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Textural properties, provenance, and environments of formation of the "rimrock" sandstone of the filled sinkholes northeast of Rolla, Missouri

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TEXTURAL PROPERTIES, PROVENANCE, AND ENVIRONMENTS OF FORMATION OF THE "RIMROCK" SANDSTONE OF THE FILLED SINKHOLES NORTHEAST OF ROLLA, MISSOURI.

BY

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THESIS

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ABSTRACT.

Filled sinkholes have long been known to occur in the carbonate rocks of Missouri. A sandstone unit occurs in these sinkholes at their outer margin, forming a rim, and is called here the rimrock sandstone. Samples of rimrock sandstone, from an area northeast of Rolla, Missouri were studied. Grain size, heavy mineral and thin section analyses of these samples were carried out.

Size analysis data suggest that, texturally, the rimrock sandstone is similar to the St. Peter sandstone and that this formation could have supplied sands for the formation of rimrock. Field evidences suggest that continental conditions prevailed at the time of the formation of the sandstone under study. The median grain size is similar all over the area for this sandstone and it is mineralogically mature. This could be due to the maturity of the source rock. Size and shape of the detrital sand grains have been altered due to secondary enlargement through silicification.

It seems that most of the filled sinkholes have resulted from the simultaneous deposition and sinking of the sediments, due to the solution activity. Association with the white and purple shales, alumina clays and coals suggest that the rimrock is of basal Pennsylvanian age.

The clay deposits resting over the rimrock sandstone in

these sinkholes are of great economic value due to their heat resisting character.

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I. INTRODUCTION.

A. PURPOSE AND SCOPE OF INVESTIGATION:

The occurrence and distribution of the filled sinkholes in the area northeast of Rolla, Missouri, have been known for a long time. A sandstone bed, commonly called rimrock sandstone, usually occurs at the outer margin of these sinkholes. In this thesis, it is referred to as rimrock sandstone because it forms a rim around sinkholes. Detailed petrographic work on this sandstone has not been done, and its origin is still a matter of controversy. Detailed study of the grain size and composition of this sandstone might yield useful information regarding the source rock. In this study of the rimrock sandstone, the following objectives were outlined:

1. To present, evaluate, and interpret the available geological information regarding the rimrock sandstone.
2. To determine the source rock of this sandstone.
3. To point out the probable environmental conditions of its deposition.

B. GEOGRAPHY:

The area studied is a sector located northeast of Rolla, Phelps County, Missouri (Fig.1). It is bounded on the north by State Highway 28 from Belle, Maries County, to Owensville, Gasconade County. U.S.Highway 66 (I-44), from Rolla to Cuba,

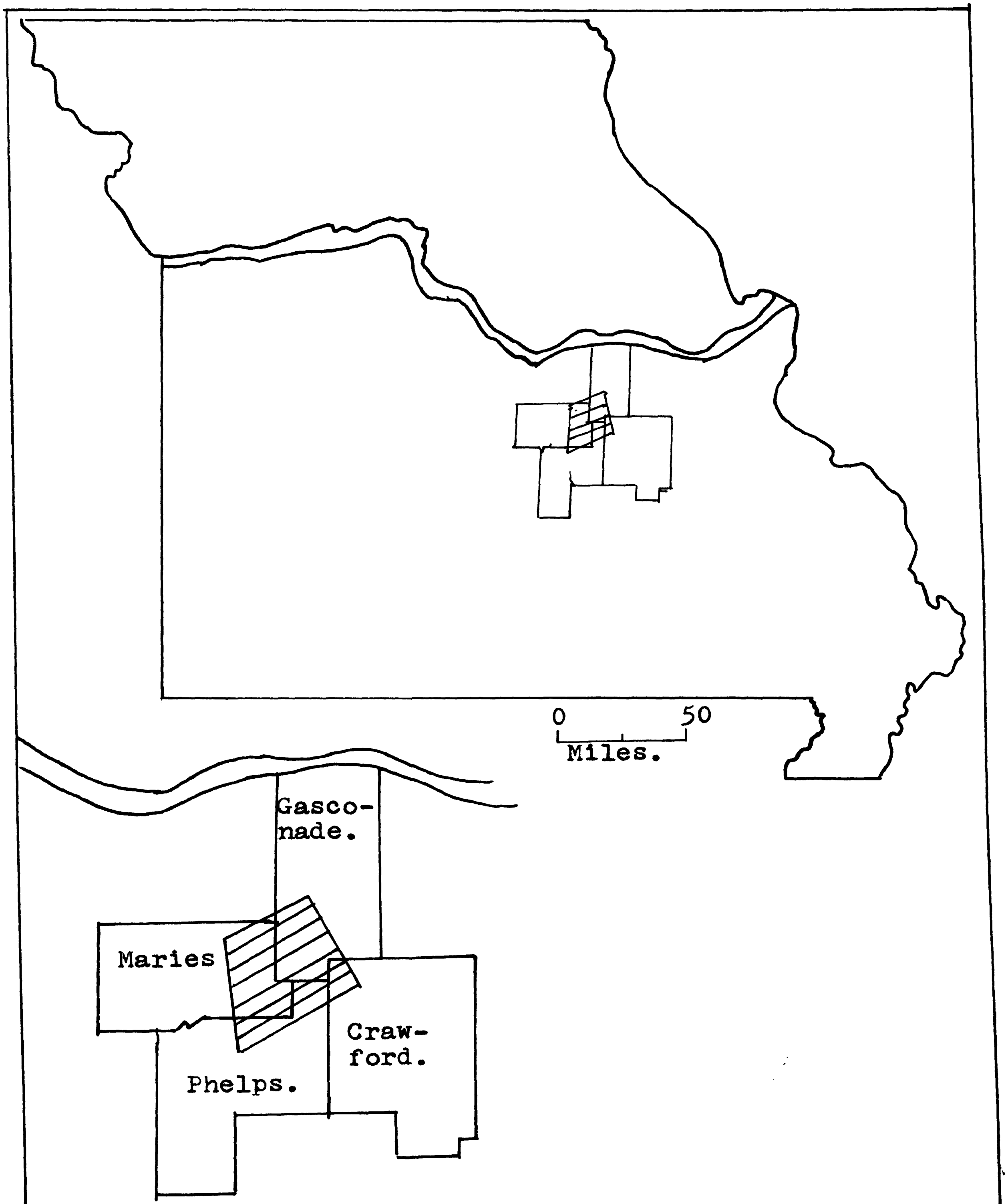


Fig.1: Index map showing the location of thesis area.

Crawford County serves as the southern boundary. State Highway 19 from Cuba to Owensville marks the eastern margin, and U.S.Highway 63 from Rolla to Vichy, Maries County, lies along the western limit. The area lies within the parallels 37° 58′ and 38° 21′ north latitude, and meridians 91° 25′ and 91° 47′ west. The region has a total surface area of about 400 sq. miles and recent topographic maps, prepared by the U.S.Geological Survey in cooperation with the Missouri Geological Survey are available for the entire region.

The geologic information was recorded on 1 : 250,000 United States Army Service Maps No. NJ 15-6 and NJ 15-9.

C. CLIMATE AND VEGETATION:

The annual mean temperature in this region is 13.6°C (56.6°F). The July mean temperature is 26.6°C (79.9°F) and that of January is -0.2°C (31.6°F). The average precipitation is 813.9 mm. (31.96″) in the form of rain and snow.

Temperate forests consisting mainly of various types of oaks, pine and gum trees cover the area, with maple, hickory, eastern red cedar, sycamore and walnut trees in lesser abundance. The climatic conditions are suitable for the cultivation of wheat, corn, soybeans and hay. The cultivation of hay encourages cattle raising in the area.

D. CULTURE:

Rolla, with a population of 13,000 inhabitants, is the largest town in this region. It is linked with St. Louis, the nearest large city, by the Frisco Railroad and the Greyhound Bus Service operating on U.S.Highway 66, and is connected with the other towns by well maintained highways. U.S.Highways 66 and 63 provide an all-weather access to the area of investigation. Improved and unimproved light duty roads forming a network make most of the area accessible.

Quarrying and transportation of refractory clays in the area is one of the chief industries. A plant in Owensville carries out primary crushing of the clays before their dispatch to refractories or chemical companies. Pits formed as a result of the removal of clays and road cuts across the sinkholes are most suitable sites for the study of the sandstone under discussion.

E. PHYSIOGRAPHY AND DRAINAGE:

The area under discussion lies in the extreme south of the southern clay district of Missouri, and is located in the northeastern portion of the Ozark Plateau. The topography of the area is flat with a gentle slope toward the northeast. The relief is relatively low, the highest elevation being about 1200 feet above mean sea level near Rolla, and the lowest elevation being less than 730 feet where Missouri Highway 19 crosses the Bourbeuse River.

The Bourbeuse River, which flows northeastward and north, and which is fed by small creeks forming a dendritic pattern, is the main perennial stream in the area. The area in the north is drained by Dry Fork Creek which flows eastward and joins the Bourbeuse River outside the eastern boundary. Highways 28 and 66 were built on drainage divides on the north and south respectively.

F. FIELD AND LABORATORY INVESTIGATIONS:

The fieldwork for this investigation was accomplished partly during the months of October and November, 1969 and partly in March and April, 1970.

This phase of work consisted of:

1. Locating the sink structures and working out the stratigraphic sequences present in them.
2. Collecting samples from the rimrock sandstone occurring in the sinkholes in the Ordovician carbonate rocks.

The clays occurring in the sinkholes were not included in this study, except for the determination of their stratigraphic position in relation to the rimrock sandstone. The laboratory investigations consisted of grain size analysis of the sandstone, binocular and petrographic examinations and heavy mineral analysis of selected samples.

G. PREVIOUS WORK:

A petrographic study of the sandstones of the filled sinkholes in the area under investigation has not been done in detail so far and no report has been published specifically on the geology of this sandstone.

Some workers have analyzed a few samples of the rimrock sandstone, while working on the problems of the Ordovician sandstones of the Ozark region.

Cordry (1929,p.59) carried out heavy mineral analyses of a few rimrock sandstone samples, while working on the heavy minerals of various sandstones of the Ozark region.

Grawe and Cullison (1931,p.305) undertook grain size analysis of the sandstone from a sinkhole in the center of section 14, T.38 N., R.8 W., about five miles north of Rolla on the west side of Highway 63.

Dake (1921) analyzed a few Pennsylvanian sandstone samples for their grain size and published the reults for comparison with those of the St. Peter Sandstone in his paper, "The Problem of the St. Peter Sandstone".

Bretz (1950,p.789) worked on the origin of the filled sinkholes.

The results and the interpretations presented by these workers are reported in the respective chapters of this thesis.

Passega (1957,p.1952 and 1964,p.830) and Visher (1969, p.1074) worked on the texture of sandstones as the basis for the interpretation of the environmental conditions. This has also been discussed in the relevant chapter.

II. STRATIGRAPHY.

A. GENERAL STATEMENT:

This chapter deals with the geology of the area under investigation. Even though several systems are represented, the rock section is not very thick. Exposed rocks in this area are essentially all Ordovician and Pennsylvanian in age with some thin local Devonian and Mississippian outcrops. The Ordovician rocks form the bed rock, and crop out over the eastern half of the area, with a few patches of Pennsylvanian rocks overlying them. Pennsylvanian rocks crop out in the western half of the area with elongated bands of Ordovician rocks exposed due to erosion of the former. The Ordovician rocks consist mainly of dolomites and minor sandstones as well as shales. Pennsylvanian rocks are composed of sandstones with chert breccia at the base and clays overlying the sandstones (Fig.2).

B. ORDOVICIAN SYSTEM:

According to Cullison (1944,p.12), "The above conditions lead the writer to conclude that, during this portion of lower Ordovician time, the Ozark region was covered by a broad shallow sea. The relation between land and sea was not stable, however, except during the short intervals of time represented by persistent thick dolomite beds."

The rocks of this system are divided into three series:

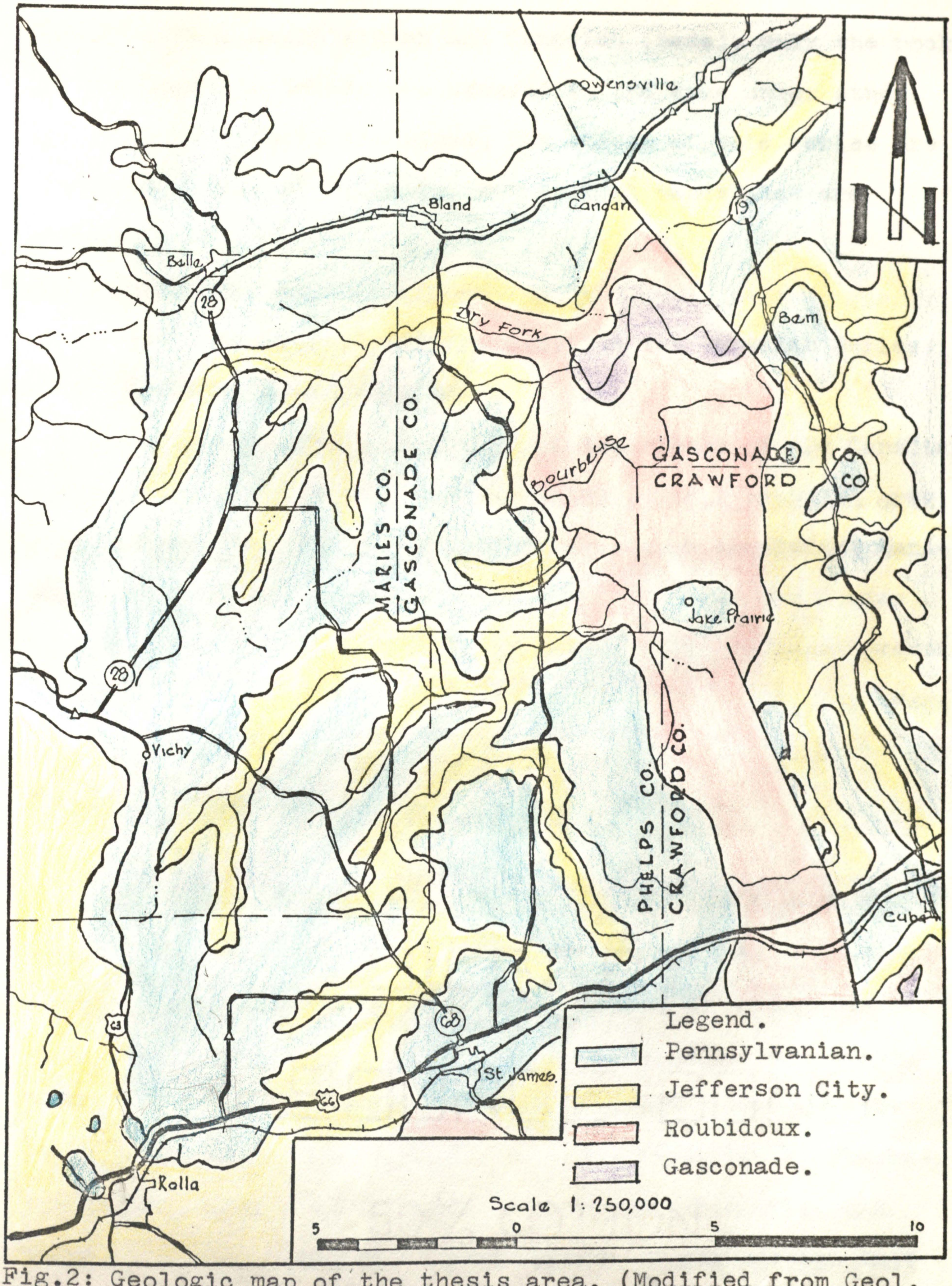


Fig.2: Geologic map of the thesis area. (Modified from Geol. Map of Missouri, 1961)

Cincinnatian, Champlainian and Canadian (base). Only the rocks of the Canadian Series are exposed in the area under study, and will be briefly discussed. The strata of this series are composed mainly of dolomite, but several sandstones are present.

1. Canadian Series:

The following formations comprise the Canadian Series:

a. Gasconade Formation:

The Gasconade Formation is the oldest of the Canadian Series. The lithology is predominantly a light brownish grey, cherty dolomite. The formation consists of a persistent sandstone unit in its lowermost part which is named the Gunter Member. Fossils are usually scarce except for molluscs present in chert and widespread masses of cryptozoan algae. The average thickness of the formation is 300 feet and is present in the subsurface throughout most of the state.

b. Roubidoux Formation:

The Roubidoux Formation by definition is a series of sandstones, dolomites and cherts that overspreads the Ozark region of Missouri. In central Missouri, it is predominantly a quartzose sandstone, whereas in other parts of the state, most of the rock is cherty dolomite. At many places in the area under study, the sandstone of this formation is characterized by exceptionally well-preserved ripple-marks, mud cracks and cross-bedding. It is exposed in the eastern half of the area under discussion. The thickness of this formation ranges from 100 to 250 feet.

c. Jefferson City Group:

The name Jefferson City was applied to the series of dolomites and cherty dolomites exposed along the Missouri River in the vicinity of Jefferson City. In 1911, Ulrich redefined the formation and included in it additional younger beds. In 1944, Cullison elevated the term to group status and divided it into two formations:

i. Rich Fountain Formation (older):

This formation crops out widely in the Ozark region. The Ordovician rocks exposed in the western half of the area under study, and east of the Cuba fault belong to this formation. The thickness of this formation is about 150 feet. The contact between the underlying Roubidoux and the Rich Fountain occurs at the middle of the outer margin of the western edge of the area. This formation consists of two different types of dolomites as follows:

1. A very fine-grained, thin- to massive- bedded, argillaceous to silty, grey to buff dolomite called "Cotton rock".
2. A medium to coarsely crystalline, massive, light buff to greyish dolomite. It contains fine crystalline quartz in small pockets distributed throughout the bed.

In addition to the dolomite, the Rich Fountain Formation also contains lenticular layers of sandstone and dull white, compact or porous chert. Some of the chert is oolitic with varying shades of colors from bluish grey to brown to white.

ii. Theodosia Formation:

The Rich Fountain is overlain by the Theodosia Formation, the junction being marked by the presence of residual chert and conglomerate. The total maximum thickness of this formation is 360 feet. It is divided into:

1. Blackjack Knob Member.
2. Lutie Member.
3. Rockaway Conglomerate (base).

The lithology of the formation is principally of the "Cotton rock" type, although some massive crystalline dolomite beds are known to occur in it. The formation contains a number of beds which are diagnostic and supposedly of considerable importance in correlation.

d. Cotter Formation:

The Cotter Formation lies conformably on the Jefferson City Group and because it is difficult to differentiate the two, they are often designated with a combined name such as the "Jefferson City-Cotter" unit. The major part of the formation is composed of a light grey to light brown, medium to finely crystalline, cherty dolomite containing thin intercalations of green shale and sandstones.

The Cotter Formation is overlain by the Powell and the Smithsville formations, which are composed of finely crystalline dolomite with thin beds of green shale and sandstone, and a dolomite with a small amount of chert. These two formations are not exposed in the area under study.

2. Champlainian Series:

The two presently recognized stages of this series are represented in Missouri by eight formations as follows:

a. Chazyan Stage (younger):

i. Joachim Formation.

ii. Dutchtown Formation.

iii. St. Peter Formation.

iv. Everton Formation (base).

b. Mohawkian Stage:

i. Kimmswick Formation.

ii. Decorah Formation.

iii. Plattin Formation.

iv. Rock Levee Formation (base).

Only the St. Peter Formation is described here as it alone is relative to this investigation.

The name St. Peter was first used in Minnesota by J.N.Nicollet in 1843, for a sandstone and an overlying limestone exposed at the mouth of the St. Peter River. The Missouri Geological Survey uses the term for the sandstone overlying the Powell Formation of southern Missouri, and underlying the Joachim Formation. The most notable exposures of this formation are observed in Lincoln, St. Louis and Jefferson counties.

The formation consists of very pure quartz sandstone, often containing 98% or more silica. Massive bedding, a high degree of sorting and sphericity are considered the distinguishing features of this sandstone. It is 75 to 80 feet thick.

C. SILURIAN TO MISSISSIPPIAN SYSTEMS:

Rocks of the Silurian System are not exposed in the area studied. During the Devonian and Mississippian times the area was covered for short intervals of time with seas. These systems are now represented by residual chert which is prevalent in the area. Both the Devonian and Mississippian rocks contain fossils.

D. PENNSYLVANIAN SYSTEM:

The basal Pennsylvanian rocks are extensively exposed in the western portion of the thesis area, and are patchy in the eastern half. They tend to be confined to filled sink structures, unconformably overlying the lower Ordovician rocks, The general sequence of the strata in the area is as follows, in increasing order of age:

3. Refractory Clays:

These clays form a commercial deposit due to their high heat-resistant character. They are white to light grey, composed mainly of clay minerals such as kaolinite and halloysite. They are sandy and ferruginous at their base.

2. Sandstone:

This sandstone forms the rimrock of the filled sink-holes. It is white to light yellow, light brown, red and violet in color. The shades of colors are due to the presence of ferruginous compounds. It is fine-grained, massive, friable, and slickensided at the base. The sand grains are rounded to well-rounded, frosted and composed of quartz. The secondary enlargement observed on these grains makes them angular. The sandstone is 2 to 10 feet thick and is underlain by chert breccia containing various types of chert fragments probably derived from the underlying Ordovician rocks.

1. Interbedded Sandstones and Clays:

In a few of the sinkholes, the sandstone and breccia described previously are underlain by a bed of intercalated sandstones and clays. The sandstones are thinly bedded, ranging in thickness from an inch to a foot. They range in color from light grey to red and violet, and are fine-grained. They are usually friable, but hard where cemented by silica. The clays are grey to red and laminated. This unit also contains thin layers of chert at irregular intervals.

The stratigraphic sections encountered in the filled sinkholes are presented in detail, in Appendix A.

E. STRUCTURE:

The Ordovician rocks in the area are generally horizontal or have a low angle of dip, except in the vicinity of the sinkholes, where they show a dip as high as 50° towards the center of the sinkhole. This high angled dip is a result of solution phenomena. Only one significant fault, the Cuba fault, running approximately north-south is exposed in the eastern part of the area.

The clays and sandstones in the sinkholes dip toward the center, and are slickensided at places. Drag folds are also observed. Chert conglomerate at the base of the rimrock is brecciated, due probably to the solution of the underlying rocks and the confining effect of the overlying sandstone.

F. GEOLOGICAL HISTORY:

The geological history of east central Missouri is not a very complicated one. During the earliest Paleozoic time (Late Cambrian and Early Ordovician) the area was covered by predominantly carbonate depositing seas and to a lesser extent by sand depositing seas.

During the post-Ordovician period, the thesis area and the surrounding Ozarks remained, more or less, a landmass, during which, due to solution activity, the sinkholes were formed on the carbonate land surface. This resulted in a karst type of topography. Up to early Pennsylvanian time, this area became a near shore swampy region. As a result, the clastics, probably derived from the erosion of the Ozark landmass in the south, were deposited to form the rimrock sandstone and clay deposits in the simultaneously subsiding sinkholes. It again emerged as a landmass, after the deposition of clays and has been subjected to weathering and erosion up to the present.

Mesozoic rocks are not found in Missouri except in the extreme south. The sea encroached further in early Cenozoic times and formed rocks of the Wilcox Group. During the latter part of this era, northern Missouri experienced glaciation with the formation of clay, silt and gravel beds, covering the exposed filled sinkholes in the area.

III. LABORATORY AND FIELD PROCEDURES.

A. COLLECTION OF SAMPLES:

170 samples, representative of the rimrock sandstone of the filled sinkholes in the area under investigation, were collected. The sinkholes are found in the area in three forms:

1. In road cuts (Pl.1A).
2. Patchy outcrops roughly forming circular patterns.
3. Abandoned clay pits (Pl.1B).

At some places it was not easy to distinguish between the rimrock sandstone and Roubidoux Sandstone exposures. Such doubtful sample locations are marked on the map (Fig.3) with a separate symbol. No samples were collected from the basal chert breccia and conglomeratic sand zones, because the chert fragments, derived due to the solution of underlying dolomite, are residual in origin. Most of the sampling was restricted to the rimrock sandstone.

In the beginning of the fieldwork, serial samples were collected at an interval of 0.5 foot along the line normal to the bedding of the sandstone. The mechanical analyses of the serial samples from any particular location exhibited no variation in grain size distribution. Hence, serial sampling was abandoned and spot samples were collected from rest of the locations.

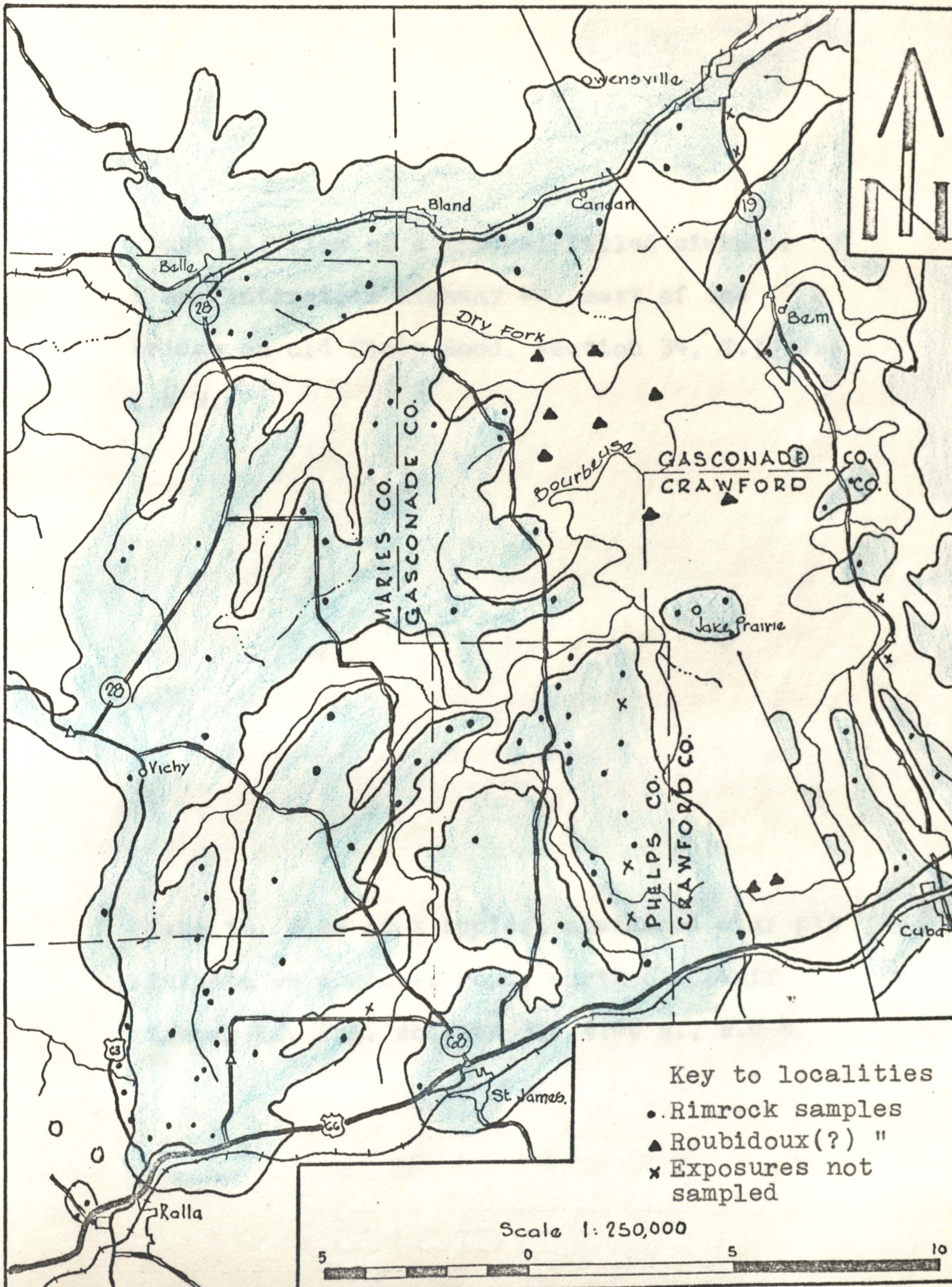


Fig.3: Map showing the locations of studied and sampled exposures. (Modified from Geol. Map of Missouri, 1961)

Plate 1A: View of a typical filled sinkhole along Interstate Highway 44, east of the bridge on old Vichy Road, section 34, T.38 N., R.8 W.

Plate 1B: View of a typical abandoned clay pit sinkhole on a gravel road, north of County Highway EE, SE$\frac{1}{4}$, section 31, T.40 N., R.8 W.

Plate: 1A.

Plate: 1B.

B. LABORATORY WORK:

After examination under the binocular microscope, 115 samples were selected for the mechanical analysis. Out of these, 10 samples were selected for heavy mineral study and 6 for thin-section study under a polarizing microscope. The localities from which these samples were obtained are shown in Fig. 4.

1. Mechanical Analysis:

The following procedure was employed for the mechanical analysis:

a. Approximately 80 to 90 grams of each sample were disaggregated and weighed accurately.

b. The samples were sieved in a Tyler Ro-Tap Sieve Shaker for 12 minutes, through a set of 14 sieves ranging in phi sizes from 0.75 to 4.0

c. The amount retained on each sieve was weighed and examined under a binocular microscope for the determination of the percent aggregate grains present.

The weights obtained as above were tabulated. A computer program was made to distribute the error in weight, for adjusting the weight of product retained on each sieve and their percentage as well as cumulative weight percentages. Cumulative curves also were drawn with the help of the computer (Fig.5). Almost all samples contained more than 90% of sand size material. The computer program is presented Appendix B.

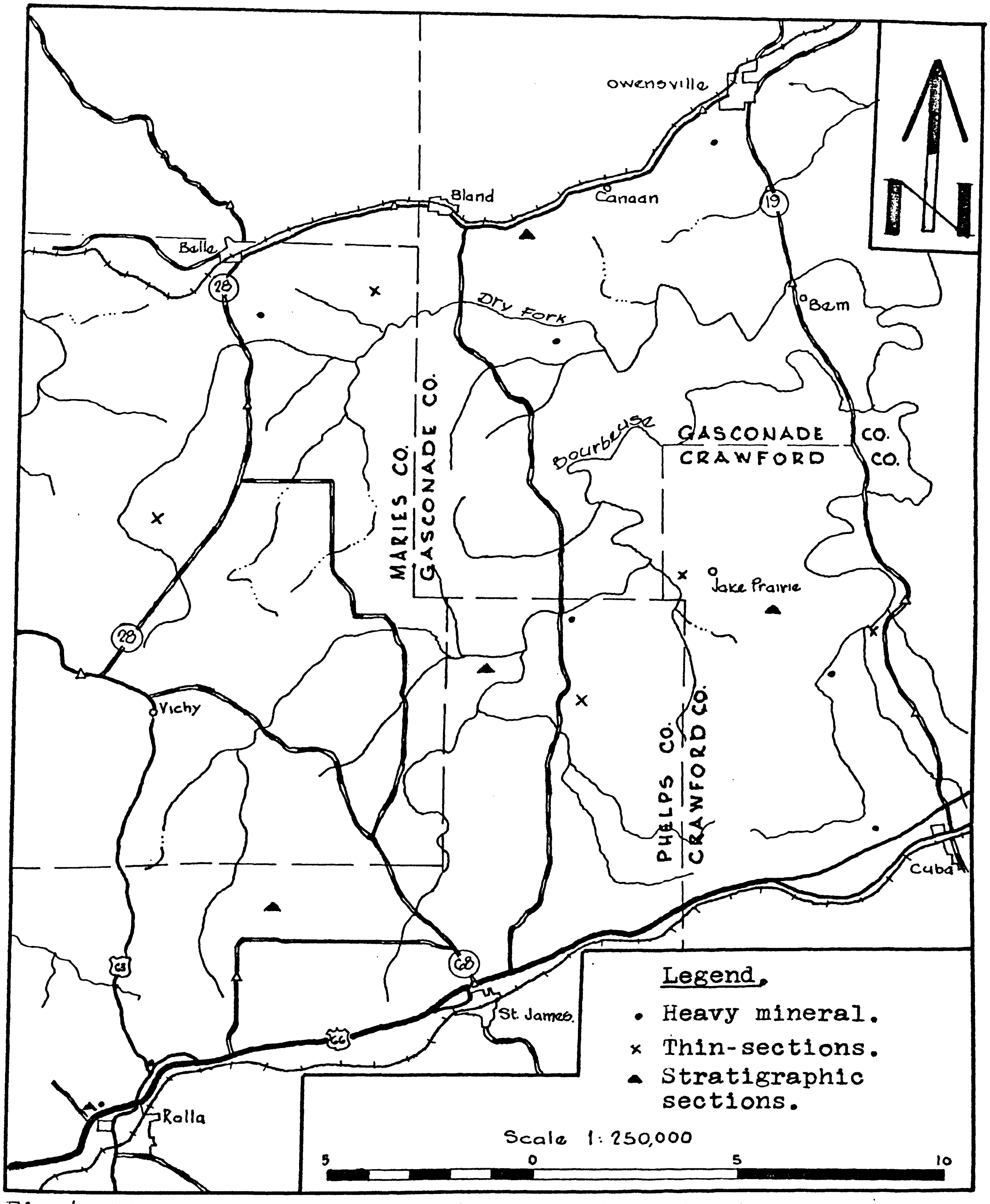


Fig.4: Map showing the sampling locations for heavy mineral and thin-section studies, and locations for which stratigraphic sections are presented.

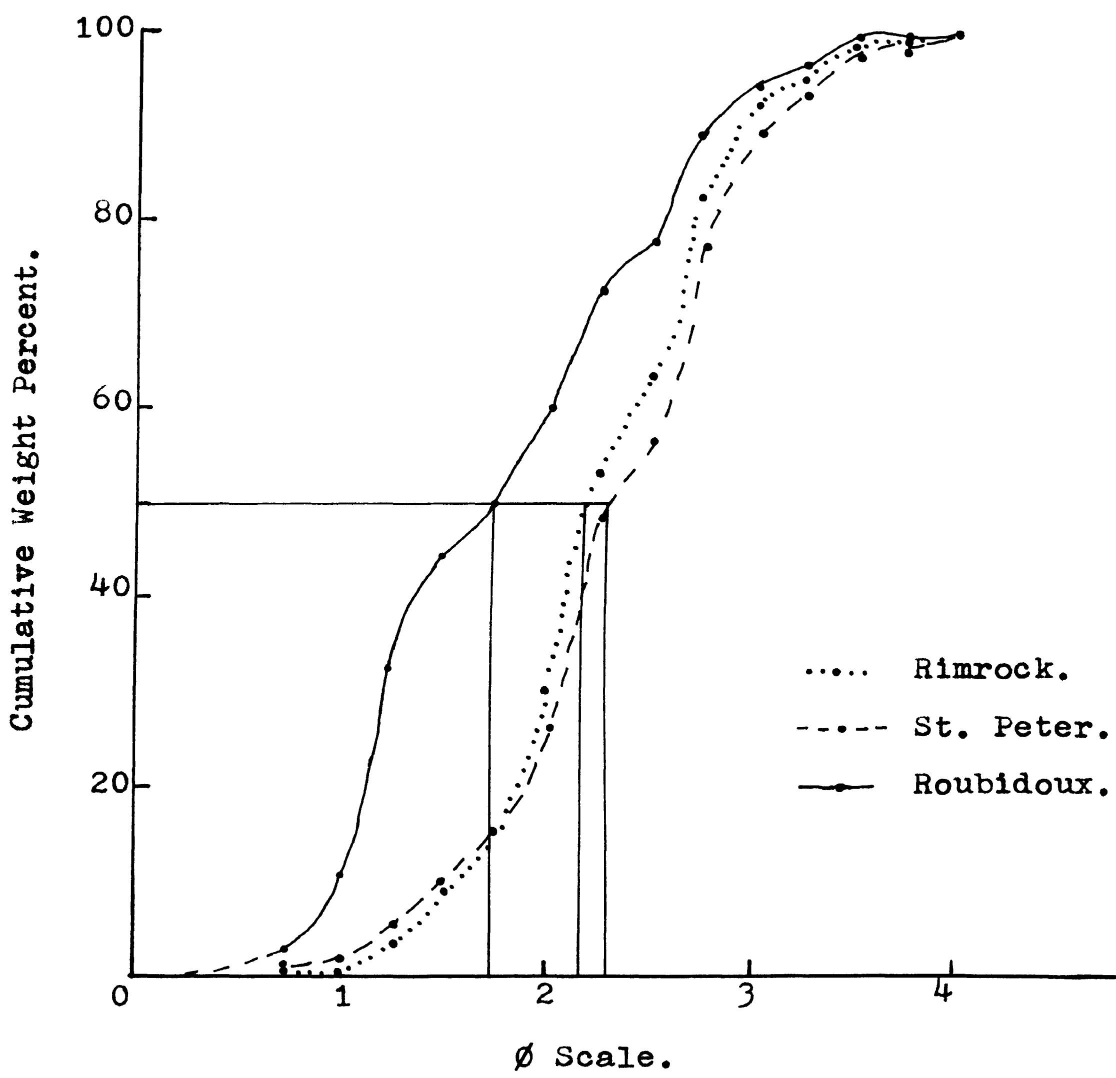


Fig.5: Cumulative curves for the rimrock, Roubidoux and St. Peter sandstones.

2. Results:

In order to compute the various grain size parameters for each sample, the phi scale values against percentile sizes of 1, 5, 16, 25, 84 and 95 were read off from the cumulative curves. The various parameters were thereafter computed as follows:

a. Average Grain Size:

Arithmetic Mean, Graphic Mean and Median are measures which may be determined for the average size of the grains. Arithmetic Means for each sample were found with the help of the computer, using the following formula:

$$\bar{X} = \frac{(x_1 \text{ x } \% \text{ wt.}) + (x_2 \text{ x } \% \text{ wt.}) + \ldots (x_n \text{ x } \% \text{ wt.})}{100}$$

where, $\bar{X}$ = Arithmetic Mean,

x_1 , x_2 ,.... x_n = Average size of each class interval,

% wt. = Weight percent of grains in each class.

The fifty percentile size values of grains for each sample were read from the cumulative curves, which represented the Median. It is the size such that half of the grains in a sample are coarser than that and half are finer than that size.

Graphic Means were calculated using the following formula suggested by Folk (1965,p.45).

$$M_z = (16_\phi + 50_\phi + 84_\phi) / 3$$

where M_z is the Graphic Mean and 16_ϕ , 50_ϕ, and 84_ϕ are respective percentile values.

The Graphic Mean values were calculated for selected samples for comparison with the Arithmetic Means and Medians of these samples. It was found, on comparing all the three values for any particular sample, that either they were the same or very near to each other. The values of the Arithmetic Mean ranged from 1.7Ø to 2.8Ø. A cumulative curve and histogram were plotted (Fig.6) for these values and their mean was read off from the curve at the 50% point. The value is 2.15Ø.

b. Sorting:

Sorting is the measure of the spread of the grain size distribution of a given sediment. Trask's Sorting Coefficient, Graphic Standard Deviation and Inclusive Graphic Standard Deviation are the measures of sorting or the uniformity of the grain size distribution.

Trask's Sorting Coefficient is expressed by the formula,

$$S_o = \sqrt{\frac{mm.25}{mm.75}}$$

where, S_o is Trask's Sorting Coefficient and mm.25 and mm.75 are the 25 and 75 percentile values in mm. This measure fails to give a good indication of sorting because it gives only the sorting in the middle of the distribution curve and ignores the ends. Therefore, this measure is no longer as popular as those given below.

The Graphic Standard Deviation is a good measure of sorting and is computed by the formula (Folk, 1965, p.45);

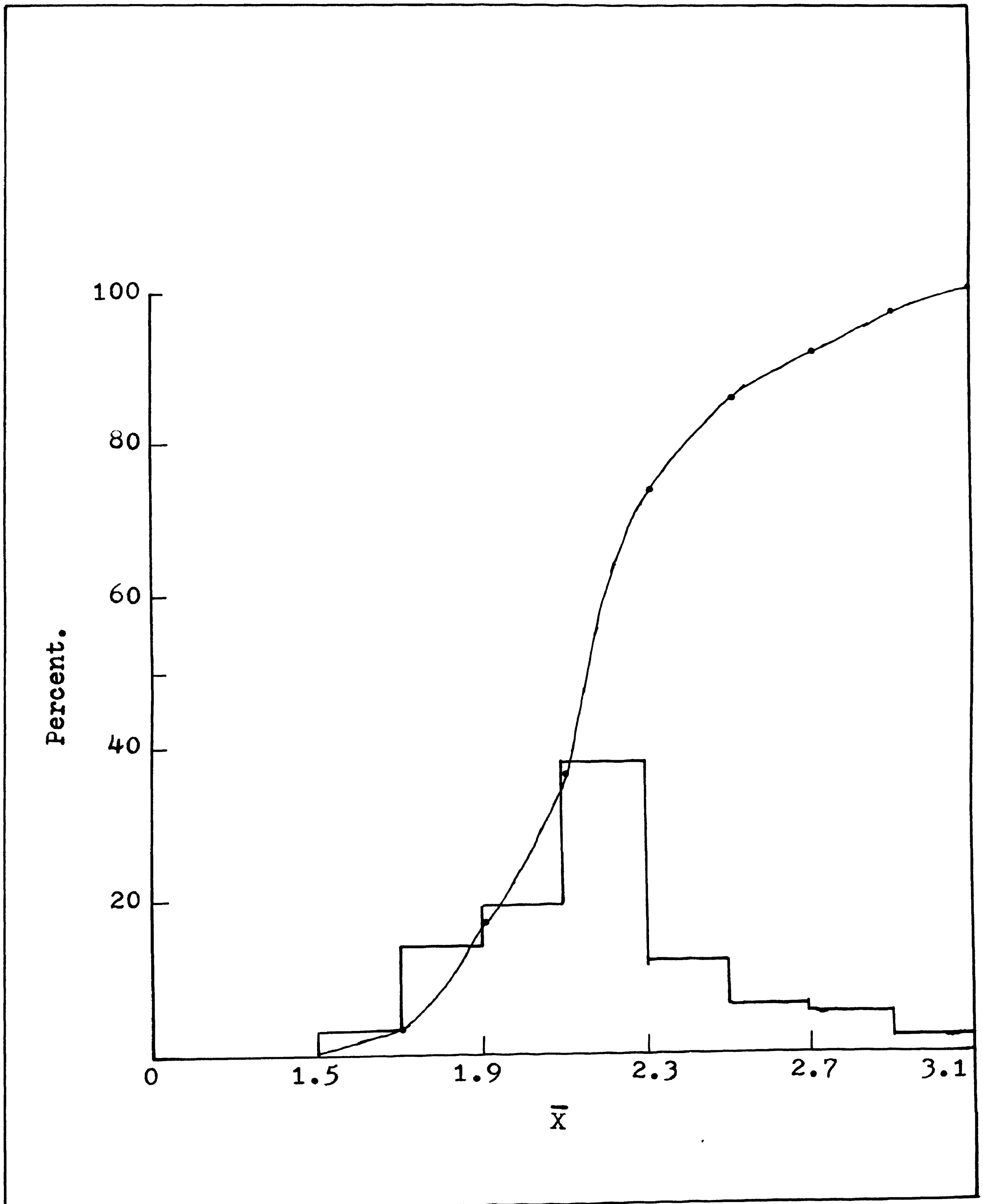


Fig.6: Histogram and cumulative curve of $\overline{X}$ values of 115 rimrock sandstone samples.

$$\sigma_G = \frac{84_\phi - 16_\phi}{2}$$

where σ_G is the Graphic Standard Deviation, and 84_ϕ and 16_ϕ are the 84 and 16 percentile values.

This measure gives the sorting of the central two-thirds of the curve. A better one is the Inclusive Graphic Standard Deviation given by the formula (Folk, 1965, p.46) :

$$\sigma_I = \frac{84_\phi - 16_\phi}{4} + \frac{95_\phi - 5_\phi}{6.6}$$

where σ_I is the Inclusive Graphic Standard Deviation, and 5_ϕ , 16_ϕ , 84_ϕ ,and 95_ϕ are respective percentile values.

This formula includes 90 percent of the distribution and is the best measure of sorting.

The values of Inclusive Graphic Standard Deviation were calculated for all the samples and those of Graphic Standard Deviation for few selected samples. It was observed that the two values for any particular sample were the same or nearly the same. They range from 0.35ϕ to 0.85ϕ. A combined histogram-cumulative curve of the above values was plotted and the 50 percent value was read from it, representing the mean value which comes to 0.54ϕ (Fig.7).

According to Folk (1965, p.46), measurement of sorting values for large number of sediments has suggested the following verbal classification scale for sorting:

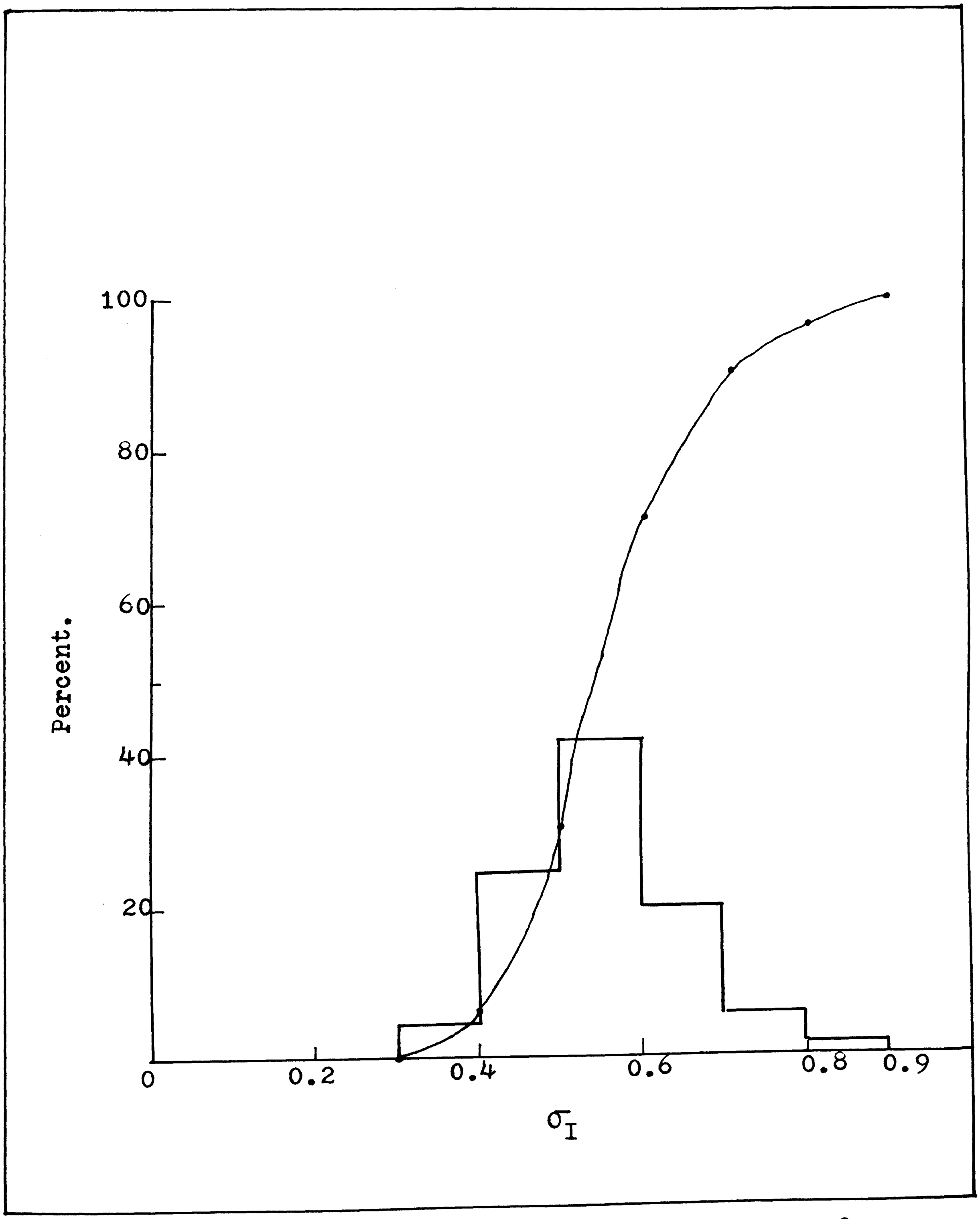


Fig.7: Histogram and cumulative curve of σ_I values of 115 rimrock sandstone samples.

Inclusive Graphic Standard Deviation,

under 0.35Ø	very well-sorted,
0.35Ø - 0.50Ø	well-sorted,
0.50Ø - 0.71Ø	moderately well-sorted,
0.71Ø - 1.00Ø	moderately sorted,
1.00Ø - 2.00Ø	poorly sorted,
2.00Ø - 4.00Ø	very poorly sorted,
above 4.00Ø	extremely poorly sorted.

According to the above scale, the value of 0.54Ø falls into the third category, which means that the sandstone under investigation can be considered moderately well-sorted.

C. HEAVY MINERAL ANALYSIS:

Heavy mineral analysis of 10 representative samples was taken up in order to know whether it offers any clue to interpret the provenance of the rimrock sandstone. The following procedure was adopted for this analysis:

1. Separation:
   a. The samples were crushed on a buckboard using a wooden mallet, care being taken to prevent any undue breaking of the individual grains.
   b. This sandstone is very low in heavy mineral content; hence, in order to recover sufficient heavy minerals, the following procedure was used on the assumption that heavy minerals, having higher specific gravity than quartz, will have associated, when the final stage of deposition is reached, with the coarser

grains of quartz. Keeping this fact in view, the crushed samples were sieved through 100 mesh sieve to increase the heavy mineral concentration. On examining the plus 100 mesh fraction, practically no heavy minerals except authigenic pyrite, hematite and probably limonite, were observed. This suggests that no significant loss of allogenic heavy minerals, was suffered in using the 100 mesh sieve.

c. 15 to 20 grams of the concentrate was subjected to separation using bromoform (sp. gr. 2.85), in a specially constructed device as outlined by Krumbein and Pettijohn (1966,p.339).

d. The heavy minerals thus separated were mounted on glass slides, using piperine (R.I.=2.68), for study under polarizing microscope.

2. Results:

The heavy minerals slides of 10 representative samples were examined in a qualitative way. The following heavy minerals were observed in order of abundance:

a. Tourmaline:

It is the most conspicuous and abundant mineral in all cases. The most common species is light brown to brown and light brown to green, pleochroic tourmaline. A few blue grains are also observed. They are well-rounded and a few of them also contain inclusions. In general, the tourmaline grains are larger than the other heavy mineral grains.

b. Zircon:

The next most frequent mineral present is Zircon. It is purple in reflected light to colorless in transmitted light. The grains are rounded to moderately well-rounded. A few grains exhibit secondary pyramidal overgrowth on the prism faces.

A few grains of anatase and rutile(?) are also observed. Opaque minerals, such as hematite and probably limonite, are found as cementing material in some of the samples studied. Authigenic pyrite is also present which has been, at some places, replaced by hematite forming pseudomorphs.

D. PETROGRAPHIC STUDY:

Thin-sections of 6 rimrock samples were prepared for petrographic study under the polarizing microscope. These samples were selected because they represent the sandstone from some of the many sinks which have their grains secondarily enlarged.

The thin-sections are colorless and transparent in polarized light, composed of more than 98% quartz. The grains are fine in size, rounded to well-rounded (Pl.2A), and angular where secondarily enlarged (Pl.2B). The enlarged grains are euhedral to subhedral and many of them exhibit a faint internal outline (halo), which represents the boundary of the original detrital quartz grain (Pl.3A and 3B).

1. Silicification:

Siever (1959,p.55) has studied the cementation in the Pennsylvanian sandstones of Missouri and other adjoining

Plate 2A: Photomicrograph of rounded sand grains from the rimrock sandstone from a sinkhole (location 132), along a gravel road about 3 miles east of Highway B, SE$\frac{1}{4}$, section 4, T.41 N., R.6 W. (X16)

Plate 2B: Photomicrograph of euhedral sand grains of the rimrock sandstone from an exposure (location 83), 2 miles west of Jake Prairie, section 24, T.40 N., R.6 W. (X16)

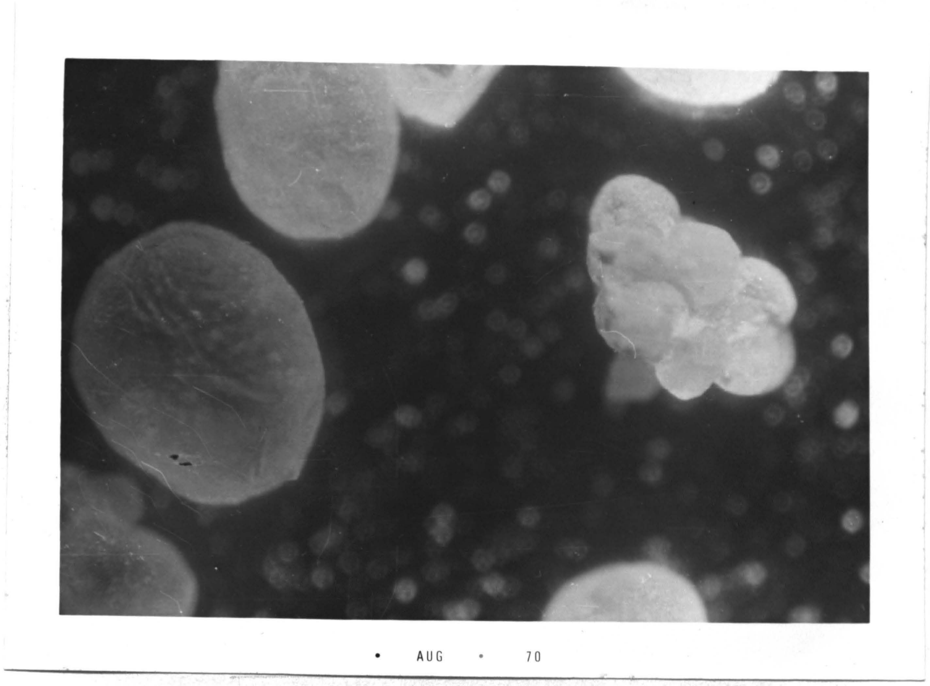


Plate: 2A

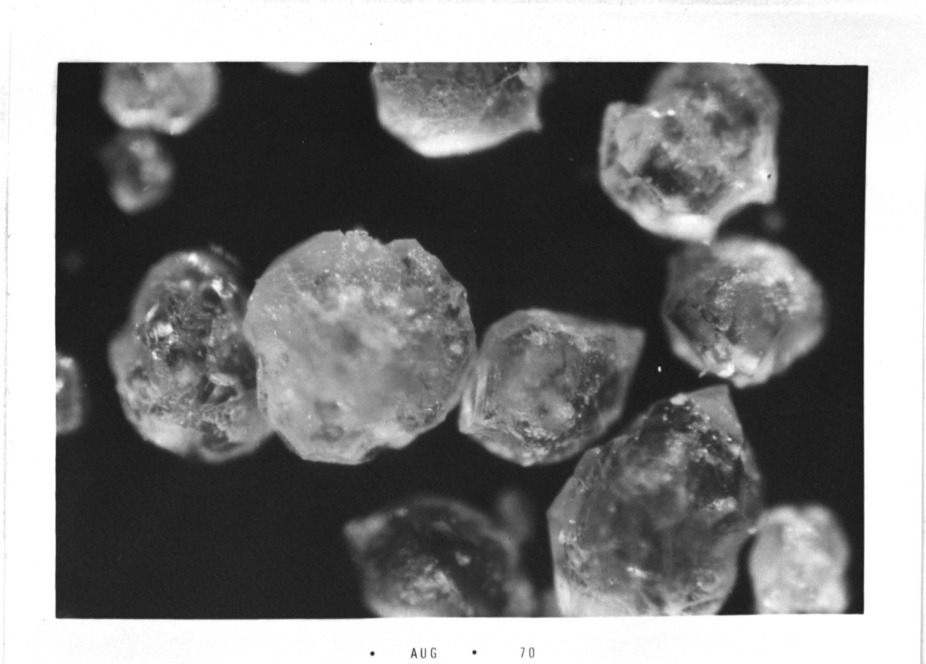


Plate 2B

Plate 3A: Photomicrograph of thin-section showing secondary enlargement of detrital sand grains of the rimrock sandstone from an exposure (location 83), 2 miles west of Jake Prairie, section 24, T.40 N., R.6 W. (X56)

Plate 3B: Photomicrograph of thin-section showing secondary enlargement of detrital sand grains of the rimrock sandstone from a clay pit on a gravel road (location 123), 2 miles south-east of Royal, section 10, T.39 N., R.6 W. (X16)

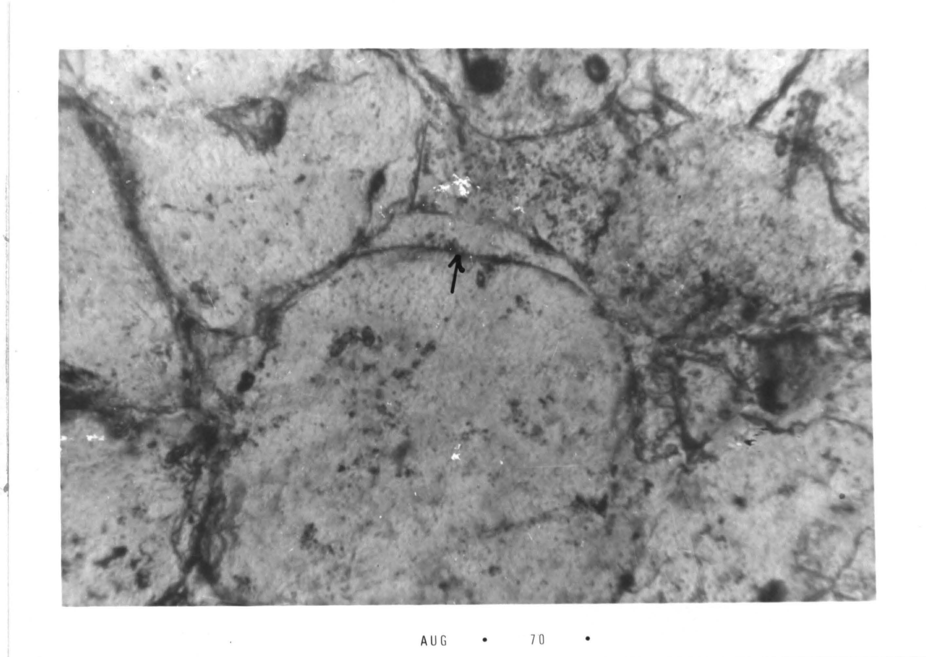


Plate: 3A

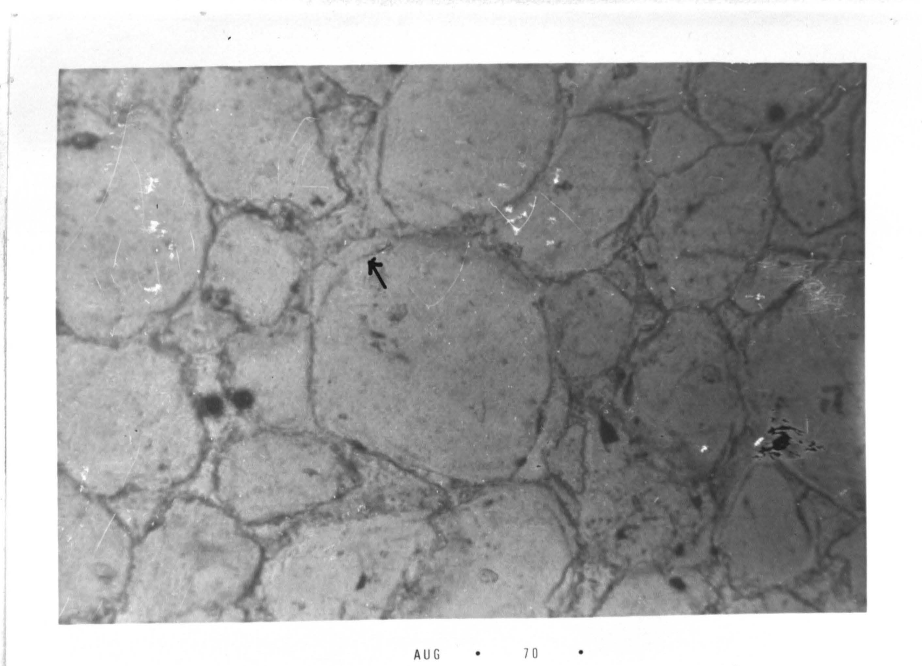


Plate: 3B

states.

> He states,"It has been noted by petrologists that there is normally an inverse relation between clay matrix content and amount of mineral cement. ... The relationship between the clay matrix and cement has commonly been ascribed to two factors: lack of pore space and low permeability."

This general relationship has been found to be true for the sandstone under study. The mineralizing solutions passing through the sandstone which had no clay matrix or very little of it, have precipitated the authigenic quartz on the rounded detrital quartz grains, in optical continuity. No enlargement is observed on the grains in argillaceous sandstone. Interpenetration of the grains is not widely observed in the thin sections. This suggests that probably no pressure phenomenon played a part in the solution of the detrital grains, but the silicification is mainly due to the silica-rich solutions which travelled through this sandstone and furnished the silica needed for the enlargement.

IV. ORIGIN OF THE RIMROCK SANDSTONE.

A. GENERAL STATEMENT:

On the basis of the results obtained from the grain size analysis, heavy mineral analysis and the petrographic study, an attempt is made to interpret the provenance and the environmental conditions of deposition of the rimrock.

In order to determine the direction of transportation of a sediment, features such as ripple-marks, cross-bedding, current lineations,etc., provide useful clues. It is also assumed that a sediment spread over a fairly even surface, would attain some normal distribution patterns. Neither the features like ripple-marks,etc., nor the distribution patterns are present in the sandstone studied. Hence, in this study, it is hard to determine the location of the source area and the direction of the currents that brought the sediments to form this sandstone.

B. PROVENANCE:

Provenance refers to the location and composition of the parent rock from which an association of sediment was derived, and includes the climatic as well as the tectonic conditons prevailing in the source area. Since the features cited above are not present in the sandstone studied, the main emphasis is placed here on the determination of the source rock rather than the source area.

> Dake (1935,p.697) states,"Since considerable areas of Ordovician sandstones were exposed on the pre-Pennsylvanian surface, it is believed that these strata, particularly the Roubidoux and St. Peter, contributed sand in important quantities to the rocks of the lower Coal Measures. As yet very little has realy been done to compare the basal Pennsylvanian sandstone and those of the older series, with regard to mechanical analysis, heavy mineral content, mica content and rounding and frosting of grains. ... "

Grawe and Cullison (1931,p.305) analyzed the rimrock sandstone from a filled sinkhole, five miles north of Rolla on Highway 63. The diagrammatic sketch of that sinkhole, presented by them, is redrawn as Fig.8.

> They state,"Texture analysis of these samples (their samples no.7a, 7b and 7c) taken across the outcrop clearly show that the two samples obtained beneath the cherty mass represent the same horizon, and that it is quite different from the one occupying the center of the structure. Comparison of these analyses with those already made shows that the outer sandstone (no.7a and 7o) is basal Cotter."

The present author also analyzed the samples of both sandstones from the same sinkhole. The results agree with those of Grawe and Cullison. It is suggested that the difference in the grain size seems to be the result of the secondary enlargement of the upper sands. The basal sandstone is argillaceous which has restricted the enlargement of the sand grains. Hence, the sands at the base are finer than those of the upper unit. Thus two different source areas are not necessarily involved but rather a single source contributed to the formation of two sandstones in the rimrock.

As suggested by Dake, the main objective of this investigation is to compare the various grain size parameters of

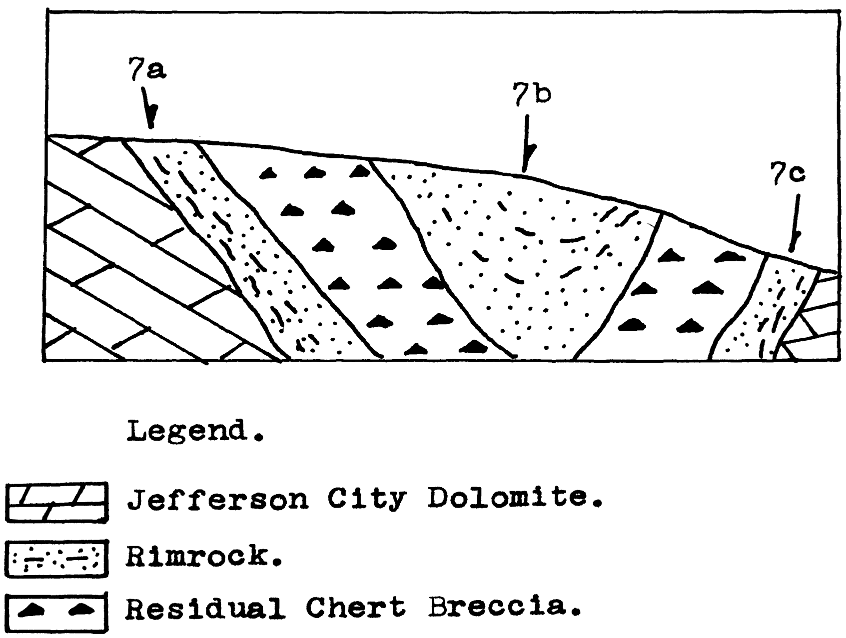


Fig.8: Diagramatic cross-section of a sinkhole along west edge of U.S.Highway 63, 5 miles north of Rolla. (From Grawe and Cullison, 1931)

the three sandstones i.e., the Roubidoux, the St. Peter (most reasonable source sandstones), and the rimrock sandstone, and to suggest the probable source rock for it.

For the purpose of comparison, data regarding the grain size parameters of the Roubidoux and the St. Peter sandstones, were collected from various sources.

1. Roubidoux Sandstone:

Grain size analysis of this sandstone collected from different localities, by various workers is compiled here:

a. Heller (1954,p.20) analyzed seven samples of Roubidoux sandstone from different localities.

b. Forest Haines, Graduate Student at the University of Missouri-Rolla, measured the Roubidoux section at Yancy Mills, Missouri. He analyzed 21 samples from this section.

c. Abd-El-Aziz Borahay, Graduate Student at the University of Missouri-Rolla, studied a Roubidoux section exposed in a new road cut on Highway I-44, 2.5 miles southwest of Rolla across from Martin's Spring in section 8, T.37 N., R.8 W.

d. Donald Fielding, Graduate Student at the University of Missouri-Rolla, studied a Roubidoux section exposed near the intersection of Highway F and the Dry Fork Creek, 7 miles east of Rolla in section 22.

e. Abdullatif Najjar, Graduate Student at the University of Missouri-Rolla, analyzed the Roubidoux sandstone, from a cut on Highway I-44, section 26, T.37 N., R.10 W.

f. The present author analyzed sandstones from the Roubidoux Formation exposed in the thesis area, north of Highway I-44, sections 27 and 28, T.39 N., R.5 W.

The average values of the $\overline{X}$, σ_I and one percentile size for the above mentioned samples are tabulated in Table 1.

The above investigation involved 30 grain size analyses. Combined histogram-cumulative curves were plotted for σ_I and $\overline{X}$ values. For this average values are 0.72Ø and 1.87Ø respectively (Fig.9).

2. St. Peter Sandstone:

Thiel (1935,p.559) has presented a cumulative curve based on the calculated averages of 8 samples from the St. Peter sandstone, from various localities in Missouri. From this curve, the value of median was read, which is 2.12Ø. The present writer collected samples of St. Peter sandstone from the following locations:

a. One mile south of Hermann, Missouri, on Highway 19.

b. One-half mile north of Holstein, Missouri, north of the Missouri River.

c. East edge of Pacific, Missouri, from exposure adjacent to the Silica Cement Company's quarry.

These samples were analyzed for their grain size distribution. The average σ_I value for them is 0.54Ø and the $\overline{X}$ values range from 2.29Ø to 2.55Ø. The one percentile value

No.	Worker.	σ_I		$\overline{X}$		1 percentile size.	
		ø	mm.	ø	mm.	ø	mm.
1.	Heller.	0.74	0.60	2.07	0.25	0.39	0.76
2.	Haines.	0.72	0.61	1.95	0.26	0.41	0.75
3.	Borahay.	0.68	0.59	1.80	0.29	0.25	0.83
4.	Fielding.	0.75	0.60	1.80	0.29	-	-
5.	Najjar.	0.75	0.60	1.66	0.32	0.30	0.80
6.	Parikh.	0.75	0.60	1.66	0.32	0.35	0.79

Table: 1. Grain size parameters of the Roubidoux sandstone from various locations.

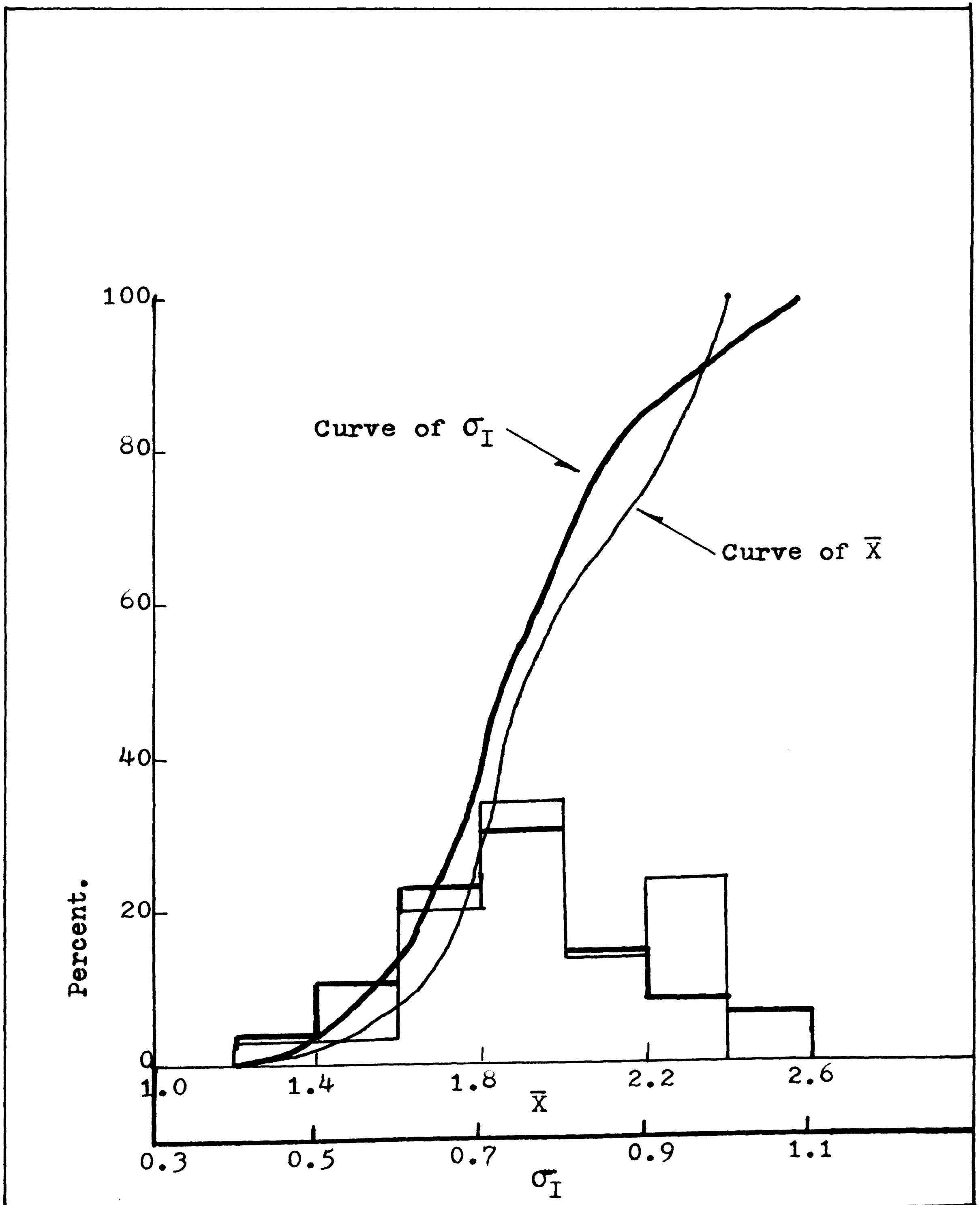


Fig.9: Combined histograms and cumulative curves for $\bar{X}$ and σ_I values for the Roubidoux sandstone.

averaged for the curves is 1.06Ø.

3. Rimrock Sandstone:

As mentioned in chapter III, the samples collected from the rimrock sandstone were analyzed for their grain size. The average values obtained for σ_I is 0.54Ø and for $\bar{X}$ is 2.14Ø. The average of the one percentile values for these samples is 1.02Ø.

Twenty five percent of the samples have their average grain size, $\bar{X}$, below 2.0Ø, ranging from 1.40Ø to 1.90Ø. This is due to secondary enlargement of the sand grains in these samples. This enlargement is proportional to the grain size and hence it does not affect the sorting values, as for example, in sample no.83 (one and one half mile west of Jake Prairie in a creek, section, T.40 N., R.6 W.: Fig. 10) the average grain size is 1.78Ø, which is coarser than the average $\bar{X}$ value 2.14Ø, but the σ_I value remains at 0.52Ø which is very close to the over all average σ_I value 0.54Ø.

4. Comparision of the Average Values:

The average values of σ_I, $\bar{X}$ and one percentile, for all the three sandstones are tabulated for easy comparison (Table 2).

From the comparisons of the values as mentioned in Table 2, it is seen that the values of rimrock sandstone are closer to those of the St. Peter sandstone than those of the Roubidoux sandstone.

5. Heavy Mineral Study:

The heavy minerals present in the rimrock sandstone,

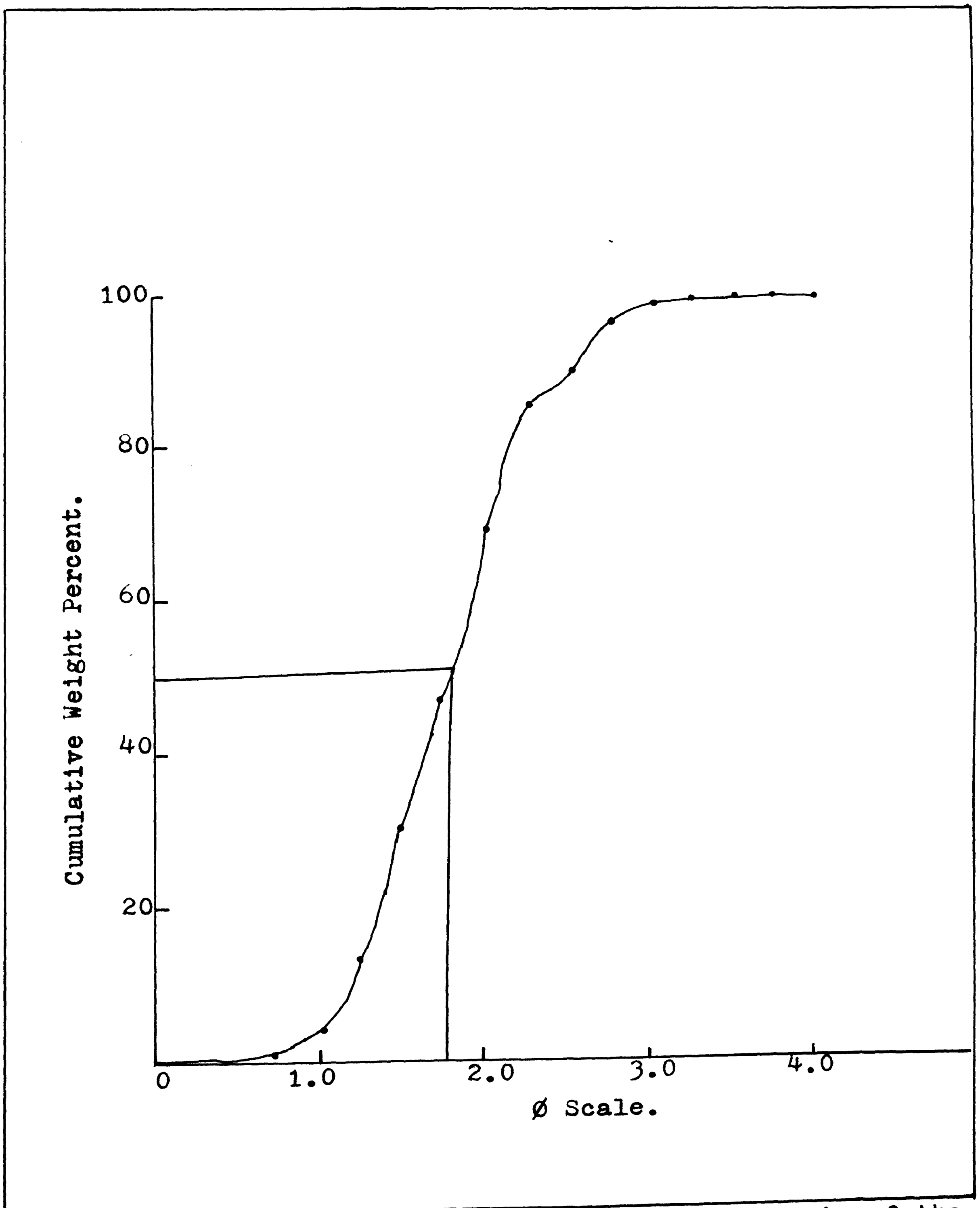


Fig.10: Cumulative curve for the grain size analysis of the rimrock (sample no.83), from an exposure 2 miles west of Jake Prairie, section 24, T.40 N., R.6 W.

No.	Name of Sandstone.	σ		$\bar{X}$		1 percentile size.	
		Ø	mm.	Ø	mm.	Ø	mm.
1.	Roubidoux.	0.72	0.61	1.87	0.28	0.38	0.78
2.	St. Peter.	0.52	0.70	2.43	0.18	1.06	0.49
3.	The rimrock.	0.52	0.70	2.14	0.22	1.02	0.50

Table: 2. Average grain size parameters of the Roubidoux, St. Peter and Rimrock sandstones.

belong to a few varieties of the ultrastable group (Folk, 1965,p.97), and have very low concentrations.

The same heavy minerals were observed by Cordry (1929, p.59) in the sandstones of the Ozark region.

> He states,"... It is not possible to discriminate between any of the five sandstones on the basis of the heavy mineral content alone. ... The similarity in heavy mineral suites and the variation in ratios between the species suggest that the sandstones studied were probably derived from a common ultimate source. The Pennsylvanian Sandstone..., was probably derived from the reworked material of all these older sandstones."

In the opinion of the present author, the heavy mineral study of the rimrock sandstone does not provide any information regarding the source of the sands. However, the stability and well-rounded character of the heavy minerals suggest that this sandstone has undergone more than one sedimentary cycle.

6. Conclusion:

Mineralogically, all the three sandstones i.e. the Roubidoux, St. Peter and rimrock are composed of quartz, and all of them contain similar heavy mineral suites. Hence, they cannot be distinguished from each other on the basis of their mineralogy.

Textural analysis gives some clues on which a distinction and comparison can be made between these sandstones. On comparing the various grain size parameters, it becomes clear that the St. Peter sandstone is texturally more similar to the rimrock sandstone, which leads one to conclude that the St. Peter sandstone could be the source rock for the sandstone under investigation.

Nothing could be concluded regarding the direction of the flow of the currents that brought the sediments for the formation of the sandstone in question, because the sedimentary structures discussed in the beginning are absent in the rock. Hence, the location of the source rock also cannot be predicted.

V. ENVIRONMENTAL CONDITIONS OF DEPOSITION OF THE RIMROCK.

A. INTRODUCTION:

An environment is a complex of chemical, physical and biological conditions of nature under which a sediment accumulates. Every environment has its own influence on the sediment formed under its domain, which is reflected in color, lithology, texture and various sedimentary structures of the rock formed. Hence, a study of these properties can help in recognizing the environmental conditions of deposition of a sediment. An approach has been made in this direction to interpret the environment of the rimrock sandstone.

B. EVIDENCE BASED ON FIELD OBSERVATIONS:

As mentioned previously, no sedimentary structures except bedding have been observed in the sandstone under investigation. Mineralogically, the rock is very simple and mature, containing mainly the stable mineral quartz with an exceedingly small amount of heavy minerals. Texturally, too, it is mature. This maturity seems to have been inherited from the source rock, and hence does not provide any clue to decipher the environment.

Fossils are scarce to absent in this sandstone. Only from one sinkhole, in the southern part of section 34, T.40 N., R.7 W., on a county road connecting Highways 28 and H, were Mississippian marine fossils found in this sandstone. Devonian marine fossils from a few of the sinkholes also have been reported. A sinkhole near Sullivan, Franklin County, which is located outside the thesis area, contains a bed of coal. Many other sinkholes in Missouri also contain coal. The scarcity of fossils and presence of coal are indicative of a continental environment.

C. EVIDENCE BASED ON GRAIN SIZE ANALYSIS:

1. CM Pattern:

An approach to the problem of environmental recognition based on grain size analysis is by means of the relatively new CM Diagram method.

Passega (1957,p.1952 and 1964,p.830) believes that if sediments of an environment are represented in a diagram by plotting C (an approximation of the maximum grain size) against M (the median diameter), the sample point pattern obtained is characteristic of the depositional agent. This resulting diagram is called a CM Pattern.

According to Passega, they are sharply defined and vary considerably with the type of depositional agent.

> He records (1957,p.1952),"The parameters of a group of samples of a depositional environment, plotted on a graph, defined sample points. As numerous examples will show, the distribution of these points is closely related to the depositional processes. Patterns formed by sample points characterize by their shape and arrangement of points, the principal depositional agents."

Passega emphasizes that the coarse fraction of a sediment is more representative of the depositional agent than the fine fraction, which could be incorporated into the sediment after deposition, or transported independently of the coarser particles. For this reason, a preference is given to the coarse fraction, "C" as an approximation of the maximum grain size as a measure of the ability of a current to transport. The parameter M (median or average coarseness), is the only one defined by both coarse and fine fractions of the sediment. The grains of modal class are common in the sediment. They are certainly transported by the current and not added to the already deposited material at a later time. Presentation of the median diameter, therefore, is important for the reason that it would suggest the average transporting ability of the current.

According to Passega (1957,p.1952), the CM pattern has to be plotted on logarithmic paper, the line determined by the values C=M is designated as the limit of the diagram, or limit C=M. To the left of this limit, the sample points can fall in any part of the diagram. Thirty samples at least should be plotted to be significant. Each sample should be a deposit of a homogeneous sedimentation, and the thirty or more samples should represent all textures available.

According to Passega (1957,p.1952 and 1964,p.830), it is possible with CM diagram, to distinguish between two types of bottom tractive currents: one that rolls particles, and the other that support them in suspension near the bottom. Rivers, marine currents, and waves touching bottom are tractive forces. A complete diagram of basic CM patterns for tractive current deposits was compiled by Passega, recognizing the various environments like beach, river, pelagic and turbidity currents (1957, Fig.12,p.1973).

2. Rimrock Sandstone CM Diagram:

The data of 31 representative grain size analyses were compiled to construct a CM pattern. The plot of these points has been superimposed here on Passega's basic diagram of CM pattern (Fig.11). The degree of dispersion reflects a mode of transport which seems to be traction in this case. By visual comparison, it seems that the pattern fits with that of a beach environment. On closer inspection of the pattern, however, it is observed that the sample points are not uniformly distributed. Two-thirds of them form a scatter of points very close to each other, on the inner boundary between Passega's patterns for the beach and river deposits, and other points are more widely scattered, even falling outside the margin of the pattern representing the beach deposit.

Thus the CM pattern in case of the rimrock sandstone, does not predict any single environment, but presents a picture of a complex environment or new one which has not been recognized by Passega.

3. Log-Probability Plots:

Visher (1969,p.1074) suggests another method for the interpretation of the environment on the basis of grain size analysis. According to him, the sediments are transported by three modes:

a. Suspension:

True suspension, caused by turbulence in which there is

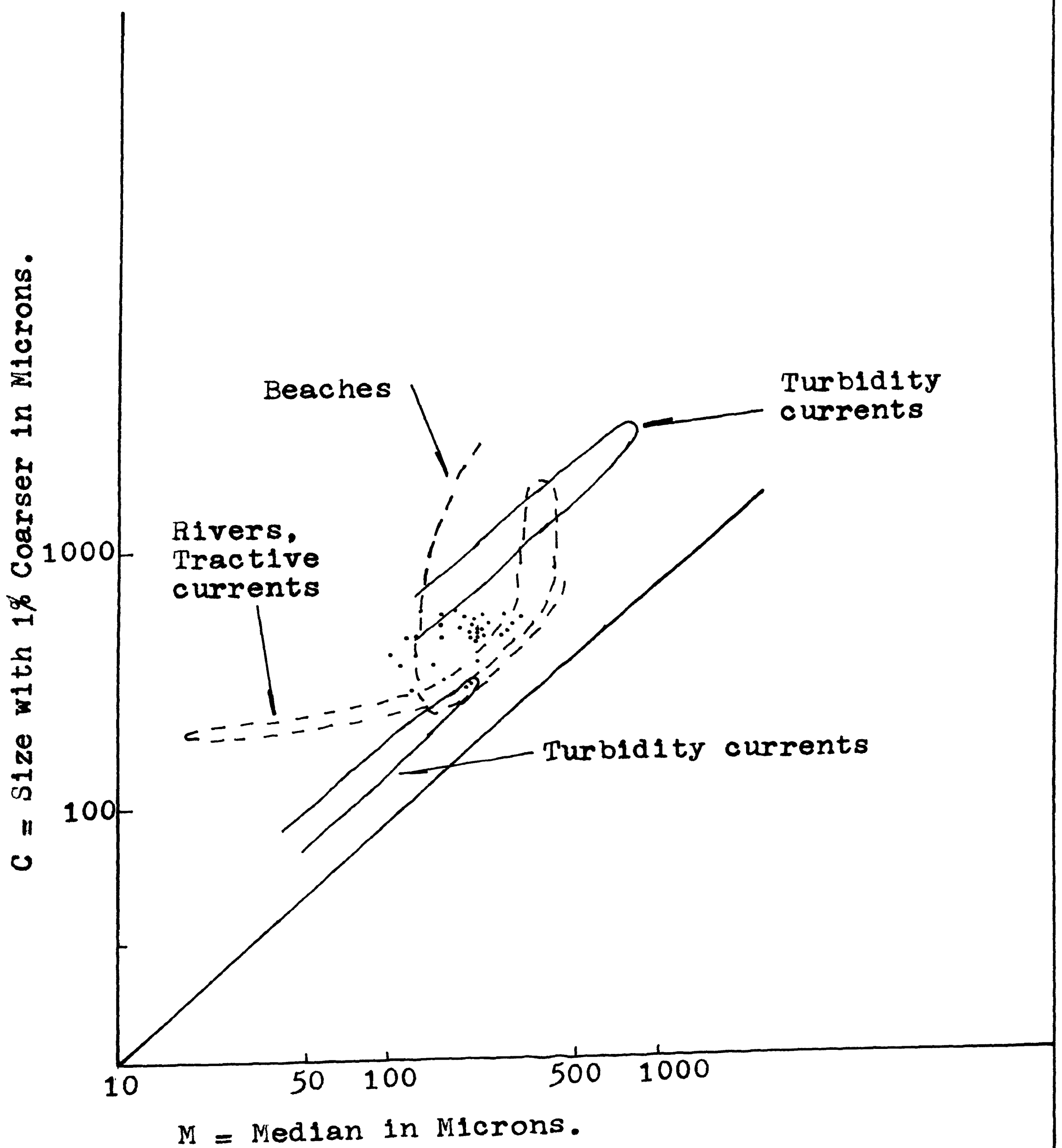


Fig.11: Basic CM patterns of Passega (1954), superimposed on the CM points of the rimrock sandstone.

no vertical change in grain size, occurs in the very fine-grained sand range, typically less than 0.1 mm.

b. Saltation:

The maximum size that moves by saltation is unknown; but from experiments done by the United States Waterways Experiment Station, it seems that grains of 0.75 to 1.0 mm. size travel by this mode of transport.

c. Surface Creep:

Coarse sand particles are transported by surface creep, which also have a different mean and degree of sorting than those of the two populations mentioned above. Certain fluviatile deposits, however, do not show this population and the saltation population includes the coarsest material in the distribution.

The grain size ranges mentioned above, which travel by the three modes of transport are not rigidly fixed but may vary with the velocity of the currents.

The plot of grain size against cumulative frequency percentage on log-probability paper gives a pattern composed of three or four straight line segments with different slopes.

According to Visher (1969,p.1074), the striking aspect of log-probability plot is that :(1) it normally exhibits two or three straight segments and, (2) the tails of simple "S" shaped cumulative curves appear as straight lines; allowing for easy comparisons and measurements. These straight line segments have been observed in nearly 2000 grain size distributions studied by him. The consistency of the position of truncation points, slopes, and other characteristics suggest that meaningful relations are reflected by log-probability plots.

The most important aspects in analysis of textural pattern is the recognition of straight line segments. Four such segments (Fig.12), occur on the log-probability curve, each defined by at least four control points. The interpretation of this distribution is that it represents four separate log normal populations. Each population is truncated and joined with the next population to form a single distribution. This means that grain size distributions do not follow a single log normal law, but are composed of several log normal populations, each with a different mean and different standard deviation. These separate populations are readily identifiable on the log-probability plot.

4. Log-Probability Plots of the Rimrock Sandstone:

Four representative sample analyses were selected for the log-probability plots. They are presented in Figures 13 and 14.

Two or three populations are obtained on these plots. In plots 1, 2, and 4, the surface creep population is lacking, whereas, it is present in the remainder. Only one saltation population is present in the plots without any truncation as shown in the Visher's plot (Fig.11). Most of the load seems to be transported by saltation, which can be verified from the plots where more than three-fourths of the points fall

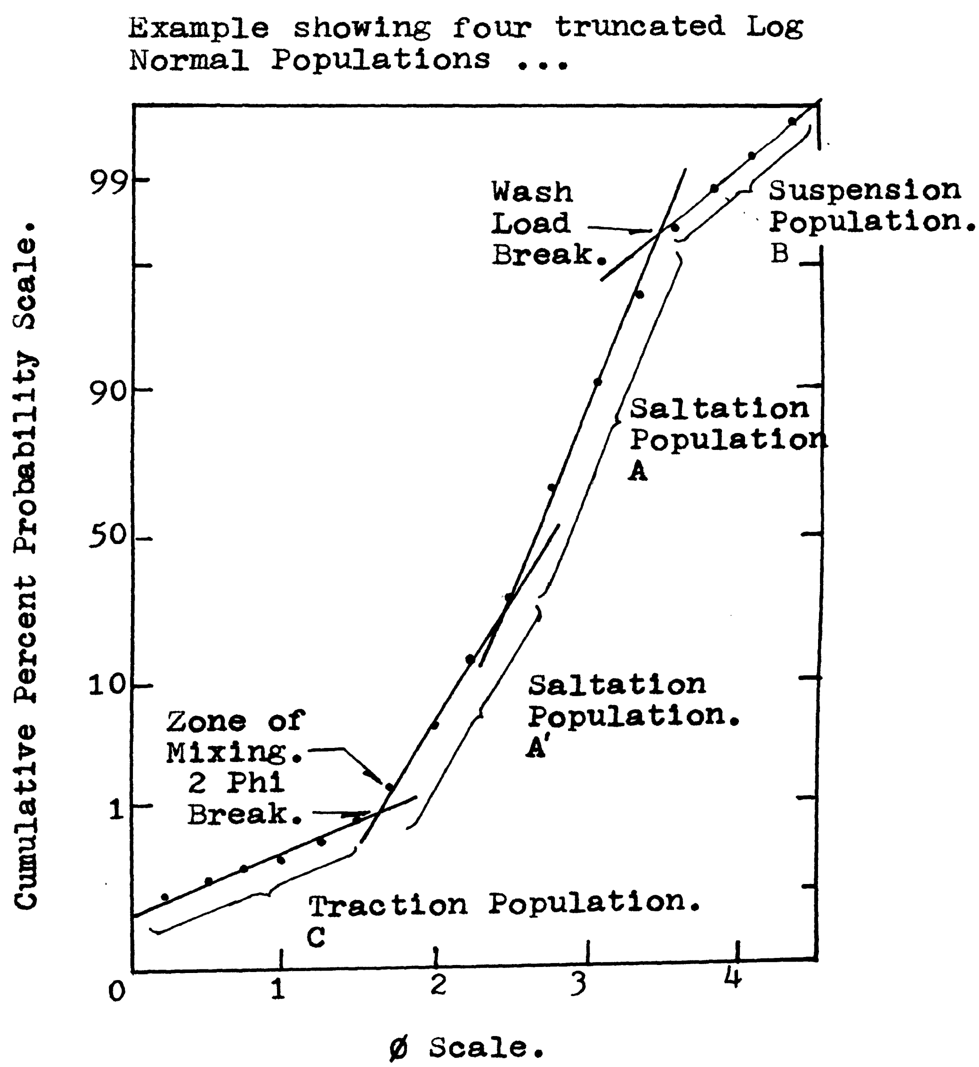


Fig.12: Log-Probability plot showing four truncated log normal populations for a sediment. (From Visher, 1969)

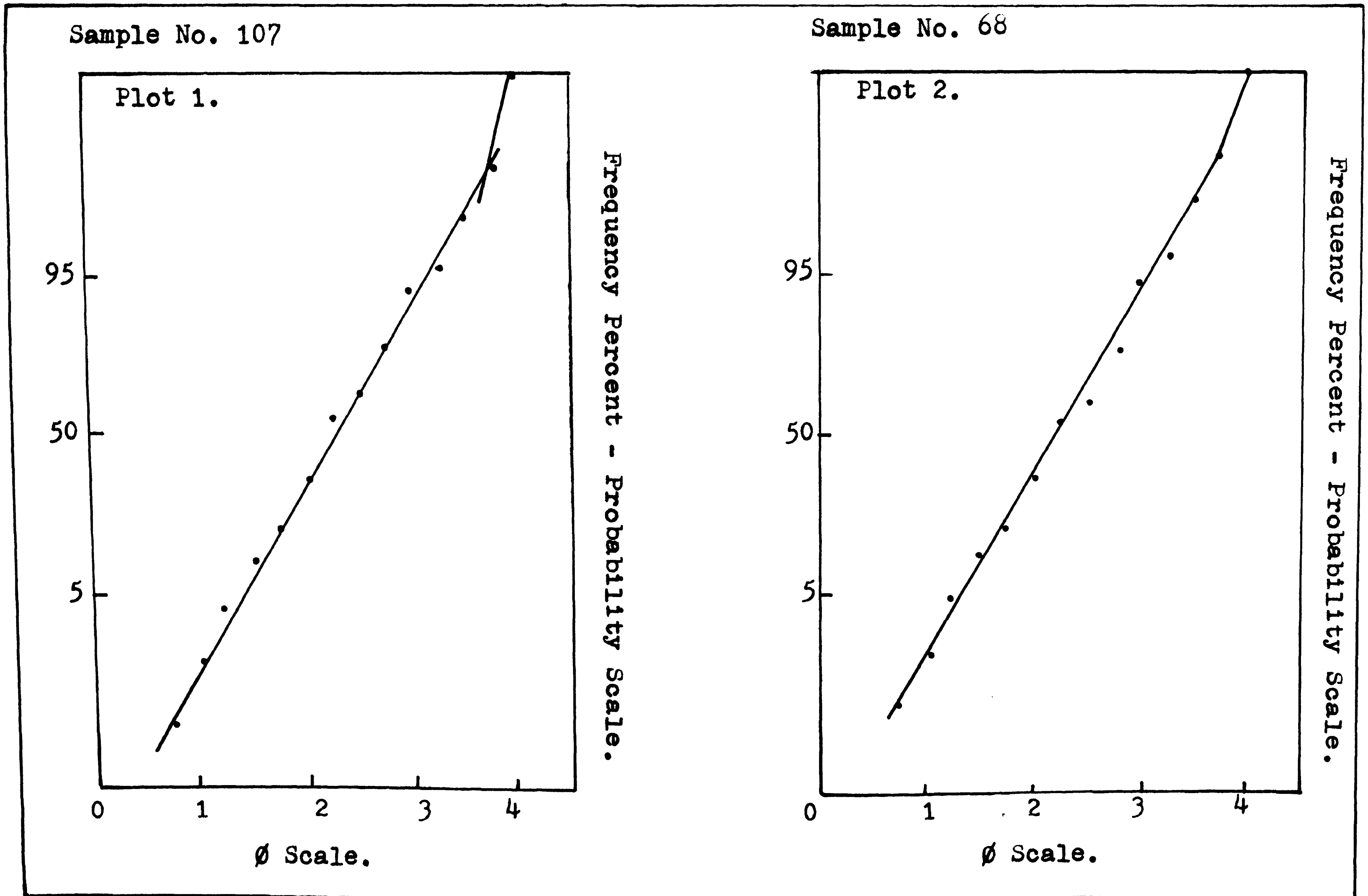


Fig.13: Log-Probability plots of the rimrock sandstone.

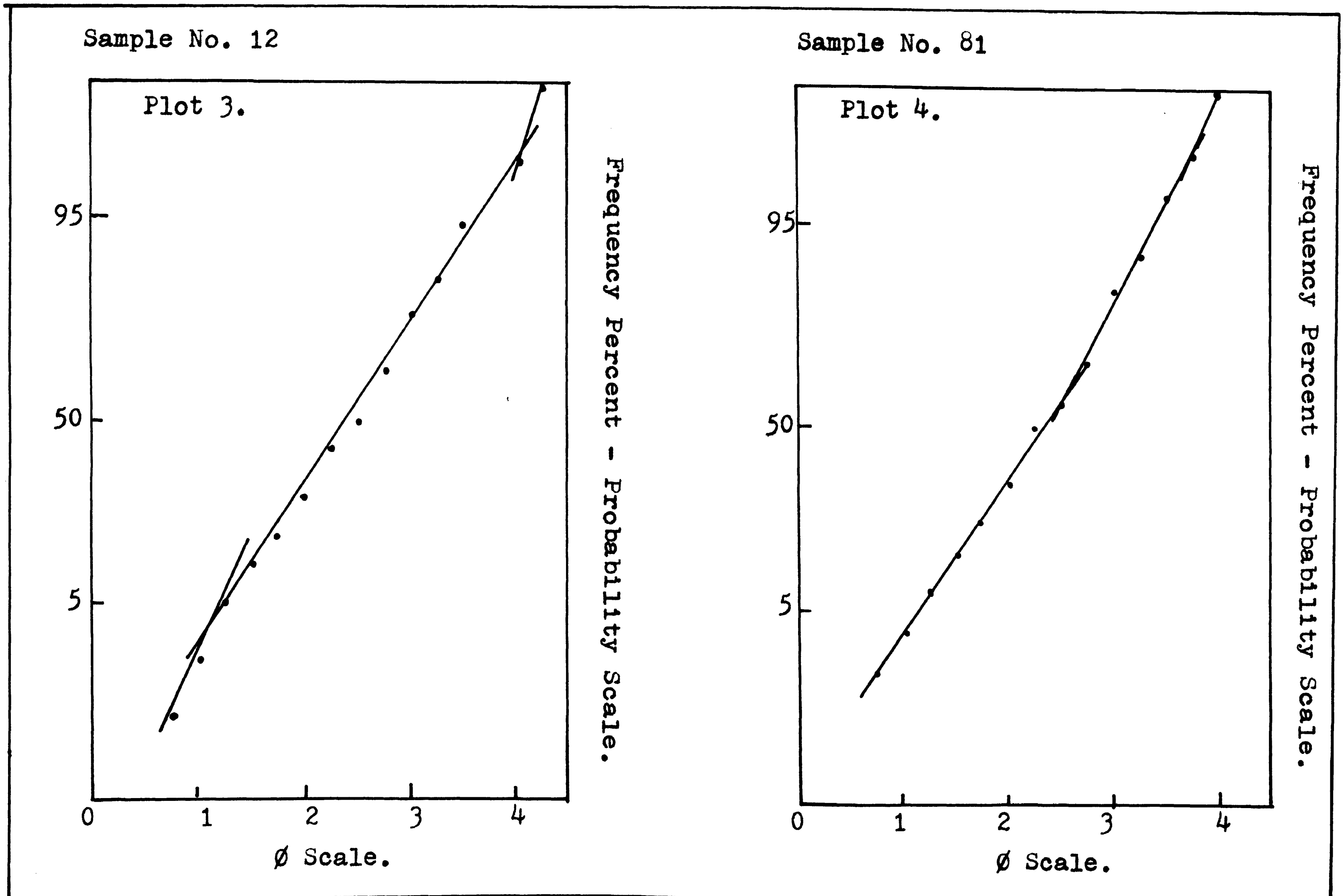


Fig.14: Log-Probability plots of the rimrock sandstone.

on segments representing a saltation population, and others are shared by suspension and surface creep populations. The intersection between the suspension and the saltation populations falls near the 99% point, and that between surface creep and saltation, near the 5% point.

This suggests that more than 90% of the material was transported by saltation, less than 1% in suspension and around 5% probably by surface creep. The points from 1.25Ø to 3.75Ø fall on the saltation population suggesting that they were transported by saltation. Similarly coarser material having grain size larger than 1.25Ø was transported by surface creep, and that finer than 3.75Ø, in suspension.

5. Conclusion:

The plots of the rimrock sandstone do not match with any of the plots presented by Visher (1969,p.1074) for different environments, although they give a clue to infer that the mode of transport is saltation. This seems to be in agreement with the mode of transport which is traction, as interpreted on the basis of CM pattern of Passega.

VI. FORMATION OF SINKHOLE SEDIMENTS.

A. INTRODUCTION:

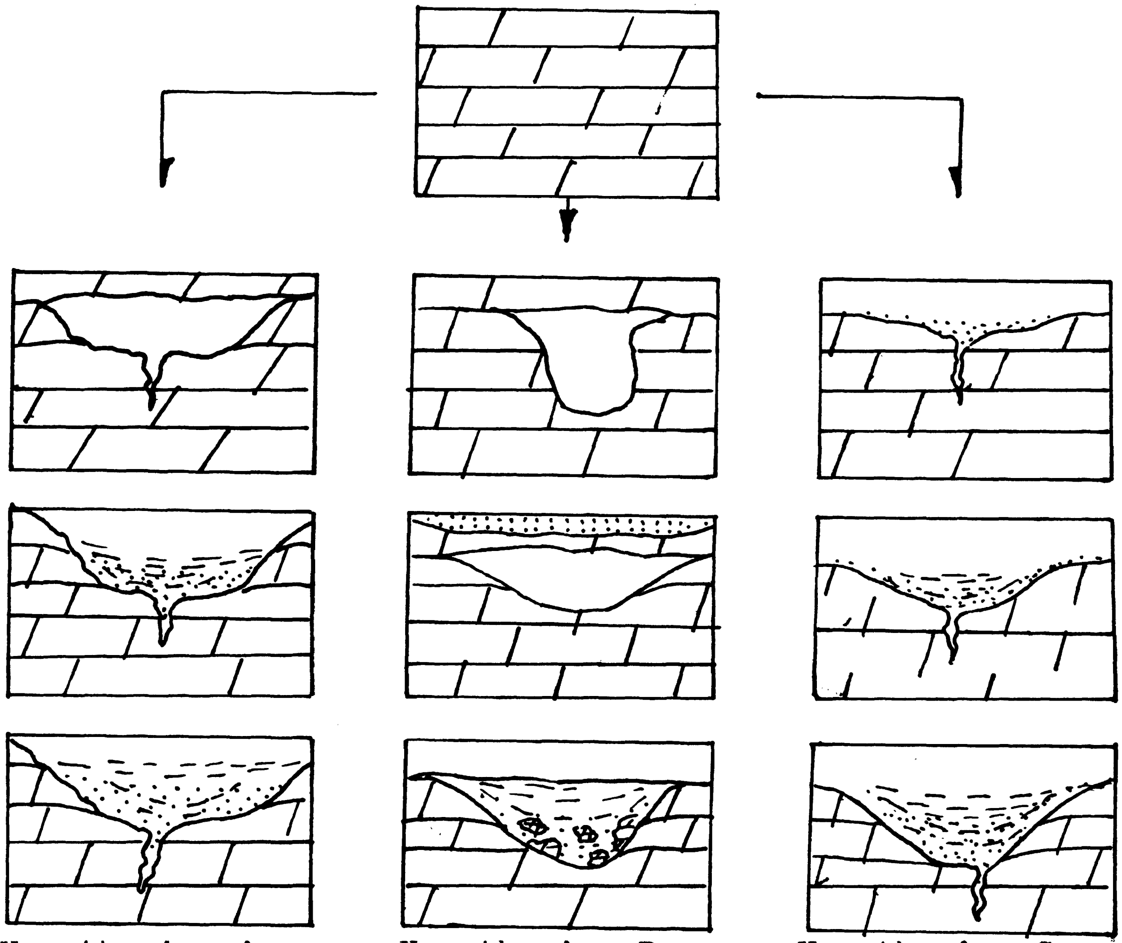
The carbonate rocks of the Ozark region have been continuously subjected to solution due to circulation of water through them. This solution activity made sinkholes in these rocks by one of the following processes:

1. Small cavities were formed in the carbonate rocks, which, with the passage of time, developed into caverns beneath the water table. These caverns often had thin roofs which, in time, collapsed into the caverns forming sinkholes open to the surface.
2. Another type of sink was formed by solution at the exposed surface without the intermediate existence of a cavern. Percolating water simply enlarged a surficial crack or fissure in carbonate rocks as it trickled downwards, and formed a sinkhole.

B. FILLING OF SINKHOLES:

The filled sinkholes in Missouri usually contain sandstone and clays, and sometimes in addition coal, iron ore or pyrite. The origin of the sandstone and clay fill is a controversial topic. Three modes of origin of this fill have been postulated:

1. The first hypothesis (Hypothesis A, Fig.15) begins with the formation of sinkholes on the surface as a



Hypothesis: A.
Sinkhole topography.
(Dake, 1935)

Hypothesis: B.
Collapse of roof rock due to overburden.
(Dake, 1935)
(McQueen, 1943)

Hypothesis: C
Simultaneous filling and sinking due to solution.
(Bretz, 1950)

Fig. 15: Three different modes of formation of the filled sinkholes.

result of the collapse of cavern roofs as well as due to widening of the cracks in the surface as described in processes 1 and 2 previously in this chapter. When this karst surface was covered with water at a later stage, sediments were laid down on it, filling the pre-existing sinkholes (Hypothesis A, Fig.15). This is one of the alternatives suggested by Dake (1935,p.700).

2. McQueen (1943,p.139) believes that the filled sinkholes have resulted from collapse of overlying younger sediments into pre-existing caverns in carbonate rocks, due to failure of their roofs (Hypothesis B, Fig.15). Dake (1935,p.700) feels that many of the filled sinkholes have formed in this manner. In other words, the sediments filling the sinkholes, were deposited over the developing caverns and prior to the collapse of their roofs to form a sink.
3. Bretz (1950,p.823) offers a third possibility, "The ... filled ... sinkhole structures are interpreted as products of slow, compressional subsidence, under a former load into enlarging solution cavities in subjacent calcareous formations, no cavity ever having been an open space in the rock."

Thus, shallow sinkholes were formed on the carbonate land surface due to the enlargement of cracks and fissures as described in process 2 previously in this chapter. A body of water forming extensive swamps or possibly marginal seas encroached upon this area, and sediments were deposited into these broad, shallow pits. Solution activity also continued simultaneously causing the pits to continue to deepen. The sediments already present in these pits also sank and, in the process were fractured and slickensided (Hypothesis C, Fig.15).

It seems to the present author that most of the filled sinkholes, at least in the area studied, have been formed as a result of simultaneous deposition and sinking of the sediments due to the solution of the underlying carbonate rocks (Hypothesis C, Fig.15). In support of this view, the following points are presented:

1. Many of the sinkholes exhibit intact rimrock lining (Pl. 4A), with a slickensided surface at the base. If it had been resting horizontally on the dolomite, and later collapsed into the sinkhole due to failure of a cavern roof, it would not have remained intact, but would have been fragmented and shattered into pieces. The slickensides seems to have been formed as a result of slippage of the sediments due to the solution of the underlying carbonate rocks.
2. If the sinks were filled due to the collapse of the cave roofs, then the sediments should now contain broken fragments of the dolomite forming the cave roof, at least in their basal part. Such fragments do occur embedded in the collapsed sediments in a

Plate 4A: Photograph showing filled sinkhole with intact rimrock sandstone, 2 miles southeast of Jake Prairie, off a gravel road, section 20, T.40 N., R.5 W.

Plate 4B: Photograph showing roof rock dolomite embedded in sink filled material, south of Interstate Highway 44, under bridge on old Vichy Road, section 34, T.38 N., R.8 W.

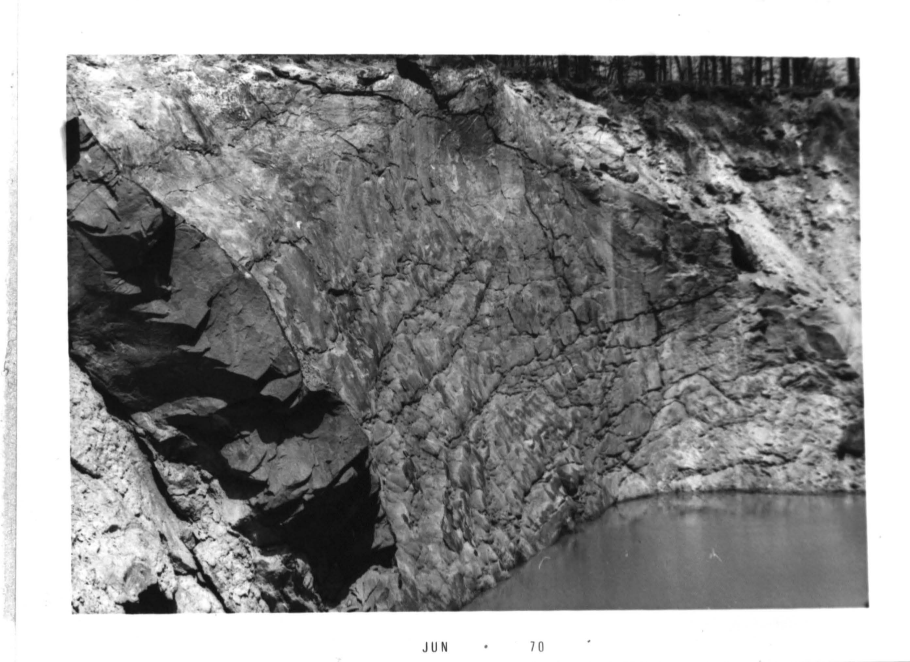


Plate : 4A

Plate: 4B

few sinkholes in this area which were probably formed by cave roof collapse. However, such material has not been observed by the writer in the exposed portions of most of the sinkholes. These are believed to be formed due to hypothesis B (Pl. 4B).

3. The rimrock sandstone is considered to be a part of the Pennsylvanian sandstone which elsewhere is conspicuously ripple-marked and cross-bedded. The author has not observed these features anywhere in the rimrock of the area studied. It appears logical to assume that the topography on which the Pennsylvanian sediments were deposited, had some relief, and that pre-existent sinkholes were responsible for this relief, creating a peculiar type of local environment which did not favor formation of the sedimentary features mentioned above.
4. In many of the open sinkholes, the rimrock sandstone has uniform thickness, at least in their exposed portions. If the sediments were deposited in deep sinkholes as suggested by Dake (Hypothesis A, Fig.15), then the rimrock sandstone would not have uniform thickness all around the sinkhole. Instead it would be very thick in the center of the sinkhole and thin out towards the edges of the sinks.

C. CONCLUSION:

The intact rimrock lining, absence of the roof rock fragments and sedimentary structures like ripple-marks and cross-bedding in many of the rimrocks indicate that the rimrock sandstone was formed due to simultaneous deposition and sinking due to solution of the underlying carbonate rocks. This conclusion is also supported by the presence of slickensides at the base of the rimrock sandstone, formed as a result of slippage of the sediments. However, the writer does not completely rule out the possibility of the formation of the filled sinkholes by Hypotheses A and B, and feels that all three may have been involved, with perhaps one mode more important in one area than another. Hypothesis C, simultaneous sinking and filling, seems to be the prevalent mode in the area of this study.

VII. HISTORY AND AGE OF THE RIMROCK.

A. HISTORY:

At the beginning of the Pennsylvanian Period a mountainous linear uplift extended all along the eastern margin of the continent, from Newfoundland to Alabama and thence across the Gulf border into northern Mexico. Shallow seas spread widely over the Rocky Mountain States and eastward into Texas and Oklahama, but from there eastward, mud and sand from the mountainous border land filled the basins as fast as they sank, holding back the sea and transforming the vast areas into low lands covered with lush forests and dotted with great swamps in which the fallen vegetation accumulated to form coal.

The eastern part of Missouri formed the western margin of these low lands during early and middle Pennsylvanian times. According to Dake (1935,p.702), this land surface formed karst topography. The detrital material formed as a result of the erosion of the Ordovician sandstones, was transported and deposited on this karst surface, during early(?) and middle Pennsylvanian times. As mentioned before, some of these sediments were deposited into already existing sinkholes, whereas others collapsed into the sinkholes at a later stage. These sediments were sandy in the beginning; these formed the rimrock. This was followed by the deposition of the argillaceous sediments, probably as a result of the further subsidence of the area. This forms the refractory clay deposits in the thesis area.

B. AGE OF THE RIMROCK:

Dake (1935,p.707) states,

> "In this report the fact is stressed that these deposits may well belong to any age during which conditions for cave and sink formation and filling existed. ... therefore, it is highly probable that such cave fillings have been formed at numerous times, from Silurian to recent, and it may well be that those exposed at the present time are of widely differing ages, but so similar lithologically as to be wholy indistinguishable."

Fossils are practically absent in the sandstone under study. Only at few places, in this sandstone, fossils of the Mississippian and Devonian ages are found. In almost all localities, within and without area under investigation, the rimrock sandstone is associated with the white and purple shales, high alumina clays and coals so characteristic of the basal Pennsylvanian age that it can be presumed that this sandstone is of the same age.

VIII. ECONOMIC GEOLOGY.

The most important fire clay districts in the world located, in east-central Missouri, are: (1) The northern district situated north of the Missouri River and, (2) the southern district situated south of the Missouri River. The thesis area forms the southern part of the second district.

The one feature that characterizes the refractory clays in the thesis area is their occurrence in sinkholes, encircled by the rimrock sandstone which is the target of study. The clays are light-colored and non-ferruginous. They are mainly of three types as follows:

1. Flint fire clay: composed of kaolinite and halloysite.
2. Burley clay: composed of kaolinite, halloysite with gibbsite and an isotropic material.
3. Diaspore clay: composed of hydrated aluminium silicate and complex aluminium titanium silicate.

The clays are very well suited for the manufacture of refractory material like fire bricks and other heat resisting articles.

Presence of sandstone patches forming a circular pattern is a good indication for occurrence of refractory clays in the area.

In addition to the fire clays, deposits of iron ores like pyrite and hematite, barite and coal from the sinkholes of southern clay district, are reported. However, these deposits do not form important commercial ore bodies in the area under study.

IX. CONCLUSIONS.

Samples were collected from the rimrock sandstone of the filled sinkholes occuring in the area under discussion. They were subjected to grain size, heavy mineral and petrographic analyses. The following conclusions were drawn on basis of the above investigations:

1. Grain size analysis indicates that texturally the sandstone under investigation is similar to the St. Peter Sandstone, and that it could be the source rock of the rimrock.
2. On the basis of field evidences, it can be suggested that the environmental conditions of deposition were continental at the time of the formation of the rimrock. However, no evidence of such environment is reflected in the diagram and plots drawn, as suggested by Passega and Visher, respectively.
3. Absence of roof rock fragments and sedimentary structures like ripple-marks and cross-bedding which are very common features of the Pennsylvanian sandstones, leads to the conclusion that the rimrock present in most of the sinks in the thesis area, resulted from the simultaneous sinking of the rimrock and solution of the underlying dolomite. Although, the other two modes of formation, namely collapse of the roof rock

and deposition in pre-existing sinks are not ruled out.

X. APPENDICES.

APPENDIX A.

STRATIGRAPHIC SECTIONS

The stratigraphic sections met with in five representative sinkholes, are presented here. In general the filled sinkholes have the following stratigraphy:

1. Refractory clays(top).
2. Ferruginous sandy clay.
3. Sandstone.)
) Rimrock.
4. Chert breccia.)

Three of the sections presented here, have one more unit at the base beneath the chert breccia. This unit seems to be the one which McQueen (1943,p.131) calls the "unnamed Formation". This unit is composed of thin alternate bands of dark colored sandstones and shales with chert beds at irregular intervals.

A. STRATIGRAPHIC SECTIONS:

1. Location 46: 6 miles northwest of St. James on a gravel road connecting extension of Highway V to Highway 68, section 5, T.38 N., R.7 W., Safe Quadrangle.

No.		Thickness in feet.
15	Refractory clay; removed from the pit . . .	-
14	Sandstone; white, light grey, light brownish to light yellow; fine-grained; argillaceous and friable	1.0
13	Clay; light yellow and grey; laminated;plastic	0.5

No.		Thickness in feet.
12	Sandstone; light yellow to white; very hard and compact; thinly bedded	0.5
11	Clay; light grey, green and purple; laminated and plastic	3.0
10	Sandstone; light yellow grey to white; fine-grained; friable to moderately compact; massive and slightly argillaceous (sample 46)	10.0
9	Chert breccia; light grey to light brown; contains rounded and angular, banded, oolitic and sandy chert	2.0
8	Clay; light greenish grey; laminated	1.0
7	Sandstone; light grey to light brown; fine-grained; hard and compact due to silicification	1.0
6	Chert breccia; red to light brown; fragments of oolitic, sandy banded chert; with intercalations of thin light grey shale and hard cherty sandstone	3.5
5	Sandstone; red, ferruginous and cherty; fine-grained and very hard	0.25
4	Shale; bands of light yellow, red and violet; fissile	0.25
3	Chert breccia; red fragments of sandy chert .	0.5
2	Shale; white to light grey with one chert bed similar to that in no.3	0.5

contd.

No.		Thickness in feet.
1	Chert breccia; red; ferruginous and sandy; chert oolitic, sandy and banded	-
	Total thickness:	24.0

2. Location 82: 2 miles southeast of Jake Prairie, on a gravel road, SE ¼, section 20, T.40 N., R.5 W., Oak Hill Quadrangle.

No.		Thickness in feet.
9	Refractory clay; removed from the pit	-
8	Sandstone; white to light brown; fine-grained, moderately compact to friable; massive (sample 81)	8.0
7	Sandstone; light grey; fine-grained, thinly bedded with light green shaly layers; sand grains enlarged	6.0
6	Chert breccia; light grey to light brown; chert fragments oolitic, banded and sandy embedded in sand matrix	2.0
5	Shale; green and red; fissile; contains 0.5' of hard cherty sandstone	4.0
4	Sandstone; light grey to light brown; fine-grained; shaly; enlarged sand grains	2.0
3	Shale; green; fissile and cherty	1.0
2	Sandstone; similar to no.5	1.0

contd.

No.		Thickness in feet.
1	Chert conglomerate; light brown to red; highly sandy; chert rounded, some oolitic, some banded	2.0
	Total Thickness:	26.0

3. Location 54: ½ mile north of County Highway EE, on a gravel road, NE ¼, section 31, T.40 N., R.6 W., Redbird Quadrangle.

No.		Thickness in feet.
4	Orthoquartzite; light brown to light grey; very fine-grained, hard and compact.(sample 54a).	
3	Sandstone; light greyish brown; fine-grained, massive to thickly bedded, argillaceous; sand grains rounded to well-rounded (sample 54b).	
2	Clay; light grey; plastic; red ferruginous bands at the bottom.	
1	Sandstone; white to light brown; fine-grained; moderately hard to friable and slickensided (sample 54c).	

Due to complicated configuration of the beddings, the thicknesses of the strata were not measured.

4. Location 120: 2 miles east of Bland, south of Highway 28, section 5, T.41 N., R.6 W., Bland Quadrangle.

No.		Thickness in feet.
9	Refractory clay; removed from the pit	-
8	Sandstone; light brown to white; fine-grained; loose friable and massive (sample 120)	7.0
7	Clay; bands of violet, light green and yellow; sandy, ferruginous, and plastic	15.0
6	Quartzitic sandstone; brownish red, fine-grained; hard and compact	0.5
5	Clay; light greenish grey; laminated and plastic	0.5
4	Sandstone; light brown; fine-grained; silicified and ferruginous; hard and compact; contains ferruginous concretions at the base .	1.25
3	Clay; light brown, purple, violet, etc.; ferruginous concretions; hard and sandy	4.0
2	Sandstone; red; ferruginous; contains angular, oolitic and sandy chert fragments	0.5
1	Breccia; red; angular chert fragments in ground mass of sand; hard and compact	-
	Total thickness:	28.75

5. Location 162: On Highway I-44, under and east of the bridge on the old Vichy road, section 26, T.38 N., R.8 W., Rolla Quadrangle.

There are two sinkholes at this location: one north and the second south of the Highway. The section in the southern sink is composed of about 30 feet of thin intercalated light grey, fine-grained, loose and friable sandstone and light greenish grey shale (Pl. 4B). The maximum thickness of the individual bed is 0.25 to 0.5 foot. Large blocks of dolomite are seen as embedded in this section.

The stratigraphy in the northern sink is as follows:

No.		Thickness in feet.
5	Clay; red, green and greenish grey; laminated and plastic	-
4	Sandstone; light grey and light brown; fine-grained; loose to moderately compact; chert breccia at the base	5.0
3	Sandstone; light grey to brown; fine-grained; argillaceous with alternating bands of cherty clay	15.0
2	Chert breccia; light greenish grey; contains clay and sand in matrix	1.0
1	Shale; green; fissile with one thin chert breccia bed of 0.25 foot in the middle	4.0
	Total thickness:	25.0

APPENDIX B

COMPUTER PROGRAM FOR GRAIN SIZE PARAMETERS CALCULATIONS

```
/WAT4  GG140958, TIME=03,PAGES=400  PARIKH UPENDRA J       70.119    JOB 569
/       (3,400)
/       CLASS=W,PRIORITY=11,READER=READER1
C
C
C      N IS THE TOTAL NO. OF SETS
C
C       M IS THE NO. OF POINT IN PHI FROM WHICH DATA IS COLLECTED
C      PHI=0.75 IS THE FIRST POINT
C
C      M1 IS THE LAST NO IN PERCENT AGGREGATE
C      PHI=0.75 IS THE FIRST POINT
C
C
       DIMENSION PHI(100),WOP(25),DISER(25),CW(25),PA(25),CWAPD(25),
      /CUMW(100),POS(25),CP(25)
       NO=15
       N=40
       DO 2 J=1,N
       PHI(1)=0.75
       DO 1 I=2,15
       PHI(I)=PHI(I-1)+0.25
     1 CONTINUE
       READ(1,801)M,M1
       READ(1,800)(WOP(I),I=1,15),SOS,(PA(I),I=1,M1)
       WRITE(3,100)J
       SUM=0.
       DO 3 K=1,15
       SUM=SUM+WOP(K)
     3 CONTINUE
       DO 4 K=1,15
       DISER(K)=(SUM-SOS)*WOP(K)/SUM
```

```
      CW(K)=WOP(K)-DISER(K)
    4 CONTINUE
      M2=M1+1
      DO 5 K=M2,15
      PA(K)=0.
    5 CONTINUE
      DO 6 K=1,15
      CWAPD(K)=CW(K)-(PA(K)*CW(K))/100.
    6 CONTINUE
      SUM1=0.
      DO 7 K=1,15
      SUM1=SUM1+CWAPD(K)
    7 CONTINUE
      DO 8 K=1,15
      POS(K)=CWAPD(K)*100./SUM1
    8 CONTINUE
      CUMW(1)=CWAPD(1)
      CP(1)=POS(1)
      MP1=M+1
      DO 9 K=2,15
      CUMW(K)=CUMW(K-1)+CWAPD(K)
      CP(K)=CP(K-1)+POS(K)
    9 CONTINUE
      XBAR=0.
      DO 10 K=MP1,15
      APHI=0.5*(PHI(K)+PHI(K-1))
      XBAR=APHI*POS(K)+XBAR
   10 CONTINUE
      XBAR=XBAR/100.
      WRITE(3,101)(PHI(I),WOP(I),DISER(I),CW(I),PA(I),CWAPD(I),POS(I),
     /CUMW(I),CP(I),I=M,15)
      WRITE(3,102)SUM,SUM1,XBAR
      CALL BYPLOT(PHI,CP,NO)
    2 CONTINUE
```

```
      100 FORMAT(////5X,'THE FOLLOWING ARE THE READINGS FOR SET # ',I3//5X,'
         /ALL THE WEIGHTS REPORTED ARE IN GRAMS'///T6,'WT OF PROD'
         /,T28,'DIST ERR',T40,'CORR WT',T53,'% AGG',T64,'CORR WT',T75,'% ON
         /SC',T88,'CUM WT',T100,'CUM %'//)
      101 FORMAT(9(F10.4,2X))
      102 FORMAT(/8X,'TOTAL',T13,F10.4,T57,'TOTAL',T61,F10.4///5X,'XBAR = ',
         /F10.4)
      801 FORMAT(2X,I2,2X,I2)
      800 FORMAT(15F5.2/F7.3/5F8.4)
          STOP
          END

          SUBROUTINE   BYPLOT(X,Y,N)
          DIMENSION X(100),Y(100),A(100),XMAR(11),YMAR(9),YVAL(51),IDEL(101)
          DATA   STAR/'****'/,BLK/'
          DO 1000 I=1,100
     1000 A(I) = BLK
          IDEL(1) = 1
          XMIN=1.E35
          L = 1
          XMAX = -1.E35
          DO 5   I=1,N
          YHOLD =  Y(I)
          DO 10 J=L,N
          IF(YHOLD .GT. Y(J)) GO TO 10
          YHOLD = Y(J)
          JJ = J
   10     CONTINUE
          Y(JJ) = Y(I)
          Y(I) = YHOLD
          XH  =  X(JJ)
          X(JJ) = X(I)
          X(I) = XH
          IF( XMIN .LE. X(I)) GO TO 3
          XMIN = X(I)
    3     IF( XMAX .GE. X(I)) GO TO 5
```

```
      XMAX = X(I)
5     L = L+1
      XDIF  =  XMAX - XMIN
      YDIF  =  Y(1) - Y(N)
      DELX =  XDIF / 10.
      DELY  = YDIF / 5.
      DO 40 I=1,11
40    XMAR(I) = XMIN + (I-1)* DELX
      YMIN = Y(N)
      YMAX = Y(1)
      DO 50 I=1,6
50    YMAR(I) = YMIN + (I-1) * DELY
      DO 75 I =1,51
75    YVAL(I) = BLK
      J = 0
      DO 76  I=1,51,10
      J = J + 1
      NN  = 7 - J
76    YVAL(I) = YMAR(NN)
      WRITE(3,70)
      JB = 1
      I = 1
      IYP1 = 1
      J = 0
152   IYP = (( YMAX -Y(I))/ YDIF) * 50. + 1.5
      IF(IYP1 - IYP) 1527,21,21
21    IXP = (( X(I) - XMIN) / XDIF) * 99. + 1.5
      A(IXP) =  STAR
      JB = JB + 1
      IDEL(JB) = IXP
      I = I + 1
      IF( I .EQ. N+1) GO TO 1527
      GO TO 152
1527  IYP1 = IYP
      J = J + 1
```

```
          IF(YVAL)J) .NE. BLK) GO TO 200
          WRITE(3,71) (A(NN),NN=1,100)
          GO TO 15279
200       WRITE(3,77) YVAL(J),(A(NN),NN=1,100)
15279     DO 23 IQ = 1,JB
          JBY = IDEL(IQ)
23        A(JBY) = BLK
          JB = 1
          IF( I .EQ. N+1) GO TO 157
          IF( IYP .EQ. J+1) GO TO 21
          GO TO 1527
157       WRITE(3,72)
          WRITE(3,73)
          WRITE(3,31670) XMAR
70        FORMAT(1H1)
71        FORMAT(19X,1H1,100A1)
72        FORMAT(20X,102,1H-))
73        FORMAT(20X,10(1H+,9X),1H+)
77        FORMAT(8X,1PE10.2,1X,1H1,100A1)
31670     FORMAT(15X,1P11E10.2)
          RETURN
          END
```

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XII. VITA.

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