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Factors Controlling Porosity and Permeability in the Curdsville Member of the Lexington Limestone

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Research Report No. 7

FACTORS CONTROLLING POROSITY AND PERMEABILITY IN THE CURDSVILLE MEMBER OF THE LEXINGTON LIMESTONE

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University of Kentucky Water Resources Institute
Lexington, Kentucky

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1967

Frontispiece

BASAL CURDSVILLE LIMESTONE SPRING

Figure 1

Nonesuch Community Spring in basal Curdsville Limestone, Salvisa Quadrangle, Woodford County, Kentucky. Hammer handle at contact of Tyrone Limestone (below) and Curdsville Limestone (above).

ABSTRACT

Factors controlling the porosity and permeability of the Curdsville Limestone Member of the Lexington Limestone of Middle Ordovician Age in the Blue Grass Region of Kentucky are geological.

Microstratigraphic analysis had led to the division of the lower Lexington Limestone, consisting principally of the Curdsville Member into three beds which may be subdivided into "zones" made up of several lithologic types and sub-types. Lower, middle, and upper bed characteristics are helpful in determining the regional depositional history in the progressively transgressing Curdsville sea. Paleogeography of Curdsville time has been determined by delineation of two local facies: (1) a carbonate bank--shoal area facies, and (2) a shelf--channel area facies.

Permeable carbonate bank--shoal facies are best developed on the structurally high Jessamine Dome Shoal Area where the Curdsville Limestone is found at shallow depth. Ground waters of meteoric origin have created sink holes, solution valleys, and caverns through solution enlargement of fractures comprising an extensive intersecting joint system.

Detailed examination of the Bryantsville Quadrangle on the Jessamine Dome Shoal Area indicates that "fracture traces" such as sink hole, solution valley, and stream channel alignments are controlled mainly by nearly vertical joints in the Curdsville and underlying Tyrone Limestones. High frequency and intersection of joint fractures may indicate the presence of permeable limestone aquifers at shallow depth. The hypothesis can be tested by drilling several wells in prospective areas.

KEY WORDS

Porosity, carbonate porosity

Permeability, carbonate permeability

Carbonate aquifer, limestone aquifer

Curdsville Limestone

Carbonate petrology

Carbonate lithology

Carbonate bank facies

Joint frequency and fracture traces

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INTRODUCTION

ACKNOWLEDGMENTS

"Factors Controlling Porosity and Permeability in the Curdsville Member of the Lexington Limestone" (OWRR Project No. A-003-KY) was sponsored by the University of Kentucky Water Resources Institute and supported by funds provided by the United States Department of the Interior, Office of Water Resources Research, as authorized under the Water Resources Research Act of 1964.

Research was begun in September 1965 and finished in June 1967, although some capital expenditures were made during fiscal year 1964-65.

Cores obtained by the United States Geological Survey and the Kentucky Geological Survey during the Kentucky Mapping Program were made available to the author. Paul Richards, Earle Cressman, Don Wolcott, and Douglas Black of the USGS Office in Lexington and Robert Cushman and Herbert Hopkins of the USGS Office in Louisville have been most cooperative in providing information and advice.

Colleagues at the University of Kentucky, Irving S. Fisher assisted in x-ray diffraction experiments and John V. Thrailkill

analyzed spring water samples. Robert Lauderdale, Director of the Water Resources Institute of the University of Kentucky and his secretary Mrs. Betty Bradshaw have aided during all stages of the project beyond normally expected assistance.

OBJECTIVES

The principal objective of this project was to analyze a typical carbonate ground water aquifer in the Blue Grass region in order to isolate the principal geological factors controlling porosity and permeability which affect movement and accumulation of ground water.

The Curdsville Limestone Member, the basal member of the Lexington Limestone of Middle Ordovician age, was selected for study because it is well exposed and easily located in the drainage of the Kentucky River and tributaries; it is limited in thickness; it contains some intergranular porosity and permeability; it is well fractured with joints, faults, and bedding planes which promote the development of solution features such as sink holes and caverns; and it contains springs and wells locally.

Locating ground water resources in the carbonate rocks of the Blue Grass region has been a problem for years. Most farmers in the area have few, if any, water wells and depend on numerous farm ponds, some local springs, or water from the Kentucky River. Studies of fairly detailed nature have been made, resulting in such publications as those of Hamilton (1950), Hall and Palmquist (1960), Hendrickson and Krieger (1964). While of importance in indicating the location, quality, quantity, and potability of water from known wells these reports are limited for several reasons. The basic geology was done on inadequate topographic base maps published prior to the availability of new larger scale, topographic base maps made from aerial photographs. Moreover, the lack of mapping detail, the lumping of several units together, and the dependence on reconnaissance geologic knowledge of earlier workers, have led to generalized conclusions, which, though helpful, have not solved many of the problems of obtaining water on individual farms.

This lack of basic, accurate, detailed, geological information in Kentucky has led to a joint 10-year federal-state Geologic Mapping Program which has already resulted in the geologic mapping of 15 Blue Grass quadrangles. The principal investigator of this project has done the geology on three of these and in the process has been on every farm in an area covering about 200 square miles and he has personally observed the importance of detailed mapping in determining the occurrence of both surface and subsurface water. The large mapping units of the past have been broken down recently into smaller members which vary considerably in porosity, permeability, composition and in lateral and vertical extent (Black and

MacQuown, 1965; Black, Cressman, MacQuown, 1965). More detailed field, microscopic, chemical, and *x*-ray work on each member and contained beds should be of considerable value in determining likely conditions for ground or surface water accumulation.

Microstratigraphic examination (detailed foot by foot examination) of the Curdsville Limestone Member at 27 surface and subsurface stations has resulted in a delineation of favorable areas for ground water accumulation which are amenable to drilling and testing and therefore the principal objective of the project has been accomplished.

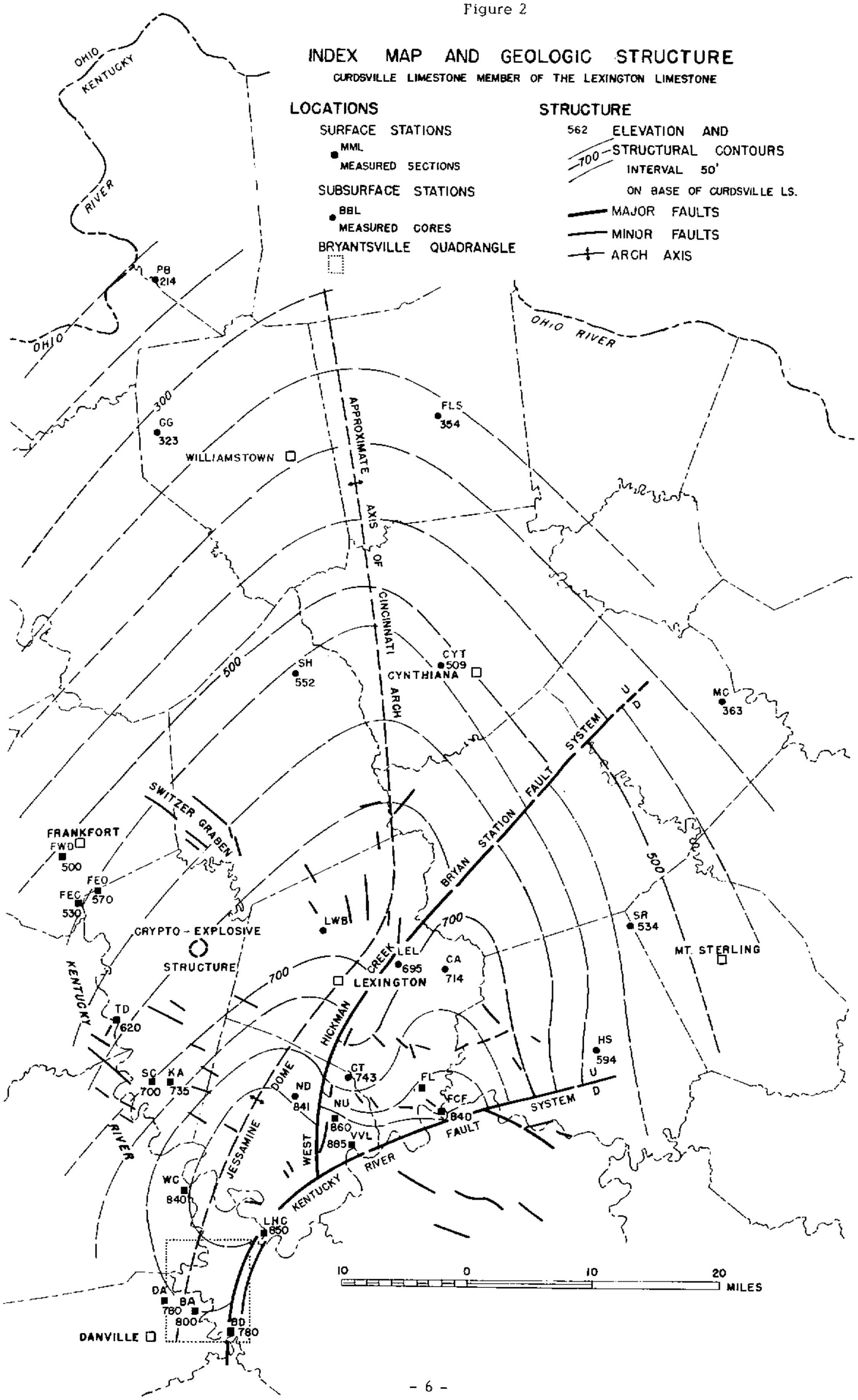
Minor objectives involving the development of techniques applicable to the study of prospective acquifers has been achieved within the limits imposed by the time available for research. Discussion of methods, results, and possible future approaches to chemical analyses, porosity and permeability determinations, *x*-ray diffraction work, and insoluble residue analysis, are discussed in attached appendices (Appendices A to D inc.). Insoluble residue work and quantitative carbonate petrology beyond the scope of this project will be pursued and should result in publishable research.

Mr. George Hine plans to complete a M.S. thesis by December 1967 involving selection of prospective ground water drill sites in the Curdsville Limestone through study of aerial photography and detailed field work.

SCOPE

Representative field exposures in the Kentucky River and tributary drainage systems and subsurface cores provided 26 complete and several incomplete 30-foot sections of the Curdsville Limestone Member at stations throughout the Blue Grass Region and north to the Ohio River (Fig. 2). Descriptive logs were prepared for each station and 510 rock samples were collected, an average of 17 samples per station or about one sample every two feet of section. Most of these samples were cut and polished for examination under the binocular microscope. Acetate peels (200) were made and sealed in slide mounts and projected on a screen to aid in sample description. Thin sections (430) were prepared from chips and stained with Alizarin red dye before examination under the petrographic microscope to aid in separating calcite from dolomite and silica. Representative point counts were made from selected thin sections. Percentages were determined for such parameters as composition, texture (including grain size, shape, roundness, sorting, cement, matrix), alteration, fossil abundance and diversity, etc. Although the results are beyond the scope of the present project, they were useful in lithological descriptions and the results will be published later. However, a complete petrographic microscope percentage analysis of the silica (detrital quartz and chert) in all thin sections was made by

Figure 2



INDEX MAP AND GEOLOGIC STRUCTURE

CURDSVILLE LIMESTONE MEMBER OF THE LEXINGTON LIMESTONE the point count method to aid in facies analysis. This method proved to be much faster than insoluble residue methods first used.

Field observations included measurement of approximately 275 joint measurements, 40 fracture frequency readings, 80 ripple mark strikes and cross bedding dips. Twelve samples of water from representative springs were collected and analyzed by Dr. Thrailkill (Appendix A). Ten core samples of representative lithologies were analyzed for porosity and vertical permeability (Appendix B).

Practical techniques were developed for future utilization of x-ray diffraction for the analysis of clay size material (Appendix C). Appendix D describes insoluble residue techniques employed for about 100 insoluble samples from 4 stations. Appendix E is a list of all station locations.

First Year's Work

A detailed progress report of the first year's work was prepared in August 1966 and submitted to OWRR by the University of Kentucky Water Resources Institute (MacQuown, 1966). Much of the significant data has been reproduced in this Completion Report. This early work was limited to an area near the Kentucky River, Dix River, and tributary streams in the Blue Grass Region of Kentucky in the outcrop belt of the Curdsville Limestone. Samples collected from this area provided the basis for subdivision of lithologic types previously employed in field mapping the area (Black and MacQuown, 1965). The Curdsville was also divided into a number of "zones" from the base to the top. Each of these included several lithologic types. The "zones" reflect the geologic history of the deposits laid down during Curdsville time. Changes in "zones" from station to station indicate the presence of local facies variation which was further delineated during the second year of the project.

Second Year's Work

During the second year of the project, the area of investigation was expanded to include much of the Blue Grass Region plus some of the surrounding region north to the Ohio River. Availability of new core data from the USGS-KGS Kentucky Mapping Program provided a broader base for analysis of the regional and local geology. Most of the detailed microstratigraphic, insoluble residue, *x*-ray, and petrographic work was done during the second year. An understanding of the geologic factors which have controlled the porosity and permeability of the Curdsville Limestone has led to positive suggestions for finding ground water as discussed in this report.

GEOLOGY

REGIONAL STRATIGRAPHY

The Middle Ordovician Lexington Limestone of the Blue Grass region includes three members in the area of this project. The basal Curdsville Limestone Member is the principal unit discussed in this report and is generally thirty feet thick in the area of study, although it varies in thickness from 20 to 35 feet. It is overlain by, and transitional with, the shaly Logana Member in the western and south central portion and by the limy and shaly Grier Member in the eastern and north central portion. Thus the upper boundary is somewhat arbitrary. The lower boundary is distinct because of an abrupt change in lithology. The coarser grained Curdsville Member is underlain by the finer grained, semi-lithographic "birdseye" Tyrone Limestone of the High Bridge Group of Middle Ordovician age. Stratigraphic relations are discussed by Black and MacQuown (1965) and Cressman, Black, and MacQuown (1965).

MICROSTRATIGRAPHY AND HISTORY OF SEDIMENTATION

The stratigraphic contribution of this report consists of the microstratigraphic, or detailed foot-by-foot, analysis of the Curdsville Limestone Member and the delineation of local facies changes.

"Zones"

Informal lithologic units called "zones" which were delineated during the first year of the project are useful in interpreting the history of sedimentation in the region as summarized in Table 1 and illustrated on cross sections (Fig. 3).

TABLE 1

GEOLOGIC HISTORY OF CURDSVILLE DEPOSITIONAL ZONES

Depositional Zones	Lithologic Types	Description	Possible Environment	Eustatic Conditions	Tectonic Events
Fossiliferous Limestone	III	Biostromal	Carbonate bank	Major transgression Deeper water locally (II). Shallower in bank areas (III). First indication of important Regional facies change (Type III ⇄ II).	Major carbonate bank buildup may be localized by ancestral high on present Cincinnati arch
Logana (basal)	II	Interbedded ls. and sh.	Infratidal shelf		
Fossiliferous Limestone	III (II), (I)	Biostromal	Carbonate bank or shoal		Upper Bentonites suggest tectonic events in Appalachians preceding major transgression.
Upper Calcirudite	Ia (III) (Ib)	Bioclastic and intraclastic	Waves and currents		
Upper 'Flow Rolls"	II, Ic (Ia, b)	Interbedded and Interlaminated	Currents	Minor cylces varying water depth regression	Middle Bentonites and bentonitic limestones suggest minor tectonic events in Appalachians
Third Calcirudite	Ia	Bioclastic	Waves and currents	transgression cyclic sedimentation	

TABLE 1 (Continued)

Depositional Zones	Lithologic Types	Description	Possible Environment	Eustatic Conditions	Tectonic Events
Middle "Flow Rolls"	Ic, II (Ib)	Interlaminated	Currents	regression early, local carbonate shoals	
Second Calcirudite	Ia, III	Bioclastic locally biostromal	Waves and currents		
Lower 'Flow Rolls"	Ic	Interlaminated	Currents	Initial transgression Deepening water	
Cross-bedded calcarenite	Ib	Bioclastic Intraclastic	Tidal (intratidal currents) well sorted)		
Basal calcirudite	Ia	Intraclastic Bioclastic	Surf zone (waves) poorly sorted	Shallow water	Lower Bentonites suggest tectonic events in Appalachians preceding transgression
Tyrone (upper)	V	Micritic lime mud	Supratidal, lagoonal, Tidal flats.	very shallow water	

Figure 3a

-CROSS SECTIONS OF CURDSVILLE LIMESTONE LITHOLOGIC TYPES AND ZONES

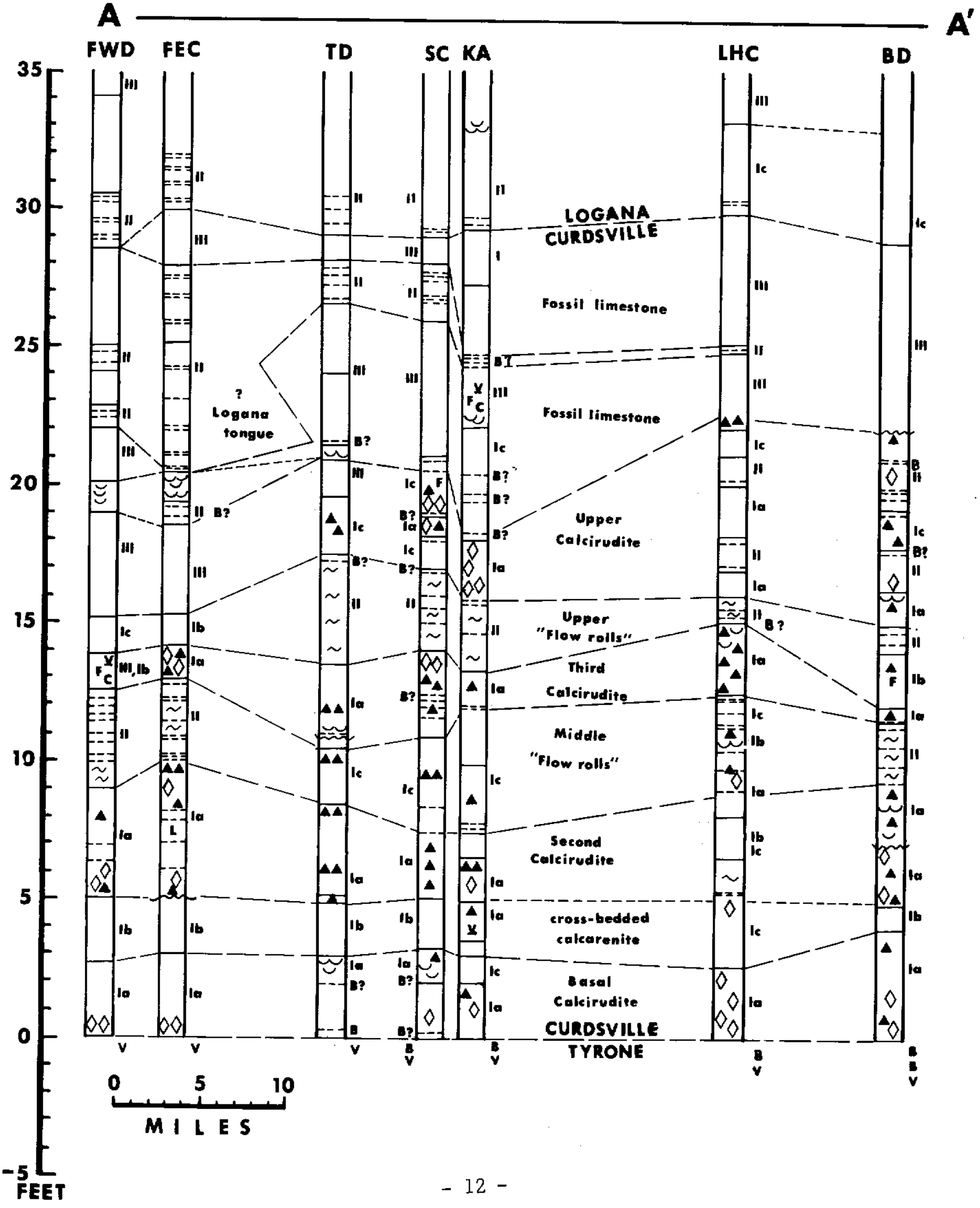


Figure 3b

CROSS SECTIONS OF CURDSVILLE LIMESTONE
LITHOLOGIC TYPES AND ZONES

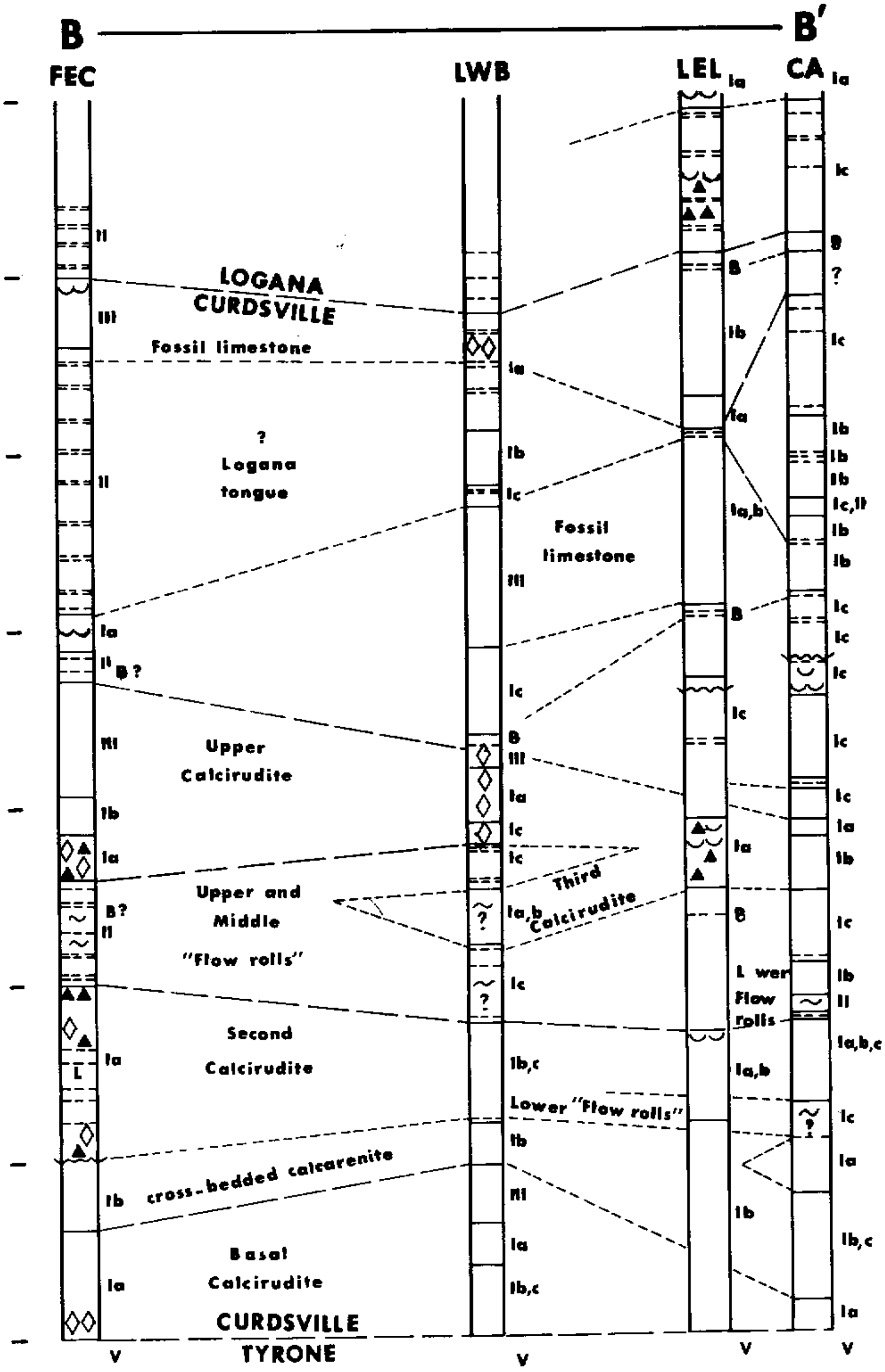
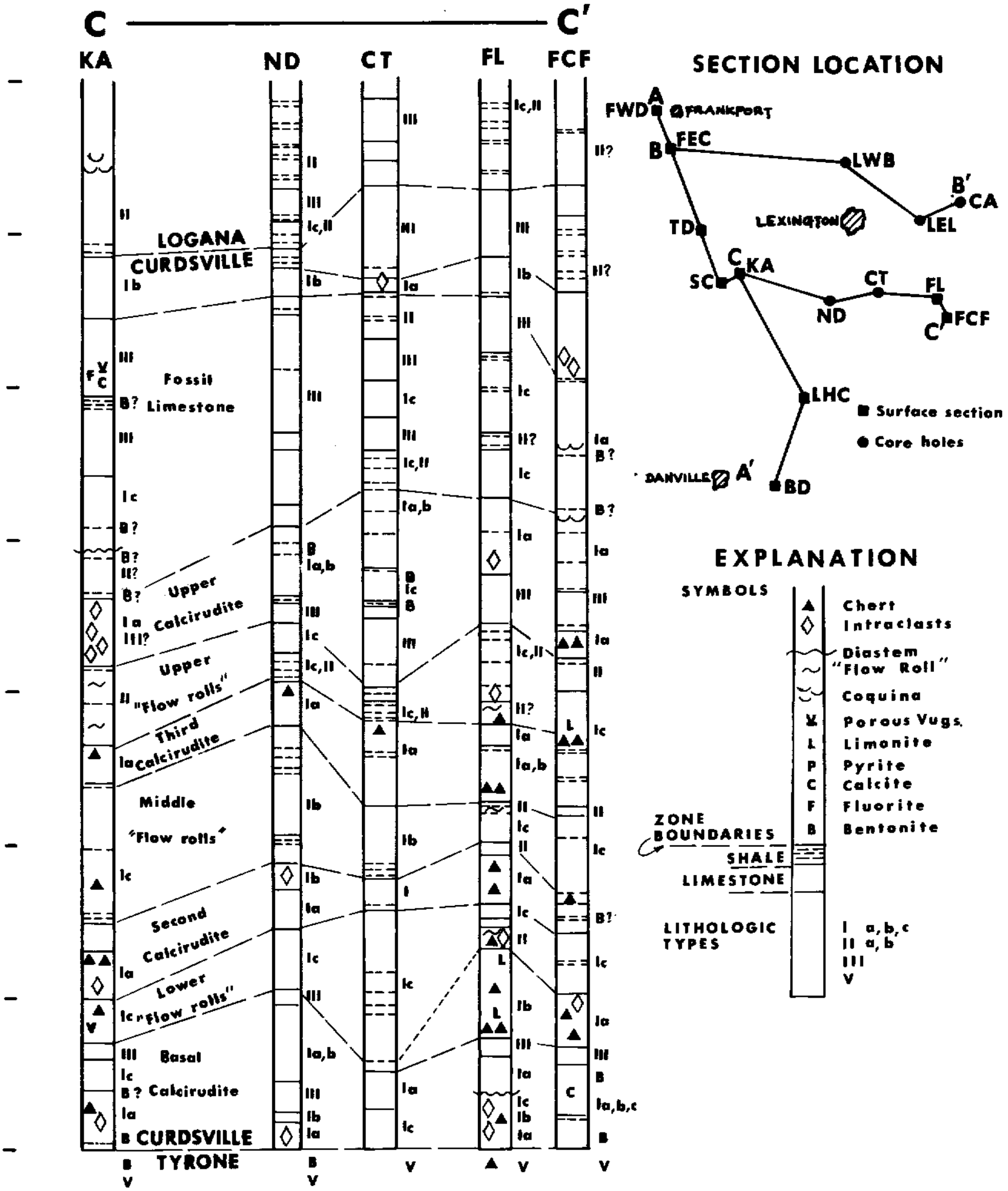


Figure 3c

CROSS SECTIONS OF CURDSVILLE LIMESTONE
LITHOLOGIC TYPES AND ZONES



Lithologic Types and Sub-types

The "zones" consist of several lithologic types. These lithologic types, first described by Black and MacQuown (1965), were divided into sub-types during the first year of the project to aid in detailed field and microscopic examination. The basis for subdivision is indicated in a series of photographic reproductions (Figs. 4-9, inc.), and summary characteristics are listed in Table 2.

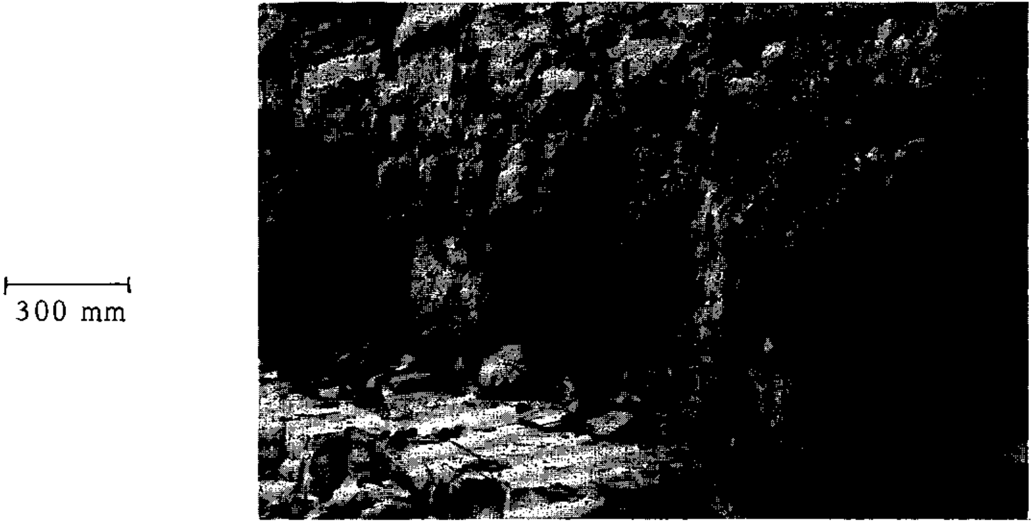
Beds

The basal Lexington Limestone, composed primarily of the Curdsville Member and lower portions of the overlying Logana or Grier Members locally has been divided into three ten-foot beds for analysis of lithologic and reservoir characteristics. Measurements have been made upward from the distinct contact of the Lexington with the underlying Tyrone Limestone. This procedure is necessary because porosity and permeability development as well as water movement and accumulation are not restricted to formal stratigraphic units such as formations and members. Key beds within formations such as impermeable shales and bentonites several feet thick may determine the base of an aquifer unit made up of portions of several members or formations.

The basis for subdivision of the lower Lexington Limestone (primarily the Curdsville Limestone Member) into three ten-foot

Figure 4. LITHOLOGIC TYPE 1a

Basal Curdsville calcirudite (Type 1a) lies above Tyrone (Type V) at hammer head. Better joint development and different joint orientation in Tyrone.

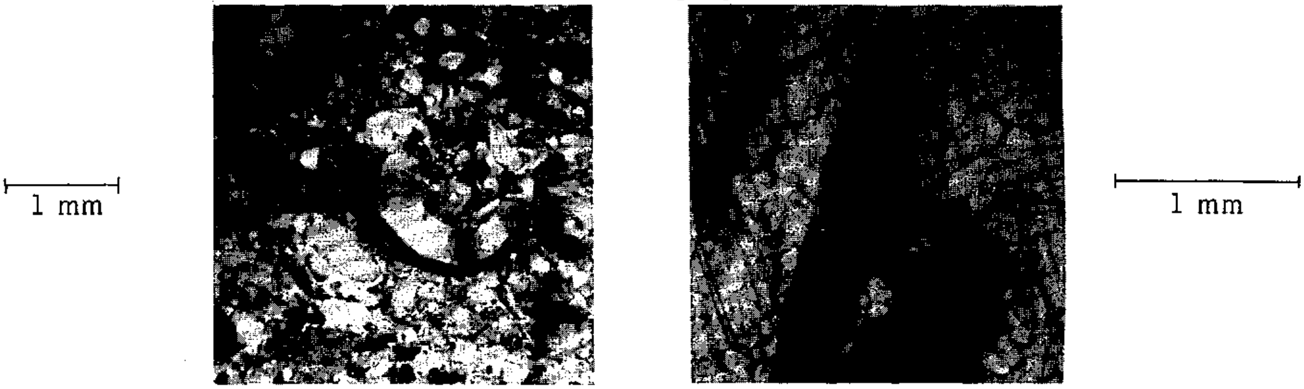


Surface section Keene Quad. (KA)

Acetate peel of polished surface

Denny Core Hole, Nicholasville Quad. (ND)

Photomicrographs

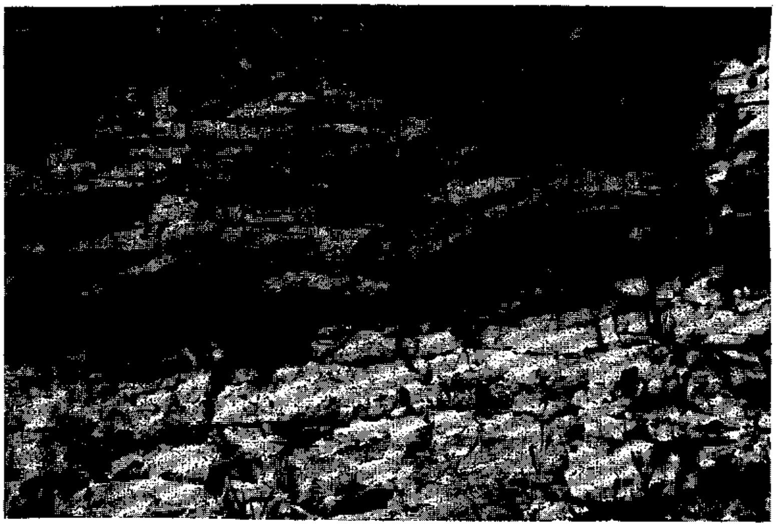


Keen A Section (KA)

Figure 5. LITHOLOGIC TYPE 1b

Curdsville calcarenite with low angle cross-bedding (Type 1b) above hammer handle. Basal calcirudite (Type 1a) below hammer. Joints better developed in Type 1b.

300 mm



Surface section Keene Quad. (KA)

Acetate peel of polished surface

10 mm

Little Hickman Quad., (LHC).
Surface Section

Photomicrograph

1 mm

Keene A Section (KA)

Figure 6. LITHOLOGIC TYPE 1c

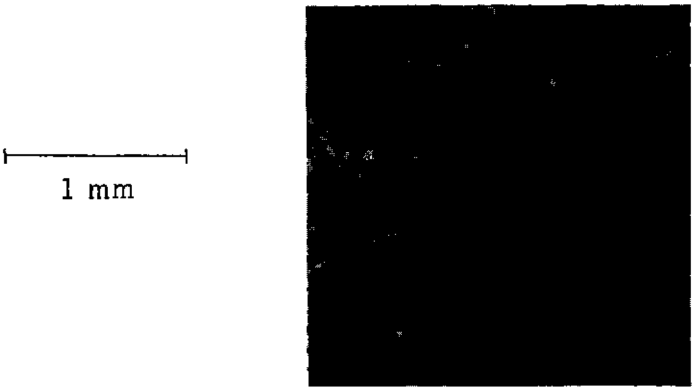
Curdsville Laminated calcisiltite (Type 1c) in 6" zone (length of hammer head) between thicker beds of Type 1a.

Surface section, Keene Quad. (KA)

Acetate peel of polished surface.

Nicholasville Quad., Denny Core Hole (ND) USGS-KSG.

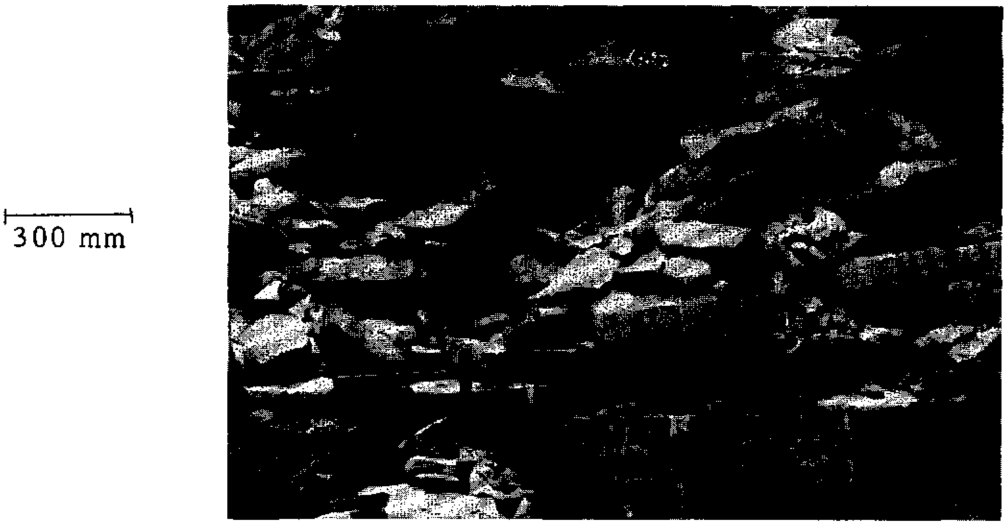
Photomicrograph



Lexington East Quad. (LEB), Core hole, Ferguson-Bosworth Co.

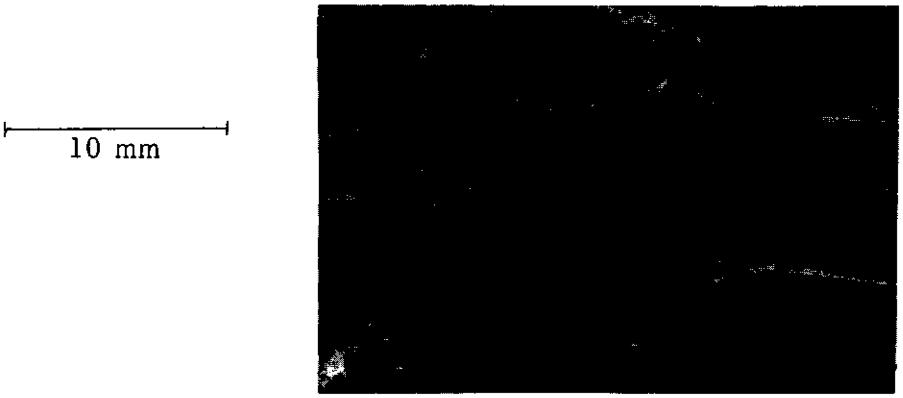
Figure 7. LITHOLOGIC TYPE 11 (a and b)

Lower Logana interbedded, tabular, micro-grained limestone (Type 11a) and shale (Type 11b). Contact with underlying Type 111 at hammer handle.



Surface section, Keene Quad. (KA)

Acetate peel of polished surface



Nicholasville Quad., Denny Core Hole (ND) USGS-KGS.

Photomicrograph

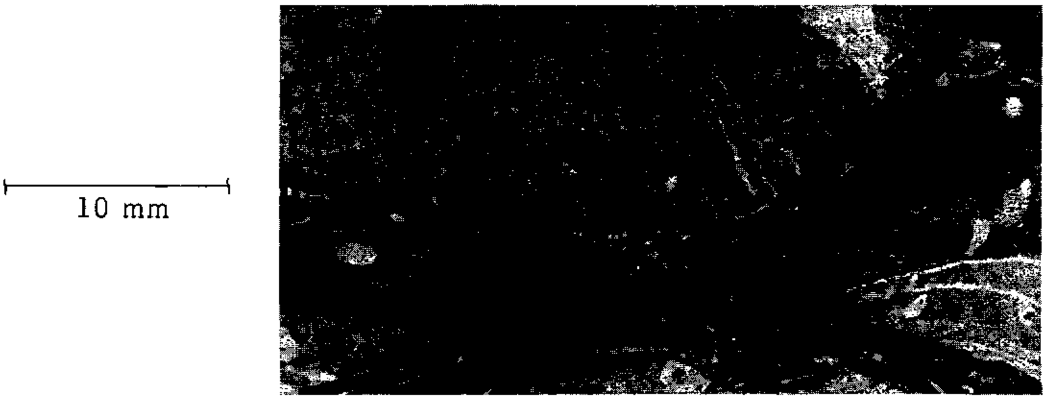
Bryantsville Quad. (BD). Surface section.

Figure 8. LITHOLOGIC TYPE 111

Upper Curdsville irregularly bedded fossiliferous limestone (Type 111). Jointing shows wavy surfaces and is discontinuous, irregular in part.

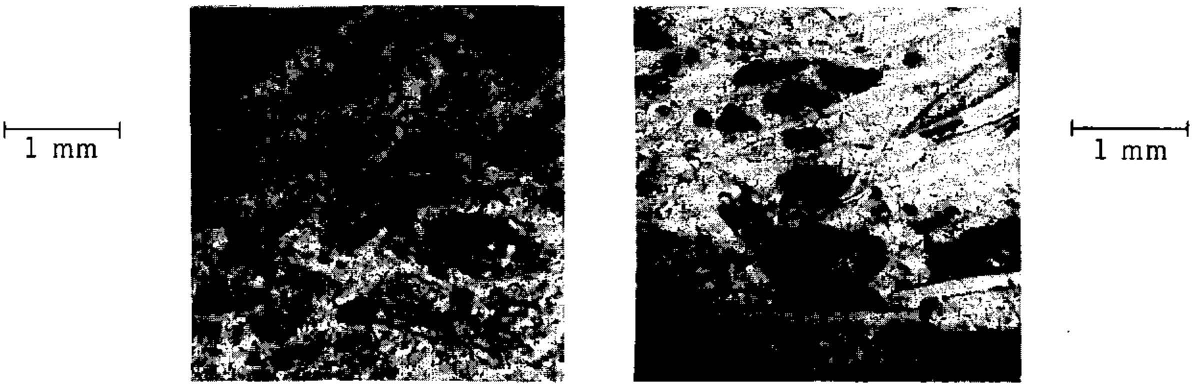
Surface Section, Keene Quad. (KA)

Acetate peel of polished surface



Nicholasville Quad., Denny Core Hole (ND), USGS-KGS

Photomicrographs



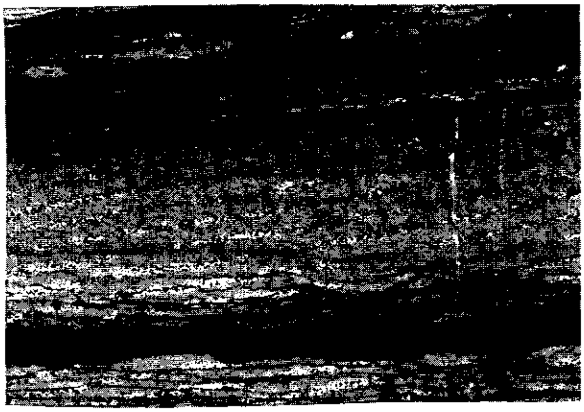
Keene Quad. (KA). Surface Section.

Figure 9. LITHOLOGIC TYPE V

Upper Tyrone semi-lithographic limestone (Type V) with well developed joint system. Stair-step offsetting of some joints.

Surface Section, Keene Quad. (KA)

Acetate peel of polished surface



Nicholasville Quad., Denny Core Hole (ND), USGS-KGS.

TABLE 2

CURDSVILLE LIMESTONE LITHOLOGIC TYPES

	Lithologic Rock Types*	Grain Texture	Cement or Matrix	Color	Bedding	General Characteristics	Porosity, Permeability and Reservoir Character
I.	Calcarenite, calcirudite, and calcisiltite	Silt to gravel size	Sparry calcite and pseudospar, microspar; sparse micrite	Light gray- Value of 5 or more. Low chroma yellow common	Planar to slightly wavy. Some cross-bedding or cross-lamination,	Grains of whole or fossil fragments (rounded and sorted generally). Intraclasts common. Sub-angular quartz grains, feldspar.	Solution and spar formation in vugs, along joints, bedding planes. Intergranular porosity locally. Springs and wells locally.
Ia**.	Calcirudite	Gravel size common and finer grains	Spar to microspar. Sparse micrite	Light gray.	Blocky, thick-bedded	Intraformational conglomerate common. Large fossils and fragments in some coquina beds. Vugs, pyrite weathering to limonite, chert and detrital quartz common. Medium washed and sorted.	Possible aquifer. Oxidation of pyrite to limonite. Chert nodules formed in surface sections. Fluorite and calcite in vugs and veins. Microcline and plagioclase feldspar a minor constitutent.

*See Black and MacQuown (1965); Black, Cressman, MacQuown (1965) for detailed descriptions.

**Subdivisions of types as proposed in this report.

TABLE 2 (Continued)

Lithologic Rock Types*	Grain Texture	Cement or Matrix	Color	Bedding	General Characteristics	Porosity, Permeability and Reservoir Character
Ib**. Calcarenite	Sand size common and finer grains	Spar to microspar. Sparse micrite.	Very Light gray.	Wavy to planar. Low angle cross-bedding common. Medium Bedded.	Light colored, well washed and sorted. Cross-laminated to blocky. Chert, detrital quartz, and minor feldspar.	Possible aquifer. Thinner bedding and cross-bedding offer additional solution avenues. Better sorting than Type Ia.
Ic**. Calcisiltite	Silt size	Microspar Sparse micrite.	Medium gray.	Thin light gray lamina Inter-bedded with thin darker gray lamina. Low angle cross laminae. Planar to wavy beds.	Transitional between Type I and II. Commonly associated with convolute "flow roll" beds. Fairly well washed and sorted.	Poor aquifer? Fine grains limit permeability. All Type I groups form typical Karst topography when exposed at surface.
II. Tabular bedded, micrograined limestone and shale Fine calcisiltite.	Fine silt to clay size	Microspar and micrite. Some pseudospar.	Dark gray Value of 5 or less. Neutral hue common.	Thin-bedded to laminated planar surfaces.	Small fossils and fragments. Small intraclasts, and pellets. Quartz grains and clay minerals. Some "flow rolls". Weathers to buff color.	Aquiclude. Little or no intergranular porosity or permeability. Perched water tables form on these beds. Farm ponds may hold surface water.

*See Black and MacQuown (1965); Black, Cressman, MacQuown (1965) for detailed descriptions.

**Subdivisions of types as proposed in this report.

TABLE 2 (Continued)

Lithologic Rock Types*	Grain Texture	Cement or Matrix	Color	Bedding	General Characteristics	Porosity, Permeability and Reservoir Character
IIa**. Micrograined limestone	Silt to clay size	Microspar and micrite	Medium dark gray values of 4 and 5	Planar, tabular, beds. Thin bedded	Darker color indicates fine grain and clay content. Weathers to buff color.	Aquiclude. Few reservoir possibilities. Types IIa and IIb prevent solution in underlying potential aquifers.
IIb**. Limy shale and shaly limestone	Clay size some fine silt.	Micrite and microspar	Dark to very dark gray Values of 3 and 4.	Thin, shaly bedding	Very dark color may be due to organic content, grain size, reducing conditions.	Aquiclude. No reservoir possiblities. Wet weather springs above.
III. Irregularly bedded to nodular fossiliferous limestone subtypes** IIIa, IIIb, IIIc	Clay to gravel size. IIIa, gravel size; IIIb, sand size; IIIc, silt size.	Spar to micrite. IIIa spar, or IIIb pseudospar; IIIc microspar.	Medium gray values of 5±	Irregularly bedded to nodular. Irregular thin shale partings	Clay size material in irregular thin laminae between rubbly, abundantly fossiliferous nodules. Grades to Types I and II.	Moderate to poor intergranular porosity. Can contain well and spring water. Probably poor to fair aquifer. Joint and bedding plane porosity.

*See Black and MacQuown (1965); Black, Cressman, MacQuown (1965) for detailed descriptions.

**Subdivisions of types as proposed in this report.

TABLE 2 (Continued)

Lithologic Rock Types*	Grain Texture	Cement or Matrix	Color	Bedding	General Characteristics	Porosity, Permeability and Reservoir Character
V. Cryptograined (sublithographic) limestone confined to Tyrone Limestone	Clay size	Micrite with some "birds-eyes"	Very light gray. "Dove" color	Medium to thick bedded, planar, tabular	Lime mud matrix, argillaceous, weathers to white, rounded tabulae. Prominent in Tyrone Limestone below Curdsville	No intergranular porosity but well developed joints provide avenues for solution and aquifer development. Springs are formed above bentonite layers. Some well possiblities.
Bentonite	Clay to fine silt size	Potassium, bearing, non-swelling variety	Pastel greenish white to buff	Tabular, shaly, bedding	Prominent near base and in middle to upper part of Curdsville. Also in upper 20' of Tyrone.	Aquiclude. Prevents solution and development of aquifers in underlying beds. Perched water tables may form above bentonites.

*See Black and MacQuown (1965); Black, Cressman, MacQuown (1965) for detailed descriptions.

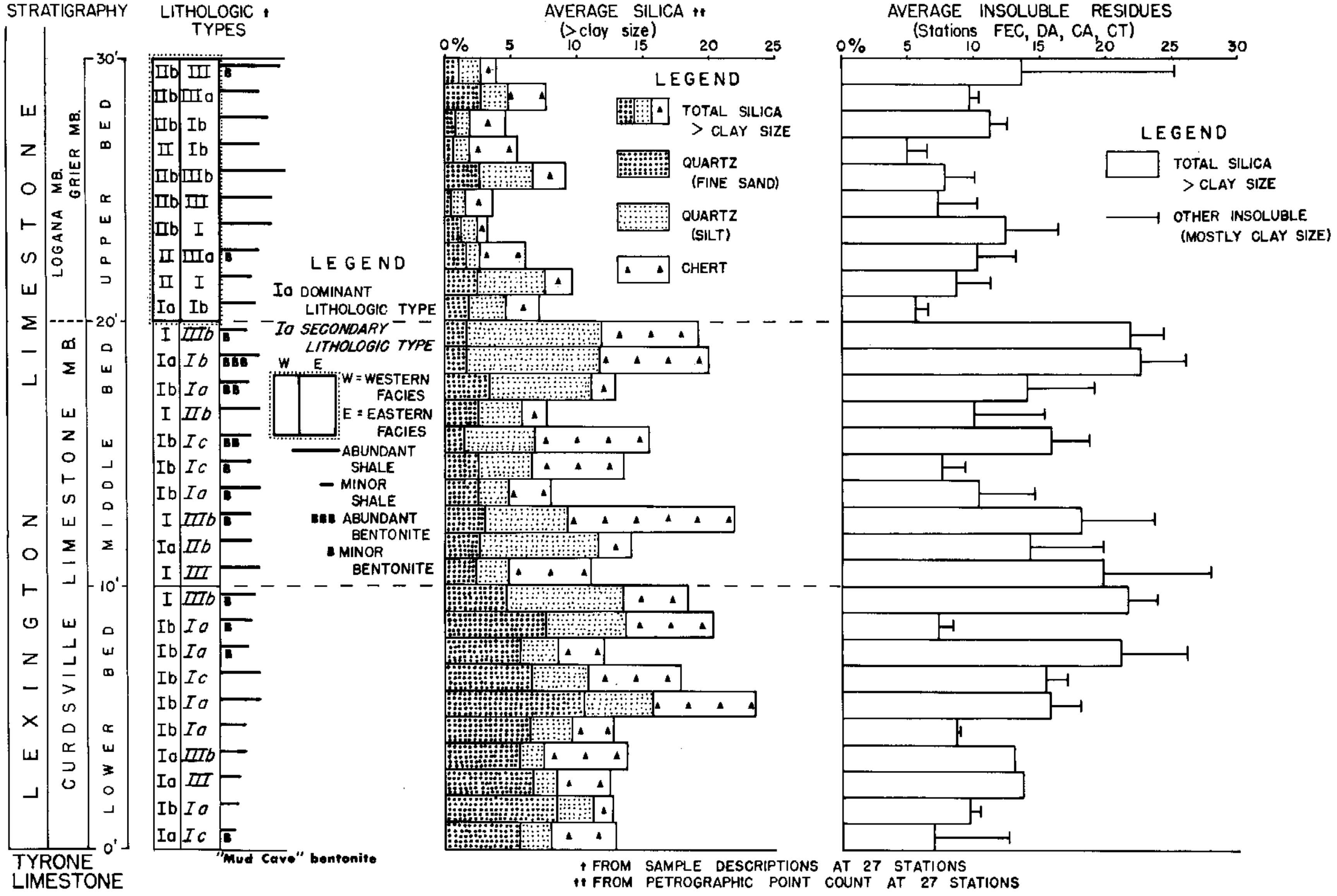
beds is graphically illustrated in Figure 10. This illustration is a summary of data compiled from a foot-by-foot analysis of rock samples from all stations. The composite log of lithologic types shows the dominant (most common) and secondary lithologies, the position of bentonites, and the relative number of shaly layers in each bed. The silica graph is particularly significant in a dominantly limestone section. Silica content (detrital quartz and chert) was first determined at four representative stations by both insoluble residue and petrographic analysis. Because results were similar, the faster petrographic point count method was then applied to a study of thin-sections at all stations. Only the silt and larger silica grains can be determined by this method, however. The graph of average insoluble residues from four stations compares favorably with the graph of average silica for all stations thus indicating that the insolubles are mostly silica.

Lower Bed

The lower bed of the Curdsville Member is largely light colored, fine to coarse crystalline, bioclastic limestone consisting of calcirudites (Type Ia), cross-bedded, ripple-marked calcarenites (Type Ib), and laminated calcisiltites (Type Ic) as shown in Figure 10. The lower bed is the only one containing more than 5% subrounded detrital quartz of fine sand size. In most sampled sections

Figure 10

CURDSVILLE BED LITHOLOGY AND SILICA CONTENT



† FROM SAMPLE DESCRIPTIONS AT 27 STATIONS
†† FROM PETROGRAPHIC POINT COUNT AT 27 STATIONS

the basal five-foot unit of the lower bed consists mainly of very light colored calcirudite and calcarenite characterized by angular edgewise conglomerate (intrasparite) made up of limestone fragments, including some derived from the underlying Tyrone Limestone (Type V), and whole or broken fragments of Curdsville fossils. The basal unit also is lower in total silica than the upper unit, although the surface sections exhibit prominent scattered chert nodules. Locally, thin bentonite layers several inches thick occur in the lower five feet. Thicker layers of the "mud cave" bentonite several feet thick occur in the underlying upper Tyrone Limestone below the Curdsville-Tyrone contact at several localities such as the type section of the Curdsville Member at Curdsville Station (WC) and at High Bridge to the north on the Kentucky River. The Clay's Ferry station (FCF) also contains a contact bentonite. Other bentonites are commonly found in the underlying Tyrone Limestone within an interval several feet below the contact, and a thick bentonite layer (the "pencil cave") occurs some fifteen feet below the base of the Curdsville. Each of these layers may act as an aquiclude (particularly the thick "pencil cave" bentonite) inhibiting the downward movement of water and all are important in the development of a number of springs locally in the basal Curdsville and upper Tyrone Limestones which together form an aquifer unit. The upper five feet of the lower bed is characterized by Type I limestones except for several thin layers (several inches thick) of darker shaly limestone (Type IIb). The ratio of silt size quartz to fine sand size quartz increases in the upper five feet partly as a result of decreasing mechanical energy in a deepening transgressive sea. The increased percentage of chert in the upper five feet is related to the great "flood" of bentonite material deposited as volcanic ash which is dominant in the lithology of the middle bed above. Chert may occur both below and above bentonite layers as indicated by Huff (1962).

Initial high to later medium mechanical energy conditions resulting from wave and current action in a transgressing sea would account for the light colored "winnowed" coarse bioclastic grains, the "edgewise" conglomerate, the ripple marks, the cross bedding, and the progressive decrease in detrital quartz grain size. Altered volcanic ash deposits formed bentonite, and the absence of bentonite locally is best explained through submarine erosion by waves and currents. At least some of the angular to sub-angular material described as quartz silt may be of volcanic origin as shown by the increased percentage of this fraction in the cherty layers. Euhedral and subhedral microcline and plagioclase feldspar in many of the limestone layers may have been derived from bentonite but work to date is not conclusive.

Shallow water environment of deposition is indicated for the Tyrone Limestone (Type V) which underlies the lower bed. The Tyrone is characterized by laminated sediment and "birdseyes" suggestive of stromatolites as found in the supratidal environments of southern Florida and the Bahamas today. Extensive tidal flats were exposed to subaerial drying during Tyrone time which resulted in mud-cracks in the dessicated lime mud later consolidated to semilithographic limestone (micrite and microsparite).

Middle Bed

The middle bed of the Curdsville Member contains gray to buff microcrystalline to medium crystalline, sparsely fossiliferous, finely laminated limestones consisting of medium dark calcisiltites (Type IIa) and darker shaly and silty calcilutites (Type IIb) in addition to interbedded calcarenites (Types Ib, IIIb), calcirudites (Type Ia), and some calcisiltites (Type Ic). A number of thin bentonites and bentonitic limestones and associated chert above and/ or below the bentonites accounts for the high percentage of chert and insoluble residue found in this bed (Fig. 10). The percentage of quartz is somewhat less than in the lower bed (particularly the fine sand size) and the silt size detrial quartz is more abundant than the fine sand size quartz thus indicating continued transgression of the sea with possible deeper water and perhaps some change in the detrital source area. Some of the silt may be of volcanic origin. Ball and Pillow structures ("flow rolls" or convolute bedding) occur locally and are common in the silty layers, particularly where they are interbedded with fine sand layers and lie above shaly layers. The origin of these features has been variously ascribed to pore pressure changes creating a submarine quicksand, earthquakes, loading of soft clay layers with blocks of partly consolidated coarser grained material, or disruption by currents or storm waves. The association of several lithologic types with bentonites of volcanic ash origin indicate an unstable sea affected by volcanic activity and possibly earthquakes, the influx of large amounts of wind-born clastic ash deposits, occasional storm waves or currents, and possible fluctuation of sea level. The increase of finer bioclastic material suggests somewhat lower mechanical energy overall as the transgressing Curdsville sea created a deeper water environment. Minor regression of the sea may explain the presence of coarser calcirudites and calcarenites near the top of the bed and in the lower part of the overlying bed,resulting from higher wave or current energy conditions in somewhat shallower water.

The Upper Bed

The upper ten-foot bed is characterized by eastern and western facies (Fig. 10). The eastern facies is dominantly a medium gray, medium to coarse grained, bioclastic limestone (Types III, I) quite similar to and difficult to differentiate from the overlying Grier Member. The western facies is dominantly a dark gray, fine grained bioclastic limestone (Type II) similar to and difficult to differentiate from the overlying Logana Member. Both facies contain interbedded Type I layers characteristic of the Curdsville Member which are particularly prominent near the base. These higher energy lithologies probably indicate a slight recession of the sea, somewhat shallower water and increased wave and current energy. However, the low percentage of detrital quartz indicates a continued dominant transgression of the seas. The few bentonites found in the upper bed are usually restricted to the lower and upper layers or are found above the top of the Curdsville Member. Therefore the chert content (usually associated with bentonite) in the upper bed is low. The progressive deposition of the western shaly facies over the eastern limy facies culminates in the deposition of the shaly Logana Member over the entire western part of the project area.

REGIONAL STRUCTURE

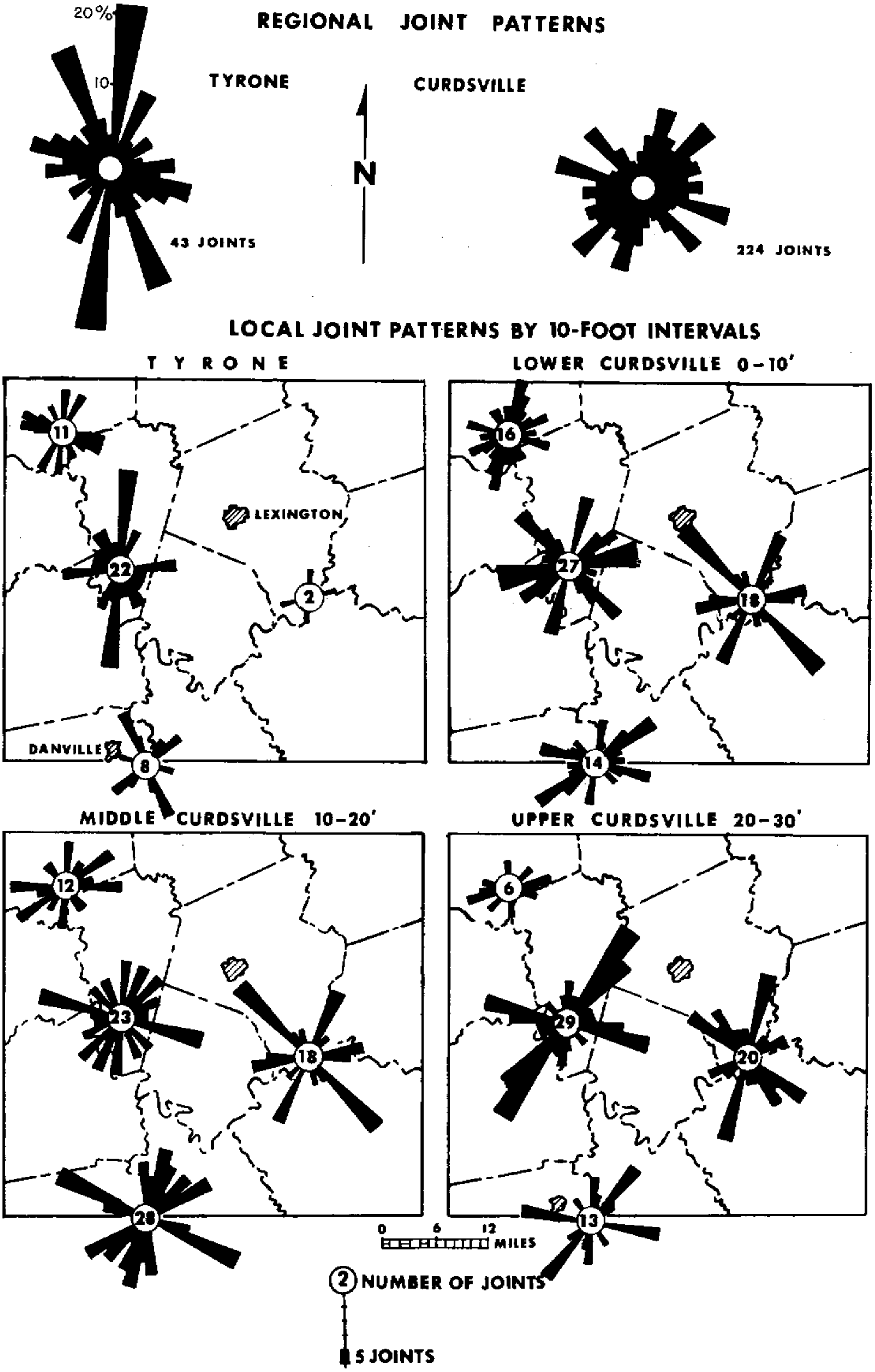
The principal regional structural features of the Blue Grass region are the north-south trending Cincinnati Arch and the major fault systems including the Kentucky River and the West Hickman Creek -- Bryan Station Faults as shown on Figure 2.

Local structural features of importance include the Jessamine Dome, which is partially truncated by the major fault systems, the Switzer Graben, the Versailles cryptoexplosive structure (Black, 1965), and numerous minor faults delineated in the Kentucky Mapping Program. The minor fault trends are generalized and the sense of movement is not indicated. In addition to faulting, numerous joints add to the fracture pattern. Several sets of largely vertical joints are dominant in an extensive network or joint system as shown by rose diagrams on Figure 11. The orientation of joints differs to some extent in the Tyrone and Curdsville Limestones indicating that the pattern is controlled in part by the difference in lithology of the two units. Orientation of jointing within the three beds of the Curdsville Limestone varies locally as shown on Figure 11 probably because of differences in lithology of each bed and also due in part to some variation in regional stresses within the various local areas. Local variation in joint directions in the Blue Grass Region has been observed by Stafford (1963). The important relationship of joints to solution, water movement, and aquifer development is discussed later in this report.

Structural History

The structure map (Fig. 2) indicates that the axis of the Jessamine Dome may have had a slightly different orientation than

Figure 11


REGIONAL JOINT PATTERNS
20%
10
TYRONE
43 JOINTS
N
CURDSVILLE
224 JOINTS
LOCAL JOINT PATTERNS BY 10-FOOT INTERVALS
TYRONE
11
22
LEXINGTON
2
DANVILLE
8
LOWER CURDSVILLE 0-10'
16
27
18
14
MIDDLE CURDSVILLE 10-20'
12
23
18
28
UPPER CURDSVILLE 20-30'
6
29
20
13
0 6 12 MILES
② NUMBER OF JOINTS
5 JOINTS

the axis of the Cincinnati Arch proper and may have been formed at a slightly different time. Both features are truncated by the major faults which may be therefore partly younger than the fold features. The minor faults appear to be influenced in part by the major faulting and in part by the Jessamine Dome.

CURDSVILLE FACIES AND PALEOGEOGRAPHY

A transgressing sea resulted in a vertical change in lithologies through time as evidenced by the previously described lower, middle, and upper beds of the Curdsville Limestone. These changes were largely regional in nature and affected the entire project area except in late Curdsville time when distinct eastern and western regional facies were deposited. However, local facies also were prominent throughout Curdsville time in specific local areas. These local area facies have been divided into two groups, (1) the carbonate bank or shoal area facies, and (2) the shelf or channel area facies. These facies intertongue, but one or the other are dominant locally. Brief area facies descriptions will be followed by evidence for their delineation (Fig. 12).

Carbonate Bank or Shoal Facies

The carbonate bank or shoal facies mainly consist of lighter colored, coarser crystalline, coarser grained calcirudites (Types Ia, IIIa) and calcarenites (Types Ib, IIIb) which were reworked, winnowed, sorted, and rounded before final deposition by medium to high energy waves and currents possibly in slightly shallower water than the surrounding shelf-channel areas. The carbonate banks are the large indefinite areas to the east that were slowly transgressed by the Curdsville sea. The shoals are the smaller banks that have been partly defined by better control in the central map area.

Shelf or Channel Facies

The shelf or channel facies mainly consist of darker colored, finer crystalline, finer grained calcisiltites (Types Ic, IIIc), very fine calcisiltites (Type IIa), and calcilutites (Type IIb) which were deposited in medium to low energy areas with limited current activity, possibly in slightly deeper water than the bank-shoal areas. The shelf is the large indefinite area to the west where the transgressing sea first deepened and where somewhat deeper water existed throughout Curdsville time resulting in the deposition of more fine shaly limestone than in the bank-shoal areas. The western facies of the upper bed consisting of the Curdsville and the overlying shaly Logana Member is particularly prominent in the shelf area. The channel areas are the narrower areas in the bank-shoal complex that also may represent slightly deeper water conditions where fine sediments probably winnowed from the shoal areas were deposited.

Evidence for Local Area Facies

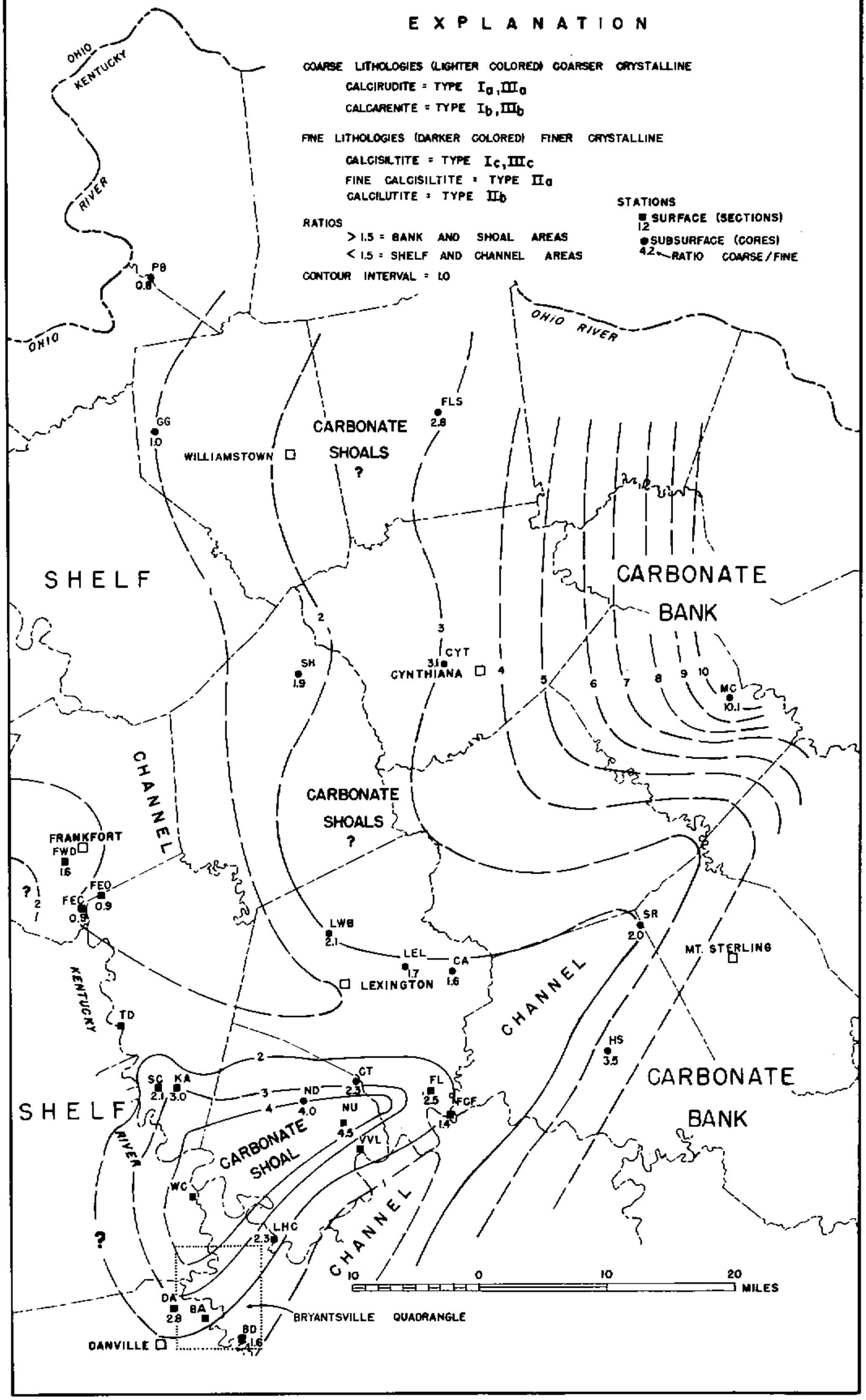
The first evidence for existence and location of the coarse bank-shoal and the fine shelf-channel facies areas is shown on the facies map of Figure 12 and is based on the ratio of the coarse to the fine lithologies at each station as determined by field and polished section descriptions. The basis for subdivisions into two lithologies is explained on the map. An arbitrary coarse/fine ratio of 1.5 was chosen as the boundary between the indicated bank-shoal and the adjacent shelf-channel areas. Support for this method of separating facies areas was tested by several other approaches. The Geological Society of America Rock Color Chart was used to determine color (value) from wet polished sections at each station and the results are illustrated on the map of Figure 13. Standard value numbers range from white (10) to black (1) but values for the Curdsville Limestone range from 8 to 3. The bank-shoal areas contain lighter colored facies and are indicated by average station values higher than 5 whereas the shelf-channel areas contain darker colored facies and are indicated by average values lower than 5. The rock color chart was also used in the preparation of the map of Figure 14 which illustrates the relationship between the two dominant hues (yellow and neutral) and the two principal facies. Stations with greater than 3% yellow hues and less than 1% neutral hues are located in the bank-shoal areas and, conversely, stations with less than 3% yellow and more than 1% neutral hues are located in the shelf-channel areas. Minor hues, including yellow-red and greenish-blue are related to weathering and are not applicable to facies differentiation. Finally, the map of Figure 15 illustrates the relationship of silica to the two major facies. The map is contoured on the basis of the percentage of silica greater than clay size as determined by examination of thin sections for each station. In the bank and shoal areas the percentage of silica is greater than 10% (detrital quartz 5% and chert 5%) whereas in the shelf-channel areas the percentage of silica is less than 10%. Both the fine-sand and silt size detrital quartz is higher in the bank-shoal areas as compared with the shelf-channel areas. The silica content appears to be related to paleogeographic areas and is not primarily a result of weathering. Chert nodules are more common at weathered surface stations than at unweathered subsurface stations but this may be due to secondary growth of nodules at the surface at the expense of finely divided silica as a result of solution and later redeposition locally without any significant change in total silica.

In summary all parameters investigated indicate the areal extent of discrete bank-shoal and shelf-channel facies thus establishing the paleogeography of Curdsville time. Other parameters have not been completely investigated. However, preliminary

Figure 12

FACIES MAP OF THE CURDSVILLE LIMESTONE

RATIO OF COARSE TO FINE LITHOLOGIES



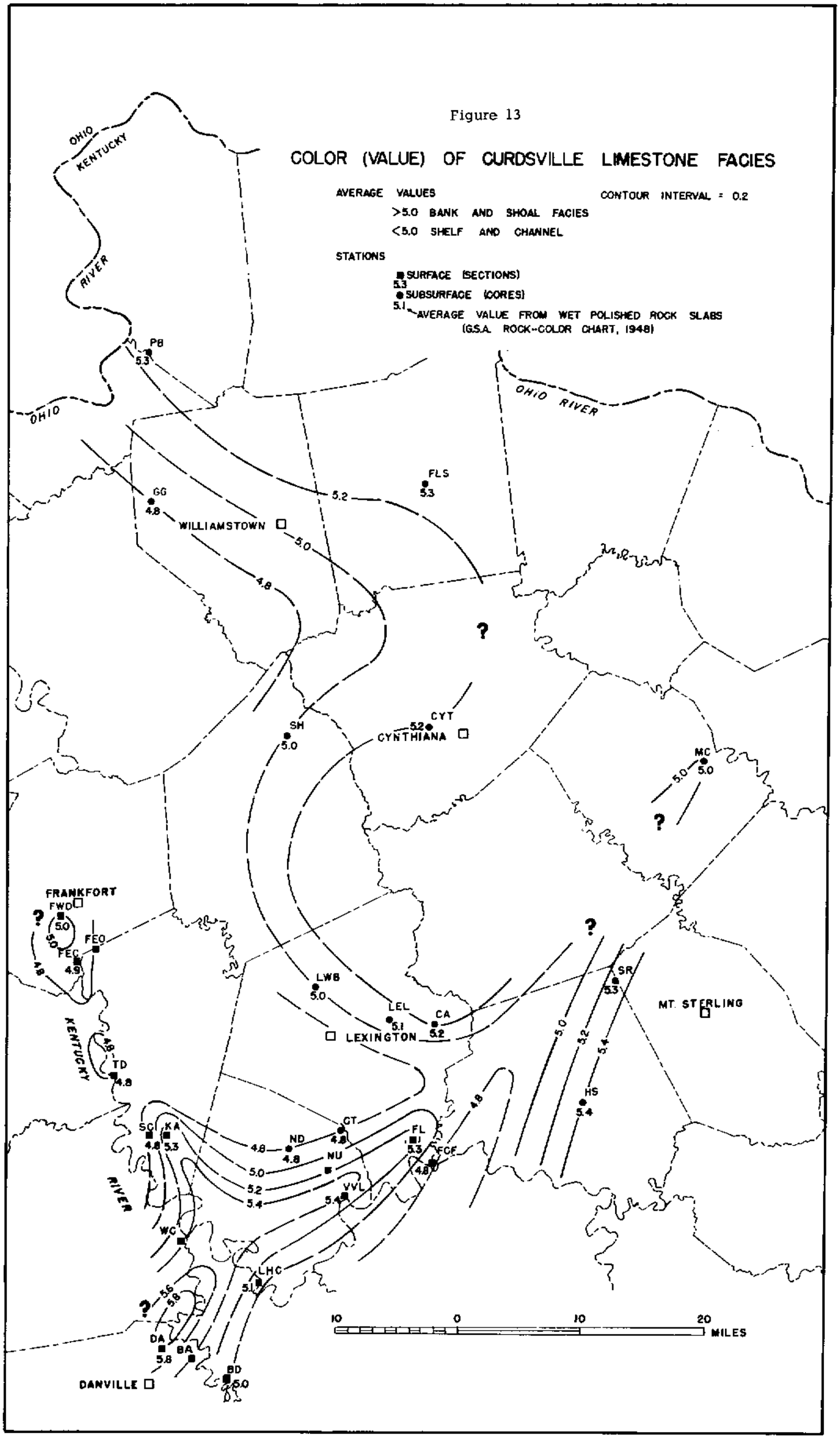


Figure 13

COLOR (VALUE) OF CURDSVILLE LIMESTONE FACIES

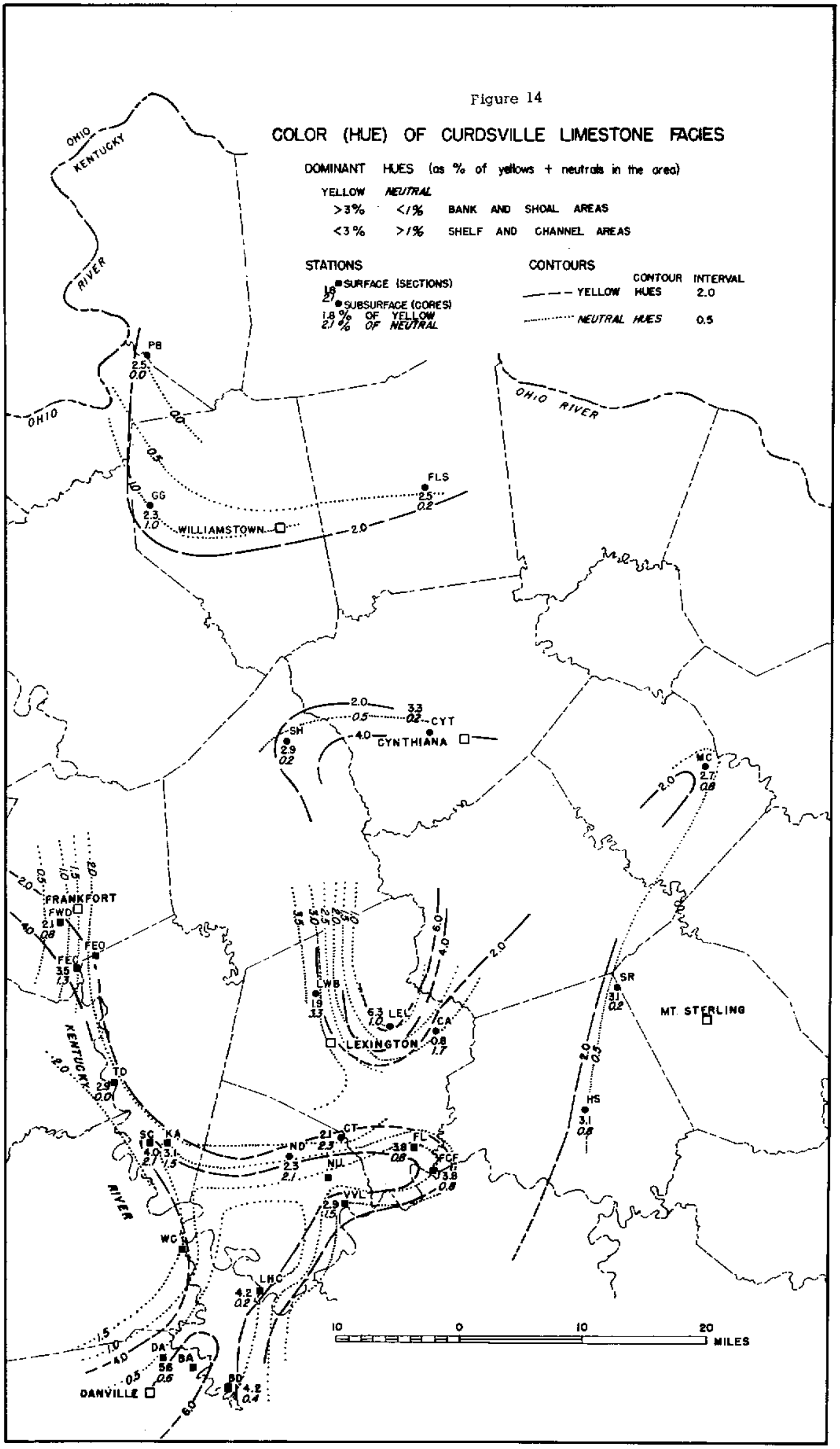


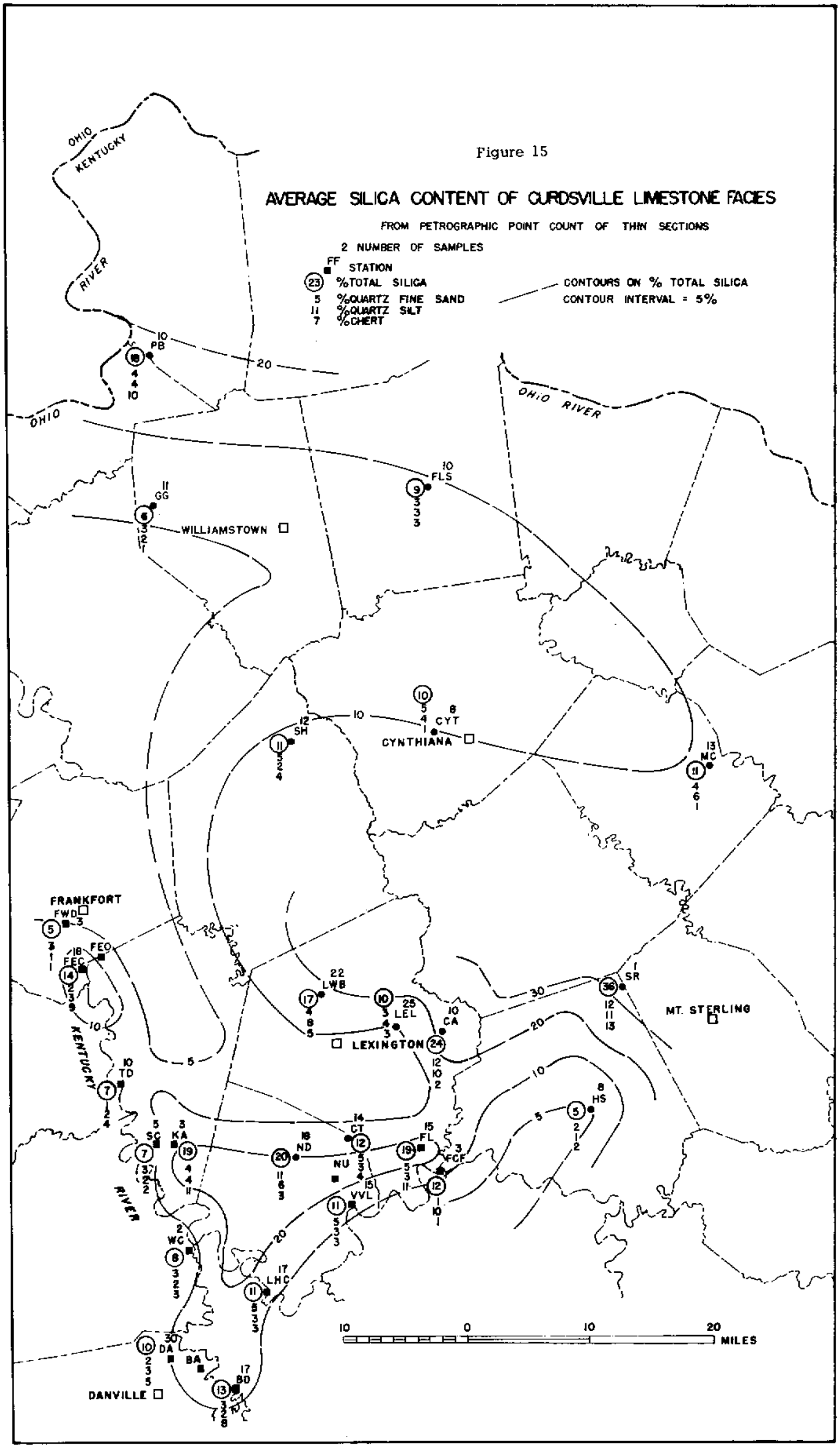
Figure 14

COLOR (HUE) OF CURDSVILLE LIMESTONE FACIES

Figure 15

AVERAGE SILICA CONTENT OF CURDSVILLE LIMESTONE FACIES

FROM PETROGRAPHIC POINT COUNT OF THIN SECTIONS



thin section analysis indicates that the greater number and diversity of fossil forms, the coarser fossil fragments, the intraclasts, the cross-bedding and coarse lamination, are characteristic in the bank-shoal areas, whereas sparse fauna in a dark micritic matrix with microspar cement, thin lamination, and shaly bedding are more characteristic of the shelf-channel areas.

Ripple Marks and Cross Bedding

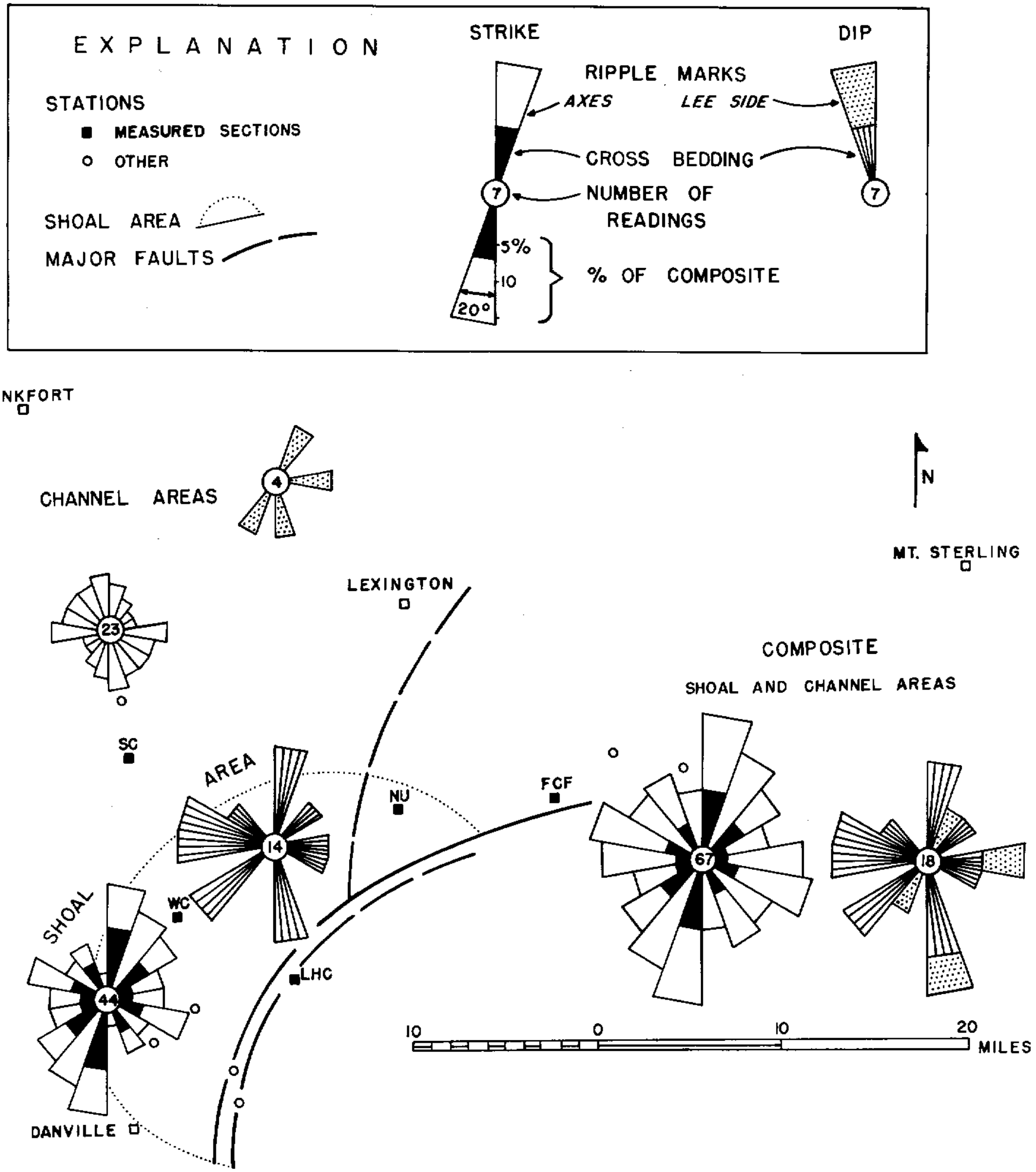
Sixty-seven strike directions of cross bedding and ripple mark axes and eighteen dip directions of cross bedding and current ripple mark steep lee slopes were measured in the Curdsville Limestone. Limited data available does not justify plotting individual rose diagrams at each field station or the preparation of vector diagrams. Strike and dip rose diagrams are shown for the principal shoal areas and for the channel or non-shoal areas. Composite diagrams summarize the total strike and dip data (Fig. 16).

Only general observations can be made. The four asymmetrical ripples observed were confined to the channel areas. Their lee side dip slopes indicate currents moved toward the southeast. The fourteen cross beds observed were confined to the shoal area and the dips show random distribution with a slight suggestion of a westward directional trend. Strike directions, in general, are northwesterly in the channel and north-northeasterly in the shoal area.

Figure 16

RIPPLE MARKS AND CROSS BEDDING

CURDSVILLE LIMESTONE



Relationship of Facies to Structure

The carbonate shoal south of Lexington shown on the facies map (Fig. 12) is remarkably similar in shape and location to the Jessamine Dome shown on the structure map (Fig. 2). Minor faults appear to be prominent in the shoal flank areas. Although the control is limited, other shoals may be present along the Cincinnati Arch. This relationship suggests that positive, or at least neutral areas resulting in higher sea bottom topography and the consequent development of carbonate shoals in medium to high energy environment were present in Curdsville time.

Therefore an ancestral Cincinnati Arch or at least an ancestral Jessamine Dome may have been present. Moreover the eastern channel area corresponds closely with the major fault system and may represent a negative area that later developed into the Kentucky River and related West Hickman Creek - Bryan Station fault systems. The channel area between Lexington and Frankfort corresponds closely to the area of the prominent Switzer Graben and the Versailles Crypto-explosive Structure mapped by Black (1965). Both channel areas could well have been located in weak structurally negative areas resulting in somewhat deeper sea bottoms locally which were filled with lower energy deposits during Curdsville time. It is interesting to speculate that the crypto-explosive structure is in fact a crypto-volcanic structure possibly resulting from a subterranean volcanic intrusion or explosion in a structurally weak zone as conceived by Bucher (1936) for the Jeptha Knob crypto-volcanic structure some miles west of the project area. If so, this structure would not then be an astrobleme resulting from a meteoric impact.

RELATIONSHIP OF GEOLOGY TO GROUND WATER

JOINT AND BEDDING PLANE FREQUENCY

Joints and bedding planes, the obvious avenues of solution and water movement, vary in length, character, and number. Generally they are better developed nearer the surface where weathering and ground water movement have been more effective. They also vary relative to lithology as shown in the following analysis.

Joint and bedding plane frequency was determined for eight surface localities located on the Jessamine Dome Shoal Area between Lexington and Danville and in the adjacent channels (Fig. 12). At each field station grids five feet square were laid out for each vertical five-foot interval of the Curdsville Limestone. The length of joints and bedding planes in the grids were measured. Data from five field stations in the shoal area and three stations in the channel areas were added and averages determined for each area as shown on Table 3.

TABLE 3

AVERAGE LENGTH OF JOINTS AND BEDDING PLANES*

In the Curdsville Limestone

Field Stations	Shoal Area DA, LHC, FL, KA, SC	Channel Area BD, FCF, Frankfort	All Areas
Joints	22'	47'	32'
Bedding Planes	106'	203'	142'
"Crack" Index (Joints plus bedding planes)	126'	250'	174'

---

[*] Average length of joints, bedding planes, and "cracks" in a five-foot square cross section of Curdsville Limestone at field stations in shoal and channel areas.

The table illustrates that in the shoal area of coarser grained crystalline limestone the joints, bedding planes, and "cracks" (joints plus bedding planes) are less numerous than in the finer grained shaly limestones of the channel areas. Therefore, potential avenues of water movement should be greater in the latter areas. However, impermeable shaly layers and the more discontinuous nature of joints largely confined to individual beds in these areas deters water movement except along some bedding planes where minor perched springs develop. Although fewer joints are found in the shoal areas, those formed are more effective and more solution cavities (sink holes and caverns) are formed. Consequently more favorable aquifer conditions exist in the coarser grained limestone of the shoal areas. Other shoal and bank areas contain favorable lithology but are not exposed at the surface and joints have not been enlarged by solution to the same extent. Moreover these more deeply buried shoals would likely contain salt and sulphur water and would therefore not be favorable fresh water aquifers. However, gas was found in the core hole at station SR in the flanks of the carbonate bank to the east. Some permeability must be present and commercial oil and gas accumulation in buried banks and shoals is possible.

CHARACTERISTICS OF CURDSVILLE WATER MOVEMENT

Water movement in the Curdsville Limestone is related to lithology and is restricted largely to joint and bedding plane fractures in limestone beds which have been enlarged by solution. The openings formed result in sink holes and solution valleys developed along joint sets and caverns developed along bedding planes. Porosity and vertical permeability in the limestone studied are very low (Appendix B), and for this reason little water moves through intergranular openings. Where the Curdsville Limestone occurs near the surface, solution can be effective. Springs and some wells are present where water fills solutional openings.

Downward movement of ground water is locally interrupted by bentonites and shales which occur at various positions within the Curdsville interval resulting in perched water tables and intermittent springs. Where bentonites and shales occur at the surface, farm ponds built on these lithologies may hold water. Bentonites act as effective barriers to water movement, partly as a result of mixed layer clays, which may swell or slough in the presence of water, thus filling effective pore space and forming an impermeable layer. Shales (mainly limy shales) may contain some bentonite, but impermeability is mainly related to the presence of compacted fine silt and clay which limits water movement thus preventing solution and the development of permeable channels. Therefore, in areas where the Curdsville contains many small shale units the water movement is restricted to the thicker, coarser limestone units between the shales. Where shales and bentonites are absent, groundwater can move downward and laterally for greater distances. The rock is more easily dissolved and channels are enlarged.

Joint characteristics are directly related to rock type. Medium to thick bedded carbonate units contain continuous, largely vertical, regular joints. Thinner bedded carbonate units contain less continuous joints commonly offset along bedding planes, but which may be effective permeable fractures. Shales and bentonites, more than a few inches thick, have few continuous joints.

Joint trends differ stratigraphically and geographically. Usually joints are larger and more numerous near fault zones and as a result many may give rise to high yield springs such as the Sulfur Well and Keene Springs near the towns bearing these names.

CURDSVILLE AND TYRONE LIMESTONE WATER ANALYSES

No attempt was made to make a complete water analysis of the water from the Curdsville and underlying Tyrone Limestone. Wells over 80 to 100 feet deep usually contain salt or sulfur water (Hendrickson and Krieger, 1964) and are therefore unsuited for most common uses. Water from shallow wells and springs contains calcium and magnesium ions, making the water hard but usable. Dr. John Thrailkill from the Departmentof Geology at the University of Kentucky analyzed 12 spring samples collected during the project for calcium and magnesium, and this report is included in Appendix A. Table 4 is a comparison of calcium-magnesium data from the work of several authors.

AQUIFER CLASSES AND DISTRIBUTION

Class I - Perched Springs

Curdsville springs can be divided into three general classes. Class I, or perched water table springs, occur in the Frankfort area in tributary streams along the Kentucky River. Springs with low flow rates occur as bedding plane seeps along the tops of impervious bentonite and shale zones as shown on the map of Figure 17. Ca/Mg ratios are low, probably as a result of fairly large amounts of dolomite associated with the finer grained rocks. Slow water movement in the rock allows time for chemical reaction between calcite, dolomite, and ground water to reach equilibrium.

Class II - Gravel Source Springs

Class II, or gravel source springs, have moderate to high rates of flow (10-60 gallons per minute) and low concentrations of dissolved materials, as indicated by the Nonesuch spring (frontispiece, Fig. 1). Water collected in high level river gravels in old stream channels at the surface enters joint controlled solution openings in the underlying limestone. Jillson, 1946-48, noted the occurrence of Irvine Gravels, deposited along the former course of the Kentucky River and current

TABLE 4

CALCIUM-MAGNESIUM GEOCHEMISTRY OF CURDSVILLE AND TYRONE LIMESTONE WATERS IN THE BLUE GRASS REGION

(Figures in ppm)

Lexington Limestone	J. V. Thrailkill* This report	Hendrickson and Krieger 1964	Palmquist and Hall 1961
Springs			
Ca	61.1**	76.7	
Mg	4.8**	6.0	
Wells and Springs			
Ca		78.1	79.0
Mg		9.1	6.0
Ca/Mg ratio (ppm)	12.7 (springs)	12.8 (springs)	13.0 (wells and springs)
High Bridge Group			
Springs			
Ca	44.3***	91	
Mg	5.5***	6.4	
Ca/Mg ratio (ppm)	8.12	14.2	

---

*See Appendix A of this report

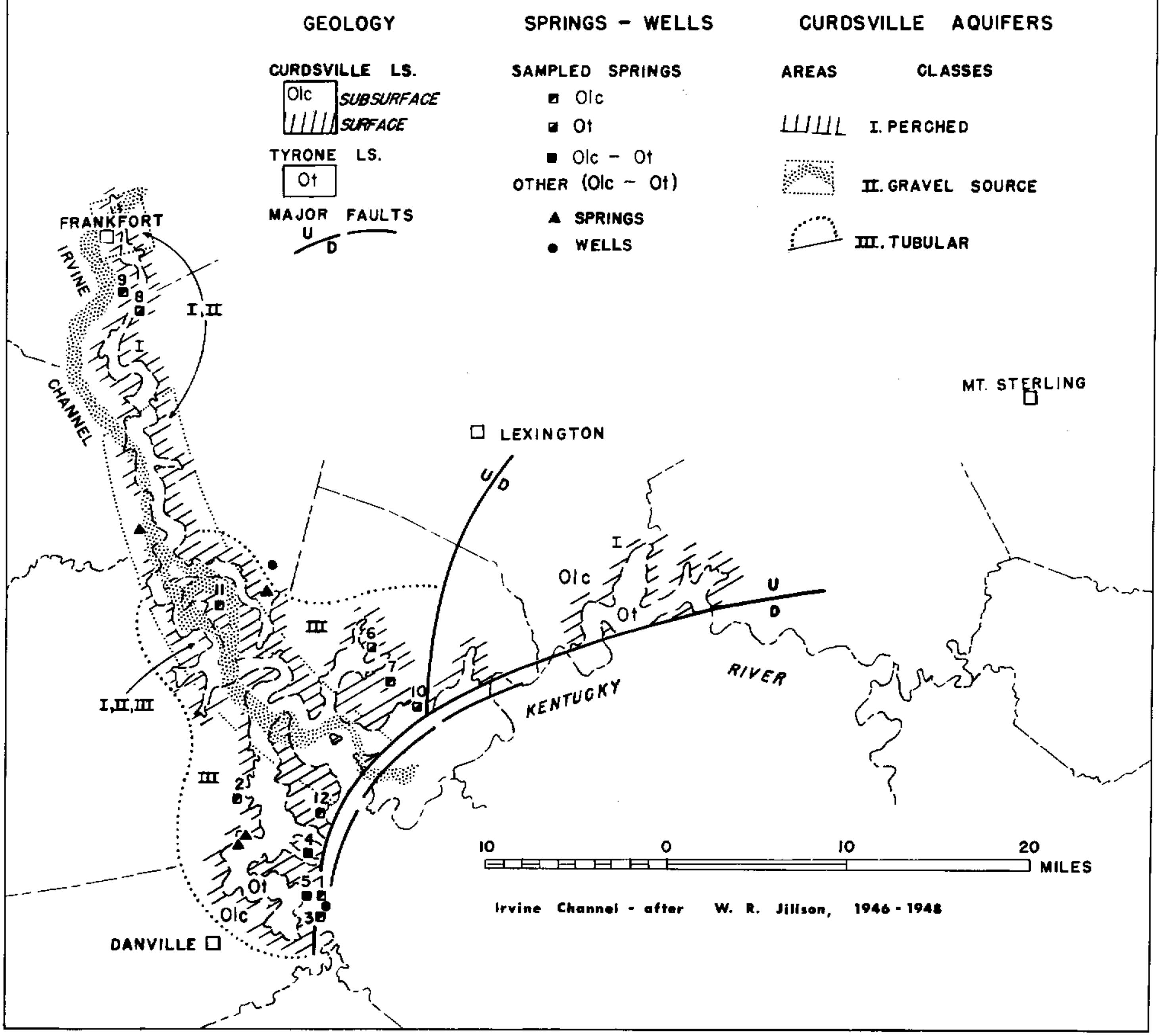
**Curdsville Member of Lexington Limestone only

***Tyrone Limestone of High Bridge Group only

Figure 17

DISTRIBUTION OF GROUND WATER

CURDSVILLE AND TYRONE LIMESTONES



Irvine Channel - after W. R. Jillson, 1946 - 1948 detailed work of the Kentucky Mapping Program is revealing more gravel deposits along former drainage channels (Earle Cressman, Personal Communication). Low concentrations of dissolved material probably is a result of short transportation in the limestone (Table 5).

Class III - Tubular Springs

Class III, or tubular springs, are common in the Jessamine Dome Shoal Area north of Danville. Flow rates are variable from 1 to 40 gallons per minute, and Ca concentrations are high (Table 5). The high Ca/Mg ratios indicates a lack of dolomite in the sediments assuming the water has had time to reach equilibrium with the rock through which it passes according to Thrailkill (Appendix A). Bentonites, forming aquicludes, occur at various levels in the area. The high percentage of limestone indicates possible high solubility for the rock and accounts for the large solution openings.

Wells

Wells were not observed, sampled, or tested in the field. Published information is not specific for wells in the Curdsville Limestone Member alone. Most produce from several horizons including the Tyrone Limestone below.

The best prospective area for Curdsville wells is probably in the Jessamine Dome Shoal Area where favorable lithology and fracture conditions exist, such as in the Bryantsville Quadrangle area.

TABLE 5

COMPARISON OF CALCIUM-MAGNESIUM IN CURDSVILLE LIMESTONE SPRINGS

(by area)

	Average		
	Ca in PPM	Mg PPM	Ca^{++}/Mg^{++}
North Danville Area	64	4.4	9.4
Frankfort Area	45	8.2	3.4
Nonesuch Spring	13	3.5	2.3

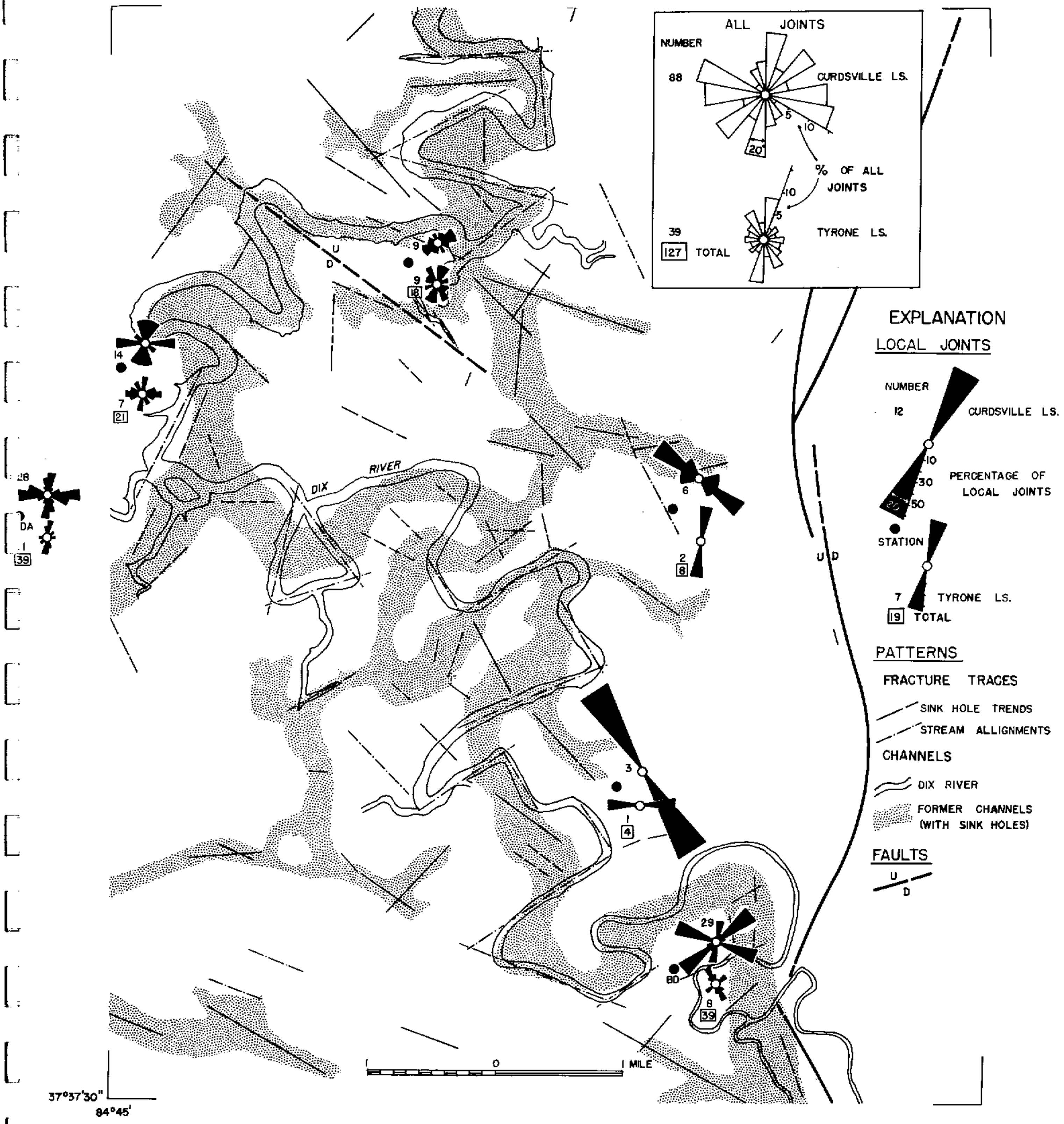
PROSPECTIVE CURDSVILLE LIMESTONE AQUIFERS IN THE BRYANTSVILLE QUADRANGLE AREA

The Bryantsville Quadrangle area, located on Figure 2, was selected for detailed study as representative of the Jessamine Dome Shoal Area. Springs and wells have been found in the Curdsville Limestone which occurs near the surface over much of the quadrangle. Because intergranular porosity and permeability are of minor importance in the Curdsville Limestone as observed in core analysis, subsurface water movement must be largely confined to fractures (joints and faults) or to bedding planes which have been enlarged by underground solution. Surface water movement is partly controlled by fractures which produce a somewhat rectangular drainage pattern in the present stream channel of the Dix River and its tributaries as shown on the map of Figure 18. Evidence of linear alignment of sink holes, solution valleys, stream valleys, and old river courses are abundant on the Bryantsville topographic quadrangle. Moreover, all these features called "fracture traces" or lineaments are remarkably similar in orientation to the measured joint fractures in outcrops of the Curdsville and Tyrone Limestones in the same area as shown on the map. Therefore, although fault fractures may be important locally, joints seem to be the dominant avenues of solution, and enlarged joints are probably the principal aquifers. Springs observed in the field issue from joints. The joints are largely vertical, and wells drilled

Figure 18

JOINT CONTROL OF FRACTURE TRACES AND CHANNEL PATTERNS

BRYANTSVILLE QUADRANGLE AREA



in areas of concentrated joints or where joint sets cross should encounter more enlarged fractures and yield more water than wells drilled in other areas. Old river courses marked by large numbers of sink holes might be particularly favorable well sites. Lattman and Parizek, 1964, applied this reasoning to a limestone area in Pennsylvania and found that wells drilled near crossing "fracture traces" encountered more cavities at depth and yielded more water than wells drilled in interfracture areas.

Further work, including drilling, is needed to prove the validity of the relationship between "fracture traces" and favorable well locations in the Bryantsville area. Aerial photographs were examined for a small portion of the Bryantsville quadrangle and indicate additional evidence for fracture traces and solution phenomena. Obvious joints were observed near the Dix River and other places. Shallow depressions, and soil color variations suggest possible alignments. Lattman and Parizek, op.cit., using infrared aerial photographs made with a blue filter were able to find soil moisture differences along fracture traces. Field examination would yield additional information in regard to fractures and fracture traces. A drilling program could be set up as a separate Water Resources Institute Project with wells proposed for favorable fracture trace areas with provision for one or more control wells in interfracture areas.

SUMMARY

The factors which control the porosity and permeability of the Curdsville Limestone are geological. Stratigraphy and structure determine water movement and aquifer development.

Microstratigraphic analysis of over 500 hand specimens and 400 thin-sections from 27 surface (outcrop) and subsurface (core) stations in the Blue Grass Region and north to the Ohio River provides the basis for subdivision of the lower Lexington Limestone, consisting principally of the Curdsville Member, into three distinct ten-foot beds. Each bed can be subdivided into less distinct "zones" consisting of several Lithologic Types. These divisions aid in the interpretation of the geologic history and paleogeography of Curdsville time.

Both vertical (stratigraphic) and lateral (facies) changes occur in the Curdsville Member. The lower bed, which has the most favorable aquifer attributes was deposited by high energy wave and current action in a shallow sea. The middle and upper beds were deposited in deeper water under lower energy conditions in a progressively transgressing sea. These latter beds contain more impervious shale and bentonite aquicludes than the lower bed. However, locally, shallow water was maintained over carbonate bank-shoal areas as compared with slightly deeper water over shelf-channel areas during most of Curdsville time. The high energy bank-shoal facies were washed free of much of the fine impervious material and thus developed into thicker potential aquifers than the shelf-channel facies.

The Jessamine Dome Shoal Area is the most favorably located shoal for ground water solution and accumulation in the Curdsville Limestone because of subsequent uplift and erosion of this feature along the Cincinnati Arch. Meteoric waters at shallow depths have replaced unpotable salt and sulphur waters still found in the more deeply buried bank or shoal areas. Dissolving ground waters have enlarged fractures (mostly joints) in the limestone resulting in sink holes, solution valleys, and caverns thus providing increased avenues for ground water movement and accumulation as evidenced by the existence of springs and wells in the area.

The Bryantsville Quadrangle north of Danville on the Jessamine Dome Shoal Area was examined in detail for joint and fault fracture frequency and alignment. Alighments of such features as sink hole trends, present and pre-existing stream channels, and prominent dry solution valleys were also determined. The obvious similarities in trend of all these lineaments or "fracture trace" features with the fracture pattern indicates that the subsurface solution and surface water erosion are controlled by the fractures. Likewise water movement and accumulation might also be found at depth in these largely vertical fractures. Thus local high frequency and crossing of plotted "fracture traces" may indicate the most likely sites for prospective Curdsville water wells. This hypothesis can be evaluated by drilling and testing several favorably located wells.

APPENDIX A(1)

CALCIUM-MAGNESIUM RATIOS IN SPRING WATERS FROM THE CURDSVILLE LIMESTONE

By John Thrailkill

Twelve water samples from springs in the Curdsville and Tyrone limestones were analyzed for calcium and magnesium ions by atomic absorption spectrophotometry. A Beckman DB-G spectrophotometer with atomic absorption accessory was used. Samples were diluted 10 fold to bring them into the linear range of the instrument, and a Na_2EDTA (ethylene diamine tetra acetate) - NaOH solution was added to eliminate Na and K enhancement and SO_4^{2-} and PO_4^{-3} interferences. The analyses were performed by M. Osolnik and R. Worley. The precision of this technique has not yet been established, but the coefficient of variation of the analyses is probably no greater than 5%. The analytic results are shown below.

Sample No.	ppm		Molality (m) x 10^3		Ratios	
	Ca^{2+}	Mg^{2+}	Ca^{2+}	Mg^{2+}	$\frac{m_{Ca^{2+}}}{m_{Mg^{2+}}}$	$\frac{Ca\ ppm}{Mg\ ppm}$
1	81	4.5	2.0	0.19	10.5	18.0
2	65	6.5	1.6	0.27	5.9	10.0
3	86	3.5	2.1	0.14	15.0	24.6
4	78	3.5	1.9	0.14	13.6	22.3

Sample No.	ppm		Molality (m) x 10^3		Ratios	
	Ca^{2+}	Mg^{2+}	Ca^{2+}	Mg^{2+}	$\frac{m_{Ca^{2+}}}{m_{Mg^{2+}}}$	$\frac{\text{Ca ppm}}{\text{Mg ppm}}$
5	88	4.0	2.2	0.16	13.7	22.0
6	42	4.5	1.0	0.19	5.3	9.4
7	46	5.0	1.1	0.21	5.2	9.2
8	41	6.0	1.0	0.25	4.0	6.8
9	49	10.5	1.2	0.43	2.8	4.6
10	50	6.0	1.2	0.25	4.8	8.3
11	13	3.5	0.32	0.14	2.3	3.7
12	44	2.5	1.1	0.10	11.0	17.6
Averages	56.9	5.0	1.4	0.21	7.8	13.0

The analyses are quite unremarkable and appear to be typical of springs from the Lexington group, as indicated by analysis in Hendrickson and Krieger (1964, p. 34-35). The high Ca/Mg ratio indicates that largely calcite has been dissolved, but the presence of some Mg suggests some dolomite solution. Because the solution kinetics of dolomite are generally thought to be slower than those for calcite, the water could have been in contact with equal amounts of both minerals.

It is not possible to determine the degree of saturation of the water with respect to calcite or dolomite with the limited data. The high Ca^{2+} concentrations indicate that the waters have either been in equilibrium with a high partial pressure of CO_2 or that there has been evaporation. In spring water, the former is a far more likely explanation, inasmuch as both ground water and vadose seepage are commonly in equilibrium with a $P_{CO}2$ higher than that of the normal atmosphere. The 88 ppm Ca^{2+} in sample 5 suggests an equilibrium $P_{CO}2$ of about 3×10^{-3} atm (10 times that of the normal atmosphere).

Although relatively little can be said about the probable history and evolution of the spring waters, it is possible to compute, assuming saturation, the equilibrium relationships with respect to calcite and dolomite, the most abundant carbonates in the rocks through which the water has passed. From the equation

$$\underset{\text{calcite}}{2CaCO_3 + Mg^{2+}} \longrightarrow \underset{\text{dolomite}}{CaMg(CO_3)\ 2 + Ca^{2+}}$$

it can be seen that the equilibrium constant $K = a_{Ca}2+ / a_{Mg}2+$ (assuming pure solid phases at unit activity). Although a complete analysis of the spring waters is not available, they are undoubtedly within the applicability range of the Deybe-Hückel equation for individual ion activity coefficients and it is unlikely that any complexing is important. Since, by the Deybe-Hückel expression,

$$\gamma Ca^{2+} \simeq \gamma Mg^{2+}, \quad \text{then } a_{Ca}2+ / a_{Mg}2+ \simeq m_{Ca}2+ / m_{Mg}2+.$$

A value of K may be derived from the expression $\ln K = -\Delta G^{\circ}_{f}/RT$ if the free energies of formation of the various species involved in the reaction are known. Of these, all are known with fair accuracy except that for dolomite. Recent determinations have tended toward values of $\Delta G^o f$ for dolomite of between -516 and -517 kcal. These values yield values of K from 0.185 to 0. Inasmuch as the ratios $a_{Ca^{2+}} / a_{Mg^{2+}}$ ($m_{Ca^{2+}} / m_{Mg^{2+}}$ in table) are considerably higher than either value of K (the lowest is 2.3 for sample No. 11), the waters at saturation are in equilibrium with calcite. Stated another way (and assuming reversible equilibria), if waters with the $m_{Ca^{2+}} / m_{Mg^{2+}}$ ratio of those sampled are saturated with respect to calcite, they are undersaturated with respect to (and hence would dissolve) dolomite.

APPENDIX A(2)

SAMPLED SPRINGS IN THE CURDSVILLE AND TYRONE LIMESTONES

Sample No.	County	Quadrangle	Farm	Carter Coordinates	Date Collected	Aquifer	Remarks
1	Garrard	Bryantsville	Maywick	16-0-59 800' FWL, 3400' FSL	11/24/66	Curdsville	
2	Mercer	Wilmore		25-P-58 900' FWL 3500' FSL	11/14/66	Curdsville	
3	Garrard	Bryantsville	Rice	5-N-59 1500' FWL, 2200' FSL	11/24/66	Curdsville or Grier	
4	Garrard	Bryantsville		11-0-58 1500' FEL 3000' FSL	11/15/66	Curdsville	Flows from joint, 110°
5	Garrard	Bryantsville	Maywick	20-0-58 1700' FEL 3000' FSL	11/24/66	Curdsville	Flows from joint on top of mud cave
6	Jessamine	Nicholasville		12-Q-59 2000' FNL 2000' FEL	9/14/66	Tyrone 10' below Curdsville Contact	Near Jessamine Creek

APPENDIX A (2)
(Continued)

Sample No.	County	Quadrangle	Farm	Carter Coordinates	Date Collected	Aquifer	Remarks
7	Jessamine	Little Hickman	Halfhill	20-Q-59 300' FNL 1100' FWL	9/14/66		
8	Woodford	Frankfort East		10-T-56 1100' FNL 700'FWL	9/13/66	50' below base of Curdsville	Old Crow Dist. Spring
9	Franklin	Frankfort East	Fint, A,W.	2-T-56 250' FEL 1900' FSL	9/13/66	Curdsville	
10	Jessamine	Little Hickman		4-P-60 200' FWL 1000' FNL	9/14/66	Tyrone	West Sulfur Well Spring
11	Woodford	Salvisa		1-Q-57 300' FEL 800' FSL	10/26/56	Curdsville	Nonesuch Community Spring
12	Garrard	Bryantsville	Mt. Oliver Church	5-O-59 500' FWL 500' FSL	9/14/66	Curdsville	Mt. Oliver Church Spring

APPENDIX B

INTERCRYSTALLINE POROSITY AND VERTICAL PERMEABILITY IN THE CURDSVILLE LIMESTONE

(After Data from Oilfield Research, Inc., Evansville, Ind.)

Area (Facies)	Station	Lithologic Type	Porosity Percent	Bulk Wet Density	Vertical Permeability Md.
Shelf	PB				
	242	la	2.1	2.66	0.14
	240	lb	1.2	2.68	<0.10
	236.8	lc	0.6	2.68	
	226.1	IIb	0.9	2.64	
	210.5	IIIa	0.6	2.69	<0.10
	246	V	0.5	2.67	
Carbonate Bank	HS				
	388.5	la	1.5	2.68	
	386.2	Ib	1.5	2.68	
	390.4	Ic	0.6	2.66	
	355	IIa	3.1	2.62	
	368.4	IIIa	0.9	2.70	
	356.6	IIIb	4.7	2.64	<0.10
	367.4	IIIc	2.2	2.71	
	SR				
	429.8	Ia	4.0	2.64	<0.10

Porosities of less than 3% are of less than normal accuracy using commercial techniques. We chose the most applicable method, and the most accurate from our laboratories - weight loss method. The entire sample received was subjected to vacuum for 1 1/2 hours and the chamber then filled with water. The fluid was then pressured to 1500 psi and let stand for 1 1/2 hours. The rock was weighed, including the contained fluid, and dried at less than 100°C for three hours. Each sample was weighed again, the weight loss representing the volume of pore space. Upon determining total volume by submersion the porosity was calculated by standard procedure.

Based on our experience and a review of the porosity results, we felt it unnecessary to test all the samples for permeability. First, many of the samples received are too small to drill a 3/4" standard plug. Although 1/2" (diameter) plugs could have been drilled, the results often leave something to be desired. However, we primarily based our decision on comparable rock lithologies which we have tested. The porosity is a good permeability indicator. Intercrystalline porosity, as observed in limestones, is normally quite low and the permeability negligible. Vugular porosity will normally be 8 to 12% and the permeability profile erratic. Dolomite porosity can be low (<8%), or high, (>20%), but with intercrystalline porosity the permeability will not be extremely high (>100 md.). The five permeability tests confirmed our preconceived ideas and, we hope, suffice for your purposes. In other words, we doubt any of the samples not tested will have measurable permeability at two atmospheres pressure differential.

Should you desire further testing, or have any questions regarding the above results contact us at your convenience. We have waived the minimum charge for these tests.

OILFIELD RESEARCH, INC.
Evansville, Indiana

Ben Ross Oates

APPENDIX C

X-RAY ANALYSIS OF CURDSVILLE LIMESTONE INSOLUBLE RESIDUES

George T. Hine

Qualitative *x*-ray diffraction determinations were made on several samples of insoluble material, from station FEC, which showed the presence of quartz, montmorillonite-illite clays, feldspar, and some carbonates. Quantitative values for the materials were not determined. Subsequent petrographic examination, of station FEC thin sections, has confirmed the presence of quartz, clay, and feldspar.

Quantitative *x*-ray diffraction determinations of quartz content in the insoluble residues was attempted with limited success. Dr. I. S. Fisher (Geology Department, University of Kentucky) has prepared a calibration curve for the determination of quartz in insoluble residues with calcite as an internal standard. This curve could not be used with the FEC samples because of the occurrence of several extraneous peaks in the vicinity of the standard calcite peak. Two attempts were made to prepare a calibration curve, one using zircon and the other using silicon as internal standards. The results obtained in each case were variable, although promising with a definite trend, indicating the need for refinement in method. Additional work with the *x*-ray was not done because work with the petrographic thin sections yielded satisfactory information as to quartz content in the Curdsville Limestone as well as distinguishing the type of quartz (chert and detrital quartz).

PREPARATION OF STANDARD MATERIAL

Quartz: Clear fragments of quartz were ground in a crusher and then powdered for five minutes in a Spex-mix No. 5000 mixer mill.

Clay filler: Mud Cave bentonite from Curdsville station was treated overnight in a bath of concentrated (commercial grade 33%) HCL. The residue was washed several times to remove the acid. The remaining material was placed in water, mixed, and the fine material in suspension was decanted, allowed to settle, and the clear water was siphoned off. The fine clay was air dired, removed from the beaker, crushed in a mortar and pestle, and placed in a closed bottle.

Zircon: Fine grained zircon sand of high purity was placed in the Spex-mix for five minutes and powdered.

PREPARATION OF STANDARD SLIDES

Six 1.25 g. samples were prepared, each containing 0.25 g. of zircon and 1.00 g. of either pure quartz, clay, or a mixture of both so that samples of 1.00 g., 0.80 g., 0.60 g., 0.40 g., 0.20 g., and 0.00 g. of quartz and an inverse amount of clay were made up. Each of the six samples was placed in the Spex-mix for one minute to produce a nearly homogenous material. The six samples were removed from the mixer and each sample was divided equally between three clean petrographic slides. A mixture of Duco Cement and acetone was added to each slide and the moistened material was then spread evenly over the slide. The fixing solution was allowed to dry and the excess material was scraped from the ends of the slide.

X-RAY DIFFRACTION PROCEDURES

The standard slides were placed in the x-ray and peaks and backgrounds were read as follows:

Readings	2 θ	d spacing
Background	32.25°	
Montmorillonite	35.00°	2.55 Å
Quartz	36.50°	2.49 Å
Background	48.00°	
Quartz	50.30°	1.82 Å
Zircon	53.50°	1.71 Å
Background	54.30°	

Machine Settings

Tube Voltage	35 kv.
Tube Current	16 ma.
Detector Voltage	1.6 kv.
Pulse Height Discrimination base	5.0 v.

Each peak and background was read three times for 100 seconds per slide and the average of the peaks and backgrounds for the three duplicate slides was calculated.

DETERMINATION OF RATIOS

The zircon/quartz ratios were calculated from the average values using the formula:

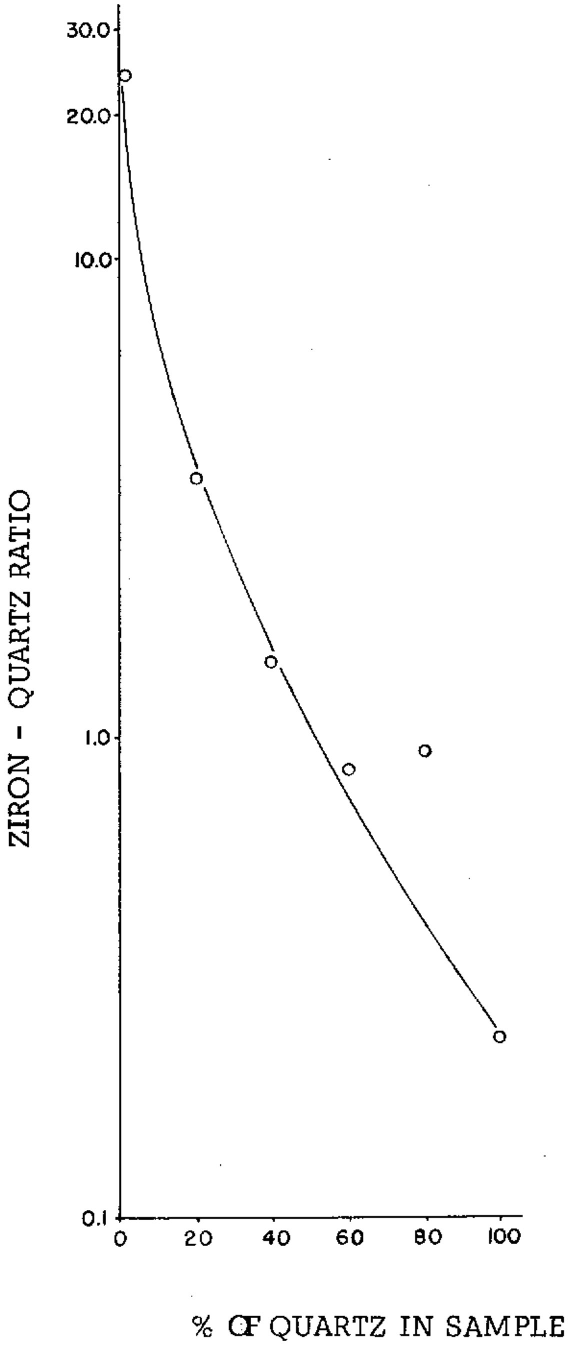
$$\frac{\text{Zircon counts - background counts}}{\text{Quartz counts - background counts}} = \text{zircon/quartz ratio}$$

These ratios were plotted on three cycle semi-logarithmic paper. The ratio for zircon/quartz (Figure 19) yielded a smooth curve except in the area of 0.80 g. quartz. The cause of the variation was not determined although additional samples were run. The other ratio (zircon/clay) showed similar deviations in the 0.80 g. quartz area perhaps indicating a mixing or packing variation with slides of the composition 0.80 g. quartz and 0.20 g. clay and 0.25 g. zircon.

A new set of standard slides, identical to the zircon standard slides except for the use of silicon as the internal standard, were prepared. Silicon is often used to calibrate the goniometer on the x-ray diffractometer since it has sharp definite peaks which can be accurately located. Using the silicon peak as a reference, counts were made as follows: Silicon (28.443°); Background (27.843°); Background (27.162°); Quartz (26.662°). The resulting curve showed even more variation than the zircon standard curve.

Figure 19

CALIBRATION CURVE FOR DETERMINATION
OF QUARTZ CONTENT



ADDITIONAL WORK

Since the completion of the x-ray work, additional information was obtained by Dr. Fisher as to recommended procedures for quantitative standardization of the x-ray to an accuracy of ± 1%. The method is as follows:

1. Crush all material to a size which will pass a 325 mesh screen.
2. Prepare the slides by back filling a hollow area in the slide so that the powder is level with the upper surface of the slide, so that it will be in the focal plane of the x-ray when in the slide holder. The old method of gluing the material to the slide introduces error as a result of differing thickness of the standard which varies the focusing of the x-ray beam.
3. The peak area should be determined using a step scanner. Because for quantitative work it is important to determine the area under the peak rather than the peak height. The peak height is more sensitive to grain size than is the peak area.
4. Readings of 50,000 counts should be made on each peak and the time required for the accumulation of this number of counts should be recorded.

The method outlined should result in a calibration standard with an accuracy of ± 1%.

APPENDIX D

INSOLUBLE RESIDUES OF CURDSVILLE LIMESTONE

By George Hine

I. Four stations were selected for insoluble content. (CA, DA, FEC, CT)

II. Modified standard insoluble techniques were used. (after Ireland, 1958, p. 75)

- A. Two sampling techniques were used.
    1. Cores were sliced to give a continuous sample for each 1 foot interval.
    2. Surface sections were sampled for each 1 foot interval and proportional amounts of each rock type present were collected.
- B. The samples were crushed to <5 mm and 10g of each was separated and placed in a 1L beaker.
- C. Each sample was dissolved in 400cc of 20% HCl for at least 10 hrs. and until all reaction had stopped.
- D. Each sample was decanted and washed three times to remove all acid and salts. Care was taken to preserve all insoluble materials.
- E. The samples were air dried, weighed, and placed in small stoppered bottles for storage.

III. Several methods of examination were used on the residues.

- A. The % insoluble for each one foot interval was plotted for each section, as were various running averages and total averages.
- B. Each sample was studied under the microscope to determine the nature of the insoluble material.

C. Color determinations were run on the samples. (GSA Rock Color Chart, 1948).

D. Grain size analysis was run on several samples and the composition of the size fraction noted.

E. Stain tests for bentonite clay were made.

F. Insoluble % were compared with γ ray logs.

G. X-ray examination was tried on several samples.

H. Relation between rock type and insoluble content were noted.

APPENDIX E

STATION LOCATIONS OF CURDSVILLE LIMESTONE SECTIONS

Station	Carter Coordinates	Quadrangle
BA	23-0-58	Bryantsville
BB	14-N-58	Bryantsville
BC	15-N-58	Bryantsville
BD	6-N-59	Bryantsville
CA	10-S-62	Clintonville
CT	17-R-61	Coletown
CYT	10-W-62	Cynthiana
DA	20-0-57	Danville
FCF	9-Q-62	Ford
FEC	8-T-56	Frankfort East
FEO	10-T-56	Frankfort East
FL	23-R-62	Ford
FLS	22-AA-62	Falmouth
FWD	17-V-56	Frankfort West
GG	21-AA-57	Glencoe
HS	13-R-65	Hedges
KA	16-R-58	Keene
LEL	6-S-62	Lexington East
LHC	22-P-59	Little Hickman
LWB	19-T-60	Lexington West
MC	13-W-67	Moorefield
ND	4-Q-60	Nicholasville
NV	10-Q-60	Nicholasville
PB	20-CC-57	Patriot
SC	19-R-57	Salvisa
SH	8-W-60	Sadieville
SR	16-T-66	Sideview
TD	24-S-57	Tyrone
VVK	11-Q-61	Valley View
VVL	17-Q-61	Valley View
WC	7-P-58	Wilmore

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