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LITHOFACIES AND DEPOSITIONAL ENVIRONMENTS OF OSAGEAN-MERAMECIAN PLATFORM CARBONATES SOUTHERN INDIANA, CENTRAL AND EASTERN KENTUCKY

A thesis submitted to the

Division of Graduate Studies
of the University of Cincinnati

in partial fulfillment of the
requirements for the degree of

Doctor of Philosophy

in the Department of Geology
of the Graduate School of Arts and Sciences

1976

BY

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I hereby recommend that the thesis prepared under my supervision by Donald Joe Benson

entitled Lithofacies and Depositional Environments of Osagean-Meramecian Platform Carbonates Southern Indiana, Central and Eastern Kentucky

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

Approved by:

Wayne A Pryor

J Barry Maynard

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ABSTRACT

With cessation of clastic influx in early Mississippian (Osagean) time, carbonate deposition was initiated on a shallow water platform on the topset portion of the Borden Delta in southern Indiana and east-central Kentucky. Material originating on this platform was swept by wave and tidal currents to the platform margin where it was deposited down the foreset slope and into deeper water. This system of clinoform sedimentation led to rapid southwestward expansion of the platform.

Nine lithofacies can be recognized in the post-Borden platform carbonates. These are: (1) bryozoan-echinoderm grainstone-packstone, (2) echinoderm grainstone-packstone, (3) bryozoan grainstone-packstone, (4) diverse grainstone, (5) foram grainstone, (6) pelletal calcisphere packstone, (7) dolowackestone, (8) dolostone, and (9) quartzose sandstone. These lithofacies represent deposition in one or several of seven depositional environments present on or adjacent to the Borden platform. These environments are: (1) supratidal, (2) intertidal, (3) lagoon, (4) shoal, (5) subtidal shelf, (6) slope-edge, and (7) basinal.

Post-Borden platform sedimentation is characterized by four general stages of deposition. Initial carbonate deposition (Stage 1), represented by the Ramp Creek Formation in Indiana and the lower portion of the Renfro Formation in eastern Kentucky, is dominated by peritidal deposition. Subsidence in Indiana led to deposition of the dominantly subtidal Harrodsburg Formation during Stage 2, while peritidal deposition continued in eastern Kentucky. Stage 3 is characterized by peritidal deposition of

the Somerset Member of the Salem Formation across the rapidly expanding platform. Subtidal deposition of the Salem Formation characterized Stage 4 deposition across most of the platform, which by the end of Salem time occupied most of southern Indiana, central and eastern Kentucky.

After deposition, post-Borden platform carbonates were affected by five major diagenetic processes including: cementation, neomorphism, pressure-solution, dolomitization, and silicification.

INTRODUCTION

Nature of the Problem

The Lower Mississippian (Osagian) Borden Formation of Indiana and Kentucky forms an unusually straight delta front deposit which trends northwest-southeast through Kentucky then swings westward through southern Indiana. This delta front defines the distal extent of the Catskill-Pocono delta system which began building westward in Late Devonian time (Kepferle, 1972). Following cessation of clastic input, this area became the site of extensive carbonate deposition on and adjacent to the Borden front.

On the topset portions of the Borden Delta, carbonate deposition occurred on a shallow-water platform. Material originating on this platform was swept by wave and tidal currents to the platform margin where it was deposited down the foreset slope and into deeper water by sediment gravity flow processes (Klein, 1974). This system of clinoform sedimentation on and adjacent to the platform led to the rapid migration of the platform margin to the southwest until the platform occupied most of central Kentucky.

A study of the carbonate sediments deposited on this platform was initiated for several reasons. The platform carbonates are relatively thin deposits (less than 100 feet), are well exposed in southern Indiana and east-central Kentucky, have highly varied lithologies, and are the source of certain stratigraphic problems.

The purpose of the study was fourfold:

(1). To describe in detail the petrography of the rocks which formed on the Borden platform.

(2). To ascertain the depositional environments in which these rocks were deposited.

(3). To develop a depositional model for post-Borden platform deposition in the study area.

(4). To resolve some of the stratigraphic problems inherent in the platform deposits as they are now defined.

Study Area

The study is designed to be a regional investigation of the post-Borden platform carbonates in Indiana and the eastern and central portions of Kentucky. These rocks outcrop in the study area from southern Fountain County, Indiana on the north to the Tennessee State line, and from eastern Simpson County, Kentucky on the west around the Cincinnati Arch to Madison County, Kentucky on the east (Fig. 1). Possibly equivalent rocks are found northeast of Madison County but are not included in the study because of tenuous correlation.

Previous Studies

There have been numerous past studies of the post-Borden platform carbonates. These studies were concerned largely with the stratigraphy, paleontology, and economic uses of the units. Many of these studies were restricted to local areas, while others were more regional in nature. Table 1 is a summary of the most important past studies of the post-Borden platform carbonates.

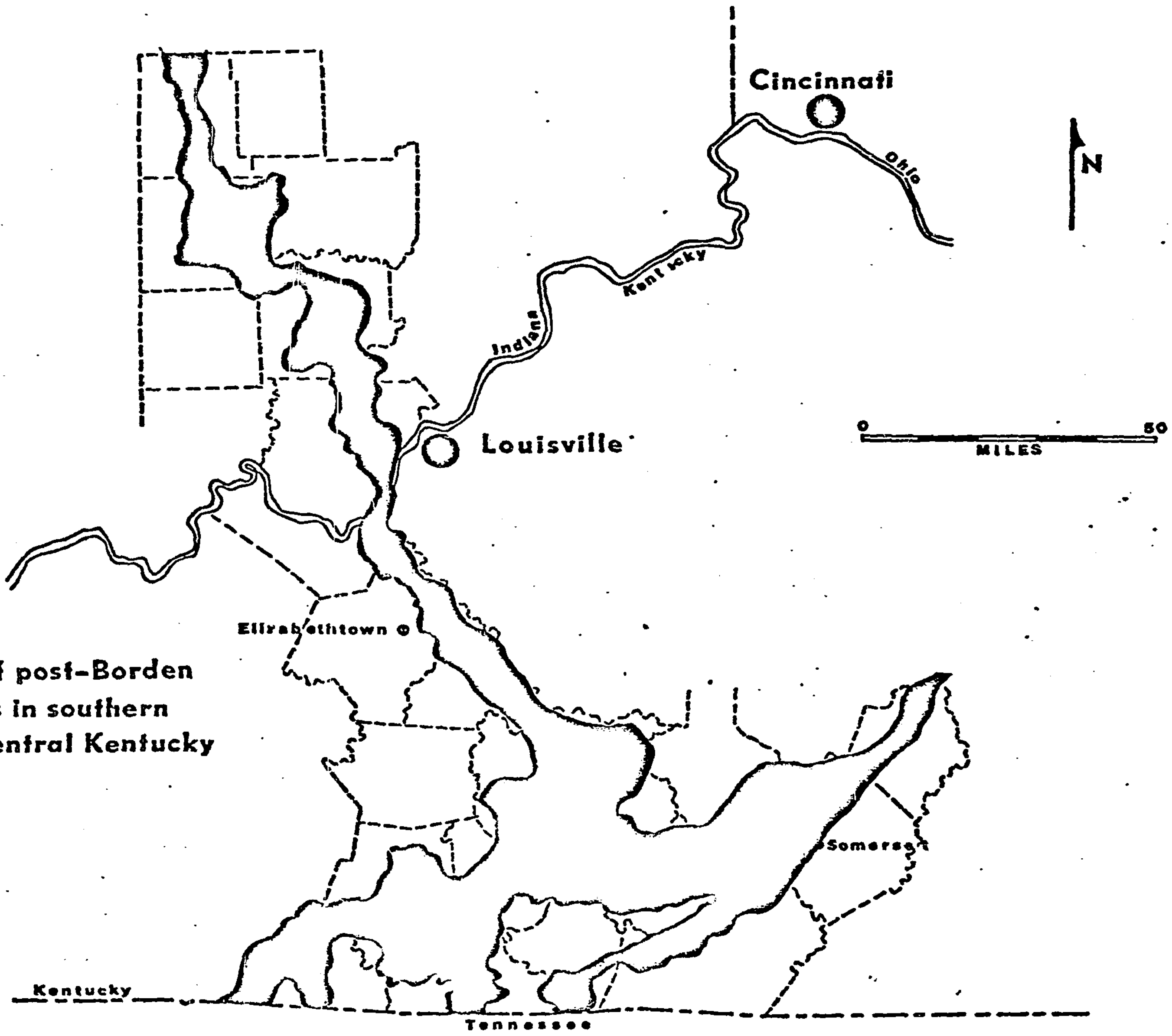

Figure 1 - Outcrop of post-Borden platform carbonates in southern Indiana and east-central Kentucky

Table 1 - Summary of important literature on the post-Borden platform carbonates of southern Indiana and central and eastern Kentucky

Reference	Remarks
Hall, 1864	Description of new species from various Carboniferous localities in Indiana and Illinois including Spergen Hill
Whitfield, 1883	Study of the Spergen Hill fauna
Hall, 1883	Expansion of 1864 study exclusively on the Spergen Hill fauna
Hopkins, and Siebenthal, 1897	Study of "Bedford" Formation; introduction of Harrodsburg Formation for coarse bioclastic limestone underlying the Salem of Indiana
Cumings, 1901	Rejection of use of the term "Bedford" because of preoccupation and introduction of Salem Formation to literature
Cumings, and others, 1906	Comprehensive study of the fauna of the Salem Formation
Udden, 1910	Study of dimension stone production from the Salem
Butts, 1915	Description and occurrence of Salem and Warsaw Formations in Jefferson County, Kentucky
Butts, 1917	Description and correlation of Mississippian Formations of western Kentucky; Salem is included in the St. Louis Formation
Butts, 1922	Description and correlation of Mississippian Formations of eastern Kentucky; Salem is included as a facies of the Warsaw Formation

Stockdale, 1929	Division of Harrodsburg Formation of Indiana into members
Stockdale, 1931	Discussion of the Borden and related rocks of Indiana; includes a section on the relation of the Borden to overlying units
Geis, 1932	Study of ostracods from the Salem of Indiana
Stockdale, 1939	Study of the Lower Mississippian of east-central interior; major emphasis on the Borden but much discussion of overlying units; introduction of facies concept to the Mississippian of the interior basin
Perry, and others, 1954	Field trip discussion of distribution and varied lithologies of Salem and associated formations of southern Indiana
Pinsak, 1957	Excellant study of Salem and related units in subsurface of Indiana with lithologic subdivision and implications as to depositional environment
Smith, 1962	Comprehensive study of Salem throughout Indiana with emphasis on lithology and its economic relationship
Taylor, 1962	Unpublished M.S. study of Salem-Warsaw of Green and Taylor Counties, Kentucky; basically a stratigraphic study which emphasises the complex lateral lithologic relations
Smith, 1965	Stratigraphic redefinition of Lower Mississippian carbonates of Indiana; introduction of Sanders Group

Lineback, 1966	Study of post-Borden carbonates of southwestern Illinois Basin; gives sequence of deposition and introduces new stratigraphic name (Ullin Formation)
Sable, Kepferle, and Peterson, 1966	Redefinition of Harrodsburg Limestone as a mappable unit in northwest-central Kentucky
Carr, and others, 1966	Investigation of cross-bedding in the Salem of the building stone district of Indiana; implications as to current direction and depositional environment
Weir, Gualtieri, and Schlanger, 1966	Definition of Borden Formation in eastern Kentucky; inclusion of Salem in Renfro Member of the Borden Formation
Donahue, 1967	Study of depositional environments of Salem in Indiana in light of modern carbonate literature
Nicoll, 1971	Conodont zonation of the Sanders Group of Indiana and north-central Kentucky; more stratigraphic changes and introduction of two more proposed members of Harrodsburg
Lineback, 1972	Discussion of transitional lithologies at the Salem-St. Louis contact
Sable, and Pryor, 1974	Regional summary of stratigraphy and sedimentation of Carboniferous of Eastern Interior Basin
Lewis, and Taylor, 1975	Introduction and description of Science Hill Sandstone Member of Salem-Warsaw of eastern Kentucky
Nicoll, and Rexroad, 1975	Redefinition of stratigraphy of Sanders Group of Indiana

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The author is indebted to the Indiana Geological Survey for making cores and well data from the Indiana portion of the study area available and especially for permitting me the use of numerous thin sections from these cores. Thanks also go to the Ohio Division of Geological Survey and Dr. Charles Kahle of Bowling Green State University for the use of their facilities during the final stages of the work.

The author benefited greatly from discussions with H. H. Gray, Donald Carr, and George Austin of the Indiana Geological Survey, R. C. Kepferle, R. Q. Lewis, and A. R. Taylor of the United States Geological Survey, and in particular Professor Paul E. Potter of the University of Cincinnati.

DEVELOPMENT OF STRATIGRAPHIC NOMENCLATURE

James Hall, in 1864, first described the fauna of the Salem Formation from the famous fossil collecting locality at Spergen Hill, Monroe County, Indiana and correlated it with the Warsaw of Illinois. Worthen (1866) placed the formation in the overlying St. Louis Formation largely on the basis of work done in the Illinois Basin.

It was not until 1897 that a comprehensive study was made of the building stone of Indiana. Hopkins and Siebenthal (1897), in a study of the rocks throughout the building stone district, proposed the name Bedford Oolitic Limestone for the building stone. In the same publication, the name Harrodsburg Limestone was proposed for the coarser grained bioclastic and impure geode bearing limestones between the "Bedford" and the clastic rocks of the Borden Formation.

Cumings in 1901 proposed that the quarry stone unit be called the Salem Limestone because the term Bedford had been used for a shale formation in Ohio. Ulrich and Smith (1905) ignored the suggestion of Cumings and instead used the term Spergen Limestone in referring to the building stone. This name was adopted by the United States Geological Survey (Wilmarth, 1938), while the Indiana Geological Survey retained the term Salem Limestone. In recent years, however, the United States Geological Survey has reverted to use of the term Salem in their Kentucky mapping program.

Up until this time, the majority of the work on the stratigraphy of the study area had centered on the building stone district of Indiana. Butts (1915), in a study of the geology of Jefferson County, Kentucky included all rocks above the top of the Borden clastics and below the coarsely crystalline gray limestone of the "Spergen" limestone in the Warsaw, which was equivalent to the Harrodsburg of Indiana. The unit was composed of siliceous, geodiferous, limestone; coarse crinoidal limestone; oolitic limestone; chert; and shale. The lower contact was marked by a thin bed of oolitic limestone or a bed of dark green glauconitic clay. This basal unit was overlain either by impure siliceous limestones or by a sequence of fine-grained silts or shales in the area of Edwardsville, Indiana. The Warsaw of Jefferson County was correlated with the type Warsaw of the Illinois Basin on the basis of stratigraphic position and lithologic similarity.

The description of the Spergen Limestone given by Butts for Jefferson County is somewhat vague, because no positive occurrence was cited. The unit is described as a coarse-grained, thick-bedded gray limestone from exposures at Edwardsville, Floyd County, Indiana.

In a study of the Mississippian series throughout Eastern Kentucky, Butts (1922) redefined the Warsaw to include all rocks between the Holtsclaw (Borden) clastics and the St. Louis Limestone. Because of the lack of the typical oolitic appearing limestone of the type Salem section, Butts regarded the Salem of Indiana to be a local lithologic facies of the Warsaw not present in Kentucky.

Three new members of the Warsaw were introduced in the same publication: the Wildie Sandstone member, the Somerset Shale member, and the Garrett Mill Sandstone member. The Wildie Sandstone, named for the town of Wildie, Rockcastle County, Kentucky is a thick-bedded, fine-grained sandstone found at the base of the Warsaw and underlain by a distinct seam of glauconitic shale which Butts correlated with the glauconite found at the base of the Warsaw in Jefferson County.

The Somerset Shale member, named after exposures near Somerset, Pulaski County, Kentucky, is a calcareous shale or shaley limestone which Butts placed near the top of the Warsaw.

The Garrett Mill Sandstone, named for Garretts Mill, Overton County, Tennessee, is described as a flaggy sandstone, 5 to 10 feet thick, found at the top of the Warsaw in the southeastern portion of the outcrop belt in Kentucky.

In the late 1920's, P. B. Stockdale began a series of investigations into the stratigraphy of the Mississippian of Indiana and Kentucky. In 1929 he published a study on the Harrodsburg of Indiana in which he recognized four distinct subdivisions of the Harrodsburg. The Harrodsburg was divided into the Upper Harrodsburg, a continuous sequence of coarse bioclastic limestones, and the Lower Harrodsburg which could be subdivided into three members: the Ramp Creek, Leesville, and Guthrie Creek. The Ramp Creek was a sequence of impure, siliceous, geodiferous limestones found at the base of the Harrodsburg. This was overlain by a prominent bed of coarse-grained, white bioclastic limestone which Stockdale termed the Leesville Member. Between the Leesville Member and the Upper Harrodsburg Limestones was a sequence of impure limestone much like the Ramp Creek but with less chert and fewer geodes which Stockdale termed the Guthrie Creek Member.

Stockdale (1931), in a study concentrating on the Borden Formation of Indiana, proposed a radically different stratigraphic terminology for the Warsaw of Butts. Much emphasis was placed on the bed of oolitic limestone and glauconitic shale described by Butts (1915) at the base of the Warsaw in Jefferson County, Kentucky and the name Floyds Knob Formation was proposed for the unit. Throughout the Borden outcrop of Indiana the Floyds Knob Formation is overlain by fine-grained siltstones and shales similar to the underlying Borden. This unit, termed the Edwardsville Formation by Stockdale, is the 40 feet of silty shale described by Butts in the lower Warsaw at Edwardsville, Indiana.

In extreme southern Indiana the rocks directly above the Floyds Knob become increasingly calcareous. Stockdale envisioned these rocks as a calcareous facies of the Edwardsville and designated it as the Stewarts Landing Facies of the Edwardsville Formation. Where this calcareous facies is well developed, distinction between it and the overlying Ramp Creek Member of the Harrodsburg is extremely difficult. Stockdale's interpretation of the units above the Edwardsville was essentially that of his 1929 study of the Harrodsburg.

In 1939 Stockdale published a comprehensive regional study of the Lower Mississippian Rocks of the east-central interior. This study incorporated work done in the Lower Mississippian of Kentucky with his 1931 study of the Borden of Indiana.

Stockdale reiterated the importance of the Floyds Knob Formation in Kentucky and, after examination of the Borden rocks of Kentucky, proposed a new formation to include those rocks above the Floyds Knob and below the Harrodsburg Restricted (Upper Harrodsburg). This new formation, the Muldraugh Formation, is thus the Kentucky equivalent of the Edwardsville Formation and the Ramp Creek, Leesville, and Cuthrie Creek Members of the Lower Harrodsburg (Stockdale, 1931).

This change was necessitated in Kentucky because of the absence of the clastic Edwardsville Formation. The entire section from the Floyds Knob horizon to the coarse bioclastic limestone of the Upper Harrodsburg is composed of impure, silty, cherty geodiferous limestone which contains restricted lenses of coarse grained bioclastic limestone. Thus the Muldraugh represents a southern extension of Stockdale's carbonate Stewarts Landing Facies of the Edwardsville of Indiana with the inclusion of the Lower Harrodsburg. This new formation was regarded as Keokuk in age whereas the Upper Harrodsburg was thought to be Warsaw in age.

Stockdale describes tracing the Lower Harrodsburg of Indiana into the Muldraugh of Kentucky where it merges with the calcareous facies of the Edwardsville. The Upper Harrodsburg was then traced across the top of the Muldraugh into northwest-central Kentucky along with the overlying Salem formation. This is in opposition to Butts who felt the Salem of Indiana was only a localized facies of the Warsaw and was not found in Kentucky. These formations were traced along the outcrop around the Cincinnati Arch into Lincoln and Rockcastle Counties where the typical Harrodsburg and Salem lithologies were not found and to the south at least as far as the Cumberland River in southern Pulaski County.

Special emphasis was placed on the confused nature of Butt's original description of the Somerset Shale. Stockdale (1939, p. 223) describes the varied stratigraphic horizons occupied by the Somerset as described by Butts (1922). One consistant horizon is apparently present, however, as Stockdale (1939, p. 226) describes tracing the Somerset Shale Member from southern Indiana to the type locality at Somerset, Pulaski County, Kentucky and interprets it as a basal argillaceous phase of the Salem.

Pinsak (1957) in an excellent study of the Salem Formation in the subsurface of Indiana, gives the first detailed description of the varied lithologies found in the Salem and their effect on the delineation of the upper and lower contacts of the unit. Stockdale's 1931 stratigraphic classification of Lower Harrodsburg, Upper Harrodsburg, and Salem is used with the Lower Harrodsburg correlated as the top of the Osage Series and the Upper Harrodsburg as the base of the Meramec.

Smith (1965) proposed, on the basis of a close lithologic relationship between the Harrodsburg and Salem Formations, a redefinition of Lower-Middle Mississippian stratigraphy in Indiana and the formation of a new group. The new group, the Sanders Group, included the Salem Limestone and a redefined Harrodsburg Limestone.

The redefined Harrodsburg Limestone includes the Harrodsburg Restricted (Upper Harrodsburg) of Stockdale (1939) plus the Guthrie Creek and Leesville Members of the Lower Harrodsburg placed by Stockdale in the Muldraugh Formation of Kentucky. The Ramp Creek Member of the Lower Harrodsburg was extended to include the calcareous Stewarts Landing Facies of Stockdale's Edwardsville in southern Indiana. The Edwardsville and Floyds Knob Formations of Stockdale were dropped from formation to member status and along with the Ramp Creek Member because subdivisions of the Muldraugh Formation of the Borden Group. (Note - The Borden is considered a group in Indiana while the U.S.G.S. considers it to be of formational status in Kentucky.)

Smith also placed the Somerset Shale, included by Stockdale (1939) as the lowest member of the Salem Formation, in the underlying Harrodsburg Formation. This was done primarily on the basis of lithologic similarity between the Somerset and the Guthrie Creek Member of the Harrodsburg.

Sable, Kepferle, and Peterson (1966), as a result of the cooperative mapping program of the United States Geological Survey and the Kentucky Geological Survey, redefined the Harrodsburg Limestone as a mappable unit in northwest-central Kentucky. The classification used was similar to that of Smith (1965) in that the Guthrie Creek and Leesville Members were included with the Harrodsburg while the Ramp Creek Member was placed in the underlying Muldraugh Member of the Borden Formation.

Tentative correlation was made between the Harrodsburg as defined in north-central Kentucky and the lower portions of units mapped as Salem-Warsaw in the Fountain Run Quadrangle of Monroe County (Hamilton, 1962), and Warsaw in Russell County (Thaden and Lewis, 1962). These beds are interpreted to interfinger with the underlying Ft. Payne Formation in these areas, suggesting the upper Ft. Payne may be a time-equivalent of the Harrodsburg.

Lineback (1966), in a subsurface study of carbonate sediments adjacent to the Borden Delta of Southern Illinois, proposed a radically different stratigraphic classification for rocks between the Borden

Formation and the Salem. A new formation, the Ullin Limestone, was proposed to include those rocks which previously had been included in the Harrodsburg Formation of Smith (1965) and Sable, Kepferle, and Peterson (1966) and the Muldraugh Member of Sable, Kepferle, and Peterson. The Edwardsville Member, included in the Muldraugh by both Stockdale (1939) and Smith (1965) was placed in the Borden Siltstone.

The Ullin was divided into two members; an upper Harrodsburg Member of light colored, coarse grained bioclastic limestone and a lower Ramp Creek Member of dark colored cherty, argillaceous limestone. The term Ramp Creek which was deemed equivalent to Muldraugh was used because of priority. The Somerset Shale Member, placed in the Harrodsburg by Smith (1965) was returned as the basal member of the Salem Limestone.

In Lincoln County, Kentucky, the predominately dark-colored limestone of both the Muldraugh and Salem-Warsaw Formations grades eastward into light gray to yellow finely crystalline argillaceous dolomite and dolomitic limestone. These rocks which appear very dissimilar to the typical Muldraugh and Salem-Warsaw lithologies were grouped together into the Renfro Member of the Borden Formation (Schlanger, 1965; Weir, Gualitieri, and Schlanger, 1966). The Renfro is arbitrarily mapped east of the Halls Gap Quadrangle, Lincoln County, Kentucky and can be traced northeast into Carter County, Kentucky where it is represented by less than 10 feet of light colored dolomite.

The stratigraphic nomenclature of the Sanders Group in Indiana was again revised by Nicoll and Rexroad (1975). The Edwardsville was returned to the rank of formation and placed within the Borden Group. The Ramp Creek which had previously been considered a member of either the Harrodsburg (Stockdale, 1929; 1931) or the Muldraugh (Smith, 1965), was raised to formational status and, on the basis of lithologic similarity, was placed in the Sanders Group rather than the Borden Group. At the same time, the Muldraugh Formation was defined as a lateral equivalent of the Ramp Creek in extreme southern Indiana and northern Kentucky. The Leesville and Guthrie Creek, which previously were members of the Harrodsburg (Stockdale, 1929; 1931; 1939; Smith, 1965) were reduced to the rank of named beds. Finally, the Somerset Shale, which had been placed in the Harrodsburg by Smith (1965) was returned to the Salem, as was done by Lineback (1966).

Lewis and Taylor (1975) described a sandstone body found in the lower portion of the Salem of eastern Kentucky and named the unit the Science Hill Sandstone Member of the Salem for exposures found near the town of Science Hill, Pulaski County, Kentucky. The unit is described as a reddish-brown, fine to coarse-grained, thin to thick-bedded, in part cross-bedded quartzose sandstone. In the type section the sandstone is interbedded with a medium to dark gray calcareous mudstone and occurs between skeletal calcarenites of the Salem and dolosiltites of the Muldraugh Member of the Borden Formation.

Considerable work by many geologists on a complex section of rocks showing wide lateral as well as vertical variability has produced a plethora of suggested stratigraphic classifications. Figure 2 is a summary of the major classifications discussed on the previous pages.

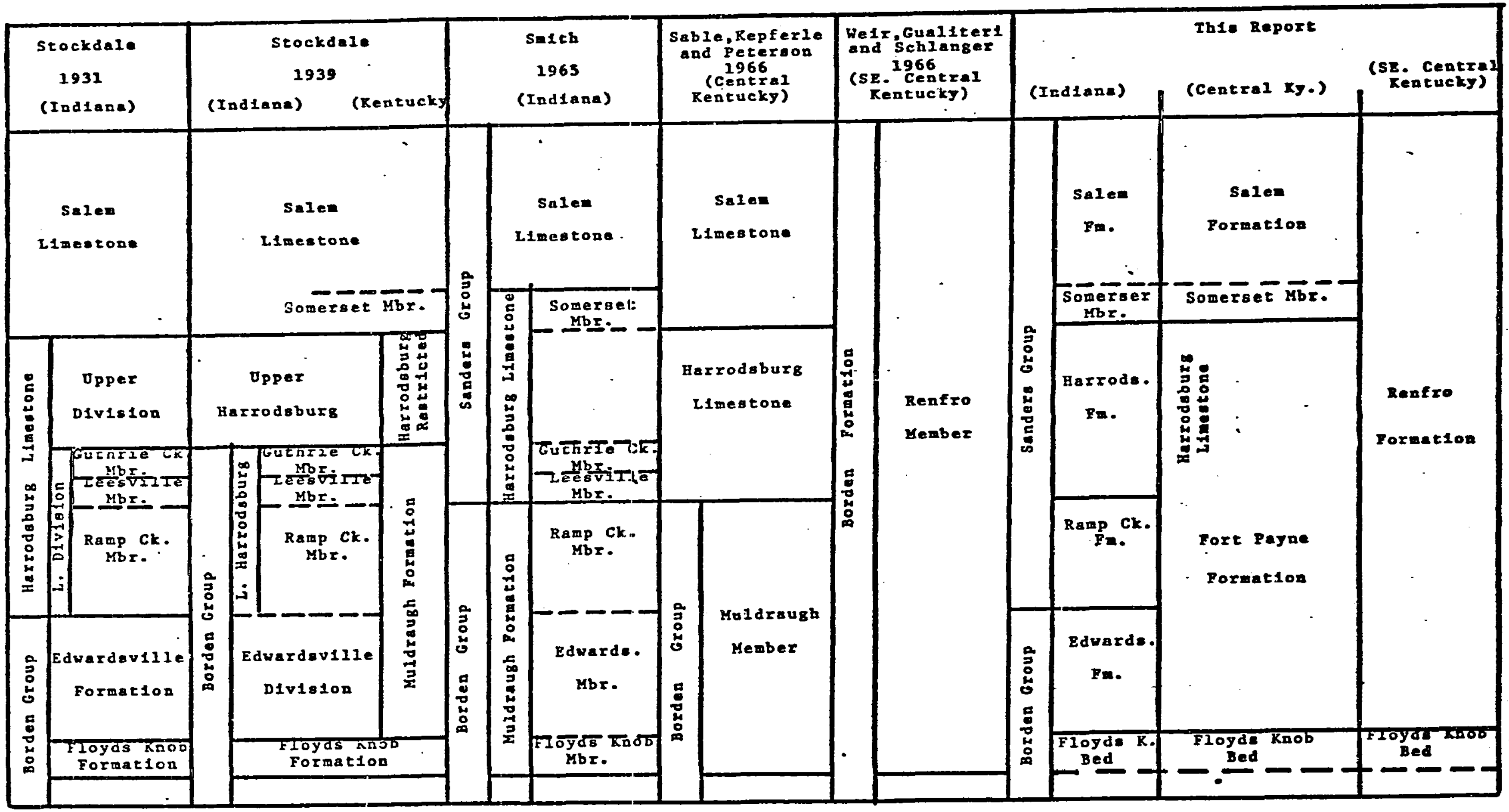


Figure 2 - Summary of major classifications proposed for post-Borden carbonates in Indiana and Kentucky

STRATIGRAPHIC REVISION

The numerous stratigraphic classifications discussed on the previous pages illustrate the diversity of opinion as to a usable nomenclature for the area. Field work throughout the area has revealed several major problems in the nomenclature of previous usage.

Any attempt to change, however, must be handled with care. Much of the area has been mapped geologically on a scale of 1:24,000 in Kentucky and 1:250,000 in Indiana. The classifications used on these maps are in common usage. The literature, as can be seen in Fig. 2, is already a plethora of stratigraphic names, therefore, an attempt has been made to formulate a classification which solves the major problems but does so without the introduction of new names and without radical alteration of the system as mapped in Indiana and Kentucky.

One of the greatest problems is to propose a classification satisfactory for Indiana, central and eastern Kentucky. These areas represent distinctly different sedimentary environments ranging from shallow-water shelf to deep-water basin. Because of varied depositional environments, each area is represented by a unique rock record for the Lower Mississippian. Thus a classification suitable for Indiana is far from acceptable in eastern Kentucky. Also, the underlying unit, the Borden, is recognized as a formation in Kentucky while it is a group in Indiana. Thus a unit which is a formation in Indiana becomes a member in Kentucky. While it is felt the Indiana classification gives greater flexibility and is probably more useful stratigraphically, an attempt to unify the nomenclature at this time would only result in confusion.

For this reason three separate classifications are proposed for the study area. These classifications for Indiana, central Kentucky, and eastern Kentucky are shown on Fig. 2. The boundaries for these areas are arbitrary but are designed to fit limits already set by the present mapping programs. The Indiana classification is used only in Indiana. The boundary between central and eastern Kentucky is picked at the eastern edge of the Halls Gap Quadrangle, Lincoln County, Kentucky and corresponds to longitude $84^{o}37'30''$W.

General Changes

Several of the changes fit the present systems of both Indiana and Kentucky without confusion and are discussed below.

Somerset Member

The Somerset Shale Member of the Warsaw of Butts (1922) has been the source of considerable stratigraphic debate. Nicoll and Rexroad (1975, p. 9-10) included the Somerset Shale Member in the Salem Formation but recognized the unit only in Harrison County, Indiana and Hardin County, Kentucky. A unit similar to the Somerset Shale has been mapped in other areas of Kentucky (Taylor, 1965), but has been given no formal name.

Part of the problem is related to confusion surrounding the original description of the Somerset Shale. The unit was named for the section along the Southern Railroad near Somerset, Pulaski County, Kentucky. Butts, at the same time, mentioned the excellant exposures found on the glades west of Colesburg, Hardin County, Kentucky and stated that had the name Colesburg not been previously used, he would have called the unit the Colesburg Shale Member. The discrepancy lies in the fact that the section at Somerset is near the top of the Salem while the one at Colesburg is near the base. Adding to the confusion is the fact that in a narrow belt parallel to the Borden front, almost the entire Salem sequence is argillaceous or dolomitic, giving several "Somerset Shales" separated by thin lensoidal limestones.

In the course of this study, a persistent zone of argillaceous dolomite or calcareous shale was found at or near the base of the Salem. This unit, which proved to be a valuable marker, was found from southern Monroe County, Indiana south to the Tennessee state line and as far east as Mount Vernon, Kentucky. The unit varies in thickness from less than 2 feet in southern Monroe County to over 20 feet in Allen County, Kentucky, showing a general thickening to the south and west, away from the Borden front.

The unit is composed of nonresistant dark gray-brown argillaceous dolomites or calcareous shales which often contain large geodes. In much of southern Kentucky the unit is underlain by a thin bed of bioclastic limestone which has been correlated with the Harrodsburg Limestone of north-central Kentucky (Hamilton, 1963). This bed, however, is more similar to the Salem Formation showing a much more diverse fauna than the bryozoan-echinoderm limestones of the Harrodsburg, and is included as the basal bed of the Salem.

Because the unit is laterally persistent, occupies a stratigraphically significant position at or near the base of the Salem, and has a mappable thickness, the name Somerset Member is proposed. The unit is redefined to include only those argillaceous carbonates or calcareous shales found at or near the base of the Salem Formation and excludes similar lithologies found at other stratigraphic horizons. Because of the confusion previously mentioned surrounding the actual designation of a type section, the section along the access road to the Waitsboro Recreation area south of Somerset is given in Appendix A as a reference section.

Floyds Knob Bed

The Floyds Knob Formation of Stockdale (1931) is presently recognized as a member of the Edwardsville Formation in Indiana (Nicoll and Rexroad, 1975) but is given no formal designation in Kentucky. It occurs in a variety of lithologies in Indiana from oolitic limestone to sandstone, but a thin zone of greenish-black glauconite, or in some areas, two glauconites separated by several feet of dolomitic siltstone (Sedimentation Seminar, 1972, p. 17) represents the horizon throughout most of Kentucky.

Stockdale (1931) first recognized the importance of the Floyds Knob in Kentucky, where it occurs between the Borden clastics and the overlying carbonates of the Muldraugh. Its significance was further demonstrated when it was used to delineate the Borden Delta front (Peterson and Kepferle, 1970).

The Floyds Knob horizon can be recognized throughout most of Kentucky and Southern Indiana (VanWie, 1971). The glauconite, which is most prevalent near the edge of the Borden Front, ranges in thickness from less than 1 inch to several inches within a short distance.

Because of the lateral extent of the Floyds Knob and its important stratigraphic position, it seems imperative to give it formal status. However, the thickness of the unit along with its somewhat spotty occurrence precludes member status. Therefore, it is proposed that it be called the Floyds Knob Bed and assigned to the Carwood Formation of Indiana or the upper member of the Borden Formation of Kentucky.

Changes in Indiana

The Indiana portion of the study area is somewhat anomalous because of the presence of a thick sequence of post-Floyds Knob clastics. This unit, the Edwardsville (Stockdale, 1931), has caused quite a bit of confusion to stratigraphers. It was felt (Stockdale, 1931), that the typical Edwardsville clastic graded into carbonates in southern Harrison County.

It was on this basis that Smith (1965) placed the Floyds Knob, Edwardsville, and Ramp Creek in the Muldraugh Formation. The Edwardsville represented the clastic facies while the Ramp Creek was the impure carbonate facies.

Recent work (Whitehead, 1973) has shown that the impure carbonate of the Ramp Creek is a distinct unit, younger than the Edwardsville clastics which thickens to the south at the expense of the Edwardsville. The Edwardsville is 56 feet thick at the type section near Edwardsville, Floyd County, thins to 11 feet at the Stewarts Landing section in central Harrison County and is missing at Evens Landing about 5 miles south of Stewarts Landing.

The siliceous, argillaceous dolomites which comprise the Ramp Creek average 35 feet in thickness throughout much of central Indiana and thicken to 76 feet at Stewarts Landing (Location 15, Fig. 6) in southern Indiana. This unit becomes the Muldraugh Member of the Borden Formation of Kentucky usage.

Thus the impure carbonates are a distinct unit, younger than rather than contemporaneous with the Edwardsville clastics. Because of their lithologic dissimilarity and because they are not time equivalents, it seems unreasonable to group the Edwardsville and Ramp Creek into the same formation.

Therefore, it is proposed that the Edwardsville be excluded from the Muldraugh Formation of Indiana, elevated to formation status and made the uppermost formation of the Borden Group.

The Edwardsville Formation then would include those clastic rocks above the Floyds Knob Bed and below the dolomites of the Ramp Creek. The change from the clastics of the Edwardsville to the carbonates of the Ramp Creek is an abrupt one and is often marked by a thin glauconite similar to the Floyds Knob Glauconite.

The Muldraugh Formation then includes only the impure carbonates of the Ramp Creek Member. There seems to be no justification for including these carbonates with the dominately clastic Borden Group. Therefore, it is proposed that the overlying Sanders Group be extended to include those rocks above the Borden clastics and below the St. Louis.

There is also some question about the use of the term Muldraugh in Indiana. While the term is widely used in Kentucky, it has found little use in Indiana, with the term Ramp Creek being used for equivalent rocks.

Maintenance of two terms for the same rock unit is superfluous and while the term Muldraugh is more firmly entrenched in the literature, Ramp Creek has preeminance.

Because the Ramp Creek represents deposition on the Borden platform, while the Kentucky rocks are largely basinal equivalents, the term Muldraugh is dropped in Indiana and Ramp Creek is used for the dolomitic units found directly overlying the Borden.

Changes in Kentucky

The Muldraugh Member of the Borden Formation in Kentucky is a sequence of impure carbonates similar to the revised Ramp Creek Formation of Indiana. The unit thickens to the south and west in Kentucky at the expense of the underlying clastic portion of the Borden until the Borden is represented only by a thin sequence of gray-green prodelta clays. Where the clastic portion of the Borden is no longer a mappable unit, the term Muldraugh is arbitrarily dropped and the sequence of impure carbonates is termed the Fort Payne Formation.

As in Indiana, there appears to be little purpose in including the dominantly carbonate Muldraugh in the clastic Borden Formation, particularly because its basinward equivalent, the Fort Payne, is a separate distinct formation. It is therefore recommended that the Muldraugh be excluded from the Borden.

Also, because the Muldraugh and Fort Payne are lateral equivalents, defined only by their position relative to the Borden clastics, and because both represent deposition in a slope or basinal environment, it again seems superfluous to maintain separate terms. Thus, the term

Muldraugh is dropped completely and the term Fort Payne is extended to include all the basinal impure carbonates persently mapped as Muldraugh.

There is also some question about the use of the term Harrodsburg in Kentucky. The occurrence of rocks correlated with the Harrodsburg of Indiana has been reported in north-central Kentucky (Sable, Kepferle, and Peterson, 1966), south-central Kentucky (Hamilton, 1963; Thaden and Lewis, 1962), and eastern Kentucky (Weir, 1970, p. 34). Field investigation in the course of this study has shown that the Harrodsburg can be traced into Kentucky only as far south as Hardin County. South of Hardin County, the lithology interfingers with the underlying Fort Payne and disappears. Lithologies tentatively correlated with the Harrodsburg from other portions of the study area were found to be more similar to the overlying Salem Formation than to the Harrodsburg as represented in Indiana and north-central Kentucky.

On this basis, the Harrodsburg is considered to be present only in Meade and Hardin Counties of north-central Kentucky.

Northeast of Lincoln County, Kentucky, a change occurs in the post-Borden sediments. A thin siltstone and shale similar to the Edwardsville Formation of Indiana is found above the Floyds Knob. Above this, the normal impure carbonates of the Muldraugh and bioclastic limestones of the Salem are replaced by light gray to yellow dolomites assigned to the Renfro Member of the Borden Formation (Weir, Gualiteri, and Schlanger, 1966).

The Muldraugh and Salem are mapped as far east as the Halls Gap quadrangle. East of the Halls Gap quadrangle, the terms Muldraugh and Salem are dropped and Renfro used instead, even though lithologies similar to the Muldraugh and Salem can be found as far east as

Maretburg (Weir, Gualiteri, and Schlanger, 1966, p. F19). A unit tentatively correlated with the Somerset Member of the Salem has been traced as far east as the type section of the Renfro at Renfro Valley, Rockcastle County, Kentucky. Northeast of the Renfro Valley subdivision of the unit becomes highly questionable.

Field observation has shown the Renfro to be a valid mappable unit in eastern Kentucky. Its inclusion in the Borden Formation, however, raises certain problems. Inclusion of the Renfro with the Borden is based primarily on its equivalence with the Muldraugh. Inclusion of Salem equivalents in the Renfro though, can lead to serious misconceptions of local geology. Weir, Gualiteri, and Schlanger (1966, p. F1) state: "The Borden is conformably overlain by the Salem and Warsaw limestones of Late Mississippian age in south-central Kentucky and by the Newman Limestone of Late Mississippian age in southeast-central Kentucky." This implies the Salem interval is absent in the southeast-central Kentucky which is not true.

Exclusion of the Muldraugh from the Borden (p. 26) removes the basic criteria for inclusion of the Renfro. This, along with the dominant carbonate lithology of the unit and its equivalence to post-Borden (Salem) units, demand its exclusion from the Borden Formation. Because it is mappable, it is recommended that it be raised to formational status and recognized as a distinct unit.

STRATIGRAPHIC SETTING

Platform carbonates occur within five separate units in the study area. All of the revised Ramp Creek, Harrodsburg, Salem, and Renfro Formations are considered to represent platform deposition. Also, portions of the revised Fort Payne Formation north of Somerset in eastern Kentucky are considered to be of platform origin.

Ramp Creek Formation

The Ramp Creek represents initial carbonate deposition on the Indiana portions of the Borden Platform. The Ramp Creek is exposed from southern Fountain County, Indiana on the north to the northern portions of Harrison County, Indiana on the south.

In southern Harrison County, the Ramp Creek overlies basinal Fort Payne deposits. These basinal deposits, since they were derived from the platform, are lithologically similar to the Ramp Creek, and in many areas it is difficult to distinguish between the two.

The unit consists of interbedded bioclastic limestones and dolomites with dolomite predominant. The limestones are generally coarse calcarenites or calcirudites composed predominately of echinoderm and bryozoan fragments. In many outcrops, the limestones grade upward into dolomites. The dolomite is light gray, weathering light brown, is cherty and contains numerous geodes.

The thickness of the Ramp Creek is relatively uniform in outcrop ranging from 19 to 30 feet (Stockdale, 1929, p. 240), and thickens only slightly in the subsurface portions of the platform west of the outcrop (Pinsak, 1957, plate 1).

The Ramp Creek overlies fine-grained siltstones of the Edwardsville Formation, with the contact often marked by a thin glauconitic shale. It is overlain by the Harrodsburg Formation, which is dominated by bioclastic limestones. The contact between the two is gradational, however, with bioclastic limestones characteristic of the Harrodsburg interbedded with typical Ramp Creek dolomites.

Harrodsburg Formation

The Harrodsburg Formation represents deposition on an expanding platform. The Harrodsburg is exposed from southern Fountain County, Indiana to Hardin County, Kentucky overlapping the underlying Ramp Creek platform deposits. Exposures of the Harrodsburg are found only west of the Cincinnati Arch. East of the arch, the typical Harrodsburg lithology is absent.

The Harrodsburg is composed dominantly of bioclastic calcarenites and calcirudites. Bryozoans, echinoderms, and brachiopods are the primary skeletal components, with bryozoans particularly abundant in the upper portion of the unit. Minor interbeds of argillaceous dolomite or shale are also present in the formation.

The Harrodsburg maintains a fairly uniform thickness in outcrop, ranging from 20 to 60 feet. In the subsurface, the thickness shows a steady increase westward into the Illinois Basin reaching a maximum in Indiana of 110 feet in Posey County (Pinsak, 1957, p.27).

The Harrodsburg shows an intertonguing relationship with the underlying Ramp Creek, but is sharply overlain by argillaceous dolomites of the Somerset Shale Member of the Salem Formation over most of the area of exposure.

Salem Formation

During Salem time the shallow-water platform expanded over the entire study area. The Salem Formation is exposed from Fountain County, Indiana on the north to the Tennessee State line and from eastern Simpson County, Kentucky on the west to Lincoln County, Kentucky on the east where the name is arbitrarily dropped and the unit becomes the upper portion of the Renfro Formation.

The Salem is composed of a mixture of several different lithologies ranging from coarse bioclastic calcarenites to fine-grained pelletal limestones and dolomites. In the Indiana portion of the study area, the most distinctive lithologies are the fine-to-medium grained calcarenite of the Salem building stone, fine-grained pelletal limestones, and coarse-grained bioclastic calcarenites which occur in the lower portions of the unit. In central and eastern Kentucky, the Salem is characterized by coarse-grained bioclastic calcarenites and argillaceous dolomites.

The Salem ranges in outcrop from 40 to 110 feet in thickness (Fig. 3). Thickness of the unit is fairly consistent paralleling the Borden front and shows a uniform increase westward into the Illinois Basin. Thinning of the unit in the south-central portion of the study area is apparently structurally controlled and related to the Nashville Dome south of the study area.

Throughout much of the study area, the lower contact of the Salem is defined by the occurrence of argillaceous dolomites of the Somerset Shale Member. The Somerset Shale forms a sharp lower contact over much

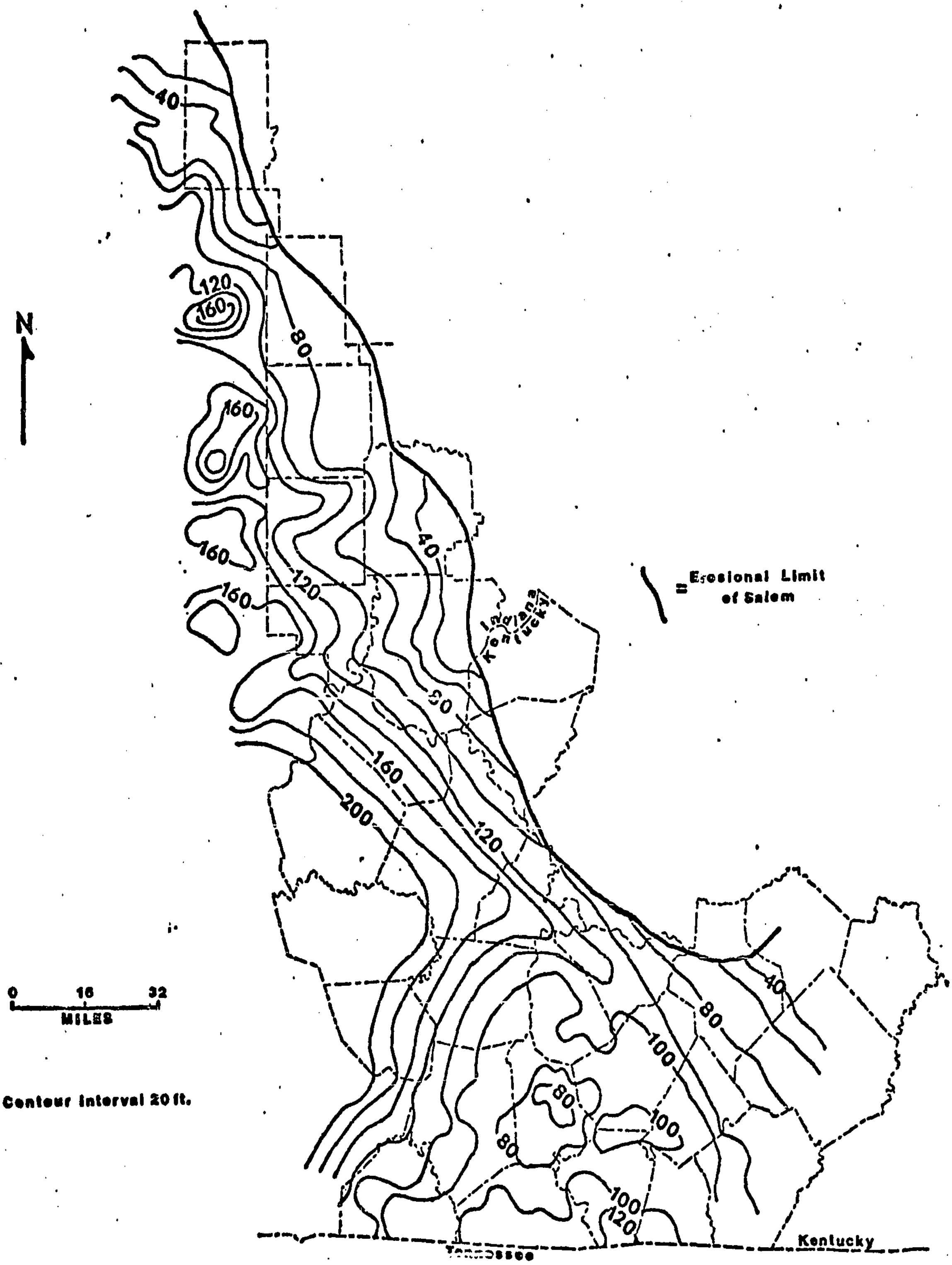


Figure 3 - Isopach map of Salem Formation in the study area (Indiana data from Pinsak (1957); Kentucky data from U.S.G.S. Geologic Quadrangle GQ maps)

of the northern portion of the study area. In the southern portions of the study area, however, the Somerset Shale interfingers with similar lithologies present in the underlying Fort Payne Formation.

The upper contact of the Salem is transitional throughout much of the study area, though Donahue (1967, p. 9) reported a sharp contact marked by a thin shale over much of the Indiana outcrop. At many places along the contact, lithologies characteristic of the upper portions of the Salem intergrade with those characteristic of the lower portions of the St. Louis Formation. It has been suggested by Lineback (1972), that, in places, the upper Salem is contemporaneous with the lower St. Louis.

Renfro Formation

The Renfro Formation is equivalent to the combined Fort Payne and Salem Formations in the eastern portions of the study area. In the area north of Somerset, Pulaski County, Kentucky, the Fort Payne, which is normally composed of basinal deposits, is of platform origin. The somewhat confusing stratigraphic relationships in this portion of the study area are illustrated in Figure 4.

The Renfro Formation is present in the study area from Madison County southwestward to the eastern margin of the Halls Gap Quadrangle, Lincoln County, where the term Renfro is arbitrarily dropped in favor of Fort Payne and Salem.

The Renfro is dominated lithologically by light colored dolomites and pelletal limestones. The unit also contains minor bioclastic limestones and calcareous sandstones near its western limits.

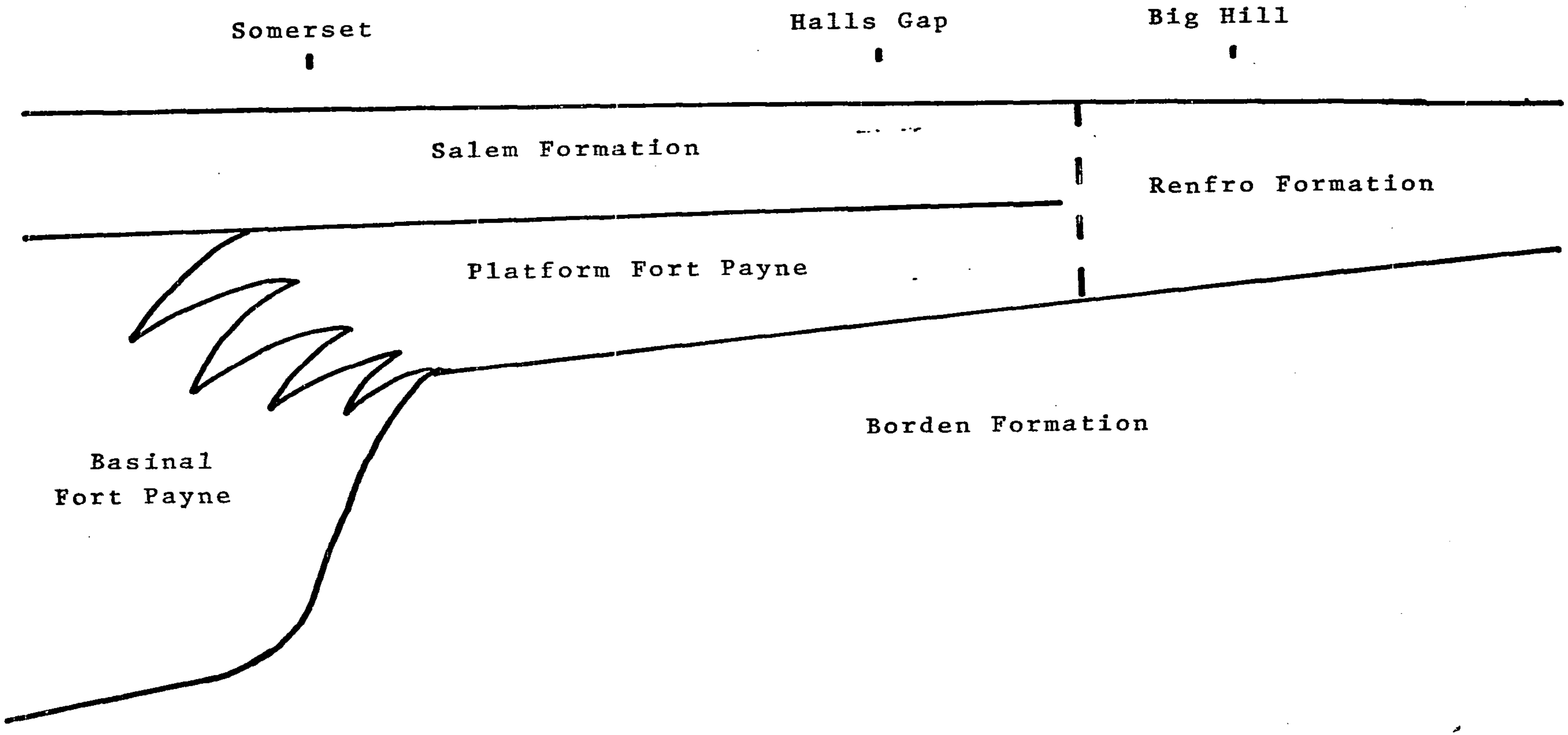


Figure 4 - Stratigraphic relations of post-Borden platform carbonates in eastern Kentucky

The unit ranges in thickness from 40 to 110 feet over the relatively small portion of the study in which it is exposed (Fig. 5). It is thinnest in the northern portions of the study area and thickens uniformly to the southwest.

The Renfro is underlain by the Wildie and Nada Members of the Borden Formation (Weir, 1970), with the contact often marked by a thin glauconitic shale. The upper contact between the Renfro and the St. Louis Formation is variable. In places it occurs as a conspicuous diastem, while at other locations the upper portion of the Renfro intertongues with the lower portions of the overlying St. Louis. This is analogous to the contact between the Salem and the St. Louis in other portions of the study area.

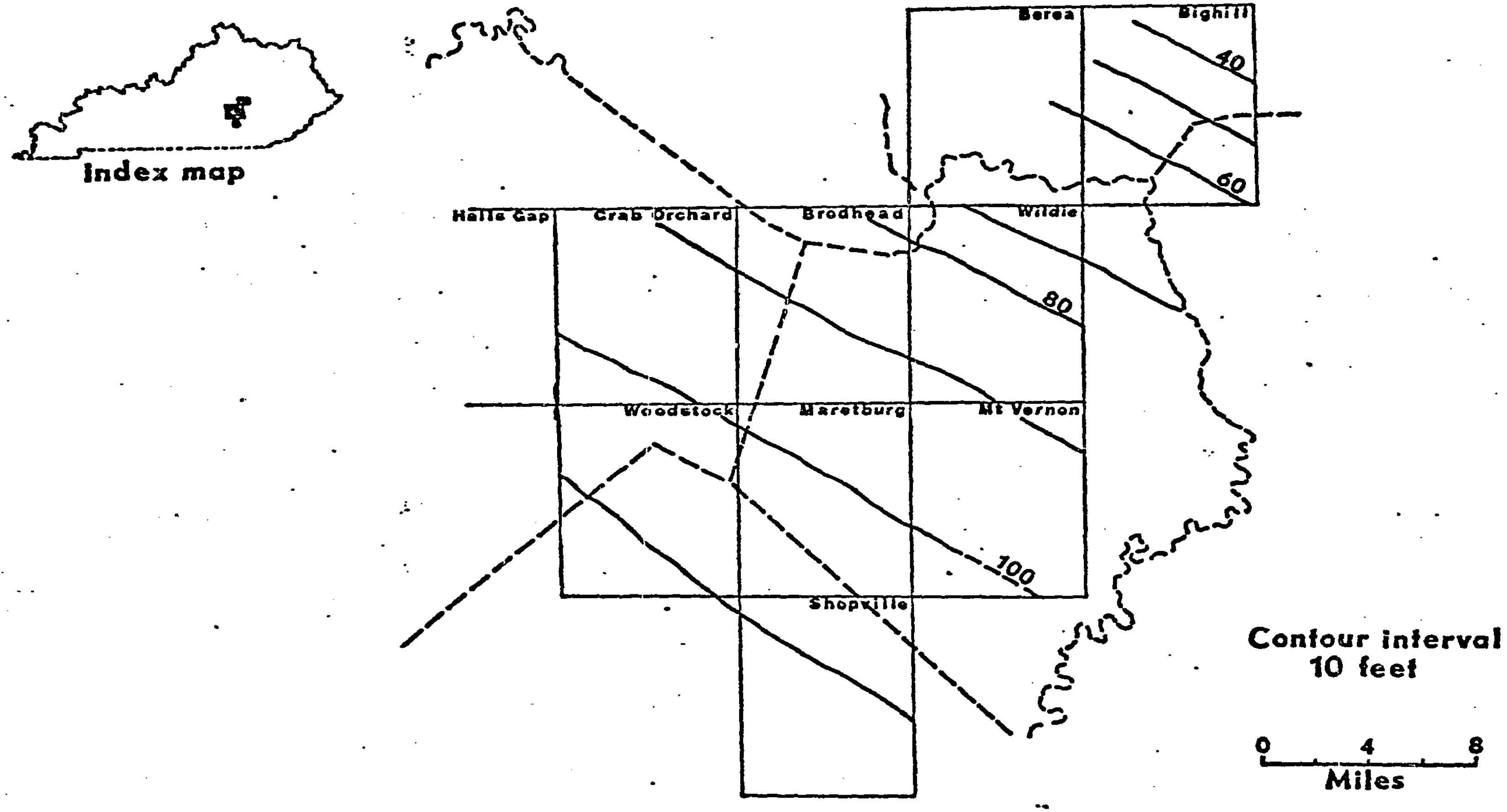


Figure 5 - Isopach map of Renfro Formation in study area (data from U.S.G.S. GQ maps shown)

METHODS

In order to completely understand the regional relations of the plaform carbonates, exposures of the Ramp Creek, Harrodsburg, Salem, and Renfro Formations were described and sampled at 64 locations in Indiana and Kentucky (Fig. 6). Features described from each section included rock type, bedding characteristics, sedimentary structures, crossbedding, and lateral continuity. Sections were measured at all of these locations where significant portions of a unit or units were exposed. Cross-sections were constructed from these measured sections and are included on Plates 1 through 5. Symbols used on these plates and elsewhere in the report are illustrated in Figure 7.

Sampling units were defined in these sections on the basis of bedding planes, composition, texture, and color. Each individual unit was sampled, regardless of thickness, with multiple samples taken from units which were in excess of 5 feet in thickness.

In addition, 3 cores from the Indiana portion of the study area (Fig. 6) were examined at the Indiana Geological Survey. These cores, which extended from the St. Louis Limestone into the Devonian Black Shale, gave complete sections of the post-Borden platform carbonates and aided greatly in correlation. Locations of sampled outcrops and cores are included in Appendix B.

Six hundred seventy-one samples were collected from the 64 localities illustrated in Figure 6. From these, 438 thin-sections were prepared from those samples most representative of the regional relations.

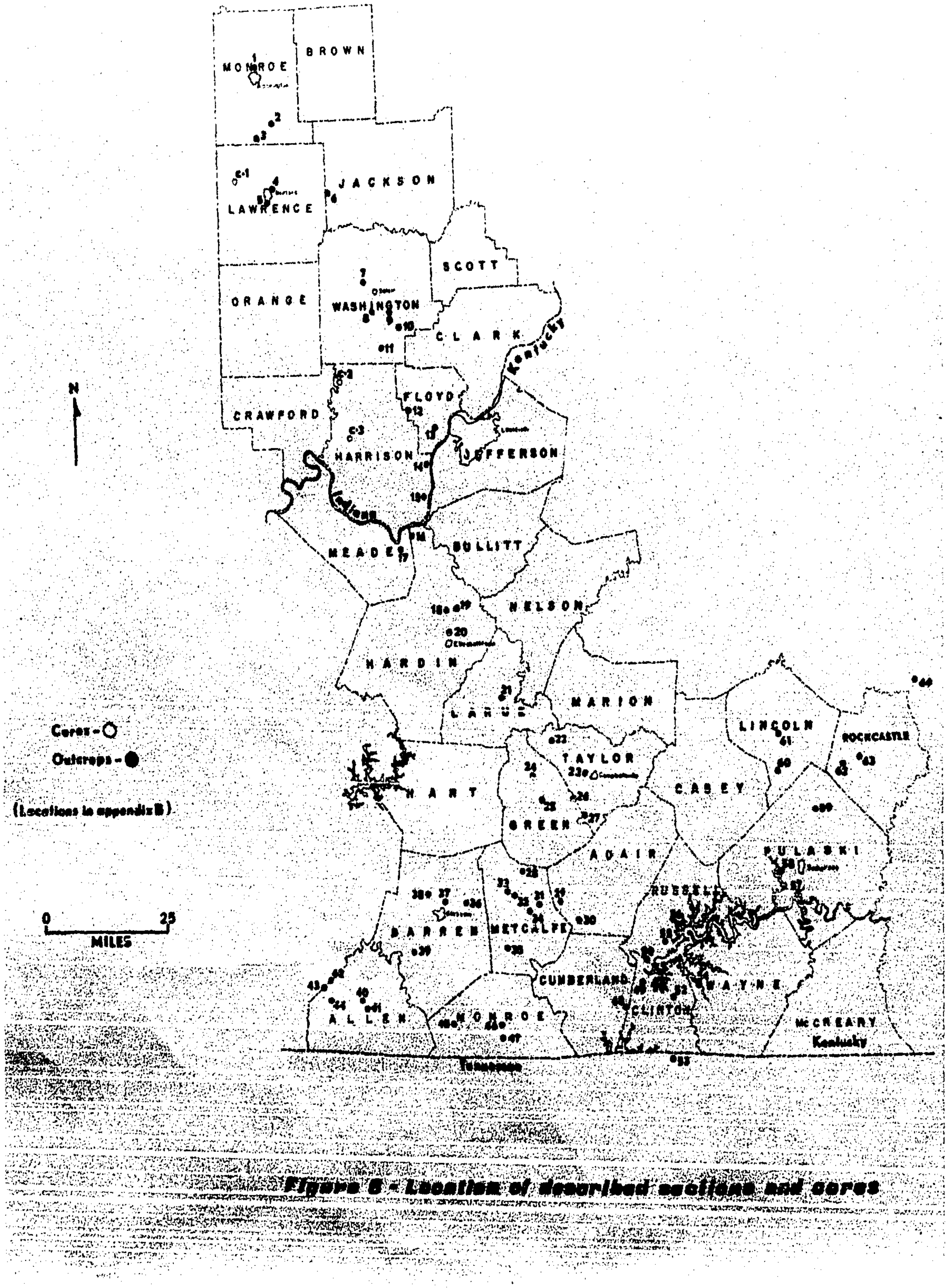


Figure 6 - Location of described sections and cores

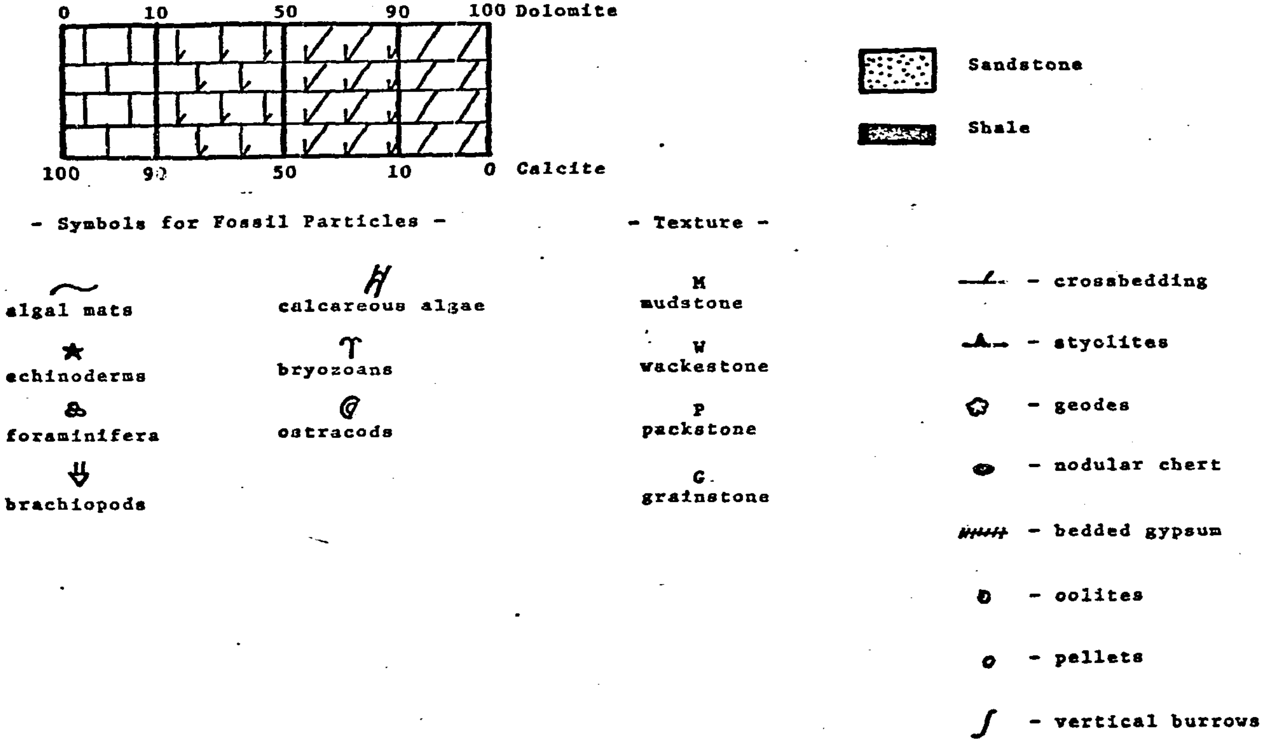


Fig. 7 - Lithologic and paleontologic symbols

These sections were stained for Mg^{++} and Fe^{++} using the method of Dickson (1965). One hundred fifty selected thin-sections were then point-counted to determine constituent particles with 200 counts made per thin-section.

Textural parameters were determined for 50 selected samples of major predetermined lithofacies. These parameters were measured visually on scaled negative enlargements of the thin-sections. Standard textural parameters (Folk, 1968, p. 44-48) were determined using a computer program written by W. A. VanWie.

Ten samples were analyzed by cathode luminescence techniques (Sippel and Glover, 1965) in an effort to delineate chemical variations in sparry cements.

Selected samples were slabbed and polished for identification of microscopic constituents and primary structures. Several of these slabs were studied by x-radiography to ascertain primary structures or burrowing.

Portions of 330 samples were powdered for x-ray diffraction analysis to determine bulk mineralogy with emphasis on the proportions of calcite and dolomite present. The powdered sample was packed into a welled plastic holder and irradiated from 20 to 35 degrees 2 theta using copper radiation. Quantitative estimates of the amounts of calcite and dolomite present were made using the methods of Tennant and Berger (1957).

X-ray diffraction analysis was also run on samples of clayey insoluble residues and shale interbeds to determine clay mineral content.

Fifty-eight samples were dissolved in dilute hydrochloric acid to determine the approximate amount and type of noncarbonate material present.

LITHOLOGIC CONSTITUENTS

One of the primary objectives of this study was to determine the depositional environments of the post-Borden carbonates. To give a reasonable hypotheses of the environment of deposition entails careful observation of many aspects of the units including mineralogy, sedimentary structures, and paleontology. Probably most important, however, is a detailed description of the lithologic constituents of the rocks themselves.

Lithologic components of carbonate rocks can be divided into three basic classes; detrital mud, chemical precipitates, and framework grains (Leighton and Pendexter, 1962).

The distribution of these components in the section is shown in Figure 8.

Detrital Mud

Fine-grained carbonate mud, more commonly termed micrite (Folk, 1959, p. 9), is the most common detrital constituent of the platform units, though in most cases it has been replaced by dolomite. There are, however, significant amounts of detrital terrigeneous mud in the units. The Somerset Shale Member of the Salem contains up to 70 percent argillaceous material in places. Argillaceous material is also abundant in the Salem in the eastern portions of the study area and in the Renfro Formation.

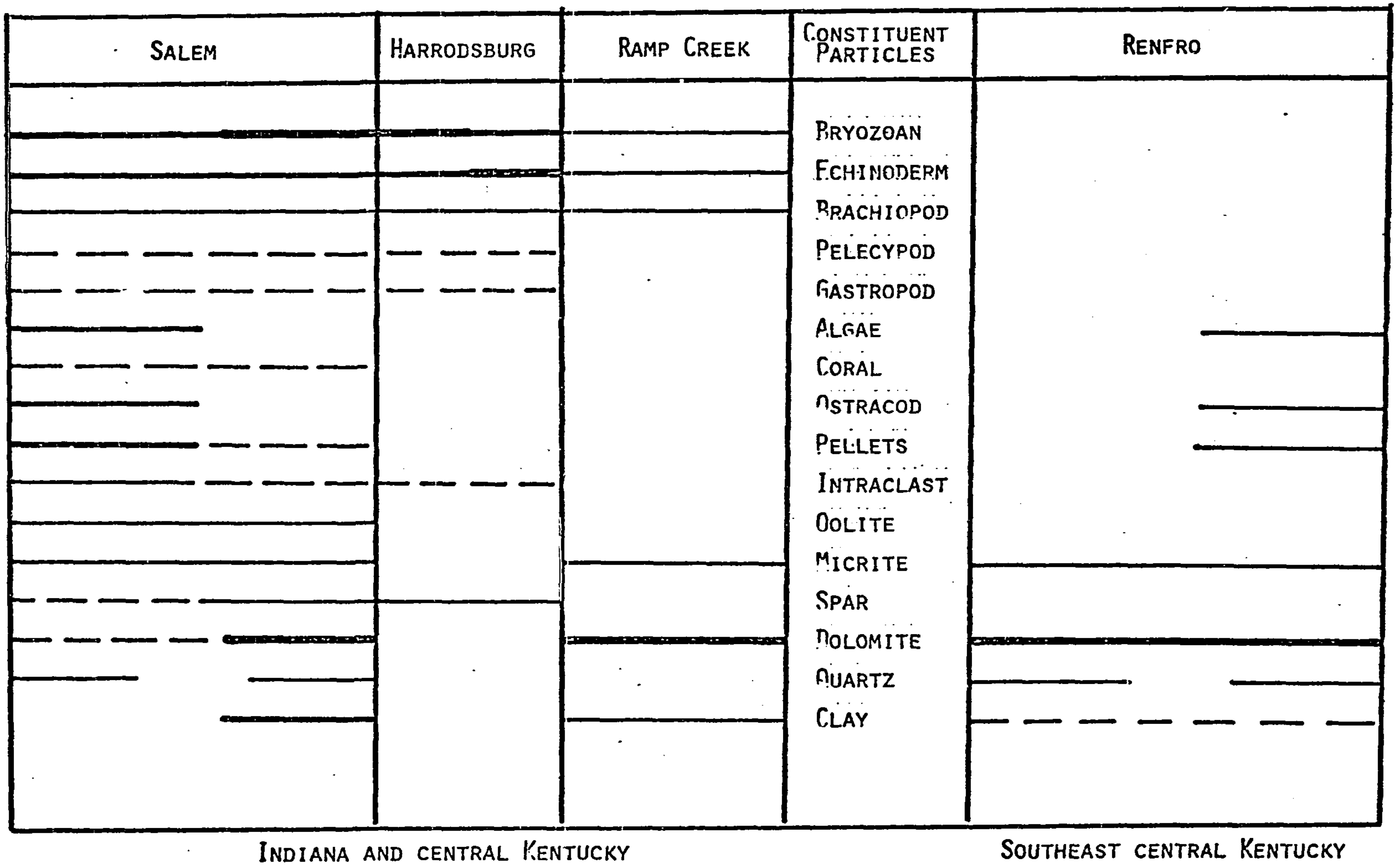


FIGURE 8 - DISTRIBUTION OF CONSTITUENT PARTICLES WITHIN PLATFORM CARBONATE UNITS

Chemical Precipitates

Calcite cements represent the majority of the chemical precipitates found in carbonate rocks. The clear, coarsely crystalline calcite cement common to many carbonates has been termed sparry calcite (Folk, 1959, p. 8) and is generally considered to represent precipitation of $CaCO_3$ in pore space within the rock or sediment. Stauffer (1962, p. 361-363) has shown that clear crystalline calcite can also form through neomorphism of micrite. Fortunately, in most thin sections, neomorphic sparry calcite can be differentiated from sparry cement.

Sparry calcite cements are common in the Harrodsburg and Salem Formations. Several types of sparry cement are present. Because of the abundance of echinoderm grains in the units, particularly the Harrodsburg, syntaxial rim cement is the most common. These are overgrowths which form in optical continuity with the host grains. Syntaxial rim cements are restricted to the echinoderm grains because the single crystal nature of the echinoderms is conducive to formation. Granular calcite cement is commonly found in areas where the framework grains are not echinoderm fragments and is also found filling cavities in the rock. Prismatic cement occurs as a first gernation cement on polycrystalline skeletal grains such as bryozoans and brachiopods.

Framework Grains

The most common and probably the most important constituents are framework grains. Skeletal grains, intraclasts, pellets, oolites, and terrigeneous detrital grains are the common framework grains found in the platform carbonates.

Skeletal Grains

Echinoderms

Echinoderm fragments are one of the most common framework constituents in the Harrodsburg Formation and are also common in the Salem and in localized limestone lenses in the Fort Payne. Columnals and spines are the most common echinoderm grains. The columnals range up to 5 cm. in diameter with the largest forms found in the Fort Payne. Echinoderm fragments are found throughout the section from the Fort Payne through the St. Louis but are most common in the Fort Payne and Harrodsburg where they comprise up to 75 percent of the rock in some cases. Echinoderm spines first appear in the Salem.

In outcrop crinoids appear to be the most abundant echinoderm present in the section, though the blastoid *Pentremites sp.* is common in the Salem (Donahue, 1967, p. 15). In the lower Mississippian section of Indiana there is a general trend from a fauna dominated by inadunate crinoids found in the clastic portions of the section (Borden Formation), to a fauna in the carbonate portions of the section (Harrodsburg and Salem Formations) dominated by camerate crinoids (Lane, 1971, p. 1432). The Lower Harrodsburg fauna is dominated by the camerate crinoids *Actinocrinites, Agaricocrinites, Macrocrinus, Dizygocrinus, Platycrinus,* and *Eretmocrinus* (Lane, 1972, p. 92). The Upper Harrodsburg and Salem fauna appears to represent a single community in which the small monobathrid camerate *Dichocrinus* is exceptionally abundant and *Batocrinus, Dizygocrinus,* and the monocyclic inadunate *Synbathocrinus* common (Lane, 1972, p. 93).

Bryozoans

Bryozoans, along with echinoderm fragments, represent the dominant skeletal constituents of the Salem and Harrodsburg Formations. Both ramose and fenestrate bryozoans are found but fenestrate bryozoans are the principal form found and range in size from fragments .5 mm. to intact fronds up to 35 cm. in length. They are found throughout the section from the Fort Payne through the St. Louis but are most common in the Fort Payne, Harrodsburg, and lower Salem. They become very abundant in places, particularly on either side of the Harrodsburg-Salem contact where they form a "bryozoan hash".

Foraminifera

Foraminifera represent one of the most characteristic fossils found in the Salem Formation. They are a minor constituent throughout the Salem but in places become quite abundant comprising up to 42 percent of the rock. They are most common in the Salem, but are found occasionally in the Harrodsburg or Fort Payne.

In the past, foraminifers from the Salem have generally been identified as *Endothyra sp.* and in some instances have been used as a guide fossil for the unit (Donahue, 1967, p. 11). Work by Zeller (1950), however, has shown there to be two different genera, *Endothyra* and *Plectogyra,* present in the Salem of Indiana. These genera where also found in Mississippian carbonates ranging from Kinderhook to Chester in age, thus negating much of their stratigraphic value.

Brachiopods

Brachiopods are commonly found as minor constituents in both the Harrodsburg and Salem Formations and in limestone beds in the Fort Payne. Spiriferid and Productid forms are the most common. Spiney forms have been recognized in this section and were apparently abundant since brachiopod spines are common constituents in portions of the Fort Payne. While they are generally found as secondary constituents comprising less than 5 percent of the total rock, beds up to .5 meter in thickness made up almost entirely of brachiopods have been found in the Fort Payne, Harrodsburg and Salem.

Many different genera of brachiopods have been identified from the Salem and associated units. Some of these are listed in Table 2.

Table 2

Brachiopods reported from the Salem and associated formations

Genus/specie	Source
Rhipidomella dubia	Taylor, 1962
Brachythyris sp.	" "
Orthotetes keokuk	" "
Spirifer lateralis	" "
Spirifer washingtonensis	" "
Spirifer bifurcatus	" "
Spirifer keokuk	" "
Productus cf. P. altonensis	Bieber, 1957
Composita sp.	" "
Marginirugus magnus	Kepferle, 1967

Ostracods

Ostracods are another common secondary constituent. They are easily identified because of their small size and distinctive shell structure. Their occurrence in the section seems restricted to the Salem Formation.

They are commonly found in mud-supported carbonates. While they are not found as a major lithologic constituent, they do have considerable environmental significance.

Molluscs

Several classes of Mollusca are represented in the section. Pelecypods are found in both the Harrodsburg and Salem Formations, though they are seldom found in abundance. Gastropods, which are a rare form in the Fort Payne and Harrodsburg, become much more common in the Salem. Both high- and low-spired forms are found and *Straparollus spergenensis* is particularly common (Donahue, 1967, p. 26).

Cephalopods are found as a rare constituent in the Salem. The goniatite *Prolecanites americanus* has been reported (Miller and Garner, 1953; Collinson, 1955) along with the orthoceracone nautiloid *Mooreoceras sp.* (Bieber, 1957).

Algae

Algal grains, while seldom found in significant quantities, represent important constituents because of their environmental significance. Two distinct types of algae are found. Thin hollow tubules representing fragments of a colonial codiacean algae are found in the Salem. Donahue (1967, p. 15) relates these forms to the codiacean genus *Ortenella sp.* (Johnson and Konishi, 1956), but identification of the grains is difficult because of recrystallization and their highly fragmented nature.

Much more abundant than the codiacean algae are the small spherical grains commonly termed calcispheres (Williamson, 1880). Recent studies suggest that they were produced by dasycladacean algae (Rupp, 1966). They have been identified in the Salem of Illinois (Baxter, 1960) and Indiana (Donahue, 1967, p. 16). They occur throughout much of the study area, generally in the upper portions of the Salem and Renfro Formations, where they are normally found in pelletal or dolomitic rocks. Calcispheres seldom comprise a significant portion of the rock because of their small size (.40 mm.) but their presence is conspicuous and they have considerable environmental significance.

Corals

Coral fragments represent the final significant skeletal constituent. Though seldom seen in thin section, they are a distinctive fossil commonly recognized in outcrop. The small horn coral *Hapsiphyllum sp.* is a common faunal element of the Salem. The St. Louis Formation is defined in places by the appearance of the corals *Lithostrotion* and *Lithostrotionella.*

Other Framework Grains

While skeletal grains represent the majority of the framework grains found in the Harrodsburg and Salem, they are not the only ones. Pellets, intraclasts, oolites and detrital quartz are also common framework grains.

Pellets

Pellets are structureless round to oval grains of carbonate mud which are probably of fecal origin. They generally range in size from 30 to 100 microns. Pellets are common constituents of the Salem Formation but are rarely found in the underlying units. They are most abundant in the upper portions of the unit.

Intraclasts

Intraclasts are minor constituents of both the Harrodsburg and Salem Formations where they are commonly found in grainstones. They represent fragments of semi-lithified sediment which has been eroded and redeposited within the basin. The intraclasts in the study area commonly consist of carbonate mud with enclosed skeletal grains or in many cases quartz grains.

Oolites

Oolites are a rather well known constituent of the Salem Formation, in large part because of inaccurate hand-speciman identification. The common Salem building stone contains large numbers of what in hand speciman appear to be oolites. Actually, these rounded grains are Endothyrid foraminifera. Oolites, however, are present in the Salem. The majority of the coated grains have only one layer and should more properly be termed superficial oolites. These grains are common within the Salem Formation of both Indiana and Kentucky.

Detrital Quartz

Detrital quartz, ranging from silt to coarse sand size is a minor constituent of the platform carbonates. Calcareous sandstones are present in the Harrodsburg of Indiana (unnamed unit) and the Salem of eastern Kentucky (Science Hill Sandstone). Detrital quartz is also present as a secondary framework constituent of certain grainstones within the study area. This quartz is normally monocrystalline, subangular to subrounded, and ranges in size from .05 to 1.5 mm.

MINERALOGY

Bulk Mineralogy

X-ray diffraction analysis of 330 powdered bulk samples from the Fort Payne through lower St. Louis show the rocks to be composed of three primary minerals (Appendix C). Calcite and/or dolomite are the principal minerals with at least trace amounts of quartz present in almost every sample. Plagioclase feldspar is also present in trace amounts in certain samples.

Calculation of calcite/dolomite percentages (Tennant and Berger, 1957) show that 55 percent of the samples contain less than 10 percent or more that 90 percent dolomite (Fig. 9). All intermediate values of dolomite content are represented, however, indicating the complete range of dolomitization which has occurred.

Comparison of the relative dolomite percentage with quartz peak height (which is a reasonable approximation of the amount of quartz present) shows (Fig. 10) that, while those samples which contain large amounts of quartz may be highly dolomitic, there is no apparent correlation between quartz and dolomite content. The same is true in a comparison between insoluble residue and dolomite contents (Fig. 11).

Clay Mineralogy

X-ray diffraction analysis was run on 34 samples of shale interbeds or clay rich insoluble residues to determine clay mineralogy. Shale samples analyzed were chosen to represent all the units under study and to give complete spatial coverage of the study area.

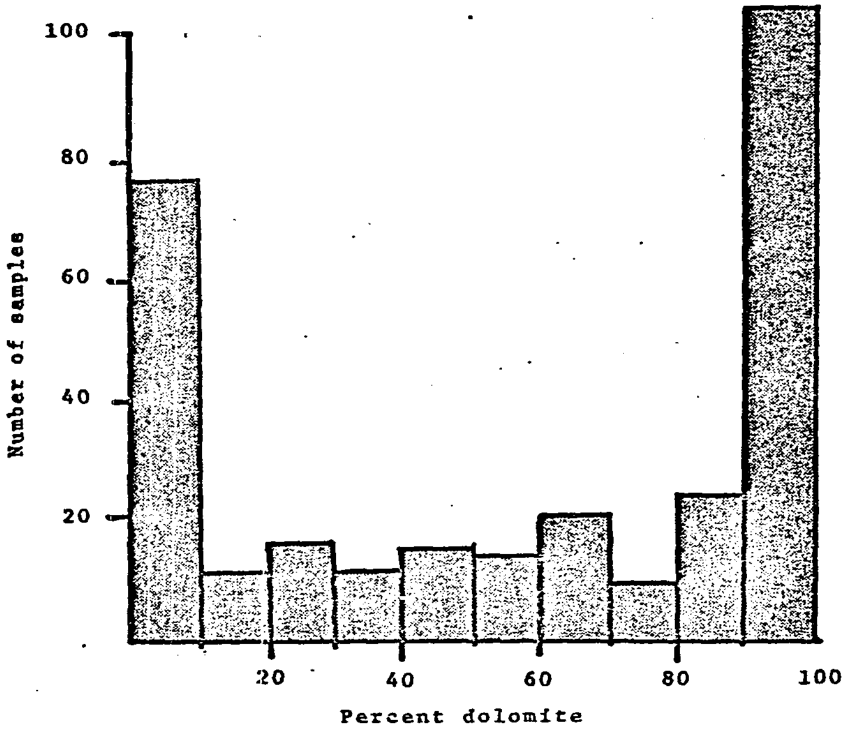


Figure 9 - Relative amounts of dolomite in platform carbonate samples

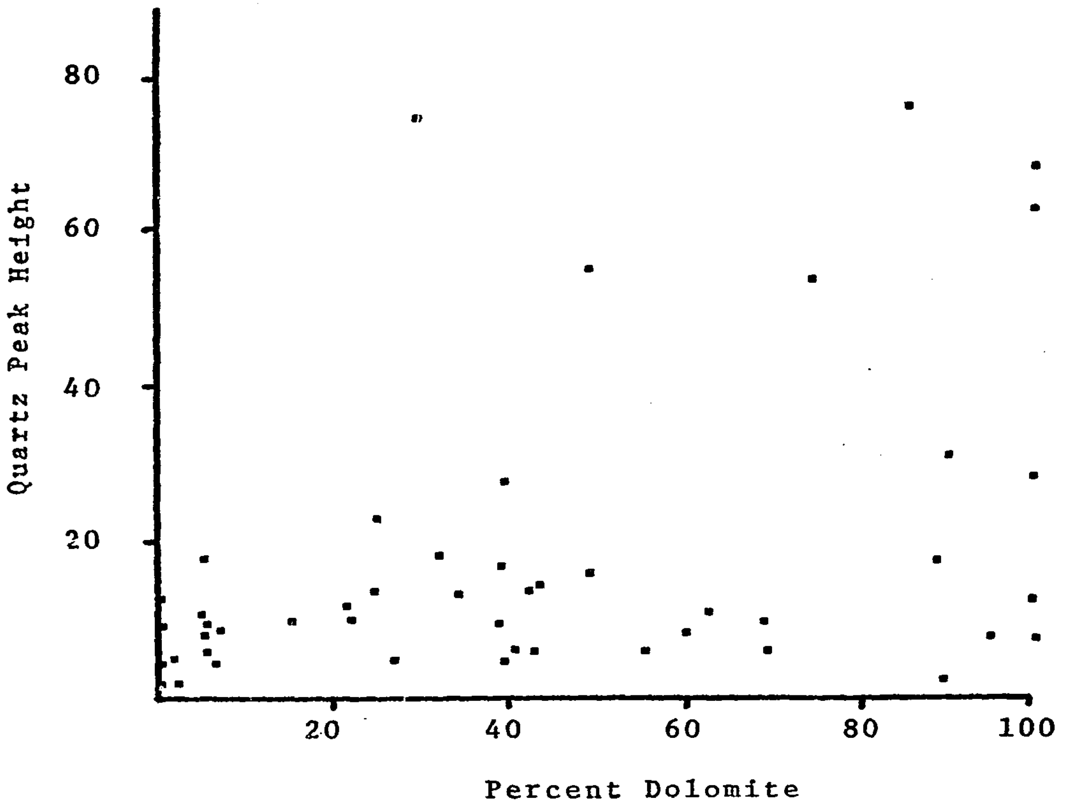


Figure 10 - Comparison between dolomite content and quartz peak height

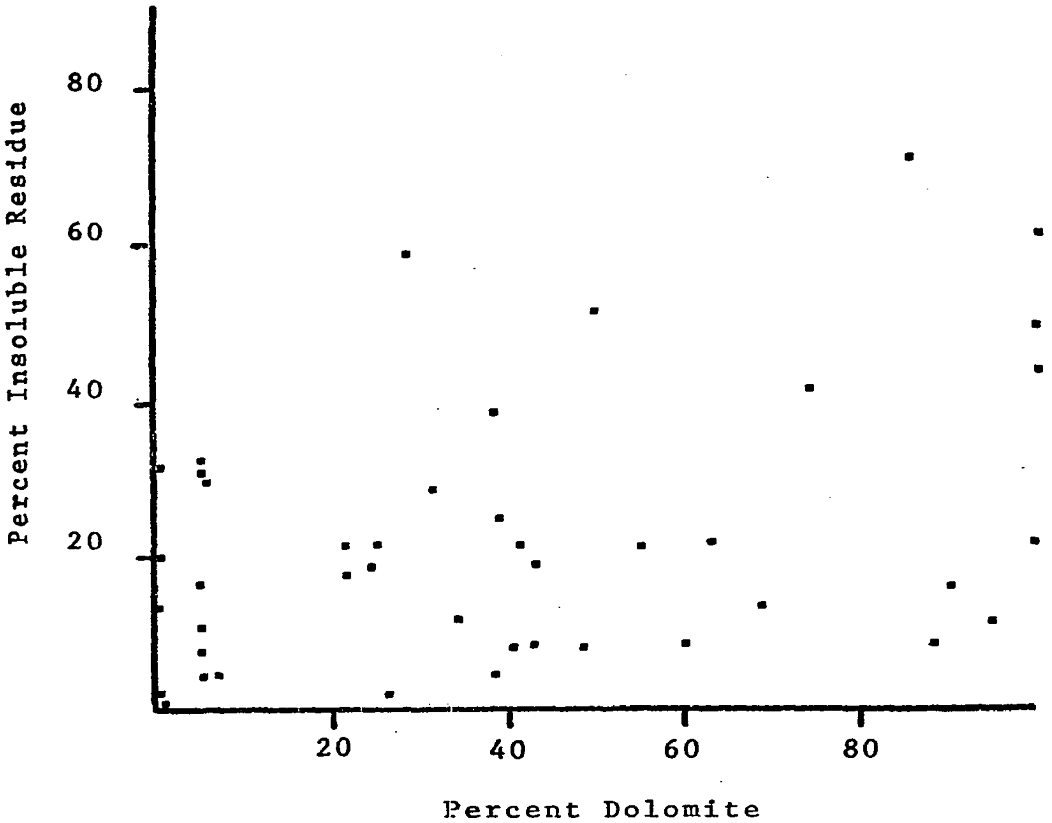


Figure 11 - Comparison between dolomite content and percent insoluble residue

Results indicate there to be little variation in clay mineral content either within the section or across the study area. The typical diffraction pattern (Fig. 12) shows illite to be the dominant clay mineral present with minor amounts of chlorite/kaolinite and mixed layer clays. Because of the small amounts present, it was impossible to distinguish between chlorite and kaolinite.

The illite present is rather poorly crystallized, as indicated by the broad irregular 10 Å peaks. Glycolation causes only a low angle broadening of the illite peak. This indicates the mixed-layer clays present are a highly degraded illite rather than a random or regular interlayering of illite and montmorillonite or illite and chlorite.

Dolomite

Dolomite is a principal lithologic constituent of all the units studied. There are four distinct types of dolomite present in the section. These are distinguished on the basis of chemical composition, crystal textures and fabric. The four are discussed below using the terminology of Friedman (1965).

Type A - Type A dolomite (Fig. 13) is a very fine-grained ferroan or nonferroan dolomite similar to the stratal dolomite of Fisher and Rodda (1969, Table 1). X-ray analysis shows it to be a non-ideal, high calcium (55% Ca, 45% Mg) variety of dolomite. Petrographically the dolomite consists of a fabric of xenotopic crystals which range in diameter from 2 to 10 microns. The crystals are tightly knit to intergrown. Porosity is generally slight.

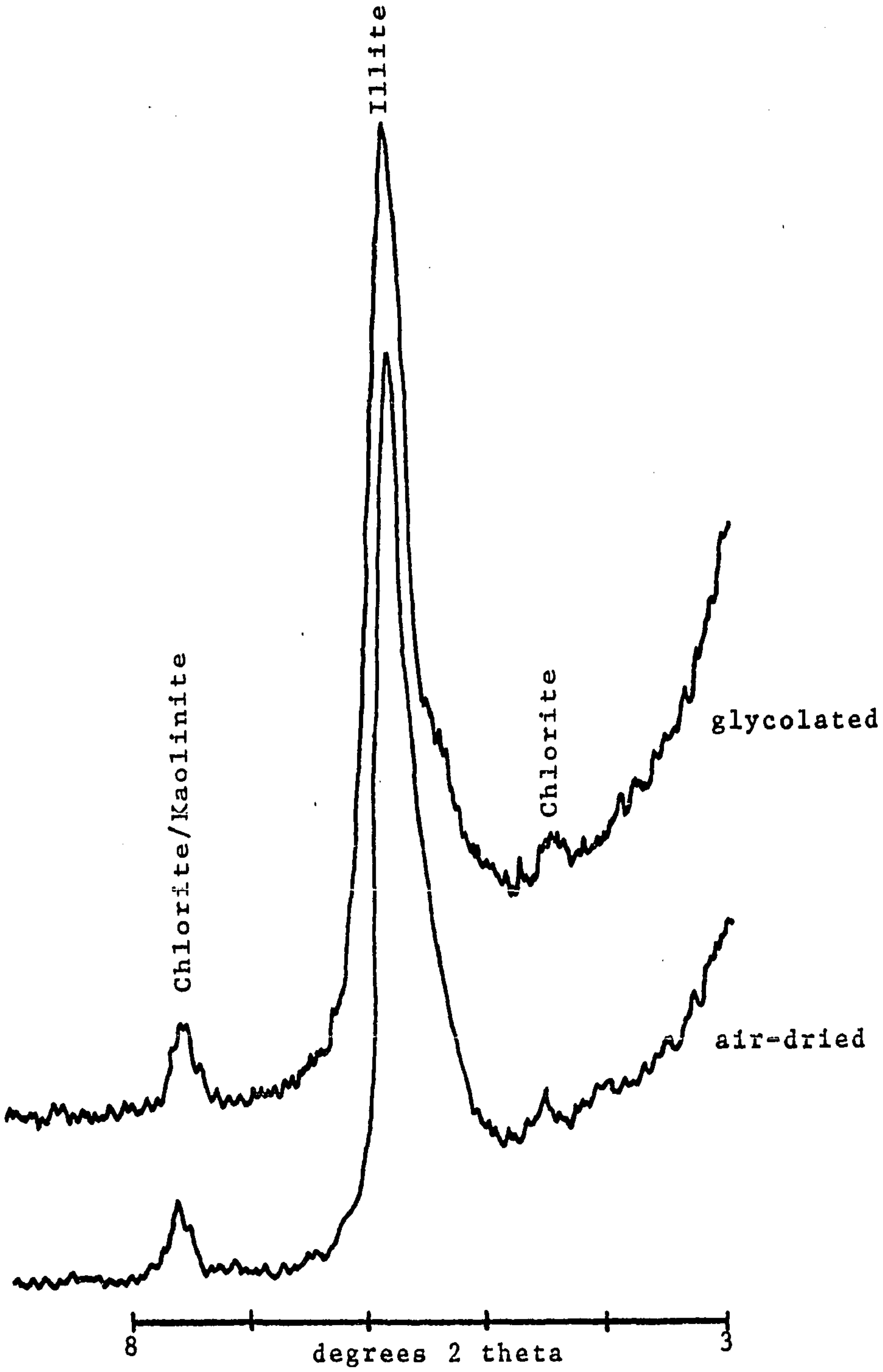


Figure 12 - Typical x-ray diffractogram of less than 200 micron fraction of shale interbeds in post-Borden platform carbonates (sample 24-9)

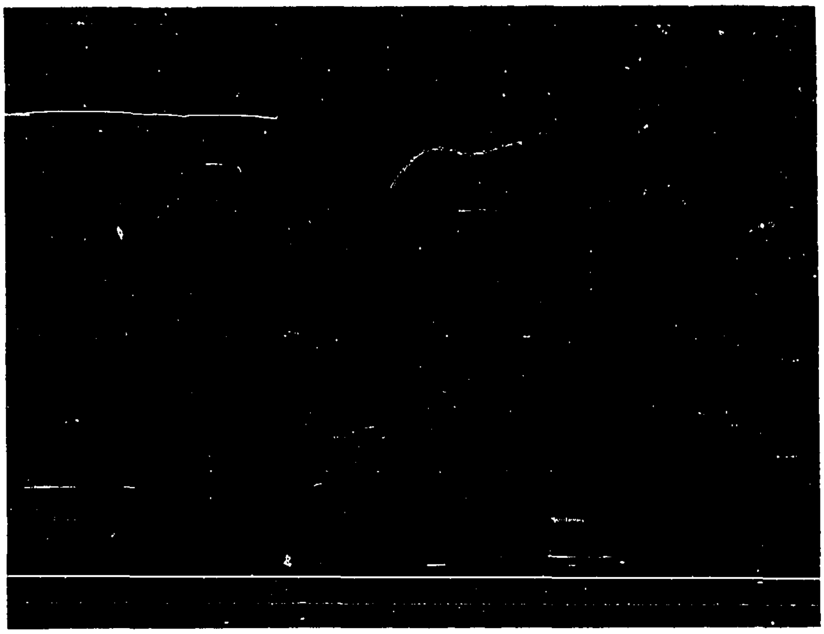


Figure 13 - Type A dolomite; fabric of 2-10 micron xenotopic dolomite crystals; note tight packing and lack of porosity (Sample 63-9; bar scale .1 mm)

Type A dolomite shows no evidence of replacement of bioclastic material. It normally occurs as an irregularity laminated to thin-bedded dolomitic mudstone which shows possible desiccation features. It is always unfossiliferous, but is commonly interbedded with non-dolomitic fossiliferous limestones. The Type A dolomites generally contain subangular to subrounded grains of quartz which are considerably larger (50 to 150 microns) than the dolomite crystals. This precludes a detrital origin (Lindholm, 1969) for the dolomite.

Based on these features, the Type A dolomite is thought to be of supratidal origin. This conclusion was based on similarities between the Type A dolomite and both Recent supratidal dolomites (Shinn, and others, 1965; and Illing, and others, 1965) and ancient dolomitic mudstones of supposed supratidal origin (Schenk, 1967, p. 372; Fisher and Rodda, 1969, p. 64-65; Braun and Friedman, 1969, p. 116; Armstrong, 1970, p.262; Kepper, 1972, p. 507-509; and Mazzullo and Friedman, 1975, p. 2133).

Type A dolomites have a restricted occurrence in the study area. They are found only in the Renfro Formation at the Renfro Valley and Big Hill sections in eastern Kentucky.

Type B - Type B dolomite (Fig. 14) is a nonferroan replacement dolomite. It consists of a fabric of hypidiotopic to idiotopic dolomite crystals. The crystals show a wide range in size from 10 to 100 microns, though most of the crystals are normally well-developed rhombs in a loosely knit fabric with moderate porosity.

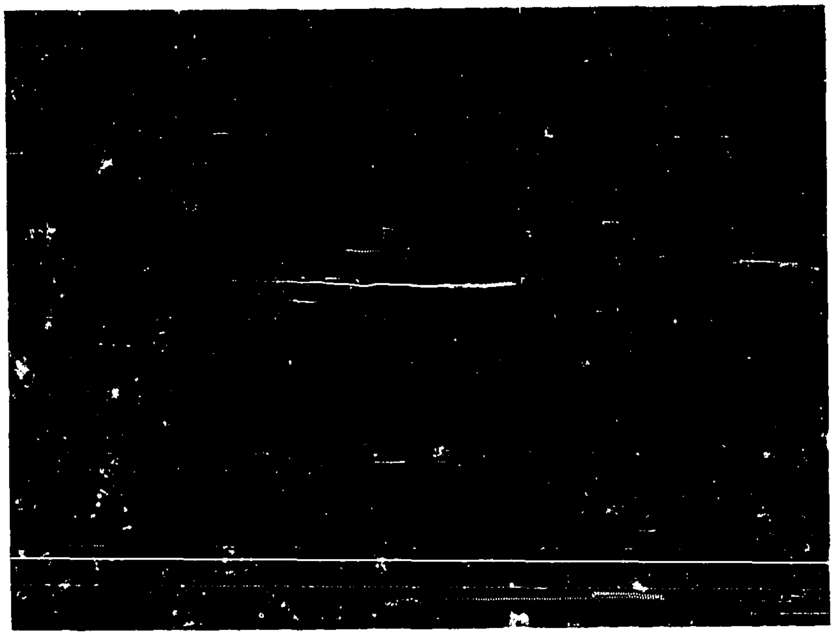


Figure 14 - Type B dolomite; nonferroan dolomite; fabric of 10-60 micron hypidiotopic to idiotopic crystals (Sample 40-2, bar scale .1 mm)

Type B dolomite shows a complete spectrum of replacement textures ranging from partial replacement of carbonate mud in packstones and wackestones to whole rock replacement. In all samples, however, carbonate mud is replaced before fossil fragments. No instances were seen where replacement of bioclasts occurred while micrite was left unaltered. This indicated that, at least initially, dolomitization was selective (Kepper, 1972, p. 522) replacing the finer grained, more reactive micrite before attaching the fossil fragments.

Type B dolomite is similar to the massive dolomite of Fisher and Rodda (1969, p. 206, Table 1), which is interpreted to have formed through seepage refluxion. Seepage-refluxion (Adams and Rhodes, 1960) involves the downward or basinward migration of highly concentrated brines, similar to those which remain after precipitation of lower rank salts (e.g. anhydrite and gypsum), through underlying intertidal and subtidal deposits. The extent of the dolomitization is related to changes in the composition and character of both the host rock and refluxing brine.

While deposits of anhydrite and gypsum (a source of concentrated brines) are absent from the units under study, they are present in the lower portion of the overlying St. Louis limestone in both Indiana (McGregor, 1954; Jorgensen and Carr, 1973) and Kentucky (McGrain and Helton, 1964). Thus the Type B dolomite is thought to represent an early secondary replacement dolomite formed through seepage refluxion.

Type B dolomites are found throughout the study area in each of the units under study.

Type C - Type C dolomite (Fig. 15) is a ferroan replacement dolomite which is petrographically very similar to Type B dolomites. It consists of a fabric of hypidiotopic to idiotopic crystals which range in size from 6 to 100 microns. The crystals are normally well-developed rhombs in a loosely knit fabric with moderate to high porosity.

Type C dolomites show the same replacement textures which characterize the Type B dolomite. The basic difference between the two is the ferroan nature of the Type C dolomite, Type C dolomites never occur alone, they are always associated with Type B dolomite. This association, and their chemical similarity to the sparry Type D dolomite, suggests they formed as late stage replacement dolomites, perhaps originating in a phreatic, reducing environment favorable for the formation of ferroan dolomite (Kepper, 1972, p. 510).

Like Type B dolomite, Type C dolomite is found throughout the study area in each of the units under study.

Type D - Type D dolomite (Fig. 16) occurs as a massive, replacement or pore filling dolomite. It is a sparry, ferroan dolomite found filling bryozoan zooecia, as a late-stage pore filling, or along fractures. It is a common constituent in packstones and grainstones which also contain ferroan calcite. It postdates cementation and usually forms planar intercrystalline boundries with syntaxial rim cements (Fig. 16). It is found in many, but not all, cases in packstones and grainstones which contain Type C dolomite.

There are no apparent regional or stratigraphic trends to the distribution of Type D dolomites.

Figure 15 - Type C dolomite; ferroan dolomite; fabric of 6-100 micron hypidiotipic to idiotopic dolomite crystals included in replacement chalcedony (Sample 19-9; bar scale .1 mm)

Figure 16 - Type D dolomite (a); note the planar intercrystalline boundries between dolomite and sparry calcite cement (b) (Sample 15-13; bar scale .5 mm)

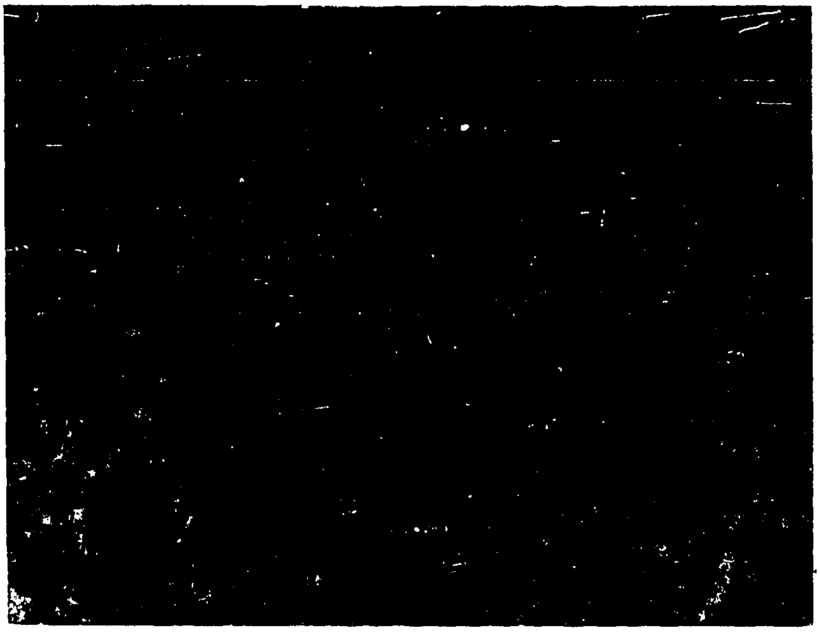


Figure 15

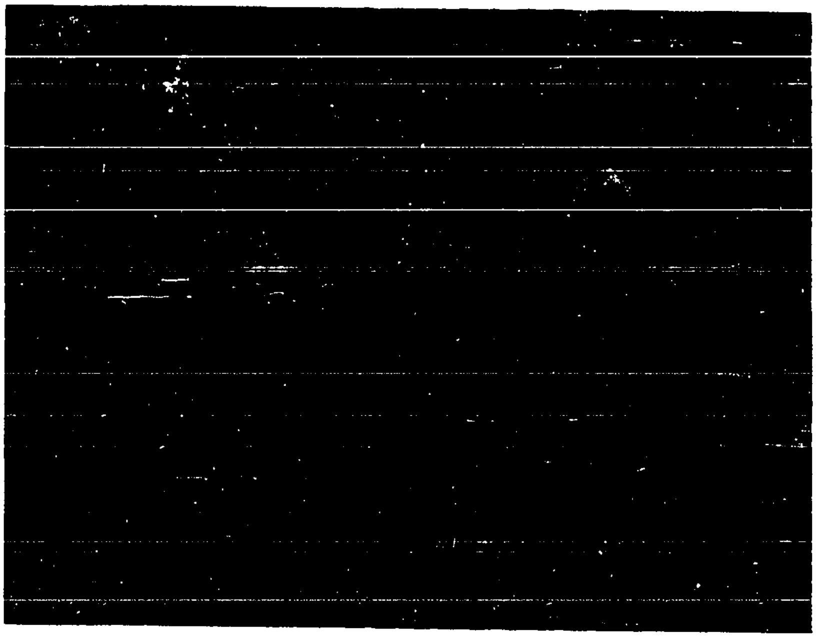


Figure 16

LITHOFACIES

Nine lithofacies were recognized in the units under study. These lithofacies were defined on the basis of faunal content, thin-section petrography, diagenetic modifications, and lithologic associations as follows: (1) bryozoan-echinoderm grainstone and packstone, (2) echinoderm grainstone and packstone, (3) bryozoan grainstone and packstone, (4) diverse grainstone, (5) foram grainstone, (6) pelletal calcisphere packstone, (7) dolowackestone, (8) dolostone, and (9) quartzose sandstone. Characteristics of each of these lithofacies are listed in Table 3.

Lithofacies 1

Bryozoan-echinoderm grainstone and packstone

Description - This lithofacies (Fig. 17) consists of thick-bedded to massive grainstones and packstones. Bryozoan and echinoderm fragments are the predominant skeletal components (Table 4), comprising from 49 to 86 percent of the total rock. Brachiopods are also found in almost every sample, but are not found in abundance. Pelecypods, gastropods, foraminifera, corals, detrital quartz, and intraclasts are other minor constituents.

The lithofacies commonly occurs as a medium to coarse grained calcarenite. The graphic mean (Folk, 1968, p. 45) for 14 representative samples (Table 5) ranges from .25 phi to 1.27 phi with an average of .75 phi. The grainstones are typically nearly symmetrical to finely skewed. Sorting ranges from moderately-sorted to moderately well-sorted in the grainstones, while the packstones are not as well sorted.

Table 3 - Petrographic summary of platform carbonate lithofacies

	Bryozoan-echinoderm	Echinoderm	Bryozoan	Diverse	Foram	Pelletal calcisphere	Dolowackestone	Dolostone	Quartzose sandstone
Framework Grains									
bryozoans	A	A	A	A	A	C	R		R
echinoderms	A	A	A	A	A	C	R		R
brachiopods	C	C	C	C	C		R		
foraminifera	R	R	R	C	A	C			
pelecypods	R	R	R	C	R		R		
gastropods	R	R		C	R				
algae				R	R	A	R		
trilobites	R	R	R	R					
ostracods				R	R	C	R		
corals	R		R	R					
quartz	R	R	R	R				R	A
pellets					R	A			
intraclasts	R	R		R	R				
oolites			R	R	R				
Micrite	R	R	R	R	R	C			
Dolomite									
type A								A	
type B	C	C	C	C	C	C	A	A	R
type C	C	C	C	C	C	C	A	A	R
type D	C	C	C	C					
Cement									
nonferroan spar	C	C	C	C	C	R			C
ferroan spar	C	C	C	C					
Grain-size									
rudite		X							
arenite	X	X	X	X	X	X			X
siltite						X	X	X	
Sorting									
poor						X	X		
moderate	X	X	X	X	X				X
good		X	X		X				

R = rare, C = common, A = abundant, X = general characteristic

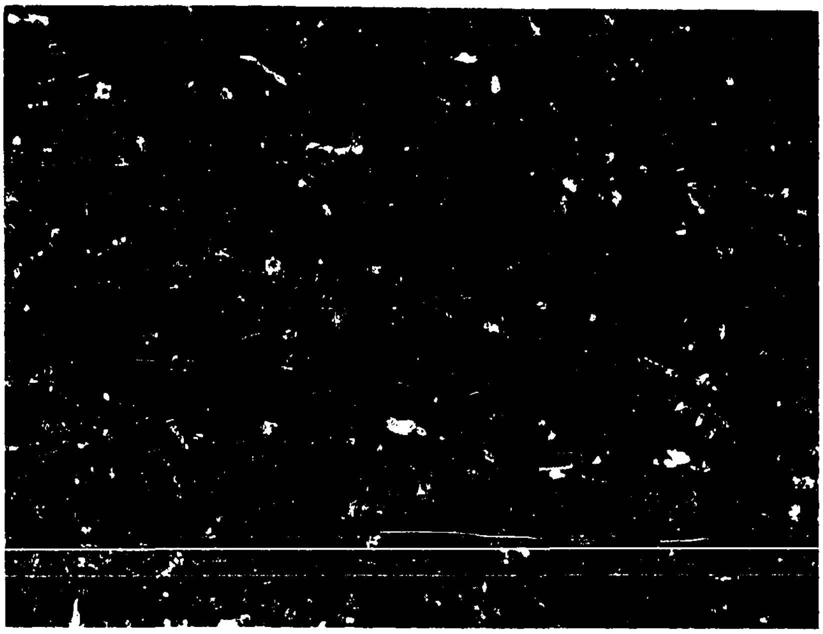


Figure 17 - Lithofacies 1; Bryozoan-echinoderm grainstone; negative print (Sample 3-4; bar scale 2 mm)

Table 4 - Petrographic summary of lithofacies 1 through 5

	Bryozoan-echinoderm				Echinoderm		Bryozoan				Diverse		Foram	
	Grainstone		Packstone				Grainstone		Packstone					
Percent	av.	range	av.	range	av.	range	av.	range	av.	range	av.	range	av.	range
Bryozoans	38	24-56	35	25-47	19	7-29	54	41-71	48	29-73	29	14-51	16	9-22
Echinoderms	35	20-53	29	18-41	56	36-74	19	12-25	14	9-21	26	10-48	22	2-50
Brachiopods	2	0-13	<1	0-9	1	0-4	2	0-6	1	0-4	3	1-11	2	1-5
Pelecypods	<1	0-1	<1	0-1	<1	0-1	<1	0-1	<1	0-5	1	0-5	<1	0-4
Corals	<1	0-7	<1	0-1			<1	0-1			<1	0-1		
Foraminifera	<1	0-1			<1	0-1	<1	0-1			1	0-10	27	18-42
Gastropods			<1	0-1	<1	0-1					1	0-5	<1	0-1
Trilobites					<1	0-1	<1	0-1			<1	0-1		
Ostracods											<1	0-5	<1	0-2
Algae											<1	0-2		
Intraclasts	<1	0-2	<1	0-1	<1	0-2					1	0-6	1	0-5
Quartz	<1	0-10			<1	0-1	<1	0-1			<1	0-8		
Oolites							<1	0-1			<1	0-6	<1	0-1
Spar	21	5-46	7	0-25	16	5-44	20	7-37	10	0-17	26	1-50	20	5-34
Matrix (micrite + dolomite)	3	0-17	23	8-46	6	0-41	4	0-17	29	9-55	10	0-53	11	2-22

Table 5 - Textural parameters of lithofacies 1 through 4

Lithofacies (no. samples)	Graphic Mean* average (range)	Inclusive Graphic Standard Deviation* average (range)	Inclusive Graphic Skewness* average (range)
Bryozoan-echinoderm (14)	.75φ (.25φ-1.27φ)	.84φ (.66φ-1.21φ)	.06 (-.03-.29)
Echinoderm (4)	1.04φ (.57φ-1.35φ)	.64φ (.45φ-.76φ)	-.02 (-.07-.01)
Bryozoan (5)	1.55φ (1.43φ-1.75φ)	.71φ (.64φ-.79φ)	-.01 (-.12-.27)
Diverse (11)	1.40φ (1.15φ-1.67φ)	.78φ (.62φ-1.19φ)	-.12 (-.30-.01)

*after Folk (1968)

The grainstones are cemented by sparry calcite which comprises from 5 to 46 percent of the total rock (Table 4). There are several generations of cement present including, in some cases, some iron rich calcite.

Fine-grained carbonate mud is found in trace amounts (0-17 percent) in the grainstones and as interstitial matrix in the packstones (Table 4). This carbonate mud (micrite) normally contains some minor terrigeneous material, and, in many cases, has been replaced by Type B or C dolomite.

The lithology is thick-bedded to massive. Beds are normally wedge-shaped and truncating. Thin, low-angle crossbeds are a common feature of the grainstone portions of the lithology. Many beds grade from a massive packstone at the base to cross-bedded grainstone at the top.

Stratigraphic Position - The bryozoan-echinoderm lithofacies is found in the Fort Payne of Indiana and Kentucky, and is the dominant lithology of the Harrodsburg Formation of Indiana. In the Fort Payne, bryozoan-echinoderm grainstones and packstones occur as thin lenses or as large-scale carbonate banks such as the Cane Valley Limestone (Sedimentation Seminar, 1972). In the Harrodsburg, cross-bedded grainstones are the dominant lithology.

Depositional Environment - The rocks of the bryozoan-echinoderm lithofacies are interpreted to represent deposition in a low to high energy, shallow, subtidal environment. The fauna and bedding characteristics found in this unit are representative of other ancient units interpreted to be subtidal in origin (Laporte, 1969, p. 110-114; Armstrong, 1974, Fig. 10; Schenk, 1975, Fig. 42-2, Table 42-1).

Wave energy apparently ranged within the lithofacies from low to high. The low energy environment is represented by bryozoan-echinoderm packstones. The presence of carbonate mud commonly indicates deposition below wave base. The lack of current activity is further illustrated by the nature and sorting of the skeletal material. Sorting of skeletal material is much poorer in the packstones than in the grainstones and bryozoan material, which is commonly highly disarticulated in the grainstones, is left relatively intact in the packstones, with bryozoan fronds up to 10 cm. in length present.

The cross-bedding characteristic of the bryozoan-echinoderm grainstones indicated a higher energy environment of deposition. This is substantiated by the fragmented nature of the skeletal material, the moderate to moderately well-sorted nature of the units and the lack of interstitial carbonate mud.

Lithofacies 2
Echinoderm grainstone and packstone

Description - Lithofacies 2 (Fig. 18) is closely related to lithofacies 1. It occurs as a grainstone or packstone dominated by echinoderm and bryozoan skeletal material. It is distinguished from lithofacies 1 by the abundance of echinoderm grains over bryozoans. There is no apparent physical break separating the two lithofacies. Lithofacies 2 is arbitrarily defined on the basis of a greater than 2 to 1 ratio of echinoderms to bryozoans (Fig. 19).

Echinoderm fragments are the primary skeletal constituents comprising from 36 to 74 percent of the total rock (Table 4). Bryozoans are also a major constituent comprising from 7 to 29 percent. As was the case in

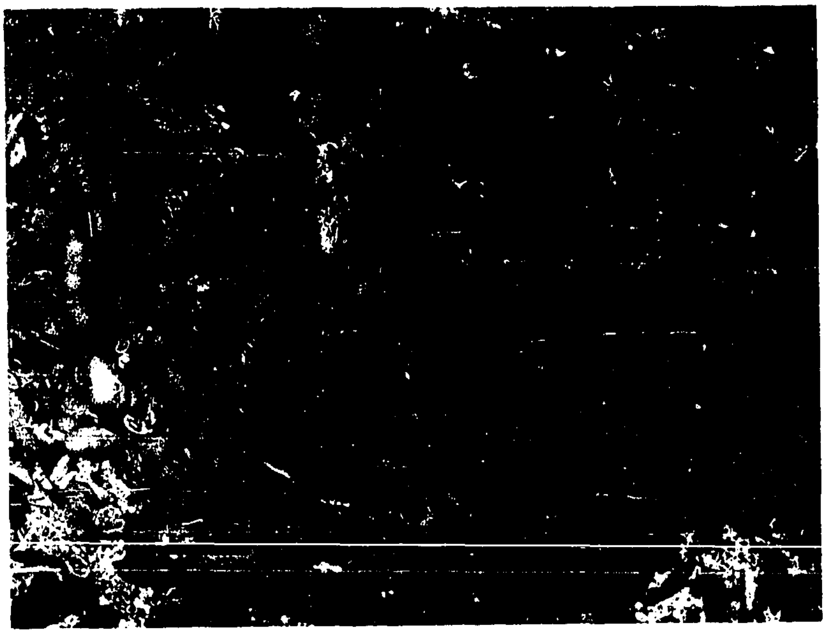


Figure 18 - Lithofacies 2; Echinoderm grainstone; negative print (Sample 15-12; bar scale 2 mm)

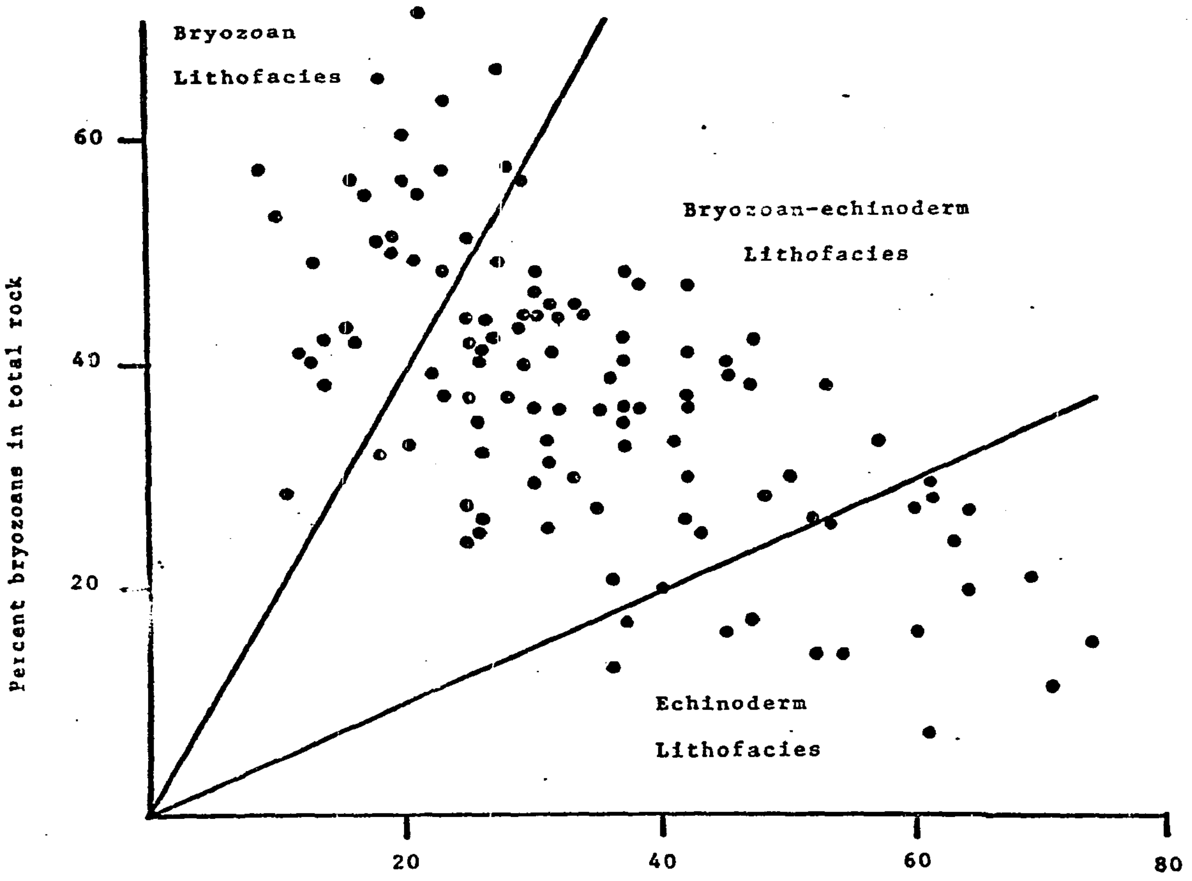


Figure 19 - Bryozoan and echinoderm content of lithofacies 1-3

lithofacies 1, brachiopods are present in almost all samples, but never occur in abundance. Other trace constituents include forams, pelecypods, gastropods, trilobites, intraclasts, detrital quartz, and glauconite.

The lithofacies commonly occurs as a medium to coarse-grained calcarenite or calcirudite. In general, grain-size decreases upward in the section, with the largest echinoderms found low in the Fort Payne and the smallest found in the Salem. Because echinoderm fragments are primarily intact columnals, this change probably represents a gradation from large stemmed forms low in the section to smaller stemmed forms in the Salem. The lithology is typically moderately-sorted to well-sorted and nearly symmetrical (Table 5), an indication of the uniformity of the constituent skeletal fragments.

The grainstones are cemented by sparry calcite which comprises from 5 to 44 percent of the total rock (Table 4). As is the case in lithofacies 1, there are several generations of cement present including a zone of iron rich calcite in some samples.

Fine-grained carbonate mud is found in trace amounts (1 to 11 percent) in the grainstones where it is found in bryozoan zooecia and brachiopod shells and as interstitial matrix in the packstone. This carbonate mud normally contains minor terrigenous material, and in many cases, has been replaced by Type B or C dolomite. Type D dolomite is also present in some of the grainstones.

Like lithofacies 1, lithofacies 2 is commonly medium to thick-bedded. Beds are normally wedge shaped and tend to truncate underlying units. The echinoderm grainstones may show some low-angle crossbedding, but it is not as prevalent as in lithofacies 1.

Stratigraphic Position - Lithofacies 2 occurs in the Ramp Creek Formation of Indiana and the Fort Payne Formation of Kentucky. It is rarely found in the Harrodsburg, and is not present in the Salem Formation.

Depositional Environment - Lithofacies 2 is interpreted to represent deposition in a shallow, low to high energy subtidal environment. The fauna and bedding characteristics of this lithofacies are similar to those of lithofacies 1, which is also interpreted to be of subtidal origin. The major differences between the two is the abundance of echinoderms in lithofacies 2.

The echinoderm grainstones are thought to have formed in a slightly higher energy environment than did the packstones. Whether this energy came from wave activity or submarine currents is unknown. The fact that echinoderm grainstones are found both on top of the Borden Delta in a shallow water environment and adjacent to it in a deeper water environment indicates that both may be, in part, responsible.

There is apparently a gradual upward decrease in the section in the number of echinoderms present relative to bryozoans. This indicates that echinoderms were the dominant faunal element during initial carbonate deposition, with bryozoans becoming relatively more abundant through time. This is probably a reflection of the type of sedimentation occurring. Insoluble residue analysis indicates the lower portions of the Fort Payne contain appreciable amounts of terrigenous material. This material was probably derived in part from reworking of the Borden clastics and in part from upland sources to the east and northeast (Sable and Pryor, 1974, p. 292). Echinoderms appear to be more abundant in this portion of the section and thus, are perhaps more tolerant to increased turbidity than are bryozoans. With decreasing clastic input, bryozoans became more abundant until they are as important a faunal element as echinoderms.

Lithofacies 3
Bryozoan grainstone and packstone

Description - Like lithofacies 2, this lithofacies (Fig. 20) is related to lithofacies 1. It occurs as a grainstone or packstone dominated by bryozoan and echinoderm skeletal debris. In opposition to lithofacies 2, bryozoans are the dominant skeletal component in lithofacies 3. Again, there is a complete gradation between the bryozoan-echinoderm lithofacies and the bryozoan lithofacies. Lithofacies 3 is arbitrarily defined by a bryozoan to echinoderm ratio greater than 2 to 1 (Fig. 19).

Bryozoan fragments are the primary skeletal constituent comprising from 29 to 73 percent of the total rock (Table 4). Echinoderms are the other principal constituent comprising from 9 to 25 percent. Brachiopods are present in almost every sample and are slightly more abundant than in lithofacies 1 and 2. Other constituents found in trace amounts include pelecypods, forams, corals, trilobites, detrital quartz, and oolites.

The lithofacies commonly occurs as a medium-grained calcarenite. The graphic mean (Folk, 1968, p. 45) for 5 representative samples (Table 5) ranges from 1.43 to 1.75 phi and averages 1.55 phi. The grainstone samples are typically moderately-sorted to moderately well-sorted and finely to coarsely skewed. The packstones are not as well sorted.

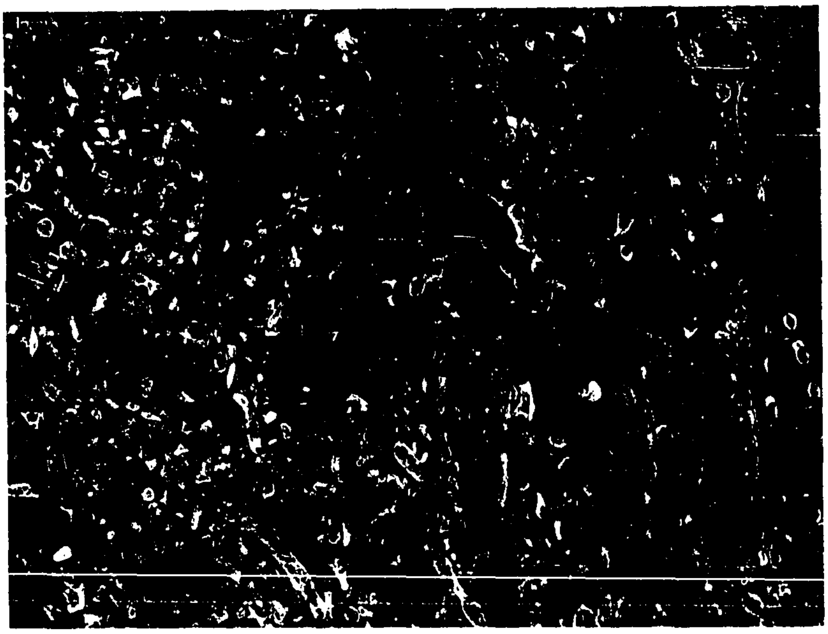


Figure 20 - Lithofacies 3; Bryozoan grainstone; negative print (Sample 16-19e; bar scale 2 mm)

Sorting is generally not as good as found in the echinoderm grainstones of lithofacies 2. This, however, is probably the result of morphological differences between bryozoans and echinoderms rather than any significant difference in currents of deposition (Folk and Robles, 1964, p. 290).

Sparry calcite is the common cement comprising from 7 to 37 percent of the total rock (Table 4). There are several generations of cement present, including a zone of iron-rich calcite in some samples.

The bryozoan grainstones contain minor amounts of carbonate mud (0 to 17 percent of the total rock). This mud, which commonly contains minor amounts of terrigenous material, occurs as interstitial matrix in the packstones and comprises from 9 to 55 percent of the total rock. In many instances, Type B or C dolomite occurs as a replacement for the carbonate mud.

In exposures, the lithology is thick-bedded to massive. Low angle, bimodal crossbedding is a characteristic feature of exposures of the bryozoan grainstones. In some outcrops, however, these crossbedded grainstones grade laterally into packstones within a relatively short distance.

Stratigraphic Position - Lithofacies 3 is found in the upper portions of the Fort Payne of Kentucky, in the Harrodsburg of Indiana, and in the lower portions of the Salem Formation of Indiana and Kentucky.

Depositional Environment - Lithofacies 3 is interpreted to represent deposition in a low to high energy, shallow subtidal environment. The faunal and bedding characteristics, along with the close association of this lithofacies with lithofacies 1 and 2 which have already been interpreted to be subtidal, lead to this conclusion

This lithofacies is interpreted to be the result of sedimentation on a shallow shelf on which bryozoans were the dominant faunal element. The reason for the abundance of bryozoans over other forms, including echinoderms, is unknown, but might reflect growth in a shallower, more highly agitated environment. Bryozoan grainstones formed on the bathymetrically higher portions of the shelf where wave activity was most intense, while bryozoan packstones formed in lower or more protected areas where wave activity was less intense. Wave activity for this lithofacies was apparently more intense than during deposition of grainstones from lithofacies 1 and 2. This is indicated by the highly fragmented nature of the bryozoan material and by the occasional development of oolitic grains.

Lithofacies 4
Diverse grainstone

Description - Lithofacies 4 shows many similarities to the first three lithofacies. It is easily distinguished petrographically on the basis of its very diverse fauna (Fig. 21). Bryozoans and echinoderms are again the dominant faunal elements (Table 4), comprising, on the average, 29 and 26 percent of the total rock respectively. However, where in lithofacies 1-3 the fauna was restricted to 3 or possibly 4 elements, in lithofacies 4 anywhere from 5 to 9 are present. Brachiopods are slightly more abundant than in the previous three lithofacies and pelecypods, gastropods, forams, and intraclasts of silty micrite are present in most of the samples. Trilobites, ostracods, corals, codiacean algea, oolites, and detrital quartz are also present in some of the samples. The best developed

Figure 21 - Lithofacies 4; Diverse grainstone; negative print (Sample 40-4; bar scale 2 mm)

oolites found in the study area occur in this lithofacies.

Lithofacies 4 typically occurs as a medium-grained calcarenite. The graphic mean (Folk, 1968, p. 45) for 11 representative samples (Table 5) ranges from 1.15 phi to 1.67 phi and averages 1.40 phi. The grainstones are typically moderately well-sorted to poorly-sorted and range from finely skewed to strongly coarsely skewed (Table 5).

The lithofacies is commonly cemented by sparry calcite cement, though it also contains minor amounts of neomorphic spar. While it is classified as a grainstone, it contains appreciably more carbonate mud than the previous three grainstone lithofacies. Five out of the 36 samples point counted can be classified as packstones. Micrite matrix ranges from 1 to 53 percent of the total and averages 10 percent (Table 4), compared to 3 to 4 percent for the lithofacies 1-3 grainstones. This carbonate mud is often replaced by Type B or C dolomite. Type D dolomite is also present in trace amounts. Micrite is also present as a coating on many of the skeletal grains (Fig. 22). This coating or micrite envelope is interpreted to represent the emplacement of micrite in discarded algal bores in the grain (Bathurst, 1971, p. 383) and has environmental significance.

In exposure, the lithology commonly occurs as a medium to thick-bedded, cross-bedded calcarenite ranging from 5 to 45 feet in thickness. Cross-bedding is low angle and bimodal (Table 6) with a class interval distribution similar to that of the cross-bedding in the building stone district of Indiana (Carr and others, 1966).

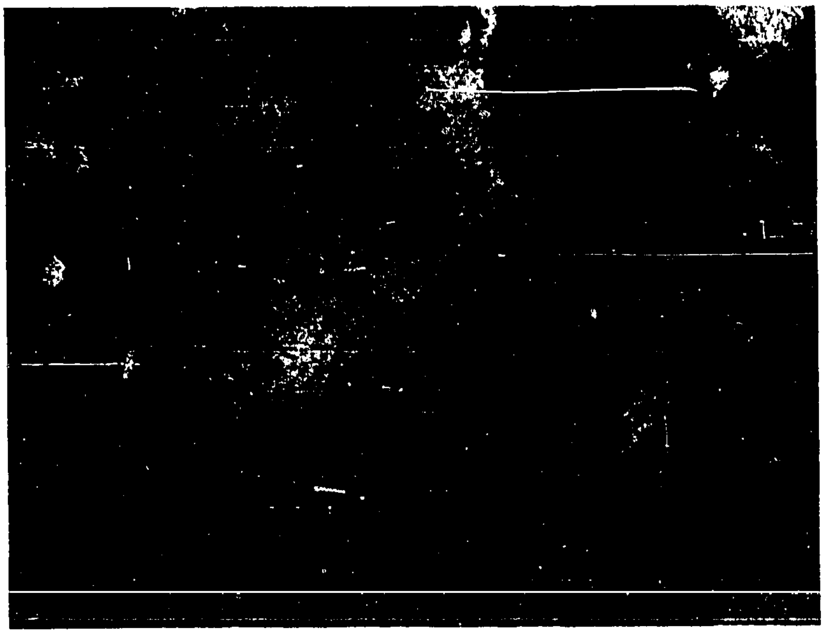


Figure 22 - Micritic rims on bioclasts including echinoderm columnals (a) and foraminifera (b) (Sample 40-4; bar scale .5 mm)

Table 6 - Comparison of class interval distribution of cross-bedding in the foram calcarenite lithofacies of the building stone district of Indiana and the diverse lithofacies of southern Indiana and Kentucky.

Class Interval (degrees)	Salem of building stone district*	Salem of southern Indiana and Kentucky
1-40	51	15
41-80	70	17
81-120	43	6
121-160	33	5
161-200	47	11
201-240	85	23
241-280	85	10
281-320	46	3
321-360	28	8
Total	488	98

* Data from Carr and others, 1966, Table 1

Stratigraphic Position - The diverse grainstone lithofacies is restricted to the Salem Formation. It is found in the lower portions of the Salem in Indiana and is the principal lithology of the Salem in central Kentucky.

Depositional Environment - Lithofacies 4 is interpreted to represent deposition in a moderate to high energy, shallow subtidal environment.

The highly diverse fauna is indicative of a subtidal environment (Laporte, 1969, p. 110; Wilson, 1974, Fig. 5). The presence of codiacean algae, gastropods, and common micrite envelopes, however, indicates water depths were not great. Swinchatt (1969) concluded that an abundance of algal bored grains with micrite envelopes indicates deposition in less than 120 feet and probably less than 45 feet of water.

The moderate to high energy of the environment is indicated by the presence of oolites (Fig. 23), the fragmented nature of some of the grains, the good sorting, and the cross-bedded nature of the lithology.

The channel-like nature of many of the exposures of the diverse grainstone, along with the bimodal cross-bedding, suggests that the lithofacies may, in part, represent deposition in tidal channels. The locally abundant intraclasts are consistent with this hypothesis (Friedman, 1969).

Lithofacies 5
Foram grainstone and packstone

Description - Lithofacies 5 is dominated by the presence of Endothyrid foraminifera (Fig. 24). They show a range of from 8 to 42 percent and average 27 percent of the total rock (Table 4). While they are not always the dominant faunal element, their presence in more than minor amounts is considered distinctive. Associated with the foraminifera are

Figure 23 - Radiaxial oolite (Sample 40-4; bar scale .1 mm)

Figure 24 - Lithofacies 5; Foram grainstone; negative print (Sample 12-3; bar scale 2 mm)

Figure 23

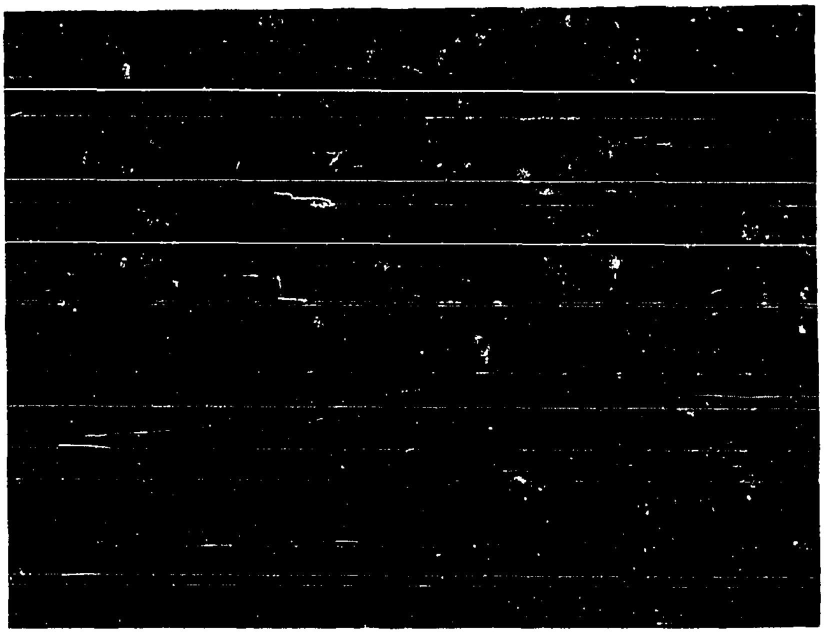


Figure 24

bryozoans and echinoderms which comprise an average of 16 and 22 percent of the total rock, respectively. Brachiopods are also present in all samples, though they average only 2 percent of the total rock. Pelecypods, gastropods, ostracods, calcispheres, pellets, intraclasts, and superficial oolites are also present in some of the samples, with gastropods and intraclasts occurring in more than trace amounts in certain samples.

The unit commonly occurs as a porous, medium to coarse-grained calcarenite, which is moderately-sorted to moderately well-sorted.

The foram grainstones are commonly cemented by sparry calcite which comprises from 5 to 39 percent and averages 20 percent of the total rock (Table 4). Several zones of calcite cement are present in this lithofacies as has been the case in the previous four lithofacies. Microspar is also present in some of the samples as a neomorphic replacement of fine-grained carbonate mud.

Fine-grained carbonate mud is a common constituent, ranging from 2 to 22 percent of the total rock and averaging 11 percent. This carbonate mud occurs as interstitial matrix, as a filling of foram tests and bryozoan zooecia, and as a micritic coating on grains. This micritic coating, or micrite envelope, gives an important clue to the depositional environment of the lithofacies.

In many cases, the interstitial carbonate mud has been replaced by Type B or C dolomite, but the micrite within skeletal grains is commonly unaltered.

The foram grainstone lithofacies commonly occurs in thick-bedded to massive units. The units are normally crossbedded and show common ripple marks. Both planar and trough crossbeds are present with an average angle of inclination of 11-15 degrees and modal bed thickness of 5 to 8 inches (Carr and others, 1966, p. 100-101). The cross-bedding is bimodal (dominantly northeast-southwest) with a high degree of variability (Carr and others, 1966, p. 108).

Stratigraphic Position - Lithofacies 5 is restricted to the Salem Formation of Indiana and is the dominant lithology of the Salem building stone. The lithofacies makes up much of the Salem section in Monroe and Lawrence counties and is also found in the southern portions of the Indiana outcrop.

Depositional Environment - Lithofacies 5 gives every indication of having formed in a high energy, subtidal environment. The common cross-bedding, highly fragmented nature of the skeletal debris, superficial oolites, and good sorting all indicate the unit has been exposed to a high degree of current activity.

The presence of calcispheres, pellets and micritic envelopes suggests a shallow water origin. Pellets are considered to be indicative of deposition in an intertidal to high subtidal environment (Laporte, 1969, Table 2; Jorgenson and Carr, 1973, p. 49; Wilson, 1974, Fig. 5). The lithofacies, however, lacks other common intertidal features. The foram grainstone bodies also occur as linear shoals approximately paralleling the general depositional strike rather than as tidal channels running perpendicular to the strike. This tends to rule out deposition in the intertidal zone and suggests lithofacies 5 was deposited in a shallow subtidal environment.

Based on these criteria, the foram grainstones are interpreted to represent a high energy shoal deposit formed in the shallow subtidal zone. Tidal currents, indicated by the bimodal crossbedding, were responsible for the accumulation of material in bathymetrically higher areas. Constituent particles were derived both seaward and landward of the deposit, thus explaining the intermixing of typical intertidal deposits with deeper subtidal deposits. The shoal had a general northwest-southeast trend and separated deposits interpreted to be definitely subtidal from intertidal deposits.

Lithofacies 6
Pelletal calcisphere packstone

Description - Lithofacies 6 (Figs. 25 and 26) is identified by the common occurrence of calcispheres. While they are never the dominant constituent particle because of their small size (.04 to .10 mm), they are present in large enough numbers to be readily apparent in thin section. The lithofacies is composed of a mixture of calcispheres, pellets, intraclasts, and skeletal fragments (Table 3). The most common skeletal components are forams, ostracods, bryozoans, and echinoderms, with the actual composition of the lithofacies highly variable from sample to sample. Ostracods, however, are much more abundant in this lithofacies than in any other.

The lithofacies typically occurs as a very fine to fine-grained calcarenite to calcisiltite. Is is poorly-sorted with skeletal grains ranging from 40 micron calcispheres to echinoderm fragments several millimeters in diameter.

Figure 25 - Lithofacies 6; Pelletal calcisphere packstone (Sample 64-4; bar scale .5 mm)

Figure 26 - Lithofacies 6; Pelletal calcisphere packstone (Sample 12-4; bar scale .5 mm)

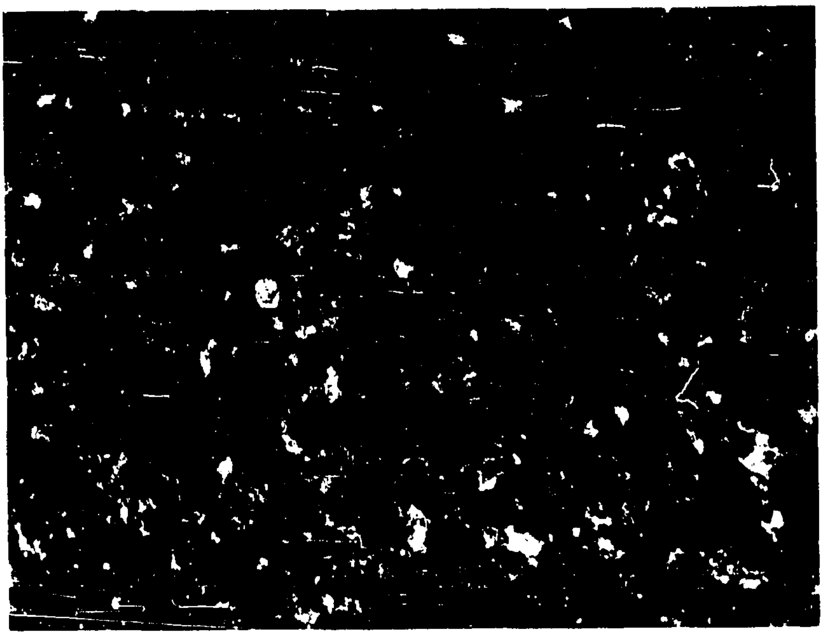


Figure 25

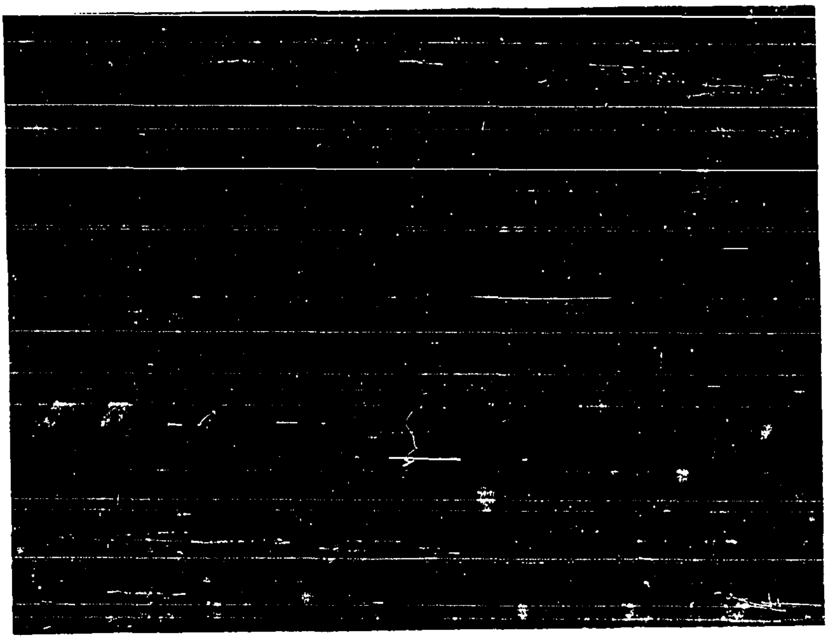


Figure 26

Fine-grained carbonate mud is a common constituent of the lithofacies. It occurs as interstitial matrix and as a filling and coating on certain skeletal grains. In some instances, this carbonate mud is replaced by Type B or C dolomite. The distribution of dolomite within the lithofacies is highly variable, however. In some cases, all carbonate mud has been replaced by dolomite, in others replacement has been minimal.

Minor amounts of sparry calcite are present. In many cases it occurs as microspar to pseudospar and probably represents neomorphic alteration of carbonate mud. Some of the spar, however, appears to be a pore-filling sparry cement.

The lithofacies is normally medium to thick bedded, though the thickness of individual beds is highly variable. The unit is commonly bioturbated and burrowed with vertical burrows common. Dark wavey lamination, interpreted to be the remains of disrupted algal mats, is a common feature apparent in both thin section and hand speciman. The unit also shows scattered occurrences of "birds-eye" type structures.

In many outcrops, the pelletal calcisphere packstones are interlaminated on a small scale with thin laminae of fine-grained carbonate mud or dolomite.

Stratigraphic Position - The pelletal calcisphere lithofacies is found in the upper portions of the Salem section of Indiana and the adjacent portions of northern Kentucky, and in the Renfro Formation of eastern Kentucky.

Depositional Environment - The physical characteristics of lithofacies 6 are similar to other units interpreted to represent deposition in a high subtidal to low intertidal, quiet water environment.

The abundant calcispheres, in particular, indicate deposition occurred in relatively shallow water. Based on present occurrence, dasycladacean algae (calcispheres) are thought to indicate deposition in 10-15 feet of water (Wilson, 1974, p. 823).

The abundance of ostracods, algal lamination, vertical burrows, abundant pellets, and common fine-grained dolomite, are all features unique to a shallow subtidal to intertidal environment (Schenk, 1975, Fig. 42-2; Wilson, 1974, Fig. 5).

The intimate small scale interlamination of the lithofacies with fine-grained carbonate muds or dolomite indicates deposition was occurring in a rapidly fluctuating environment such as the intertidal zone.

With the exception of sparse birdseyes, however, there is little evidence to indicate prolonged subaerial exposure. The common desiccation cracks which are indicative of prolonged exposure in the high intertidal to supratidal zone (Friedman, 1969) are absent.

This suggests deposition occurred in the shallow subtidal to lower intertidal zone. The lithofacies, in general, fits well into the restricted platform environment of Wilson (1974, Fig. 5) and Armstrong (1974, Fig. 10) or the lagoon environment of Schenk (1975, Fig. 42-2).

Lithofacies 7
Dolowackestone

Description - The rocks in this lithofacies (Fig. 27) represent original lime wackestones or packstones which have been altered by dolomitization. There is a complete spectrum to the degree of replacement which occurs in the lithofacies. Dolomitization ranges from partial replacement of lime

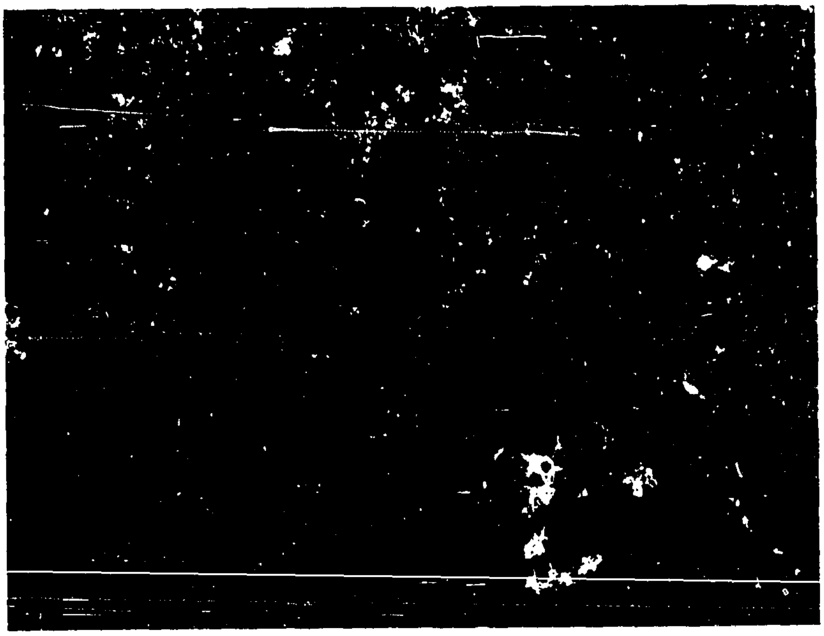


Figure 27 - Lithofacies 7; Dolowackestone; note eroded bioclastic material (a) in matrix of inequigranular hypidiotopic to idiotopic dolomite crystals (Sample 15-11; bar scale .5 mm)

muds in wackestones to total replacement of both matrix and skeletal material. The dolomite content ranges from 16 to 100 percent of the carbonate total. In the case of total replacement, a hint to the original rock type is often given by ghosts of the replaced skeletal material. These ghosts occur either as variations in the grain size of the replacing dolomite, or as pyritic remnants of the skeletal grains themselves.

The lithofacies is sparsely fossiliferous. Skeletal grains found include ostracods, algae, forams, bryozoans, echinoderms, brachiopods, and pelecypods (Table 3).

The dolomite within the lithofacies is a combination of Type B and Type C dolomite and is very similar to the massive dolomite of Fisher and Rodda (1969). It consists of a fabric of inequigranular, hypidiotopic to idiotopic dolomite crystals. The crystals range in size from 6 to 100 microns, though most are in the 20 to 60 micron range. The crystals are normally well-developed rhombs in a loosely knit fabric with moderate porosity.

The lithofacies contains disrupted dark, wavey organic laminations which are interpreted to be remnant algal laminations. In places, the lithofacies contains detrital quartz grains and is somewhat pyritiferous.

The lithofacies is commonly light yellow to brown in color and medium to thick bedded. The units are frequently bioturbated, in places intensely, and contain both vertical and horizontal burrows. The dolowackestones are commonly interbedded with rocks of the dolostone lithofacies and with subtidal shelf units of lithofacies 1 through 5.

Stratigraphic Position - The dolowackestone lithofacies is found throughout the units under study. It is, however, most common in the Ramp Creek of Indiana, in the upper portions of the Salem of Indiana, and in the Renfro of eastern Kentucky.

Depositional Environment - Rocks of the dolowackestone lithofacies are interpreted to represent sediments originally deposited in low energy intertidal or subtidal environments which have subsequently been dolomitized, either partially or completely, by the process of reflux dolomitization (Adams and Rhodes, 1960; Deffreys and others, 1965; Lucia, 1972).

While it is impossible, due to dolomitization, to discern the original depositional environment of all the rocks in the lithofacies, many of the features of the lithofacies are characteristic of low energy, intertidal to subtidal deposition.

The presence of fine-grained carbonate mud (Laporte, 1969, p. 110; Braun and Friedman, 1969, p. 122; Wilson, 1974, Fig. 5) or pelletal mud (Laporte, 1969, Table 2; Schenk, 1975, Fig. 42-2, Table 42-1) is common in the intertidal zone, though not particularly distinctive. Calcareous algae (Laporte, 1969, Table 2; Wilson, 1974, Fig. 5) or algal lamination indicative of algal mat formation (Armstrong, 1974, Fig. 10; Schenk, 1975, Fig. 42-2, Table 42-1) are keys, however, to the intertidal zone. Abundant bioturbation is another distinctive feature (Laporte, 1969, p. 110; Schenk, 1975, Fig. 42-2). Rhoads (1967) has suggested that vertical burrowing, in particular, is characteristic of the intertidal zone, while horizontal burrowing is more common in subtidal environments. The mixture of vertical and horizontal burrows found in much of the dolowackestone lithofacies, therefore, indicates original deposition in the lower intertidal to shallow subtidal zone. This interpretation is strengthened by the lack of any desiccation features commonly associated with deposition in the high intertidal zone.

The above features, along with the abundance of dolomite which characterizes the lithofacies, and the interbedding of the lithofacies with units interpreted to represent supratidal and subtidal environments, together suggest an intertidal origin for much of the lithofacies.

Lithofacies 8
Dolostone

Description - There are two subfacies present which have been combined to form the dolostone lithofacies. Both these subfacies are pure dolomite. Skeletal material is absent, as are any features (ghosts) which indicate the rocks originated by replacement of skeletal carbonates. Petrographically, however, the two are distinctly different and have been subdivided into a primary dolostone subfacies, and a secondary dolostone subfacies.

The primary dolostone subfacies is composed of Type A dolomite (Fig. 13). It occurs as a very fine-grained (2 to 10 micron) mosaic of tightly knit xenotopic to hypidiotopic crystals. The Type A dolomites are generally slightly silty and pyritiferous.

Exposures of primary dolostones are light yellow to light brown and irregularily laminated to thin-bedded. They commonly contain dark wavey laminations (Fig. 28) interpreted to be algal in origin, along with sparse "birds-eye" structures and minor brecciation. Mudcracks have not been observed. The primary dolostone subfacies is commonly interbedded with

Figure 28 - Dark wav~~e~~y algal lamination common to dolostone and dolowackestone lithofacies; negative print (Sample 8-5; bar scale 1 mm)

nondolomitized pelletal muds.

The secondary dolostone subfacies is composed of Types B and C dolomite (Figs. 14 and 15). It consists of inequigranular, hypidiotopic to idiotopic dolomite crystals which range in size from 6 to 100 microns, though most of the crystals are in the 20 to 60 micron range. This is distinctly coarser than the Type A dolomite and the two are easily distinguished petrographically.

Like the primary dolostones, the secondary dolostones are commonly silty and pryitic. In places, they contain gypsum nodules or gypsum-filled geodes. They also frequently contain wavey algal lamination and occasional "birds-eye" structures, but mudcracks or other features suggestive of prolonged exposure and desiccation have not been observed.

In outcrop, the subfacies ranges from light brown to dark gray, is thin-bedded to massive and, in places, highly argillaceous. It also is commonly interbedded with nondolomitized units.

Stratigraphic Position - The primary dolostone subfacies is limited to exposures in the Renfro of eastern Kentucky. The secondary dolostone lithofacies occurs in the Ramp Creek and Salem of Indiana and the Salem of Kentucky.

Depositional Environment - The primary dolostone subfacies is interpreted to represent dolomite formed as an original precipitate or penecontemporaneous replacement product in an intertidal to supratidal environment (Friedman and Sanders, 1967).

The unit shows many of the same features of the early dolomite of Larporte (1969, p. 106) or stratal dolomite of Fisher and Rodda(1969, Table 1), both of which were interpreted to be supratidal or intertidal in origin. The lack of fossils, very fine grain size, thin-bedding, and interbedding with nondolomitized units are features characteristic of sediments found in certain modern supratidal and intertidal environments (Deffeyes and others, 1965; Illing and others, 1965; Shinn and others, 1965; and Kinsman, 1966).

While many of the characteristics listed above indicate a supratidal origin for the primary dolostone lithofacies, the lack of mudcracks is somewhat puzzling. Mudcracks, an indication of subaerial exposure, are common features of many ancient supratidal deposits (Laporte, 1967, 1969; Braun and Friedman, 1969; Fisher and Rodda, 1969; Armstrong, 1975; and Mazzullo and Friedman, 1975). The fact that they have not been observed in the primary dolostone units indicates that the units did not undergo prolonged periods of desiccation. This suggests that deposition occurred low in the supratidal zone where the water table was high and the surface was kept wet by capillary action.

The depositional environment of the secondary dolostone subfacies is somewhat more ambiguous. The unit contains many features common with the primary dolostones. The lack of fossils, thin bedding, algal laminations, and interbedding with nondolomitic units are all characteristic of a primary supratidal origin for the dolomite. The common gypsum nodules and geodes found in the unit have also been interpreted to indicate a supratidal origin (Chowens and Elkins, 1974). The presence of Types B and C dolomite, however, suggests a replacement origin.

The secondary dolostones show no traces of skeletal material or of the replacement of skeletal material, indicating the original lithology was a nonfossiliferous fine-grained carbonate mud. In the supratidal environment, dolomitization of this material would form a dolomicrite (Friedman, 1964, 1966; Friedman and Sanders, 1967) similar to the primary dolostones. The coarser grain size of many of the crystals in the secondary dolostones suggests recrystallization. Kinsman and Patterson (1973) have suggested that many ancient dolomites of penecontemporaneous, supratidal origin have undergone diagenetic recrystallization with a concomitant coarsening in grain size. This is felt to be the process responsible for the formation of the secondary dolostones. A similar interpretation for dolomites from the Tribes Hill Formation (Lower Ordovician) of New York was given by Braun and Friedman (1969).

Lithofacies 9
Quartzose sandstone

Description - While detrital quartz is present as a trace constituent in several of the other lithofacies, quartzose sandstones are a minor facies in the units under study.

These sandstone (Fig. 29) are typically very fine to coarse grained, poorly sorted quartzose sandstones. They contain both monocrystalline and polycrystalline quartz, though monocrystalline predominates. They also contain abundant clay matrix, detrital dolomite, and in some cases, highly fragmented carbonate skeletal material.

They are generally thin-bedded to massive, bioturbated, and show high angle cross-bedding. They commonly are interbedded with fine-grained limestones or dolomites.

Stratigraphic Position - Significant accumulations of quartz sand are found only in the eastern portions of the study area. These sandstones are restricted to the Salem Formation where they occur in the upper and/or lower portions of the unit (Fig. 30).

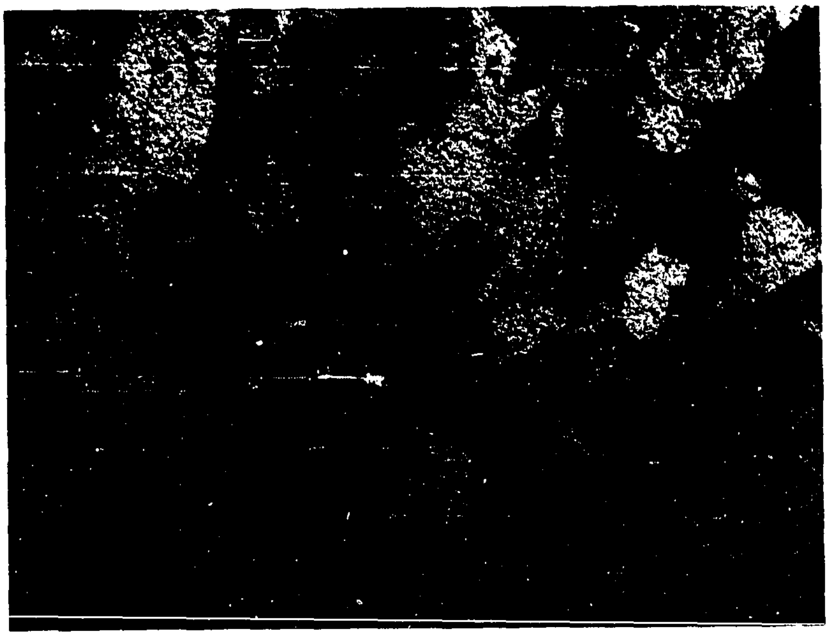


Figure 29 - Lithofacies 9; Quartzose sandstone; mixture of bioclastic grains and poorly sorted monocrystalline and polycrystalline quartz; crossed nicols (Sample 57-12; bar scale .5 mm)

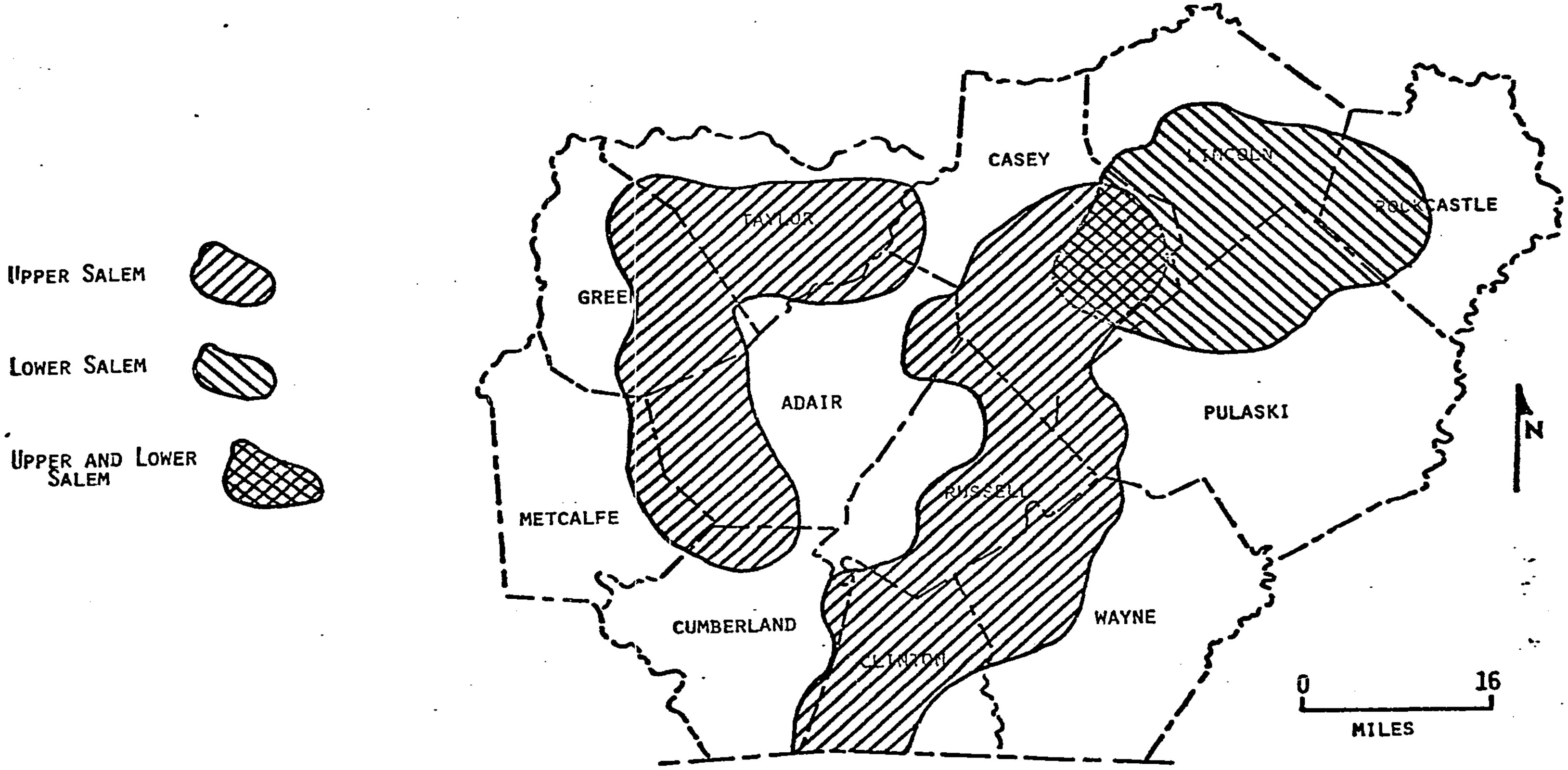


Figure 30 - Distribution of sand in the Salem of southeast central Kentucky

The thickest sandstone in the study area is the Science Hill Sandstone (Lewis and Taylor, 1975) which occurs over a 1000 square mile area north of Somerset Kentucky (Fig. 30).

Depositional Environment - Based on limited exposures, the sandstone lithofacies is interpreted to represent deposition in an intertidal to high subtidal environment of medium to high energy.

The common burrowing, along with the association of the sandstone lithofacies with carbonate units interpreted to represent deposition in an intertidal to high subtidal environment, suggests deposition occurred in a shallow water environment. The common crossbedding indicates moderate to high energy.

DEPOSITIONAL MODEL

There have been many carbonate depositional models proposed to fit specific rock units. Many of these are based on comprehensive studies of carbonate sedimentation in the Holocene (Purdy, 1963; Illing and others, 1965; Shinn and others, 1965; Kendall and Skipwith, 1969; Logan and others, 1969; Logan and others, 1970; and Lucia, 1972). Recent carbonate sedimentation is rather restricted in the present world ocean, and most information has been derived from studies of only a few local areas (i.e. the Bahama Bank, Trucial Coast, South Florida, Sharks Bay, Yucatan). The broad, extensive, gently sloping, shallow shelves upon which much Paleozoic carbonate sedimentation occurred are not represented in the Holocene, thus it is often difficult to specifically relate ancient carbonate deposits to the recent.

Several general theories of carbonate or clear water sedimentation have been presented. Among the best known are the general models of Shaw (1964) and Irwin (1965) and the more comprehensive model of Wilson (1970). All of these theories contain certain concepts of carbonate sedimentation which appear to be inherent to both ancient and recent carbonates.

One of these basic concepts is, that because of low depositional slopes, the depositional environment can be divided into three zones (Fig. 31) oriented approximately parallel to the strand. These zones are defined on the basis of the relative wave and tidal energy expended in each.

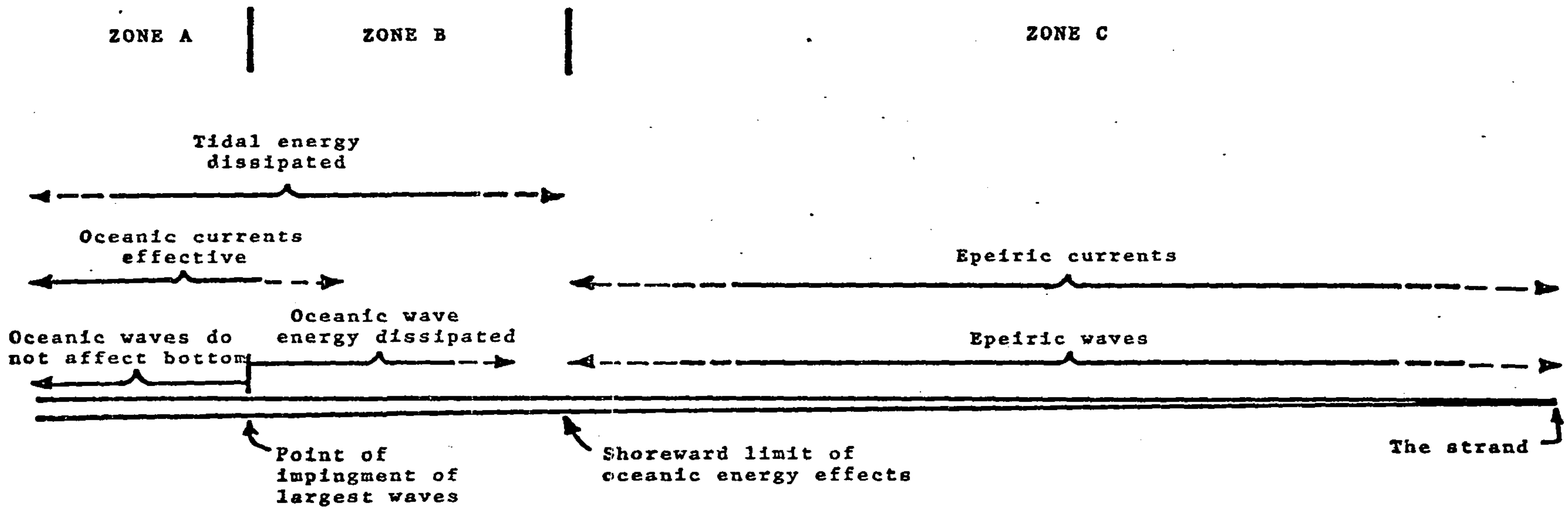


Fig. 31 - Theoretical energy distribution across a wide, shallow platform (From Shaw, 1964, p. 43)

Zone A (Fig. 31) is a low energy zone lying below wave base which is unaffected by wave activity. It is essentially a zone of accumulation of carbonate debris, characterized by lime wackestones to packstones. The limestones are commonly thin-bedded to massive, cherty, thoroughly burrowed, and show features characteristic of slumping or turbidity type currents (Wilson, 1974, Fig. 5).

Zone B is a high energy zone of strong wave or tidal influence located between the point where waves first touch bottom and the point where wave and tidal action is largely dissipated by friction. This zone is characterized by abundant fragmented skeletal material. The rocks are normally grainstones or packstones and are commonly crossbedded, showing the effects of wave or tidal activity. In very active waters, oolites are common.

Zone C (Fig. 31) is a low energy zone where wave and tidal action are minor, having been largely dissipated by friction with the bottom or restricted by a bathymetric high such as a reef or shoal. Storm activity represents the major energy input. Lithologies in this zone are highly variable. Highly bioturbated lime wackestones to grainstones are common in the lower portions of the zone. As you move shoreward, the lithologies become increasingly dolomitic, ranging from dolomitic wackestones and packstones to finely crystalline dolomites. Further landward, gypsum and anhydrite are common lithologic constituents.

The width of these zones is dependent upon the depositional slope. Slopes of less than 1 foot per mile have been described in other Paleozoic environments (Laporte, 1969, p. 115). This differentiates the depositional environment into zones several miles to several tens of miles in width.

Recent studies of Holocene carbonate environments have put increased emphasis on the affects of tidal influence on carbonate sedimentations. Three general environments (Fig. 32) have been proposed based on position in relation to tidal range.

(1) Subtidal Zone - the zone below mean low tide, represents an area which is constantly covered with water.

(2) Intertidal Zone - the zone between mean low tide and mean high tide; represents a zone which is alternately covered and exposed.

(3) Supratidal Zone - the zone above mean high tide which is only infrequently covered with water.

This second subdivision, while based on a completely different characteristic, can be easily combined with the energy model. The subtidal environment includes all of Zones A and B and the lower portions of Zone C. The intertidal and supratidal environments then make up the remainder of Zone C.

The Specific Model

By comparing the characteristics of the nine lithofacies defined in the study area with the general characteristics for carbonate or clear water sedimentation discussed previously, a specific model was developed for Osagian-Meremecian platform carbonate deposition. This model (Fig. 33) contains 7 separate depositional environments ranging from supratidal flats to deep-water basin.

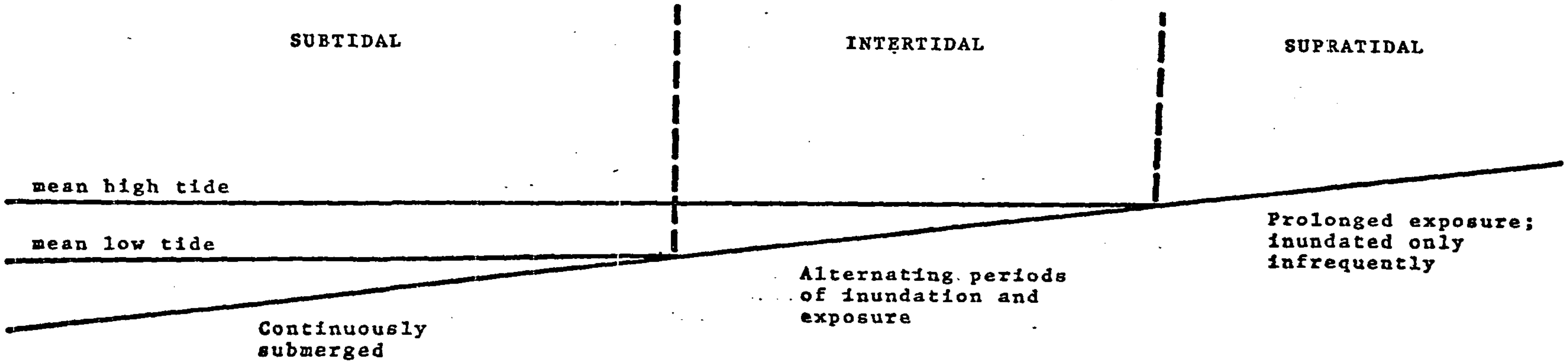
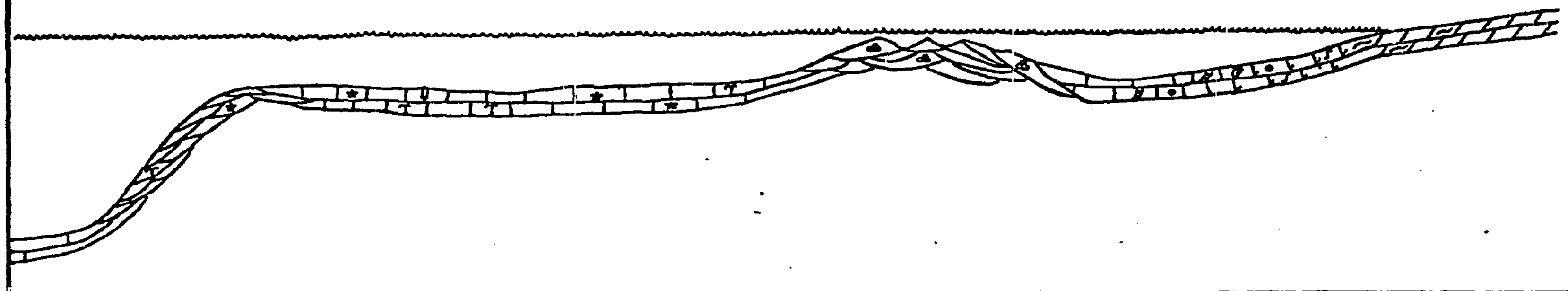


Fig. 32 - Tidal subdivision of a shallow water platform



Depositional Environment	Basin 7	Slope-edge 6	Subtidal shelf 5	Shoal 4	Lagoon 3	Intertidal 2	Supratidal 1
Lithology & Lithofacies	fine-grain limestones & shales	med.-coarse limestones Lith. 1 & 3	medium to coarse grained bioclastic limestones Lithofacies 1,2,3 & 4	fine-coarse grained bioclastic limestones Lithofacies 4	fine-grained limestones and dolomites Lithofacies 6 & 7	fine-grained dolomites and dol. limestone Lith. 6,7,8 &9	fine-grain dolomite & evaporites Lith. 8
Color	dark gray-dark brown	light-dark gray	light gray	light gray	light gray-light brown	light brown	light-brown to yellow
Grain Type & Depositional Texture	argill. mudstone & shale	bioclastic packstones & grainstones	bioclastic packstones and grainstones	bioclastic grainstones	pelletal wackestones & packstones; dolomitic in places	mudstones & wackestones; some clastics	mudstones
Bedding & Sedimentary Structures	thinly lam. graded bedding	crossbedded, gravity flow structures	medium-bedded to massive some crossbedding	common crossbedding	burrows common; disrupted algal lam. in higher zones	irregular lam algal lam. "birds-eye"	irreg. lam. gypsum nodules & geodes
Biota	bioclastic material from platform	bioclastic material from platform	echinoderms, bryozoans, brachiopods, & pelecypods	few indigenous forms, forams abundant	algae, ostracods, forams, burrowing organisms	algae, burrowing organisms	no indigenous forms

Figure 33 - Depositional model for post-Borden platform carbonates showing environments, rock types, sedimentary structures and biota.

Supratidal Flat Environment

Deposition in the supratidal flat environment is represented by a single lithofacies, the dolostone lithofacies (Table 7). Deposition occurred in a low relief zone above the limits of normal high tide. The zone was, however, periodically inundated by storm tides.

The supratidal environment is characterized by a dearth of fossils (with the exception of algal mat structures) and by an abundance of dolomite. Dolomite forms penecontemporaneously in the supratidal environment, while downward or lateral migration of hypersaline brines (seepage reflux) is responsible for diagenetic dolomitization of underlying or adjacent intertidal sediment (Deffeyes and others, 1965). These hypersaline brines are also responsible for the formation of bedded or nodular sulfate (gypsum and anhydrite) within the supratidal or underlying intertidal sediments (Curtis and others, 1963; Kinsmann, 1966, 1969; and Shearmann, 1966).

The supratidal environment is dominantly an area of prolonged exposure and desiccation. Features such as mudcracks and "birds-eye" structures are common indications of desiccation in intertidal or supratidal sediments. The paucity of "birds-eye" structures and lack of mudcracks in the units under study implies that the sediment did not undergo prolonged desiccation. This suggests that these units were deposited low in the supratidal zone when the water table was relatively high and the surface sediments were kept wet by capillary action. This corresponds to the lower supratidal zone as described by Woods and Brown (1975, p. 228) from Shark Bay, Australia.

Table 7 - Depositional environments and associated lithofacies of post-Borden platform carbonates

Depositional Environment	Associated Lithofacies
(1) Supratidal flat	Dolostone
(2) Intertidal	Dolostone Dolowackestone Pelletal calcisphere Quartzose sandstone
(3) Lagoon	Pelletal calcisphere Dolowackestone
(4) Shoal	Foram
(5) Subtidal shelf	Bryozoan-echinoderm Echinoderm Bryozoan Diverse
(6) Slope-edge	Bryozoan-echinoderm Bryozoan
(7) Basinal	(Platform lithofacies not represented)

Intertidal Environment

Intertidal deposition is suggested by four of the nine lithofacies (Table 7). In most cases, however, these lithofacies are not restricted to the intertidal zone, but represent deposition in a combination of intertidal-supratidal or intertidal-subtidal environments.

The intertidal environment represents deposition in the zones between mean high tide and mean low tide. The width of this zone is determined by the depositional slope and tidal range. Conditions in this environment alternate between periods of inundation (high tide) and exposure (low tide). The presence of "birds-eye" structures in some of the units indicates subaerial exposure, but the lack of mudcracks suggests exposure was probably not prolonged.

The abundance of fine-grained carbonate mud suggests a low energy environment of deposition and implies that much of the wave energy had been expended further offshore.

The units under study commonly show disrupted algal lamination, a common criterion of intertidal deposition (Laporte, 1969, p. 106). They are also intensely burrowed, and, in many cases, vertical burrowing predominates over horizontal burrows. This is another feature interpreted to be characteristic of intertidal deposition (Rhoads, 1967).

Several of the lithofacies common to this environment contain abundant dolomite. This is particularly true for the dolostone and dolowackestone lithofacies. No modern examples of subtidal dolomite are known. It has been postulated (Friedman and Sanders, 1967) that all dolomite is related to hypersaline brines originating in the supratidal environment. Thus the abundant dolomite in many of these units indicates they were intimately related to supratidal deposition. Because they have few features of supratidal sediments, this suggests deposition in an intertidal to high subtidal environment.

Lagoonal Environment

Deposition in this environment is represented by two lithofacies (Table 7); the pelletal calcisphere lithofacies and the dolowackestone lithofacies.

The environment is a shallow, low energy lagoon with somewhat restricted circulation, and possibly slightly increased salinities. The quiet water was related to the presence of a shoaling environment seaward, which buffered most wave and tidal energy.

The shallow nature of the environment is best illustrated by the abundance of calcispheres. Calcispheres are considered to be reproductive cysts of dasycladacean algae (Rupp, 1966), which, based on modern occurrence, indicate deposition in 10-15 feet of water (Wilson, 1974, p. 823). Calcispheres, along with the generally restricted fauna, are also indicators of a restricted, slightly hypersaline environment (Ginsburg, 1956; Logan, 1961; Kendall and Skipwith, 1969; and Wilson, 1974, p. 823).

The interpretation of the low energy nature of the environment is supported by the abundance of fine-grained carbonate mud and pellets, and by the very poor sorting of the units.

The abundant dolomite in the unit is again indicative of an intimate relationship between lagoonal and supratidal environments. With dolomitization of lagoonal sediment occurring by seepage reflux of hypersaline brines from overlying supratidal units.

When all factors are considered, this environment duplicates very closely the open and restricted platform environments of Wilson (1970).

Shoal Environment

The shoal environment is represented by a single lithofacies (Table 7), the foram lithofacies. This lithofacies represents deposition in a shallow, high energy environment characteristic of Zone B of the energy model (Fig. 31).

The shoal environment represents deposition in bathymetrically higher areas by wave and tidal exchange. With significant accumulation, the shoal forms an effective barrier to wave action and tidal exchange in the areas shoreward of it. The shoal environment in the study area occurs in a relatively narrow belt trending northwest-southeast through the Indiana portion of the study area, and separates quiet water lagoonal sediments from more highly agitated open marine shelf sediments.

The high energy nature of the environment is well illustrated by the relatively small amount of interstitial micrite present, the well-sorted texture, the presence of oolites, and the characteristic well defined biomodal crossbedding.

The bimodal nature of the crossbedding (Carr and others, 1966, p. 104), along with the unique faunal assemblage indicate a strong tidal influence. Bimodal crossbedding is a characteristic feature of tidally influenced deposits (Klein, 1970, p. 1104). The ambiguous faunal combination of typical shallow, quiet water forms (forams, pellets, calcispheres, ostracods) with forms characteristic of deeper water, and a more highly agitated environment (bryozoans, echinoderms, brachiopods) suggests material has been derived both landward and seaward of the feature and transported to the shoals by tidal currents.

Subtidal Shelf Environment

The subtidal shelf environment is one of the most important in the depositional model since it is the most widespread. It is represented by four separate though intimately related lithofacies (Table 7), and is interpreted to represent deposition on a low relief subtidal shelf. Deposition occurred at or above wave base (Zone B, Fig. 31) and thus was affected by wave action and tidal currents. The environment supported an abundant and relatively diverse fauna of largely sessile, suspension feeding organisms.

Carbonate production was profuse in the environment as indicated by the abundant fauna and the relatively large amounts of carbonate mud present.

These large amounts of fine-grained carbonate mud imply a quiet water mode of deposition. Many grainstone units, which show evidence of current stratification, grade laterally into packstones. Many beds also grade upward from packstones into well-washed, crossbedded grainstones. This suggests that wave and tidal influence was not as great as in the shoal environment, perhaps affecting only the bathymetrically higher areas or tidal channels, while in the bathymetrically lower areas, accumulation exceeded the rate of removal.

The grainstones are felt to represent two separate depositional modes in the environment. Some of the grainstones show typical features of tidal channel deposits. The units are cut into the adjacent lithologies with sharp contacts, are biomodally crossbedded, and bedding surfaces tend to truncate underlying units. The channel fill lithologies also contain intraclasts of material from adjacent lithologies.

Not all the subtidal grainstones, however, show these typical tidal channel features. Many of them are not channel-like, show no crossbedding, and grade laterally into packstones. These are interpreted to represent deposition in bathymetrically higher areas where the production of skeletal grains was profuse, but currents or wave activity was only great enough to remove the fine-grained carbonate material.

Slope-edge Environment

The presence of the Borden Delta played an important role in succeeding carbonate deposition. The Borden front divided the study area into two general zones, a shelf zone on top of the Borden Delta and a deeper water basinal zone south and southwest of the front. Wave and tidal influences were, in all probability, restricted to the shelf area while the basinal zone was essentially an area of accumulation of carbonate and clastic debris originating on the shelf.

Material originating in the subtidal shelf environment on top of the Borden Delta was transported seaward by tidal currents and accumulated near the break in slope of the front. Slope breaks such as this are commonly areas of relatively strong wave and current activity (Swift, 1970), and the material accumulated as well-winnowed, crossbedded, elongate barrier which paralleled the slope break (Cane Valley Limestone). As this material accumulated and became unstable, it was carried down the foreset slope by turbidity currents, grain flows, and debris flows and was redeposited at the foot of the slope (Klein, 1974).

This slope-edge environment is represented by two lithofacies (Table 7), which are also found in the subtidal shelf environment, the bryozoan and bryozoan-echinoderm lithofacies. The units range from fine to coarse calcarenites, are well-sorted and commonly crossbedded (Sedimentation Seminar, 1972), reflecting the relatively high energy of their environment of deposition.

The units commonly occur as carbonate banks enclosed in more basinal sediments and have a pronounced downslope dip (Sedimentation Seminar, 1972). This downslope dip led to the association of these slope-edge carbonates with basinal carbonate bodies such as the Beaver Creek Limestone (Klein, 1974). The time-contemporaneous relationship of these shelf-edge carbonate banks with basinal carbonate bodies suggests a clinoform nature to shelf edge deposition. This clinoform type sedimentation implies a progradation of the slope-edge to the south and southwest and a corresponding southwesterly decrease in age for the units in question.

Basinal Environment

The basinal environment represents accumulation of carbonate and clastic material in deeper waters adjacent ot the Borden front. As such, it does not represent platform deposition and is not represented by any of the platform lithofacies. Material accumulating in the basinal environment, however, is derived from the platform and the environment is included to complete the depositional model.

Water depths ranged up to at least 200 feet (Sedimentation Seminar, 1972, p. 18) with deposition occurring below wave base. Thus, the environment was an area of rapid accumulation of sediment.

The lithologies characteristic of the basinal environment are dominantly medium to dark gray, poorly sorted, cherty, packstones and wackestones. They are normally dolomitic, but the dolomite has been shown to be of detrital origin (Hannan, 1975) and probably originated in shallow water environments on the Borden platform.

The basinal units are commonly highly bioturbated and contain a large amount of terrigeneous material in the form of quartz silt and clay minerals. In places, the units are so rich in terrigeneous material that they are calcareous siltstones or shales (Hannan, 1975).

CYCLIC SEDIMENTATION

One of the characteristic features of shallow water carbonate sedimentation is the apparent cyclic nature of the units. This cyclicity is defined by the repetative occurrence of certain lithologies and both small and large scale cycles may be present.

Cyclicity in shallow water carbonates has been well documented in literature (Fischer, 1964, 1975; Laporte, 1967, 1975; Read, 1973, 1975; Coogan, 1969; Hoffmann, 1975; Jorgenson and Carr, 1973). Both large and small scale cycles are illustrated, with small scale cycles, in some cases, superimposed on large scale cycles. This is particularly well illustrated by Laporte (1969, 1975) for the Helderburg Group (Lower Devonian) of New York.

A normal carbonate cycle consists of subtidal, intertidal, and supratidal lithologies with the intertidal lithology repeated in some cases (Jorgenson and Carr, 1973, Fig. 4). Not all cycles are complete, however, either because of erosion or nondeposition and often only a portion of the complete cycle is present.

The thickness of the individual components of a cycle is highly variable, depending, in large part, on the nature of the depositional system. In the lower St. Louis Formation of southern Indiana, the cycles are dominated by intertidal and supratidal components, with the subtidal component playing a minor role (Jorgenson and Carr, 1973, Fig. 3). In the Dachstein Limestone (Late Triassic) of the Northern Alps, the subtidal component, on the other hand, is the dominant component while the intertidal and supratidal portions are relatively minor (Fischer, 1975, Fig. 27-1).

There is also considerable variation in the overall thickness of a cycle. The thickness is determined by the completedness of the cycle, the rate of carbonate production, and the length of time the cycle represents. Shearman (1966, p. B211) described 3 complete cycles in 17 feet of section in the Jurassic of southern England. Jorgenson and Carr (1973, p.46) reported 18 cycles in 163 feet of section with cycles ranging from 4 to 25 feet in thickness. Fischer (1975, Fig. 27-1) illustrates 20 cycles in 360 feet of section from the Triassic of the Alps with individual cycles ranging from 3 to 45 feet in thickness.

This cyclicity in carbonate sediments represents the lateral migration of environments within the depositional system. This migration is a reflection of the complex interplay between rates of sediment accumulation, subsidence, and variations in sea level.

If, during a period of sea level stability, accumulation exceeds subsidence, regression will occur (Fig. 34). Supratidal sediments will prograde over intertidal sediments which, in turn, will overlap subtidal sediments. This advance of nearshore sediments over deeper water sediments will continue as long as the controlling factors are unchanged. However, should subsidence exceed the rate of accumulation or there be a rise in sea level, the trend will be interrupted, transgression will occur, and a second cycle will begin over the first.

Indiana Platform

The cyclic nature of shallow water carbonate sedimentation is well illustrated in the units under study, particularly by the Ramp Creek in Indiana. This unit represents initial carbonate deposition on the

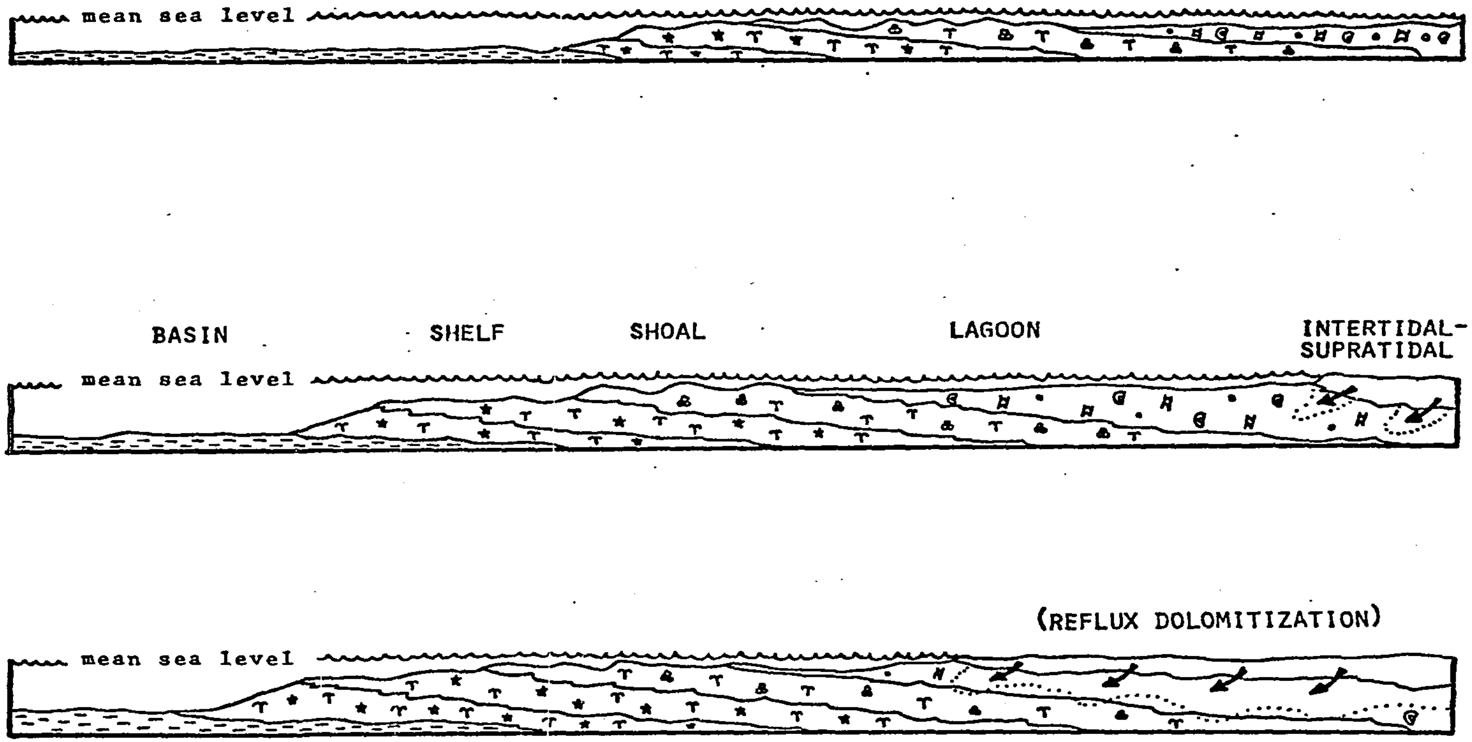


FIGURE 34 - MODEL OF REGRESSION ON A SHALLOW-WATER CARBONATE PLATFORM (FROM ARMSTRONG, 1974)

topset portions of the Borden Delta.

The Ramp Creek section, as sampled at Bloomington (Fig. 6, section 1) in the northern portion of the study area, consists of alternating units of peritidal and subtidal origin (Fig. 35 and Appendix A).

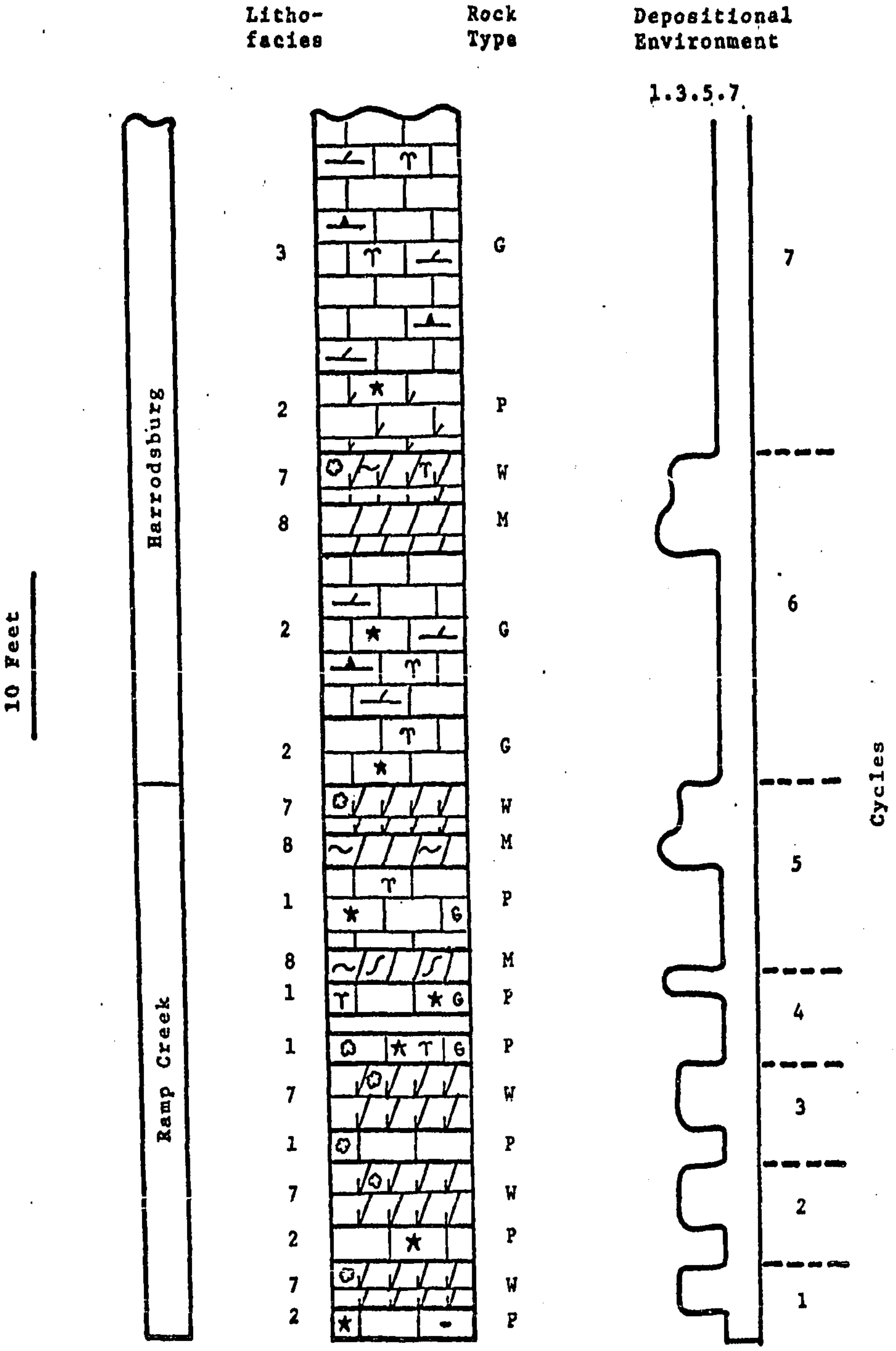
Five cycles are evident in the 34 feet of Ramp Creek present. Each cycle consists of a subtidal and a peritidal (intertidal-supratidal) component. The subtidal components are echinoderm or bryozoan-echinoderm packstones and grainstones (lithofacies 1 and 2). They are commonly glauconitic, somewhat cherty, and contain scattered calcite geodes.

The peritidal components are dolowackestones or dolostones (lithofacies 7 and 8) with a dolomite content which is consistantly over 80 percent. They are sparsely fossiliferous, highly bioturbated, contain disrupted, wavey algal lamination, and abundant geodes composed primarily of length-slow chalcedony which are interpreted to represent replaced sulfate nodules (Chowens and Elkins, 1974).

In the normal cycle, the subtidal unit grades from grainstone at the base to packstone at the top and fines slightly. It is then gradational into the overlying peritidal portion of the cycle which commonly grades from dolowackestone at the base to a thin dolomite at the top. The contact between the peritidal sediments and the overlying subtidal portion of the next cycle is generally sharp and erosional. In some cases, the lower portions of the subtidal units contain intraclasts of underlying peritidal sediment.

These cycles represent a general shoaling trend in the environment. Carbonate sedimentation exceeds subsidence and the units grade from subtidal shelf sediments into intertidal dolowackestones or supratidal

Fig. 35 - Lithologies, lithofacies, and depositional environments of section measured along Indiana Route 37, 1 mile north of Bloomington, Monroe County, Indiana (section 1, figure 6).



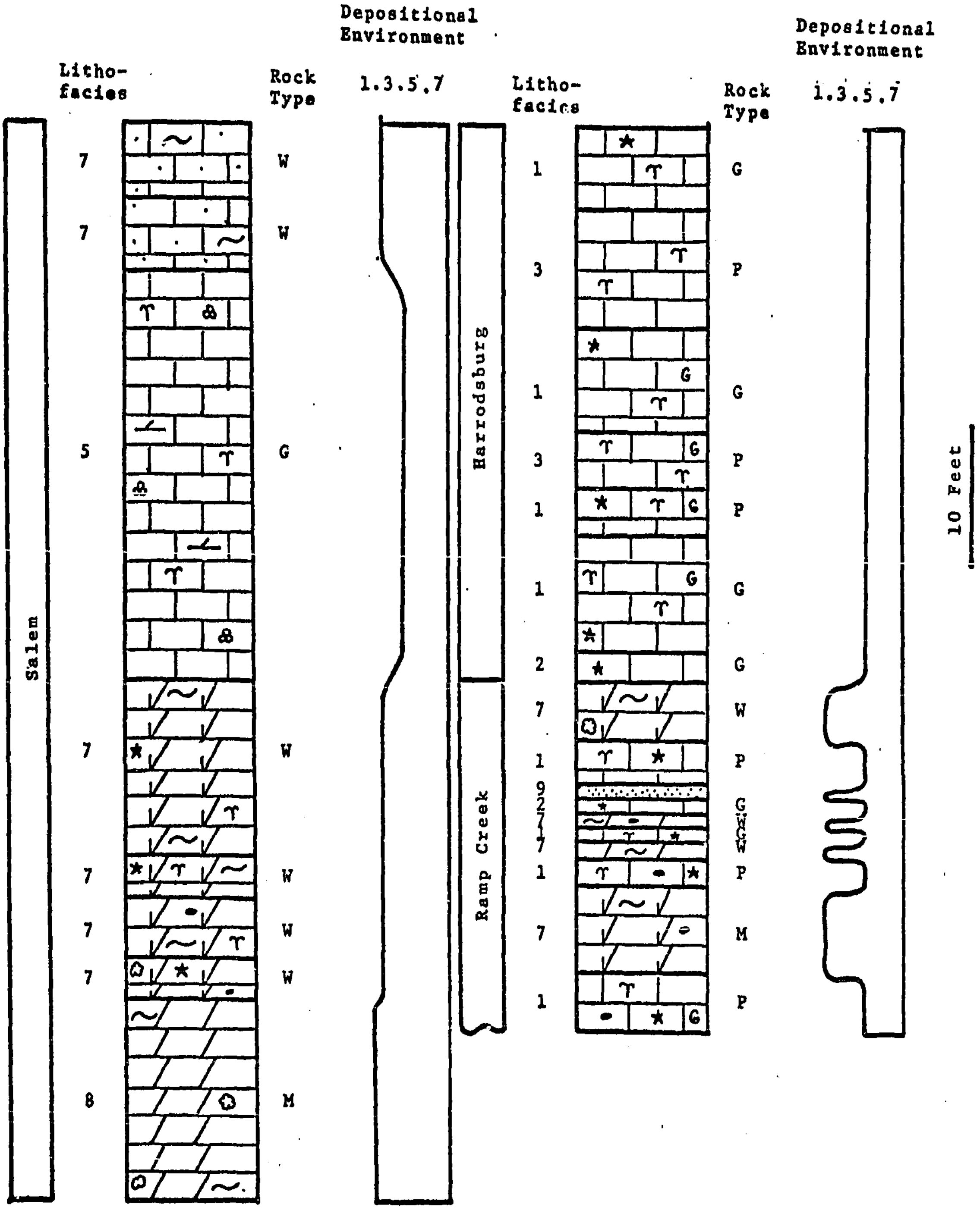
dolostones before the cycle is ended, presumably by a rise in relative sea level.

The similarity between the peritidal and subtidal sediments at this exposure and those found at other localities of the Ramp Creek of Indiana (Plate 1) suggests a fairly simple depositional system existed on the platform during this time. The complex depositional environments found on recent carbonate platforms (Purdy, 1962; Shinn and others, 1969; Logan and Cebulski, 1970) were absent and the platform was separated into a subtidal zone of bryozoan-crinoid meadows and an intertidal-supratidal zone characterized by deposits of dolomite and evaporites.

The frequent alternation of peritidal and subtidal sediments (the large number of cycles) indicates an instability in relative sea level during the period and suggests that deposition occurred very near mean sea level.

The shift from Ramp Creek to Harrodsburg deposition signified a change in the nature of carbonate sedimentation on the Indiana portion of the Borden platform. While Ramp Creek sedimentation showed a rapid alternation between peritidal and subtidal deposition, peritidal deposition dominated (Fig. 35). During Harrodsburg time subtidal sedimentation dominated. While cyclic sedimentation still occurred, the cycles were fewer, more irregular, and were weighted heavily toward the subtidal component. At Stewarts Landing in southern Indiana (Fig. 6, section 15), the entire Harrodsburg section is composed of subtidal lithologies (Fig. 36 and Appendix A). In the eight Harrodsburg sections sampled, there are no more than three cycles represented (Plate 2).

Fig. 36 - Lithologies, lithofacies, and depositional environments of section measured in roadcut and small quarry along Indiana Route 211, 1 mile west of Stewart's Landing, Harrison County, Indiana (section 15, figure 6).



The typical Harrodsburg section (Fig. 36) consists of bryozoan-echinoderm, echinoderm, or bryozoan grainstones and packstones of lithofacies 1, 2, or 3. The units are clean, well-sorted, and commonly cross-bedded, indicating deposition in a moderate to high energy environment. The uniformity of lithologies throughout the Indiana portion of the platform (Plate 2) indicates an extremely widespread depositional environment.

Subsidence of the underlying Borden clastics appears to be the most likely explanation for the predominance of subtidal sediments in the Harrodsburg. The few cycles present suggest that, either most of the deposition was occurring far enough below mean low tide that minor changes in relative sea level would have no effect, or that sea level was much more stable during Harrodsburg time than it had been during Ramp Creek deposition.

Salem deposition was initiated by a general regression throughout the Indiana portion of the study area, and, as a whole, the Salem represents deposition in a more shallow water environment than occurred during Harrodsburg deposition. The depositional system was also much more complex during Salem time that it had been previously.

The Salem Formation is represented at various localities by six different lithofacies representing peritidal, lagoonal, shoal, and subtidal shelf environments. The section is dominated by peritidal, lagoonal, and shoal deposits, with subtidal shelf deposits clearly secondary (Plate 2).

The cyclic nature of the sedimentation is greatly subdued and, in many cases, clear cut cycles are not apparent (Fig. 36). Since most of the sedimentation occurred in shallow water environments close to mean low tide, this lack of cyclicity implies a fairly stable environment.

Some large scale cyclicity is illustrated, however. Initial Salem deposition commonly occurred in a peritidal environment. This peritidal deposition is indicated by algal laminated, gypsiferous, geodiferous dolomites and dolowackestones. The thickness of this initial peritidal unit (Somerset Member) is highly variable, and in some places it is apparently not present.

Initial peritidal deposition is followed by a general transgression with deposition of lagoonal and shoal-type sediments of the dolowackestones, pelletal calcisphere, and foram calcarenite lithofacies. This is, in turn, followed by a second regression which culminated in the deposition of sabhka-type evaporites in the Lower St. Louis.

In the Indiana portion of the Borden Platform then, two megacycles, characterized by periods of sedimentation dominated by first peritidal and then subtidal deposition, are present. The first of these encompasses the peritidally dominated sedimentation of the Ramp Creek Formation combined with the subtidal deposition of the Harrodsburg. The second cycle combines the peritidal sedimentation of the Somerset Member of the Salem with the shallow subtidal portion of the remainder of the unit.

Eastern Kentucky Shelf

Post-Borden carbonate sedimentation on the Borden Platform in eastern Kentucky is markedly different from that observed in Indiana. Where cyclic sedimentation was well developed in the Indiana section, particularly in the lower portions, it is very poorly developed in eastern Kentucky, And, where the Indiana section showed two megacycles, the eastern Kentucky section is dominated by peritidal sediments throughout. Only southwest of Somerset, Kentucky do subtidal sediments comprise a significant portion of the section (Plate 3).

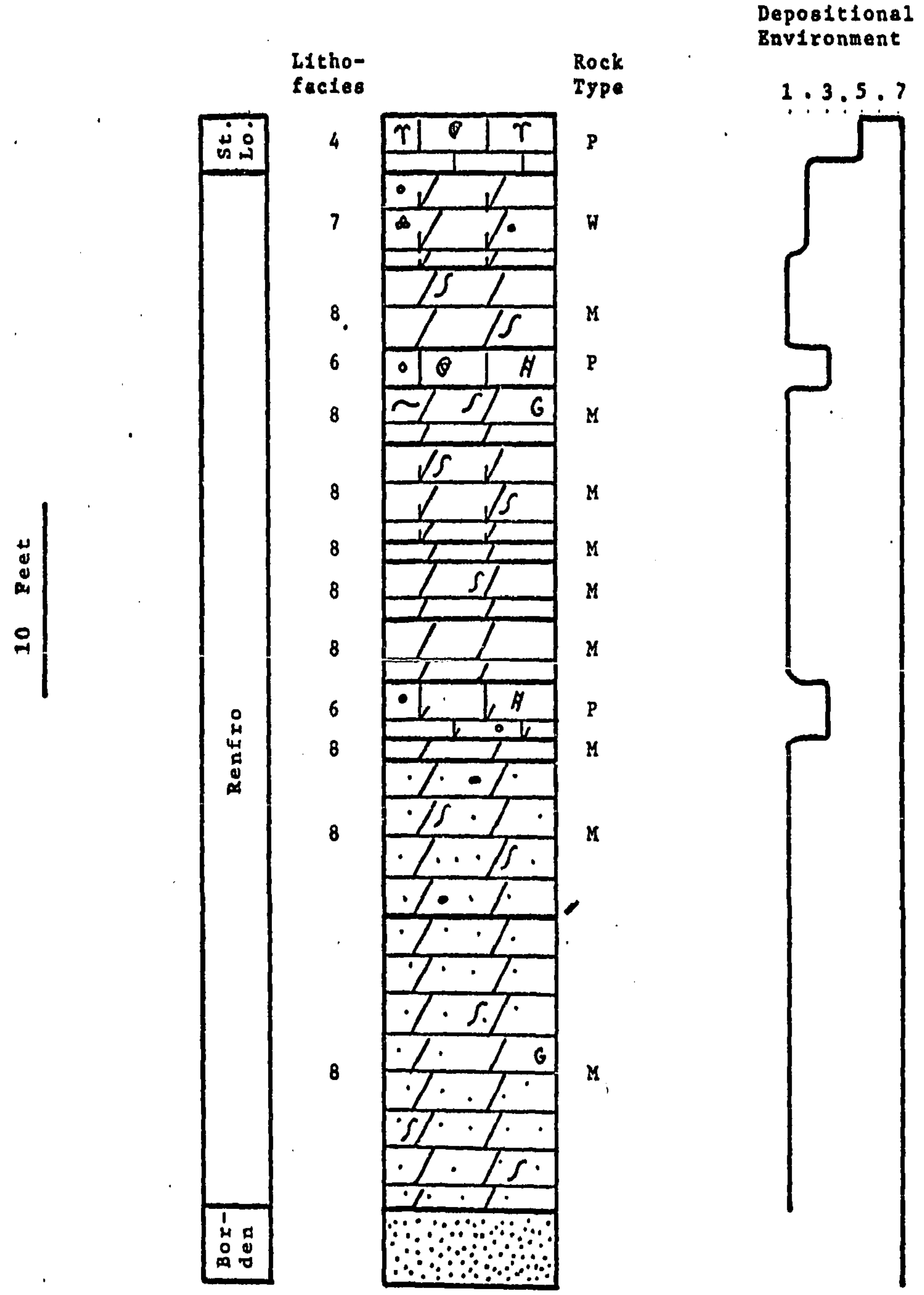
Peritidal deposition in eastern Kentucky as sampled at Big Hill (Fig. 6, section 64), is represented by rocks of the dolostone and dolowackestone lithofacies (Fig. 37 and Appendix A). These rocks are light brown to tan, sparsely fossiliferous, and occasionally cherty. They are commonly algal laminated, highly bioturbated and contain sparse "birds-eye" structures. The minor amount of subtidal deposition which occurred is represented by pelletal calcisphere packstones of lithofacies 6. Appreciable amounts of quartz sand and silt are present in the lower portions of the section.

The continuity of peritidal deposition displayed in the eastern Kentucky portion of the platform, along with the minor cyclicity, indicates an extremely stable depositional system.

Central Kentucky

Cyclic deposition is present in the Salem Formation of central Kentucky. The section at Summersville (Fig. 6, section 24), which ranges from the upper portion of the Fort Payne into the St. Louis, is representative of deposition during this period throughout central

Fig. 37 - Lithologies, lithofacies, and depositional environments of section measured in roadcut along Kentucky Route 421, 1 mile south of Big Hill, Madison County, Kentucky (section 64, figure 6).



Kentucky (Plates 4 and 5).

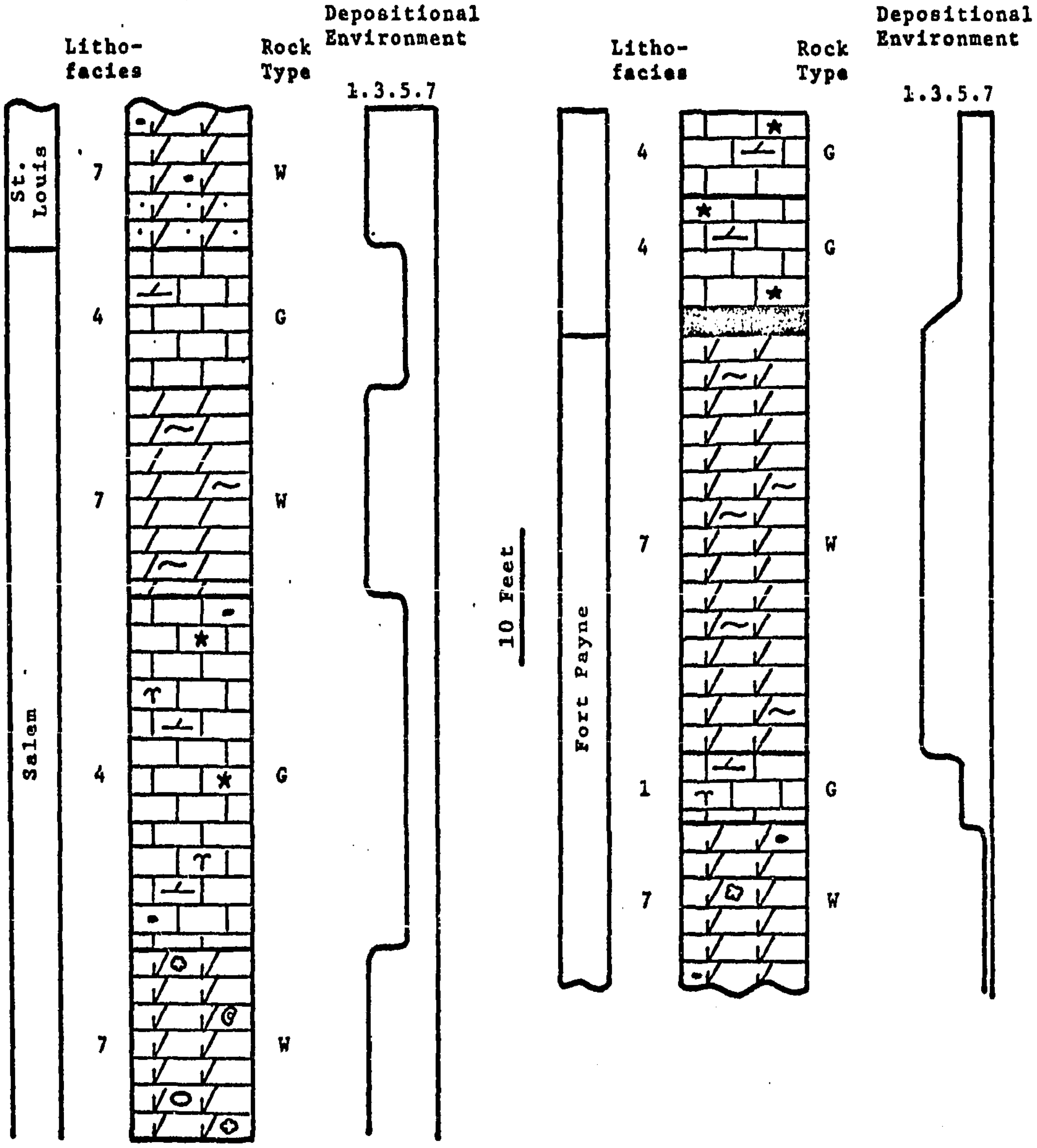
Four cycles are present in the 137 feet of section sampled (Fig. 38 and Appendix A) with each cycle consisting of a subtidal and a peritidal component.

The lower portion of the section sampled is composed of dark gray dolosiltstones of the basinal environment. These units are cherty, contain detrital dolomite, are highly argillaceous, and commonly show low angle, truncating bedding. They are typically poorly sorted and contain only minor skeletal material.

These basinal deposits are overlain by crossbedded grainstones of either the slope-edge or subtidal shelf environment, which are in turn overlain by thin peritidal deposits. These peritidal sediments are gray to gray-brown dolowackestones which contain scattered, disrupted, wavey algal lamination.

The remaining three cycles make up the remainder of the Salem and the lower portions of the St. Louis Formation. The subtidal portions of these cycles (Fig. 38) are represented by crossbedded diverse grainstones and packstones. The fauna of these units is diverse and oolites, pellets, intraclasts, and coated grains are common secondary constituents. The subtidal units normally grade upward from packstones to grainstones and fine upward. The upper portion of the Salem section throughout much of central Kentucky is characterized by extremely fine-grained grainstones represented here by the upper 10 feet of the Salem (Fig. 38).

Fig. 38 - Lithologies, lithofacies, and depositional environments of section measured in roadcut along Kentucky Route 61, just north of Pitman Creek bridge, Green County, Kentucky (section 24, figure 6).



The peritidal portions of the cycles are commonly represented by medium to dark gray-brown dolowackestones. These units are sparsely fossiliferous, bioturbated, contain common quartz geodes and abundant wavey algal lamination.

In general, these cycles are very similar to those of the Ramp Creek section of Indiana except that they occur on a much larger scale and the subtidal portion of the cycles predominates.

DEPOSITIONAL HISTORY

The previous section has given a description of the cyclic nature of post-Borden carbonate deposition at various locations within the study area. The examples used illustrate fairly well the fluctuating nature of carbonate deposition through time at a single location. Perhaps of more importance, however, is the determination of the spatial variation of environments at a single moment in time, and from this, formulation of the depositional history of the units under study.

A general discussion of the history of post-Borden platform deposition is given below. This discussion centers around sedimentation occurring on the platform, but some mention is made of corresponding slope or basinal deposition. The depositional history has been divided into four stages as revealed by the vertical sequence of lithologies in Indiana.

Stage 1

Initial carbonate sedimentation on the Borden platform is represented by the Ramp Creek Formation of Indiana and by the lower portions of the Renfro of eastern Kentucky. The areas are discussed separately, because erosion has removed most of the intervening platform deposits and correlation between the two areas is impossible.

Stage 1 sedimentation (Fig. 39) is characterized by the cyclic deposition of peritidal and subtidal carbonates in Indiana (Plate 1) and dominately peritidal deposition in eastern Kentucky (Plate 3).

This peritidally dominated platform sedimentation contributed large amounts of detrital dolomite and minor skeletal material to the basinal environment and southwesterly progradation of the platform

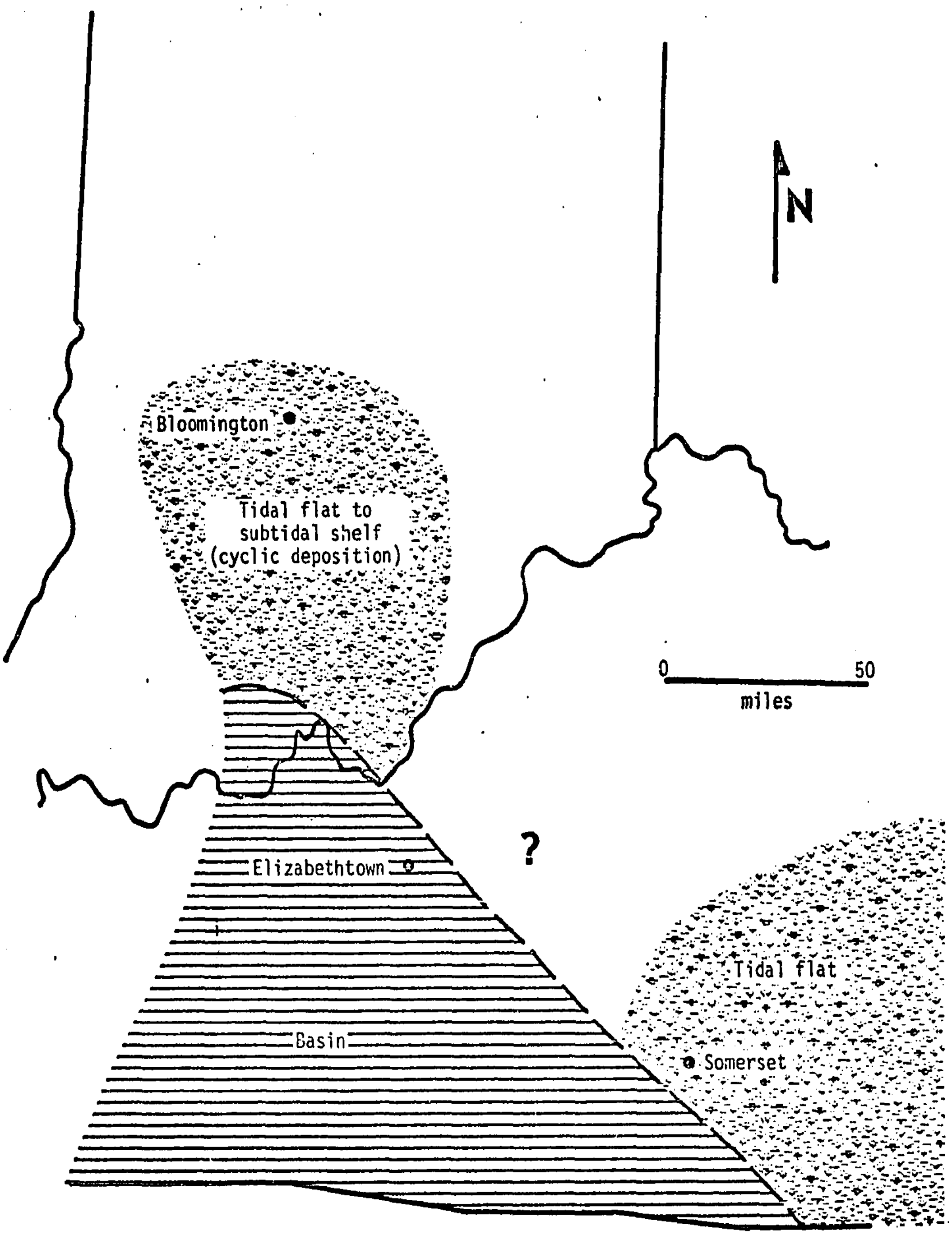


Fig. 39 - Paleoenvironmental map of post-Borden Stage 1 carbonate deposition

margin began.

The introduction of appreciable clastic material into the depositional system, either from a northeasterly or easterly upland source, or by reworking or previously deposited Borden clastics, led to formation of the Knifley Sandstone as a shallow water, barrier shoal along the platform margin (Sedimentation Seminar, 1972).

Stage 2

Stage 2, represented by the Harrodsburg Formation in Indiana and a portion of the Renfro Formation in eastern Kentucky, was initiated by pronounced subsidence on the western portion of the Borden platform, possibly related to compaction of the underlying Borden clastics. This subsidence was restricted to the Indiana portion of the platform where deposition shifted from dominately peritidal to dominately subtidal (Plate 2). The eastern Kentucky portion of the platform was apparently more stable, as peritidal deposition continued (Fig. 40).

On the Indiana portions of the platform, abundant bryozoan and echinoderm skeletal material was accumulating and being carried to the platform margin by tidal currents. This material accumulated along the slope break as carbonate banks such as the Cane Valley Limestone (Sedimentation Seminar, 1972). Some sediment was carried down the slope by sediment gravity flows and accumulated at the base of the slope in deposits such as the Beaver Creek Limestone (Klein, 1974).

Cyclic sedimentation, though not as pronounced as before, was still occurring on the Indiana portions of the platform (Plate 2), and during periods of peritidal depostion, dolomite was formed and carried into the basin by tidal currents. Dolomite was also being introduced into the

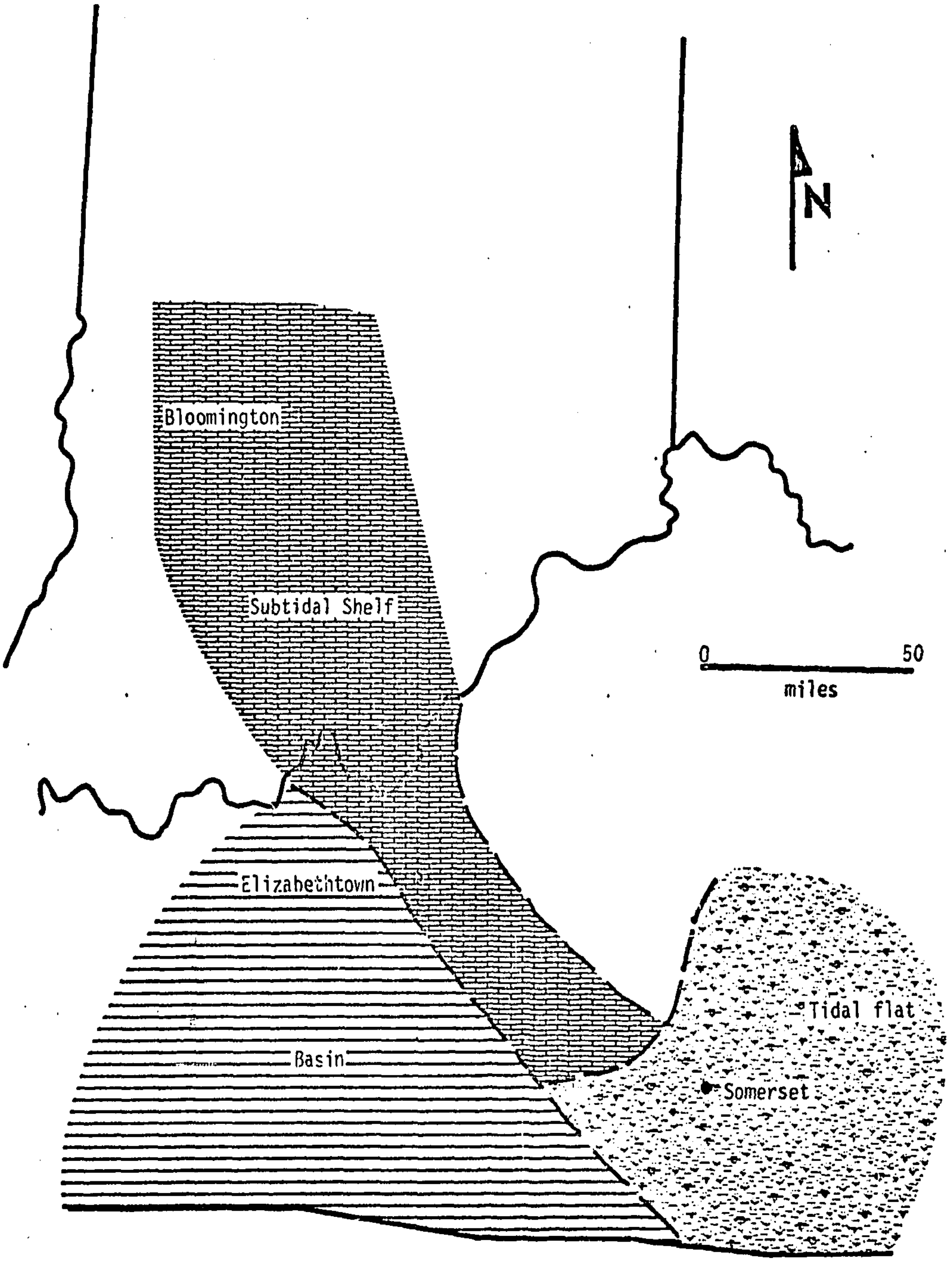


Fig. 40 - Paleoenvironmental map of post-Borden Stage 2 carbonate deposition

basin from the eastern Kentucky platform where peritidal deposition was dominant.

During this period, progradation of the platform margin was enlarging the platform, and subtidal shelf sediments were being deposited over slope-edge and basinal deposits. The platform margin had advanced at least 15 miles since carbonate deposition began, as witnessed by the position of the Cane Valley Limestones (slope-edge deposits) some 15 miles southwest of the Borden front.

Stage 3

A pronounced drop in sea level initiated stage 3 of the depositional history. Stage 3 is characterized by peritidal deposition over much of the platform (Fig. 41). This peritidal deposition, represented by the Somerset Member of the Salem Formation and by the Renfro in eastern Kentucky, produced large quantities of dolomite which was carried to the platform edge and deposited basinward.

There was also a major clastic influx from the northeast or east associated with Stage 3 peritidal deposition on the eastern Kentucky portion of the platform. This clastic influx is represented by the Science Hill Sandstone Member of the Salem and by the high terrigenous content of the associated portions of the Renfro.

Stage 4

Stage 4 is represented by deposition of the Salem Formation in Indiana and central Kentucky and the upper portions of the Renfro Formation in eastern Kentucky. Stage 4 began with general subsidence throughout much of the study area and a general shift from peritidal to shallow subtidal deposition. Peritidal deposition continued in the

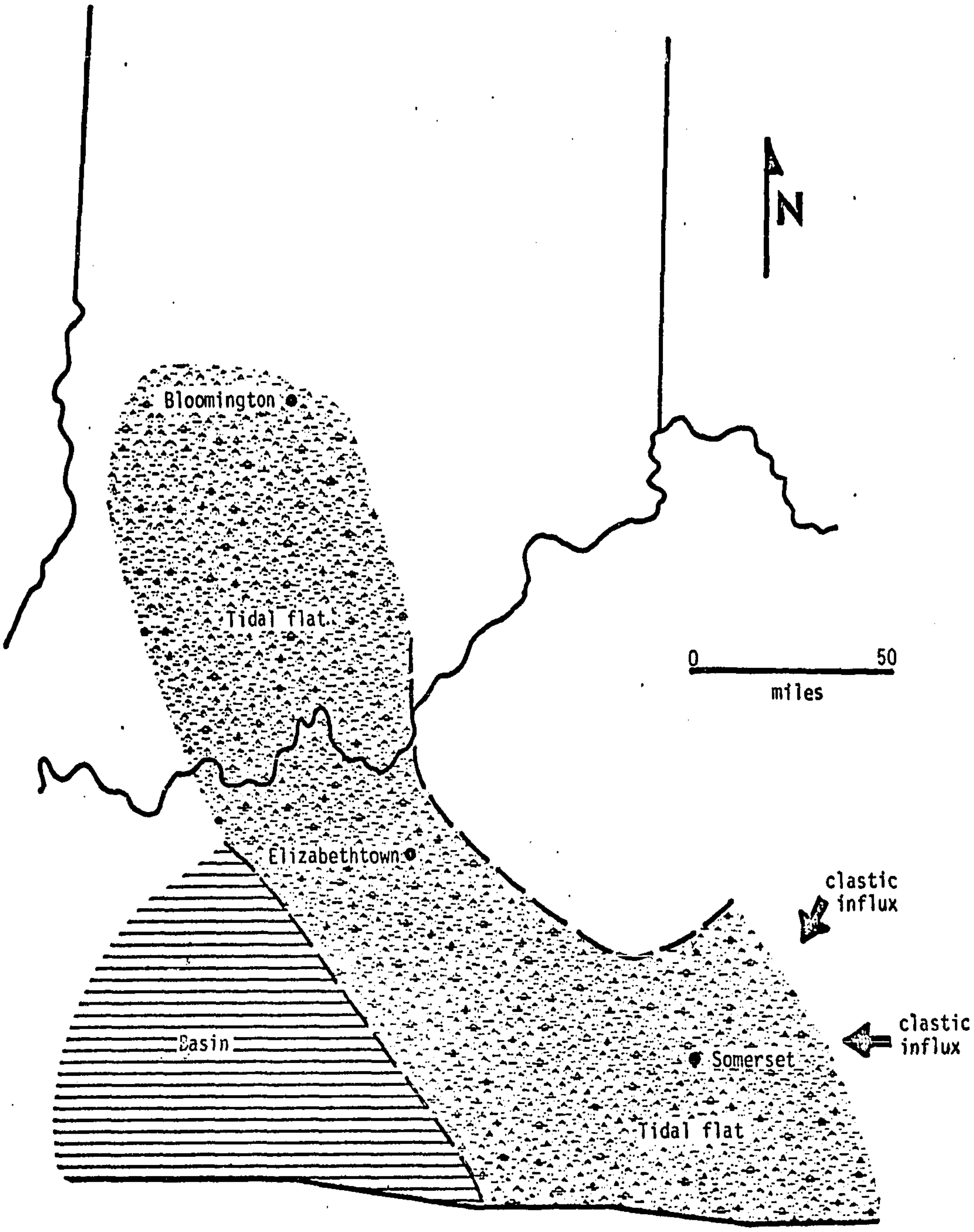


Fig. 41 - Paleoenvironmental map of post-Borden Stage 3 carbonate deposition

eastern portions of the platform, but the majority of the platform was the site of shallow subtidal deposition (Fig. 42). Clastic material was again entering the platform from the northeast or east as witnessed by the heavy clastic content of the upper portions of the Salem in eastern Kentucky (Fig. 42).

In the Indiana portions of the platform, the Salem shows a general shallowing upward trend, with the formation of linear, tidally influenced shoals, deposition occurred in shallow, low energy, restricted lagoons. This shoaling continued into the St. Louis, where dolomites and evaporities were deposited in a sabkha type environment. There is evidence to suggest that shallow subtidal sediments in the upper portions of the Salem may be the lateral equivalents of sabkha deposits in the lower St. Louis (Lineback, 1972).

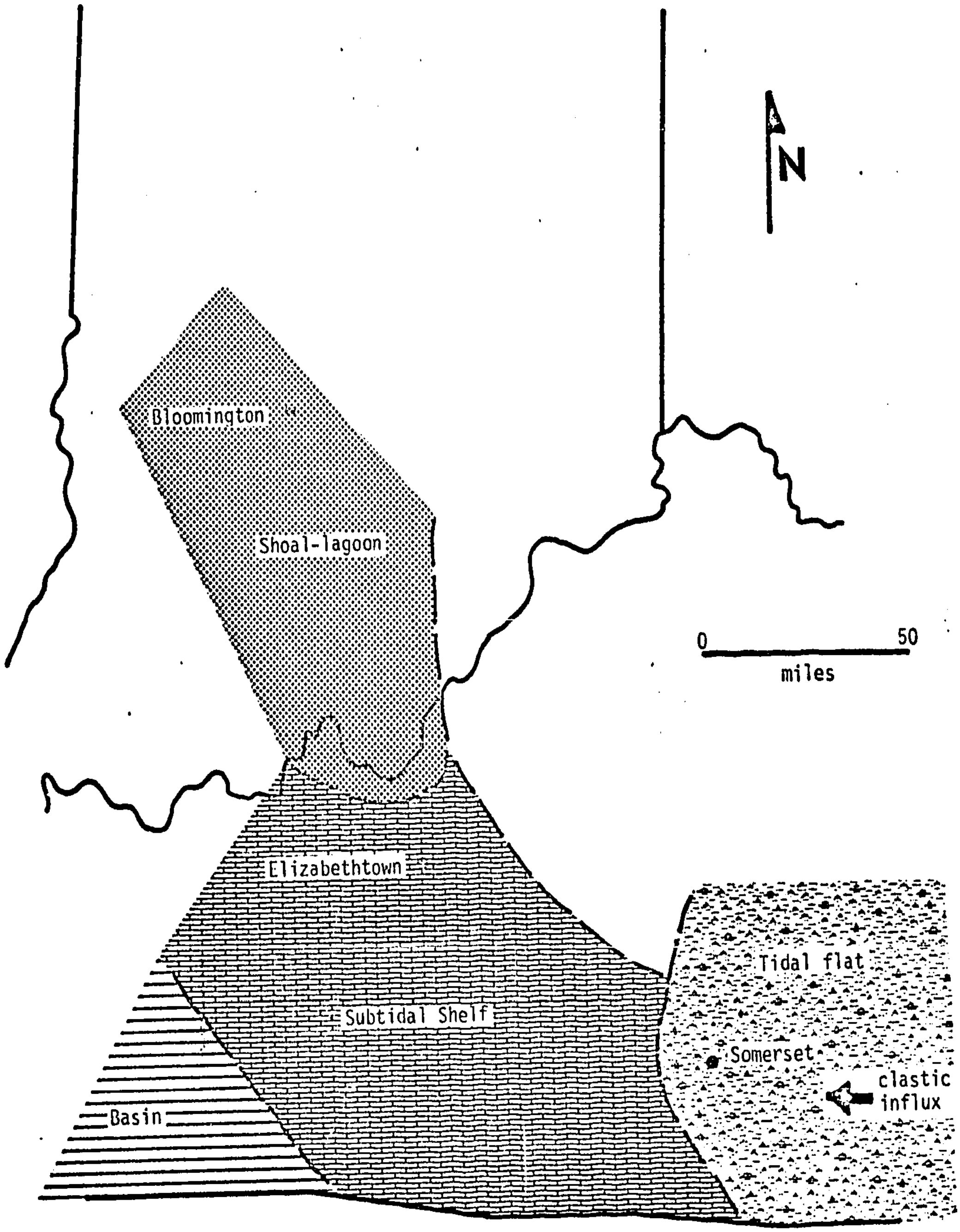


Fig. 42 - Paleoenvironmental map of post-Borden Stage 4 carbonate deposition

DIAGENESIS

Diagenesis is an inclusive term used to describe all the chemical, physical, and biologic changes, modifications, or transformations undergone by a sediment after its deposition, and during and after its lithification exclusive of surficial alteration (weathering) and metamorphism.

The term encompasses many, more specific individual processes, five of which are well illustrated in the rocks under study. These are: (1) cementation, (2) neomorphism, (3) pressure-solution, (4) dolomitization, and (5) silicification.

While a detailed explanation of the diagenetic alterations of the Osagian-Meramecian carbonates is a study in itself, a complete petrographic description of the units requires at least a cursory description of the processes and their products as represented in the units under study. Toward this end, a brief description of the effects of the five previously mentioned processes on the units under study is given below with each of the processes considered separately.

Cementation

Cement is the term given to chemically precipitated mineral material that occurs in the spaces among the individual grains of a consolidated sedimentary rock, thereby binding the grains together as a rigid, coherent mass. In carbonate rocks it is taken to include all passively precipitated space-filling carbonate crystals which grow attached to a free surface (Bathurst, 1971, p. 416). As such it is equivalent to the "precipitated calcite" of Folk (1965, p. 26).

One of the inherant problems in a description of carbonate cements is the accurate identification of the cement itself. Not all the interparticulate sparry calcite in a limestone is cement, some may be neomorphic in origin. Thus, one of the first acts in a description of carbonate rocks is to distinguish between cements and neomorphic sparry calcite. Toward this end, Bathurst (1971, p. 417-419) has presented a set of fabric criteria characteristic of calcite cements (Table 8). While very few of these criteria are unequivocal evidence of the presence of cement, combined they give a strong inference concerning the origin of sparry calcite in limestones.

Examination of over 400 thin sections of the rocks under study has shown that, based on the characteristics given in Table 8, most of the sparry calcite present was precipitated as pore-filling cement. While it is not the intent of this study to delve intimately into the cementation history of these rocks, some generalized conclusions can be made based on thin-section petrography and limited application of cathode luminescence.

There are three morphologically separate types of cement present in the units under study: (1) a fine-grained prismatic or "dog-tooth" spar which occurs as a first generation cement on polycrystalline skeletal grains (Fig. 43), (2) a coarser, granular cement (Fig. 44), and (3) a coarse syntaxial rim cement overgrowing echinoderm grains.

The syntaxial rim cements are volumetrically the most common, particularly in those rocks rich in echinoderm grains. Growth of these cements is apparently more rapid or preferential to growth of the other

Table 8 - Criteria characteristic of cement in limestones (after Bathurst, 1971, p. 417-419)

(1) Occurrence of interstitial spar with well-sorted and abraded particles which are in depositional contact with each other

(2) Presence of two or more generations of spar

(3) Absence of relict structures common in neomorphic spar

(4) Presence of unaltered micritic particles (i.e. pellets)

(5) Unaltered micritic coatings on grains

(6) Presence of unaltered mechanically deposited micrite

(7) Sharp contacts between spar and particles

(8) Coincidence of the margin of sparry mosaics with surfaces that were once free

(9) Spar lining an incompletely filled cavity

(10) Spar occupying the upper portions of a cavity floored by more or less flat-topped internal (geopetal) sediment

(11) Sparry mosaic with a form expected of a pore-filling

(12) Presence of planar intercrystalline boundries

(13) A general increase in crystal size away from the boundries of the initial substrate

(14) A preferred optic axis orientation normal to the initial substrate of the crystals of the sparry mosaic

(15) A preferred shape orientation with longest axises normal to the initial substrate for the crystals of the sparry mosaic

(16) A high percentage (30-73%) of enfacial junctions among the triple junctions of the mosaics

(17) Absence of fabrics characteristic of neomorphic spar

Figure 43 - Prismatic cement (a) as first generation cement on skeletal grains (Sample 18-11; bar scale .1 mm)

Figure 44 - Granular cement (a) filling ostracod shell; note early stage prismatic cement (Sample 40-4; bar scale .5 mm)

Figure 43

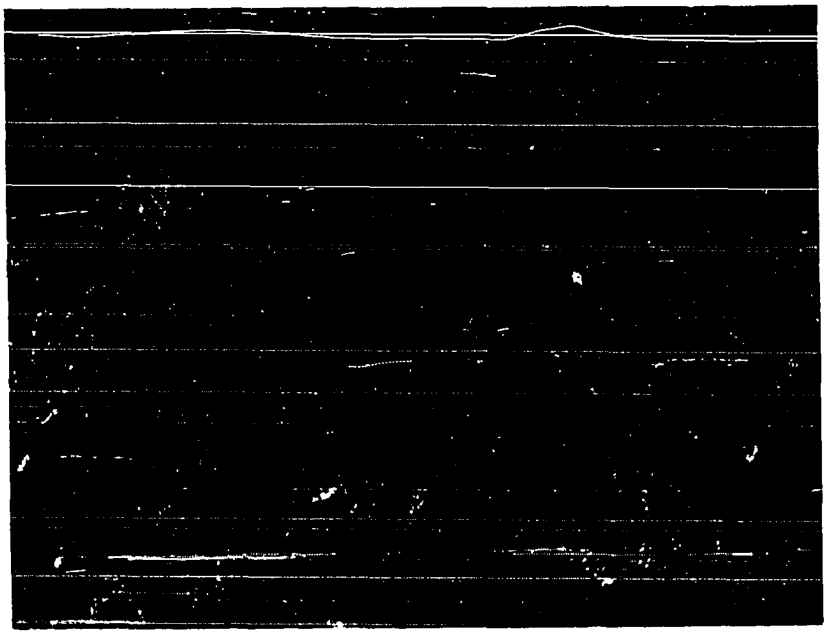


Figure 44

types since syntaxial rim cements commonly engulf other skeletal grains.

Granular cements occur in portions of the rock that were protected from invasion by syntaxial rim cement such as inside bryozoan zooecia, brachiopod shells and so forth.

The fine-grained prismatic or "dog-tooth" spar occurs as a first generation cement on polycrystalline skeletal grains, particularly brachiopods. It predates precipitation of syntaxial rim cements and compaction. Figure 45 (enchanced by cathode luminescence) shows a fractured molluscan grain. Prismatic cement is present everywhere on the grain except on the fractured surface, indicating the precipitation of the prismatic cement occurred before compaction and fracturing. Morphologically this prismatic cement is very similar to recent submarine cements (MacIntyre, Mountjoy, and d'Anglejan, 1971).

Staining of these rocks with potassium ferrocyanide shows the syntaxial rims contain two compositional zones, an early zone of nonferroan calcite followed by a zone of ferroan calcite. The proportions of these two zones varies greatly from rock to rock. In some samples most of the cement is nonferroan calcite with only minor amounts of ferroan calcite present (Fig. 46). In others, the nonferroan zone is relatively small and most of the cement is ferroan calcite (Fig. 47).

Application of cathode luminescence techniques shows the cementation history is actually more complex than it appears, even with staining. The nonferroan cements contain several subzones (Fig. 48) due to variations in the amount of Mn++ in the calcite lattice (Sippel and Glover, 1965). Zones containing appreciable amounts of Mn++ luminescence

Figure 45 - Sketch made from cathode luminescence enhanced thin-section showing fractured molluscan grain with prismatic cement absent on fractured surface; indicated compaction and fracturing post-dates prismatic cement (Sample 32-1; bar scale .1 mm)

Figure 46 - Zoned syntaxial rim cement showing dominant early nonferroan zone (a) and secondary ferroan zone (b) (Sample 43-7; bar scale .5 mm)

Figure 47 - Zoned syntaxial rim cement with ferroan cement (b) dominant and early nonferroan cement (a) secondary (Sample 35-2; bar scale .5 mm)

Figure 48 - Cathode luminescence enhanced thin-section showing zoned syntaxial rim cement on echinoderm grain (a) (Sample 2-5 ; bar scale .5 mm)

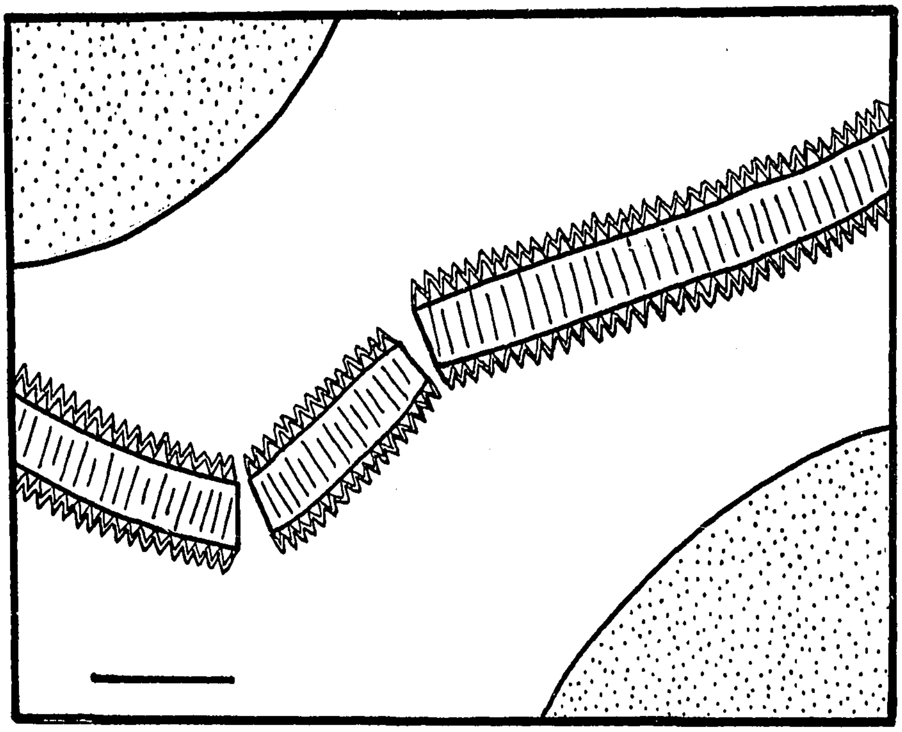


Figure 45

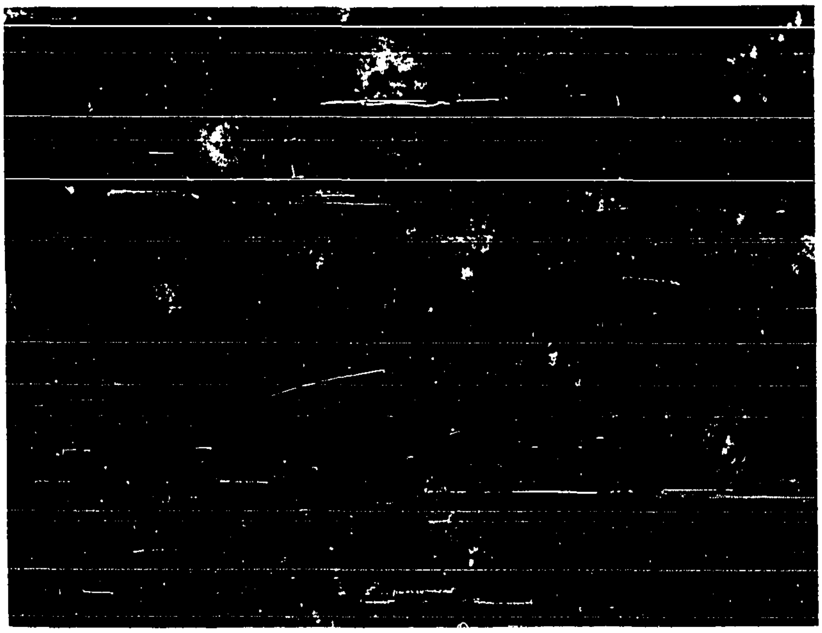


Figure 46

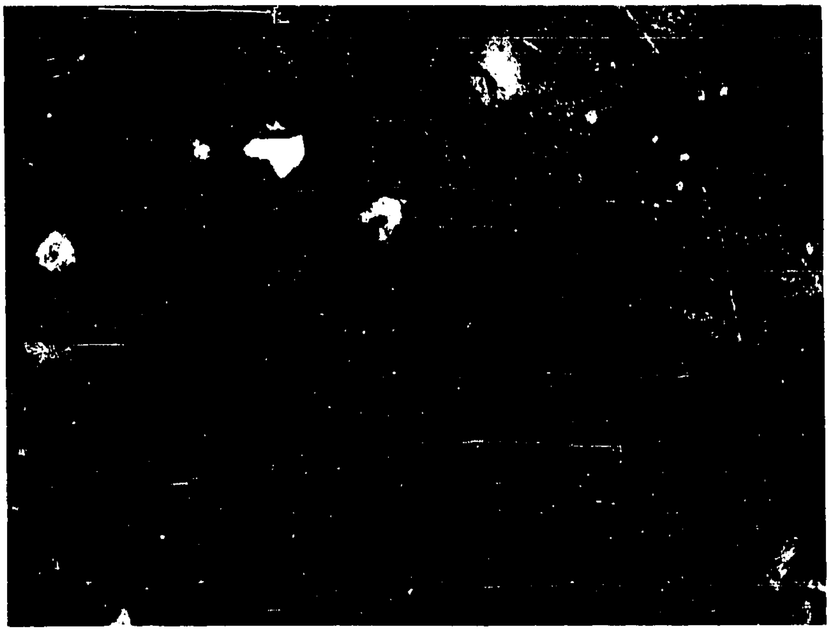


Figure 47

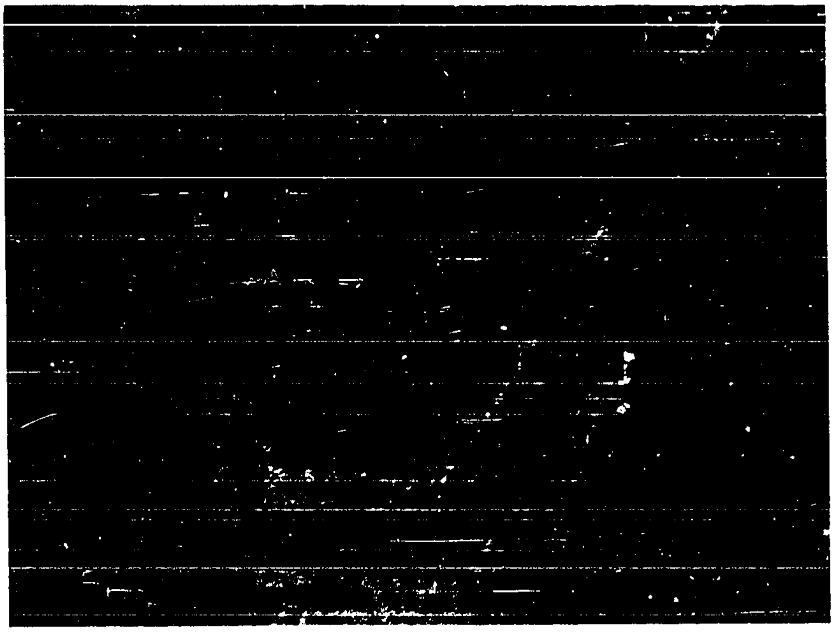


Figure 48

orange (Meyers, 1974, p. 841). The few samples studied show anywhere from 2 to 4 zones present within the nonferroan cement. This is similar to zoning found in the Mississippian Lake Valley Formation of New Mexico (Meyers, 1974).

This common zonation found in the sparry cements is a direct reflection of chemical changes of the pore fluids (Bathurst, 1971, p. 433-434). This change might be the result of variations in the cementation environment (i.e. vadose vs. phreatic), changes in the solution chemistry (i.e. ionic content), or changes in the microenvironment of precipitation (i.e. changes in Eh and pH).

Based on analysis of selected quaternary vadose and marine cements, Meyers (1974, p. 855-858) has found that these normally do not contain high enough Mn++ levels to cause luminescence, while phreatic cements do contain luminescing zones. A marine origin for luminescing and ferroan cements is also rejected because of the inadequate concentrations of Mn++ and Fe++ in normal marine waters (Meyers, 1974, p. 859).

Based on these criteria, the majority of the cement in the units under study appears to be phreatic in origin. Evidence for this is the common luninescing zones found in nonferroan cements and the abundant ferroan cement present. A possible exception to this theory of phreatic origin is the prismatic cement found on some of the polycrystalline grains. This cement is always nonferroan calcite and commonly nonluminescent, suggesting it may represent marine cement.

Neomorphism

The term neomorphism was proposed by Folk (1965, p. 20-21) to include "all transformations between one mineral and itself or a polymorph ..... whether the new crystals are larger or smaller or simply differ in shape from the previous ones. It does not include simple pore-space filling; older crystals must have gradually been consumed, and their place simultaneously occupied by new crystals of the same mineral or a polymorph." The process of neomorphism normally begins in partly consolidated sediment and may occur throughout the diagenetic history (Bathurst, 1971).

Folk (1965) proposed three basic types of neomorphism which have been redescribed by Bathurst (1971, p. 475-476) as polymorphic transformations (Folk's "inversion"), recrystallization, and aggrading neomorphism.

Folk (1965) defined four separate processes of polymorphic transformation (or inversion) but of the four only one, the wet, in situ transformation of aragonite to calcite, is common in carbonate diagenesis (Bathurst, 1971, p. 475).

Recrystallization, in which the mineralogy remains unchanged during the reaction, is also subdivided into three separate processes. Again, however, these processes are, for the most part, unknown in carbonate diagenesis, being restricted to the metamorphic realm. The only exception is wet recrystallization which may occur during the late stages of aggrading neomorphism.

Probably the most important neomorphic process in carbonate rocks is aggrading neomorphism (Folk, 1965, p. 23). This is the process through which finer crystal mosaics are replaced by coarser crystal mosaics of the same mineral or its polymorph without the intermediate formation of visible porosity. The term is commonly used, but not restricted to, the alteration of micrite or micron-sized skeletal fabrics to sparry calcite.

The actual process of neomorphic aggradation is something of an enigma to geologists. Folk (1965, p. 21) excludes passive dissolution and precipitation as contributing factors, while Bathurst (1971, p. 481-482) includes the wet transformation of aragonite to calcite and passive dissolution-precipitation. About the only definitive statement which can be made about the process is that it results in the formation of coarser sparry calcite from finer-grained initial constituents.

The sparry calcite formed through aggrading neomorphism is, in many cases, very similar to sparry calcite cement. Thus, we are again faced with the problem of distinguishing between sparry cement and neomorphic spar. Just as Table 8 lists criteria diagnostic of sparry cement, there are certain fabrics characteristic of neomorphic spar. A listing of these, taken from Bathurst (1971, p. 484-490) is given in Table 9.

Neomorphism apparently had only a very minor affect on the rocks under study. Most of the sparry calcite present has features characteristic of pore-filling cement.

Table 9 - Criteria characteristic of neomorphic spar in limestones (after Bathurst, 1971, p. 484-490)

(1) Common crystal diameters from 50-100 microns and ranging upwards from 4 microns

(2) A generally abrupt contact between unaltered, micron-sized material and secondary spar

(3) An irregular and patchy variation in crystal size

(4) A radial-fibrous arrangement of crystal shapes

(5) Intercrystalline boundries are generally curved to wavey rather than planar

(6) Large crystals at the margins of sparry masses embay adjacent detrital micrite

(7) Relics of micron-sized material (patches of micrite, skeletal walls, peloids, etc.) are entirely surrounded by spar

(8) Transection of replacement of initially aragonitic or high-magnesium calcite skeletal structures by sparry calcite

(9) Presence of neomorphic aragonite in aragonitic skeletons

(10) Relatively few (less than 5%) enfacial junctions amount the triple junctions of the mosaic

(11) Presence of overgrowths on cement crystals

(12) An apparent well-ordered replacement pattern of certain fabrics

Two neomorphic processes are represented, however. The first of these is the wet, in situ, polymorphic transformation of aragonite to calcite (Folk's "inversion"). This is illustrated in the rocks under study by the transformation of aragonitic skeletal grains (Primarily gastropods, pelecypods, and algae) to pseudospar (Fig. 49). That this is an in situ transformation, rather than solution-precipitation is witnessed by the unaltered and unbroken micritic rims, and the nature of the sparry calcite.

Some aggrading neomorphism is also apparent, with the formation of microspar and pseudospar from original fine-grained calcitic muds (Fig. 50). The neomorphic origin of this microspar or pseudospar is evidenced by the relatively fine crystal size; the irregular, patchy variation in crystal size; the relics of micron-size material, particularly pellets; and the general gradual transition in crystal size from fine-grained carbonate muds, through microspar to pseudospar.

The products of aggrading neomorphism are only minor constituents of the rocks under study. They do, however, appear to be more apparent in the Salem Formation than in other portions of the section.

Pressure-Solution

The effects of pressure solution are well illustrated in the Osagian-Meremecian rocks of the study area on both a micro scale (grain-to-grain) and a macro scale (styolitization).

Grain-to-grain pressure solution occurs when unconsolidated sediments are present in grain-to-grain contact and immersed in a saturated solution. Increased pressure at the points of contact

Figure 49 - Neomorphically altered gastropod shell; note micritic filling of chamber and micritic coating of grains (Sample 40-4; bar scale .5 mm)

Figure 50 - Aggrading neomorphism of matrix micrite (a) to microspar (b) and pseudospar (c); bioclasts dominantly bryozoans (Sample 14-5b; bar scale .5 mm)

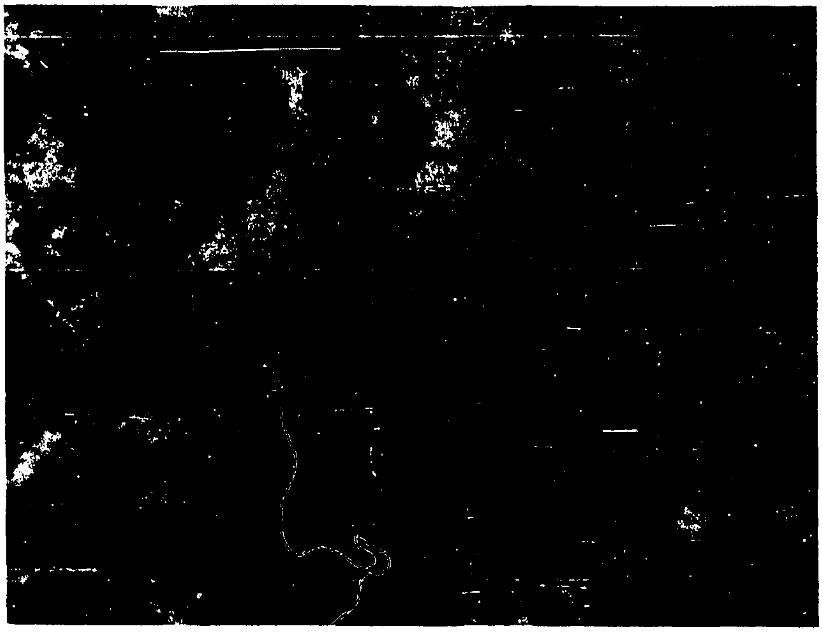


Figure 49

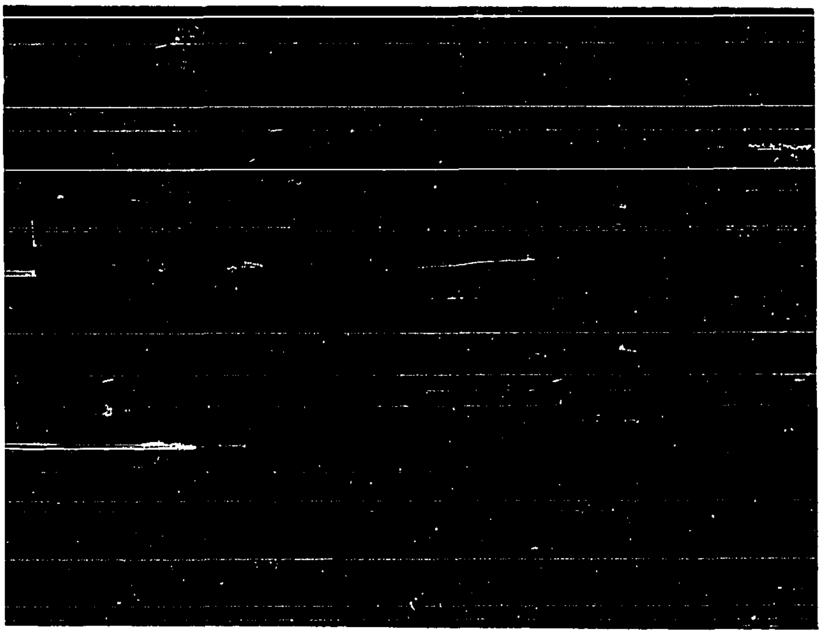


Figure 50

between grains causes an increase in solubility and solution occurs. Away from the contact points the solubility product is lower, the influx of ions from solution at the contact points causes local supersaturation and precipitation of $CaCO_3$ may occur on these unstrained surfaces.

The most common grain-to-grain pressure solution observed in the units under study involves two echinoderm grains (Fig. 51). Thus, the process is most apparent in units rich in echinoderm skeletal material, particularly lithofacies 2. The process is normally characterized by the embaying of one echinoderm grain into another, with the contact between the two being a smooth gently curved surface. In some cases, however, microstyolites form along the contact (Fig. 51). If compaction was great enough or there were few echinoderm grains present, other skeletal grains become involved (Fig. 52).

Grain-to-grain pressure solution between echinoderm and quartz grains also occurs in some of the rocks (Fig. 53). In this situation, the echinoderm grain is always embayed and the contact between the two is linear rather than styolitic.

Chronologically, grain-to-grain pressure solution must occur before major cementation, since this would prevent relative movement between grains. It may, however, follow precipitation of first generation cements (Bathurst, 1971, p. 465).

Pressure solution on a macro scale is illustrated by the pressure of styolites. Styolites are similar to grain-to-grain pressure solution, differing only in scale. Styolites transect the whole rock rather than individual grains. They also occur after cementation.

Figure 51 - Grain to grain pressure solution between echinoderm grains; note suturing at contact (Sample 19-6; bar scale .1 mm)

Figure 52 - Grain to grain pressure solution between echinoderm (a) and brachiopod (b); some suturing at contact (Sample 60-1; bar scale .1 mm)

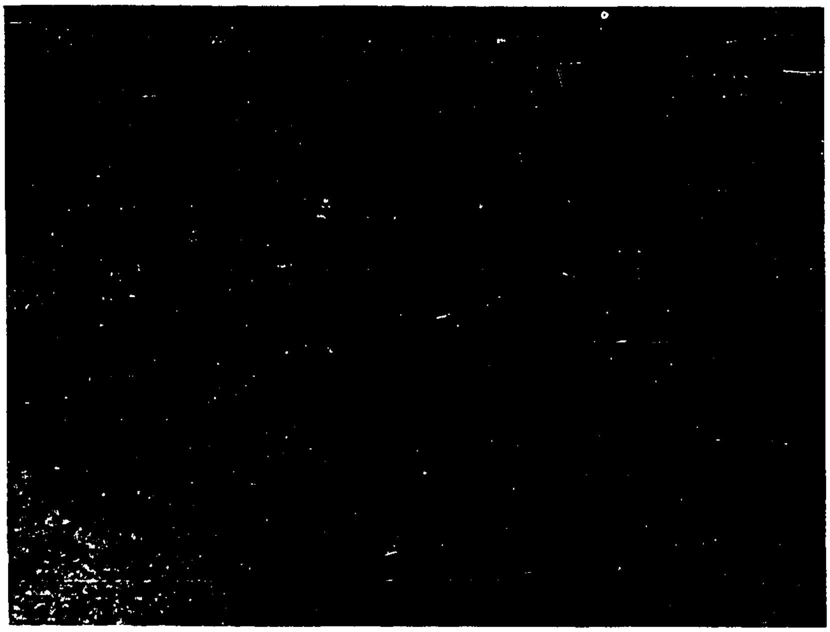


Figure 51

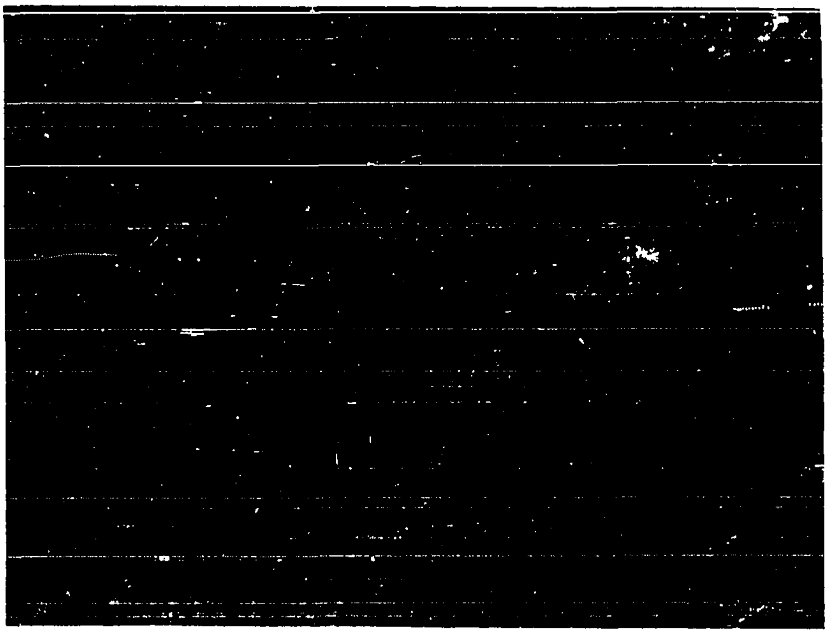


Figure 52

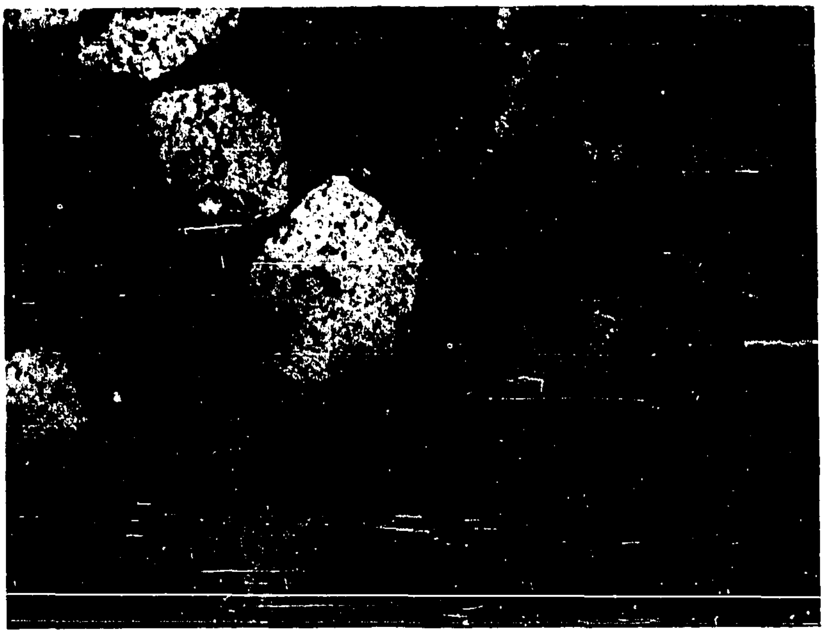


Figure 53 - Grain to grain pressure solution between quartz grain (a) and echinoderm fragment (b); note solution of echinoderm and embayed nature of contact (Sample 57-12; bar scale .5 mm)

Styolites form by pressure induced solution along a surface which crosses grains, matrix, and in some cases lamination. The orientation of the initial surface is determined by the orientation of stress axis, and since this stress normally comes from overburden, styolites generally parallel bedding. The common interdigitation form of styolites is caused by lateral variation along the interface of solubility differences across the interface (Bathurst, 1971, p. 469).

Large scale pressure solution, as witnessed by the formation of styolites, was an active process in the units under study. Styolites are present throughout the section. They are, however, restricted to the grainstone and packstone lithologies.

The styolites are oriented parallel to bedding and have an amplitude of generally less than .3 meters.

Silicification

Cryptocrystalline silica, more commonly termed chert, is a common constituent in all of the formations under study. This chert occurs as discrete nodules within limestones and dolomites and as microscopic surface encrustations on skeletal grains. All the chert observed in the units sampled appears to be of replacement origin. Bedded cherts, interpreted to be of primary origin, are present in the Fort Payne Formation south of the study area (Marcher, 1962).

Petrographically the chert occurs as either cryptocrystalline or chalcedonic silica. The chalcedonic silica is present as irregularly shaped spherulites which occur singly or in groups (Fig. 54). The chert nodules are composed entirely of the cryptocrystalline silica, while the surface encrustations on skeletal grains may be either cryptocrystalline or chalcedonic silica.

The replacement nature of the silicification is well illustrated in the chert nodules. These nodules show clear-cut ghosts of replaced carbonate skeletal material (Fig. 55). They also contain discrete unreplaced dolomite rhombs (Fig. 56), both ferroan and nonferroan. This indicates that dolomitization preceeded silicification, and that the silica preferentially replaced calcite rather than dolomite.

The silicification also shows a preference for replacement of echinoderm skeletal grains. Siliceous surface encrustations (Fig. 57) are most common on echinoderms, occurring less frequently on brachiopods and bryozoans. These encrustations may replace only a small portion of a skeletal grain, or the replacement may envelope the entire grain and portions of the adjoining cement.

Dolomitization

Dolomitization of the post-Borden carbonates occurred in several stages during the diagenetic history of the rocks under study. Both the processes involved and their products have been described earlier in the text. A summary of the dolomitization is given below.

(1). Penecontemporaneous dolomitization occurred in the supratidal environment (Type A dolomite).

(2). Intertidal and subtidal sediment was dolomitized by hypersaline brines refluxing from the supratidal environment (Type B dolomite).

(3). Secondary dolomitization occurred after cementation, causing recrystallization of previously formed dolomites (Type C dolomite) and deposition of sparry, ferroan dolomite (Type D dolomite) in pores and along fractures.

Figure 54 - Spherulitic chalcedony replacing brachiopod fragment; note radiaxial crosses; crossed nicols (Sample 20-11; bar scale .5 mm)

Figure 55 - Ghosts of bioclastic material replaced by chalcedony; note nonreplaced dolomite matrix; crossed nicols (Sample 19-11; bar scale .5 mm)

Figure 56 - Mixture of ferroan and nonferroan dolomite rhombs included in replacement chert; indicates dolomitization predated silicification (Sample 19-9; bar scale .1 mm)

Figure 57 - Chalcedonic surface encrustation on echinoderm grain; crossed nicols (Sample 16-15; bar scale .5 mm)

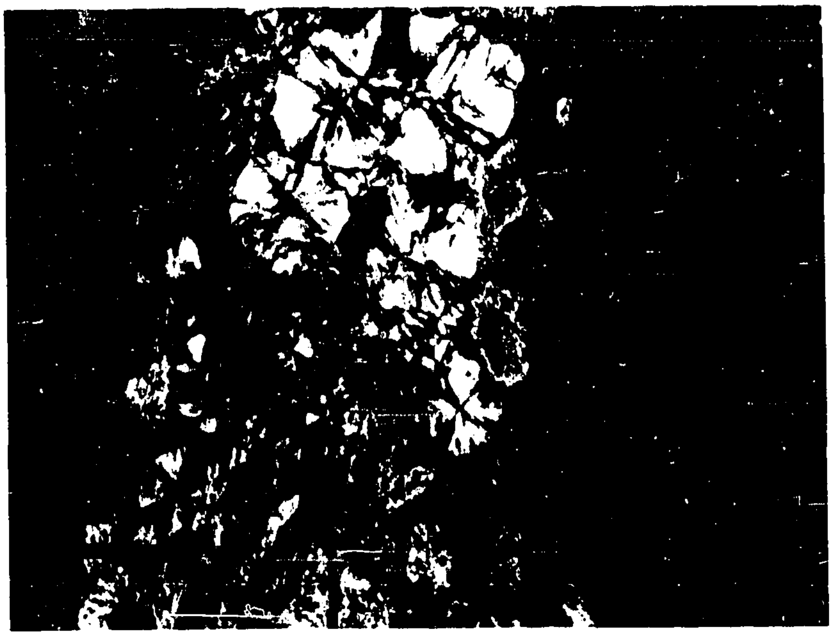


Figure 54

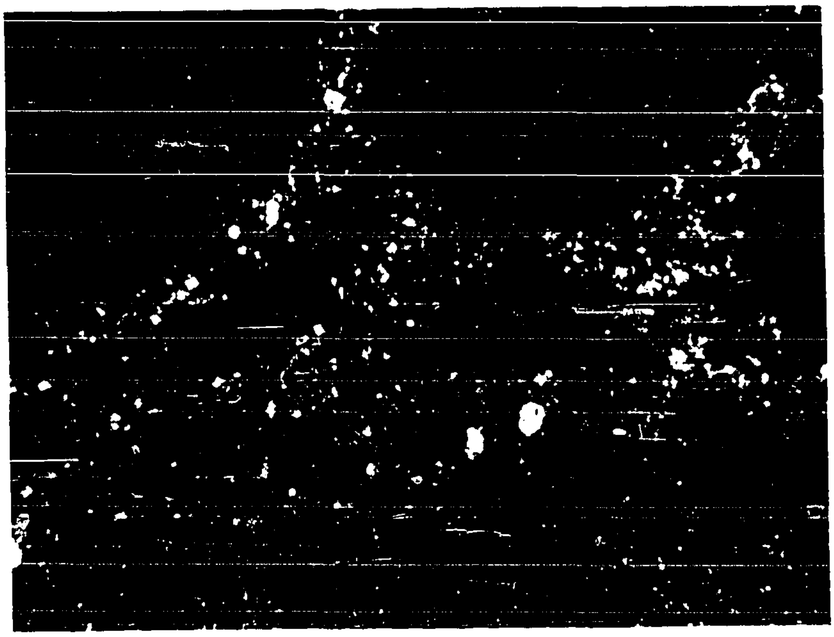


Figure 55

Figure 56

Figure 57

Summary of Diagenesis

Five major diagenetic processes altered the post-Borden carbonates after their deposition. These were: cementation, neomorphism, pressure-solution, silicification, and dolomitization. The general chronological order of occurrence of these processes is shown in Table 10.

Table 10 - Generalized sequence of diagenetic events

(1) Deposition

(2) Early dolomitization - penecontemporaneous or reflux dolomitization on or adjacent to supratidal flats

(3) Marine cementation - precipitation of prismatic marine cements (may predate early dolomitization in some or all cases)

(4) Neomorphism - inversion of aragonite shells to calcite and aggrading neomorphism of fine-grained carbonate mud (may occur anytime after deposition

(5) Pressure solution - grain to grain pressure solution

(6) Phreatic cementation - precipitation of syntaxial and granular cements

(7) Late dolomitization - precipitation of ferroan dolomite in pore space and redolomitization of some early dolomite

(8) Pressure solution - formation of styolites (may predate late dolomitization

(9) Silicification - replacement of calcite by microcrystalline silica (chert)

Conclusions

(1) Certain changes are necessary in the present stratigraphic nomenclature of the post-Borden carbonates. These include:

(a) Adoption of the term Somerset Member for the characteristic, widespread zone of impure dolomite found at the base of Salem.

(b) Formal status of the Floyds Knob as a named bed and its inclusion in the Carwood Formation of Indiana or the upper member of the Borden Formation in Kentucky.

(c) In Indiana, the exclusion of the impure dolomite found between the Edwardsville clastics and the clean bioclastic limestones of the Harrodsburg Formation from the Borden Group and their inclusion in the Sanders Group as the Ramp Creek Formation.

(d) In Kentucky, elimination of the term Muldraugh and removal of the rocks presently termed Muldraugh from the Borden Formation. The Fort Payne Formation should be extended to include these laterally equivalent rocks.

(e) The Harrodsburg Formation is a mappable unit only in Meade, Hardin, and adjacent counties in north-central Kentucky as defined by Sable, Kepferle, and Peterson (1966).

(f) In eastern Kentucky, the rocks presently mapped as the Renfro Member of the Borden Formation should be removed from the Borden and, since they are a distinct mappable unit, should be termed the Renfro Formation.

(2) Nine separate and distinct lithofacies were recognized in the units under study. These are:

(a) Bryozoan-echinoderm grainstone and packstone
(b) Echinoderm grainstone and packstone
(c) Bryozoan grainstone and packstone
(d) Molluscan grainstone
(e) Foram grainstone
(f) Pelletal calcisphere packstone
(g) Dolowackestone
(h) Dolostone
(i) Quartzose sandstone

(3) These lithofacies represent deposition on a shallow platform which was rapidly prograding to the southwest. The depositional system can be divided into seven separate distinct environments. These environments are:

(a) Supratidal flat
(b) Intertidal
(c) Lagoon
(d) Shoal
(e) Subtidal shelf
(f) Slope-edge
(g) Basin

(4) These depositional environments are represented by one or several of the above lithofacies as follows:

Depositional Environment	Associated Lithofacies
(1) Supratidal flat	Dolostone
(2) Intertidal	Dolostone Dolowackestone Pelletal calcisphere Quartzose sandstone
(3) Lagoon	Pelletal calcisphere Dolowackestone
(4) Shoal	Foram
(5) Subtidal shelf	Bryozoan-echinoderm Echinoderm Bryozoan Diverse
(6) Slope-edge	Bryozoan-echinoderm Bryozoan
(7) Basinal	(Platform lithofacies not represented)

(5) The rapidly fluctuating nature of the depositional system in portions of this platform led to cyclic deposition of peritidal and subtidal units.

(6) Post-Borden platform sedimentation is characterized by four stages of deposition.

    (a) Stage 1 - Peritidal deposition of the Ramp Creek Formation in Indiana and the lower portion of the Renfro Formation in eastern Kentucky.

    (b) Stage 2 - Subtidal shelf deposition of the Harrodsburg Formation on the Indiana portion of the platform while peritidal deposition of the Renfro Formation continued in eastern Kentucky.

    (c) State 3 - Peritidal deposition of the Somerset Member of the Salem Formation across most of the rapidly expanding platforms.

    (d) Stage 4 - Subtidal deposition in subtidal shelf, shoal, and lagoon environments represented by the Salem Formation across most of the expanded platform; peritidal deposition of the Renfro Formation continues in portions of eastern Kentucky.

(7) After deposition, the post-Borden carbonates were affected by five major diagenetic processes including:

    (a) cementation
    (b) neomorphism
    (c) pressure solution
    (d) dolomitization
    (e) silicification

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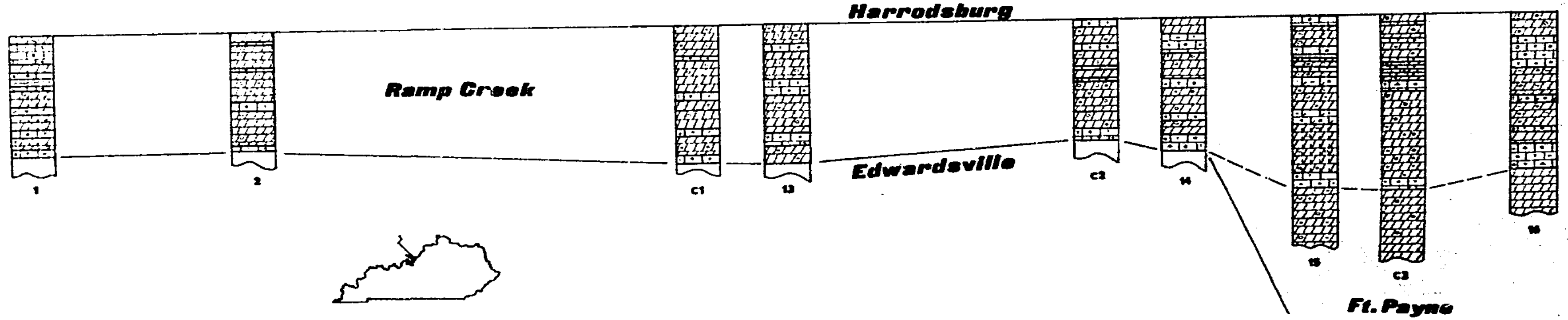

Plate 1 - Cross-section of the Ramp Creek Formation in southern Indiana and north-central Kentucky

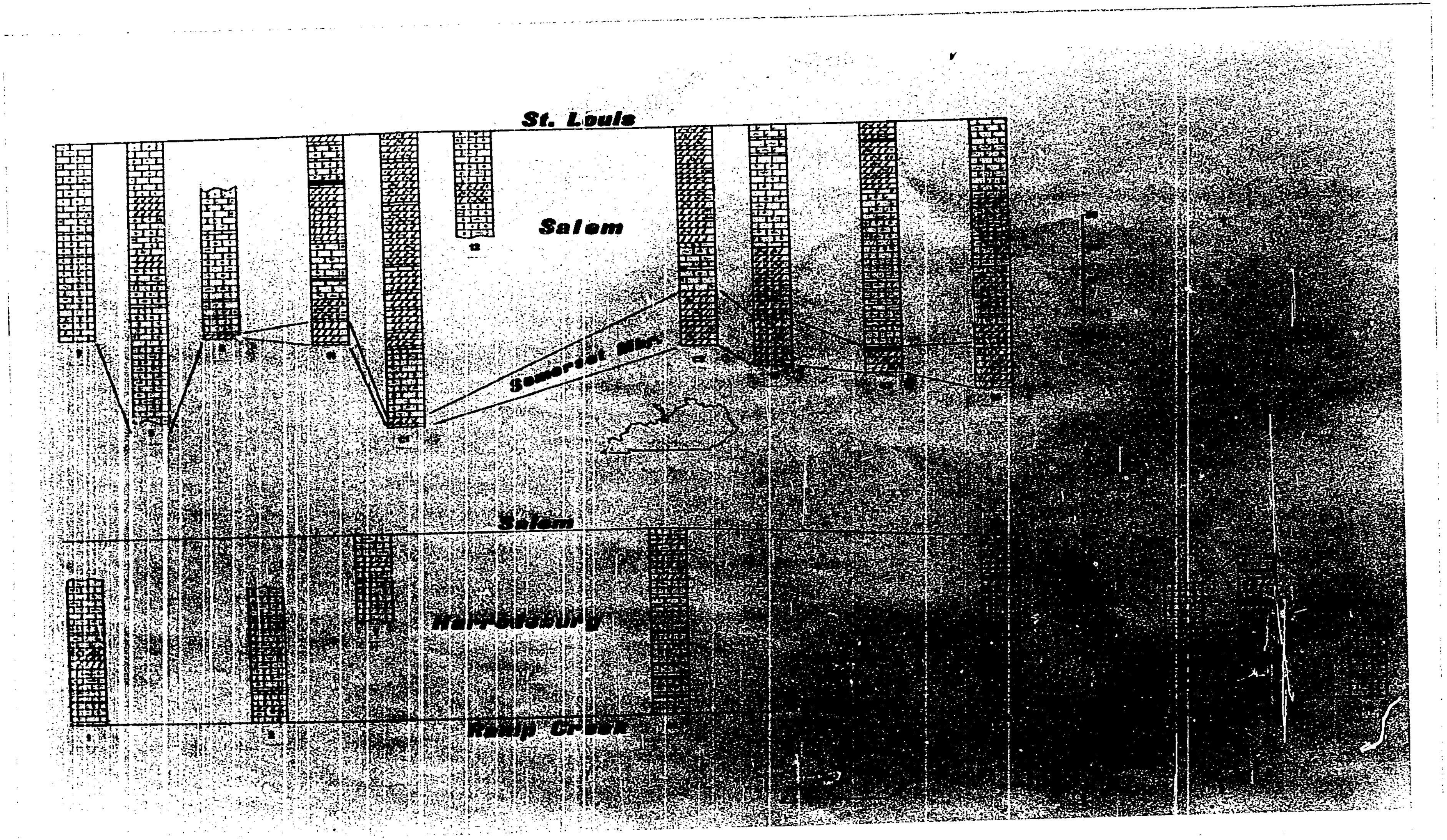

Plate 2 - Cross-section of the Harrodsburg and Salem Formations in southern Indiana and north-central Kentucky

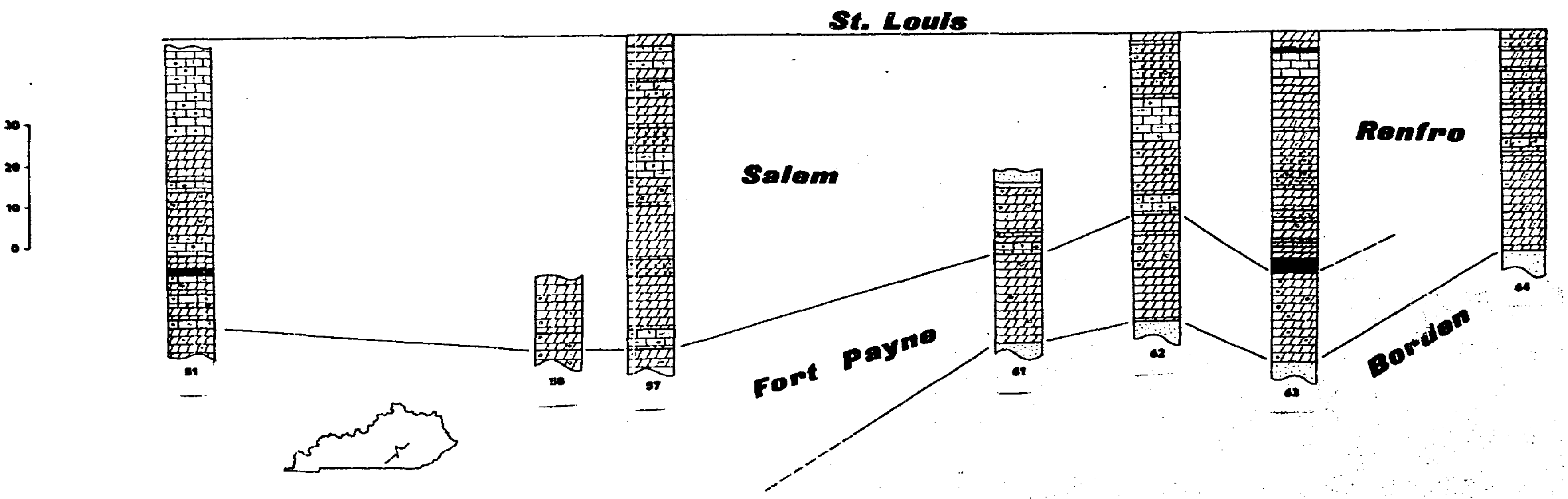

Plate 3 - Cross-section of platform carbonate units in eastern Kentucky

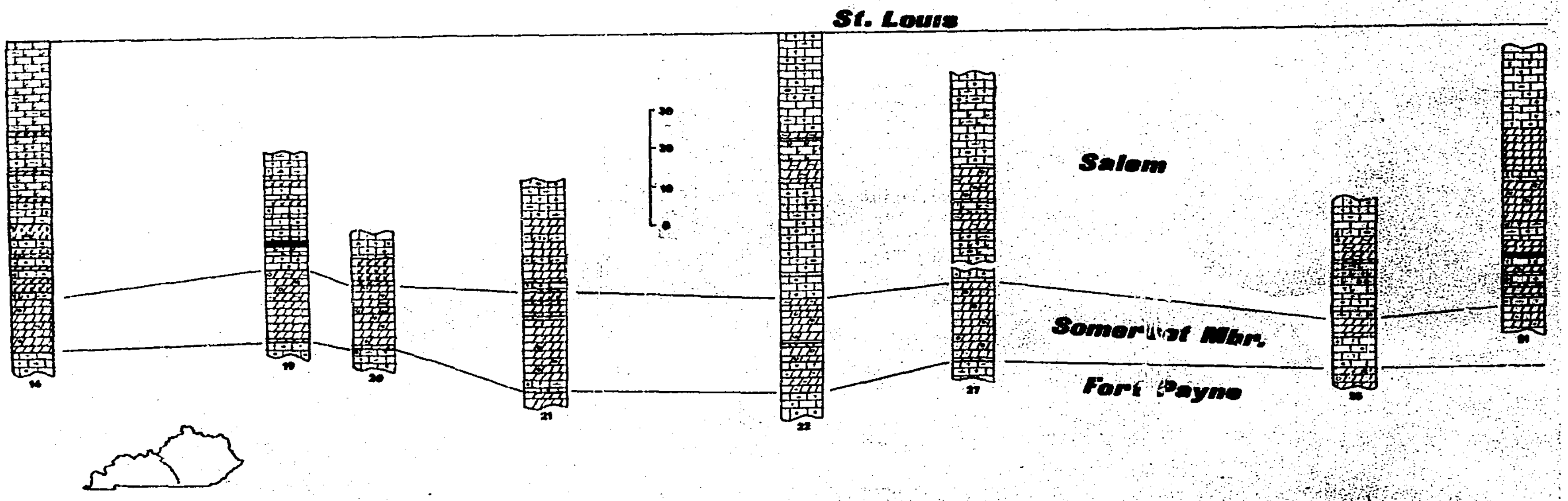

Plate 4 - Cross-section parallel to the Borden front of platform carbonate units in central and eastern Kentucky

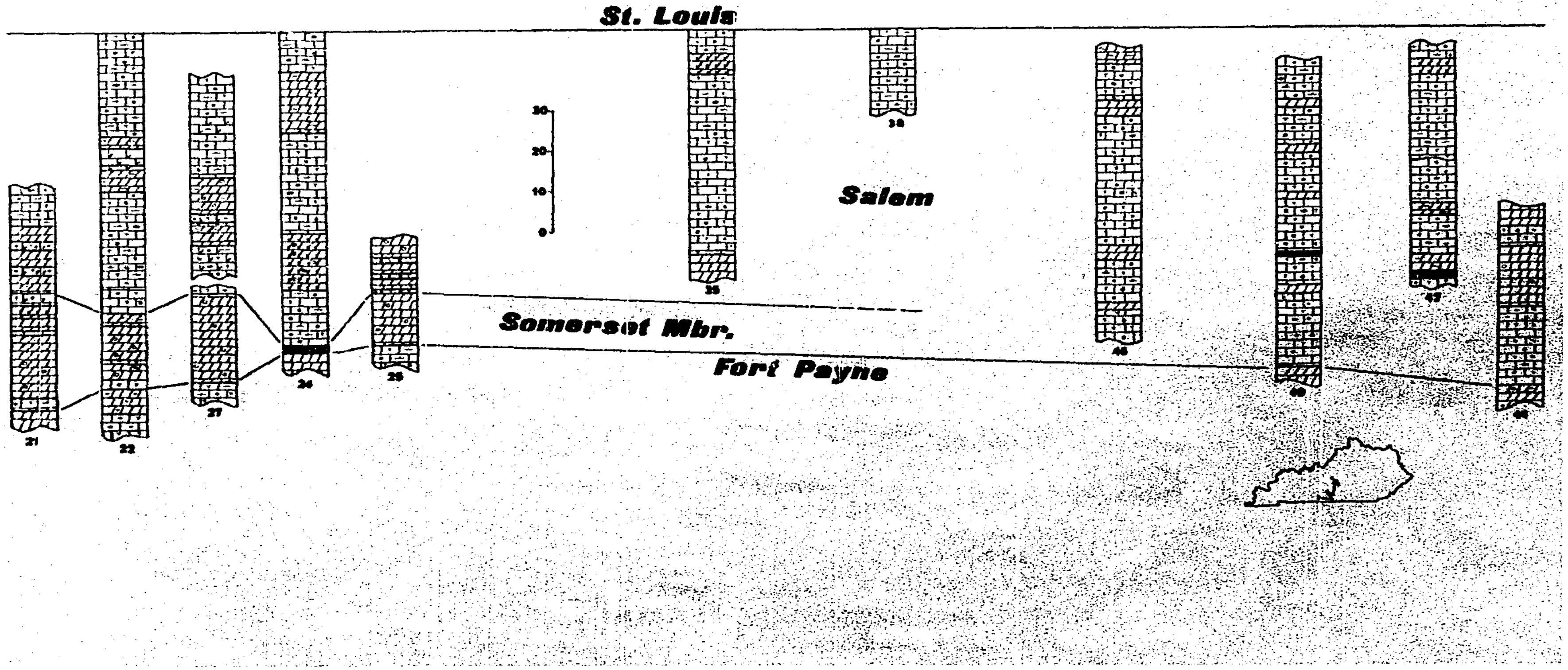

Plate 5 - Cross-section normal to the Borden front of platform carbonate units in central Kentucky

APPENDIX A

Measured Sections

Bloomington Section
(section 1, figure 6)

Section along Indiana Route 37, 1 mile north of Bloomington, Monroe County, Indiana. (NW¼, sec. 28, T9N, R1W)

Mississippian   Feet

Harrodsburg Formation

19. Limestone, light gray, fine to medium-grained, fossiliferous, abundant bryozoans; well defined high angle, bimodal crossbedding; styolites common; top covered 16

18. Limestone, light gray to brown, fine to medium-grained, fossiliferous, abundant echinoderms; dolomitic, medium-bedded; some silicification 5

17. Dolomite, light gray to gray-brown, weathers tan; fine-grained, scattered bryozoan fronds; dark wavey algal laminations; calcite geodes; thickness variable. 3

16. Dolomite, medium brown, fine-grained, indistinct lamination; "birds-eye" structures. 3

15. Limestone, light gray-brown, fine to medium-grained, abundant bryozoans and echinoderms, crossbedded, styolitic, glauconitic 10

14. Limestone, medium gray, fine to medium-grained, fossiliferous, abundant bryozoans and echinoderms; glauconitic. . 4

Ramp Creek Formation

13. Dolomite, light gray, weathers tan to light brown; calcite geodes; scattered bioclasts 3

12.	Dolomite, light gray, indistinct dark wavey algal lamination.	2
11.	Limestone, light gray-brown, fine to medium-grained, fossiliferous, abundant bryozoans and echinoderms; glauconitic.	5
10.	Dolomite, light-medium brown, fine-grained, dark wavey algal lamination; spally, vertical burrowing.	2
9.	Limestone, light brown to tan, fine to medium-grained, fossiliferous, abundant bryozoans and echinoderms; glauconitic.	2
8.	Shale, medium gray, slightly calcareous.	1
7.	Limestone, light-medium gray, fine to medium-grained, fossiliferous, abundant bryozoans and echinoderms; glauconitic, dolomitic	2
6.	Dolomite, light gray-brown, fine-grained, geodiferous	4
5.	Limestone, light-medium gray, fine to medium-grained, fossiliferous, dolomitic, scattered geodes.	2
4.	Dolomite, light gray-brown, fine-grained, geodiferous; massive, indistinct lamination.	4
3.	Limestone, light-medium gray, fine to medium-grained; fossiliferous; abundant echinoderms	2
2.	Dolomite, light gray to tan, fine-grained, geodiferous, massive	3
1.	Limestone, light-medium gray, fine to medium-grained, abundant echinoderms; cherty, lower contact sharp	2

Edwardsville Formation (not measured)

Total thickness of measured section 78

Stewart's Landing Section
(section 15, figure 6)

Section in roadcut and small quarry along Indiana Route 211, 1 mile west of Stewart's Landing, Harrison County, Indiana. (SE¼, sec. 26, T4S, R5E)

Mississippian	Feet
Salem Formation	
25. Limestone, light gray, weathers light brown; fine-grained, dolomitic, sandy, dark wavey lamination	5
24. Limestone, light gray, weathers light brown; thin-bedded, fine-grained, dolomitic, sandy, dark wavey lamination	5
23. Limestone, light gray to buff, fine-grained, fossiliferous, abundant Endothyrid foraminifera; massive, styolitic, comprises most of quarry	28
22. Dolomite, light to dark brown, massive, irregular bedding; slightly fossiliferous; scattered bryozoans and echinoderms; some dark wavey lamination	12
21. Dolomite, light gray, weathers reddish-brown; fine-grained, scattered bioclasts; few dark wavey lamination	3
20. Dolomite, light gray, fine-grained, scattered bioclasts; massive, cherty	4
19. Dolomite, medium-dark gray, fine-grained, scattered bioclasts; abundant large calcite geodes; cherty	3
Somerset Member	
18. Dolomite, light brown to buff, massive, argillaceous, spally, contains abundant quartz and calcite geodes; dark wavey lamination	14

Harrodsburg Formation

17. Limestone, light gray, fine to medium-grained, fossiliferous, contains abundant bryozoans and echinoderms; cross-bedded .. 6

16. Limestone, medium-dark gray, fine to medium-grained, irregular bedding; fossiliferous, contains abundant bryozoans 8

15. Limestone, light gray, fine to medium-grained, fossiliferous, contains abundant bryozoans and echinoderms; glauconitic, cross-bedded, occurs as two prominent beds; upper 1 foot highly argillaceous 7

14. Limestone, light gray, medium-grained, fossiliferous, contains abundant bryozoans; glauconitic, styolitic, upper surface undulatory 4

13. Limestone, light gray, fine to medium-grained, fossiliferous, abundant bryozoans and echinoderms; glauconitic, styolitic .. 3

12. Limestone, light gray, fine to medium-grained, fossiliferous, abundant bryozoans and echinoderms; glauconitic 8

11. Limestone, medium gray, fine to medium-grained, fossiliferous, abundant echinoderms; scattered geodes 2

Ramp Creek Formation (incomplete)

10. Dolomite, light gray, weathers light brown; massive, weathers spally; scattered bioclasts; abundant geodes; dark wavey lamination 4

9. Limestone, medium gray, fine to medium-grained, fossiliferous, abundant bryozoans and echinoderms; medium-bedded 3

8.	Siltstone, light gray, calcareous, contains scattered fossil debris	1
7.	Limestone, light gray, medium-grained, fossiliferous, abundant bryozoans and echinoderms; cherty	1
6.	Dolomite, light-medium brown, spally, fine-grained, scattered echinoderm fragments; dark wavey lamination	1
5.	Limestone, light gray, medium-grained, fossiliferous, abundant echinoderms; cherty	1
4.	Dolomite, light gray, weathers gray-brown; massive, weathers spally; abundant small quartz geodes	1
3.	Limestone, light gray, medium-grained, fossiliferous, abundant bryozoans and echinoderms; slightly silty; cherty	2
2.	Dolomite, light-medium gray, weathers light brown, fine-grained, massive, weathers spally; abundant geodes, contacts undulatory	6
1.	Limestone, light gray, medium-grained, fossiliferous, abundant bryozoans and echinoderms; cherty	4

Total thickness of measured section .... 136 feet

Summersville Section
(section 24, figure 6)

Section along Kentucky Route 61 at first roadcut north of Pitman Creek bridge, Green County, Kentucky. Carter coordinates 9-J-48.

Mississippian   Feet

St. Louis Formation (incomplete)

11. Dolomite, light gray, weathers yellow-brown; fine-grained, arenaceous, cherty. . . . . 18+

Salem Formation

10. Limestone, medium gray, fossiliferous, abundant bryozoans and echinoderms; high angle crossbedding. 10

9. Dolomite, light gray, weathers yellow-brown to tan; fine-grained, dark wavey disrupted algal lamination. 15

8. Limestone, light gray to tan, medium to coarse-grained, fossiliferous, abundant bryozoans and echinoderms; high angle crossbedding; cherty. 25

7. Dolomite, light gray, weathers tan to yellow-brown; scattered bioclastic material; calcite and quartz geodes common. 14

6. Limestone, dark gray, medium-grained, fossiliferous, abundant echinoderms; thick-bedded, high angle crossbedding . . 6

5. Limestone, dark gray, fine-medium grained, fossiliferous, abundant echinoderms and dwarfed gastropods; crossbedded 8

4. Shale, light gray, calcareous, ferrugineous, scattered fossils 2

Fort Payne Formation (incomplete)

3. Dolomite, light to medium gray, weathers buff, fine-grained, silty, scattered bioclasts; dark wavey lamination 30

2. Limestone, medium to dark gray, medium to thick-bedded, crossbedded, coarse-grained, fossiliferous, abundant bryozoans and echinoderms; styolitic . . 5

1. Dolomite, light bluish-gray, thick-bedded, silty, fine-grained, abundant calcite geodes; cherty . . . . 18+

Total thickness of measured section. . . . .151+

Cumberland Lake Section
(section 57, figure 6)

Section along access road to Waitsboro Recreation Area, 4 miles south of Somerset, Pulaski County, Kentucky. Carter coordinates 23-G-59

	Mississippian	Feet
	St. Louis Formation (incomplete)	
14.	Dolomite, light-brown, fine-grained, massive, slightly silty.	5+
	Salem Formation	
13.	Limestone, light gray, weathers tan to brown; highly argillaceous, fissile, contains two more resistant beds of irregular thickness.	11
12.	Limestone, dark gray, fossiliferous, contains abundant bryozoans, echinoderms, and brachiopods; argillaceous, occurs as two prominent wedges.	4
11.	Dolomite, light gray, weathers tan to brown; argillaceous, fissile to spally, grades into underlying unit; fossiliferous at base.	7
10.	Limestone, light gray, weathers brown; dolomitic, fossiliferous, fine to medium-grained, contains bryozoans and echinoderms.	3
9.	Limestone, light gray, dolomitic, arenaceous, fossiliferous, fine-grained, bioturbated, ripple laminated, thickness variable	3
8.	Limestone, light gray, fine-grained, fossiliferous, arenaceous, low angle crossbedding, slightly cherty; unit thickens to southwest.	6

7. Dolomite, light gray, weathers tan to brown; silty, massive, nonresistant, bioturbated, contains quartz geodes . . . 3

6. Dolomite, light brown to tan, silty, massive, thickness variable; bioturbated, quartz geodes 4

5. Limestone, light gray, weathers tan; highly argillaceous, fissile. 13

4. Limestone, light to medium gray, fossiliferous, abundant bryozoans, echinoderms, brachiopods, and corals; low angle crossbedding; gradational into overlying unit. 4

Somerset Member

3. Dolomite, light gray, weathers light tan; highly argillaceous, spally to fissile; bioturbated, good slope former. 13

2. Limestone, light to medium gray to gray-brown, medium-grained, fossiliferous, abundant bryozoans, echinoderms and brachiopods; low angle crossbedding . . . 5

Fort Payne Formation (incomplete)

1. Dolomite, light gray, weathers tan to brown; massive to spally, silty, cherty, quartz geodes . . . . 50+

Total thickness of measured section . . . . . 131+

Big Hill Section
(section 64, figure 6)

Section in roadcut along Kentucky Route 421, 1 mile south of Big Hill, Madison County, Kentucky. Carter coordinates 13-M-64.

	Mississippian	Feet
	St. Louis Formation (incomplete)	
14.	Limestone, light gray, thin-bedded, pelletal, fine-medium grained, fossiliferous, contains abundant bryozoans	6
	Renfro Formation	
13.	Dolomite, light yellow-brown, thin-bedded, arenaceous, locally cherty; in places fossiliferous with scattered bryozoans, echinoderms, brachiopods, and foraminifera.	5
12.	Dolomite, light gray to yellow-brown, thin-bedded, very fine-grained, bioturbated	4
11.	Limestone, medium gray, nondolomitic, pelletal, siliceons, fine-grained, forms prominent ledge	2
10.	Dolomite, light gray to yellow-brown, fine-grained, arenaceous, glauconitic, bioturbated, dark wavey disrupted algal laminations	3
9.	Dolomite, light gray, weathers tan to yellow-brown; massive, fine-grained, intensely burrowed; occurs as a bed	5
8.	Dolimite, yellow-gray, fine-grained, possbily brecciated; thickness variable	1
7.	Dolomite, yellow-gray, fine-grained, massive, bioturbated.	3

6.	Dolomite, medium gray, weathers light brown to tan; fine-grained, thin-bedded argillaceous, interbedded with light to medium gray-green calcareous shale in beds up to .2 feet in thickness. . . .	3
5.	Limestone, medium brown, massive, fine-grained, pelletal, siliceons, occurs as single prominent bed	3
4.	Dolomite, light-medium gray, weathers tan to yellow-brown; fine-grained, light gray calcareous shale occurs at top and base of unit.	1
3.	Dolomite, yellow-gray to yellow-brown, fine-grained, massive, arenaceous, bioturbated, cherty; 3 inch shale at base.	8
2.	Dolomite, light gray, weathers tan to yellow-brown; fine-grained, medium to thin-bedded, bedding irregular; arenaceous, glauconitic, bioturbated, contains thin shale interbeds; lower contact marked by 3 inch gray-green glauconitic shale	15
Borden Formation (incomplete)		
1.	Siltstone, gray-green, glauconitic, bioturbated	10+
	Total thickness of measured section	69+

APPENDIX B

Location of measured sections and cores

APPENDIX B

Location of measured sections and cores
(Numbers correspond to figure 6)

1. Along Indiana Route 37, 1 mile north of Bloomington, Monroe County, Indiana; NW¼, sec. 28, T9N, R1W
2. Along entrance road to Monroe Reservoir Dam, Monroe County, Indiana; SE¼, sec. 28, T7N, R1W
3. Along old Indiana Route 37, .1 mile north of the Monroe-Lawrence County line, Monroe County, Indiana; SW¼, sec. 32, T7N, R1W
4. Along U.S. Route 50, ½ mile east of Bedford, Lawrence County, Indiana; SE¼, sec. 13, T5N, R1W
5. Along Indiana Route 37, 2 miles south of Bedford, Lawrence County, Indiana; NE¼, sec. 26, T5N, R1W
6. Along county road, 3 miles south of Leesville, Lawrence County, Indiana; SE¼, sec. 21, T5N, R2E
7. In Hoosier Lime and Stone Co. quarry, Washington County, Indiana; NE¼, sec. 24, T2N, R3E
8. Along Indiana Route 135, ½ mile south of Lake Salida, Washington County, Indiana; NE¼, sec. 32, T2N, R4E
9. Along Indiana Route 60, 2 miles south of Salem, Washington County, Indiana; NW¼, sec. 35, T2N, R4E
10. Along Indiana Route 60, 3 miles northwest of New Pekin, Washington County, Indiana; SW¼, sec. 2, T1N, R4E
11. In abandoned quarry ½ mile east of Pierce School, Washington County, Indiana; NE¼, sec. 28, T1N, R4E
12. In cut along Southern Railroad southwest of Georgetown, Floyd County, Indiana; SE¼, sec. 31, T2S, R5E
13. In abandoned quarry and along old Indiana Route 62, east of Edwardsville, Floyd County, Indiana; NE¼, sec. 1, T3S, R5E

14. Along county road up escarpment near Locust Point, Harrison County, Indiana; SW¼, sec. 12, T4S, R5E

15. In abandoned quarry and along Indiana Route 211, Harrison County, Indiana; SE¼, sec. 26, T4S, R5E

16. Along U.S. Route 31W, 7 miles southwest of West Point, Hardin County, Kentucky; C.C. 15-R-43

17. Along Kentucky Route 1638, 3 miles west of Muldraugh, Meade County, Kentucky; C.C. 22-R-42

18. Along Kentucky Route 434, 3½ miles west of Colesburg, Hardin County, Kentucky; C.C. 20-P-44

19. Along Kentucky Route 434, ½ mile west of Colesburg, Hardin County, Kentucky; C.C. 13-P-45

20. In cut of L&N Railroad, ½ mile north of Tunnel Hill, Hardin County, Kentucky; C.C. 5-0-45

21. Along U.S. Route 31E, ½ mile northwest of White City, Larue County, Kentucky; C.C. 25-N-47

22. Along Kentucky Route 210, just north of Mill Creek, Taylor County, Kentucky; C.C. 7-K-49

23. Along U.S. Route 68, 1 mile west of Campbellsville, Taylor County, Kentucky; C.C. 23-K-50

24. Along Kentucky Route 61, 1½ miles south of Summersville, Green County, Kentucky; C.C. 9-J-48

25. Along U.S. Route 68, 1½ miles north of Greensburg, Green County, Kentucky; C.C. 15-J-49

26. Along Kentucky Route 1701, 1½ miles west of Burdick, Taylor County, Kentucky; C.C. 24-J-50

27. Along Kentucky Route 1701, 1 mile north of Lemon Bend Church, Taylor County, Kentucky; C.C. 4-I-50

28. Along U.S. Route 68, ½ mile north of Kentucky Route 70, Metcalfe County, Kentucky; C.C. 22-H-47

29. Along Kentucky Route 80, ½ mile north of Nell, Adair County, Kentucky; C.C. 17-G-49

30. Along Kentucky Route 61, 1½ miles north of Breeding, Adair County, Kentucky; C.C. 10-F-49

31. Along Kentucky Route 80, 1 mile northeast of Gaston, Metcalfe County, Kentucky; C.C. 24-G-48

32. Along Kentucky Route 1240, just south of VanSant School, Metcalfe County, Kentucky; C.C. 17-G-47

33. Along Kentucky Route 1240, 3 miles southeast of Clarks Corners, Metcalfe County, Kentucky; C.C. 16-G-47

34. Along U.S. Route 68, 1 mile north of Edmonton, Metcalfe County, Kentucky; C.C. 2-F-47

35. In abandoned quarry 1 mile northeast of Summer Shade, Metcalfe County, Kentucky; C.C. 9-E-46

36. Along U.S. Route 68, 1½ miles east of Lecta, Barren County, Kentucky; C.C. 25-G-45

37. Along U.S. Route 31E, ¼ mile north of 31E by-pass, Glascow, Barren County, Kentucky; C.C. 25-G-44

38. Along Kentucky Route 351, 2 miles northwest of Glascow, Barren County, Kentucky; C.C. 12-G-43

39. Along U.S. Route 31E, 1 mile east of Lucas, Barren County, Kentucky; C.C. 9-E-42

40. In active quarry, 3 miles northwest of Scottsville, Allen County, Kentucky; C.C. 14-D-40

41. Along U.S. Route 231, west of Scottsville at Bay's Fork, Allen County, Kentucky; C.C. 23-D-40

42. Along county road ¼ mile west of Allen Springs, Warren County, Kentucky; C.C. 25-E-39

43. Along county road 2 miles west of Allen Springs at Trammel Creek, Warren County, Kentucky; C.C. 5-D-39

44. Along secondary road, ½ mile northeast of Butlersville, Allen County, Kentucky; C.C. 15-D-39

45. Along Kentucky Route 100, 1 mile south of Flippen, Monroe County, Kentucky; C.C. 13-C-44

46. In abandoned quarry south of Tompkinsville, Monroe County, Kentucky; C.C. 19-C-46

47. Along secondary road, 2 miles south of Tompkinsville, Monroe County, Kentucky; C.C. 22-C-46

48. Along Kentucky Route 90, 2 miles west of Seminary, Cumberland County, Kentucky; C.C. 20-D-51

49. Along U.S. Route 127, ½ mile north of Aaron, Clinton County, Kentucky; C.C. 2-D-52

50. Along U.S. Route 127, ¼ mile north of Russell-Clinton County line, Russell County, Kentucky; C.C. 16-E-53

51. Along Kentucky Route 538, 4 miles north of Cumberland City, Clinton County, Kentucky; C.C. 16-E-54

52. Along Kentucky Route 90 at Otter Creek, 8 miles southwest of Monticello, Wayne County, Kentucky; C.C. 17-D-55

53. In abandoned quarry adjacent to Tennessee Route 42, 2 miles northeast of Byrdstown, Pickett County, Tennessee; C.C. 18-B-53

54. Along Kentucky Route 90 at Beaver Creek, 1½ miles southwest of Monticello, Wayne County, Kentucky; C.C. 3-D-56

55. Along Kentucky Route 1370, 1 mile east of U.S. Route 127, Russell County, Kentucky; C.C. 10-E-53

56. Along Kentucky Route 92, 3 miles south of Jamestown, Russell County, Kentucky; C.C. 18-F-54

57. Along access road to Waitsboro Recreation Area, 4 miles south of Somerset, Pulaski County, Kentucky; C.C. 23-G-59

58. Along Kentucky Route 80 at Fishing Bridge west of Somerset, Pulaski County, Kentucky; C.C. 10-G-58

59. Along Kentucky Routes 39 and 439 at Woodstock, Pulaski County, Kentucky; C.C. 22-J-60

60. Along U.S. Route 127, 1 mile north of Kentucky Route 501, Lincoln County, Kentucky; C.C. 5-K-59

61. Along U.S. Route 27 at Hall's Gap, Lincoln County, Kentucky; C.C. 14-L-59

62. Along L&N Railroad midway between Maretburg and Brodhead, Rockcastle County, Kentucky; C.C. 15-K-62

63. Along U.S. Route 25, 3 miles north of Renfro Valley, Rockcastle County, Kentucky; C.C. 25-L-63

64. Along Kentucky Route 421, 1 mile south of Big Hill, Madison County, Kentucky; C.C. 13-M-64

C-1. Indiana Geological Survey Core 193, Lawrence County, Indiana; NW¼, NE¼, sec. 28, T6N, R2W

C-2. Indiana Geological Survey Core 181, Harrison County, Indiana; SE¼, NE¼, sec. 35, T1S, R2E

C-3. Indiana Geological Survey Core 180, Harrison County, Indiana; SW¼, NE¼, sec. 30, T3S, R3E

APPENDIX C

Bulk Mineralogy

APPENDIX C

Bulk mineralogy by x-ray diffraction analysis of post-Borden platform carbonates

Sample No.*	Peak Height			Calcite/Dolomite
	Calcite	Dolomite	Quartz	Percent**
1-1	7	-	59	100/00
1-2	60	14	7	75/25
1-3	-	75	12	00/100
1-4	44	1	3	100/00
1-6	51	4	3	95/05
1-7	-	54	13	00/100
1-8	47	5	3	90/10
1-9	-	38	6	00/100
1-9a	38	3	3	95/05
1-10	74	2	6	100/00
1-10a	35	-	3	100/00
1-11	49	-	3	100/00
1-12	6	68	9	10/90
1-13	65	15	5	75/25
1-13a	46	73	13	30/70
1-14	60	-	3	100/00
2-1	-	80	18	00/100
2-2	-	-	61	00/00
2-3	-	22	90	00/100
2-5	23	9	26	65/35
2-7	33	34	6	45/55
2-9	-	39	10	00/100
3-1	40	4	3	90/10
3-2	51	-	4	100/00
3-3	55	-	2	100/00
3-4	49	-	4	100/00
3-5	43	43	4	45/55
3-6	-	41	3	00/100
3-7	44	-	3	100/00
3-8	70	-	5	100/00

* Sample designation = section (Fig. 6) - sample

** Calculated to nearest 5 percent by method of Tennant and Berger (1957)

Sample No.	Peak Height			Calcite/Dolomite
	Calcite	Dolomite	Quartz	Percent
4-1	63	4	5	95/05
4-2	55	3	4	95/05
4-3	65	-	4	100/00
4-4	-	50	15	00/100
4-5	55	-	3	100/00
4-5a	5	4	22	50/50
4-6	50	-	5	100/00
5-1	50	-	3	100/00
5-2	72	-	5	100/00
5-3	61	-	3	100/00
5-3a	-	78	5	00/100
5-4	83	-	5	100/00
5-5	39	35	6	50/50
5-6	35	-	5	100/00
6-1	-	66	5	00/100
6-2	85	8	10	90/10
8-3	71	-	6	100/00
8-3a	90	4	12	95/05
8-5	35	84	5	25/75
8-5a	48	6	4	85/15
8-4	90	-	8	100/00
9-1	-	-	85	
9-3	15	21	11	35/65
9-9	10	41	11	15/85
9-10	-	-	40	
9-11	-	-	40	
9-12	-	-	75	
10-1	41	-	2	100/00
11-2	29	31	3	45/55
11-4	29	105	3	05/96
11-6	7	36	3	10/90
11-7	4	70	9	05/95
11-8	12	58	2	15/85
11-11	32	3	8	90/10
11-13	56	14	7	75/25

Sample No.	Peak Height Calcite	Dolomite	Quartz	Calcite/Dolomite Percent
12-1	58	-	4	100/00
12-2	77	-	6	100/00
12-3	64	-	5	100/00
12-4	54	45	8	50/50
12-5	44	-	3	100/00
15-2	13	16	12	40/60
15-3	95	4	11	95/05
15-4	5	100	18	05/95
15-6	26	24	13	45/55
15-11	33	82	11	25/75
15-17	95	-	5	100/00
15-19	78	-	4	100/00
15-20	88	-	4	100/00
15-21	-	67	12	00/100
15-22	-	100	14	00/100
15-23	26	24	5	45/55
15-24	24	27	4	40/60
15-25	43	48	3	40/60
16-7a	56	17	75	70/30
16-7b	50	-	13	100/00
16-7c	5	21	82	15/85
16-8	49	-	6	100/00
16-9	60	43	55	55/45
16-10	49	13	23	75/25
16-11	-	70	64	00/100
16-13	-	81	29	00/100
16-13a	-	31	69	00/100
16-14	26	60	54	25/75
16-14a	64	2	8	100/00
16-15	-	68	18	00/100
16-16	26	41	6	30/70
16-17a	35	-	5	100/00
16-17b	79	-	5	100/00
16-17c	58	17	5	75/25
16-17d	-	56	7	00/100
16-17e	56	-	3	100/00
16-17f	44	-	3	100/00
16-17g	60	3	8	95/05
16-17h	5	50	31	10/90

Sample No.	Peak Height Calcite	 Dolomite	 Quartz	Calcite/Dolomite Percent
16-19	58	13	10	80/20
16-19b	74	4	9	95/05
16-19c	40	21	17	60/40
16-19d	49	22	14	65/35
16-19e	73	4	6	95/05
16-19f	70	9	10	85/15
16-20	88	-	10	100/00
16-20a	61	4	10	95/05
16-20b	30	41	11	35/65
16-20c	22	26	9	40/60
16-20d	52	32	6	55/45
16-21	56	28	10	60/40
16-21a	53	29	6	60/40
16-21b	38	19	5	60/40
16-21c	66	3	18	95/05
16-22	39	24	15	55/45
16-22a	40	10	14	75/25
16-22b	60	13	12	80/20
16-22c	37	21	14	60/40
16-22d	31	11	18	70/30
16-22e	46	46	6	45/55
16-22f	43	22	27	60/40
16-23	6	59	3	10/90
16-23a	3	46	7	05/95
16-23b	16	89	18	10/90
16-23d	37	66	10	30/70
16-25	44	31	16	50/50
19-1	77	17	32	80/20
19-2	10	13	30	40/60
19-3	50	35	30	50/50
19-4	24	13	25	60/40
19-5	87	7	8	95/05
19-6	55	2	5	95/05
19-7	-	64	10	00/100
19-8	78	9	14	90/10
19-9	-	86	40	00/100
19-10	-	44	75	00/100
19-11	45	5	11	90/10
19-12	-	51	37	00/100
19-13	-	81	44	00/100
19-14	55	3	7	100/00
19-15	55	-	4	100/00
19-16	35	27	36	50/50

Sample No.	Peak Height			Calcite/Dolomite
	Calcite	Dolomite	Quartz	Percent
19-17	66	-	4	100/00
19-18	64	17	7	75/25
19-19	40	4	3	90/10
19-20	41	63	19	35/65
19-21	72	4	4	95/05
20-3	7	80	29	05/95
20-4	80	45	22	60/40
20-7	28	14	23	60/40
20-8	19	90	23	10/90
20-12	90	3	9	100/00
20-15	-	90	6	00/100
20-16	10	41	10	15/85
20-17	15	73	6	15/85
20-21	-	27	21	00/100
20-22	-	80	16	00/100
20-24	4	80	6	05/95
21-2	-	64	32	00/100
21-4	-	78	33	00/100
21-9	5	75	16	05/95
21-11	12	-	26	100/00
21-12	11	18	10	30/70
21-13	32	25	8	50/50
21-14	74	3	10	95/05
22-1	11	-	26	100/00
22-6	23	-	39	100/00
22-7	17	28	6	30/70
22-11	-	90	14	00/100
22-12	59	18	9	70/30
22-13	7	25	9	15/85
22-15	57	-	31	100/00
22-15a	26	36	3	35/65
24-1	10	51	22	15/85
24-3	8	32	3	15/85
24-7	-	100	14	00/100
24-7a	21	39	3	30/70
24-9	-	56	8	00/100
24-11	19	41	9	25/75

Sample No.	Peak Height			Calcite/Dolomite
	Calcite	Dolomite	Quartz	Percent
27-1	-	21	18	00/100
27-2	-	19	14	00/100
27-3	20	9	11	65/35
27-4	20	13	5	55/45
27-5	5	18	14	15/85
27-6	-	54	13	00/100
27-7	-	53	15	00/100
27-7a	-	35	8	00/100
32-2	-	18	10	00/100
32-4	8	80	7	05/95
32-6	-	25	8	00/100
35-1	5	90	25	05/95
35-5	18	25	4	35/65
35-6	38	-	8	100/00
36-3	6	29	8	15/85
36-4	-	80	16	00/100
36-5	3	48	15	05/95
36-6	45	-	10	100/00
38-2	-	20	16	00/100
38-3	-	28	17	00/100
38-4	53	-	4	100/00
38-5	11	19	6	30/70
39-1	15	3	20	90/10
39-2	13	15	17	40/60
39-4	17	80	30	15/85
41-2	-	80	19	00/100
41-3	-	85	11	00/100
41-5	-	67	7	00/100
42-3	60	-	4	100/00
42-4	15	33	4	25/75
43-2	-	80	9	00/100
43-3	-	75	9	00/100
43-4	-	23	10	00/100
43-5	-	-	5	-
43-8	60	-	8	100/00
43-9	28	37	4	40/60

Sample No.	Peak Height Calcite	Dolomite	Quartz	Calcite/Dolomite Percent
44-2	-	28	17	00/100
44-4	-	80	20	00/100
48-1	-	46	96	00/100
48-2	-	92	30	00/100
48-3	64	44	12	55/45
48-4	84	-	29	100/00
49-2	-	25	35	00/100
49-3	6	15	21	25/75
49-4	-	28	33	00/100
49-6	-	-	33	-
50-1	-	55	27	00/100
50-3	75	5	20	95/05
50-4	40	10	6	75/25
50-6	-	85	29	00/100
50-7	-	48	15	00/100
51-2	10	18	16	30/70
51-3	35	51	24	35/65
51-5	15	63	13	15/85
51-7	6	32	13	15/85
51-10	44	-	7	100/00
51-12a	35	25	20	50/50
51-12b	90	-	12	100/00
54-1	39	69	17	30/70
54-2	-	43	31	00/100
54-3	74	-	12	100/00
54-6	98	42	18	65/35
54-7	-	100	15	00/100
54-8	100	-	15	100/00
55-1	-	26	13	00/100
55-3	-	23	17	00/100
55-8	22	19	7	50/50
55-9	20	19	7	50/50
55-10	5	30	25	10/90
56-1	-	48	25	00/100
56-4	95	45	25	60/40
56-4a	-	-	75	-

Sample No.	Peak Height			Calcite/Dolomite
	Calcite	Dolomite	Quartz	Percent
57-2	5	-	25	100/00
57-5	-	55	25	00/100
57-7	4	22	24	15/85
57-9	16	3	19	80/20
57-10	-	71	15	00/100
57-11	-	43	13	00/100
57-15	-	15	25	00/100
57-17	22	-	19	100/00
57-18	-	39	12	00/100
58-1	-	34	23	00/100
58-2	-	9	14	00/100
58-3	-	31	18	00/100
58-4	-	8	20	00/100
58-5	-	80	25	00/100
58-6	-	15	25	00/100
58-7	25	3	14	85/15
58-8	8	19	4	30/70
58-9	-	30	8	00/100
59-1	-	-	90	-
60-2	-	80	10	00/100
60-5	14	12	14	45/55
60-6	63	6	90	90/10
60-8	40	10	85	75/25
61-24	-	-	68	-
61-26	-	5	43	-
61-27	-	21	55	00/100
61-27a	-	27	44	00/100
61-29	-	61	15	00/100
61-31	-	80	31	00/100
61-36	-	-	30	-
61-37	-	-	70	-
62-1	10	90	28	05/95
62-2	5	44	9	05/95
62-3	-	70	28	00/100
62-3a	-	75	6	00/100
62-6	76	30	23	70/30
62-7	-	37	6	00/100
62-8	19	57	6	30/70

Sample No.	Peak Height Calcite	 Dolomite	 Quartz	Calcite/Dolomite Percent
63-1	33	2	5	95/05
63-2	41	53	4	40/60
63-3	3	38	13	05/95
63-4	4	60	4	05/95
63-6	-	40	4	00/100
63-7	15	25	4	35/65
63-8	35	36	5	45/55
63-9	4	68	12	05/95
63-10	27	90	36	15/85
63-11	13	43	6	20/80
63-12	-	50	9	00/100
63-13	12	27	8	25/75
63-14	-	37	10	00/100
63-15	-	29	11	00/100
63-16	-	40	15	00/100
63-17	-	-	50	-
63-18	4	80	18	05/95
63-19	-	40	7	00/100
63-20	-	63	5	00/100
64-2	9	35	8	15/85
64-3	-	90	8	00/100
64-4	66	-	5	100/00
64-5	-	39	6	00/100
64-6	6	43	4	10/90
64-9a	7	22	28	20/80
64-10	48	12	4	75/25
64-12	-	35	19	00/100
64-13	-	37	9	00/100