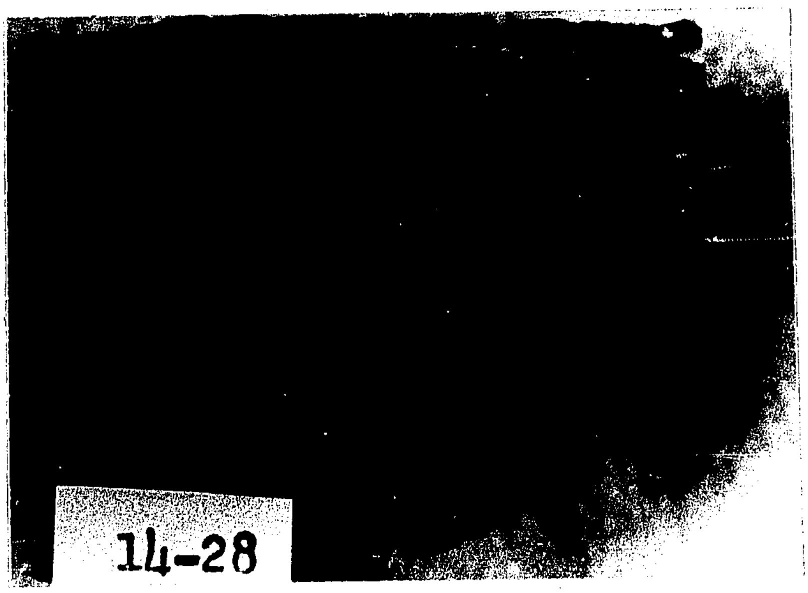
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Fig. 45. Photomicrograph (40X) of the hematitic Brassfield 817-822 cm above the Elkhorn Formation at Section 14, Lumberton, Ohio. The zooaria of the bryozoan at the side of the photo are filled with hematite.

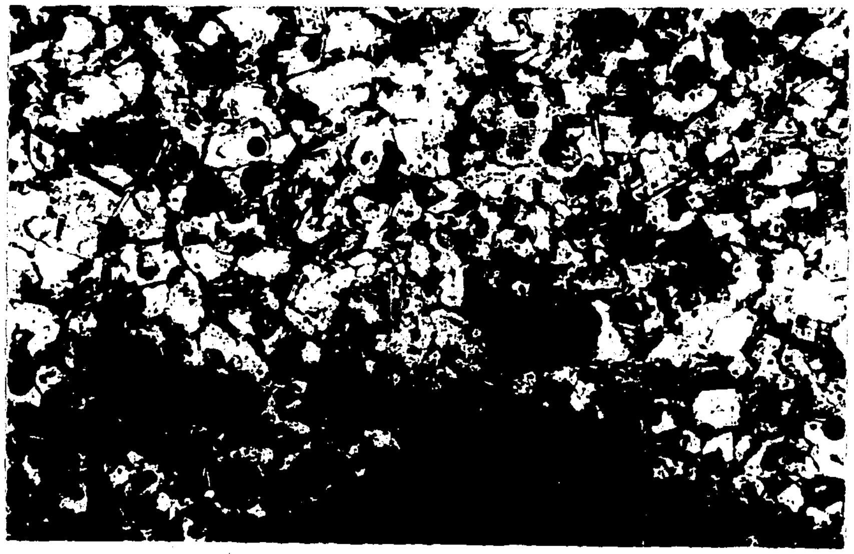
Fig. 46. Photomicrograph (80X) of the Belfast Member 149-155 cm above the Elkhorn Formation at Section 4, Elkhorn Falls, Indiana, showing fossil fragments replaced by glauconite.

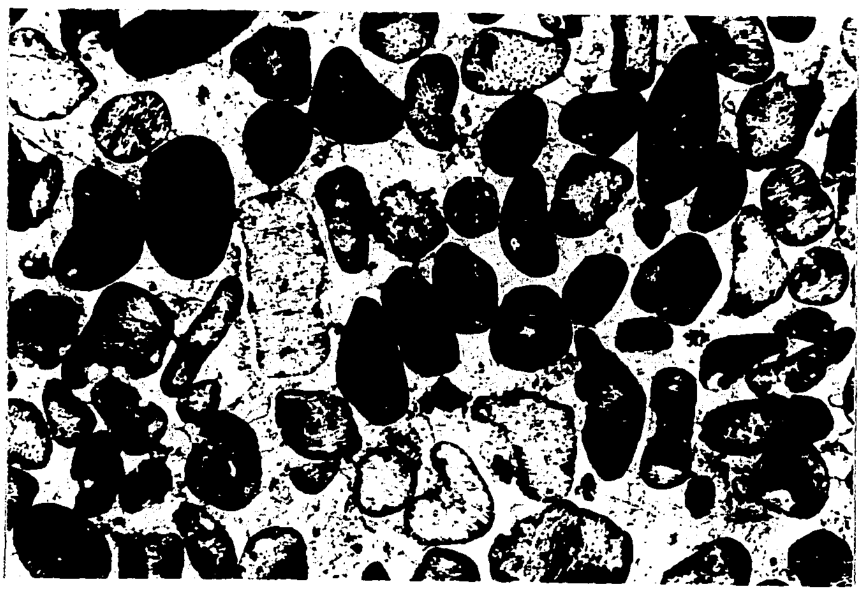
Fig. 47. Photomicrograph (40X) of the same slide shown in Fig. A. Several of the hematite pellets are in the center of the photo. Hematite can be seen filling and surrounding fossil fragments.

Fig. 48. Photomicrograph (40X) of the hematitic Brassfield at Section 14, Lumberton, Ohio showing partial replacement of a crinoid columnal by hematite.

Fig. 49. Photomicrograph (40X) of a medium crystalline biogenic dolomite from the Brassfield Formation 1 meter above the Elkhorn Formation at Section 41, Ohio River, and Ohio Brush Creek. The dark porous object at the bottom center of the photo is a crinoid plate which has been replaced by glauconite.

Fig. 50. Photomicrograph (40X) of the hematitic Brassfield at Section 14, Lumberton, Ohio showing replacement of crinoid plates by hematite. Replacement has been selective in that not all the crinoid plates contain hematite. The clear sparry calcite cement indicates that replacement has taken place prior to cementation.





Origin of the Chert

Concerning the carbonate-silica relationships in sediments there is a more or less reciprocal relationship between the solubilities of calcite and quartz in near surface diagenetic environments (Sierver, 1959, p. 76). The solubility of silica increases with a rise in temperature while calcite solubility decreases with increasing temperature, at least up to 120° C., provided the partial pressure of CO_2 remains constant (Miller, 1952, p. 175). An increase of pH decreases the solubility of calcite, whereas pH has little effect on the solubility of silica up to pH 9. Above this value its solubility sharply rises. However increasing pressure effects the quartz and calcite solubilities at about equal rates.

The origin of chert is dependent on this carbonate-silica relationship. During Early Diagensis, in carbonate sediments which contain a minor amount of detrital quartz, such as the Brassfield, the quartz will equilibrate with silica in interstitial solutions. Depending on the saturation of the solution, either deposition of authigenic quartz or dissolution of the detrital quartz will result. With deeper burial, temperature will rise and the interstitial water which was in equilibrium with respect to quartz and calcite will result in the deposition of calcite, provided the partial pressure of CO_2 does not change. According to Dott (1958, p. 7) dissolved or colloidal silica is gradually concentrated by ionic and Van der Walls forces. A decrease in temperature brought about by uplift or migration of the interstitial water will result in the deposition of silica accompanied by solution of the calcite.

The chert in the Brassfield is clearly a replacement type as illustrated in fig. 53. Fossil fragments have been metasomatically replaced. The excellent preservation indicates a volumetric rather than an ion for ion replacement. The presence of well rounded glauconite pellets randomly distributed throughout the cherts indicate that their formation ante-dated the chert. Many of the chert nodules contain pyrite which makes up as much as 20% of their volume. Garrels (1960, p. 254) established the stability field relationship of pyrite in terms of Eh and pH. According to Garrels, pyrite forms from slightly oxidizing to reducing conditions (Eh+0.02 volts to -0.35 volts) and a pH from 4.0 to 8.6. Calcite will go into solution at a pH of less than 7.8. Its' close association with pyrite in so many limestones does not, of necessity indicate a state of disequilibrium although decaying matter in the presence of sulfate reducing bacteria could result in acid conditions with accompanying negative Eh. This environment could exist on a microscopic scale but would be favorable for the formation of pyrite, chert, and glauconite.

The source of silica for the formation of chert and the mechanism of concentration are two problems in the explanation of their genesis. Silica can be derived in three principal ways:

(1) Vulcanism

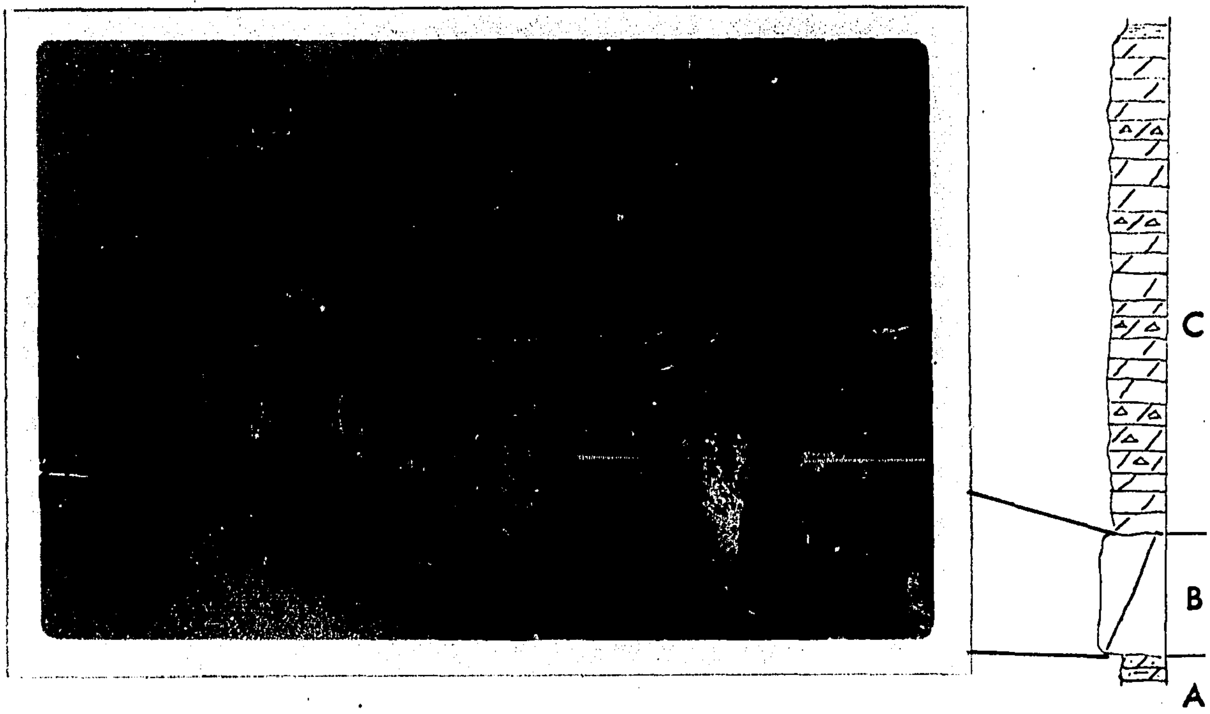
(2) Subaerial weathering

(3) Biological activity.

Vulcanism is unlikely. If it were an important source of silica the chert should be more extensive. The latter two mechanisms acting in combination are more likely. For example the ancestral Appalachians were exposed to subaerial weathering during Lower Silurian time. Silica was leached from the rocks by chemical weathering and was transported by streams and rivers westward towards the "Brassfield Sea". Direct inorganic precipitation may have resulted in the deposition of some of the silica, however, biological activity is an important factor. Diatoms, radiolaria, sponges, and silicoflagellates all extract amorphous silica from sea water. Chillinger (1956, p. 1559) believes that the waters of the modern oceans are undersaturated with respect to SiO_2 because the interstitial waters of sea bottoms can contain as much as 80 mg. SiO_2/liter. Living silica secreting organisms show no signs of dissolution of their tests or skeletons. Apparently they have a protective organic cover or a shield of polyvalent cations on their outer surface (Degens 1965, p. 78). Upon the death of the organism, the amorphous silica is no longer protected and begins to dissolve. During diagenesis, amorphous silica, according to Bramlett (1946, p. 52), would migrate in true ionic solution in the direction of a concentration gradient to precipitate as quartz and accumulate at points of least solubility.

Fig. 51. Bedded cherts in the Upper thinly bedded member (C) of the Brassfield on the Kentucky Blue Grass Parkway near Bardstown, Kentucky (Section 18). The contact between the Lower massively bedded Brassfield (B) and the Upper thinly bedded Brassfield (C) is marked by a distinctive change in color.

Fig. 52. Detail of a slump structure in a nodular chert layer at Section 18. The steep angle of the chert indicates that slumping took place after the formation of the chert nodules but prior to lithification.


C
B
A

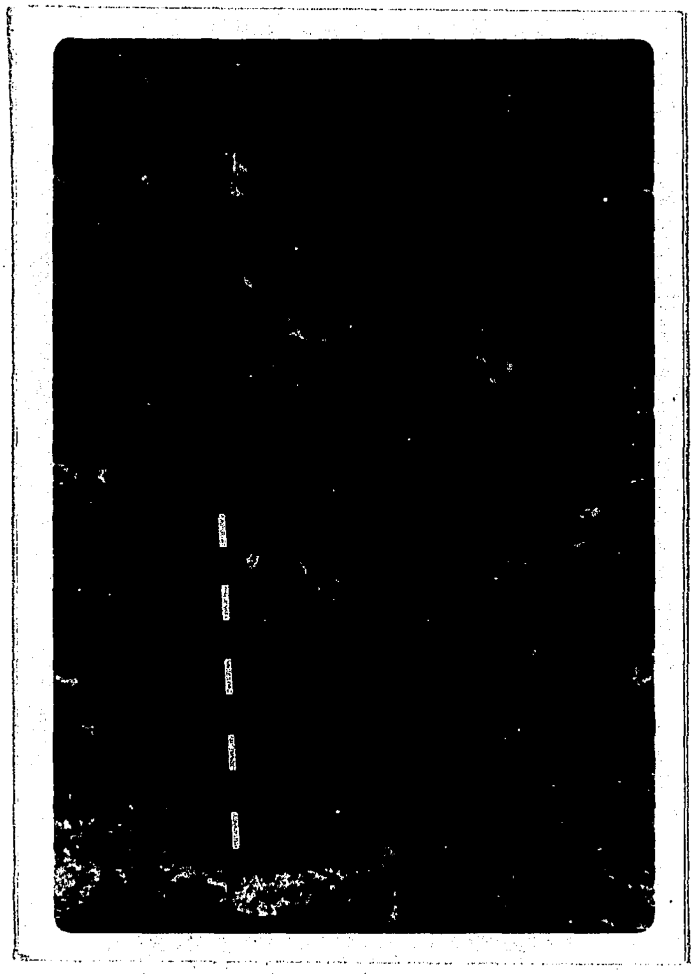
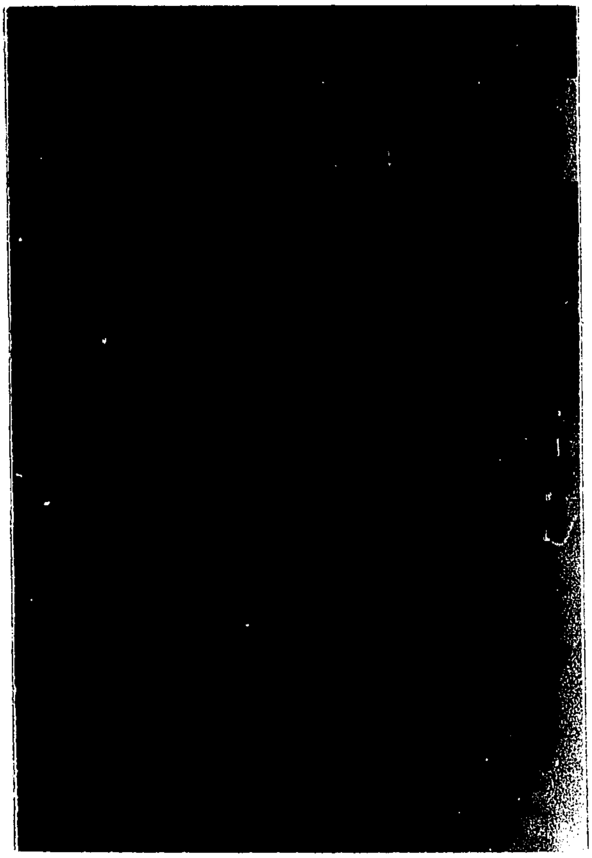
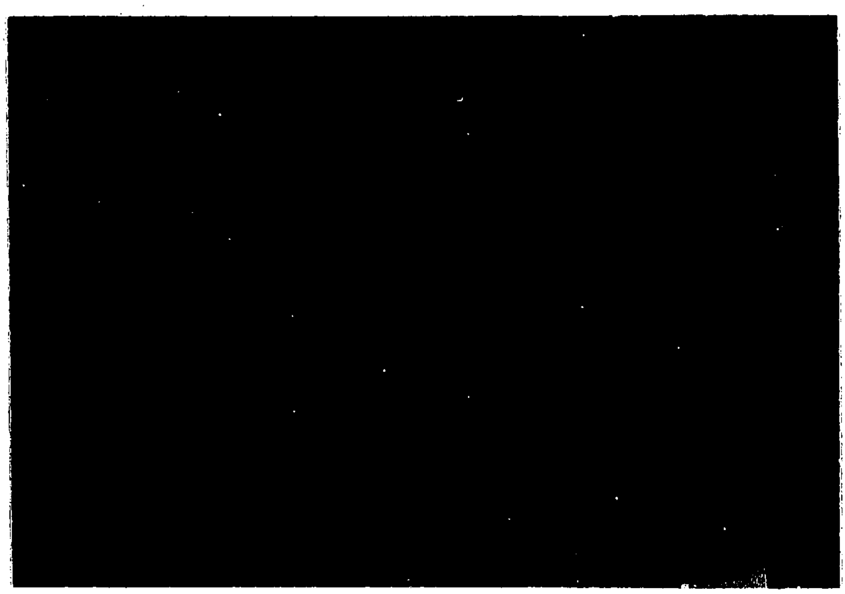


Fig. 53. Chert nodule collected from the Brassfield Formation at Section 42, Jacksonville, Ohio. Note the bryozoan fragements which have been replaced by chert. The dark specks in the chert are glauconite. (1.75X).

Fig. 54. Irregularly shaped chert nodule from the Brassfield Formation 5 meters above the Saluda Formation at Section 16, Bardstown, Kentucky. The light colored portion of this specimen is chert speckled with pelletoidal glauconite. The darker material at the top of the specimen is dolomite. (1.75X).





Origin of the Glauconite

One of the most distinctive features of the Brassfield Formation is the presence of glauconite which is disseminated throughout the unit. Glauconite appears to be absent from the underlying Ordovician units in outcrop. Only the basal part of the superjacent Crab Orchard Formation has a very high pelletoidal glauconite content which could have been derived from reworked Brassfield material.

The Brassfield Formation contains glauconite in close association with chert nodules, and in beds of almost pure glauconite in a pelletoidal form (fig. 14). It is also randomly distributed throughout the rocks as irregular patches or as a replacement material for bioclasts (figs. 46, 49).

Smulikowski (1954) in his paper on "The Problem of Glauconite" maintained that glauconite originated as a colloid and could be characterized as a mixed ferric (ferro?) alumino-siliceous hydrogel with adsorbed potassium. Such an origin of glauconite, as an adsorptive rather than a pure chemical compound might explain the variability of its compostion. This variability in chemical composition may be the result of two principle causes: (a) the physical condition and concentration of chemical elements in the sedimentary environment influence the composition of glauconite at the time of its precipitation, (b) in the course of its formation glauconite tends to approach a certain chemical composition expressing chemical equilibrium of the submarine environment. However while undergoing diagenesis it may depart from its original composition.

Concerning the origin of glauconite, apparently it can be derived from a great variety of parent material under the proper physio-chemical conditions. Takahashi (1939, p. 506-507) stated that it probably comes from "... several different substances which are gelatinized before being transformed into glauconite", i.e., pyroxene, feldspar, "mica", clayey materials, colloidal silica, fecal pellets, fragments of volcanic glass, opaline silica, and sponge spicules. Galliher (1939, p. 515) says that some glauconites are derived from biotite.

As to the actual mechanism for the formation of glauconite, Hummel (1931, p. 484) stressed the process of halmyrolysis or submarine weathering. According to Hummel halmyrolitic action would typically result in the selective leaching of aluminum from various primary aluminosilicates with the simultaneous enrichment in iron followed by the adsorptive drawing of potassium and magnesium from sea water. Obviously for halmyrolysis to be an operative process the the primary material must react with sea water for as long as possible. This would take place in places on the sea floor where sedimentation is halted or, at least, strongly retarded by agitated water. Smulikowski (1954, p. 96) differs with Hummel as to the importance of halmyrolysis.

He says that "...The chief role then be assigned to the process of coagulation of suspensions and colloids originating from the constituents, with simultaneous adsorption of potassium from the sea water...Common coagulation of all these amorphous and cryptocrystallization products in agitated water leads to the formation of grains of glauconite." According to Smulikowski he coined the term glauconitization in 1924 to describe a process in which many mineral substances including illite, montmorillonite, biotite, feldspar, and volcanic glass alter to a state of physio-chemical equilibrium of which the end product is glauconite.

Smulikowski (1954, p. 24) summarized the factors which enter into the formation of glauconite when he wrote that:

> "Glauconite always forms in the course of retarded, interrupted or even negative sedimentation, frequently in connection with interformational conglomerates, hence in agitated water, under decreased deposition of detrital material, and especially with the practical exclusion of finest silt. It is connected with rather cold water, slightly acidified by carbon dioxide, and it avoids highly oxidizing, as well as strongly reducing conditions at the sea bottom. The

> presence of organic matter is not necessary for glauconite generation, but in moderate amounts it seems to be rather favorable thereto. The conditions of glauconite formation are difficult to explain, because its grains are frequently deposited on secondary beds, and such circumstances can seldom be demonstrated."

There is some divergence of opinion concerning the temperature and depth at which glauconite is formed. Takahashi (1939, p. 504) said that temperatures not less than 15° C. are required. Smulikowski (1954, p. 25) stresses a cold water origin. Galliher (1935, Fig. 16) indicated that glauconite occurs in recent sediments from 65° S. to 80° N. From this Cloud and Barnes (1948, p. 54) concluded "...that glauconite is not a reliable temperature index, although it may suggest waters that were not markedly warm." Lockman (1949, p. 56) reviewing the same evidence, stated that "...water temperatures in favorable stations range from 8° C. to somewhat over 20° C., with the average around 14°-15° C., a temperate to warm condition."

Cloud (1955) reviewed the depth range of glauconite from the literature and concluded (p. 88) that:

(1) Glauconite occurs as traces from just off shore to a depth of about 2400 fathoms.

(2) It is probably rare above 5 and below 1,000 fathoms.

(3) Glauconite is commonest at depths of 10-400 fathoms.

(4) It may originate mainly in the upper part of the 10-400 fathom interval.

Thorp (1936, p. 83) reports the rarity of glauconite in the lime muds of the Bahama banks and Kuenen (1943, p. 252) reports finding glauconite exclusivly below 180 feet and in reasonable abundance only below 780 feet in the tropical seas of Indonesia. The paucity of glauconite in the upper part of the neritic zone may be due to a combination of factors. Temperature, degree of oxigenation, of the sea water, and degree of agitation may be controlling factors in the genesis of glauconite.

From the presence of the glauconite-rich beds in the Brassfield, the following conclusions can be inferred:

(1) Slow or impeded sedimentation as attested to by the fact that only 1-50 feet of carbonate sediments (Brassfield) were deposited on the craton while over 800 feet of clastics (Tuscarora Formation) were being deposited in the Appalachian Basin.

(2) Conditions on the sea floor were neither strongly oxidizing or reducing as indicated by the fact that glauconites usually contain both ferrous and ferric iron.

(3) Water temperatures were probably not very warm if the modern marine environment serves as a model for the geologic past. Temperatures could have ranged from 8° C.

to 20° C. and may have averaged around 14°-15° C.

(4) Water depth was most likely shallow in terms of modern oceanic depths, but in terms of the Paleozoic seas it may have been relatively deep. As mentioned in (3), water depth and temperature may be interrelated. In terms of a tropical sea the glauconite rich beds probably formed at a depth greater than 180 feet.

(5) Water salinity was close to normal because glauconites are known to originate only in waters of normal salinities (Cloud, 1955, p. 490).

The randomly distributed patches and pellets of glauconite, found throughout the Brassfield, indicate little of the sedimentary environment in which they were formed. They are associated with each of the five micro-facies and were probably formed in both shallow and deep water. They rarely constitute as much as 1% of a rock sample. They may represent reworked material, or an environment in which optimum conditions for glauconite formation were not reached. The glauconite beds found in close association with the chert beds however indicates cool water temperatures and imply depths greater than 180 feet.

Origin of the Dolomite

As can be seen from fig. 38, the Brassfield Formation is dolomitic south of the Ohio River on both sides of the Cincinnati Arch. North of the River the Dayton Formation, which is probably an extension of the Waco tongue of the Brassfield, the Osgood Formation, and the Lower massive Brassfield, and the Belfast Members are dolomitic. Except for the Lower massive Brassfield in Madison, Estill, and Lincoln Counties, Kentucky, fossil ghosts are common to very abundant in all the dolomites; and sedimentary structures such as cross-bedding and ripple marks are well preserved. The Lower massive Brassfield in the three Kentucky Counties just mentioned represents Microfacies III, the medium crystalline dolomite facies. In contrast to the Upper thin bedded and Noland Members of the Brassfield, this Member is probably a quiet (deep?) water deposit.

The actual origin of the dolomite may have been brought about by the mechanism suggested by Deffeyes, Lucia, and Weyl (1965). They felt that dolomitization could be brought about by a reflux of hypersaline water produced by partial evaporation of sea water. To increase the Mg : Ca ratio of the hypersaline waters, gypsum must be first precipitated. In a humid environment the gypsum was subject to dissolution. Refluxing is most likely to take place in a supratidal zone as has been reported by Shinn et al. (1965, p. 123) in the Bahamas, and Illing et al. (1965, p. 110) in the Persian Gulf. In the zones where modern supratidal dolomites are forming there is a saline water table a few inches beneath the surface. Shinn _et_ _al_. (1965, p. 122) report that normal sea water has a molar ratio of Mg to Ca of about 5 : 1. They found that the molar ratio of Mg to Ca measured in supratidal water at Sugarloaf Key was in excess of 40 : 1 with a salinity of 5 to 6 times that of sea water. The level of these interstitial brines fluctuates with the tides and at the same time are drawn up through the sediments to the surface by capillary action to the surface where they are evaporated. Salts are precipitated and interstitial brine is produced in the upper few inches of sediment. The Mg content of the brine is concentrated by the precipitation of gypsum. The Mg is free to act on skeletal material and aragonitic muds to produce "penecontemporaneous" dolomites or to replace Ca in shell fragments to form secondary dolomites. With only a gentle lowering of sea level in Early Silurian time much of the Brassfield would fall into an environment in which refluxing could take place.

Although the sediments that Illing _et_ _al_. (1965) and Shinn _et_ _al_. (1965) were studying consisted of fine grained material, this is not to say that the reflux mechanism could not work in the case of the Brassfield. What would be required would be calcareous starting material, a lowering of sea level, and local evaporite conditions.

Another possibility for the origin of the dolomite is a later replacement of the calcium by magnesium introduced by connate waters, following burial of the sediments (Pettijohn, 1957, p. 424). This idea is rejected for there is no evidence that the Brassfield's dolomites are structurally or stratigraphically controlled.

PALEOGEOGRAPHY

Depositional Environment

FOSSIL EVIDENCE: Reconstruction of the depositional environment must take into consideration the fossil evidence as well as the physical evidence. No detailed paleo-ecological study of the Brassfield was done, and it is beyond the scope of the present study to do this. When fossils were encountered they were collected and marked as to the precise stratigraphic horizon from which they came. It was noted that most fossils are found towards the top of the formation. The rocks of the lower part are composed primarily of crinoid fragments. Corals, bryozoans, and brachiopods become more common towards the top of the unit. Ecologically the hermatypic corals such as *Favosites* sp. and *Halysites* sp. and an unidentified stromatolite which were found in the upper two meters of the Brassfield at Sections 11, 12, 6, and 46 are most significant. In the modern marine environment hermatypic corals and algae live within the photic zone (approximately 100 meters or less depending on turbidity) and in waters with a minimum temperature not much below 21° C. (Swartzbach, 1963, p. 29). Strictly speaking, we cannot draw a direct analogy with the ecological limitations of modern hermatypic corals because the genera found in the Brassfield lack close modern relatives. However the great abundance of calcium carbonate in the sediments associated with these corals tends to indicate that they lived in warm waters. Thus we can conclude that the upper few meters of the Brassfield and the Oldham and Waco Dolomites which also contain hermatypic corals (Foerste, 1931, p. 186-187) represent warm waters, of a moderately high to high energy regime, shallow in depth (within the photic zone).

Ziegler and Boucot (manuscript in preparation) recognize two faunal communities in the Cincinnati Arch Area: (1) the "deeper" water Platymerella community (2) the "shallower" water Cryptothyrella community. The interpretation as to depth has been made on a variety of physical and biological parameters, among them is the fact that when the two communities are plotted on paleogeographic maps, the Cryptothyrella assemblage falls closer to shore; and in the case of a marine transgression, Platymerella is always found above Cryptothyrella.

Stratigraphically the Platymerella assemblage represents the lower part of the Brassfield while the Cryptothyrella community represents the upper part of the Brassfield.

PHYSICAL EVIDENCE: The mineralogy of the Brassfield, the bedding characteristics and fabric of the rocks suggest both shallow and deep water conditions in the depositional basin. The terms shallow and deep are used in a relative sense. Depths of several hundred meters are quite shallow in terms of the modern oceans but in the case of epicontinental seas can be considered to be deep. The terms shallow and deep, as used here, will approximate the infralittoral and circalittoral zones of Krumbein and Sloss (1963, p. 259). They arbitrarily set the boundary between the two environments at 50 meters. According to Krumbein and Sloss that represents the depth to which sunlight penetrates oceanic waters. Above this depth the energy of the environment is dominantly mechanical and is related to waves and currents. Below 50 meters the energy is primarily thermal.

The bedding characteristics of the lower part of the Brassfield from Highland County, Ohio (Section 7) on the east side of the Cincinnati Arch, south as far as Lincoln County, Kentucky (Section 30) and in Nelson County, Kentucky on the west side of the Arch (Sections 16, 17, 18, and 19) probably indicate quiet water conditions. It is in these rocks that glauconite and chert are found in abundance. The rocks commonly exhibit massive bedding, thin laminations, or where they are thinly bedded they maintain a more or less constant thickness in outcrop. This part of the Brassfield stands in contrast with the remainder of the unit which is irregularly bedded, cross-laminated, and indicates high energy conditions. It should be noted that even these "quiet water" deposits were subject to occasional current and storm action. A basal conglomerate was found at the the base of the Lower massive Brassfield near Berea, Kentucky (Section 31)(see fig.13), and an intraformational conglomerate was found towards the top of the chert bearing beds south of Jacksonville, Ohio (section 42, see fig. 15).

According to Folk (1962, p. 241) the degree of sorting (σ_I = 0.98 Ø) of the crinoidal biosparites (Microfacies I) found in the Upper thin bedded Brassfield would fall within the field of submerged carbonate sediments as opposed to beach material. In fact only 7% of the beach samples have sorting values higher (worse) than 0.90 Ø but 79% of the submerged samples have worse sorting (ibid.). The degree of sorting of the Brassfield is what Folk would call moderate and it probably represents some current winnowing.

In the section of this study on the "Origin of glauconite", it was noted that the genesis of glauconite is favored by cool waters, within a range of 8° to 20° C. and an average of around 14°-15° C. (Lochman, 1949, p. 56). The glauconite-rich beds in the Brassfield are found in close association with the chert beds whose genesis is also favored by cool waters. The upper range of temperatures for the formation of glauconite falls close to the minimum temperature for the growth of hermatypic corals. The glauconite beds usually occur beneath the corals and not in the same stratigraphic horizon with them. The bedding of the glauconite-rich beds indicate quieter waters than the beds in which the corals are found. There is some evidence that glauconite is formed in deeper waters in the tropics where water temperatures are cooler. In the waters surrounding Indonesia, Kuenen (1943, p. 252) found glauconite in abundance exclusively below 60 meters and in reasonable abundance only above 260 meters. According to Cloud (1955, p. 488) when glauconite constitutes as much as 5-10% of the volume of the sediment, it implies water depths between 20 and 800 meters. Therefore it is concluded that the glauconite-rich beds in the Brassfield represent deeper water conditions than the upper part of the formation.

The hematite-rich beds in the Brassfield are in the upper part of the formation on the east side of the Cincinnati Arch. They are closely associated with *Cryptothyrella* and are always found above the chert beds. They are well sorted calcarenites, crinoidal-bryozoan biosparites and are ripple marked and cross-laminated indicating that they were deposited in a high energy environment. Where hematite oölites are present they probably indicate very shallow water. Newell, Purdy, and Imbrie (1960) in their study of Bahamian oölitic sands found that the greatest bulk of oölites are forming in shallow, well agitated waters at depths less than two meters.

In summary then, we can conclude that the chert and glauconite-rich lower part of the Brassfield from Highland County, Ohio to Lincoln County, Kentucky, on the east side of the Cincinnati Arch, and in Nelson County, Kentucky, on the west side of the Arch, represents a quiet water environment which probably fell within the lower limits of the photic zone. Water temperatures were probably cool and may have averaged around 14^{o}-15^{0} C. The remainder of the Brassfield, that is, the upper part in Kentucky, the Noland Member, and almost the entire formation in southeastern Indiana and southwestern Ohio, north of Highland County, probably represent a shallow water, high energy environment.

Rate of Deposition

The rate of deposition of the Brassfield Formation cannot be directly measured by radiometric means or by zonal fossils at the present time. The decay of K^{40} to Ar^{40} in the glauconite found in the Brassfield offers the most promise for the "absolute" dating of the rocks. The glauconite is presumably authigenic and is quite abundant. However the experimental error for Silurian age determinations based on the K/Ar method is about $\pm$ 10 million years (Holmes, 1965, p. 361). Unfortunately this is too high to give a reliable value for the depositional rate of the Brassfield. Also considering the anomaly between the ages indicated by the brachiopod and conodont assemblages in the Brassfield, it is impossible to speculate, with any hope of accuracy, upon the rate of deposition.

There is a possibility of using the weight percent of insoluble material as a guide to the rate of deposition of the Brassfield. For example, if we consider the Lower massive Brassfield in Southwestern Ohio (Quadrant I) and east central Kentucky (Quadrant II) in Table III we can see that Quadrant I contains 12% of insoluble residue by weight. In Quadrant II this is 26% or 2.2 times that of Quadrant I. If the rate of influx of terrigenous material was constant this would imply that the carbonate fraction in Quadrant II accumulated at a rate of 0.46 times (12%/26%) that of Quadrant I, or in other words at about half the rate of

Quadrant I. However a number of other factors must be considered. Diastems have not been taken into account. The number and magnitude of any present cannot be ascertained at present. Another point is that no calculations have been done on the insoluble material to find out what percent has been derived from outside the depositional basin. The greatest problem is that Quadrant II lies closer to a source of clastic detritus as can be seen from the Clastic Percent Map (fig. 10) therefore the depositional rates for the two areas will be different.

In spite of the problems just cited, the rate of deposition of the Brassfield must have been quite slow. We can make an analogy with the modern oceanic environment where the non-carbonate fraction of the sediments is accumulating at a rate ranging from 0.1 cm/1000 years in the South Pacific up to 4.8 cm/1000 years in the North Atlantic (Sackett, 1964, p. 344). In a 1 cc rock sample of the Lower Brassfield from Quadrant I, which is composed of 88% calcite with a density of 2.71, and 12% of insoluble material with an approximate density of 2.4 (Holmes, 1965, p. 1123) there would be 2.38 grams of calcite and 0.29 grams of insoluble material. If the insoluble material is accumulating at a rate of 0.1 cc/1000 years (0.24 gms/1000 years) then it would take 1212 years to form 1 cc of rock. If we assume a higher rate of accumulation for the non-carbonate material (4.8 cc/1000 years) then 1 cc would represent 25.2 years.

In a similar fashion in Quadrant II where the rocks are primarily dolomites with a density of 2.84 and have an insoluble residue content of 26% then 1 cc of rock would be deposited somewhere between 130 and 6240 years.

There are two other lines of evidence which suggest slow sedimentation. One is the presence of glauconite throughout the Brassfield. Smulikowski (1954, p. 24) says that it is formed during times of slow or negative sedimentation. Another indication of slow sedimentation is the lack of mega-fossils in the shaly portions of the Upper Brassfield and the Noland Member. When deposition is slow, the complete dissolution of shells by sea water prevents their preservation.

Geologic History

LATE ORDOVICIAN: To see this problem in its proper perspective we should consider the physical setting of the Appalachian Basin and the Cincinnati Arch in Late Ordovician-Early Silurian time. The Taconic Orogeny began in the Northern Appalachians in Upper Ordovician time (Clark and Stearn, 1960, p. 100). Its effect was felt to differing degrees in the various parts of the geosyncline. Perhaps the most strongly deformed rocks were in the northern part from Pennsylvania to Quebec where eugeosynclinal material was thrust at least 30 miles north and westward into contact with miogeosynclinal or shelf limestones and shales. The southward limit of the Taconic deformation is less definite. Rocks in the Valley and Ridge Province south of Pennsylvania do not appear to have been deformed at this time. Clark and Stearn (ibid., p. 101) state that it has been suggested by "several geologists" that the metamorphic rocks of the Piedmont area were formed in the Taconic orogeny through deformation of the southern part of the Appalachian geosyncline.

With the Taconic deformation a wedge of terrigenous detritus was introduced into the miogeosyncline and on out onto the craton. One of the most prominent features of this wedge was the Queenston delta complex which was best developed in New York State. The Queenston redbeds extended over large areas in western New York, southern Ontario and into Ohio to within a few miles of Cincinnati The last expression of the redbeds are the dusky red (5R 3/4) and grayed red-purple (5RP 4/2) shales of the Elkhorn formation (fig. 59).

The uppermost Ordovician rocks (Richmond Group) around the Cincinnati dome are divided into three lithologic facies:

(1) A greenish gray (5GY 6/1) and dusky red (5R 3/4) calcareous shale and dolomitic mudstone facies (Elkhorn facies)

(2) A mud cracked, ripple marked, silty dolomite facies (Saluda-Drakes facies)

(3) A calcareous mudstone in Indiana (Whitewater facies).

The Elkhorn Formation is a marine deposit in southwestern Ohio as evidenced from its abundant marine fauna and it is very likely that it was derived in part from material derived from the Queenston delta complex. This is supported by the fact that the Queenston Formation has yielded Richmondian fossils (Liberty, 1964, p. 47) in southern Ontario. Also the red shale of the Queenston can be traced in subsurface westward from Ontario and New York toward the Cincinnati Arch. The Whitewater Formation represents a normal marine carbonate bank deposit. The Saluda and the Drakes, because of stratigraphic position and similarity of the gross lithology of the rocks, are probably the same formation but are found on opposite sides of the Cincinnati Arch. Geographically there is a 40 mile break between outcrops of the two "formations" along the south end of the Arch where the Upper Ordovician rocks were removed by post Brassfield-pre-Boyle (Middle Devonian) erosion. Lithologic differences between the Saluda and Drakes are most likely the result of distance from a source area. The Drakes was closer to a source of terrigenous detritus and has a clay-silt content approaching 50%. Upon weathering it resembles a shale. The Saluda has about 25% clay-silt and resembles a sandstone when it is weathered. The Saluda-Drakes silty dolomites probably represent a very shallow water, low energy environment.

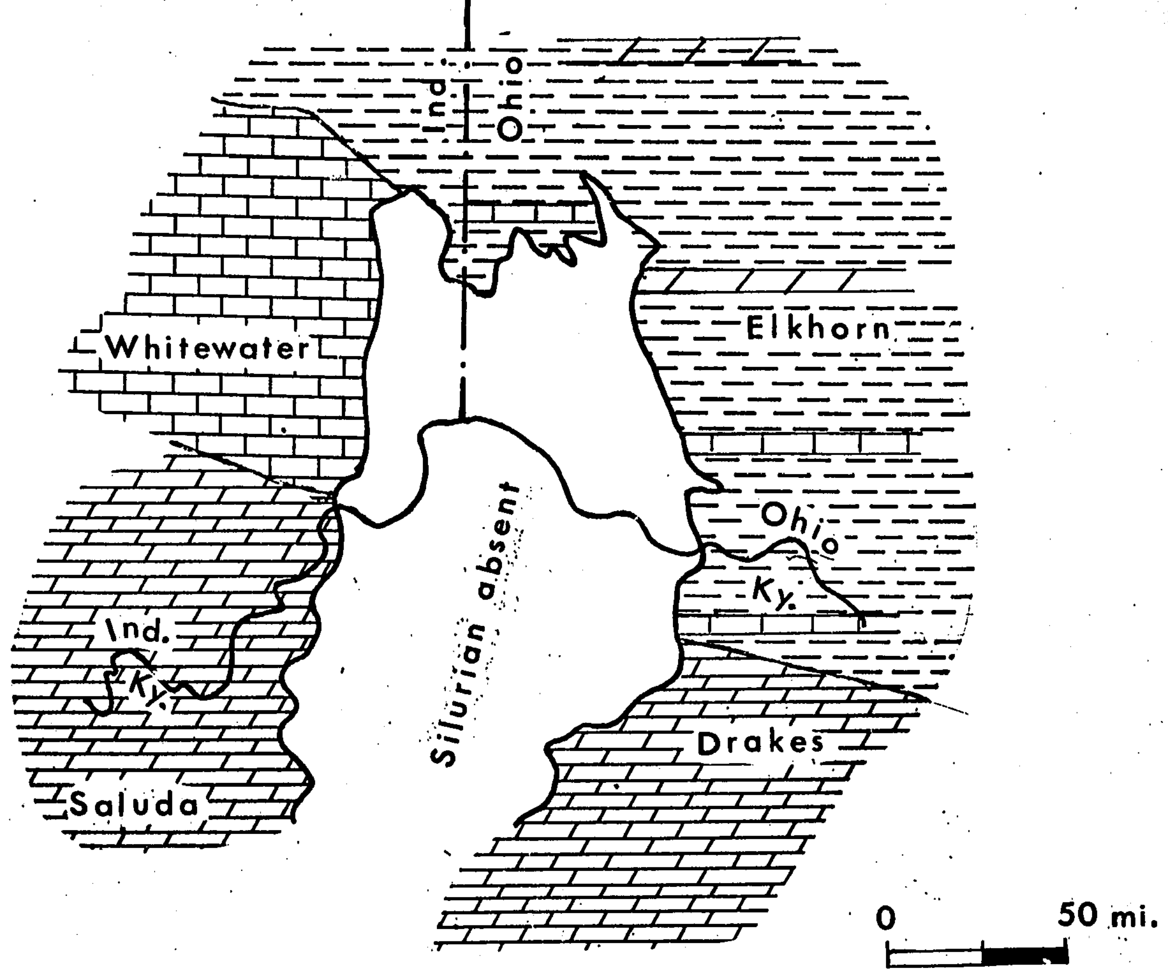
Examination of figs. 60 and 61 show a close correspondence between the Saluda-Drakes dolomite facies and the dolomitic portion of the lower Brassfield. Also it should be remembered that the Elkhorn is dolomitic in part. Where the Elkhorn is dolomitic the lower Brassfield is dolomitic. Where the Whitewater is calcareous the Brassfield is calcareous. Hence, the physical setting for the deposition of the Brassfield had already been reached in Upper Ordovician time.

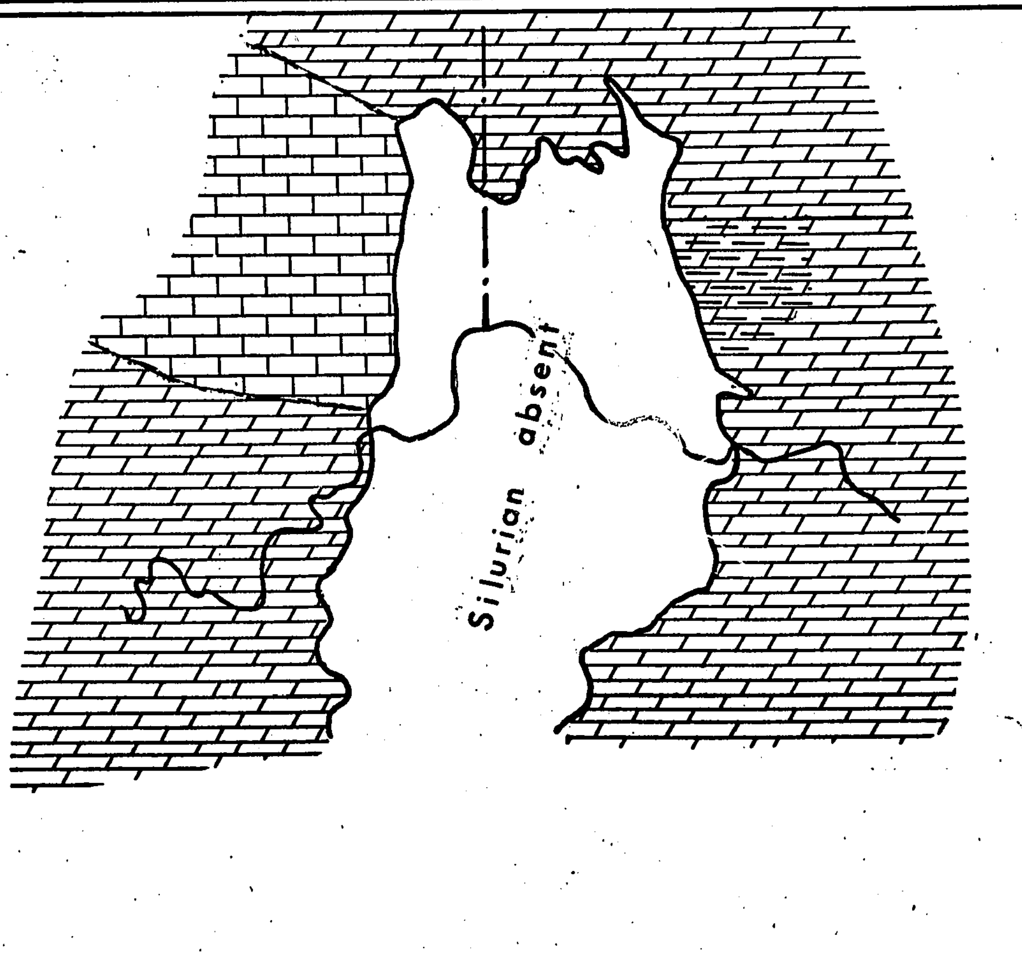
LOWER SILURIAN -- EARLY LLANDOVERY: Strata of Early Llandovery age are missing from the Cincinnati Arch Area. Ziegler and Boucot's maps of the North American animal communities (manuscript in preparation), although of a preliminary nature, suggest the extension of the Cryptothyrella faunal community across this area. According to them, Cryptothyrella represents a shallow water assemblage, although at present, only relative depths can be put on the

Fig. 59. Contact of the Brassfield and Elkhorn Formations in Adams County, Ohio. The dusky red color of the Elkhorn Formation is readily seen. It represents the furthest extension of the red clastics of the Queenstone delta complex. (Photo courtesy of Robert Galbraith).

Fig. 60. Pre-Brassfield (Richmondian) lithofacies map of southeastern Indiana, southwestern Ohio, and central Kentucky.

Fig. 61. Lithofacies map of the lower 0.5 meter of the Brassfield Formation in southeastern Indiana, southwestern Ohio, and central Kentucky.


Ind.
Ohio
Whitewater
Elkhorn
Ohio
Ky.
Silurian absent
Ind.
Ky.
Drakes
Saluda
0
50 mi.


Silurian absent

Cyrptothyrella assemblage. Most likely following the Taconic deformation in Late Ordovician time the seas either retreated from the Cincinnati Arch Area or were displaced to the west. There may have been an Early Silurian transgression of the seas in which case the Arch Area was covered with a comparatively shallow body of water (Cryptothyrella assemblage).

MIDDLE LLANDOVERY TO C_3: This time interval is represented in the geologic column by the Brassfield Formation. The Brassfield rests disconformably on Upper Ordovician strata in the Cincinnati Arch Area. If any strata were laid down in Lower Llandovery time as was postulated in the previous section, they were removed by pre-Brassfield erosion. Platymerella is the oldest zone fossil found in the Brassfield and indicates an age from Middle to Upper Llandovery (B_1? to C_2). Microcardinalia is the youngest zonal fossil and it indicates an age of C_3.

There appears to be no evidence of an ancestral Cincinnati Arch during Lower Silurian time. The Brassfield outliers at Scrubgrass Creek near Mitchellsburg, Kentucky and Jeptha Knob near Shelbyville, Kentucky indicate that it once covered the Arch Area. The lithologic characteristics of the Brassfield such as the dolomite content, presence of chert, and the microfacies, are independent of the present day Arch. Two noteable exceptions are the hematite beds found close to the top of the Brassfield, which are thought to represent a near shore marine environment; and the higher clastic percent of the upper Brassfield (Noland Member) in east central Kentucky. The latter is interpreted as representing closer proximity to a souce area which lay to the southeast, rather than the Arch acting as a barrier to sedimentation preventing the deposition of clastics in southeastern Indiana and west central Kentucky.

According to Boucot (1967, written communciation) the Brassfield is diachronous and it was deposited first in Central Kentucky. With time the Brassfield "sea" migrated north and northwestward into southwestern Ohio and southeastern Indiana. Deepest water conditions were in central Kentucky and southwestern Ohio and they are represented by the glauconite and chert rich beds. As time progressed water conditions became shallower in Kentucky, and the shoreline which stood in western Pennsylvania or eastern Ohio (Yeakel, 1962, p. 1535) migrated westward. A greater influx of clastics reached the Arch area. The upper part of the Brassfield, that is, the Noland Member is gradational with the overlying Crab Orchard Formation in east central Kentucky. The alternating carbonate-shale beds reflect many minor advances and retreats of the sea. The Oldham and Waco Dolomite tonues are two major advances and the Plum Creek and Lulbegrud Shale lentils of the Noland are two regressions of the sea. The hematite beds were formed in a marine environment probably close to shore. Eventually the sea withdrew from the Cincinnati Arch Area and according to Ziegler and Boucot (manuscript in preparation) C_4 - C_5 (post-Brassfield) strata are missing.

The time of dolomitization is impossible to ascertain other than to say that it was post-depositional. Dolomitization is unrelated to the position of the present day Cincinnati Arch and it shows no stratigraphic or lithologic control. However it does approximate the position of the Ancestral Lexington Dome of Freeman (1951; 1959, p. 6), in north central Kentucky. Dolomitization may have taken place during a low stand of sea level sometime late in the formation of the Brassfield, or in post-Brassfield time on a very shallow water carbonate platform.

SUMMARY AND CONCLUSIONS

The Brassfield Formation is a distinctive unit because of its bedding characteristics, presence of chert, glauconite, and hematite. It is recognized in Ohio, Indiana, Kentucky, Tennessee, and Arkansas and is correlative with the Sexton Creek Limestone and Kankakee Dolomite of the Illinois Basin, Tuscarora Formation of the Appalachian Basin, and the Medina Group and part of the Clinton Group of New York. Summarized below are the observations and conclusions of this study.

(1) The Brassfield is a time transgressive unit of Middle and Upper Llandovery age (B_1?-C_3).

(2) The Brassfield is thickest in the region which embraces the southern part of west central Kentucky, and on the east side of the Cincinnati Arch in southwestern Ohio, and the northern part of east central Kentucky. Along the outcrop belt it thins to the north and west; and it is locally absent in southeastern Indiana. The greatest thickness is on the east side of the Arch and is due, in part, to a higher proportion of shales which have been derived from a souce area in the southeast. Thickness is unrelated to the Cincinnati Arch.

(3) Three major lithosomes are recognized:

(a) limestone lithosome

(b) dolomite lithosome

(c) clastic lithosome

The limestone lithosome is found in southeastern Indiana and southwestern Ohio. The dolomite lithosome is located throughout the remainder of Indiana and Kentucky. The clastic lithosome is found in Ohio, Kentucky, and West Virginia, to the east of the Cincinnati Arch. There is no relationship between the lithosomes and the present Cincinnati Arch.

(4) Within the three major lithosomes five microfacies are recognized:

I Crinoidal-bryozoan biosparite

II Biogenic dolomite

III Medium crystalline dolomite

IV Hematitic-biosparite

V Dolomitic biosparite

Microfacies I and IV indicate high energy environments while microfacies V indicates a low energy environment. Microfacies II probably represents both high and low energy conditions which suggests that dolomitization was independent of lithologic control. Recrystallization has been so extensive in microfacies III that it is impossible to speculate on the energy of the environment.

(5) There was a more or less constant influx of fine sand and silt size quartz, garnet, and zircon grains into the depositional basin. The latter two are very well rounded while the quartz is subangular to subround and probably has undergone at least one cycle of erosion and

deposition. Although it is impossible to measure directly the rate of influx of terrigenous material into the depositional basin, the presence of glauconite, and the abundance of such filter feeders as corals and bryozoans suggest that it was slow and that the waters were clear, rather than turbid. In the modern oceanic environment the rate of accumulation of terrigenous material ranges from around 0.5 cc/1000 years to 4.8 cc/1000 years. Considering the percent of insoluble residue in the carbonate portion, the Brassfield may have accumulated at a rate varying from 25 years/cc to 6240 years/cc.

(6) The Brassfield was deposited first in central Kentucky, and as time progressed the Brassfield "sea" reached southwestern Ohio and southeastern Indiana.

(7) Initially water conditions in central Kentucky, and the southern part of southwestern Ohio were relatively deep and probably represent the lower limits of the photic zone. Chert and glauconite were formed in what were probably the deepest water sediments.

(8) Water conditions were probably never deep in the northern portion of southwestern Ohio and southeastern Indiana and probably represent a shallow water high energy environment.

(9) As time progressed the sea became shallower in east central Kentucky and probably retreated from souther Ohio and southern Indiana, resulting in a disconformity

between the Brassfield and Dayton Formations in Ohio. Deposition was more or less continuous in east central Kentucky and the Dayton is considered to be correlative with the Waco tongue of the Brassfield. The hematite-rich beds were formed at this time when sea level was low.

(10) There is no evidence for the existence of the Cincinnati Arch in Early Silurian time. The lithology and thickness of the Brassfield is unrelated to the present Arch. Anomalies such as a higher clastic percent on the east side of the present Arch can be better explained as the result of proximity to source area rather than the Arch acting as a barrier to sedimentation.

(11) As an outgrowth of this study the following nomenclature changes are proposed:

(a) The Brassfield "limestone" be recognized as the Brassfield Formation.

(b) The Crab Orchard "group" is better evaluated as the Crab Orchard Formation.

(c) The names Alger Formation, Indian Fields Formation, and Estill Shale of the Crab Orchard "group" are highly local expressions and little is gained by continuing to employ these designations regionally.

(d) The Noland Formation of the Crab Orchard "group" is best evaluated as a member within the Brassfield Formation.

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INDEX OF MEASURED SECTION

Indiana

1. Laurel Indiana--natural exposure in northeast fork of Sains Creek approximately 2.3 miles west of Laurel, Franklin County. sw¼ ne¼ sec. 7, T 12 N, R 12 E.

3. Laurel, Indiana--natural exposure on hillside along dirt road approximately 1000 feet southeast of Section 1.

4. Elkhorn Falls--natural exposure in a stream cut of Elkhorn Creek at Elkhorn Falls on the west side of Indiana Rt. 227, 2 miles southeast of Richmond, Wayne Co., se¼, nw ¼ sec. 22, T 13 N, R 1 W.

5. Powerhouse Road--exposure in road cut on Indiana Rt. 62, 1.8 mile west of the entrance to Clifty Falls State Park, near Madison, Jefferson Co., ne ¼, ne ¼ sec. 5, T 3 N, R 10 E.

23. Richmond--natural exposure on Straight Road about 3 miles south of Richmond, Wayne Co., on southeast bluff of first stream cut south of Elkhorn Creek, nw¼, sw¼, nw¼, sec. 28, T 15 N, R 1 W.

24. Hanging Rock Hill--natural exposure on north side of Indiana Rt. 7, 1 mile north of Madison, Jefferson Co. nw¼, ne¼, sec. 34, T 4 N, R 10 E.

25. Hanover College--natural exposure in a small waterfall on the north side of the Hanover College Campus, Hanover, Jefferson Co., se¼, sw¼, nw¼, sec. 7, T 3 N, R 10 E.

26. Fourteenmile Creek--exposure in roadcut on Indiana Rt. 62, on the north side of the highway where it crosses Fourteenmile Creek about 3 miles northeast of Charlestown, Clark Co.

27. Bethlehem--exposures in roadcut 1.0 mile west-northwest of Bethlehem, Clark Co., on the center of the west line of sec. 8, T 1 N, R 10 E.

44. Osgood--natural exposures along a small east-west stream approximately 2.3 miles north-northeast of Osgood, Ripley Co. se¼, sw¼, and sw¼, se¼, sec. 3, T 8 N, R 11 E.

45. Cross Plains--east face of quarry wall of the Tri County Stone Co., 4 miles south of Cross Plains, Ripley Co., ne¼, nw¼, sec. 9, T 5 N, R 12 E, section is in Switzerland Co.

Ohio

2. Todd Fork--natural exposures on the northeast bank of Todd Fork, 200 yards south of where Center Road crosses the creek, about 3.2 miles northwest of Wilmington, Clinton Co.

6. Taylorsville Dam--exposure in an abandoned quarry 100 yards south of Ohio Rt. 440, 0.5 mile east of Taylorsville Dam, Montgomery Co. se¼, ne¼, sec. 31, T 2, R 8.

7. Belfast--natural exposure on northwest bank of a creek 0.7 miles wouthwest of Belfast, Highland Co., where Ohio Rt. 795 crosses Rock Lick.

8. Turtle Creek--exposure in an abandoned quarry behind a saw mill, 500 feet south of Turtle Creek on a secondary road to Hillsboro about 1.5 miles east of Lynchburg, Highland Co.

9. Turtle Creek--natural exposure on north bank of Turtle Creek across the secondary road to Hillsboro, opposite farmhouse occupied by Mr. Cooper. Located about 1,500 feet northeast of section 8, and about 1.5 miles east of Lynchburg.

10. Wright Brothers Memorial--natural exposure at the Wright Brothers Memorial on Ohio Rt. 444 just opposite Huffman Dam. Section was measured down from the point of the hill by the U.S.G.S. bench mark, se¼, sw¼ sec. 7, T 2, R 8, Greene Co.

11. Sevenmile Creek--natural exposure on Sevenmile Creek about 2 miles south of Eaton, Preble Co., where Ohio Rt. 127 crosses the creek. Section measured about 500 feet west of the highway. nw¼, se¼, sec. 11, T 7 N, R 2 E.

12. Sevenmile Creek--natural exposure on Sevenmile Creek at the same place as Section 11 but the section was measured about 700 feet east of the highway. ne¼ nw¼, sec. 11, T 7 N, R 2 E.

13. Belfast--natural exposure 0.25 mile southeast of Belfast, Highland Co., where Ohio Rt. 73 crosses Ohio Brush Creek.

14. Lumberton--abandoned quarry about 1000 feet east of McKay Road 0.2 mile south of where McKay Road crosses Anderson Fork, near Lumberton, Clinton Co. 39° 33' 30" N. Lat, 83° 52' 00" W. Long.

15. Lumberton--natural exposure on north side of Anderson Fork 1500 feet southeast of section 15. Section measured at a point where a tree had fallen across Anderson Fork making a natural bridge.

41. Ohio Brush Creek--exposure in road cut along U. S. 52 where Ohio Brush Creek enters the Ohio River 9 miles east of Manchester, Adams Co. Section measured on north side of highway and the west side of the creek.

42. Jacksonville--exposure in roadcut on west side of Ohio Rt. 41, south bluff Ohio Brush Creek, 1.4 mile south of Jacksonville, Adams Co.

43. Louden--natural exposure on the south side of Ohio Rt. 73, 1.6 miles west of Louden, Adams Co. where the highway crosses Flat Run.

46. West Milton--exposure in roadcut on Ohio Rt. 71, 0.25 mile east of West Milton, Miami Co., sw¼, se¼ sec. 16, T 7 N, R 5 E.

Kentucky

16. Bardstown--exposure in roadcut on north side of Blue Grass Parkway at the U. S. 31E exit, 2 miles south of Bardstown, Nelson Co., and 0.5 mile west of the Kentucky Rt. 49 overpass.

17. Buffalo Creek--exposure in roadcut on the north side of U. S. 62, 2.2 miles west of Bardstown, Nelson Co.

18. Carvens--exposure in roadcut on south side of the Blue Grass Parkway where it crosses Beech Fork, 2 miles south of Cravens, Nelson Co.

19. New Hope--exposure in a small abandoned quarry 0.3 mile north of New Hope, Nelson Co. on Kentucky Rt. 52, just north of where the highway crosses Pottinger Creek.

20. Cox's Creek--exposure in roadcut on Kentucky Rt. 480 about 1 mile west of where the highway crosses Cox's Creek and 3 miles west of the Bullitt-Nelson County Line in Bullitt Co.

21. Ridge Road--natural exposure along Kentucky Rt. 480 about 1 mile west of Section 20, just past intersection with Ridge Road where the highway crosses a small creek.

22. Mt. Washington--exposure in roadcut on U. S. 31E about 1.3 miles north of Mt. Washington, Bullitt Co., on the south bank of Floyds Fork.

28. Bybee--exposure on a fresh roadcut for the new Kentucky Rt. 52 (?) on the northeast side of an unnamed tributary flowing from the northwest into Drowning Creek, 1 mile southeast of Bybee, Madison Co.

29. Type Brassfield Section--exposure on an abandoned cut of the Louisville and Atlantic Railroad between Brassfield and Panola, Madison Co. 3-N-65.

30. Crab Orchard--exposures in roadcut on north side of U.S. 150, "the Wilderness Trail", 3 miles northwest of Crab Orchard, Lincoln Co., where the highway crosses Cedar Creek.

31. Berea--exposure in roadcut on the west side of U. S. 25, 2.8 miles northeast of Berea, Madison Co.

32. Middletown--exposure in roadcut on east side of I-75 about 500 feet north of overpass of Kentucky Rt. 595 about 3 miles northwest of Berea, Madison Co.

33. Farristown--exposure on west side of Louisville and Nashville Railroad cut where secondary road crosses the railroad tracks about 0.5 mile north of Farristown Church.

34. Waco--exposure in roadcut on the north side of Kentucky Rt. 52, 0.5 mile west of Waco, Madison Co., where the highway crosses Muddy Creek.

35. Type Noland Section--natural exposure along a private road on a hilltop in a section called "The Bend" (of the Kentucky River) about 1.6 miles northeast of College Hill, Madison Co. 11-P-65.

36. Red River--exposure in a roadcut on the east side of Kentucky Rt. 89 near top of south bluff of the Red River 6-P-66, Estill Co., 37° 49' N. Lat., 83° 04' W. Long.

37. Sugar Grove Church--exposure in roadcut on the east side of Stepstone Road where it ascends hill just after crossing I 64 adjacent to Sugar Grove Church 3 miles south of Owingsville, Bath Co. 38° 6' 15" N. Lat., 83° 49' 50" W. Long.

38. Peasticks--natural exposure along an unnamed secondary road 0.25 mile west of Hedrick Church about 3.2 miles east of Peasticks, Bath Co. 38° 09' N. Lat., 83° 38' W. Long.

39. Goddard--exposure in a roadcut along Kentucky Rt. 32 about 1 mile northwest of Goddard, 6.5 miles southeast of Flemingsburg, Fleming Co.

40. Tollesboro--exposure in roadcut on Kentucky Rt. 10, 2.5 miles east of intersection with Kentucky Rt. 57 in Tollesboro, Lewis Co. 3-Y-72.