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MICROFACIES AND GEOCHEMISTRY OF THE BRERETON LIMESTONE (MIDDLE PENNSYLVANIAN) OF SOUTHWESTERN ILLINOIS, U.S.A.

BY

Mohamad R. KHAWLIE and Albert V. CAROZZI ¹

ABSTRACT

The Brereton Limestone in southwestern Illinois is a transgressive carbonate unit over a delta system. It represents marine deposition in three interdeltic troughs, and over an open shelf. The environment of deposition, entirely under relatively low energy conditions, consists of a general infratidal slope extending from a prodelta edge to a shelf and showing topographic irregularities such as depressions, corresponding to protected areas, and elevations represented by organic mounds and banks, and bioclastic bars.

Detailed petrographic analysis reveals thirteen distinct microfacies divided into three series: arenaceous, argillaceous, and weakly argillaceous. They are characterized by the following benthonic associations: phylloid algae-bryozoans, crinoids-brachiopods-pelecypods, and fusulinids-arenaceous foraminifers. Ostracods and sponge spicules behave as components transported down the slope in association with silt-size detrital quartz. The irregularities displayed by the infratidal slope are the major factors controlling the space distribution of the carbonate microfacies. These conditions indicate that the Brereton Limestone is a variety of the "Bank Model" of deposition typical of the Pennsylvanian of the Mid-Continent.

The environment of deposition has been analyzed from a geochemical viewpoint. The geochemistry confirms the results obtained by petrographic investigation. The continental influx shoreward, and the open shelf conditions seaward, are the two major factors controlling the distribution of the various parameters. The transition between shore and shelf is accompanied by locally restricted conditions.

The clay mineral distribution is controlled by their particular properties of flocculation and deposition: the kaolinite is shoreward; illite tends to concentrate shoreward but is not localized; chlorite, a syngenetic alteration product of mixed-expandables, occurs mostly seaward with the latter. The carbonate-fluorapatite is generally associated with the clay minerals. The organic carbon and hematite are brought in by the fresh water, though there is some *in situ* contribution of organic matter from the decay of marine organisms. The hematite later alters to pyrite and siderite.

Concentrations of Fe, Ga, Mo, Cu, Co, B, Mn, Pb, and Ni shoreward are mostly due to their association with detrital components, whereas their concentrations seaward are due to the influence of the marine carbonate deposition. Boron values around 300 ppm indicate that in general the depo-

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sition of the Brereton Limestone took place in an environment of normal marine salinity. Species brought mostly by freshwater, and those which are dominant in the marine environment, indicate an increasing continental influence, stratigraphically upwards, revealing the onset of the overlying deltaic phase. Dolomitization is a major late diagenetic process being mostly non-selective with respect to microfacies.

RÉSUMÉ

Le Calcaire de Brereton dans le sud-ouest de l'Illinois représente une unité carbonatée transgressive sur un système deltaïque déposée dans trois dépressions interdeltaïques et sur une plateforme ouverte. Le milieu de sédimentation, entièrement sous conditions de faible énergie, correspond à une pente générale infracotidale qui s'étend d'un bord prodeltaïque à une plateforme et qui montre des irrégularités topographiques telles que des dépressions correspondant à des zones protégées et des élévations représentées par des monticules et bancs organiques et des barres bioclastiques.

L'étude pétrographique détaillée a révélé l'existence de treize microfaciès distincts, divisés en trois séries: quartzreuse, argileuse et faiblement argileuse. Ils sont caractérisés par les associations benthiques suivantes: algues phylloïdes-bryozoaires, crinoïdes-brachiopodes-pelecypodes, fusulinides-foraminifères arénacés. Les ostracodes et les spicules de spongiaires se comportent comme composants transportés le long de la pente avec les apports de quartz détritique fin. Les irrégularités de la pente infracotidale sont les facteurs responsables de la distribution dans l'espace des microfaciès carbonatés. Ces conditions indiquent que le Calcaire de Brereton est une variante du modèle de sédimentation dit « de banc », typique du Pennsylvanien du Middle West.

Le milieu de sédimentation a également été étudié par la géochimie, et cette dernière confirme les résultats obtenus par la pétrographie sédimentaire. Les apports continentaux en milieu côtier et les conditions de mer ouverte sur la plateforme sont les deux principaux facteurs qui règlent la distribution des divers paramètres. La transition entre le domaine côtier et celui de la plateforme s'accompagne par des conditions localement confinées.

La distribution des minéraux argileux est contrôlée par leurs propriétés particulières de flocculation et de sédimentation: ainsi la kaolinite se dépose en milieu côtier; l'illite tend à se concentrer sur la plateforme mais pas de façon localisée; la chlorite, produit d'altération synsédimentaire des interstratifiés gonflants, se rencontre principalement en milieu marin ouvert associée avec ces derniers. La calci-fluorapatite est en général liée aux minéraux argileux. Le carbone organique et l'hématite sont apportés par l'eau douce bien qu'il y ait une certaine contribution *in situ* de matière organique par la décomposition des organismes marins. L'hématite s'altère par la suite en pyrite et sidérose.

Les concentrations de Fe, Ga, Mo, Cu, Co, B, Mn, Pb et Ni en domaine côtier sont principalement dues à leur association avec les apports détritiques alors que leurs concentrations dans le domaine marin ouvert sont dues à l'influence du milieu carbonaté. Le bore avec des valeurs d'environ 300 ppm indique qu'en général le Calcaire de Brereton s'est déposé en milieu marin à salinité normale. Les espèces apportées par l'eau douce et celles qui prédominent en milieu marin indiquent une influence croissante des apports continentaux stratigraphiquement vers le haut, exprimant le début de la phase deltaïque suprajacente. La dolomitisation est un processus important de diagenèse tardive et ne montre aucune sélectivité par rapport aux microfaciès.

INTRODUCTION

The purpose of this study is to reconstruct the environment of deposition of the Brereton Limestone by using a combination of carbonate microfacies and geochemical techniques. This double approach is particularly well suited to this problem because the investigated rock is a variably argillaceous limestone.

The Brereton Limestone (Middle Pennsylvanian) is a member of the Brereton cyclothem. It is relatively thin and extends over a distance of about 700 miles

(\approx 1100 kilometers) from western Kentucky to northeastern Oklahoma (Tubb, 1963). These features are typical of the Pennsylvanian System of the Mid-Continent in which rapid and sharp vertical changes in lithology are associated with individual units having a great lateral persistence. These conditions result from the interaction of marine transgressions and regressions with deltaic processes occurring over extensive and gentle slopes. The present study was limited to a relatively small area in southwestern Illinois so as to reach a detailed and precise understanding of the conditions of deposition.

Thin sections of the limestone were subjected to petrographic investigation and divided into thirteen microfacies using textural and microfaunal criteria. Average values of measured parameters were plotted for each microfacies. This information was used to develop a depositional model. This model represents a sequence deposited over a gentle slope extending from prodelta to shallow shelf with local depressions and elevations. Inferred relationships among the thirteen microfacies were confirmed by testing their parameters with a classification program as well as by obtaining their correlation coefficients.

Geochemical parameters consisting of nine elements (Fe, Cu, Pb, Ni, Mn, Co, Ga, Mo, and B), organic carbon, clay minerals (illite, mixed-expandables, kaolinite and chlorite), insoluble residue, dolomite, siderite, pyrite, hematite and carbonate-fluorapatite were analyzed and the results used to illustrate the physico-chemical aspects of the inferred model of deposition.

LOCATION AND TECTONIC SETTING

The area of study is located in southwestern Illinois, east of the Mississippi River (Fig. 1). It is within the boundaries of Pleistocene glaciation and mostly covered by tills and loess ranging in thickness from less than 20 inches to more than 25 feet (\approx 8 meters). The area is 70 kilometers wide and 130 kilometers long. It lies within the intracratonic Illinois Basin, and corresponds in particular to the Sparta Shelf, separated from the Fairfield Shelf (the deeper part of the Illinois Basin to the east and southeast) by the north-south trending DuQuoin Monocline. The Ozark Dome forms the southwestern boundary (Fig. 2).

STRATIGRAPHY

The Brereton Limestone is a member of the Brereton cyclothem of the Carbondale Formation, Middle Pennsylvanian (Fig. 3). The Carbondale Formation has a thickness of 250 feet (76 meters), whereas the Brereton Limestone ranges from 0 to 30 feet (9 meters) and averages around six feet (2 meters).

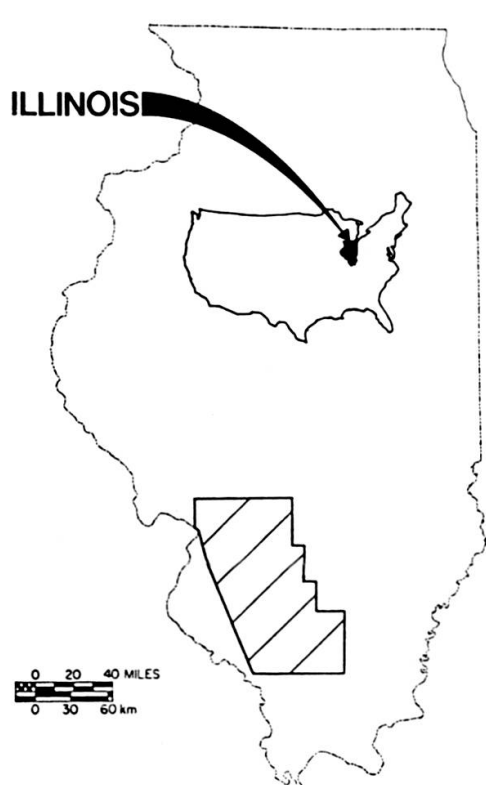


FIG. 1. — Location of investigated area.

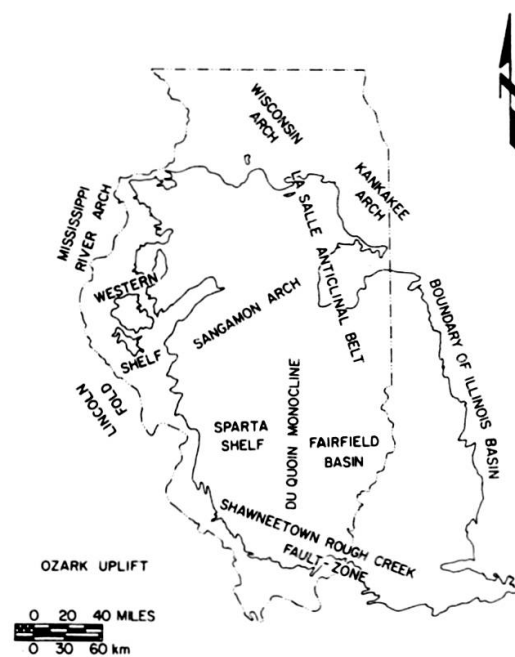


FIG. 2. — Major structural features of the Illinois Basin.

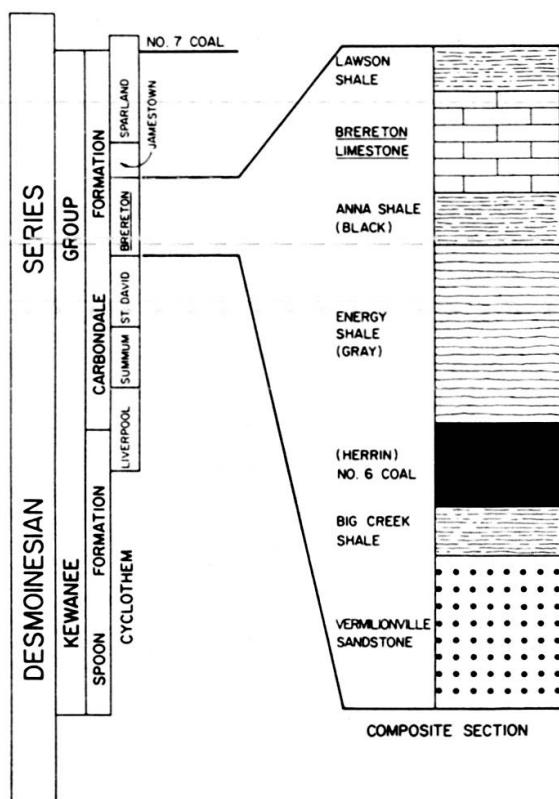


FIG. 3. — Stratigraphic position of Brereton Limestone.

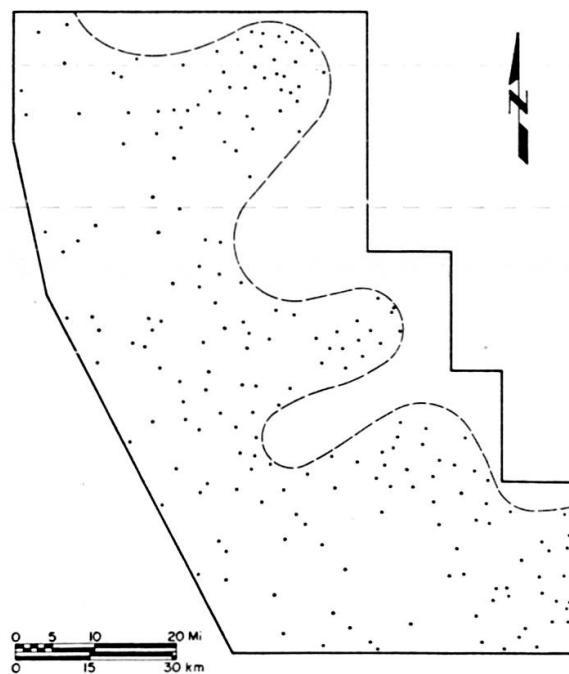


FIG. 4. — Distribution of sampling points.

Problems still exist concerning the precise position of the upper boundary of this limestone in many localities, as recently shown by Johnson (1972). The lower part of the overlying Lawson Shale consists locally of alternating layers of shale and limestone, which led Givens (1968) to suggest placing the upper boundary of the Brereton Limestone at the top of the first limestone layer. Johnson, on the other hand, believes it is best located at the last limestone layer included within the Lawson Shale unit. In fact, the Brereton Limestone can be divided into a lower purer portion and an upper more argillaceous portion. This study shows that the uppermost alternating shale and limestone layers have similar microfaunal and geochemical features as the argillaceous portion of the limestone. Hence, it is suggested that the upper boundary be put at the last limestone layer of the Lawson Shale. The lower boundary is usually distinct, overlying either the black Anna Shale or directly the Herrin (No. 6) Coal.

REVIEW OF PREVIOUS WORK

The name "Fusulina limestone" was first given to the Brereton Limestone by Worthen (1866) who showed the diagnostic fossil to be *Fusulina girtyi*. It was mentioned by Cady (1926) as the caprock of the Herrin (No. 6) Coal. Savage (1927) named this unit the Brereton Limestone.

Lennon (1957) in his study of the textural properties of the Pennsylvanian limestones of southwestern Illinois (Seville to Trivoli cyclothems), said that the Brereton was deposited in relatively deep water at least in Perry County; the sea having become deeper through time.

Wanless (1958) showed the fauna of Brereton to be mostly brachiopods, bryozoans, pelecypods and gastropods, associated with the diagnostic *Fusulina girtyi*; an assemblage he interpreted as characteristic of clear and moderately deep water.

Tubb (1961, 1963) gave several sedimentary environmental maps for the Brereton cyclothem covering Illinois, Missouri, and parts of Kansas, Iowa, Kentucky, and Indiana. His maps show the percentage of insoluble residue increasing to the northeast. Tubb's maps also show that deposition was due to a very rapid marine transgression over a very large area. He pointed out that the Brereton Limestone consists of several lithologic types; calcilutite, calcisiltite, and calcirudite with only the lithocalcirudites, which are rare and restricted to the top, showing a high energy environment. Tubb added that the Brereton Limestone deposition was terminated by an increased influx of prodelta muds from the east and the northeast rather than by a sea regression. The limestone correlates with the Myrick Station Limestone of Missouri and Iowa, and with the Providence Limestone of Kentucky.

Wanless *et al.* (1963) presented several environmental sedimentary maps of the cyclothem sequences in the Illinois Basin and adjacent areas indicating fluvialite,

deltaic, and coal swamp environments prevailing in Illinois, Indiana, and Kentucky, while marine conditions predominated in Missouri and Kansas. They added that differential compaction of deltaic sediments had a great effect in the distribution of succeeding deltaic deposits. This differential compaction left both positive and negative features which prevented the succeeding deltaic deposits from having the same trend as the previous ones. The marine transgression which followed each deltaic cycle thus inundated both positive and negative features.

Wetendorf (1967) described the environment of deposition of the Brereton, Jamestown, and Bankston cyclothems in Williamson County, Illinois, and presented a deltaic sequence as an explanation for the Pennsylvanian cycles.

Givens (1968) studied the Brereton and Jamestown cyclothems of Williamson County, Illinois. He concluded that the argillaceous Brereton Limestone was deposited in shallow quiet water of normal marine salinity whereas the pure limestone variety was deposited further offshore in open marine slightly deeper water and subjected to more vigorous energy.

A detailed stratigraphic analysis of the interval between the No. 6 Coal and the Piasa Limestone was completed by Johnson (1972). He described the Brereton Limestone as "a gray to dark gray, hard, dense, fossiliferous, and somewhat carbonaceous limestone, ranging from very argillaceous to almost lithographic. It contains numerous shale partings and argillaceous lenses in its upper half. The lower purer portions of the limestone have a characteristic gray homogeneous appearance which is often recorded as 'typical Brereton Limestone'." He presented several facies maps for that interval.

Johnson's maps show the crevasse deposits and the levees of the Walshville channel as positive features. The Walshville channel was the major channel of the contemporaneous delta (northeast of study area) during the time of deposition of the Brereton Limestone. According to Johnson the purer limestone is limited to areas generally west of the Walshville channel whereas the argillaceous facies is dominant east and southeast of it. For Johnson, the Brereton Limestone is the terminal stage of the destructive phase of a deltaic cycle leading toward open marine conditions. It is equivalent to member 9 of Weller's "Ideal Cyclothem" (Table 1).

In conclusion, it should be recalled that cyclothems are produced as a response to a natural sedimentary process. If the rate of deposition and that of subsidence change periodically, episodically, or repetitively, a cyclic effect is produced (Curtis, 1970). A deltaic process tends to develop internal cyclothem patterns independent of external factors. The process may be controlled by local variables such as delta abandonment, changing channel course, overbanking and splay deposition, etc. Cyclothems in one part of the delta may have a different origin from those in another part. This is why particular cyclothems or units should be considered and not a group of them (Oomkens, 1970).

TABLE 1

Ideal Cyclothem in Relation to Deltaic Sedimentation, after Johnson, 1972

| Ideal Cyclothem | | Delta | |
|-----------------|---|------------------------|---|
| Member | Lithology | Phase | Environment |
| 9 | Limestone | Destructive (Terminal) | Marine |
| 8 | Black shale (becoming calcareous upward) | Destructive (Initial) | Abandoned lobe-bay estuarine and mud or tidal flat |
| 7 | Limestone | Destructive | Marine |
| 6 | Gray shale (may be sandy and contain marine or plant fossils) | Constructive | Upper delta plain-crevasse splay |
| 5 | Coal | Transitional | Lower delta plain to alluvial plain-swamp |
| 4 | Underclay | Constructive | Delta plain-interdistributary bay and crevasse splay |
| 3 | Fresh-water limestone | Constructive | Lower delta plain-lagoon, lacustrine, and interdistributary bay |
| 2 | Gray sandy shale (may contain plant fossils) | Constructive | Lower delta plain-levee, crevasse splay and interdistributary bay |
| 1 | Sandstone | Constructive | Delta front-distributary sands |
| 10 | Shale with ironstone bands and nodules | Constructive | Prodelta |
| 9 | Limestone | Destructive (Terminal) | Marine |

METHODS OF STUDY

I. SAMPLING PROCEDURE

Due to the lack of surface exposures, sampling relied on already existing cores from the Illinois State Geological Survey, which provided 255 specimens. To these were added 56 specimens from strip mines (Southern Illinois and Consolidation Coal Companies). Only two natural outcrops were found in Madison County from

which eight specimens were picked. This allowed a good control on the lateral distribution of the samples (Fig. 4). Although this map shows one sample per location, there are scattered sites in which small vertical sections provided lateral and vertical samples as well. A larger scale map showing the coded identification of the sampling locations, and the corresponding raw petrographic and geochemical data are deposited with the Department of Geology, University of Illinois. The dashed line on the figure represents the general limit of deposition of the open marine shelf to interdeltic trough facies of the Brereton Limestone in the investigated area, immediately east of which are contemporaneous and more strongly deltaic-influenced deposits not included in this study.

II. PETROGRAPHIC ANALYSIS

Thin sections numbering 319, were cut to a thickness slightly above the standard value of 0.03 mm to allow better contrast among microscopic components. These sections were studied following the method proposed by Carozzi (1958) and expanded by coworkers (Stricker and Carozzi, 1974) which consists of tabulating the indices of clasticity and frequency of detrital components, and frequency index of all benthonic and pelagic organic components of a carbonate rock.

The index of clasticity for any given component in a thin section is defined as the average maximum diameter of the six largest grains of that component. The final expression of the index of clasticity is a numerical figure which represents the largest diameter of a grain that could be set in motion by the average transporting forces acting in the environment of deposition.

The frequency index of a given parameter is defined as the number of its particles present in any given area of a thin section. An area was selected for each clastic component which had a diameter of at least ten times the average diameter of the component. In the present study, standard surface areas used for frequency of crinoids, ostracods, sponge spicules, brachiopods, pelecypods, fusulinids, arenaceous foraminifers and bryozoans was 181.2 mm²; for detrital quartz, it was 30.9 mm².

The frequency of the other components not abundant enough to be computed as above, such as phylloid algae, gastropods, trilobites, calcispheres, echinoid spines, authigenic quartz, glauconite and intensity of bioturbation (burrows, swirls, etc.), was estimated by means of a relative scale with limits set as follows: Abundant = 20, Common = 10, Rare = 5, Absent = 0. However, the phylloid algae in the microfacies which they characterize, were given a value of 100 to accommodate computer requirements.

Pellets, mostly fecal and sometimes lithic, although locally present, were not counted because they either merge into a matrix or occur isolated within burrows.

Glauconite is present both as detrital grains and as a replacement product within organisms, mainly the smaller fusulinids, and in fecal pellets (Porrenga,

1967). The presence of phosphate grains was only recorded, because the relative abundance of carbonate-fluorapatite was determined by x-ray diffraction.

Thin sections were subdivided into preliminary microfacies. Subdivision was first based on the matrix, which was designated as arenaceous when containing more than 30% insoluble residue with quartz concentration; argillaceous when containing between 30% and 20% insoluble residue; and weakly argillaceous when containing less than 20% insoluble residue. Further subdivision was based on the size and amount of biogenic components. Thus, the upper limit of calcisiltites was set at 10% sand-size bioclasts, mud-supported biocalcarenes were divided into two groups, namely 10% to 20% and 20% to 40% sand-size bioclasts; grain-supported biocalcarenes display more than 40% sand-size bioclasts. Systematic clasticity and frequency measurements were made on all thin sections within each type of preliminary microfacies, and upon completion of statistical measurements of parameters, thirteen microfacies were established.

III. GEOCHEMICAL ANALYSIS

Rock chips prepared for thin sections were smoothed very thoroughly and x-rayed in the range $20^{\circ}2\theta$ to $35^{\circ}2\theta$ following the technique of Hughes *et al.* (1960), using a Norelco x-ray diffractometer with $\text{CuK}\alpha$ radiation. In this range peaks for quartz, calcite, dolomite, siderite, pyrite, hematite and carbonate-fluorapatite were detected. To check the validity of this technique, several samples were powdered and x-rayed. The patterns were similar to those obtained from the smoothed rock chips. From these patterns, semi-quantitative estimates of the amount of dolomite for each sample were obtained following the technique of Royse *et al.* (1971), and relative abundance of pyrite, hematite, siderite and carbonate-fluorapatite was obtained by measuring the heights of x-ray peaks of these minerals by arbitrary units above a common base line on the diffraction pattern. The close agreement between the diffraction patterns of these minerals for different samples of the same microfacies, indicates that the values of relative abundance have reliable precisions. The above data reveal the sedimentary mineral associations and provide some clues to diagenetic effects.

The insoluble residue was separated from the limestone by using dilute acids (acetic and/or HCl) to preserve the clay minerals, following the technique of Ostrom (1961). Upon standing the insoluble residue suspension, the fine fraction (less than 5μ) was separated by pipetting the upper few millimeters. The separated fine fraction was dried and the powders x-rayed in the range $4^{\circ}2\theta$ to $35^{\circ}2\theta$. This allowed determination of the clay minerals association and semi-quantitative estimation of their abundance following a technique commonly in use at the Illinois State Geological Survey by Dr. A. White (personal communication). The clay mineral distribution is especially significant because clays are good hosts for trace

metals. The clays would usually take up these metals within their lattices either by absorption and/or adsorption or by substitution in order to satisfy their deficient electrical charges.

Chemical analysis of the insoluble residue of 180 samples was made for Fe, Mn, Cu, Ni, Mo, Co, Pb, and Ga using a Jarrell-Ash atomic absorption spectrophotometric unit following the Jarrell-Ash manual (1972); the precision value for this analysis was $\approx 12\% \pm$. Boron was determined by a Spectroni Colorimeter following the technique of Heck (Schleicher and Heck, 1970); the precision value for this analysis was $\approx 10\% \pm$. The organic carbon was determined on total rock by the acid evolution-gravimetric method (Kuhn, 1973); the precision value for this part was $\approx 3\% \pm$.

IV. STATISTICAL ANALYSIS AND COMPUTER TECHNIQUES

The validity of separating the thin sections into their respective microfacies was checked objectively by using the ITERIM classification program (Demirmen, 1969). Validity of the map showing spatial distribution of microfacies, produced by considering the dominant microfacies at one site as representative of that particular point, was checked by using the SOUPAC Correlation Coefficient Program of means and discriminant scores of the various variables against the thirteen microfacies (Tables 2, 3).

The product-moment correlation coefficients, skewness, kurtosis, means and standard deviations for the geochemical data were computed by using the MISR subroutine (IBM ssp, 1970). For these purposes, the digital computer facilities at the University of Illinois consisting of an IBM 360/75 computer were used.

The digital computer facilities at the Illinois State Geological Survey were used to contour the geochemical parameters. The base maps for this study were produced by the Illinois State Geological Survey ILLIMAP system (Swann *et al.*, 1970). The STAMPEDE program (IBM, 1968) was used to produce numerical surfaces of the study area in order to show spatial relationships among the geochemical parameters. ISOCON maps, on which lines of equal concentrations are plotted, were generated by STAMPEDE directly on the maps.

To delineate gross patterns and separate regional from local effects, trend surface maps were generated for Ga, B, organic carbon, illite, mixed-expandables and kaolinite by using TRENSURF (also in the STAMPEDE program). Since more information describing various local changes would be gained, the third degree trend surface (cubic) was used rather than the first (linear) or second (quadratic) trend surfaces. The fourth and higher degrees usually give similar results or may even add noise with no gain of information compared to the third degree. Both the contouring and the trend surface maps were plotted by the University of Illinois OS/360 Calcomp plotting system.

TABLE 2
Correlation Coefficients of Microfacies by Means

| Microfacies | | | | | | | | | | | | | |
|-------------|-------|-------|-------|-------|-------|-------|-------|-------|------|-------|-------|------|---|
| 1 | 1 | | | | | | | | | | | | |
| 2 | .978 | 2 | | | | | | | | | | | |
| 4 | .954 | .975 | 4 | | | | | | | | | | |
| 3 | .480 | .573 | .608 | 3 | | | | | | | | | |
| 8 | .165 | .326 | .364 | .621 | 8 | | | | | | | | |
| 5 | .010 | .070 | .133 | .379 | .547 | 5 | | | | | | | |
| 7 | .320 | .447 | .391 | .263 | .164 | .164 | 7 | | | | | | |
| 10 | .111 | .070 | .267 | .301 | .778 | .393 | .898 | 10 | | | | | |
| 12 | .021 | .172 | .123 | .397 | .675 | .301 | .778 | .811 | 12 | | | | |
| 9 | .190 | .220 | .215 | .014 | .251 | .098 | .745 | .628 | .416 | 9 | | | |
| 11 | -.005 | -.035 | .015 | -.172 | -.090 | -.042 | .359 | .267 | .061 | .864 | 11 | | |
| 13 | -.131 | -.058 | -.071 | .220 | .113 | .113 | .499 | .468 | .652 | .627 | .554 | 13 | |
| 6 | -.069 | -.048 | -.092 | .100 | .034 | .031 | -.014 | -.024 | .303 | -.003 | -.096 | .216 | 6 |

TABLE 3
Correlation Coefficients of Microfacies by Discriminant Scores

| Microfacies | | | | | | | | | | | | | |
|-------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|------|---|
| 1 | 1 | | | | | | | | | | | | |
| 2 | .811 | 2 | | | | | | | | | | | |
| 4 | .089 | .515 | 4 | | | | | | | | | | |
| 8 | -.336 | .515 | .128 | 8 | | | | | | | | | |
| 3 | .092 | .004 | .175 | -.084 | 3 | | | | | | | | |
| 13 | -.173 | -.140 | -.021 | .092 | .813 | 13 | | | | | | | |
| 6 | .076 | -.070 | -.218 | -.346 | .516 | .201 | 6 | | | | | | |
| 9 | .379 | -.144 | -.558 | -.651 | -.186 | -.518 | -.354 | 9 | | | | | |
| 11 | .298 | .090 | .195 | -.265 | .099 | -.486 | -.624 | .659 | 11 | | | | |
| 5 | -.281 | -.425 | -.623 | .128 | .107 | .142 | -.210 | .377 | .080 | 5 | | | |
| 10 | -.649 | -.572 | .290 | -.066 | -.145 | -.193 | -.179 | -.189 | .153 | -.357 | 10 | | |
| 12 | -.274 | -.289 | -.571 | -.067 | -.665 | -.153 | .212 | -.080 | -.709 | .042 | -.028 | 12 | |
| 7 | .201 | .238 | -.092 | -.077 | -.935 | -.794 | .195 | -.109 | -.100 | -.354 | .032 | .615 | 7 |

MICROFACIES DESCRIPTION

A limit between carbonate skeletal material and matrix material was set arbitrarily at $60\ \mu$ because of the difficulty of identifying and counting skeletal debris below that size.

The recognized microfacies were divided into arenaceous, argillaceous, and weakly argillaceous series (Fig. 5). They are described in order of general relative depth increase in the inferred depositional environment, which is a gentle infratidal slope forming the seaward continuation of a prodelta edge and displaying some mounds, banks or bars, and depressions.

I. THE ARENACEOUS SERIES

Microfacies 1

Arenaceous and argillaceous calcisiltite with scattered sand-size bioclasts, commonly massive (Plate 1A, B). This microfacies has relatively few ostracods, brachiopods and pelecypods. In places, it is almost a quartzose sandstone with a calcisiltite matrix. Glauconite and bioturbation are rare.

Microfacies 2

Arenaceous and argillaceous mud-supported biocalcarene massive or bedded with 20% to 40% sand-size bioclasts in a calcisiltite matrix (Plate 1, C). Ostracods, brachiopods, crinoids, and pelecypods are relatively abundant. Few phosphate and glauconite grains are present, but in one thin section the latter is abundant. Bioturbation is common to abundant.

Microfacies 3

Arenaceous and argillaceous grain-supported biocalcarene, mostly bedded with a calcisiltite matrix (Plate 1, D). Ostracods, crinoids, and brachiopods are abundant and associated with a few bryozoans. Phosphatic nodules consisting of pellets in a sparite cement are noted. Glauconite is common. Bioturbation is common to abundant.

Microfacies 4

Grain-supported slightly arenaceous biocalcarene with a sparite cement, mostly massive (Plate 1, E). The major organic components are ostracods, brachiopods, crinoids and pelecypods. Pellets are rather abundant; detrital quartz is associated with rare authigenic crystals. Bioturbation is common to abundant.

Microfacies 5

This microfacies although not arenaceous, is included in this series because it is genetically associated with it.

Phylloid algal controlled limestone (*Ivanovia* sp.) with a calcisiltite matrix (Plate 1 F, G). This microfacies is weakly argillaceous with less than 15% insoluble residue; only two thin sections show slightly greater insoluble residue values due to the presence of a few detrital quartz grains and authigenic quartz crystals. Only the ostracods and bryozoans are common, whereas other organic components are rare. Bioturbation is common.

II. THE ARGILLACEOUS SERIES

Microfacies 6

Argillaceous grain-supported biocalcarenite in a calcisiltite matrix, mostly bedded (Plate 1, H). Ostracods, brachiopods, crinoids and pelecypods are the major components and abundant. Trilobites are common whereas the fusulinids, arenaceous foraminifers, algae, and gastropods are rare. Detrital quartz is rare, but glauconite and phosphate rather common. Bioturbation is common.

Microfacies 7

Argillaceous ostracodal calcarenite with a calcisiltite matrix (Plate 2, A). It is laminated and consists almost entirely of highly compacted disarticulated ostracod valves. Some detrital silt-size quartz particles and a few authigenic quartz crystals are present. Bioturbation is rare.

Microfacies 8

Argillaceous mud-supported biocalcarenite (10% to 20% bioclasts), massive or bedded with a calcisiltite matrix (Plate 2, B). Bryozoans are abundant; with ostracods and sponge spicules being fairly common. A few thin sections show argillaceous bands surrounding small nodular masses of carbonates accentuated by differential compaction. Some detrital quartz is present with rare glauconite and phosphate grains. Bioturbation is common.

Microfacies 9

Argillaceous mud-supported biocalcarenite (20% to 40% bioclasts), massive or bedded with a calcisiltite matrix (Plate 2, C). Trilobites are abundant. Most other organic components are common except for a few gastropods, algal bioclasts, and fusulinids. Some detrital, as well as authigenic quartz crystals are present, with rare glauconite and phosphate. Bioturbation is common.

Microfacies 10

Argillaceous calcisiltite, commonly massive (Plate 2 D, E). Sponge spicules are predominant with some associated ostracods; all other components are rare. Some detrital quartz is present with rare glauconite. Bioturbation is common.

III. THE WEAKLY ARGILLACEOUS SERIES

Microfacies 11

Weakly argillaceous mud-supported biocalcarene (20% to 40% bioclasts) in a calcisiltite matrix, massive or bedded (Plate 2, F). Some sponge spicules are associated with lesser amounts of ostracods, brachiopods, pelecypods and trilobites. The matrix sometimes consists of merged pellets; some big equisized pellets occur either in sparite filled burrows or scattered in the matrix. Few authigenic quartz crystals are found; detrital quartz, glauconite and phosphates are rare. Bioturbation is common.

Microfacies 12

Weakly argillaceous mud-supported biocalcarene (10% to 20% sand-size bioclasts) in a calcisiltite matrix, commonly with merged pellets, massive or bedded (Plate 2, G). Sponge spicules are more common than other organic components. Detrital quartz, glauconite and phosphate are rare. Bioturbation is abundant.

Microfacies 13

Weakly argillaceous calcisiltite commonly massive, but sometimes bedded (Plate 2, H). Sponge spicules are extremely abundant; other components are rare. Some detrital quartz particles occur, and bioturbation is very abundant.

DEPOSITIONAL MODELS

The general environment of deposition of the Brereton Limestone in the investigated area can be represented by a paleoenvironmental map showing the space distribution of the thirteen recognized microfacies (Fig. 6). Two sections across this map (AA' and BB') were used to analyze the behavior of the petrographic parameters and to interpret the environment of deposition in terms of relative energy level. AA' is designated the Algal Mound Section, and BB' is designated the Crinoidal-Brachiopod Bank Section.

Both sections show that the inferred depositional environment is a gentle infratidal slope forming the seaward continuation of a prodelta edge and displaying some irregularities in bottom topography due to the existence of local depressions

ARENACEOUS SERIES:


MICROFACIES 1  MICROFACIES 2 

MICROFACIES 3  MICROFACIES 4 

ARGILLACEOUS SERIES:

MICROFACIES 6  MICROFACIES 7 

MICROFACIES 8  MICROFACIES 9 

MICROFACIES 10 

WEAKLY ARGILLACEOUS SERIES:

MICROFACIES 5  MICROFACIES 11 

MICROFACIES 12  MICROFACIES 13 

FIG. 5. — Table of symbols.

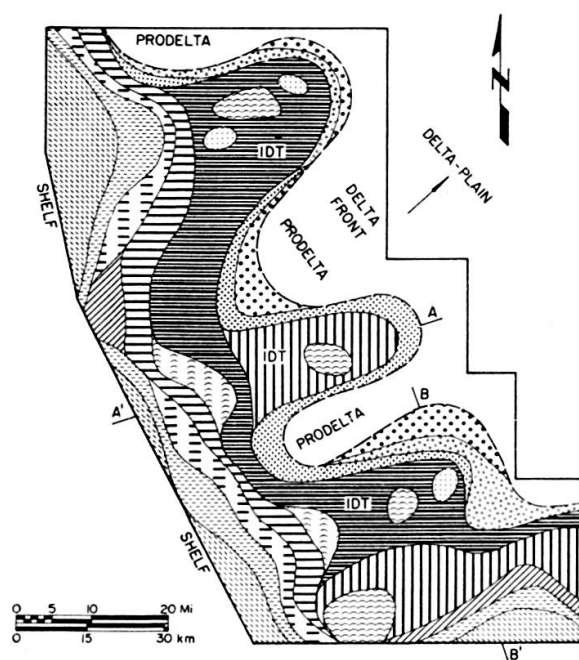


FIG. 6. — Microfacies distribution map.

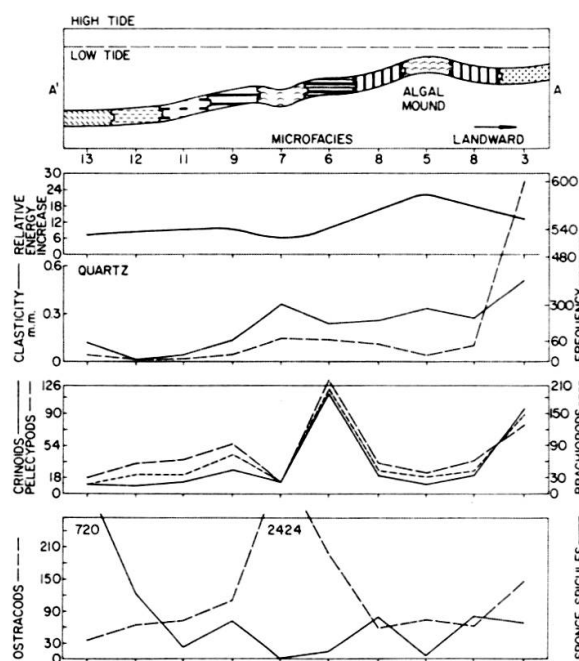


FIG. 7. — Horizontal environmental interpretation of microfacies: Algal mound section.

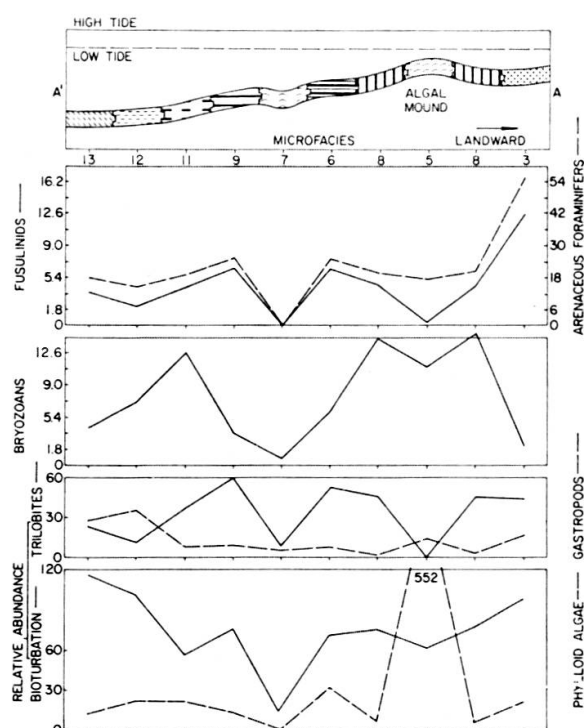


FIG. 8. — Horizontal environmental interpretation of microfacies: Algal mound section.

and elevations. The latter are essentially mounds associated with and partly controlled by phylloid algal colonies (*Ivanovia*), or with banks of crinoids and brachiopod communities slightly reworked in places into bars. Tables 4 and 5 give the characteristic values of frequency and clasticity for the components in the two sections.

I. ALGAL MOUND SECTION

Quartz (Fig. 7)

Quartz frequency and clasticity decrease generally seaward, rapidly after microfacies 3 and then gradually until microfacies 7, which shows high values due to quartz, brought in by suspension, being trapped in the depression and prevented from further transportation seaward. After that, the frequency and clasticity decrease again gradually toward microfacies 13. The scale for quartz frequency is logarithmic from 0-100, multiplied by 6.

Crinoids, Brachiopods, Pelecypods (Fig. 7)

This is a characteristic benthonic community of Pennsylvanian shallow seas which under favorable conditions (see other model), may develop into prolific banks (Neal, 1969 and Frost, 1975). In this section they reach a common peak in microfacies 6 in conjunction with suitable ecological conditions, and their frequency decreases gradually down the seaward slope.

Ostracods (Fig. 7)

The Ostracods, behaving as pseudo-pelagic fauna, are transported as disarticulated valves seaward and trapped, like quartz, in depressions where they accumulate in enormous quantities in microfacies 7.

The transported origin of the ostracods is clearly shown by the texture of microfacies 7 in which bands of highly concentrated ostracods and maximum influx of quartz alternate with bands poor in ostracods and rich in clay minerals. Furthermore, essentially no other organisms are present, and bioturbation is at a minimum indicating an absence of *in situ* bottom communities. This ecologically restricted environment is confirmed by the values of the geochemical parameters indicating inhibited water circulation over the sea floor.

Sponge Spicules (Fig. 7)

Calcified monoaxonic sponge spicules are not abundant along most of the section and randomly distributed, but reach their highest concentration in microfacies 13 after extensive transportation. Cavaroc and Firm (1968), in their study of sponge spicules in the Pennsylvanian of the Appalachian Basin, reached the conclusion that in the deltaic environment leached silica is concentrated along the shores

TABLE 4
Values of Petrographic Parameters by Microfacies for Algal Mound Section

| Components | Microfacies | | | | | | | | | | | |
|-------------------------|-------------|--------|-------|--------|---------|--------|-------|--------|--------|--|--|--|
| | 13 | 12 | 11 | 9 | 7 | 6 | 8 | 5 | 3 | | | |
| Quartz Freq. | 33.30 | 7.92 | 13.74 | 33.66 | 81.96 | 71.64 | 58.20 | 19.44 | 633.60 | | | |
| Quartz Clasticity (mm.) | 0.138 | 0.036 | 0.060 | 0.156 | 0.342 | 0.222 | 0.240 | 0.306 | 0.474 | | | |
| Ostracod Freq. | 37.38 | 70.56 | 77.88 | 118.02 | 2426.22 | 209.94 | 65.40 | 78.12 | 150.96 | | | |
| Brachiopod Freq. | 18.84 | 33.42 | 33.66 | 76.68 | 27.30 | 171.06 | 37.02 | 31.62 | 124.74 | | | |
| Crinoid Freq. | 11.04 | 10.44 | 12.12 | 27.66 | 13.44 | 118.68 | 19.92 | 10.92 | 98.94 | | | |
| Pelecypod Freq. | 18.66 | 38.10 | 43.32 | 58.86 | 16.08 | 118.14 | 36.24 | 24.84 | 80.34 | | | |
| Bryozoan Freq. | 4.86 | 7.80 | 13.32 | 4.14 | 0.00 | 6.12 | 14.94 | 11.58 | 2.94 | | | |
| Arenaceous Foram. Freq. | 19.80 | 14.76 | 20.04 | 22.80 | 1.32 | 26.22 | 20.94 | 18.42 | 51.90 | | | |
| Sponge Spicules Freq. | 723.36 | 137.28 | 24.06 | 7.35 | 0.00 | 12.66 | 80.10 | 5.10 | 69.36 | | | |
| Fusulinids Freq. | 3.84 | 2.40 | 3.78 | 7.80 | 0.00 | 6.90 | 4.68 | 0.48 | 13.50 | | | |
| Phylloid Algae | 13.20 | 24.00 | 21.30 | 15.00 | 0.00 | 13.98 | 5.88 | 555.00 | 22.50 | | | |
| Gastropods | 27.60 | 36.00 | 7.62 | 10.56 | 6.66 | 7.98 | 1.98 | 15.00 | 18.78 | | | |
| Trilobites | 24.00 | 11.64 | 37.08 | 60.00 | 10.02 | 54.00 | 46.32 | 0.00 | 45.00 | | | |
| Bioturbation | 120.00 | 105.66 | 56.46 | 77.64 | 13.22 | 72.00 | 79.56 | 62.52 | 101.28 | | | |

TABLE 5
Values of Petrographic Parameters by Microfacies for Crinoidal-Brachiopod Bank Section

| Components | Microfacies | | | | | | | | |
|-------------------------|-------------|--------|--------|-------|--------|--------|--------|--------|--------|
| | 13 | 12 | 10 | 8 | 6 | 4 | 3 | 2 | 1 |
| Quartz Freq. | 33.30 | 7.92 | 37.32 | 58.20 | 71.64 | 151.62 | 633.60 | 757.20 | 968.46 |
| Quartz Clasticity (mm.) | 0.138 | 0.036 | 0.204 | 0.240 | 0.222 | 0.504 | 0.474 | 0.60 | 1.02 |
| Ostracod Freq. | 37.38 | 70.56 | 49.98 | 65.40 | 209.40 | 223.98 | 150.96 | 100.50 | 40.68 |
| Brachiopod Freq. | 18.84 | 53.42 | 18.24 | 37.02 | 171.06 | 195.30 | 124.74 | 75.12 | 14.34 |
| Crinoid Freq. | 11.04 | 10.44 | 6.18 | 19.92 | 118.68 | 146.34 | 98.94 | 62.70 | 2.82 |
| Pelecypod Freq. | 18.66 | 38.10 | 16.20 | 36.24 | 118.14 | 126.30 | 80.34 | 30.12 | 7.98 |
| Bryozoan Freq. | 4.86 | 7.80 | 6.66 | 14.94 | 6.12 | 6.78 | 2.94 | 5.64 | 4.02 |
| Arenaceous Foram. Freq. | 19.80 | 14.76 | 11.28 | 20.94 | 26.22 | 17.40 | 51.90 | 21.24 | 0.00 |
| Sponge Spicules Freq. | 723.36 | 137.28 | 209.10 | 80.10 | 12.66 | 18.00 | 69.36 | 0.00 | 0.00 |
| Fusulinids Freq. | 3.84 | 2.40 | 4.38 | 4.68 | 6.90 | 4.80 | 13.50 | 0.78 | 4.02 |
| Phylloid Algae | 13.20 | 24.00 | 18.84 | 5.88 | 31.98 | 24.60 | 22.50 | 18.78 | 0.00 |
| Gastropods | 27.60 | 36.00 | 0.00 | 1.98 | 7.98 | 49.20 | 19.78 | 3.78 | 0.00 |
| Trilobites | 24.00 | 11.64 | 8.58 | 46.32 | 54.00 | 24.00 | 45.00 | 18.78 | 0.00 |
| Bioturbation | 120.00 | 105.66 | 57.42 | 79.56 | 72.00 | 100.02 | 101.28 | 90.00 | 19.98 |

thus generating favorable conditions for the growth of sponges. This seems to be also the case here; the sponge spicules were transported seaward. The transportation of the sponge spicules is shown by their occurrence in bands aligned parallel to bedding associated with silt-size quartz. The characteristic appearance of *in situ* sponges as concentration of micrite with oriented spicules was not observed.

Fusulinids and Arenaceous Foraminifers (Fig. 8)

Whereas arenaceous foraminifers are fairly abundant in general, the fusulinids are relatively rare. Both curves of frequency are almost parallel with a maximum in microfacies 3, and a general decrease seaward. The area of maximum frequency is located behind the phylloid algal mound in what appears to be a relatively protected but not restricted environment (Mamet, 1968). Discussion of these occurrences will be presented with the bank section.

Bryozoans (Fig. 8)

Bryozoans are predominantly of the encrusting rather than the erect type. Although they do not have a distinct pattern of distribution, they tend to associate with the phylloid algae by encrusting them.

Trilobites (Fig. 8)

The distribution of trilobites shows several frequency peaks. These organisms are responsible for textural types of bioturbation (twirls, irregular churning, etc.) which are very common in the investigated microfacies and their association is also revealed by the partial similarity between the frequency of trilobites and that of bioturbation.

Gastropods (Fig. 8)

The gastropod distribution is random and ubiquitous.

Phylloid Algae (Ivanovia) (Fig. 8)

These algae are located in the upper part of the slope (microfacies 5) where they associate with mounds due to their partial control of fine carbonate mud deposition (Wray, 1975). Scattered debris of these algae occur in the other microfacies, and are associated with encrusting bryozoans (Frost, 1975).

Bioturbation (Fig. 8)

This feature is common in the shoreward portion; decreases in the middle and intensifies in the offshore environment. As mentioned previously, a partial relationship exists between the degree of bioturbation and the frequency of the trilobites. This relationship disappears offshore, and the type of bioturbation changes to burrows suggesting the action of annelids in that area.

Energy Level (Fig. 7)

From the shore, the energy increases to a maximum at the algal mound, and then decreases gradually seaward reaching a local minimum in the depression (microfacies 7).

Conclusions

With increasing relative depth we find the following ecological communities:

1. Arenaceous foraminifers and fusulinids.
2. Phylloid algae and encrusting bryozoans.
3. Crinoids, brachiopods and pelecypods.

Ostracods and the sponge spicules behave as winnowed and redeposited components related to the distribution of detrital quartz. The intensity of bioturbation relates first to the frequency of trilobites and then to that of the annelids seaward.

II. CRINOIDAL-BRACHIOPOD BANK SECTION

Quartz (Fig. 9)

The size and frequency decrease seaward rapidly until reaching the bank, then a slow decrease occurs in the rest of the section. Again, the frequency scale is logarithmic.

Crinoids, Brachiopods, Pelecypods and Ostracods (Fig. 9)

This is the same community of benthonic components as in the previous section which reaches a large development in the upper part of the slope as a bank, locally reworked into a bar (microfacies 4, presence of sparite cement). In this section the ostracods were transported seaward and trapped behind the bank, as shown by their frequency which is identical to that of the associated benthonics.

Fusulinids and Arenaceous Foraminifers (Fig. 10)

These components have their maximum frequency in microfacies 3 shoreward of the crinoid-brachiopod bank or bar, under somewhat protected conditions where arenaceous foraminifers are known to thrive (Mamet, 1970). Both curves of frequency decrease seaward. The area of maximum frequency of the two components is clearly enclosed between the bank and an arenaceous-argillaceous calcisiltite locally grading into a sandstone, again in coincidence with a protected but not restricted environment.

Although there is no general agreement on the paleoecology of the fusulinids, they seem to occur in environments which have the following properties: within the photic zone in normal marine salinities, below wave base (Heath, Lumsden

and Carozzi, 1967), in slightly protected conditions (often intertonguing with bioherms). They do not seem to occur in shoreward areas of high energy, nor in seaward areas of low energy (Ross, 1961, Stevens, 1969 and 1971, Langenheim *et al.*, 1975). Hence these ecological conditions seem comparable with those of the present study, although the fusulinids appear to be in a marginal environment with respect to their normal habitat.

Bryozoans (Fig. 10)

They display a peak in microfacies 8 in the lower part of the slope probably as a lateral effect of phylloid algal community in the vicinity (see map, Fig. 6).

Sponge Spicules (Fig. 10)

As in the previous section, the sponge spicules were transported from the shore all the way to microfacies 13.

Trilobites (Fig. 10)

The trilobites are irregular in distribution and a partial relationship to bioturbation is observed.

Gastropods (Fig. 10)

The gastropods are ubiquitous and do not show any interpretable trend.

Phylloid Algae (Ivanovia) (Fig. 10)

The algae debris are scattered throughout the section not showing any major influence as is the case in the other section.

Bioturbation (Fig. 10)

It is at a minimum in the shoreward microfacies 1 where the trilobites, responsible for bioturbation, seem to have been unable to cope with clastic sedimentation. It becomes common in the other microfacies and intensifies in microfacies 13. In this section also there is a partial relationship between the degree of bioturbation and the frequency of trilobites which disappears offshore where the action of annelids is suggested for that area.

Energy Level (Fig. 9)

From the shore, the curve increases to a maximum in the crinoidal-brachiopodal bank or bar which lies at low tide level. It decreases seaward and is minimum at microfacies 13.

Conclusions

In this section the communities with increasing relative depth are:

1. Arenaceous foraminifers and fusulinids.
2. Crinoids-brachiopods-pelecypods.

The ostracods are trapped behind and on the bank, and the sponge spicules are transported all the way to microfacies 13.

III. RELATIONSHIP BETWEEN INVESTIGATED MICROFACIES AND DELTAIC PROCESSES

After the completion of the constructional phase of the delta—deposition of marsh and fluviatile cap deposits—a destructional phase due to the marine transgression takes place and combines compaction and reworking processes of the underlying clastics resulting in a complex topography of depressions and elevations (Scruton, 1960). Microfacies 4 and 7 of this study can be interpreted in this way.

In spite of the fact that the marine transgression deposits carbonate sediments over a partially destroyed deltaic system, some of the latter's original features can still be detected. For instance, if we consider the energy level, the prodelta slope remains under higher energy than the open shelf although both represent low energy conditions (Fig. 7, 9, and see also Allen, 1970). In the shelf area with low depositional rates and low energy, burrowing remains very intense; such is the case in microfacies 12 and 13 (Fig. 8, 10). In the marginal bay environment, the marine conditions range from open to restricted (Shabica, 1970), and microfacies 7 corresponds to the latter case.

The quartz content of microfacies 7 can also be used to illustrate another feature related to deltaic processes. During an earlier phase—delta construction—river and sea water interact to produce a stratified salt-wedge system. High saline water could occur near the bottom close to the shoreline. Fresh river water would flow over this wedge and thus transport sands and silts into the sea, as much as 30 kilometers. While spreading, the velocity diminishes with sand dropping from suspension in the marine environment (Nelson, 1970).

Limestones at the base of a cyclothem may contain, in their upper portions, beds of different lithology; indeed the Brereton Limestone is composed of an upper argillaceous portion and a lower purer portion. The upper portion represents the shoreward microfacies (Fig. 6), some of which could be a calcareous sandstone (Moore, 1959), and microfacies 1 of this investigation. The lower purer portion apparently represents the open shelf weakly argillaceous microfacies 11, 12 and 13.

Characteristics of the environment of deposition of the Brereton Limestone: namely, shallow depths, low energy level, bottom irregularities and many distinct

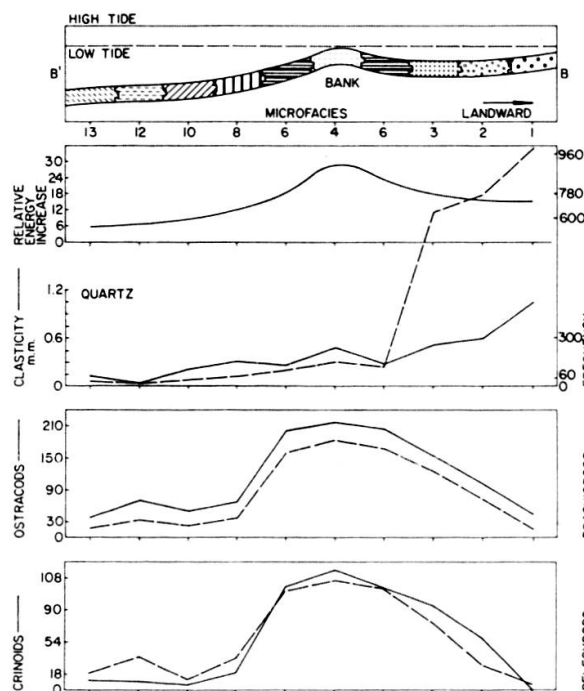


FIG. 9. — Horizontal environmental interpretation of microfacies: Crinoidal-brachiopod bank section.

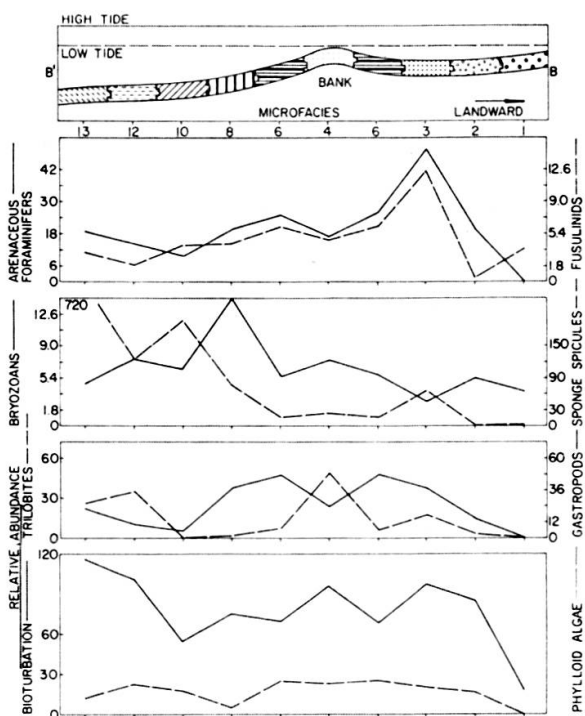


FIG. 10. — Horizontal environmental interpretation of microfacies: Crinoidal-brachiopod bank section.



FIG. 11. — Isopach map of open marine shelf to interdeltic facies (feet).

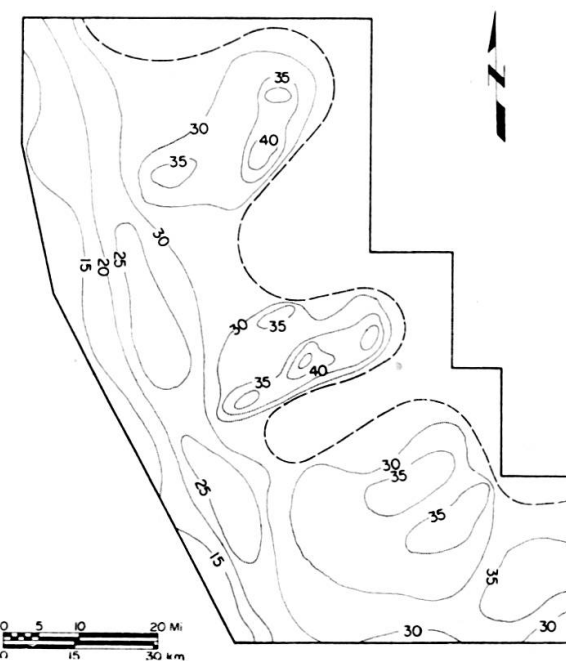


FIG. 12. — Insoluble residue distribution map (% of total rock).

carbonate microfacies, make this unit similar to limestone units in Kansas (Neal, 1969 and Frost, 1975). These conditions indicate that the Brereton Limestone is a variety of *the bank model* of deposition typical of the Pennsylvanian of the Mid-Continent (Laporte and Imbrie, 1964). The major feature of such a model is that benthonic communities thrive on bank areas which are partially controlled by leaflike algae (Harbaugh, 1964 and Wray, 1975).

GEOCHEMICAL ANALYSIS AND DIAGENESIS

Because the Brereton Limestone is variably argillaceous, and because argillaceousness plays an important role in defining large properties of the microfacies, the geochemistry of this limestone may be studied in order to appropriately illustrate the physico-chemical aspects of the inferred model of deposition. Geochemical parameters consisting of nine elements (Fe, Cu, Pb, Ni, Mn, Co, Ga, Mo, and B), organic carbon, insoluble residue, clay minerals (illite, mixed-expandables, kaolinite and chlorite), dolomite, siderite, pyrite, hematite and carbonate-fluorapatite were studied.

I. RELATIONSHIPS BETWEEN GEOCHEMICAL SPECIES

For comparative purposes the coefficient of variation (C.V. = Mean/Standard Deviation) was obtained and used to show the relative variability among the different species. This parameter is preferable when measurements of different variables are made: elements, minerals, organic matter, etc. Accordingly the variables are grouped into four categories:

| | | | |
|-----|-----------------|---|--------------------|
| | | | Greatest Variation |
| A - | (C.V.) ≥ 5 | Cu, Pb, Co | |
| B - | 4-4.9 | Ni, Mo, Illite, Mn, B, siderite | |
| C - | 2-3.9 | Ga, hematite, mixed-expandables, pyrite, carbonate- fluorapatite, chlorite | |
| D - | < 2 | Fe, kaolinite, organic C | |
| | | | Smallest Variation |

Skewness (Sk) of frequency curves of the species was used to show whether the variables are relatively enriched or not; a positive or negative skewness indicates that the mean is displaced in the direction of the positive or negative tail of the

frequency curve (horizontal scale on frequency curve). Hence, a large positive number shows that the observations have small values, i.e., not enriched, and the opposite is true for a negative skewness.

Likewise, kurtosis (Kt) of frequency curves of species indicates how many observations show enrichment effects (vertical scale on frequency curve). Thus a large positive kurtosis value indicates that a considerable number of observations is affected. For both skewness and kurtosis the variables are also grouped into four categories:

| | | | |
|-------------------|--|--------------------------|--|
| | | Least Enrichment | |
| | | ↓ | |
| A - (Sk) ≥ 2 | pyrite, carbonate-fluorapatite, Fe, hematite | | |
| B - 1-2 | organic C, chlorite, kaolinite | | |
| C - 0-0.9 | siderite, Mn, Ni, mixed-expandables, Cu, Mo, Ga | | |
| D - < 0 | Co, illite, Pb, B | | |
| | | ↓ | |
| | | Greatest Enrichment | |
| A - (Kt) ≥ 5 | pyrite, carbonate-fluorapatite, hematite, Fe | (Extremely Leptokurtic) | |
| B - 1-4.9 | Pb, siderite, Mn, organic C, chlorite, kaolinite | (Leptokurtic) | |
| C - 0-0.9 | B, mixed-expandables, Ni, illite | (Platykurtic-Mesokurtic) | |
| D - < 0 | Ga, Cu, Co, Mo | (Extremely Platykurtic) | |

Correlation coefficients between species were obtained and values of +0.5 or -0.5 are considered significant, whereas values of +0.3 to +0.4 and -0.3 to -0.4 are considered of marginal significance and values of +0.2 or -0.2 are taken to show weak correlations. These limits are set arbitrarily to help associate species more specifically and give a significance to their distribution. The following is obtained:

| <i>Positive</i> | | <i>Negative</i> | |
|-----------------|---------------------------------|-----------------|----------------------------------|
| +0.7 | pyrite-hematite | -0.5 | mixed-expandables-illite |
| +0.6 | pyrite-Fe | -0.4 | kaolinite-illite |
| +0.3 | Fe-hematite | -0.4 | kaolinite-mixed-expandables |
| +0.3 | Fe-Mn | -0.3 | pyrite-siderite |
| +0.3 | Ga-Mn | -0.3 | chlorite-illite |
| +0.3 | mixed-expandables-chlorite | -0.3 | kaolinite-carbonate-fluorapatite |
| +0.3 | chlorite-carbonate-fluorapatite | -0.3 | siderite-carbonate-fluorapatite |

The weak correlations are:

| | +0.2 | -0.2 |
|-----|--|---|
| Fe: | Ni, siderite | B |
| Cu: | organic C, Ni, siderite, Fe, Mn, Ga | |
| Pb: | Ga, organic C, Co | kaolinite, Mo |
| Ni: | Cu, Mn, Fe, Ga, organic C | B, carbonate-fluorapatite |
| Mn: | mixed-expandables, hematite, Cu, Ni, siderite | chlorite, carbonate-fluorapatite |
| Co: | illite, pyrite, Pb, chlorite | mixed expandables |
| Ga: | Pb, Cu, B, pyrite, Ni, organic C | mixed expandables |
| Mo: | B, organic C, illite, mixed- expandables | carbonate-fluorapatite, Pb |
| B: | illite, organic C | chlorite, carbonate-fluorapa- tite, siderite, mixed expand- ables, Ni, Fe |

Correlations of significance or of marginal significance exist between mineralogical species and almost none between elements. This is because the "hosts" involved with the elements are numerous: clay minerals, organic matter, sulfides, carbonates, hydroxides and oxides of Fe and Mn. Moreover, elements showing weak correlations display extreme characteristics: those showing large variation (Cu, Pb, Co, Mo, Ga) are enriched and tend to be polymodal indicating that they are controlled by several factors; those showing the smallest variation (Fe, organic C) are relatively depleted and controlled by one or two factors. Hence, "hosts" for these elements were acting interdependently to acquire them. The following relations seem apparent:

| <i>Host</i> | <i>Elements</i> |
|-----------------|--------------------|
| pyrite-hematite | Fe, Mn |
| siderite | Fe, Cu, Mn |
| organic carbon | Cu, Ni, Ga, Pb, Mo |
| clays minerals | Co, B, Mo, Pb |

Although MnO_2 was not detected, small amounts are usually associated with Fe_2O_3 . This explains the correlation coefficient value of +0.3 for Ga-Mn. The MnO_2 being a powerful colloidal matter in nature would adsorb the Ga as well as other species. Similar results have been obtained by Ruch *et al.* (1974). Some of these relations were found only indirectly especially for B, Mo, Ni, and Ga. This may be explained by the complexity of the environment: physico-chemical conditions of deposition, rates of sedimentation, degree of bioturbation, and diagenetic history.

The Fe-compounds would also be expected to host Pb, Co, and Ni; the clay minerals would host Fe, and Mn; whereas organic matter would host Fe, and B as well. In this carbonaceous limestone the organic matter is acquiring an appreciable portion of the elements.

Large positive correlation between pyrite (a reduced phase) and hematite (an oxidized phase) indicates that both oxidizing and reducing conditions could exist contemporaneously, but not necessarily at the same place. Another explanation is that hematite was brought in the basin of deposition and was later locally reduced to pyrite. Geochemical bottom conditions could be fluctuating. Glauconite in the limestone indicates low rates of deposition, an overall aerobic condition with intermediate fluctuating redox potential (Berner, 1971, pp. 201). On the other hand, the marginally significant negative correlation between pyrite and siderite is expected as both require low Eh, low $pS^=$, and low Eh, high $pS^=$ respectively (Berner, 1971, pp. 199-202). However, the formation of the two probably did not occur at the same time, the siderite appearing later.

The correlation between different clay minerals, especially -0.5 (illite and mixed-expandables) could be explained by differential sedimentation related to current action, particle size, flocculation tendencies and place of deposition. The mixed-expandables would be carried farther than illite because they would stay in suspension longer.

The carbonate-fluorapatite shows weak correlations with both oxidizing and reducing phases as well as clay minerals, again indicating the fluctuating geochemical conditions during deposition. Phosphates are adsorbed by clay minerals, the extent depends mostly on pH and initial phosphate concentration—the phosphate ion is independent of Eh (Krumbein and Garrels, 1952)—with maximum retention occurring around a pH of 7.

Ronov and Ermishkina (1959) made empirical studies which indicated that sediments deposited in a humid climate are enriched in Mn several times compared with those formed in arid climates. This is due to the waters rich in organic acids in the humid environment tending to concentrate the Mn. Mn contents greater than 0.01% should indicate a humid climate in the source area. The results of this investigation show that over 70% of the samples have Mn contents greater than 0.01%. This confirms geochemically the humid climate which characterizes the Pennsylvanian coal swamps.

Wherever several vertical samples were taken at one site, the change for some species stratigraphically upwards is noted as follows:

| <i>Increasing</i> | <i>Decreasing</i> |
|--------------------|-------------------|
| insoluble residue | B, Mn, Pb, Ni |
| organic carbon | |
| Fe, Ga, Mo, Cu, Co | |

This change indicates more continental influence with time expressing onset of the overlying deltaic phase. Species which are increasing stratigraphically upwards are brought in the basin of deposition by freshwater, while those species that are decreasing upward associate more with a marine influence.

II. ENVIRONMENTAL SIGNIFICANCE OF GEOCHEMICAL SPECIES

The microfacies map (Fig. 6) and the two sections AA' (Fig. 7, 8) and BB' (Fig. 9, 10) can be used to illustrate how the geochemical species relate to the environment of deposition. Essentially, the microfacies map presents two major depositional trends: one NNW-SSE along the shelf and roughly parallel to the shore; the other ENE-WSW along the interdeltic troughs and roughly normal to the shore. The two sections, on the other hand, present a gentle slope with irregularities due to depressions and elevations.

Isopach Map of Open Marine Shelf to Interdeltic Trough Facies (Fig. 11)

This simplified map shows a general wedging out to the NE toward the delta environment combined with local thickenings. In reality, the carbonate deposition is much more complex and consists of many juxtaposed irregular lenses separated by areas where carbonates may even be missing and replaced by delta-influenced clastics (Walshville Channel). This irregular type of carbonate deposition which cannot be represented graphically at this regional scale is well expressed by the distribution of all the mineralogic and geochemical parameters. Similar maps were presented by Brown *et al.* (1973) in their investigation of the Pennsylvanian of north-central Texas.

Insoluble Residue (Fig. 12)

The importance of argillaceousness is emphasized in this map which shows the same major depositional trends presented by the microfacies map (Fig. 6). Toward the shelf area, bands of less than 20% insoluble residue are obvious. Shoreward, the percentage increases to more than 30% in coincidence with the arenaceous microfacies.

The Clay Minerals

The clay minerals will be discussed in an order corresponding to a shoreward direction.

Mixed-Expandables (Fig. 13, 14)

Consisting mostly of imperfect crystallites of different clay minerals and due to their fineness, the mixed-expandables are carried long distances over the shelf.

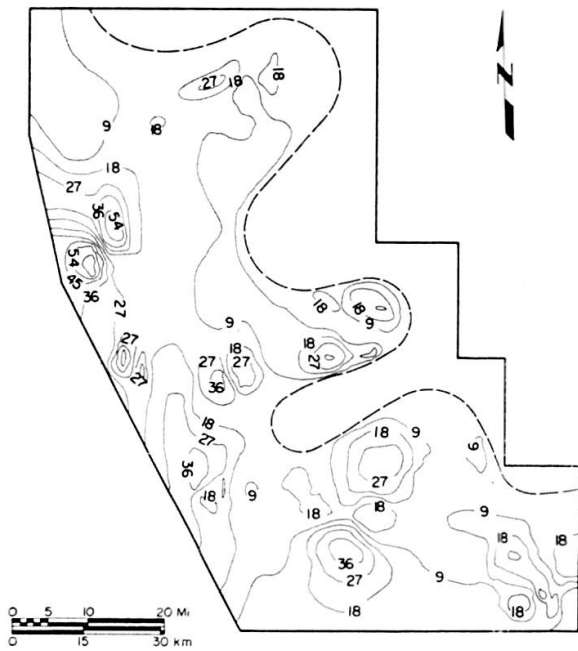


FIG. 13. — Mixed-expandables distribution map (% of total clays).

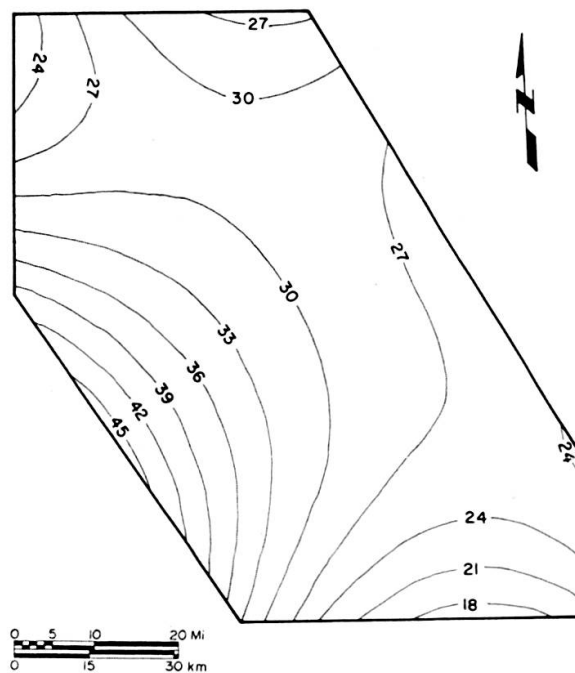


FIG. 14. — Mixed-expandables 3rd degree trend surface map.



FIG. 15. — Chlorite distribution map (% of total clays).

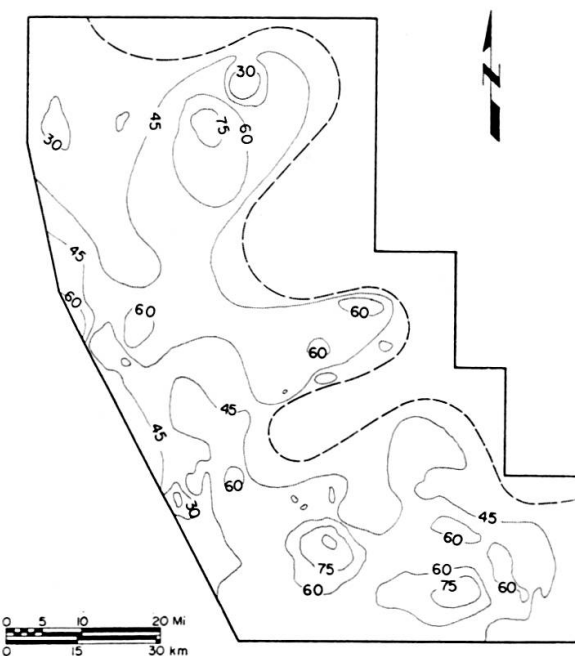


FIG. 16. — Illite distribution map (% of total clays).

Most of the maximums in the distribution map are thus explained. The two depositional trends are apparent. The trend surface map shows larger values to the southwest indicating the seaward direction, with decreasing values to the north, east, and southeast.

Chlorite (Fig. 15)

Because most of the chlorite is a synsedimentary alteration product of mixed-expandables, its maximums are spread over the area with some coinciding with those of the mixed-expandables. In fact, the chlorite is expected to be more stable in the alkaline marine environment toward the shelf. The mixed-expandables are considered degraded clay minerals, which could regrade partially into chlorite. The two depositional trends are clearly shown.

Illite (Fig. 16, 17)

Illite maximums are irregularly distributed, yet a weak tendency exists for concentration shoreward. The two depositional trends are weakly developed. The trend surface map shows values increasing shoreward to the east though with a plateau along the shore vicinity.

Kaolinite (Fig. 18, 19)

All kaolinite maximums are found along the shore. This is expected because the relatively larger kaolinite particles would settle faster than the other clay minerals. The two depositional trends are barely developed. The trend surface map shows decreasing values to the southwest, and increasing values to the east, the northwest and southeast.

Carbonate-Fluorapatite (Fig. 20)

Only one clear maximum occurs in the carbonate-fluorapatite distribution map. This maximum coincides with similar ones in the chlorite and mixed-expandables maps confirming the +0.3 correlation coefficient value noted before for the carbonate-fluorapatite and chlorite. It shows a weak tendency for minor concentration toward the shelf area. The two depositional trends are clearly expressed.

The Iron Minerals

The order of description is directed by the fact that hematite is brought in by freshwater and later diagenetically altered to pyrite and siderite.

Hematite (Fig. 21)

One maximum occurs in the northernmost interdeltaic trough with minor ones occurring roughly parallel to the shore. Because Fe_2O_3 is a colloidal substance,

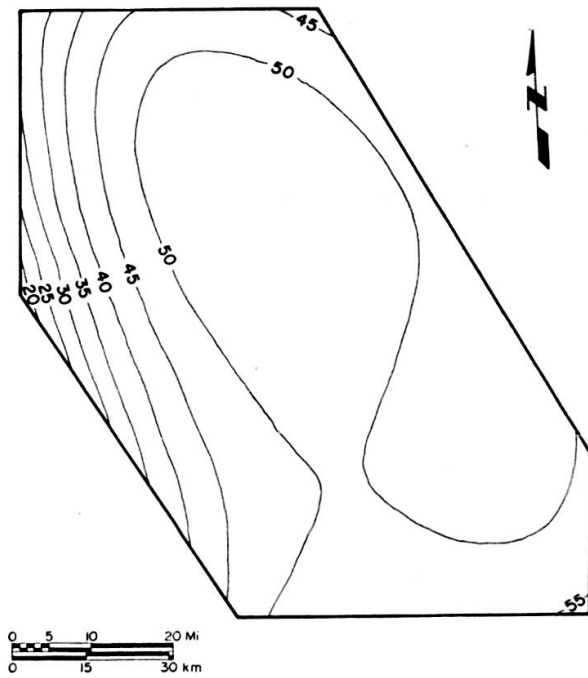


FIG. 17. — Illite 3rd degree trend surface map.

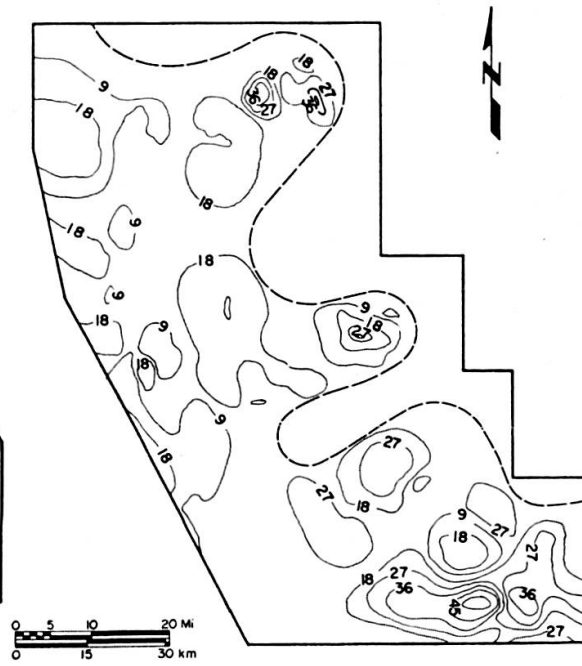


FIG. 18. — Kaolinite distribution map (% of total clays).

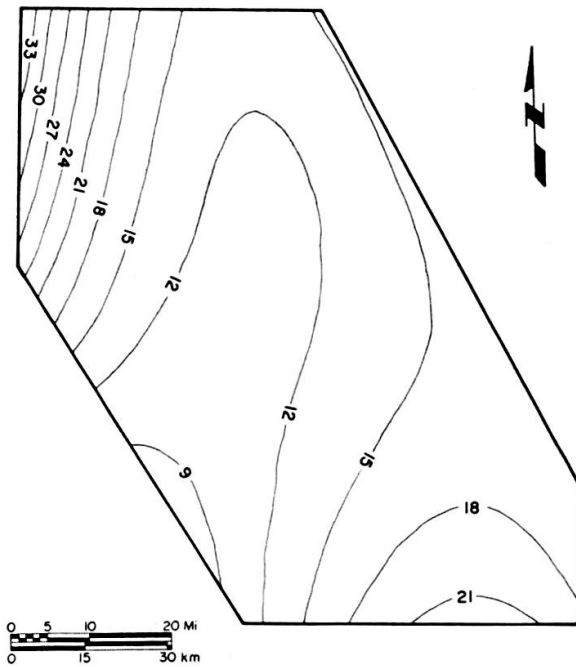


FIG. 19. — Kaolinite 3rd degree trend surface map.

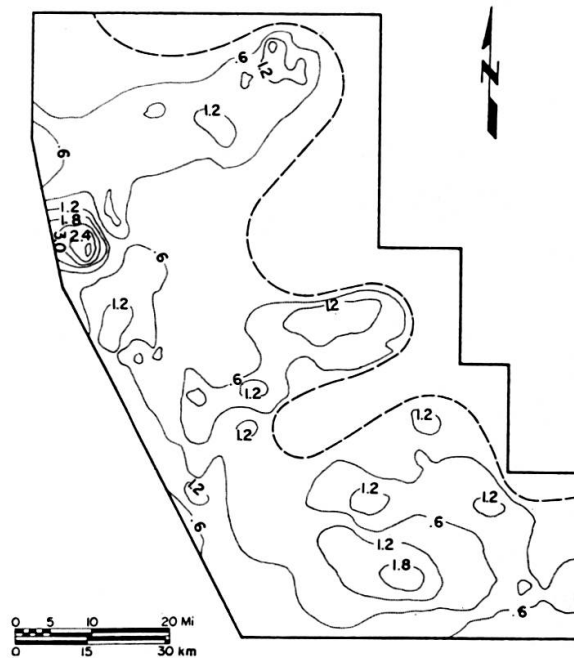


FIG. 20. — Carbonate-fluorapatite distribution map (relative abundance).

it is transported for a long distance, therefore the hematite does not show distinct concentration, and the two depositional trends are weakly developed.

Pyrite (Fig. 22)

Pyrite shows roughly the same distribution as the hematite indicating that the former is a syngenetic alteration of the latter. The maximum coincides with that of hematite, and the two depositional trends are almost missing.

Siderite (Fig. 23)

Although siderite is another early diagenetic alteration product, it shows only minor similarities to the distribution of hematite and pyrite. This is because the siderite is dependent on the carbonate sedimentation supplying the $\text{CO}_3^{=}$ ion. The two depositional trends are again obvious and result from the combination of the effects of the continental supply (iron minerals) and of the shelf carbonate environment.

Iron (Fig. 24)

The iron brought in by freshwater is mostly concentrated in the interdeltic troughs, and towards the shelf it displays bands of decreasing concentration clearly reflecting the two depositional trends. Maximum values associate with the maximums of all the preceding iron minerals.

Organic Carbon (Fig. 25, 26)

Like iron, the organic matter is predominantly brought in by freshwater and derived from plant materials originally growing in the delta plain marshes and swamps; an additional contribution is from the *in situ* decay of the tissues of marine organisms. This is the reason why maximum values occur both seaward and shoreward, again the two depositional trends are barely visible. The trend surface map shows values decreasing seaward, south, southwest, and west, while increasing in the other directions.

Boron (Fig. 27, 28)

As the clay minerals take up boron in relation to its concentration in solution, the boron has been used to show influence and degree of paleosalinity of the environment of deposition. Normal marine paleosalinity values scatter around 300 ppm (Rumeau in Carozzi *et al.*, 1972). This is confirmed in this study as the boron values seaward are mostly around 325 ppm. Shoreward, due to restriction, values are higher. Such a situation also occurs in intermediate local areas indicating restriction, which could be explained by referring to the depressions existing along the slope (section AA', Fig. 7, 8). The two depositional trends are visible. On the other hand,

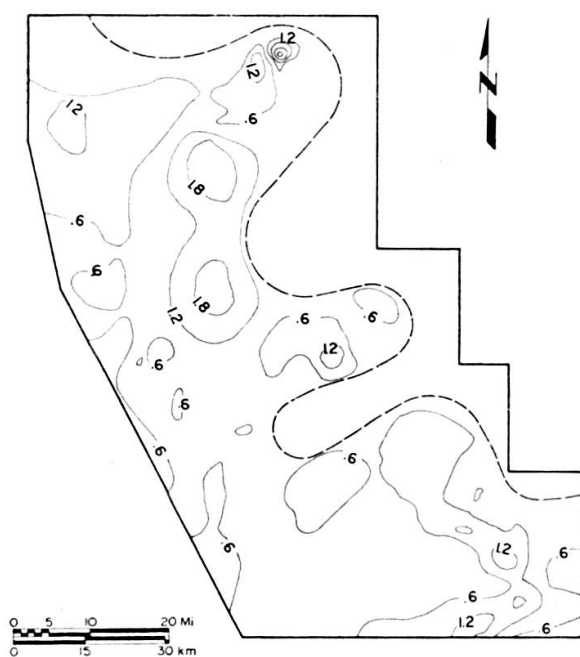


FIG. 21. — Hematite distribution map (relative abundance).



FIG. 22. — Pyrite distribution map (relative abundance).

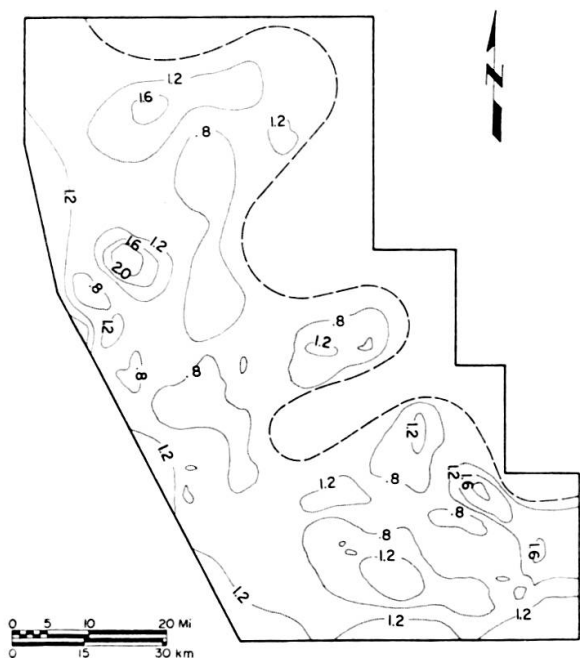


FIG. 23. — Siderite distribution map (relative abundance).

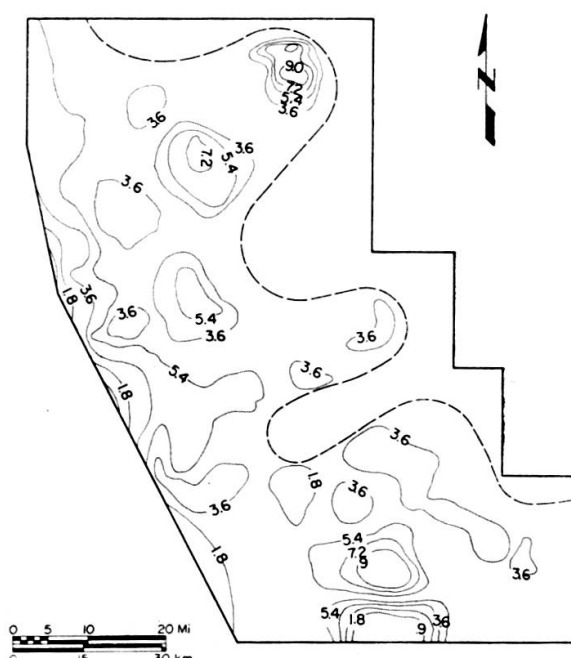


FIG. 24. — Iron distribution map (%).



FIG. 25. — Organic carbon distribution map (% of total rock).

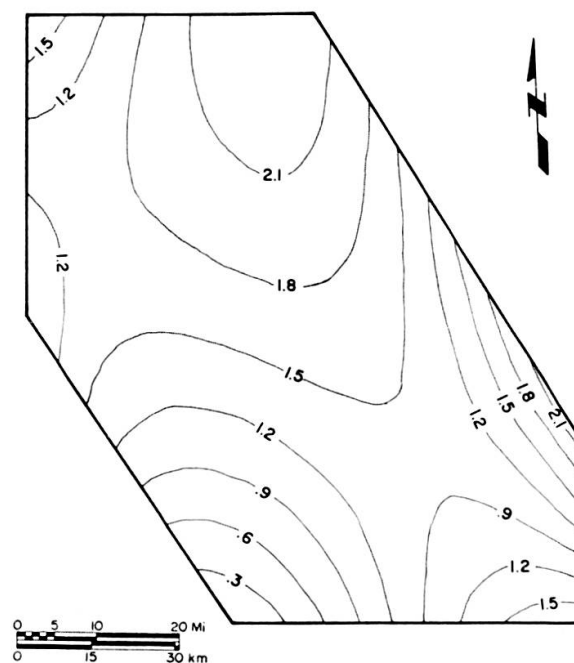


FIG. 26. — Organic carbon 3rd degree trend surface map.



FIG. 27. — Boron distribution map (ppm).

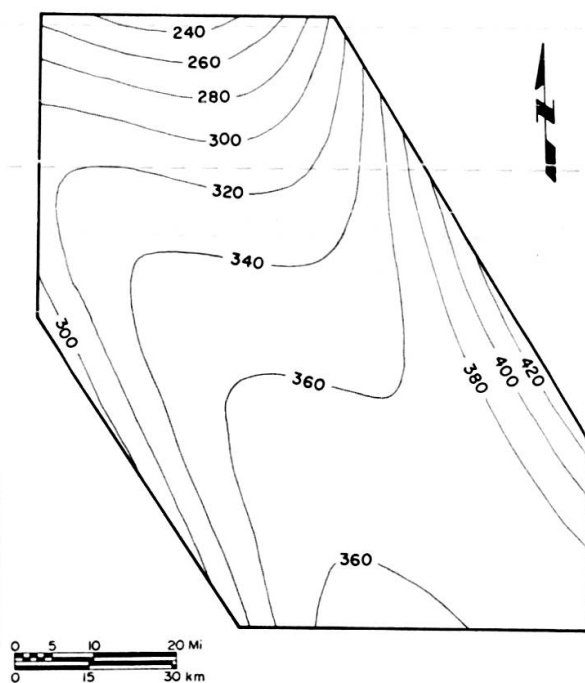


FIG. 28. — Boron 3rd degree trend surface map.

the trend surface map depicts increasing values shoreward to the east due to restriction, a plateau-like area of normal salinities 320-360 ppm, and a slight decrease to the north and northwest due to freshwater dilution.

Gallium (Fig. 29, 30)

Among a suite of other elements used in conjunction with boron for paleo-environmental studies (Swaine, 1967), Ga seems to show influence of continental influx. The distribution map shows the two depositional trends. Concentration is located toward the shore, whereas bands of weaker values are noticeable seaward. The trend surface map also confirms this with values increasing to the northwest and east, whereas decreasing seaward to the south, southwest and west.

Molybdenum (Fig. 31)

Presents the same behavior as Ga, both being associated to a high degree with organic matter.

Copper (Fig. 32)

The copper distribution map reveals very clearly the two depositional trends. Large concentration values toward the shore are probably due to reducing environments associated with organic carbon (Fig. 25), and contrast with the lower values concentration bands toward the shelf.

Manganese (Fig. 33)

This element displays quite well the two trends except that the outer shelf bands show the greater values. This is expected as the manganese would be associated with carbonate sedimentation. Manganese would associate also with iron-minerals explaining the shoreward concentrations.

Nickel (Fig. 34)

Keck (1973) showed, in his work on trace elements in Pennsylvanian and Mississippian sediments, an increase in nickel with more marine influenced environments. In this investigation similar results are obtained. The nickel map shows large concentration bands towards the shelf. However, nickel would also be associated in reducing environments with organic carbon (Fig. 25) thus explaining the other shoreward concentration areas. The two depositional trends are clearly displayed.

Cobalt (Fig. 35)

The cobalt being mostly associated with the clay minerals has a widely scattered distribution throughout the area. It is also partly associated with organic matter

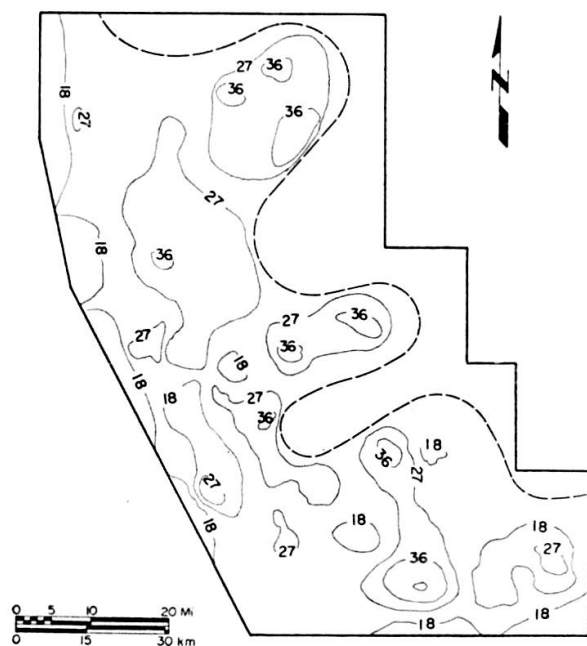


FIG. 29. — Gallium distribution map (ppm).

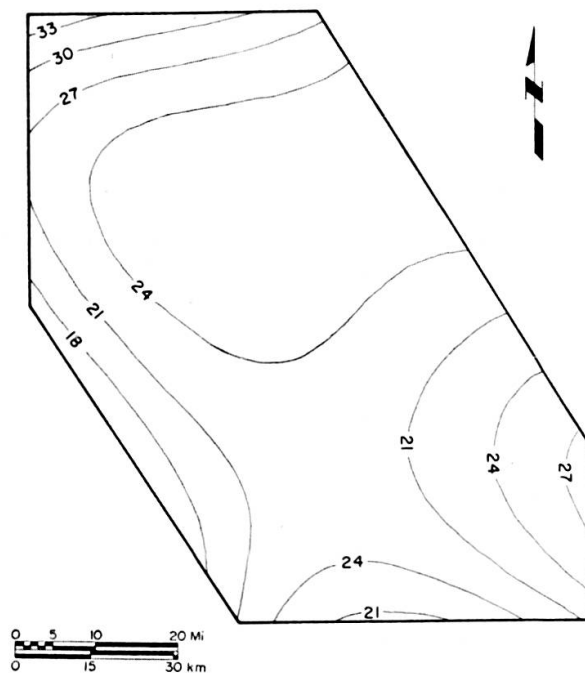


FIG. 30. — Gallium 3rd degree trend surface map.

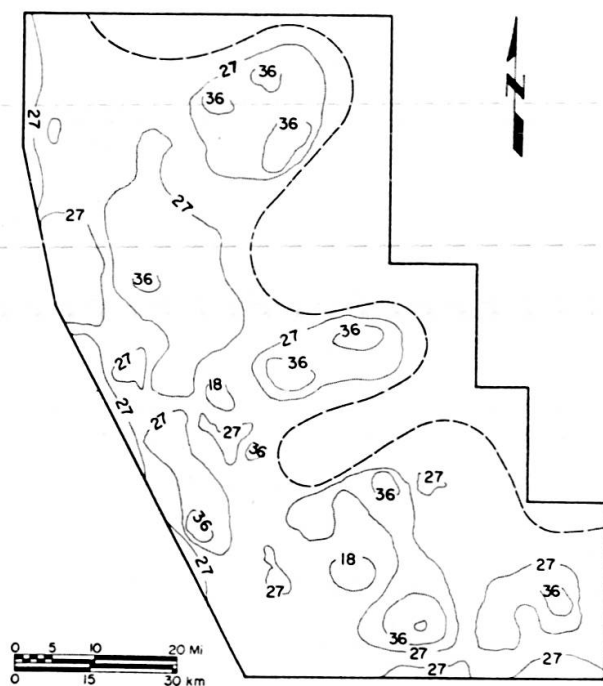


FIG. 31. — Molybdenum distribution map (ppm).

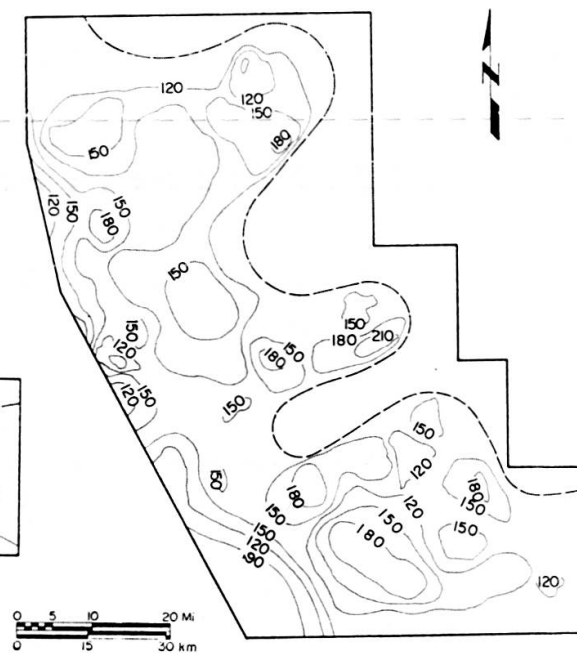


FIG. 32. — Copper distribution map (ppm).



FIG. 33. — Manganese distribution map (ppm).

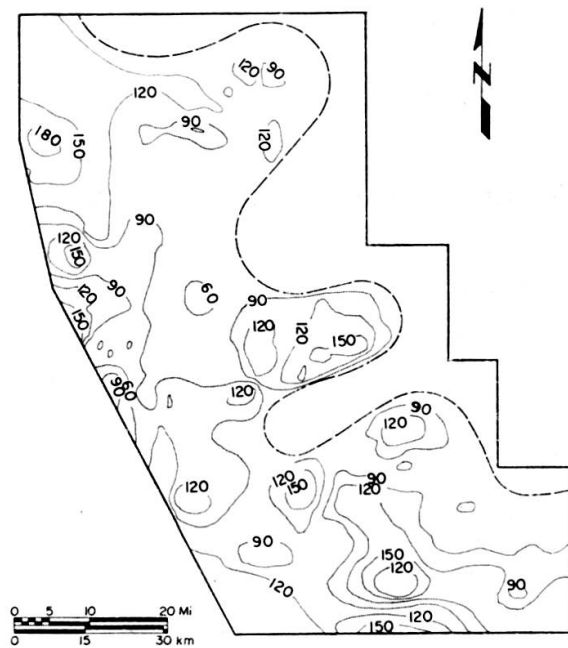


FIG. 34. — Nickel distribution map (ppm).

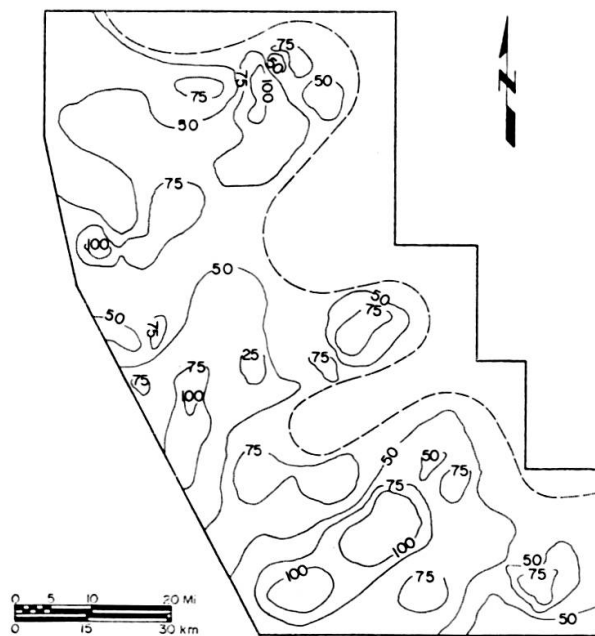


FIG. 35. — Cobalt distribution map (ppm).

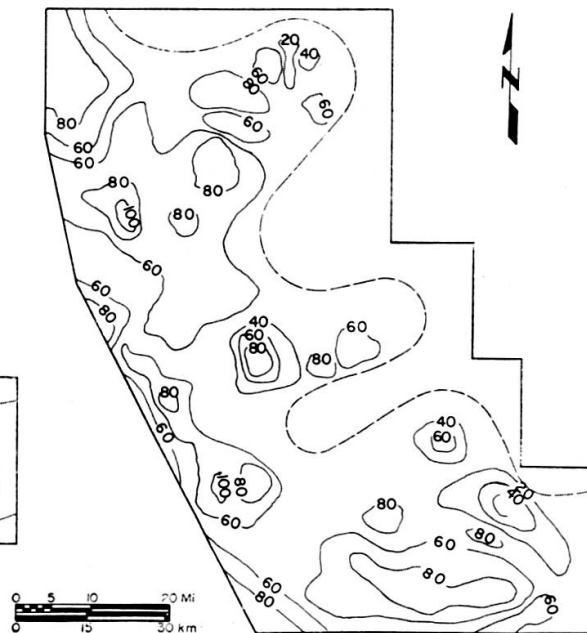


FIG. 36. — Lead distribution map (ppm).

thus explaining the shoreward maximums. The two depositional trends cannot be recognized.

Lead (Fig. 36)

In this investigation lead associates mostly with organic matter and partly with the clay minerals. This explains the higher concentrations toward the shore. The two depositional trends are clearly shown, probably due to the incorporation of lead in solid solution in aragonite which later transforms into calcite releasing the lead along the shelf.

III. RELATIONSHIPS BETWEEN GEOCHEMICAL SPECIES AND MICROFACIES

Average values of the previously mentioned elements and organic carbon (Table 6), were obtained and plotted against microfacies (Fig. 37).

In the ten curves presented, two groups, each having its own character, are obvious. The first group includes B, Fe, organic C, Ga, Mo and Cu. The curves for this group start with rather large values in the shoreward microfacies 1 and 2 (sometimes 3), decrease to microfacies 4 either rapidly or gradually, then increase to microfacies 7 where they reach another peak. After that the curves decrease again to become constant toward the shelf microfacies. The values for B, other than in microfacies 7 and shoreward, cluster around 300 ppm indicating normal paleosalinities. The high values for B shoreward as well as in microfacies 7 are probably due to restriction (Moore, 1966). The other curves in this group can be explained similarly at microfacies 7, but shoreward they indicate association with detrital components brought in by freshwater.

The second group of curves includes Mn, Co, Pb, and Ni. The curves of this group have gentle slopes and sometimes are level. Co and Pb show minor peaks at microfacies 7, whereas Mn and Ni show minor depressions at the same place. The latter two elements are more common in open marine than in restricted conditions.

Dolomitization (Fig. 38)

Dolomitization is a major diagenetic process in the Brereton Limestone. Around 70% of the samples studied show dolomitization to varying degrees ranging from less than 10% to more than 90%. Apparently, the dolomitization process was not selective, as shown by the distribution map, with respect to environment and microfacies. Dolomitization is expressed for a given location by the following formula: $\text{thickness} \times \text{weight \% of dolomite}/100$, in order to standardize values obtained from sites consisting of one sample and from others consisting of several vertically distributed samples. Concentration of the Mg ions was obtained from several sources:

TABLE 6
Average Values of Geochemical Species by Microfacies

| Components | Microfacies | | | | | | | | | | | | |
|-------------------|-------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
| Iron, % | 3.00 | 2.88 | 2.67 | 2.40 | 2.30 | 2.34 | 3.03 | 2.80 | 2.26 | 2.40 | 2.34 | 2.50 | 2.50 |
| Organic Carbon, % | 2.64 | 1.93 | 1.30 | 0.86 | 1.28 | 1.10 | 2.42 | 1.02 | 0.95 | 1.02 | 1.10 | 1.03 | 1.11 |
| Boron, ppm | 405.00 | 370.00 | 355.00 | 320.00 | 320.00 | 350.00 | 420.00 | 330.00 | 325.00 | 345.00 | 340.00 | 350.00 | 340.00 |
| Gallium, ppm | 26.50 | 24.85 | 19.63 | 19.23 | 16.18 | 18.05 | 23.80 | 16.25 | 16.30 | 16.55 | 16.62 | 15.16 | 16.33 |
| Molybdenum, ppm | 28.80 | 28.45 | 22.16 | 23.05 | 20.19 | 19.86 | 22.70 | 18.30 | 18.68 | 18.55 | 18.62 | 19.16 | 18.60 |
| Manganese, ppm | 86.20 | 98.80 | 105.66 | 105.30 | 111.16 | 121.10 | 104.00 | 112.36 | 118.40 | 108.44 | 112.25 | 111.25 | 116.30 |
| Cobalt, ppm | 107.40 | 98.33 | 102.16 | 106.40 | 108.22 | 100.66 | 108.80 | 99.31 | 110.33 | 111.66 | 102.60 | 109.80 | 110.10 |
| Copper, ppm | 233.30 | 224.00 | 218.40 | 163.47 | 165.83 | 163.45 | 192.66 | 172.20 | 175.60 | 180.17 | 185.80 | 175.00 | 167.85 |
| Lead, ppm | 124.60 | 120.75 | 132.25 | 108.00 | 114.66 | 120.54 | 132.00 | 125.30 | 115.66 | 116.33 | 132.75 | 131.50 | 136.70 |
| Nickel, ppm | 126.00 | 128.75 | 138.50 | 136.18 | 146.00 | 142.60 | 131.66 | 126.70 | 132.33 | 143.55 | 148.75 | 141.82 | 143.14 |

sea water, clay minerals, clastic influx, and probably phylloid algae (Frost, 1975). It is most likely that the dolomitization process is late diagenetic as no signs of primary or penecontemporaneous dolomites are visible petrographically.

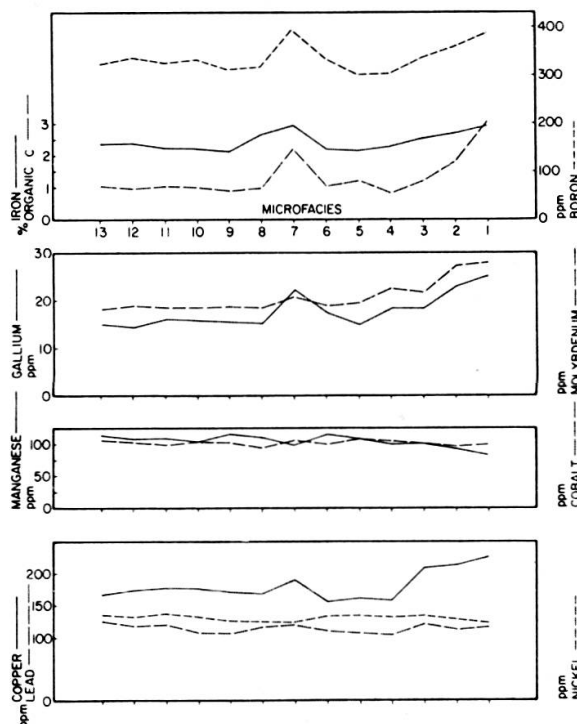


FIG. 37. — Distribution of elements by microfacies.

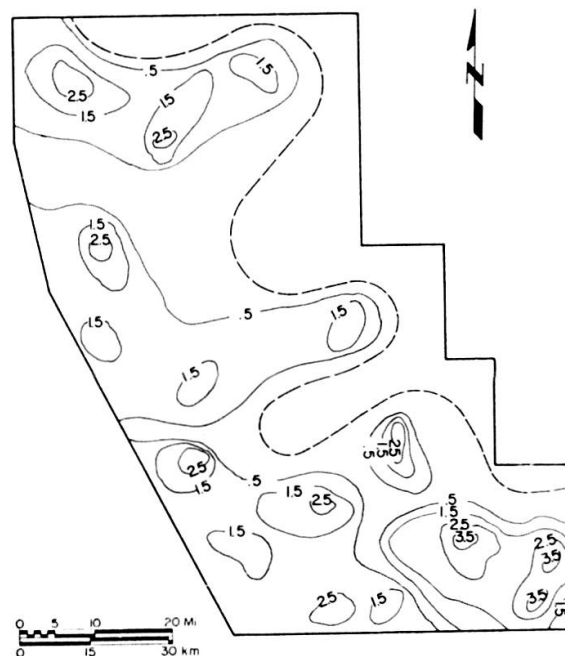


FIG. 38. — Dolomitization distribution map = thickness \times wt.% dolomite/100.

Conclusions

The above geochemical study reveals that some elements, like copper, show great variations, are extremely platykurtic, and relatively enriched, whereas others like iron, display minor variations, are extremely leptokurtic, and relatively depleted. Correlation coefficients—identifying host-element relationship—show that the organic matter played a more active role in acquiring elements than the iron minerals or clay minerals. The depositional environment seems to have had low rates of deposition, overall aerobic conditions, and intermediate fluctuating redox potential.

The geochemical analysis also confirms the results obtained by petrography concerning the environment of deposition of the Brereton Limestone. It indicates two major depositional trends in the study area affecting the distribution of the various parameters. These two trends are dictated by the continental influx shoreward in the interdeltic troughs, and by the predominant shelf conditions seaward. Moreover, the transition between shore and shelf is accompanied by some local environments that are restricted probably due to inhibited water circulation controlled by local elevations and depressions which existed along the general slope. Other than

these local phenomena, conditions are normal marine as indicated by boron values scattering around 300 ppm. Species coming mostly with freshwater, and those that are dominant in the marine environment indicate an increasing continental influence stratigraphically upwards pointing toward beginning of the overlying deltaic phase. The 3rd degree trend surface maps reveal that the marine influence was to the west, southwest, and south, whereas the opposite directions express the shoreward influence. Dolomitization is late diagenetic, and non-selective with respect to microfacies.

CONCLUSIONS

The Brereton Limestone in the investigated area is a transgressive unit over a delta system. It represents marine deposition in three interdeltic troughs, and over an open shelf. The environment of deposition, illustrated by two sections, consists of a general infratidal slope extending from a prodelta edge to a shelf with some topographic irregularities consisting of depressions and elevations. The elevations are due to mounds, and banks locally reworked into bars, and the depressions are partially restricted and protected areas. These features are revealed by the space distribution of thirteen microfacies divided into three groups: arenaceous, argillaceous, and weakly argillaceous. The relative energy is generally low, though variations exist due to bottom irregularities.

Petrographic analysis reveals that the microfacies contain a varied fauna. The most important *in situ* contributors are: phylloid algae, the association crinoids-brachiopods-pelecypods and fusulinids-arenaceous foraminifers. Other important elements, which represent transported faunas, are sponge spicules and the ostracods. The space distribution of these faunas is represented along the two sections designated as the Algal Mound Section and the Crinoidal-Brachiopod Bank Section. The irregularities displayed by the infratidal slope obviously control the deposition in the investigated area. All these features indicate that the Brereton Limestone is a variety of the *bank model* of deposition typical of the Pennsylvanian of the Mid-Continent.

The environmental model derived from the microfacies has been analyzed from a geochemical viewpoint. The geochemistry confirms the results obtained by petrography. It indicates two major depositional trends in the study area affecting the distribution of the various parameters. One is the continental influx shoreward in the interdeltic troughs, the other is the open shelf conditions seaward. Moreover, transition between shelf and shore is accompanied by some locally restricted environments due to inhibited water circulation controlled by bottom irregularities.

The clay mineral distribution is mostly controlled by their particular properties of flocculation and deposition. Hence, the kaolinite is shoreward; illite tends to concentrate shoreward but is not localized; chlorite—a syngenetic alteration

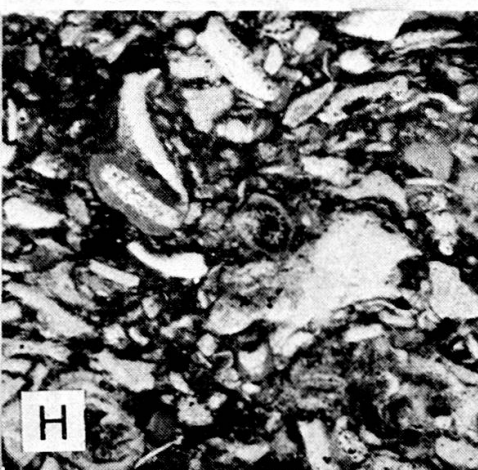
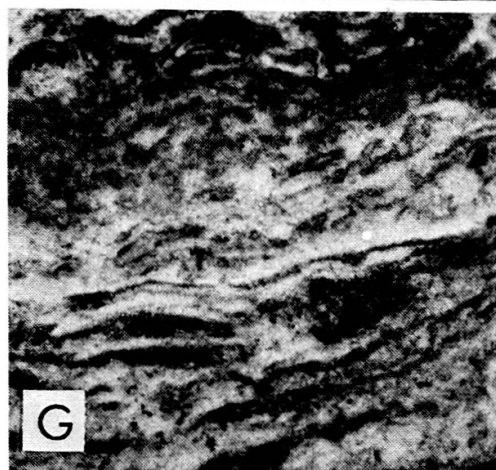
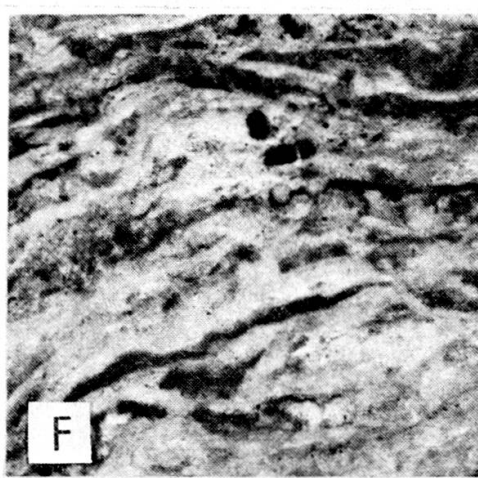
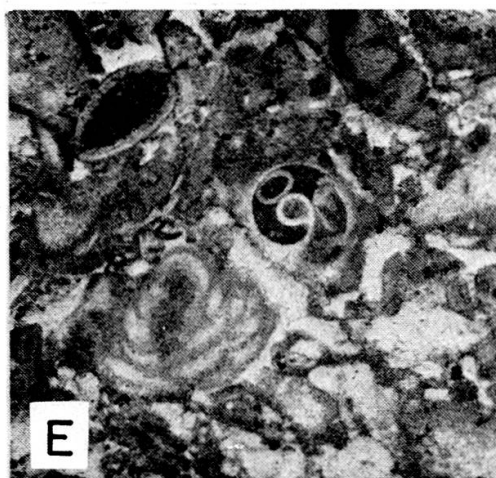
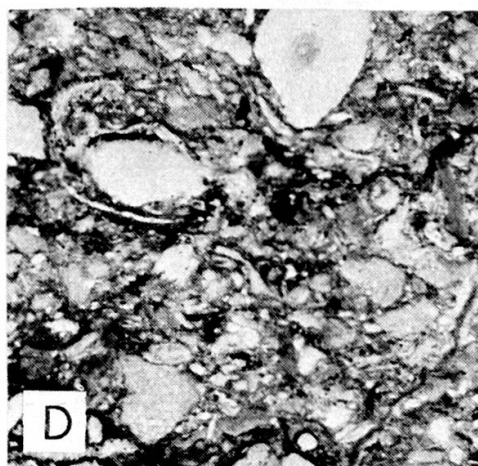
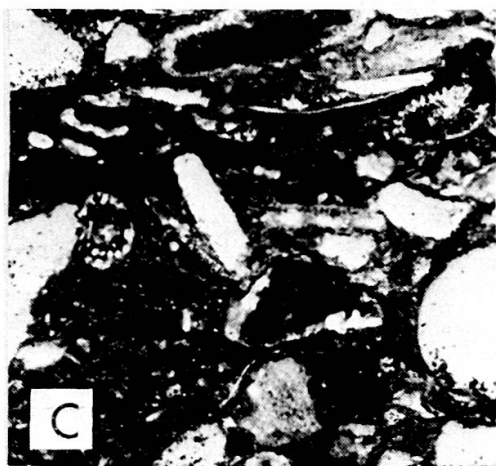
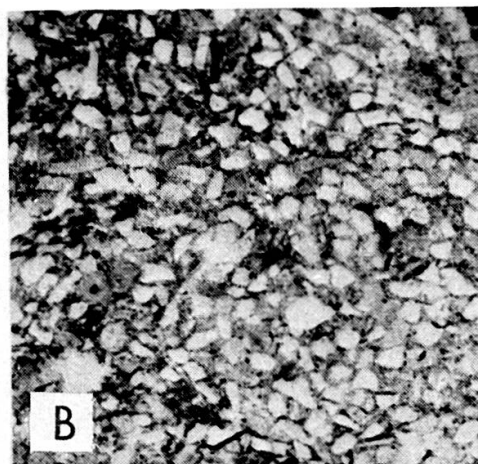
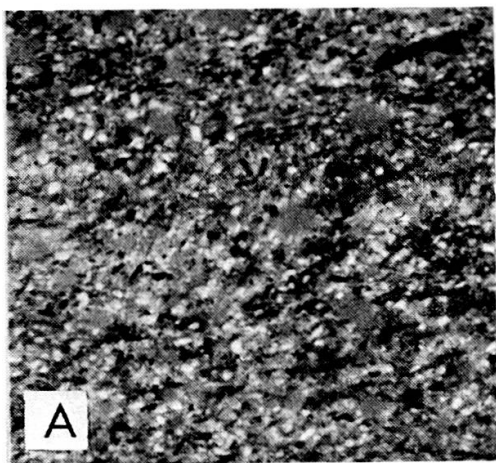
product of mixed-expandables—occurs mostly with the latter seaward. Carbonate-fluorapatite is associated with the clay minerals. The iron minerals, pyrite and siderite, are mostly alteration products of hematite, the latter is coming with the freshwater. The organic matter, also largely coming with the freshwater, behaves similarly to hematite. Concentrations of the elements (Fe, Co, Ni, Cu, Ga, Pb, Mo, Mn and B) shoreward are due to their association with continental detrital components, whereas their concentrations seaward are due to association with a marine carbonate sedimentation. Boron values around 300 ppm indicate that generally, the deposition of the Brereton Limestone took place in an environment of normal marine salinity. Species which are coming mostly with the freshwater, and those which are dominant in the marine environment indicate an increasing continental influence with time, thus revealing the beginning of the overlying deltaic phase. Dolomitization is a major late diagenetic process, being non-selective with respect to microfacies.

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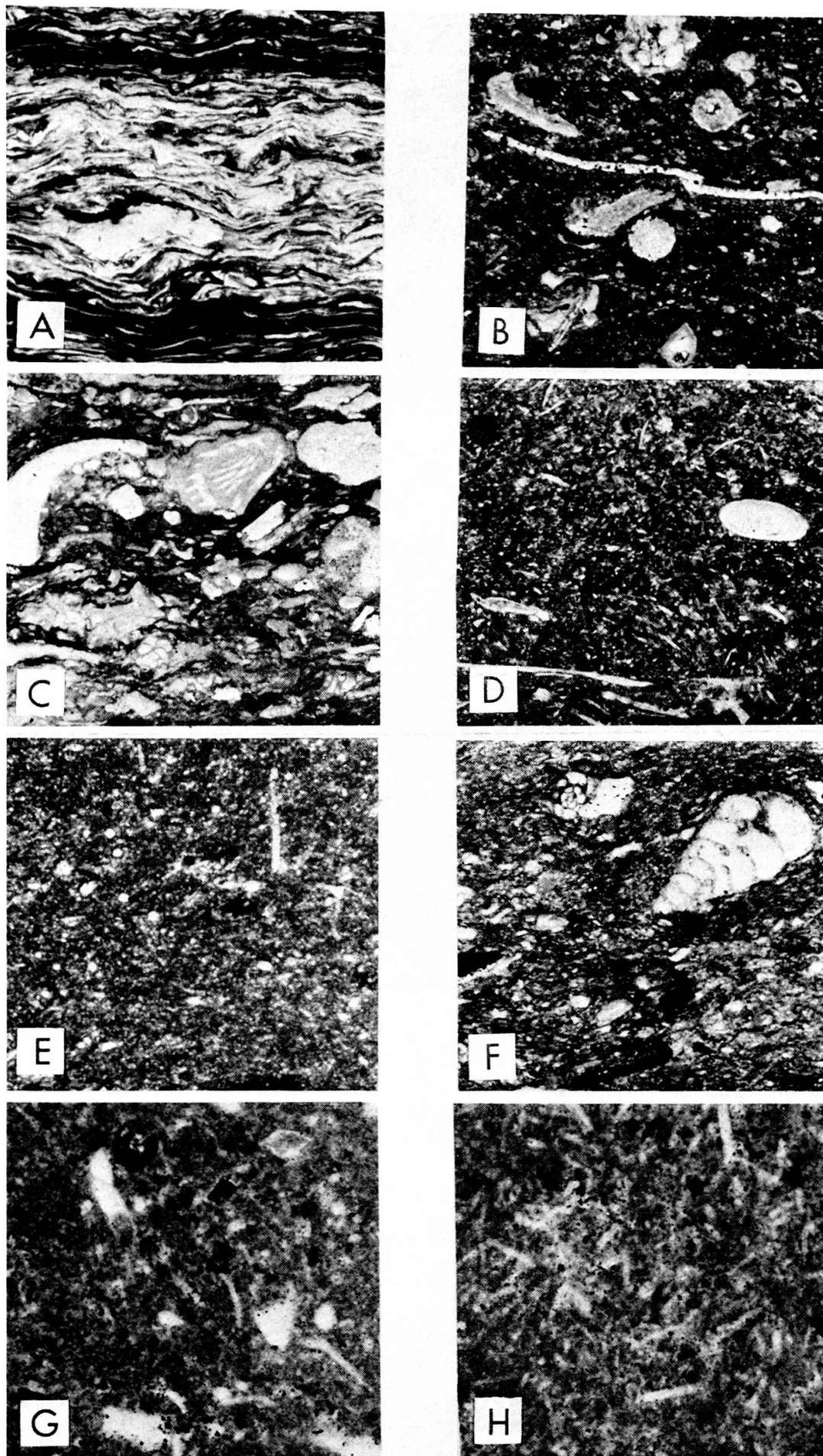
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PLATE I: MICROFACIES 1 THROUGH 6

PLATE 1

Microfacies 1 through 6

- A. Arenaceous and argillaceous calcisiltite with fine silt-size quartz particles. Rare bioclasts, frequent bioturbation, scattered pyrite grains (Microfacies 1).
- B. ~~Arenaceous and argillaceous calcisiltite with coarse silt-size quartz particles to quartzose sandstone with a calcareous matrix. Pyrite is common (Microfacies 1).~~
- C. Arenaceous and argillaceous mud-supported biocalcarenite, bedded with bioclasts of ostracods, brachiopods and crinoids in a calcisiltite matrix (Microfacies 2).
- D. Arenaceous and argillaceous grain-supported biocalcarenite, with ostracods, crinoids and pelecypods in a calcisiltite matrix. Rare bryozoans and arenaceous foraminifers, bioturbation is common (Microfacies 3).
- E. Slightly arenaceous grain-supported biocalcarenite with a sparite cement. Bioclasts are crinoids, ostracods, brachiopods, pelecypods and gastropods (Microfacies 4).
- F. Weakly argillaceous phylloid algal controlled limestone with a calcisiltite matrix. The platy elements of *Ivanovia* sp. represent the dark bands, while the light bands are interstitial micrite recrystallized to pseudospar. Some encrusting bryozoans are common (Microfacies 5).
- G. Weakly argillaceous phylloid algal controlled limestone, as above but better aligned platy elements indicating attached colonies to micrite partly recrystallized to pseudospar (Microfacies 5).
- H. Argillaceous grain-supported biocalcarenite with a calcisiltite matrix. Brachiopods, crinoids and ostracods are major organic components. Arenaceous foraminifers and calcispheres are frequent (Microfacies 6).



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PLATE 2: MICROFACIES 7 THROUGH 13

PLATE 2

Microfacies 7 through 13

- A. Argillaceous ostracodal calcarenite with a calcisiltite matrix. The highly compacted and disarticulated ostracod valves occur with distinct bands associated with scattered silt-size detrital quartz (Microfacies 7).
- B. Argillaceous mud-supported biocalcarene, with a bedded calcisiltite matrix. Scattered brachiopods, crinoids, ostracods and bryozoans (Microfacies 8).
- C. Argillaceous mud-supported biocalcarene, with a bedded calcisiltite matrix. Arenaceous foraminifers, fusulinids, brachiopods, crinoids and ostracods are common (Microfacies 9).
- D. Argillaceous calcisiltite, abundant sponge spicules with brachiopod spines and well developed bioturbation (Microfacies 10).
- E. Argillaceous calcisiltite, with sponge spicules and minor debris of ostracods and brachiopods (Microfacies 10).
- F. Weakly argillaceous mud-supported biocalcarene in a bedded calcisiltite matrix. Frequent arenaceous foraminifers, ostracods and brachiopods (Microfacies 11).
- G. Weakly argillaceous mud-supported biocalcarene in a massive calcisiltite matrix. Frequent sponge spicules and ostracods, pyrite pigments are common (Microfacies 12).
- H. Weakly argillaceous calcisiltite, consisting essentially of sponge spicules to the exclusion of other organic components, pyrite pigments are common (Microfacies 13).