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GEOLOGY OF ANCIENT BLANKET AND CHANNEL DEPOSITS  
EXPOSED NEAR WAMEGO, KANSAS

by

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## INTRODUCTION

The Willard Shale, Wabaunsee Group, Upper Pennsylvanian Series, of northeast Kansas exhibits a widespread blanket sandstone. Such deposits, associated with the basal 'non-marine' phases of Wabaunsee-type cycles of sedimentation, mark local diastems. Wabaunsee Group and the overlying Admire Group, Lower Permian Series, also show channels cut into almost every shale formation and member. The channels are presumed to have been eroded subaerially, and the fill of most of them is considered to be non-marine.

## LOCATION

Just west of Wamego, Kansas, in south-central Pottawatomie County, an interesting exposure of both blanket and channel sandstones may be studied in a recent stream cut (see Fig. 1). The area which has been studied in detail lies in sections 5, 6, 7 and 8, of TWP 10S, RGE 10E (see Fig. 3). Cat Creek is a small incised stream which empties into the Kansas River, roughly 1½ miles southwest of Wamego. Near the intersection of the section-line road and Cat Creek a channel sandstone of undetermined age cuts through a blanket sandstone of the Willard Shale.

## PURPOSE OF INVESTIGATION

This study was made to explore possible relationships between blanket and channel sandstone deposits from a particular local occurrence, stratigraphically near the Pennsylvanian-Permian boundary in northeastern Kansas. A blanket sandstone is in the Willard Shale, and has not been reported this far south. The channel, with sandy fill, is in contact with the blanket deposit and has been known for many years as the Indian Cave Sandstone, locally marking the boundary between the Pennsylvanian and Permian Systems.

## PREVIOUS INVESTIGATIONS

Since the 1930's the uppermost division of the Pennsylvanian System has come to be accepted as the Brownville Limestone (see Fig. 2). In so defining the systemic boundary Moore and Moss (1934) pointed to the fossil record and to channel-development originating within the sheet sandstone of the Towle Shale. Jewett (1933) and Moore (1936, 1940) mentioned that the pattern of sedimentation characteristic of Wabaunsee time continued into the Permian, and they noted the similarity of the Admire section to the underlying Wabaunsee rocks.

Regional studies by Mudge (1956) indicated that nearly every shale formation in the upper Wabaunsee-lower Admire section contained both blanket and channel sandstones. A more recent publication stressed that the section encompassing the systemic boundary is dominantly clastic, largely conformable, and relatively nonfossiliferous (Mudge and Yochelson, 1962).

The channel sandstone exposed near Wamego has long been considered to be the Indian Cave Sandstone of Towle age (Harned and Chelikowsky, 1945). Mudge (1956) visited the site and postulated two channels, one superimposed on another, or a single channel illustrating two periods of degradation separated by a period of aggradation. He felt that while the evidence was meager, the channel was probably of Caneyville or Pony Creek age, and not of Towle age. The blanket sandstone, which is a sandy phase contained within the Willard Shale, is widely persistent to the north (Moore, 1949; Mudge, 1956; Scott et al, 1959; Mudge et al, 1959) but has not been reported this far south.

## PROCEDURE

Geometry of the two sandstone bodies was established by drilling records of the Kansas Highway Department. Local stratigraphy, from the Auburn Shale to the Dover Limestone Member of the Stotler Limestone was measured and described in the immediate area of investigation. Exposures of blanket and channel sandstone were measured, described, and sampled in the steeply cut banks of Cat Creek and along U.S. Highway 24. A total of 31 samples was taken: 20 of the Willard mudstone and associated sandstone, and 11 of the channel sandstone body. Thin sections were prepared of eight field samples selected to cover the range of lithologies observed, and modal analyses made. A single basic procedure was followed to integrate the studies of grain size analysis, heavy mineralogy, and clay mineralogy for each sample. Apart from the above samples muscovite was separated from the sandstones of the Willard Shale and the channel deposit for geochronological investigations.

## ACKNOWLEDGEMENTS

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## STRATIGRAPHY AND GEOLOGIC SETTING

## REGIONAL STRATIGRAPHY

Northeast Kansas is in the western part of the Central Lowland physiographic province (Fenneman, 1931; Frye & Swineford, 1949). The western boundary of the province is taken to be on a nearly N-S line roughly 40 miles west of Riley and Geary counties (see Fig. 1). West of this boundary is the Great Plains province.

West of the axis of the Nemaha Anticline, the eastern boundary of the Flint Hills uplands is defined by a series of crude arcs (not shown in Fig. 1) from central Marshall, west-central and southwestern Pottawatomie, extreme southeastern Riley and west-central Wabaunsee counties. The Flint Hills owe their existence to a sequence of alternating shale and cherty carbonate beds of the Lower Permian Series overlying the Admire Group (see Fig. 2), which are more resistant to erosion than the rocks of the Upper Pennsylvanian Wabaunsee Group and Lower Permian Admire Group. Except locally in the area just east of the axis of the Nemaha anticline the Late Paleozoic rocks dip uniformly to the west at about one fourth degree.

The rest of the region shown in Figure 1 consists of flat to gently rolling lowland plains which, south of the Kansas River, abut sharply against the east-facing Flint Hills Cuesta. These lowlands formed on the more easily eroded strata mentioned above. North of the Kansas River, Pleistocene glacial action greatly modified and obscured the boundary of Flint Hills uplands and lowland plains.

The study area is approximately on the east-facing escarpment of the Nemaha Anticline (see Fig. 1). Northeastern Kansas and adjoining areas in Nebraska, Iowa and Missouri were uplifted at the end of Mississippian deposition.

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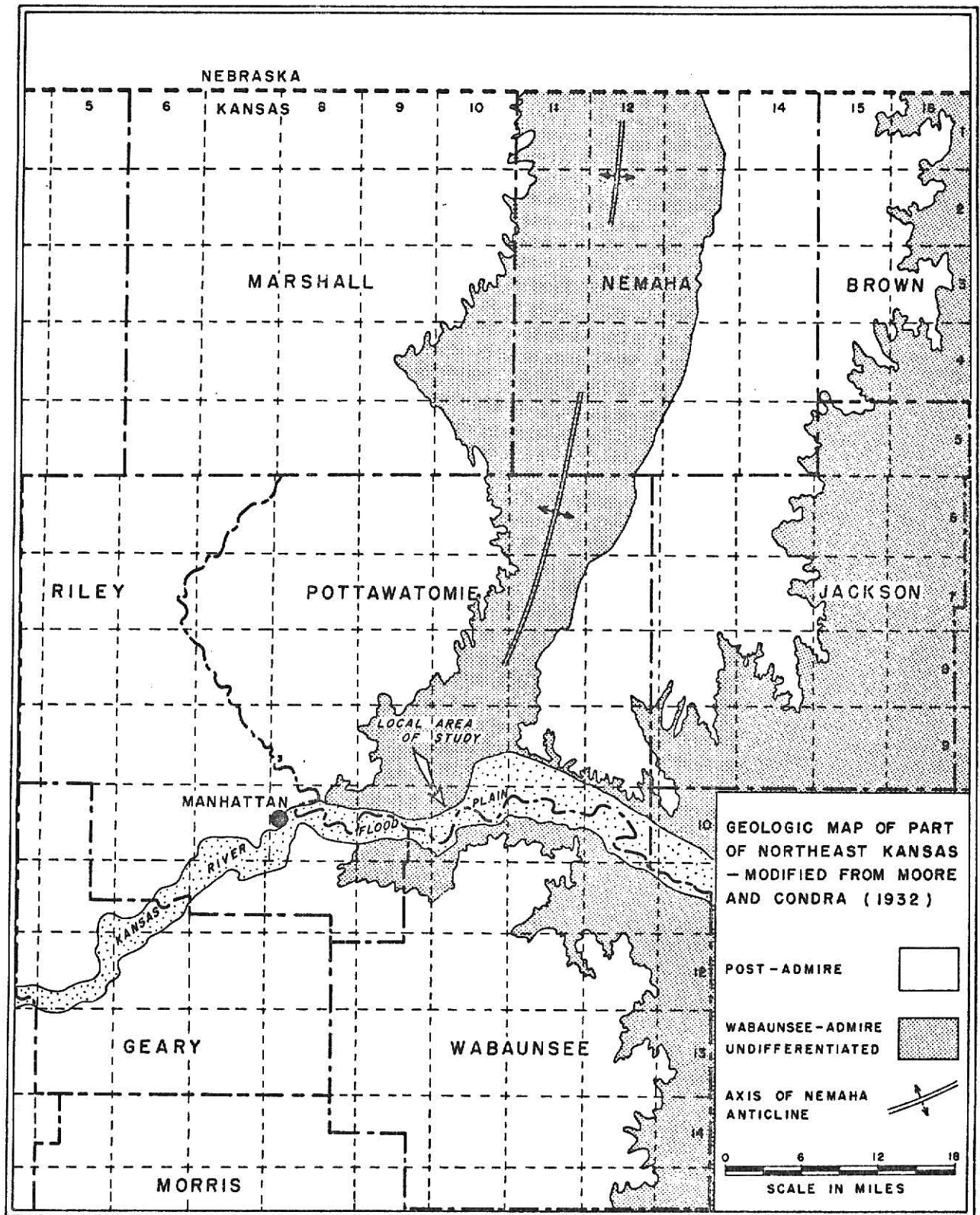


Fig. 1

Late Mississippian to Middle Pennsylvanian downwarp of peneplained terrain coupled with re-elevation of the Nemaha granite ridge produced the present Forest City basin (Lee, 1943; Jewett, 1951).

By early Middle Pennsylvanian time normal marine conditions of sedimentation again spread across the region from the south. The Precambrian core of the anticline was exposed during late Mississippian early Pennsylvanian emergence. As evidenced by several mechanical well logs the core remained a sediment - shedding upland in Riley and Pottawatomie Counties until early Upper Pennsylvanian time. To the south the anticline retained a cover of Cambrian-Ordovician rocks. Nearly 1000 feet of Pennsylvanian rocks within the Forest City Basin are older than the initial sediments laid down in the study area.

The Upper Pennsylvanian Series, bounded by disconformity and paleontological break at the base and by more or less arbitrary convention at the top, is comprised of the Missourian and Virgilian Stages (Zeller, 1968, see Fig. 2). Eastern Kansas contains a well-exposed nearly complete section of Virgilian rocks, both marine and continental, displayed in a regular succession dipping to the west. Middle and Upper parts of this succession, namely the Shawnee and Wabaunsee Groups, are characterized by uniformity of lithology, thickness and paleontology of individual stratigraphic units (Moore, 1949).

The stratigraphic section encompassing the upper part of the Wabaunsee Group and overlying Admire Group in northeast Kansas is dominantly clastic, with thin carbonates and minor coal beds that are relatively nonfossiliiferous and are seemingly conformable. Commonly the systemic boundary is drawn just below the earliest occurrence of the fusulinid zone of Pseudoschwagerina and Properrinites (Tomlinson et al, 1940; Moore, 1940). Available evidence to date, however, has not indicated any major or profound break in the above fusulinid evolutionary succession (Mudge and Yochelson, 1962). Furthermore,



## REGIONAL STRATIGRAPHY

HAMLIN SHALE	JANESVILLE SHALE	ADMIRE GROUP	GEARYAN STAGE	L. PERM. SERIES	PERM. SYSTEM
FIVE POINT Ls.					
WEST BRANCH Sh.					
	FALLS CITY Ls.				
HAWXBY SHALE	ONAGA SHALE				
ASPINWALL Ls.					
TOWLE SHALE					
BROWNVILLE Ls.	WOOD SIDING FORMATION	RICHARDSON SUBGROUP	WABAUNSEE GROUP	VIRGILIAN STAGE	UPPER PENNSYLVANIAN SERIES
PONY CREEK Sh.					
GRAYHORSE Ls.					
PLUMB SHALE					
NEBRASKA CITY Ls.					
FRENCH CREEK Sh.	ROOT SHALE				
JIM CREEK Ls.					
FRIEDRICH Sh.					
GRANDHAVEN Ls.	STOTLER Ls.				
DRY SHALE					
DOVER L'STONE					
	PILLSBURY Sh.				
MAPLE HILL Ls.	ZEANDALE Ls.				
WAMEGO SHALE					
TARKIO L'STONE					
	WILLARD SHALE	NEMAHA SUBGROUP	WABAUNSEE GROUP	VIRGILIAN STAGE	UPPER PENNSYLVANIAN SERIES
ELMONT L'STONE	EMPORIA Ls.				
HARVEYVILLE Sh.					
READING Ls.					
	AUBURN SHALE				
WAKARUSA Ls.	BERN LIMESTONE				
SOLDIER CREEK Sh.					
BURLINGAME Ls.					
SILVER LAKE Sh.	SCRANTON SHALE				
RULO LIMESTONE					
CEDAR VALE Sh.					
HAPPY HOLLOW Ls.					
WHITE CLOUD Sh.					
UTOPIA L'STONE	HOWARD Ls.				
WINZELER SHALE					
CHURCH Ls.					
AARDE SHALE					
BACHELOR Cr. Ls.					
	SEVERY SHALE				

PALEOZOIC ERA

FROM ZELLER (1968)

Fig. 2



no recent study has yet uncovered more than local disconformity at the accepted systemic boundary (Walters, 1953, 1954; Mudge, 1956; Scott et al, 1959; Mudge et al, 1956a, 1959b; Mudge and Yochelson, 1962).

#### WABAUNSEE GROUP

The Wabaunsee Group was first defined as a formation encompassing the stratigraphic interval from a part of the Howard Limestone to the base of the Cottonwood Limestone Member of the Beattie Limestone, not shown in Figure 2 (Prosser, 1895, in Moore, 1949). Since 1934, usage has come to take in a more restricted interval from the base of the Severy Shale to the top of the Brownville Limestone Member of the Wood Siding Formation (Moore and Moss, 1934; Zeller, 1968). The group crops out in a belt to the east of the study area and along the axis of the Nemaha Anticline where it is exposed through and surrounded by rocks of the Permian System (Fig. 1).

Lithologically and stratigraphically the section is dominated by relatively thick olive-grey, grey and blue-grey silty shale and mudstone units which yield gentle erosional slopes and generally poor exposures. Zones of tan to grey sand and siltstone, very thin coal seams and stringers, and very thin-bedded black shale are locally present in almost every shale-mudstone unit and become increasingly common north of the Kansas River (Mudge, 1956; Mudge and Yochelson, 1962). Many of these beds are in small cut-and-fill structures of channels. Limestones of the Wabaunsee Group, several of which form prominent hillside benches are easily distinguished from underlying Shawnee and earlier Pennsylvanian carbonate rocks by general thinness of beds and predominance of tan-brown and cream colors.

The regularly alternating succession of beds of coarse and fine clastic, coal, shale and carbonate rocks also document a history of cyclic deposition. No part of the Pennsylvanian across the northern midcontinent exhibits clearer evidence of this phenomenon than the Wabaunsee group (Moore, 1949). The cycles, while lacking certain phases of Moore's ideal Late Pennsylvanian cyclothem are remarkably well-differentiated and widely persistent (see Table 1 and Fig. 4). The overlying Permian Admire Group also exhibits Wabaunsee-type cycles of sedimentation (Mudge and Yochelson, 1962).

Regionally the group is reported to be a uniform 500 feet thick (Lee, 1943; Moore, 1949; Zeller, 1968). I noted from well logs a consistent pattern of thinning of clastic units in the lower part of the Wabaunsee section from Jackson and Wabaunsee counties east of the buried Namaha granite ridge to central Pottawatomie and southern Riley counties on the west (see Fig. 1). Unfortunately few wells had been logged to the surface and no definite statement regarding a trend can be made at this time. Marked local variation in thickness of shale units, with a general tendency of units to thicken southward and take on a 'more marine' character, was reported by Mudge, but only surface exposure was included in that study (Mudge and Yochelson, 1962).

#### ADMIRE GROUP

The Admire Group is defined as encompassing the interval from the base of the Towle Shale Member of the Onaga Shale to the top of the Hamlin Shale Member of the Jamesville Shale (Moore et al, 1951; Zeller, 1968). Stratigraphically and petrologically rock units of the Permian Admire Group are obviously more similar to the underlying Wabaunsee Group than to any later Permian strata.

## Explanation of Table 1

"The sandstone (0) may rest disconformably on underlying beds and appears definitely to represent the initial deposits of the cyclothem. Locally a thin conglomerate may occur at the base of the sandstone. The succeeding shale and coal (1) are clearly continental in origin and indicate deposits made on an extremely low, flat coastal plain. The mollusk-bearing shale and limestone (2 and 3) indicate the submergence of the coal swamps or coastal plain by a very shallow sea, and overlying shale (4) marks continued marine transgression that culminates in making the off-shore fusulinid-bearing limestone (5). The succeeding parts of the cyclothem appear to signify marine regression which leads to shoaling waters inhabited by mollusks and favoring growth of algae (6, 7, and 8). The terminal unit of the cyclothem (9) is generally an unfossiliferous shale, but may contain remains of land plants."\*

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\*Moore (1936)

Formations and members of shale vary only slightly in gross character from those of the Wabaunsee Group. Development of sandy lithologies is as prevalent, but channels are fewer and less extensive in width and depth than those of latest Pennsylvanian age (Mudge, 1956). Beds of carbonate rock in the Admire Group strongly resemble those of formations and members of the Wabaunsee Group in being thin and commonly tan-brown to cream. Along the outcrop, which parallels that area of Wabaunsee exposure, the Admire Group averages about 110 feet and thickens in gross aspect to the south by increase of shale and mudstone (Mudge and Yochelson; 1962).

Table 1

## Ideal, Late Pennsylvanian Cyclothem

Moore, Elias, Newell (1934)

9	Unfossiliferous, may have plant remains
8	Mollusks, or unfossiliferous
7	Algae, mollusks, brachiopods, bryozoans
6	Brachiopods, byrozoans
5	Fusulinids dominant, may have bryozoans
4	Brachiopods, bryozoans
3	Mollusks, brachiopods, bryozoans
2	Mollusks, esp. Myalina and Orthomyalina
1c	Coal
1b	Underclay
1a	Land Plants
0	May contain land plants

## LOCAL STRATIGRAPHY

Pleistocene (Kansas Stage) glacial action largely reduced the Flint Hills upland to a series of less conspicuous rolling hills and covered most of Pottawatomie County with a mantle of till. Extreme northern Wabaunsee County to about the boundary of T9S and T10S was the site of maximum advance of the ice sheet (see Fig. 1). The terminal moraine is evident at several locations within sight of the Kansas River. At that time the ancestral Kansas River was dammed and temporarily diverted through a tributary system of that river just to the south (Mudge and Burton, 1959a).

Throughout most of Pottawatomie and counties to the north, exposure of bedrock is dependent upon recent stream rejuvenation. Thickness of till cover, however is less and is at places lacking on the south and west-facing walls of certain stream cuts. Terraces have formed along all larger streams, but are best developed and broadest in the valley of the Kansas River.

The local stratigraphic section includes units from the Auburn Shale, immediately adjacent to the Kansas River flood plain, up to the Dover Limestone Member of the Stotler Limestone, capping hills to the west and south of the stream known locally as Cat Creek (see Figures 3 and 4). The interval includes the middle part of the Wabaunsee Group\* and consists of regularly alternating 'marine and nonmarine' beds or phases of Wabaunsee-type cyclothems. The Tarkio cycle (D in Fig. 4) is typical of the pattern of sedimentation prevalent throughout the Wabaunsee-Admire section with an initial or basal 'nonmarine' sandy phase contained within the Willard Shale, the 'marine' Tarkio Limestone Member, and 'regressive marine' mudstone phase of the Wamego Shale Member of the Zeandale Limestone.

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\* I prefer not to use Wabaunsee subgroup terminology in this study because of its lack of application to the south of the study area (Mudge, M.R., personal communication, 1968).

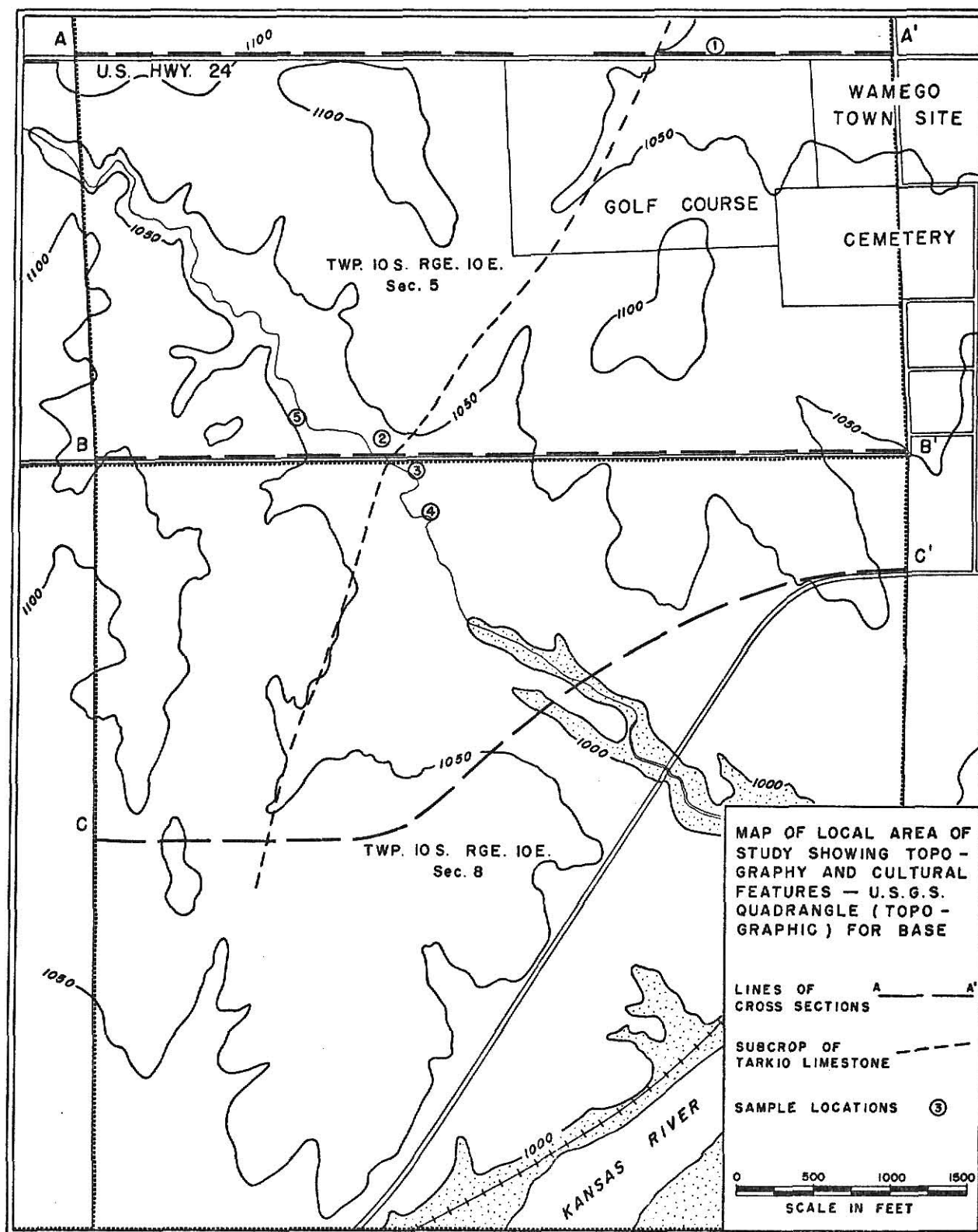


Fig. 3

The following discussion of stratigraphic units cropping out in the immediate area of Cat Creek emphasizes general petrography, weathering and erosional characteristics and thickness of formations and members illustrated in Figure 4. Historical reference and location of type sections are found in Moore (1949) and Moore and Mudge (1956).

#### AUBURN SHALE

The greater part of the Auburn Shale remains covered by alluvial flood plain deposits of the Kansas River. A resistant and rather unusual carbonate bed forms a prominent bench just above the highest terrace of the Kansas River Valley. The bed is about five feet thick and is a cross-bedded, argillaceous, intraformational conglomeritic and coquinoid limestone. The fresh exposure is hard and light grey but the weathered surface is softer and tan-cream. About eight feet of tan-grey sandy very thin-bedded siltstone and silty shale overlies the carbonate unit.

#### EMPORIA LIMESTONE

In ascending order the Emporia Limestone includes the Reading Limestone Member, Harveyville Shale Member, and the Elmont Limestone Member.

Reading Limestone Member.-- The Reading Limestone Member is about 20 inches thick consisting of two beds of hard, dense, grey, very fine crystalline limestone with a very thin clay and limonite parting. The weathered surface is tan-grey with fairly abundant white fusulinids and crinoid columnals which stand out in relief. The Reading Limestone Member is too thin to form an obvious hillside bench.

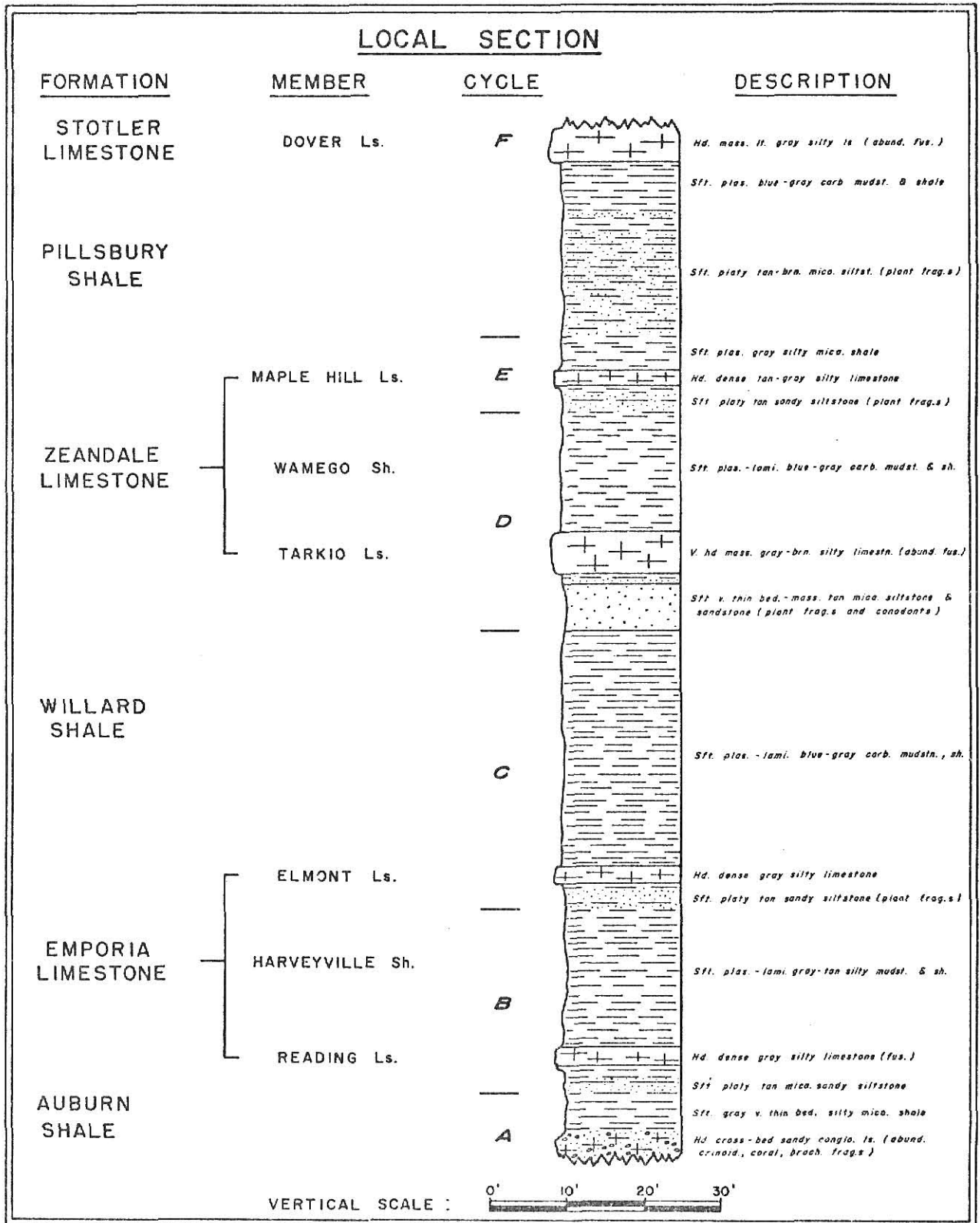


Fig. 4



Harveyville Shale Member. -- The Harveyville Shale Member overlies the Reading Limestone and underlies the Elmont Limestone Member, is 23 feet thick and thus accounts for about 90 percent of the Emporia Limestone. The unit is comprised of soft, but very cohesive grey shale which is silty at the base and grades to an argillaceous tan-grey siltstone with an abundance of carbonized plant fragments, particularly on bedding planes. No other fossil remains are evident. The unit forms a fairly steep erosional slope.

Elmont Limestone Member. -- The Elmont Limestone Member is a hard dense grey carbonate bed about 20 inches thick. Weathering and erosional characteristics are identical to the Reading Limestone but the unit consists of a single bed which is highly fractured; the upper surface of this bed is heavily stained with iron oxides. Otherwise the two limestones could be easily confused.

#### WILLARD SHALE

Bounded by the thin relatively inconspicuous Elmont Limestone Member below and the prominent Tarkio Limestone Member of the Zeandale Limestone above, the Willard Shale is predominantly a blue-grey silty shale and mudstone that is about 39 feet thick and which grades from that lithology to very thin-bedded grey-tan siltstone to cross-bedded tan sandstone, in the upper few feet. The shale or mudstone is locally slightly calcareous and, except for carbonized plant fragments, contains no fossils. The siltstones and sandstones are very micaceous and contain an abundance of plant fragments. Despite a clay-limonite 'binder' the coarse clastics are very friable while the argillaceous siltstones, particularly if calcareous are hard and resistant.

Both hematite and limonite concretions and nodules are prevalent in the upper sandy phase of the unit. Further description of this zone will be found in the discussion of the Willard Sheet Sandstone Body in the next section. The Willard forms a gentle erosional slope and is usually poorly exposed.

#### ZEANDALE LIMESTONE

The Zeandale Limestone consists, in ascending order, of the Tarkio Limestone Member, Wamego Shale Member and Maple Hill Limestone Member.

Tarkio Limestone Member. -- The Tarkio Limestone Member consists of two massive beds of subequal thickness separated by a shale of only a fraction of an inch and only visible on a weathered surface; total thickness of the unit is about six feet. The lower bed which is about 3.5 feet thick is a hard, finely crystalline to granular grey-brown limestone with abundant snow white fossils - most notably fusulinids but also corals, crinoid columnals and brachiopods. The same weathered rock exhibits a rich brown color with fossils, standing in relief. The lower bed is crossed by a series of joints which leave large nearly rectangular blocks. The upper bed is similar in gross appearance but is softer, more granular, slightly silty, and weathers in irregularly shaped shelly slabs about two inches in thickness. The Tarkio Limestone Member forms the most conspicuous limestone bench on the hills overlooking the Kansas River in the local area of study.

Wamego Shale Member. -- The Wamego Shale Member overlies the Tarkio Limestone Member and underlies the Maple Hill Limestone Member and is about 23 feet thick. The major part of this interval consists of grey and blue-grey silty and carbonaceous mudstone and shale with laminar tan-grey siltstone lenses. A calcareous zone two feet thick occurs about ten feet up from the base. The uppermost four feet of the unit consists of very thin-bedded siltstone with

lenses of fine sandstone. Abundant plant fragments and mica occur particularly on bedding planes. The Wamego Shale Member forms a gentle erosional slope and is generally poorly exposed.

Maple Hill Limestone Member. -- The Maple Hill Limestone Member of the Zeandale Limestone is a thin (20 inches thick) massive bed of dense tan-grey fine crystalline limestone. The bed weathers brown and is highly jointed. Fossil content is restricted to a few fusulinids. The hillside bench of the Maple Hill Limestone member is not comparable to that of the Tarkio Limestone Member but may stand out at a given location due to the gentle slopes of fine clastic units above and below.

#### PILLSBURY SHALE

The Pillsbury is comprised of a fairly uniform grey silty shale and mudstone for most of its 18 feet. Many thin beds of tan siltstone occur in the middle part of this unit. Erosional slope of the Pillsbury Shale is fairly steep at some locations, but like the Willard Shale, this formation needs more and better road cuts through it as good exposure is rare.

#### STOTLER LIMESTONE

The only member of the Stotler Limestone in the local area is the Dover Limestone Member which is a hard dense grey finely crystalline and granular limestone about 2.5 feet thick. Weathering produces a tan color and not only do fusulinids stand in relief but may actually be rubbed off the surface. The unit is otherwise quite similar to the lower carbonate bed of the Tarkio Limestone Member and could be confused with it where the upper Tarkio bed is missing. The Dover Limestone Member forms flat-topped benches capping hills to the west and southwest of Cat Creek.

# GEOLOGY OF BLANKET AND CHANNEL SANDSTONES EXPOSED IN CAT CREEK

## STRATIGRAPHIC RELATIONS

Whatever the manner in which terrigenous clastics (sands) were brought into and spread across northeast Kansas in late Pennsylvanian and early Permian time, conditions must have favored development of blanket and channel sandstone accumulations. Regional investigations, most notably by Mel Mudge (1956) have shown nearly every shale formation encompassing the systemic boundary to contain local, and, often extensive blanket sandstones, and channels which seem to have been subaerially cut and the fill of which is commonly sandstone. Students of cyclical sedimentation mainly J.M. Weller (1930) and R.C. Moore (1936) have shown the development of these sandstones to be associated with the 'non-marine' phases of relatively simple and repetitive cycles of deposition.

In this study the local stratigraphy has been discussed, and cycles of deposition described which consisted of basically two phases: a clastic or sandy phase contained within a thicket shale-mudstone formation or member, and a relatively thin carbonate phase (see Fig. 4). The Willard Shale exhibits a widespread blanket sandstone which is the basal sandy phase of cycle 'D' in the Figure. A few miles to the north, in TWP 7S, RGE 10 and 11E, I observed Willard Shale sections which were composed dominantly of thin-bedded sandstone and siltstone and contained shallow channel structures which may have been up to 20 feet deep. Mudge (1956) and Scott et al (1959) report that while the thickness of the Willard blanket sand is usually about six feet, locally the formation consists almost entirely of sandstone; Mudge also noted channel development in the Willard Shale in northcentral Pottawatomie County.

Both blanket and channel sandstones may be examined in the recent incised stream (known locally as Cat Creek) 1/2 mile southwest of Wamego in Figure 3. The Willard Shale is 39 feet thick at this locality approximately the upper 22 feet of which is exposed. On the west side the Tarkio Limestone Member forms a well-developed bench above the terrace of the stream throughout much of its length. A small amount of excavation below this limestone reveals the basal sandy phase and below that a typical section of Willard shale and mudstone lithologies. Except for a limited area a few feet northeast of the intersection of the section-line road and Cat Creek (a bridge is present but not shown in Fig. 3) the Tarkio Limestone Member and upper Willard Shale have been lost to erosion. The west flank of an ancient channel, with predominantly sandstone fill, lies in unconformable contact with the Willard blanket sandstone. The particular orientation of rock units and present stream cut, with ever present glacial out wash and recent alluvium cover, obscures relationships and has resulted in some confusion in the past.

Field studies and drilling records of the Kansas Highway Commission are combined in the interpretation of geometry of sandstone bodies shown in Figure 5.\* Forty-six bore holes constitute the major control for the diagram. The three E-W sections are spaced at 1/2 mile intervals; the northern-most section corresponds to U.S. Highway 24. The channel sandstone accumulation (coarse stipple pattern) is seen to be largely covered with Pleistocene outwash and Recent alluvium. The Willard blanket sandstone (fine stipple pattern) occurs

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\* Original profiles of these sections, 24-75-F-605-(1) and 40-75-F-203-A and B are on file with the Records Section of the State Highway Commission of Kansas, Topeka, Kansas. The logs of these bore holes are also on file with the commission and are available for inspection at their offices in Topeka.

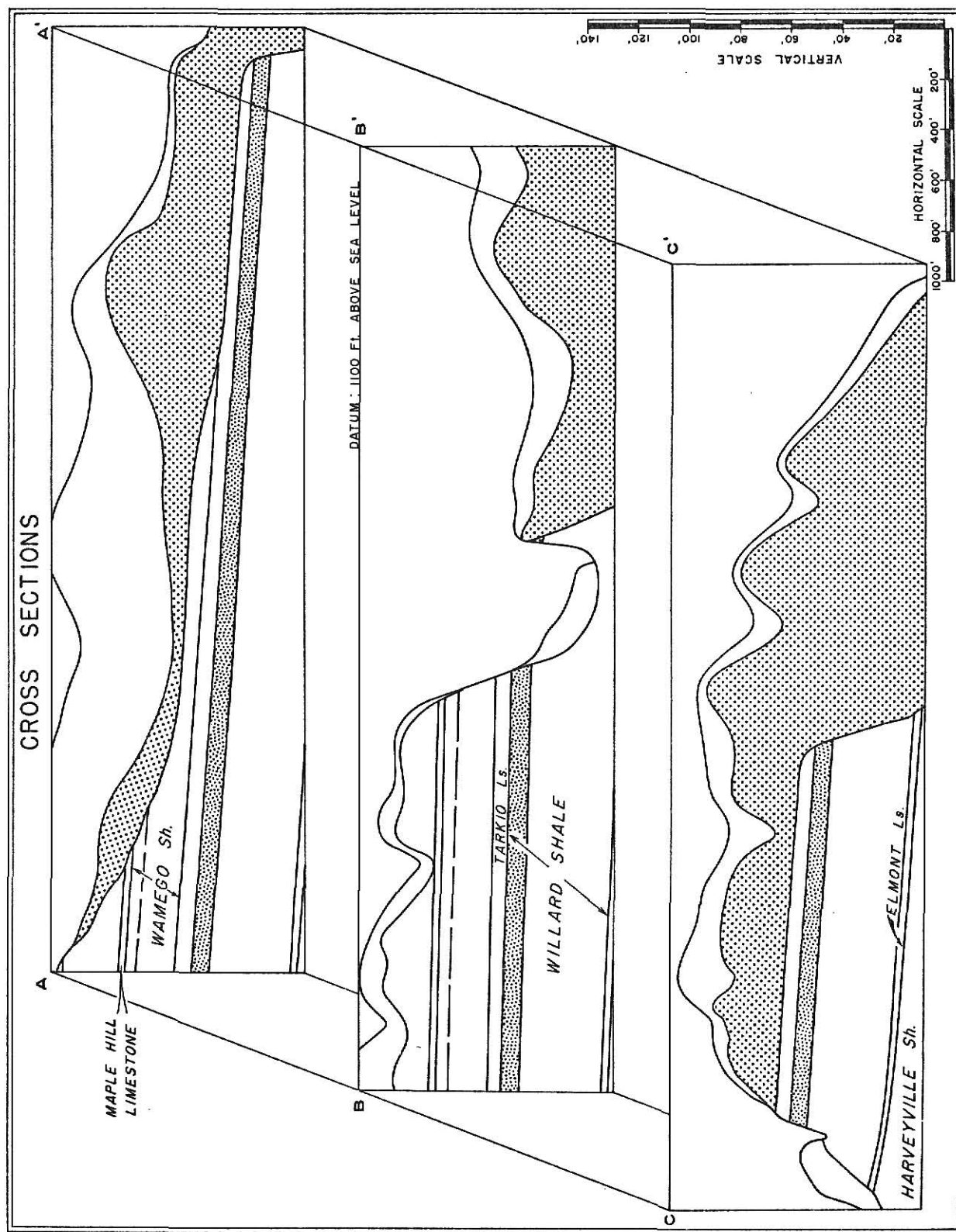


Fig. 5

at the base of the Tarkio Limestone Member. Section B-B' runs along the section-line road referred to above; roughly midway along this section is the recent stream cut.

#### DESCRIPTION OF BLANKET-SAND BODY

Sample locations 2 and 5 are here described (See Fig. 3). The blanket-sand deposit is completely gradational from the under-lying beds of shale and mudstone of the Willard Shale. A few thin grey-tan siltstone stringers and lenses first appear in the blue to olive-grey carbonaceous mudstone about seven feet below the Tarkio, and the proportion of siltstone increases upward at the expense of mudstone. At about six feet below the Tarkio the lithology is dominantly very thin-bedded tan siltstone with grey clayey lenses and partings. Still higher, fine and micro-crossbedded tan and brown siltstone interlenses with fine sandstone and locally shows small unconformable structures filled with sandstone. The complete gradation takes place within 20 to 30 inches. From about four and one-half feet below to within 10 to 12 inches of the Tarkio Limestone Member the lithology is tan fine to very fine, carbonaceous and micaceous silty sandstone. The bedding is thin to very thin and usually regular; a few cut-and-fill structures contain cross-bedded slightly coarser sandstone. Bedding planes are darkly colored by carbonaceous material and marked by abundant coarse mica (mostly muscovite) flakes. Approximately 20 pounds of blanket sandstone were taken at sample location 2 for muscovite separation for isotopic age determinations to be discussed in another section. During muscovite separatory procedures 14 conodonts were recovered which were tentatively identified as a Late Pennsylvanian platform type and a bar type. No other fossils were found in any blanket sandstone lithology.



## DESCRIPTION OF CHANNEL-SAND BODY

The channel sandstone body is well exposed at locations 1 (on Highway 24, north of the golf course) and at 3 and 4 (south of the bridge on Cat Creek) (see Fig. 3). The fill consists of three major units distinguished on the basis of gross variation in bedding characteristics and color. A distinctive facies is encountered at locations 3 and 4 which is defined as the coarse-clean facies; it is generally massive to thick-bedded, tan, fine to very fine sandstone with hematite concretions, and with abundant widely disseminated mica and carbonized plant remains. A thinner bedded variation of this facies, with mica also abundant on bedding planes was chosen for muscovite dating purposes. Cross-stratification, when present, is tangential and tabular - planar. A second facies, interbedded with the first, at locations 3 and 4, is defined as the fine-dirty facies; it is a very thin-bedded to laminar, grey, sandy siltstone and very fine sandstone with pyrite concretions, and abundant mica and carbonaceous matter both disseminated and concentrated along bedding planes. Current ripples and micro cross-lamination are found but the facies is mostly regular-bedded. The third facies defined in the channel fill is called the main channel facies; a massive, tan, fine-medium grained sandstone with hematite concretions. This facies is exposed at a single crop along U.S. 24 north of the golf course.

Blocks of Tarkio Limestone up to seven feet in long dimension are seen interbedded with channel fill just south of the bridge and between sample locations 2 and 3. Discontinuous coal seams and clay lenses are common along this western flank of the channel. Fossil plants of the form genera Neuropteris sp. and Pecopteris sp. were taken at location 3, and identified by Kenneth Warren, Jr. at Kansas State University. These are typical Late Pennsylvanian



and possible Early Permian seed-fern and true fern foliage remains (Warren, K. Jr., personal communication, 1968). Another fossil taken from the channel fill near location 3 is the pelecypod Permophorus sp. of Late Paleozoic range.

The age of this channel has been postulated as being lowermost Permian (Indian Cave Sandstone, Towle Shale Member of the Onaga Shale) by Harned and Chelikowsky (1945). They found by drilling that the base of the channel here is in the middle part of the Auburn Shale, about 75 feet beneath the Tarkio Limestone Member of the Zeandale Limestone. Mudge (1956) felt that although evidence was not conclusive one or two channels of possibly Pony Creek age were exposed along the recent stream cut and presumably another of 'Langdon' (Pillsbury) age along U.S. 24 (location 1). Since the upper part of the channel, and eastern flank, have been lost to erosion no definite statement can be made at this time regarding the age of this channel.

Certain points are obvious from the above discussion and are here listed:

- 1) the blanket and channel sandstone deposits are clearly separate and distinctive rock stratigraphic units; 2) the sheet sandstone is a basal non-marine sandy phase in the Willard Shale; 3) the channel sandstone can not be named in light of the present study but is of unquestionable Late Paleozoic (post-Tarkio Limestone Member) age.

## P E T R O L O G Y

One of the chief goals of this study was to determine the petrological character of blanket and channel sandstones from a particular local occurrence. It was hoped that specific differences, particularly with regard to composition and texture, could be established for use in distinguishing between the two bodies. Further, information gained in search of the above comparison could provide insight as to the provenance of the sediments.

## SAMPLE COLLECTION AND NOTATION

A total of 31 field samples, each from 2 to 3 pounds, was taken from the two sandstone bodies. In addition, roughly 20 pounds of sandstone were taken from both deposits for muscovite separation and age determination. Sample collection points are illustrated in Figure 3. Sampling notation is outlined in Table 2. In the notation, the location (L-1, L-2, L-3, L-4, L-5) is followed by duplicate sets of samples (A,B) which were offset by a few feet. The abbreviations (CC, FD and MC) used in the channel-sample notation stand for "coarse-clean", "fine-dirty" and "main channel" facies.

Table 2

<u>Sandstone Body</u>	<u>Notation</u>
Blanket-sand	L-2-A: 1,2,3,4,5
	L-2-B: 1,2,3,4,5
	L-5-A: 1,2,3,4,5
	L-5-B: 1,2,3,4,5
Channel-sand	L-1-A: MC
	L-1-B: MC
	L-3-A: CC, FD
	L-3-B: CC, FD
	L-3-C: FD
	L-4-A: CC, FD
	L-4-B: CC, FD

## GRAIN SIZE ANALYSIS

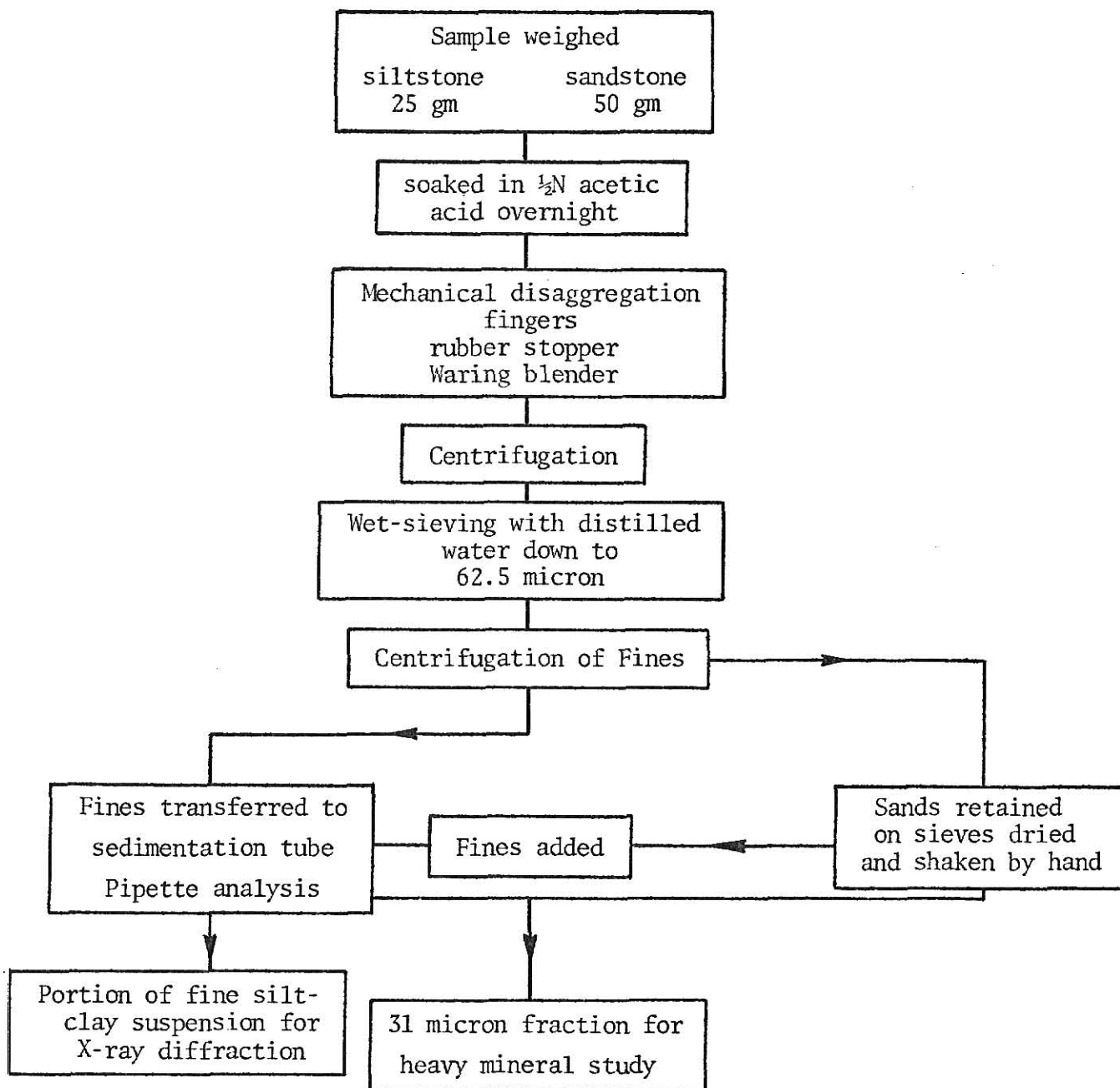
A single basic procedure was followed which integrated the studies of grain-size distribution, heavy mineralogy, and clay mineralogy of samples collected from the sheet and channel sandstone deposits. The flow sheet for the general petrologic technique is shown in Figure 6 and discussed below. Grain-size analyses were made by sieving down to 62.5 microns (lower limit of very fine sand). Smaller size grades were determined by pipette methods.

Depending upon whether an individual sample was fundamentally a siltstone or sandstone, either 25 or 50 grams (air-dried) were split from the stock sample. Weighing was carried out on a torsion balance to 0.01 gram. Because of the 'binder' effect of clays and iron oxides it was necessary to employ a weak acid treatment. Each sample was soaked overnight in 150 milliliters of  $\frac{1}{2}$ N acetic acid. Most samples evolved a small amount of gas during this treatment, indicating a slightly calcareous nature. While the effect of acid on the true grain-size distribution of the samples was not determined, the treatment was a constant in the procedure.

Samples were transferred to a large porcelain dish and disaggregated with a rubber stopper and fingers, followed by a five minute agitation in an electric blender. A check with a binocular microscope was made for aggregates, and hematite and pyrite concretions; if the sum of these appeared to exceed 4 percent of the sample, the sample was discarded and another split taken from the stock sample. By this means it was hoped that the degree or rigor of the disaggregation process would be held fairly constant. Of the rocks sampled, eight were found troublesome in this respect. If aggregates were not a problem the sample was repeatedly washed with distilled water and centrifuged to remove acid and solubles, preparatory to sieving and pipette analysis.

Fig. 6

## Flow Sheet for Petrologic Technique



### Sieving Procedure

Optimum sample size for sieving depends in large part upon the grain-size distribution of the sample and the number of class intervals to be employed. I determined that some Cat Creek sandstones would yield only about 10 percent fines, being dominantly composed of sand-size grades. On the other hand, very fine sandstones and sandy siltstones commonly would yield 80 percent fines and correspondingly only 20 percent sand grades. The problem was that the various lithologies required different amounts of initial sample for best results in sieving and pipette analyses.

In this study smaller samples were used (25 or 50 grams) which would contain the 'best' amount of clays and silts for pipette analysis, size-fractionating the sand grades on 3-inch diameter sieves.

Washed, dispersed sample was immediately wet-sieved after the technique discussed in Krumbein and Pettijohn (1938). U.S. Standard mesh, 3-inch sieves, spaced at  $\frac{1}{2}\phi$  (phi) were used. The loaded sieves were held over a large pan while a soft spray of distilled water was directed into the top sieve. Rotary motion was supplied by hand and the procedure continued until only clear water was recovered, usually after about 20 minutes.

Sand grades retained on each sieve were dried with acetone and the whole series resieved by hand until further effort brought negligible return. The pan fraction thus gained was added to the suspension of silts and clays which previously had passed the 62.5 micron sieve and the total set aside, to be used in the pipette analysis of the sample.

The above sand grades were carefully removed from the sieves, dried a second time on top of an oven, and weighed to 0.01 gram. Each size fraction was checked for percent aggregates through a binocular microscope and that

figure noted with the raw weight. Practically, aggregates were limited to the coarser grades or classes, and in no case constituted over 25 percent of the weight in any class.

### Pipette Procedure

In this study, grain-size analysis by pipette method was based on Stokes law. The technique employed for withdrawing aliquots at appropriate times and depths is discussed in Krumbein and Pettijohn (1938).

The suspension of silts and clays retained from the sieving operation typically filled a gallon jar, or more. Both to reduce the volume and remove any remaining acid, the suspension was centrifuged and the fines transferred to a sedimentation cylinder for pipette analysis. Enough distilled water was added to bring the volume to 1 liter, and, 0.6 gram of sodium oxalate (dispersing agent) was added. The suspension was agitated (homogenized) by repeatedly inverting the cylinder, which was then allowed to stand overnight. No flocculation was observed in any sample having undergone the above treatment over the time span necessary to complete the analysis.

Aliquots of 20 milliliters were taken at  $\frac{1}{2} \phi$  (phi) intervals from  $4\phi$  to  $6\phi$  and whole  $\phi$  intervals from  $6\phi$  to  $10\phi$ , which were carefully washed into 50 milliliter beakers. The beakers with aliquots were placed in an oven at 100 degrees C for 24 hours, and were then allowed to cool at room temperature and humidity for a similar period. All weighing during pipette analysis was done on a torsion balance to 0.01 gram. Weight of dispersant (0.01 gram/20 ml suspension) was subtracted from each aliquot during tabulation.

Remaining suspension in the cylinder was fractionated by decantation into coarse silt, which was dried and saved with the sand grades for use in heavy mineral analyses, and, medium silt to clay grade, which was kept in suspension for clay mineral analysis.

## Computation

Table 3 illustrates the method of computing analyses. The sample is of the "coarse-clean" facies of the channel deposit.

Table 3

SAMPLE L-3-A: CC

<u>Class Interval</u>	<u>Raw Weight</u>	<u>% Aggregates</u>	<u>Corrected Weight</u>	<u>Cumulative Weight</u>	<u>Cumulative %</u>
1 $\phi$	0.15	5	0.14	0.14	0.3
1½	0.46	10	0.41	0.55	1.2
2 $\phi$	0.13	10	0.12	0.67	1.5
2½	8.57	5	8.14	8.81	19.2
3 $\phi$	0.72	5	0.68	9.49	20.7
3½	4.73	-	4.73	14.22	31.1
4 $\phi$	20.05	-	20.05	34.27	74.9
PAN			11.50	45.77	100.0

	<u>Weight of Aliquot</u>	<u>Less Dispersant</u>	<u>Corrected Weight</u>	<u>X50</u>	<u>Cumulative %</u>
4 $\phi$	0.24	0.01	0.23	11.50	74.9
4½	0.08	0.01	0.07	3.50	92.4
5 $\phi$	0.05	0.01	0.04	2.00	95.6
5½	0.04	0.01	0.03	1.50	96.7
6 $\phi$	0.04	0.01	0.03	1.50	96.7
7 $\phi$	0.04	0.01	0.03	1.50	96.7
8 $\phi$	0.03	0.01	0.02	1.00	97.8
9 $\phi$	0.02	0.01	0.01	0.50	98.9
10 $\phi$	0.01	0.01	0.00	0.00	100.0

Weights of each class interval were cumulated, from which cumulative percentages were derived. These, in turn, are plotted against  $\phi$  (phi) diameter on arithmetic probability paper. Properties of the frequency distributions were determined graphically from the cumulative curves, read to the nearest 0.01 $\phi$ . Cumulative frequency curves of representative samples may be found in Appendix I. The statistical parameters of Folk and Ward (1957) were used in this study.

They are:

$$\text{Graphic Mean} = \frac{\phi_{16} + \phi_{50} + \phi_{84}}{3}$$

$$\text{Inclusive Graphic Standard Deviation} = \frac{\phi_{84} - \phi_{16}}{4} + \frac{\phi_{95} - \phi_5}{6.6}$$

$$\text{Inclusive Graphic Skewness} = \frac{\phi_{16} + \phi_{84} - 2\phi_{50}}{2(\phi_{84} - \phi_{16})} + \frac{\phi_5 + \phi_{95} - 2\phi_{50}}{2(\phi_{95} - \phi_5)}$$

$$\text{Graphic Kurtosis} = \frac{\phi_{95} - \phi_5}{2.44(\phi_{75} - \phi_{25})}$$

### Results

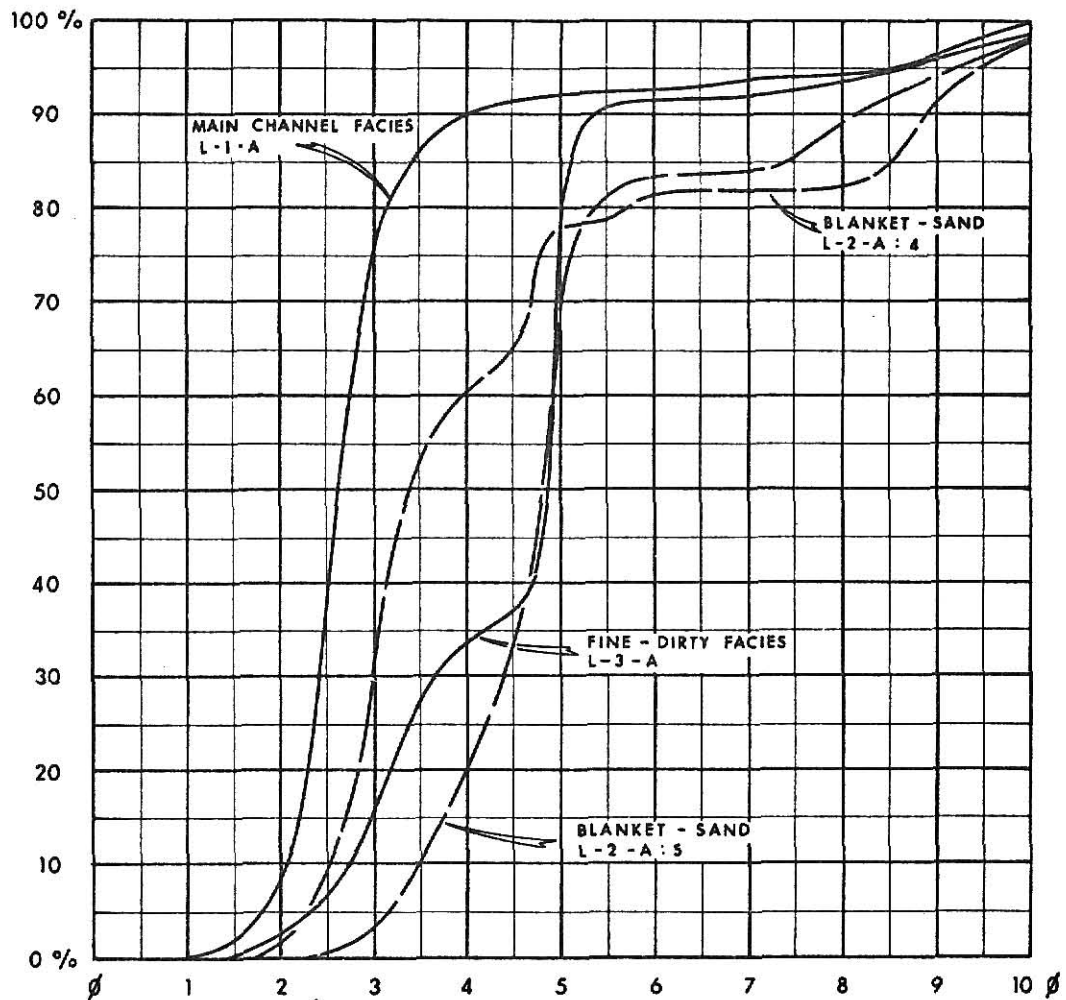
Table 4 gives the effective ranges of statistical parameters, obtained as above, from representative blanket and channel sandstone samples. Texturally the sandstones are slightly clayey, silty, and poorly sorted. Plots of cumulative weight percentage against  $\phi$  diameter, on arithmetic paper (S-shaped curves), are shown superimposed in Figure 7, along with a verbal designation of each sample.

Table 4

<u>Body</u>	<u>Sample</u>	<u>Mean</u>	<u>Standard Deviation</u>	<u>Skewness</u>	<u>Kurtosis</u>
Blanket	L-2-A: 4	4.65 $\phi$	$\pm 2.45 \phi$	+ 0.69	1.51
	L-2-A: 5	5.21 $\phi$	$\pm 1.71 \phi$	+ 0.46	2.44
Channel	L-3-A: FD	4.32 $\phi$	$\pm 1.46 \phi$	- 0.20	1.69
	L-1-A: MC	2.75 $\phi$	$\pm 1.29 \phi$	+ 0.47	4.12



**CUMULATIVE CURVES (ARITHMETIC ORDINATE)**  
**BLANKET and CHANNEL SAMPLES**



**VERBAL DESIGNATION**

**MAIN CHANNEL FACIES:** Slightly muddy fine sandstone, poorly sorted, strongly fine-skewed, extremely leptokurtic.

**FINE-DIRTY FACIES:** Sandy coarse siltstone, poorly sorted, coarse-skewed, very leptokurtic.

**BLANKET-SAND 4:** Sandy coarse siltstone, very poorly sorted, strongly fine-skewed, very leptokurtic.

**BLANKET-SAND 5:** Sandy coarse siltstone, poorly sorted, strongly fine-skewed, very leptokurtic.

Fig. 7

## CLAY MINERALOGY

Six samples considered representative of the blanket and channel sandstone deposits were studied in detail for clay mineral content; remaining samples were checked for variation. Clay mineral groups were defined by their basal spacings obtained by X-ray diffraction of air-dried, oriented mounts. Such groups are to be distinguished from specific clay mineral species. Problems are inherent, and in some cases beyond the scope of this study, in determining the precise nature of the clay components. However, it was comparatively simple to document that, in addition to kaolinite and a chlorite-group mineral (observed in thin sections and heavy mineral mounts), illite and illite-mixed-layer or interstratified clay groups are present in the samples from both deposits. Flow sheet for diffraction of clay mounts is illustrated in Figure 8.

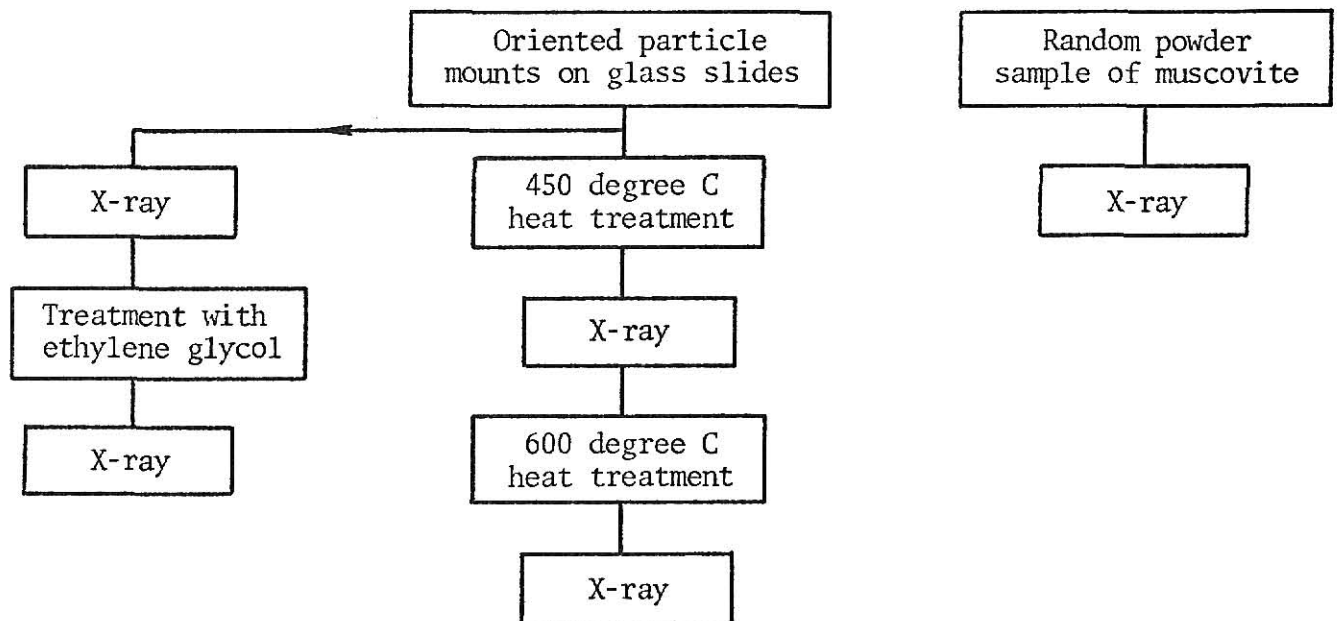
### Procedure

Sample treatment leading to the preparation of clay mounts to be used in X-ray diffraction analysis was covered in the section dealing with grain-size analysis. The suspension of medium silt to clay grade sediment was transferred to a smaller cylinder for further size fractionation. Fifty to 100 milliliter aliquots of 10, 2, and 0.5 micron grades were taken at times and depths determined by Stokes law. In the case of some sandstones there was insufficient 0.5 micron sediment to make a clay mount. The aliquots were placed on top of an oven and allowed to evaporate to increase the density of the suspension, which was then mounted on glass slides with an eyedropper. Clay suspension was added until the film just obliterated a wax pencil mark on the slide. Mounts were carefully air-dried.

Samples were scanned using Ni-filtered  $\text{Cu-K}_{\alpha}$  radiation on a Phillips-Norelco X-ray Diffractometer. In addition to an untreated run, three treatments were employed: Glycolation, heating to 450 degrees C, and heating to 600 degrees C. Figure 8 contains the flow sheet for X-ray diffraction analysis.

Fig. 8

## Flow Sheet For X-ray Diffraction Of Clay Mounts



Quantative determination of individual clay mineral groups would be an important aspect of a study such as this. Unfortunately, a standard technique has yet to be worked out as an accurate tool for this purpose. Height and definition of X-ray diffraction peaks for a particular mineral are a function of several factors, including grain size and degree of crystallinity of the particles, as well as structural and chemical variations between mineral groups and even within species (Pierce and Siegel, 1969). I feel that the number of uncontrolled variables which are thought to influence diffraction

data precludes any attempt at quantification in this study.

### Clay Mineral Identification

Chlorite, illite-mixed-layer or interstratified clay, illite, and kaolinite clay mineral groups are present in samples from both sandstone deposits. Table 5 summarizes data taken from three representative samples.

Table 5

<u>Sample</u>	<u>10 micron</u>	<u>2 micron</u>	<u>0.5 micron</u>
L-3-A: CC <sup>1</sup>	kaolinite illite mixed-layer	more kaolinite illite more mixed-layer	less kaolinite more illite much more mixed-layer chlorite (?)
L-3-A: FD <sup>2</sup>	kaolinite illite chlorite mixed-layer	illite kaolinite more chlorite mixed-layer	kaolinite illite mixed-layer chlorite (?)
L-2-A: 4 <sup>3</sup>	kaolinite illite mixed-layer chlorite	kaolinite illite mixed-layer chlorite	kaolinite illite mixed-layer chlorite

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1 "Coarse-clean" facies of channel sandstone deposit.

2 "Fine-dirty" facies of channel sandstone deposit.

3 Sample of blanket sandstone deposit.

Chlorite was distinguished from montmorillonite or vermiculite that might have been present by heat-treating the mount to 450 degrees C;

such treatment would remove absorbed water from basal planes of a swelling 14A clay and change the (001) spacing to roughly 10A. Likewise, glycolation did not expand the presumed chlorite (001) spacing, lending support to the above evidence.

The difficult distinction to be made is between chlorite and kaolinite. In most samples the (001) and (003) spacings of chlorite are subdued and ill-defined, while (002) and (004) spacings practically coincide with (001) and (002) respectively of kaolinite. Often, however, the (002) spacing of kaolinite showed two distinct peaks (doublet), or a deflection on the high angle side, caused by (004) chlorite.

The weak intensity of first and third order reflections suggests an ironchlorite species. Special treatment with warm 10 percent HCl for 24 hours did not remove the characteristic chlorite peaks, however. Possibly the weak "odd-order" reflections are due to a disorganized or poorly crystallized nature of the chlorite component. Longer or repeated sediment transport, resulting in decrease in chlorite grain size, may account for the weak intensities. Ten micron mounts prepared from the same samples do suggest that the degree of crystallization improves with increasing grain size of chlorite. Likewise, while heat treatment to 450 degrees C produced a decrease in intensity of (001) chlorite in the 0.5 micron mounts, that effect was lessened in the 2 micron mounts and was not noticeable in the 10 micron mounts.

I believe that most of the chlorite in the samples is terrigenous, showing better crystal organization with increasing grain size. This does not exclude the possibility of a mixed-layer chlorite-like clay mineral formed as a product of post-depositional authigenic or diagenetic action.

Illite and illite-mixed-layer or interstratified clay groups are present in all samples. Illite is identified by its well developed (001), (002), and (003) spacings that were insensitive to glycolation and heat treatment to 450 degrees C. This clay component exhibits a degraded,  $K^+$ -depleted, structure with a small amount of interlayer water, as indicated by the asymmetry of the peaks. The 10A peak tails off to the low angle side while the 3.33A peak tails off to the high angle side. Furthermore, the position of the first order spacing is slightly variable about the 10A location from sample to sample. Glycolation "collapsed" the asymmetric flank of illite (001), sharpening the reflection. The structure proved to be non-expanding. Rather, I believe this behavior indicates that glycol molecules improve the order (interlayer dimension) of the degraded illite structure.

Illites are potassic and are characterized by being nonexpandable, whereas montmorillonites may contain  $Na^+$ ,  $Ca^{++}$  and/or  $Mg^+$  in the interlayer position and are expandable. Hower (1967) showed that an approximately linear relationship exists between 1) nonexchangeable  $K^+$  and  $Na^+$ , and 2) the percentage of nonexpandable layers in illite-montmorillonite clays. Glycolation of 0.5 micron mounts usually brought about an expansion and localizing of illite-montmorillonite (001) diffraction band to about 13.5A to near 15A. Heating to 450 degrees C collapsed the latter band apparently to about 10A, sometimes leaving a residual chlorite-group (001) reflection. Chlorite, however, was not common in 0.5 micron mounts.

Illite-nonexpanding mixed-layer clay was unaffected by the above treatments, showing that this clay component is distinct from both "normal" degraded illite and illite-montmorillonite in the samples. The possibility of the illite-nonexpanding component being an illite-chlorite mixed-layer clay exists, but is not documented in this study.

Kaolinite was present in all samples. Identification was based upon a strong (001) reflection at about 7.2A which was unaffected by glycolation but was weakened by heat-treatment to 450 degrees C and destroyed at 600 degrees. This is not definitive, as chlorites may behave in the same manner. As mentioned previously, however, the occurrence of the doublet peak of kaolinite (002) and chlorite (004) around 3.55A, coupled with observations during thin section analysis, clearly point to the presence of both clay mineral groups.

The kaolinite of coarse-grained sandstone lithologies is well crystallized, yielding sharp, intense, peaks. Samples of siltstones and mudstones, on the other hand, yield kaolinite basal spacings in slightly varying position and with greatly reduced intensity and definition.

#### Results and Interpretation

The study of the clay suites of the sheet and channel sandstone deposits was inconclusive regarding both a differentiation of, or between, the deposits, and in inference about the respective environments of deposition. The same clay mineral groups are present in both deposits, with possible variation in relative abundances. The character of the suites from similar lithologies in both deposits was nearly identical and it is suggested that post-depositional diagenetic alteration and authigenic development may have played an important role in determining the present state of some clay mineral species observed in the samples.

## GEOCHRONOLOGIC INVESTIGATION OF MUSCOVITE

In an attempt to study and date the provenance area of the terrigenous sediment of the sheet and channel sandstone bodies  $^{40}\text{K}$ - $^{40}\text{Ar}$  and  $^{87}\text{Rb}$ - $^{87}\text{Sr}$  were carried out on the muscovite component of two samples: one from the upper sandy phase of the Willard Shale and one from the coarse-clean facies of the channel sandstone. Muscovite has a high retentivity for both radiogenic  $^{40}\text{Ar}$  and  $^{87}\text{Sr}$  which allows for its use as an indicator of provenance age (Armstrong, in Schaeffer and Zahringer, 1966). Muscovite has always yielded equal or lower K-Ar dates relative to the Rb-Sr dates except where the initial  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio is uncertain (D.G. Brookins, personal communication, 1968).

## Procedure

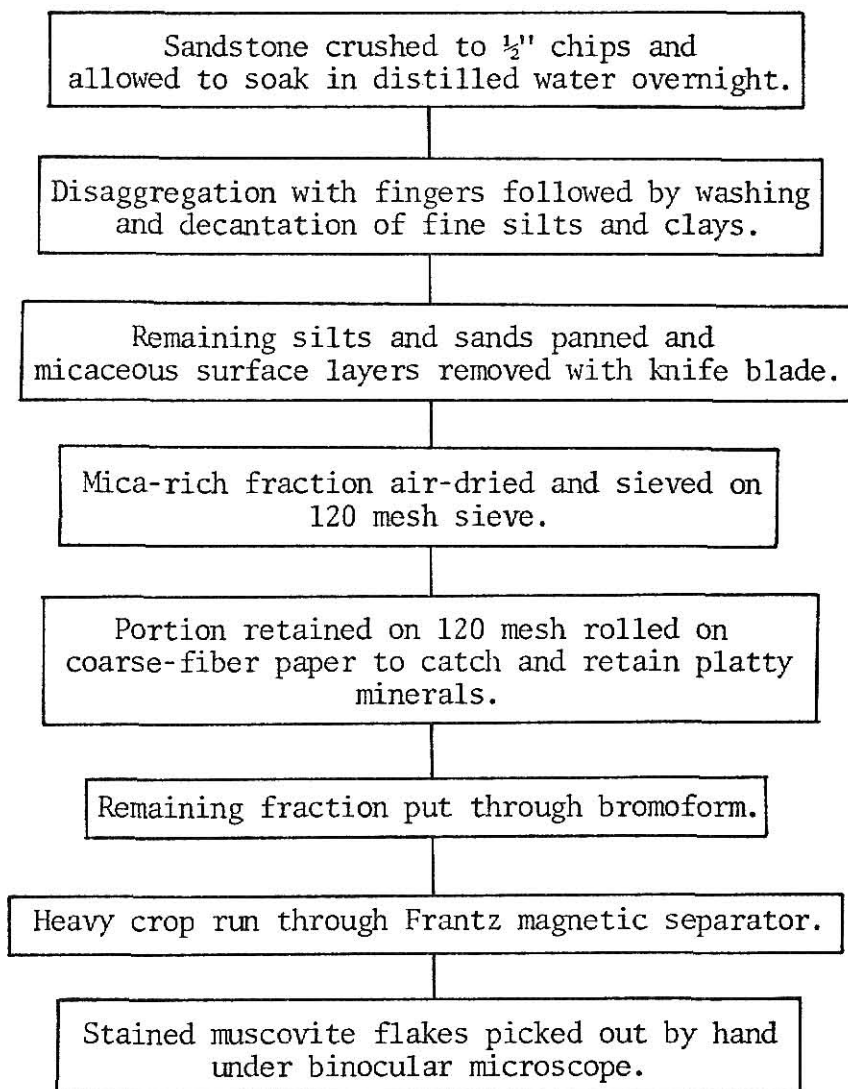
The procedure for muscovite separation is outlined in the flow sheet (see Fig. 9). Original sandstone lithologies contained about 2 percent muscovite. Final mineral concentrates used for age work were at least 99.5 percent pure. X-ray diffraction analysis of a powder sample of muscovite showed only the  $2\text{M}_1$  polymorph. This mica-type is believed to form at much higher temperatures than could ever have occurred in the sandstone deposits, which were never deeply buried.

Analysts for the K-Ar age determinations were H. Kreuger, Geochron Laboratories, Cambridge, Mass., and R.E. Dennison, Mobil Research and Development Corp., Dallas, Texas. Rb-Sr age determinations were performed by Dr. D.G. Brookins at Kansas State University.



Fig. 9

## Flow Sheet For Muscovite Separation



Potassium was determined by flame photometry and argon and radiogenic potassium by isotope dilution. Total strontium and rubidium were determined by isotope dilution using  $^{86}\text{Sr}$ -enriched and  $^{87}\text{Rb}$ -enriched spikes; strontium isotopic composition was determined on a separate, unspiked, sample. Tables 6 and 7 contain the data and results of the four analyses made.

Sample L-2-A: 4 is from the sheet-sand body, and sample L-3-A: CC is from the channel deposit.

Table 6

Potassium-Argon Age Data<sup>1</sup>

<u>Body</u>	<u>Sample</u>	<u>K (%)</u>	<u>K<sup>40</sup> (ppm)</u>	<u>*Ar<sup>40</sup> (ppm)</u>	<u>*Ar<sup>40</sup>/total Ar</u>	<u>Age (m.y.)</u>
Blanket	L-2-A: 4	8.087	9.87	0.225	0.985	389 ± 8
Channel	L-3-A: CC	8.060	9.83	0.240	0.975	377 ± 11

1 All determinations done in duplicate. The constants used are:

$\lambda_{\text{Ke.c.}}^{40} = 0.585 \times 10^{-10}/\text{y}$ ,  $\lambda_{\text{Kbeta}}^{40} = 4.72 \times 10^{-10}/\text{y}$ ,

$\text{K}^{40}/\text{Sum Total K} = 1.22 \times 10^{-4} \text{ g/g}$ .

Table 7

Rubidium-Strontium Age Data<sup>1</sup>

<u>Body</u>	<u>Sample</u>	<u>Rb (ppm)</u>	<u>Sr (ppm)</u>	<u>Sr (87/86)</u>	<u>Age (m.y.)</u>
Blanket	L-2-A: 4	364.0	50.33	0.8266	401 ± 20
Channel	L-3-A: CC	456.0	5635	0.8277	368 ± 20

1 Initial Sr (87/86) = 0.706 assumed;  $\lambda_{\text{Rb}}^{87} = 1.39 \times 10^{-11} \text{ y}^{-1}$  used for age calculations.

## Results and Interpretation

Within the stated limits of analytical error there is no difference in age between the muscovite component from the sheet and channel-sand deposits (Brookins and Voss, 1970). In view of stratigraphic relationships and major

lithologic similarities of the deposits the close agreement in the two ages is hardly surprising.

The strontium contents of these muscovites are significantly higher than that of common primary igneous muscovites. A metamorphic muscovite, on the other hand, has a high strontium content. It is therefore suggested that the muscovites in these sandstones are probably metamorphic in origin. A detailed discussion on the age and origin of these muscovite has been reported by Brookins and Voss (1970).

## THIN SECTION PETROGRAPHY

### Procedure

Thin sections were prepared of eight field samples selected to cover the range of lithologies observed. At the time of collection samples were marked with their proper orientation in the field; thus oriented thin sections were obtained, cut normal to the bedding planes. Except for two mudstones all samples were friable and required impregnation.

Lithologies under study were predominantly terrigenous in origin and are described by the five-fold petrographic naming system of Folk (1968). Five properties deemed fundamental to describing the lithology are 1) Detrital grain size, 2) Chemical cement (s), 3) Textural maturity, 4) Miscellaneous transported constituents, and 5) Clan designation.

The first fundamental property was determined by mechanical grain size analyses run on all samples (of which eight had been selected for thin section study). To determine the second, third, and fourth properties of the naming system each thin section was carefully scanned; depending upon the framework grain size, 10 to 15 while fields of view were studied and described. In addition, at this time certain genetic quartz varieties were identified, and terrigenous framework components defined (necessary steps prior to attacking the last fundamental property).

Folk's concept of Rock Clan is based on composition of the source area, of provenance. If one assumes a classification system based on paleogeology of the source terrane (mineralogy) the question of which mineral species and varieties, and rock fragments will be allotted to igneous, metamorphic, and sedimentary source is paramount.

To determine the last property (Clan designation) the point-counter method of Chayes (1954) was used in performing modal analyses. 1400 points were counted on traverses made perpendicular to the bedding of the coarsest textured sample from both the blanket and channel sandstone deposits. One hundred points were counted in similar fashion on the remaining thin sections. A given terrigenous framework component fell into one of several categories discussed below and shown in Table 8.

Table 8

Unstrained monocrystalline quartz.....	Q <sub>1</sub>
Strained monocrystalline quartz.....	Q <sub>2</sub>
Polycrystalline quartz.....	Q <sub>3</sub>
Microcrystalline quartz.....	Q <sub>4</sub>
Orthoclase feldspar.....	F <sub>1</sub>
Microcline feldspar.....	F <sub>2</sub>
Perthite feldspar.....	F <sub>3</sub>
Plagioclase feldspar.....	F <sub>4</sub>
Shale-slate-phyllite.....	RF <sub>1</sub>
Coarse mica.....	RF <sub>2</sub>
Miscellaneous.....	M

The terrigenous mineralogy of the sheet and channel samples is essentially the same, with some variation in relative proportions. Results of the analyses are shown in Table 9 and are detailed in Appendix III. Mudstones are not shown. Five-fold rock names of the samples are shown in Table 10.

Table 9

Sample	Framework Components In Percent									
	Q <sub>1</sub>	Q <sub>2</sub>	Q <sub>3</sub>	Q <sub>4</sub>	F <sub>1</sub>	F <sub>2</sub>	F <sub>3</sub>	F <sub>4</sub>	R <sub>1</sub>	R <sub>2</sub>
	Q-pole				F-pole				R-pole	
L-1-A: MC *			73%				12%			15%
L-3-A: CC			77%				8%			15%
L-3-A: FD			84%				6%			10%
L-2-A: 5			85%				4%			11%
L-2-A: 4 *			77%				9%			14%
L-2-A: 3			79%				8%			13%

\* Based on 1400 point count

Table 10

<u>Sample</u>	<u>Five-fold Rock Name</u>
L-1-A: MC	fine sandstone: slightly limonitic, immature, micaceous, feldspathic, litharenite
L-3-A: CC	very fine sandstone: slightly limonitic, immature, micaceous, sublitharenite
L-3-A: FD	siltstone: immature, micaceous, sublitharenite
L-2-A: 5	siltstone: slightly limonitic, immature, micaceous, sublitharenite
L-2-A: 4	fine sandstone: slightly limonitic, immature, micaceous, sublitharenite
L-2-A: 3	very fine sandstone: slightly limonitic, immature, micaceous, sublitharenite.

## Mineralogy

Quartz.-- Quartz is the major constituent of all samples, averaging 79 percent and ranging from 71 to 85 percent, of framework components. The following quartz varieties after the genetic classification of Folk (1968, modified from Krynine) were observed: 1) Common (plutonic), 2) Vein (hydrothermal), 3) Recrystallized (metamorphic), 4) Stretched (metamorphic), 5) Recycled (sedimentary), and 6) Microcrystalline (cherty). These genetic quartz varieties are defined and illustrated on the following pages.

It is difficult to maintain and use the genetic classification of quartz varieties, important though it is in reconstructing the heritage of a sandstone. Folk points out that quartz varieties are more diagnostic of formative conditions than of specific lithologic type of source rock. Further, there is an inherent subjectivity in the above classification which is impossible to evaluate from worker to worker. Folk (1968) recommends an empirical binomial classification for purposes of point-counting. Six extinction types and an appropriate number of classes of inclusions are used to pigeonhole a given quartz grain. The empirical classification is more objective and amendable to comparison of samples.

Blatt and Christie (1963) review quartz classification schemes of several workers, e.g. Folk. I am impressed with their argument that it is not valid to subdivide strained quartz, having evaluated the extinction habit on a flat stage. Their work also suggests that the amount of polycrystalline quartz is a direct function of grain size, and decreases with decrease in grain size.

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## Explanation of Plate I

"Common (plutonic)" quartz grain center, consists of single crystal unit displaying straight or slightly undulose extinction habit (less than 5 degrees rotation on a flat stage). The variety commonly contains liquid-filled vacuoles, and more rarely rutile, tourmaline, and zircon, as inclusions.

Common quartz constitutes 50 percent, or more, of the total quartz in any sample, ranging in grain-size from 0.15 mm to clay grade detrital material; it is probably the only quartz variety below 0.03 mm in size. In this study, this variety is considered as Strained Unicrystalline quartz.

Note prevalent angularity of quartz with exception of broken round grain, upper left, derived from older sediments. Mica flake is deformed by the latter grain.

Fig. 1. Crossed nicols

Fig. 2. Plane polarized light

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## PLATE I

Fig. 1

0.10 MM

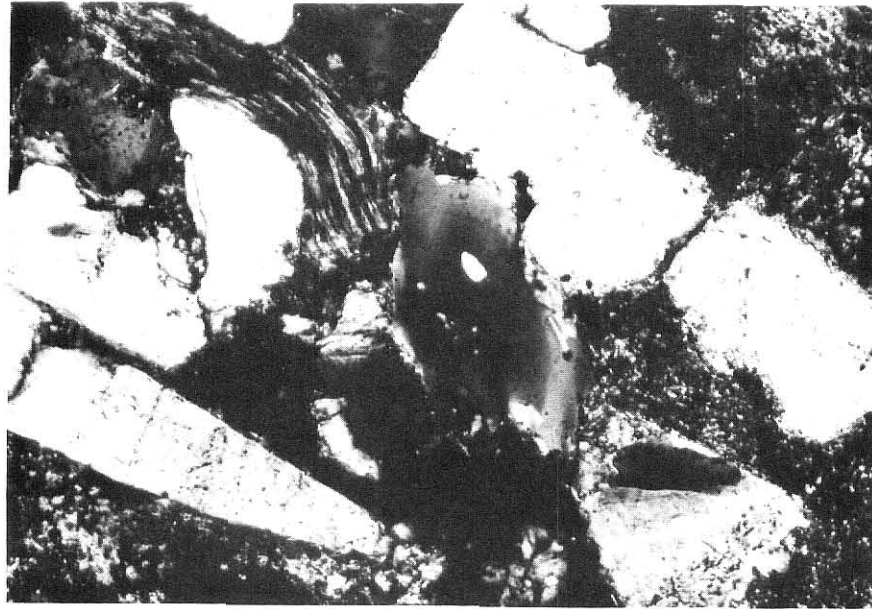
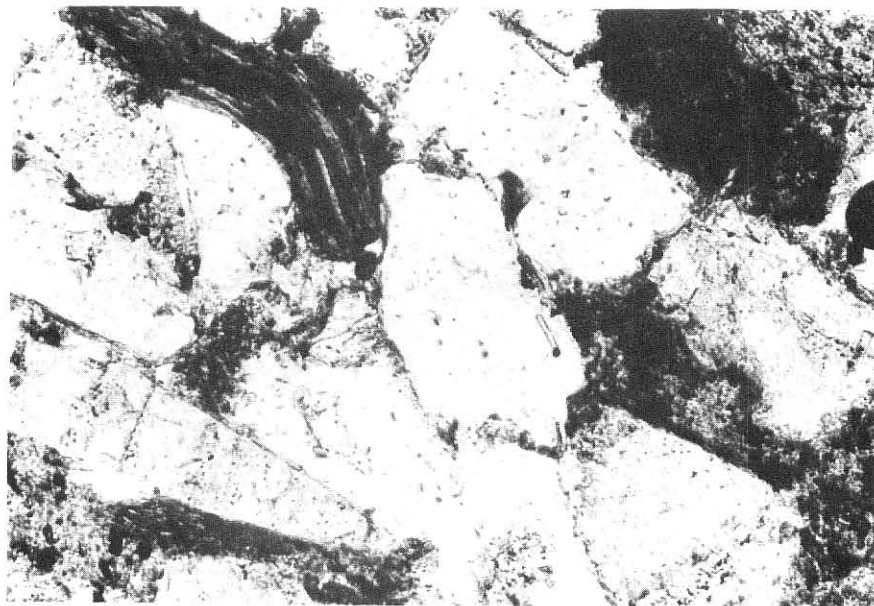


Fig. 2



## Explanation of Plate 11

"Vein (hydrothermal)" quartz, center, includes both single and composite grains displaying straight to slightly undulose extinction of individual crystallographic units. Inclusion-types are limited to abundant liquid-filled vacuoles (randomly distributed, and in well defined 'trains'), and vermicular (wormy) chlorite. Vein quartz constitutes on the average, less than 5 percent of total quartz, and was limited to sand-size grades. In the modal analyses, vein quartz was probably tabulated as Polycrystalline.

It is important to note that quartz grain boundaries, while appearing to be corroded and embayed, are made hazy and indistinct by a combination of clay-iron oxide films, and authigenic chlorite development, and the excessively thick nature of the thin section (causing many grains to overlap). An angular feldspar cleavage fragment is present on the left.

Fig. 1. Crossed nicols

Fig. 2. Plane polarized light

## PLATE II

Fig. 1

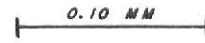
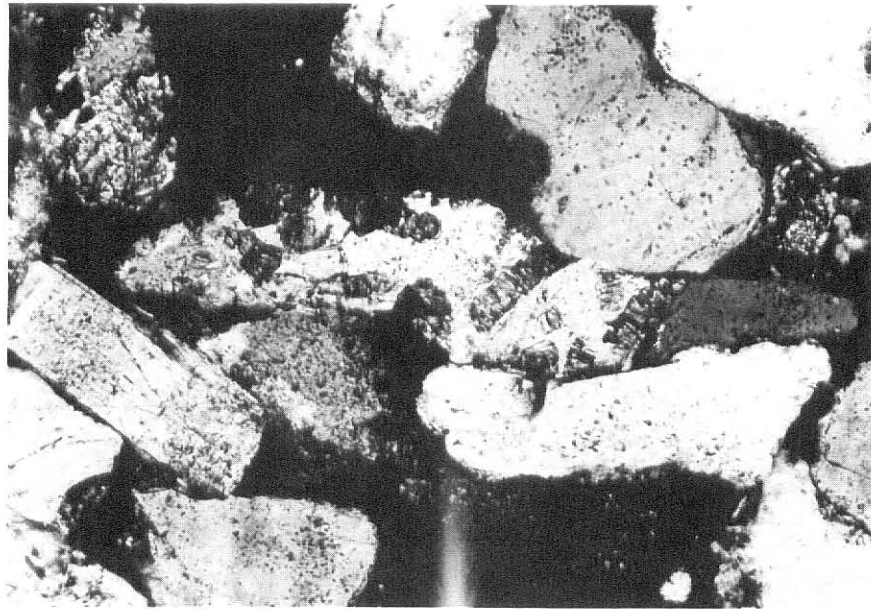
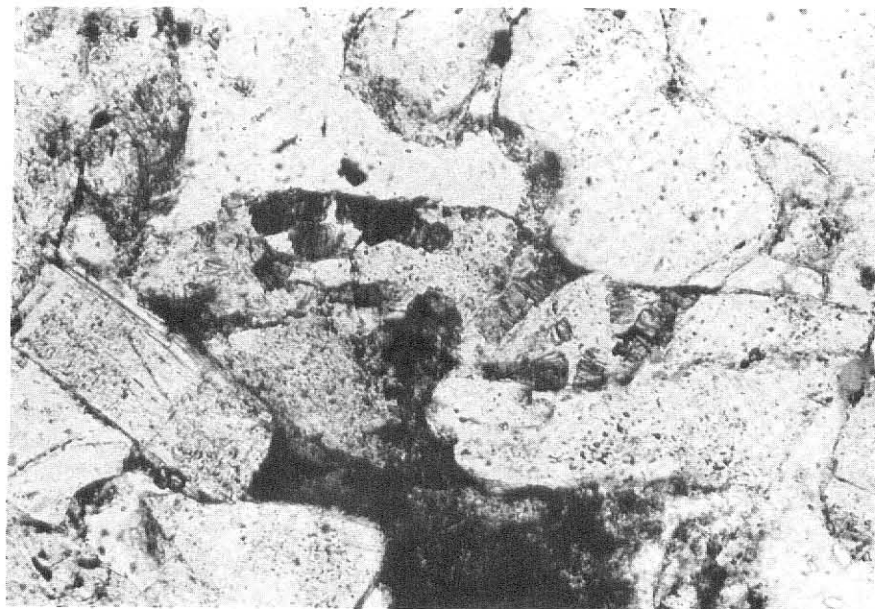
A horizontal scale bar with vertical end caps, labeled "0.10 MM".

Fig. 2



### Explanation of Plate III

"Recrystallized (metamorphic)" quartz, center, consists of composite grain displaying subunits of widely differing optic orientation, each of which possesses straight to slightly undulose extinction. Inclusions are rare and restricted to liquid-filled vacuoles. Recrystallized quartz (metaquartzite) constitutes less than 10 percent of any sample, and is limited to sand-size grades. This genetic quartz variety is defined as Polycrystalline.

Typically, framework quartz (coarser than 30 microns) contained abundant elongate, platy and sliver-shaped grains, as evidenced in this field of view.

Fig. 1. Crossed nicols

Fig. 2. Plane polarized light

## PLATE III

Fig. 1

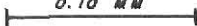
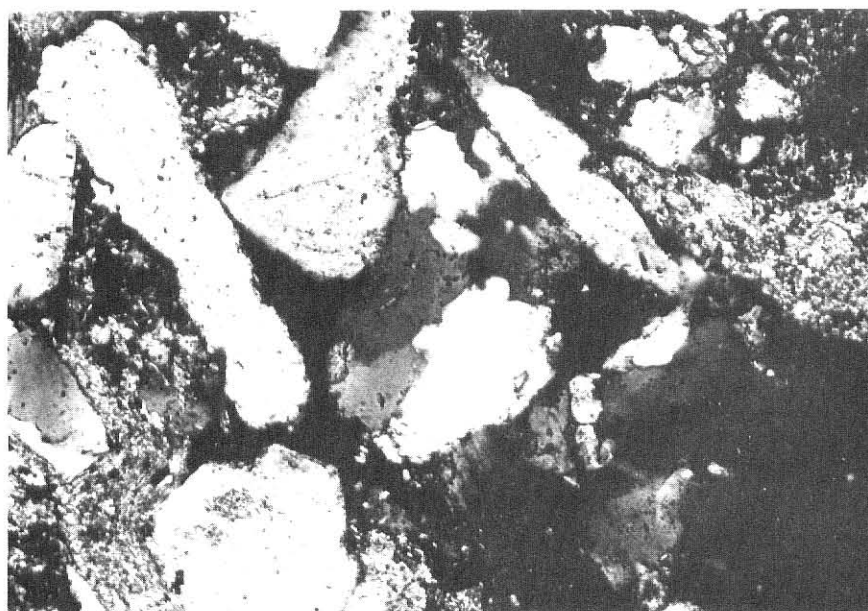
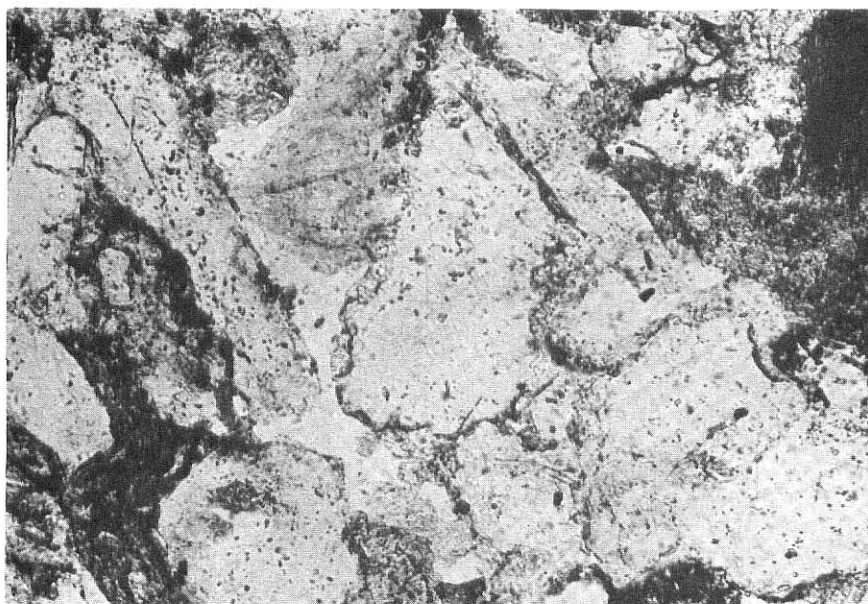
0.10 MM

Fig. 2



## Explanation of Plate IV

"Stretched (metamorphic)" quartz, center, consists of composite grain displaying subunits of similar optic orientation, each of which possesses slightly to strongly undulose (greater than 5 degrees rotation on a flat stage) extinction. Unlike recrystallized metaquartzite, which was subjected to lithostatic pressure, this variety has been subjected to shearing stress, hence the "smeared out" shape of the subunits. Inclusions are rare and restricted to liquid-filled vacuoles. Frequency of occurrence and size distribution are the same as that of recrystallized metaquartzite. As with the latter, stretched metamorphic quartz is considered as Polycrystalline in this study. A rock fragment (probably sedimentary) is seen just below the stretched metaquartzite.

Fig. 1. Crossed nicols

Fig. 2. Plane polarized light



## PLATE IV

Fig. 1

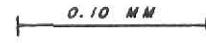
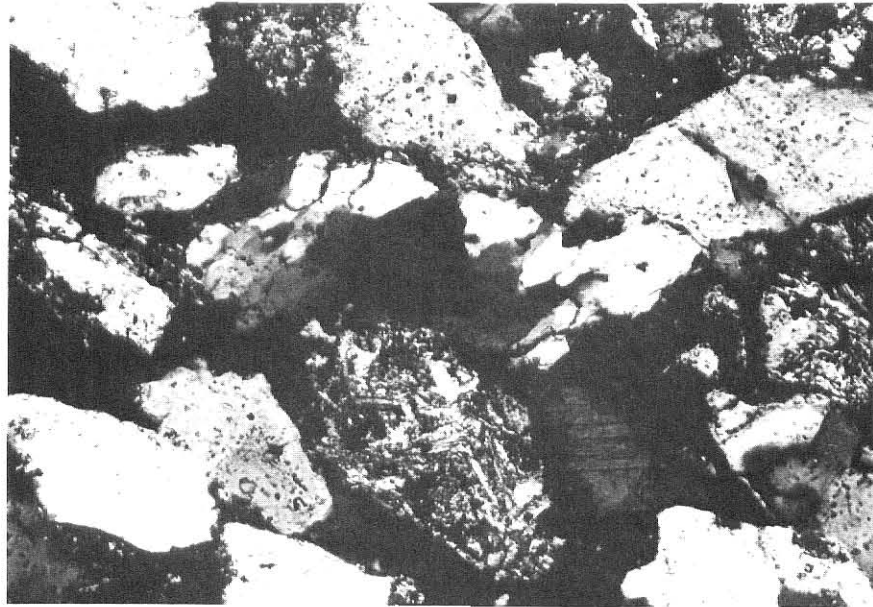
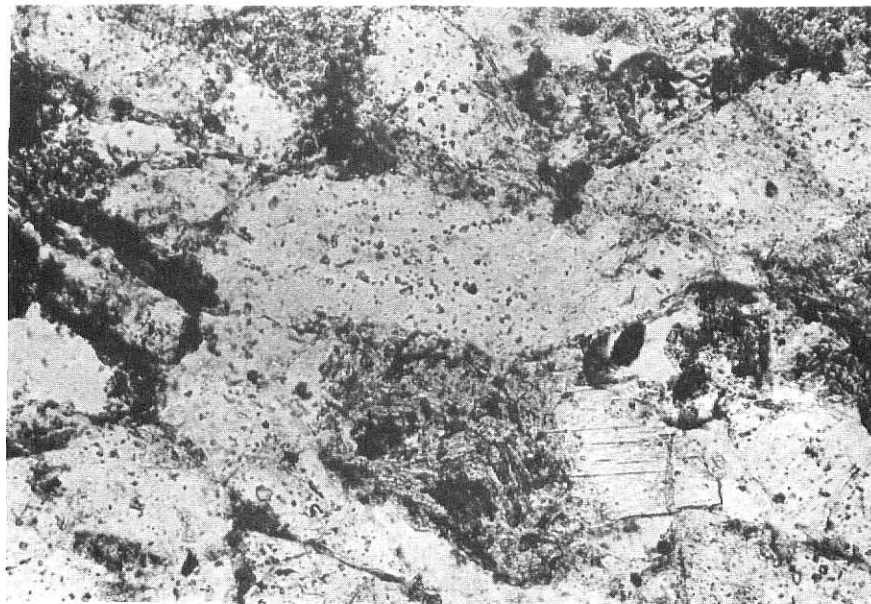
A horizontal scale bar with vertical end caps, labeled "0.10 MM".

Fig. 2



## Explanation of Plate V

"Recycled (sedimentary)" quartz grain, center, shows notably higher rounding value and sphericity than the bulk of framework quartz. Extinction habit can vary from straight to strongly undulose. Inclusion types are the same as for common (plutonic) quartz. Recycled quartz did not account for more than a few percent of total quartz in any sample and is restricted to sand-size grades. In most cases this variety of quartz was tabulated during the point-count as strained or unstrained uniaxial.

Chert grain lies next to and below the recycled quartz grain. A rock fragment composed for the most part of white mica (sericite) to the left. The grain could be a completely altered feldspar.

Fig. 1. Crossed nicols

Fig. 2. Plane polarized light

## PLATE V

Fig. 1

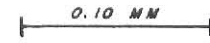
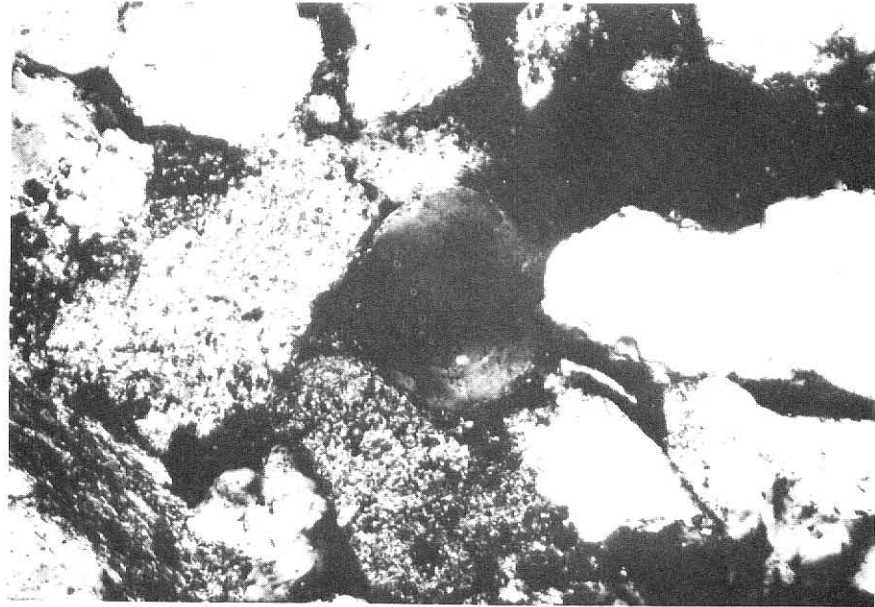
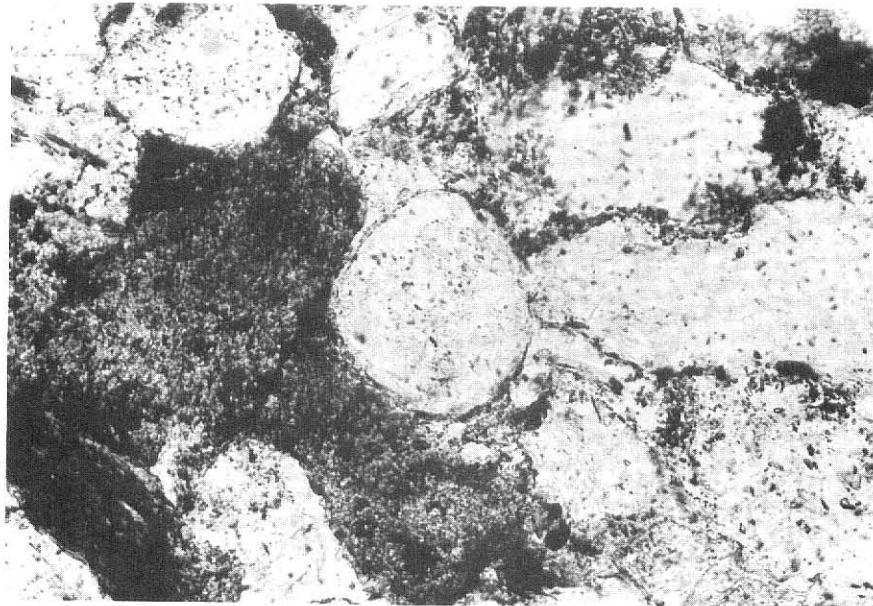
A horizontal scale bar with vertical end caps, labeled "0.10 MM".

Fig. 2



## Explanation of Plate VI

"Microcrystalline (cherty)" quartz, center, is an aggregate of individual crystal units, each from 5 to 20 microns, which give the grain a characteristic "pin point" extinction pattern. Clay minerals, fine mica, and carbonaceous material are usually present within the grain. Reasonably, one could call this quartz variety a sedimentary rock fragment. Its occurrence varies from a trace to about 5 percent, being practically limited to sand-size grades. Cherty quartz was so-called in the modal analyses of this study.

Field of view suggests the relatively loose packing of moderate to well sorted framework components, weakly held together by a volumetrically small amount of matrix.

Fig. 1. Crossed nicols

Fig. 2. Plane polarized light

## PLATE VI

Fig. 1

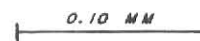
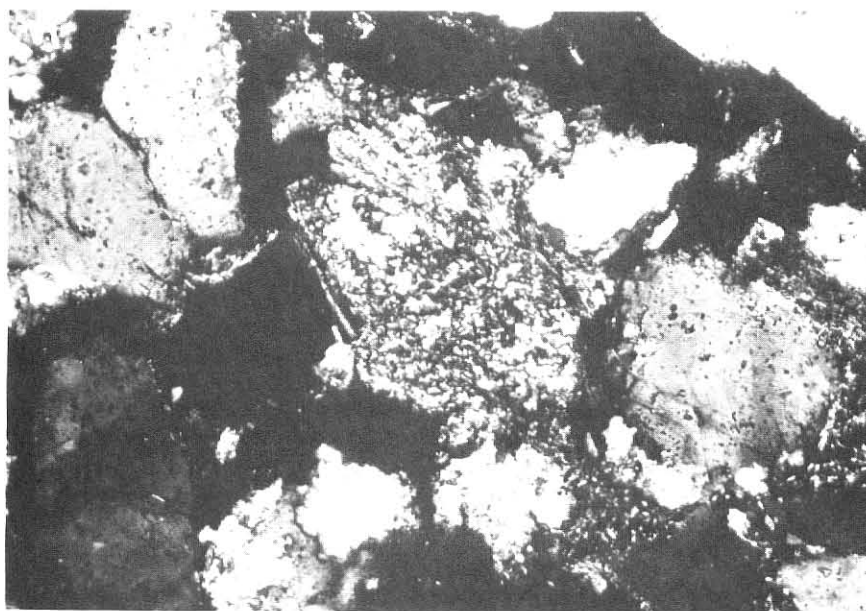
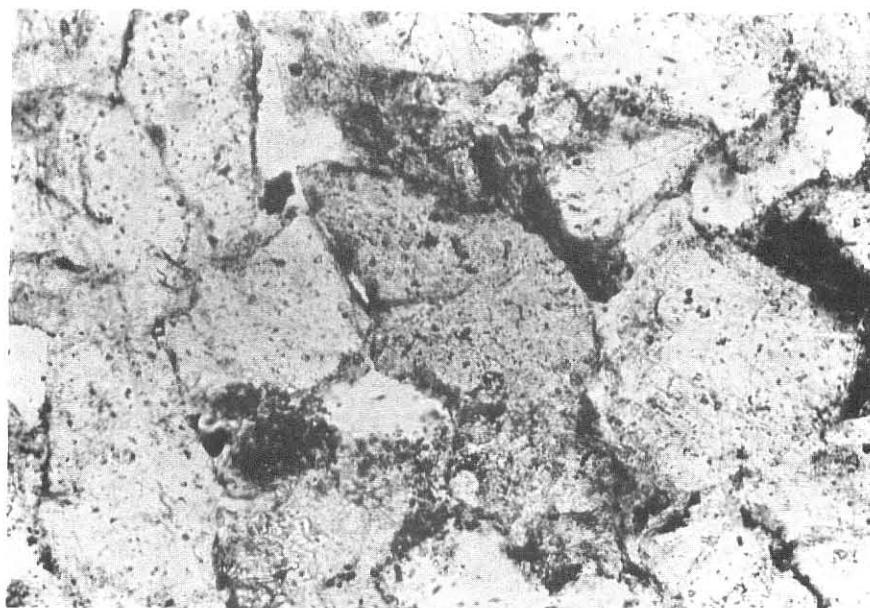
A horizontal scale bar with vertical end caps, labeled "0.10 MM".

Fig. 2



After scanning each thin section, prior to modal analysis, I determined that the sandstones of Cat Creek did not submit to meaningful subdivision of polycrystalline (Folk's composite and semicomposite) quartz grains. This is probably due to the very fine sand to coarse silt modes of most samples, with little terrigenous detrital component greater than 3ø (120 microns)\*. Further, it was decided that the presence or absence of strain in quartz would depend on whether more or less than two degrees of rotation (flat stage) was necessary for the deepest part of the extinction shadow to sweep the grain.

In this study, for purposes of point-counting, quartz was tabulated as either unstrained or strained unicrystalline, polycrystalline, or microcrystalline. Unstrained unicrystalline quartz is completely extinguished upon rotation of less than two degrees. Strained unicrystalline quartz requires rotation of greater than two degrees. Polycrystalline quartz is composed of two or more crystal units. Microcrystalline quartz is a complex aggregate of individual crystallographic subunits, each from 5 to 20 microns in size; commonly fine mica, clay and carbonaceous matter are contained within the grain.

The operator must make a decision as to what is microcrystalline (cherty) quartz and what is recrystallized metaquartzite, one of the polycrystalline quartz types. Otherwise there is no problem in quickly subdividing quartz into the above categories. These empirical quartz varieties do not speak of the provenance of the sands, as do the genetic varieties, but may be used to compare samples.

Examined under higher magnification, few quartz grains did not contain inclusions. By far the most common were spherically shaped, liquid-filled vacuoles. This inclusion-type appears both randomly scattered and localized

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\* 1000 microns equal one millimeter.

in streaks or trains; some grains have a great density of vacuoles that suggest milky or vein quartz. Another, less common, inclusion-type was accicular rutile which appeared as fine, hair-like crystallite, generally 10 to 20 microns in long dimension. Relatively uncommon inclusion-types were micas (muscovite and chlorite, the latter present in a vermicular habit), plate-like hematite crystallites, zircon, and tourmaline.

Feldspar.-- The feldspar family was represented in the sandstones under study by orthoclase, microcline, perthite, and plagioclase. The ratio of species present was roughly 2:1:1:2. Total feldspar constituted, on the average, eight percent, ranging from 6 to 11 percent. The amount of feldspar seemed to be largely a function of grain size, decreasing with decrease in grain size. The feldspar species are defined and illustrated on the following pages.

Orthoclase occurs as angular (cleaved fragments) to subrounded, equant grains. Cleavage is usually well expressed to perfect. Extinction is either parallel or off of parallel by six to eight degrees. Most grains are un-twinned, but a few Carlsbad twins occur. The same sample (thin section) displays great heterogeneity in weathering characteristics, from fresh to severely altered. Alteration products consist of liquid-filled vacuoles and white mica. Both vacuolization and sericitization may occur through hydrothermal action on a feldspathic plutonic source rock, however, the great range of weathering (alteration) observed does not enhance this hypothesis. On the other hand, there is little or no evidence of post-depositional alteration and intrastratal solution. This matter will be discussed again when the question of provenance is covered.

## Explanation of Plate VII

Orthoclase grain, center, is subangular, subequant cleavage fragment (perfect cleavage parallel (001)). While this particular grain is quite fresh, unweathered, all degrees of alteration were noted in the species within a given slide, as evidenced by the neighboring grain on the right. Chief alteration product consists of liquid-filled vacuoles which occur both as "clouds", and stringers associated with cleavage planes and fractures.

Polycrystalline quartz grain below exhibits a rutilated subcrystal unit.

Fig. 1. Crossed nicols

Fig. 2. Plane polarized light



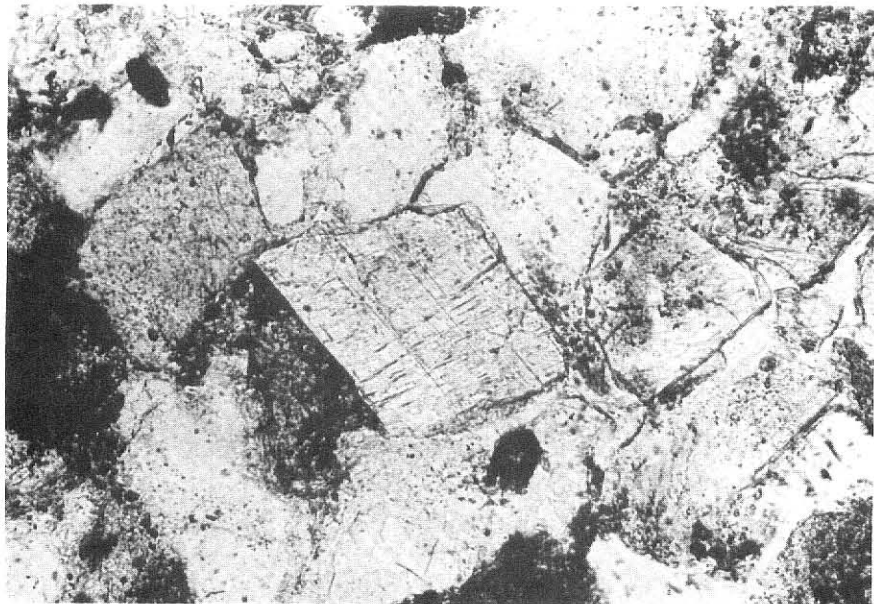
## PLATE VII

Fig. 1

0.10 MM



Fig. 2



### Explanation of Plate VIII

Microcline grain, center, is subangular, subequant cleaved fragment displaying characteristic combined albite-pericline cross-hatched twinning. The grain is typical in that the species is generally fresh to only slightly altered. A single, large, quartz inclusion (?) occurs in this grain.

Chert grain displaying pin-point extinction pattern on right side of field of view. Unhappily, the thin section is a little dirty.

Fig. 1. Crossed nicols

Fig. 2. Plane polarized light

## PLATE VIII

Fig. 1

0.10 MM

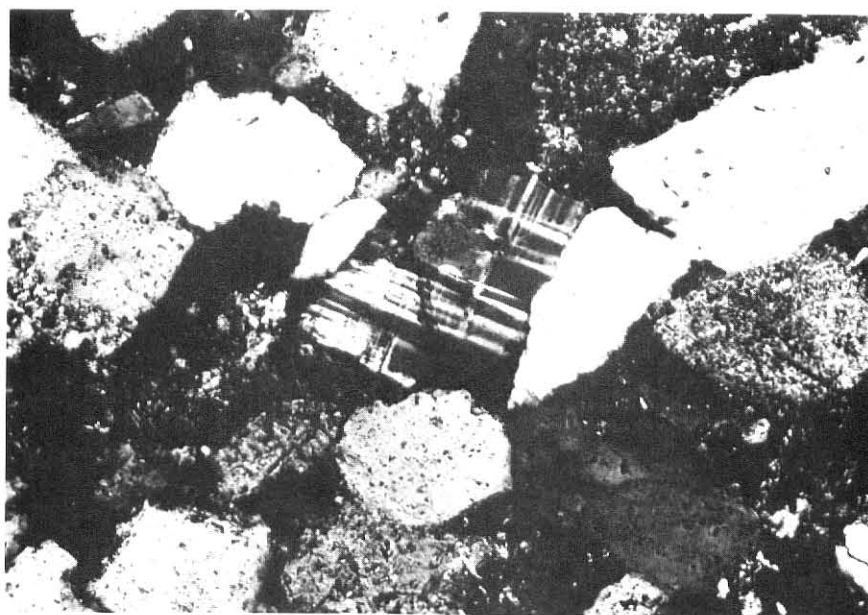
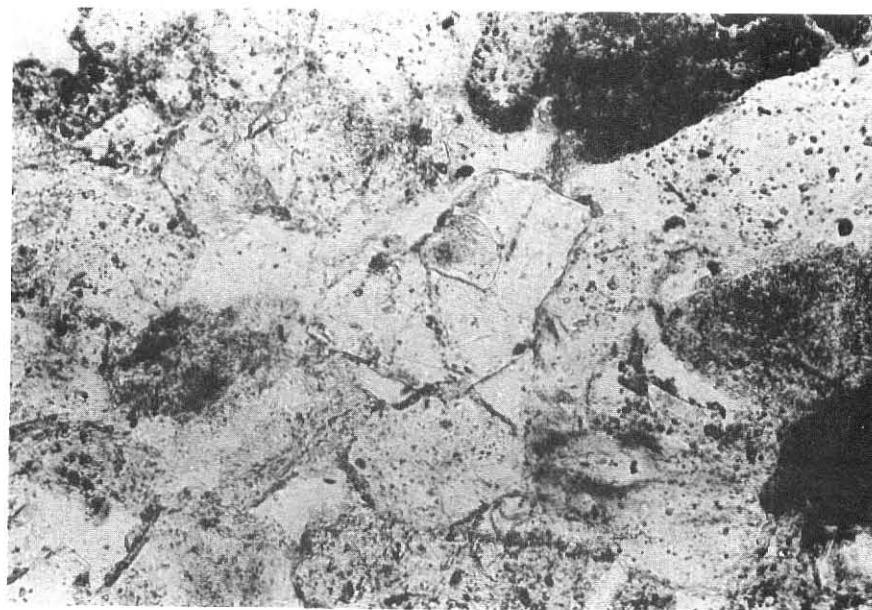


Fig. 2



## Explanation of Plate IX

Perthite, center, is subrounded, elongate grain exhibiting exsolution of sodic plagioclase through potash feldspar. This particular example is a string perthite, so-called because of characteristic exsolution fabric; no other fabrics were noted in this species. Vacuolization and sericitization are prevalent alteration processes acting on the species.

Note the alteration and disintegration of softer rock fragments to matrix in the field of view.

Fig. 1. Crossed nicols

Fig. 2. Plane polarized light

## PLATE IX

Fig. 1

0.10 MM


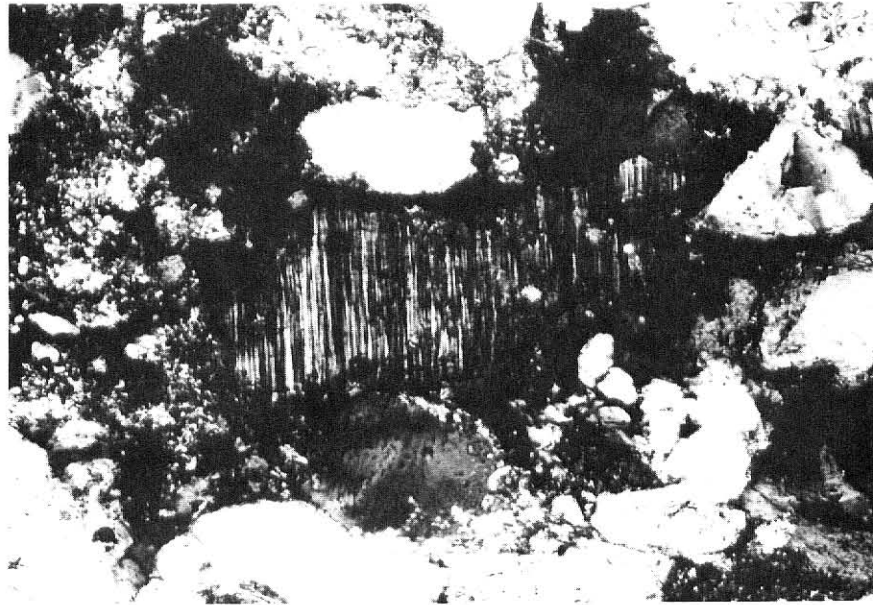
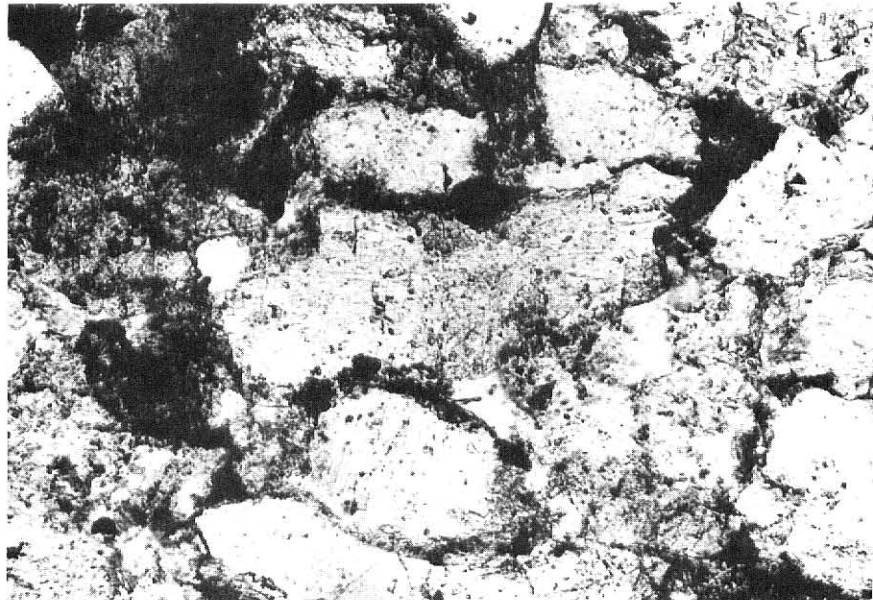
A horizontal scale bar with vertical end caps, labeled "0.10 MM".

Fig. 2



## Explanation of Plate X

Plagioclase (oligoclase) subangular, subelongate cleavage fragment, center, is twinned according to albite law. Grain is typical in being faintly prismatic, having broken along (001) and (010) cleavages. This grain is relatively fresh, but the species shows wide variation; vacuolization and kaolinization are particularly evident in plane of cleavage. Note that crystal fragment has been deformed (dynamic metamorphism).

Parts of another feldspar fragment and tourmaline are seen in upper left corner. The micaceous, clayey, iron oxide matrix acts as a binder for framework components.

Fig. 1. Crossed nicols

Fig. 2. Plane polarized light

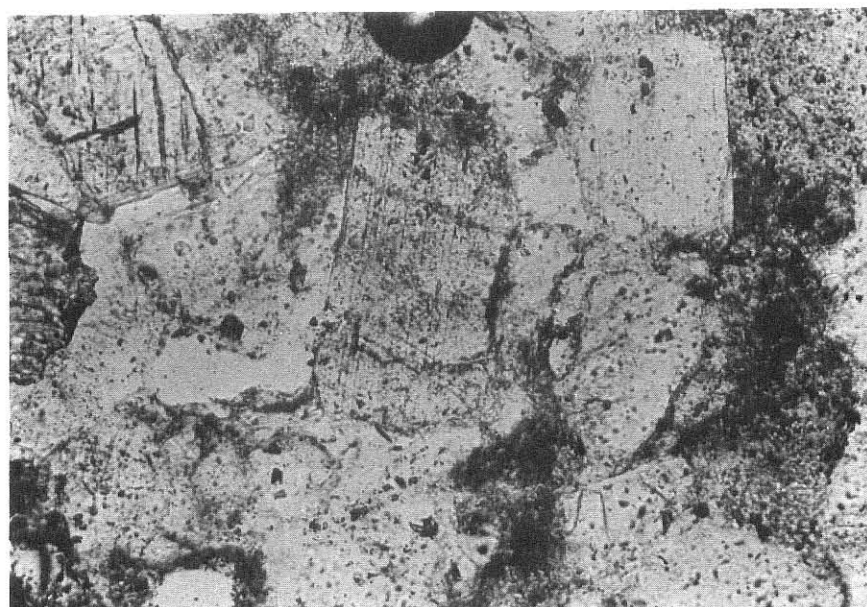
## PLATE X

Fig. 1

0.10 MM



Fig. 2



Microcline occurs as subangular to subrounded, subequant grains with generally poorly expressed cleavage, compared to orthoclase. Microcline is easily identified in the thin section by its polysynthetic twinning. Most grains are only slightly altered, the products consisting again of brown vacuoles and white mica. Unlike orthoclase, interference figures of microcline are notably poor.

Perthite occurs as subround, subelongate grains with poorly expressed cleavage. The species is an intergrowth of sodic plagioclase in either microcline or orthoclase, and is easily identified by the stringy, exsolution, grain fabric. All grains are moderately to severely altered, displaying a patchy, dusty-brown appearance due to vacuolization. Interference figures are nonexistent.

The last feldspar species, plagioclase, shows great variation in roundness and weathering characteristics; most grains are elongate. Relatively fresh, cleaved grains occur in the same slide with subrounded and severely altered grains which are difficult to distinguish from rock fragments. Generally, however, identification can be made on the basis of polysynthetic albite twinning. A few grains display Carlsbad twinning as well. The composition of the plagioclase, determined by the Michel-Levy method, is more sodic than  $Ab_{75}An_{25}$ . Alteration products consisted of liquid-filled vacuoles and lesser kaolinite. Several grains show curved twin lamellae, indicating crystal deformation in the source rocks.

Rock Fragments.-- For practical reasons, in the modal analyses, all rock fragments were tabulated simply as RF's, averaging 14 percent and ranging from 9 to 17 percent. I found it impossible to objectively define the 'boundary' between clay-shale fragments, with generally well oriented clays



and fine mica, and weakly metamorphosed slate and phyllite fragments, displaying a range of recrystallization effects (foliation). No igneous rock fragment was observed in any thin section although it should be pointed out that the very fine sand to coarse silt modes of the samples may preclude the occurrence of such a component. Included in the category of RF's are coarse micas (greater than 30 microns); otherwise, the most common rock fragment is probably shale or claystone. RF's are operationally defined and illustrated on the following pages.

Sedimentary rock fragments are well rounded and subequant. A source of error, which is difficult to evaluate, is post-depositional disintegration of softer rock fragments to matrix-like material. Grain (fragment) boundaries of even slate and phyllite are sometimes vague against matrix. Rock fragments in the thin sections studied, however, contained little silt-size quartz, which was abundant in the native matrix of the sandstones.

Relatively weakly metamorphosed sericitic-slate rock fragments, grading to phyllite, are of subequal abundance to presumed sedimentary fragments discussed above. Slate-phyllite fragments are rounded and subequant to elongate, and are composed predominantly of recrystallized clays. Sericite and chlorite mask any other minerals that might be present. A few grains appeared to contain quartz blebs (stringers) of metasomatic (?) origin. The degree of foliation of the fragments ranged from little better than the orientation of clays and fine mica of sedimentary fragments to excellent.

Matrix.-- Matrix is considered as all terrigenous sediment finer than 30 microns. Grain-size analyses yielded an optimistic figure for percent and range of matrix in the samples when compared with observation of thin sections ( see Fig. 7). Except for mudstones the rocks contained less than 10 percent matrix, based on visual estimate.

## Explanation of Plate XI

Coarse mica (greater than 30 microns) is considered as an RF component in this study. This particular grain (flake) is slightly stained muscovite. Flake morphology is usually subangular and subequant, with sharp to frayed edges; a few flakes are elliptical to circular and well rounded. In coarser lithologies, such as this sample, mica is heterogeneously distributed throughout rock. Biotite and chlorite are far less abundant species in all samples.

Well rounded quartz grain is suggested to right of muscovite flake.

Fig. 1. Crossed nicols

Fig. 2. Plane polarized light

## PLATE XI

Fig. 1

0.10 MM

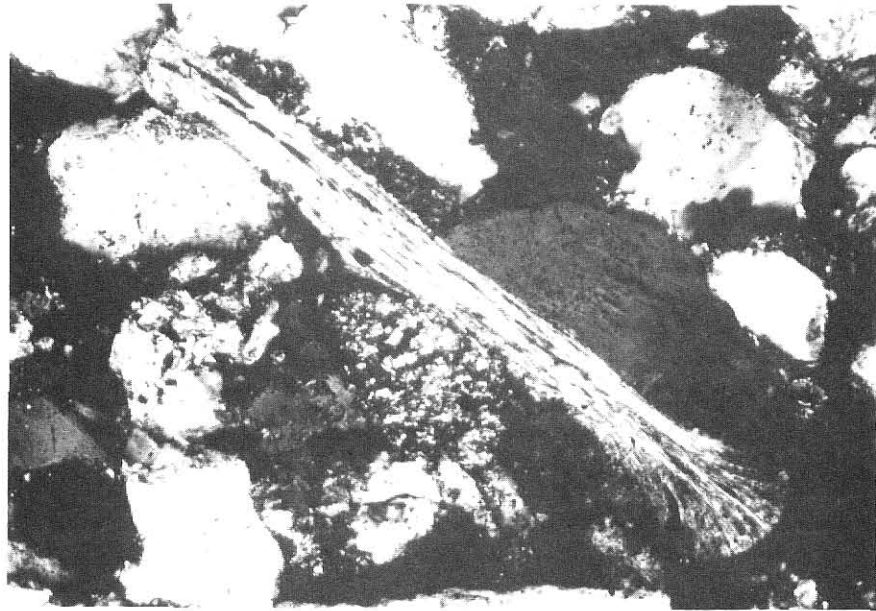
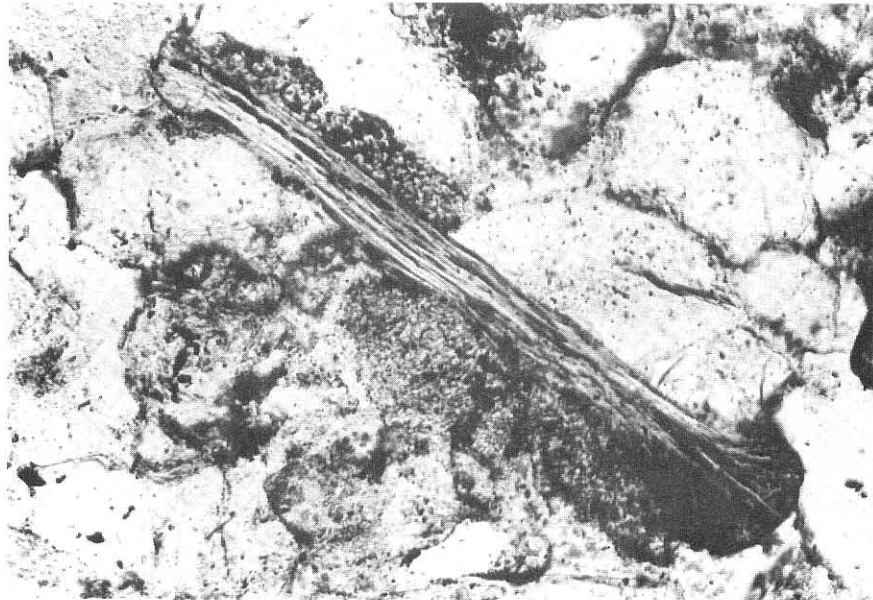


Fig. 2



## Explanation of Plate XII

Shale-slate-phyllite rock fragment, center-right, was tabulated as an RF during modal analysis. Low rank metamorphic character is apparent from degree of recrystallization. Composed predominantly of sericite, with lesser chlorite, the fragments are relatively soft; the morphology of this fragment is typical in being subround and subelongate.

Another metamorphic rock fragment is located at the top of the field of view, but the degree of recrystallization (expressed by foliation) makes it equivocal, i.e., could it be a compact clay-shale with well oriented fine micas? A third, probable metamorphic component is viewed in left-center. In the pre-1968 classification of Folk this quartz variety would be considered along with MRF's; in this study it was tabulated as polycrystalline quartz.

Fig. 1. Crossed nicols

Fig. 2. Plane polarized light

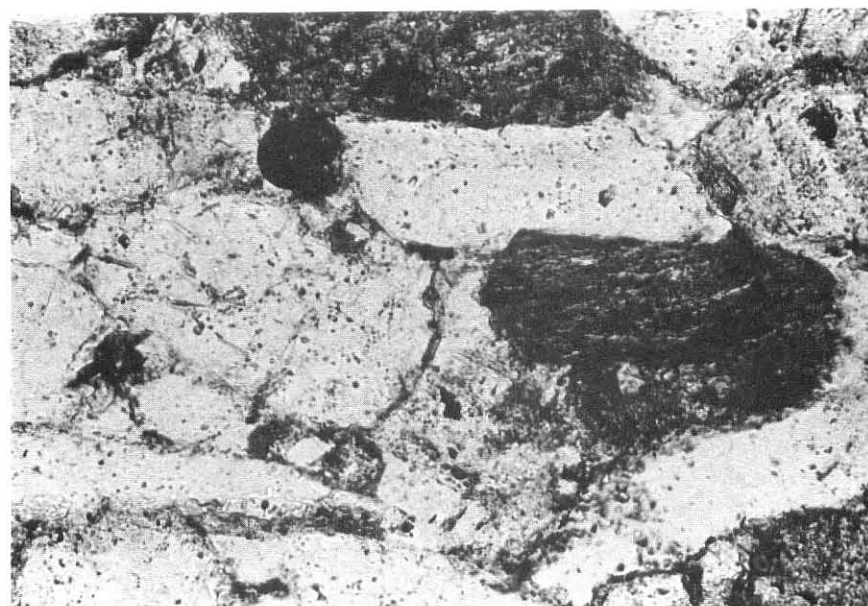
## PLATE XII

Fig. 1

0.10 MM



Fig. 2



Clay minerals and fine mica dominate the less than 30 micron fraction, and with carbonaceous matter, probably constitute on the average 80 percent of total matrix by volume. The remaining 20 percent consists largely of fine silt-size quartz, with greatly subordinate feldspar. Quantitative determination of matrix components was very difficult due to heavy iron oxide straining, and authigenic clay development. For convenience, in the modal analyses, all of the above matrix elements, plus heavy minerals, were tabulated as Miscellaneous (see Table 8).

Thin section study aided in the determination of the clay suites, discussed in another part of this work. As mentioned in connection with quantitative determinations of matrix components, both detrital and authigenic clays were present in the samples. On the other hand, no evidence was gained which would suggest clay genesis by in situ (post depositional) alteration and disintegration of framework grains, except in the case of soft rock fragments. In this connection, a critical source of error was introduced during sample preparation.

Kaolinite was present as elongate crystals or books. The development is better observed in plane polarized light as the crystals are nearly isotropic. Direction of elongation is perpendicular to basal cleavage. An empty core runs the length of the books.

Authigenic chlorite was present as tiny, 5 to 10 microns, crystallites growing out of framework quartz grains. While I found no evidence of recrystallization of clayey matrix to chloritic hash or paste, a clay component of a chlorite-mixed-layer nature was suggested during the clay mineral study. Detrital chlorite, as against the above authigenic and diagenetic varieties, is discussed in the section of the work covering heavy minerals.

Cement.-- True cementing minerals are practically limited to a small amount of disseminated iron oxides, principally limonite. Together with matrix components, however, the iron oxides act as a more or less effective binder. Lithologies about bedding planes and fractures are well cemented and constitute a harder rock.

During heavy mineral study I came across an occasional perfectly formed euhedral quartz crystal, doubly terminated, showing no evidence of having been transported. This was in the 'light' fraction, and loose. No such development was encountered in the thin section analysis, but the possibility of silica precipitation must be considered. By the same token, although carbonate minerals were not observed in any thin section, the preparation of samples discussed in the section dealing with grain-size analysis suggested a slightly calcareous nature to all.

## HEAVY MINERALOGY

### Procedure

Samples of the blanket and channel sandstone lithologies were treated as described in the section dealing with mechanical grain size analysis. Silt and sand size fractions coarser than 30 microns were recombined and oven-dried at 100 degrees C for one-half hour. Standard separatory procedures were followed as outlined in Krumbein and Pettijohn (1938) using bromoform. The heavy crop was filtered, washed with alcohol and mounted on glass slides with Canada Balsam. Typically, more heavy residue was obtained than could be mounted on a single slide, so that micro-splites had to be taken and mounted. The total heavy crop of individual samples ranged from three to seven percent.

Preliminary review showed that the disaggregation process employed left many grains coated with clay and iron oxides. Some "opaque minerals" were likewise considered to be fragments of clay-ironstone. Treatment with warm 10 percent HCl was used as a check against the standard procedure. The stronger treatment was clearly advantageous except that all opaques were removed.

Heavy mineral species were identified and tabulated with the aid of a petrographic microscope. Mounted samples were counted by whole fields of view, randomly arranged, until 300 nonopaque, nonmicaceous grains had been tabulated. Such counts were made on five samples of the blanket sandstone and three samples of the channel sandstone lithologies. The remaining samples were scanned to see if marked variation existed; none did. Table 11 summarizes the heavy mineral data taken. Details of the analyses may be found in Appendix IV. No attempt has been made to convert number percentages to volume or weight percentages.



Table 11

<u>Mineral</u>	<u>Percent in Blanket-sand</u>	<u>Percent in Channel-sand</u>
Zircon	28 - 44	37 - 46
Tourmaline	26 - 47	12 - 45
Garnet	5 - 12	7 - 33
Rutile	5 - 14	6 - 12
Staurolite	1 - 4	0 - 3
Apatite	0 - 1	0 - 2
Miscellaneous	5 - 14	5 - 10

## Mineralogy

Basically, the same heavy minerals are common to both blanket and channel sandstone lithologies. Variation in abundances of individual species was correlative with mean grain size of the sample. The suite is ultra-stable, with a ZTR index of 91 (Hubert, 1962). A description of the heavy minerals follows.

Magnetite -- Present in all samples, magnetite is probably the most abundant of the opaque heavy minerals. The grains are rounded and equant. The mottled gray-tan color suggests alteration to limonite. Identification was made chiefly on the basis of attraction to an unmagnetized iron needle, and was difficult with the mounted sample.

Illmenite -- This species was the only other opaque which was abundant in all samples. It occurs as subround to round, sub-equant grains which are often altered to dull, yellow-gray leucoxene. These grains are attracted to a magnetized needle.

Hematite -- The occurrence of hematite was spotty among samples, but when present, the mineral proved to be next in abundance to magnetite and illmenite. Grains are round and equant to subelongate, and are easily distinguished by an earthy-red color. This opaque species should not be considered in the suite as it is probably a penecontemporaneous or post-depositional precipitate.

Pyrite -- As with hematite, this species is spotty in occurrence, being abundant only in the 'fine-dirty' facies of the channel deposit. It consists of angular, equant grains (pyritohedra) and fine crystalline aggregates which are a striking brassy-yellow color. Again, as with hematite, this opaque heavy mineral probably does not belong to the natural suite of the sandstones but rather reflects the depositional and post-depositional environment.

Zircon -- Three shapes of zircon were distinguished: 1) euhedral, 2) subrounded to rounded, and 3) angular fragments. Zircon in the sand-size range was dominantly subrounded to rounded, with angular fragments next in abundance, and euhedral grains least abundant. In the silt-size range, euhedral zircon was dominant and angular fragments least abundant. The proportion of zircon of the total nonopaque, nonmicaceous fraction dropped from the sand-size range to silt-size, with a reversal in the zircon to tourmaline ratio.

Tourmaline -- Two varieties of tourmaline were distinguished: 1) yellow-brown, and 2) blue-black (the darker color, associated with the direction of maximum absorption) is observed with the long dimension of the grain in an E-W direction. Tourmaline in the sand-size range was almost entirely of the yellow-brown variety, while in the silt-size range the ratio of yellow-brown to blue-black was only about 2 to 1. Except for a few well rounded grains in the sand-size range, tourmaline was consistently euhedral or exhibited fresh (?) angular fractures.

Rutile -- Two distinct types of rutile were distinguished: 1) euhedral, prismatic, geniculately twinned, reddish-brown grains, and 2) subrounded, pale amber fragments showing striations. The former type is slightly pleochroic. In the latter, striae can be of two sets intersecting at about 40 degrees.

Garnet -- Pink almandine garnet varied widely in abundance. Probably due to the inherent paucity of silt-size grains of this mineral, it is a rare member of the suite in the very fine sand to coarse siltstones of the blanket and channel deposits. A few grains of this heavy mineral were so pale as to be almost colorless. Most grains showed subrounded to rounded, equant morphology, but many appeared to fragments broken from larger crystals. Etching, pitting, and a distinctive rectangular surface feature were common to all grains.

Apatite -- The general petrologic procedure employed during sample preparation has likely affected this mineral, which is rare to absent in the samples. Round, irregularly shaped, faintly prismatic, clear to pale green grains are 30 to 40 microns in long dimension. Identification was not conclusive.

Staurolite -- This species, as with apatite, is rare to absent in the tabulations of samples from both sandstone deposits. Staurolite, however, being chemically more stable than the latter, probably withstood sample preparation better. The yellowish-brown to pale yellow grains are subround and subelongate. Numerous quartz inclusions give a distinctive "Swiss cheese" appearance to many grains, while others bear surface grooves which are deep and produce a 'saw-tooth' pattern at the edges of the grain.

Miscellaneous -- This category includes all grains unidentified either because of severe weathering and alteration or due to clay-iron oxide coatings. The numerical frequency of these grains ranged from 5 to 14 percent, with an average of 8 percent.

Muscovite -- This micaceous component completely dominated all heavy mineral crops (estimated 70 to 90 percent). Most flakes are subangular to subround. A few perfectly circular flakes with 'clean' edges are matched in number by those notably frayed in character. Typically colorless, a relatively large number of flakes (maximum 10 percent) are stained yellow to brown with iron oxides and could be confused with leached biotite. Inclusions were rare and limited to very fine rutile crystallites. A few muscovite flakes possessed an undulatory extinction habit.

Biotite -- Light brown to yellowish-tan biotite was common to all heavy crops but never approached the abundance of muscovite. Morphology of the flakes is the same as for muscovite. Alteration to chlorite is present in varying degree in all flakes, causing the figures of the species to be poor.

Chlorite -- Detrital chlorite, coarser than 30 microns, is the least abundant mica in the blanket and channel sandstones. Clear, green to pale green, slightly pleochroic flakes of chlorite are usually subequant with ragged edges. Small size of the flakes made precise identification of the mineral tenuous; I prefer merely to refer to the component as a chlorite group mineral.

## DETERMINATIONS OF PROVENANCE

Lithologic types contained in the blanket and channel sandstones exposed in Cat Creek are restricted to feldspathic litharenite, and sublitharenite. Individual component abundances among samples are a function of mean grain size; modal grain size of components seems to be independent of occurrence in deposits. The main control on component grain size and abundance is probably the modal size of various minerals and rock fragments as liberated from the immediate source rocks of these sediments.

It became apparent during modal analyses that there were certain possible sources of error in the tabulations. An inherent problem, due to the fine-grained and clayey texture of most samples, was that of distinguishing between rock fragments and altered feldspar. Also, it was sometimes difficult to distinguish between fine crystalline metaquartzite and cherty rock fragments. Finally, fresh untwinned feldspar and quartz grains with the c-axis (often elongated) in the plane of the bedding presented the usual problem.

Blatt and Christie (1963) and Blatt (1967) examined some of the hypotheses dealing with quartz varieties upon which interpretations of provenance are commonly based. Unfortunately, the conclusions reached in these works considerably water-down any high expectations for genetic and to a lesser extent empirical classification schemes advanced to date. Yet, I believe certain qualitative statements bearing on provenance may be propounded in this study via the application of such schemes. The principal value of these efforts lay in the accumulation of data and ideas, which take on greater or lesser significance and authority as other studies are made.

Terrigenous quartz varieties in the Cat Creek sandstone accumulations make up roughly 70 to 80 percent of all framework components. To the extent that these varieties reflect their original environments(s) of formation, this mineral would be a most important indicator of source area lithology.

In most cases an iron oxide-stained matrix of clay and fine silt, coupled with plus 30 micron thickness of thin section, denied a detailed study of framework grain morphology. However, a mixture of monocrystalline, subangular, elongate (slivers and plates or disks) grains of quartz, together with well-rounded, equant (spherical) grains was present in the size fraction greater than about 80 microns. Between these extremes, in the same size fraction, most quartz grains are subangular to subround and, subelongate to subequant. I believe the slivers and plates or disks, which rarely exceeded 150 microns, point to metamorphic, possibly a quartz schist, origin. The other extreme in shape is strongly suggestive of recycled or polycyclic quartz. No case of abraded quartz overgrowths was observed however. It is quite possible, indeed likely, that volumetrically, recycled quartz (sedimentary origin) is the most important quartz variety in the Cat Creek sandstones. It is apparent that adequate criteria are lacking with which to distinguish between primary quartz, derived directly from igneous or metamorphic source rocks, and recycled quartz from older sedimentary rock.

Polycrystalline quartz varieties, practically limited to the grain size fraction greater than 80 microns, included some with individual subcrystal units showing a preferred crystallographic orientation. This is evidenced by insertion of a gyp plate. According to Blatt (1967) the feature is reasonably diagnostic of a metamorphic environment of formation. Other polycrystalline varieties could be broadly lumped into pressure-metamorphic quartz and microcrystalline (cherty) quartz. Criteria for the former are limited to

extinction behavior and suturing of subcrystal boundaries. The reliability of these indicators has not been demonstrated, however Blatt did find that for any grain size, polycrystalline quartz from metamorphic source rocks will be more finely polycrystalline than will grains from plutonic (igneous) rocks. The fine to very fine modes encountered in this work, may thus suggest that the polycrystalline quartz component is metamorphic.

Microcrystalline (cherty) quartz is diagnostic of an older sedimentary source, and its presence in the sandstones of Cat Creek supports the earlier contention that a sedimentary source was important in the provenance of the sediment. Typically, inclusions of clay, fine mica and organic matter helped to discriminate between this component and very fine polycrystalline metamorphic quartz varieties. It seems reasonable that chert would be associated with carbonate rocks in a sedimentary terrane.

Inclusions of chlorite in a vermicular habit, represented by relatively few grains in the samples, are a positive indication of hydrothermal or vein quartz (Folk, 1968). Because there seemed to be a disproportionate number of liquid-filled vacuoles associated with this variety, I assume that other highly vacuolized grains, lacking chlorite inclusions, are likewise of that origin. Most hydrothermal or vein quartzite grains are monocrystalline, but a few possess three to five subunits. No "cockscomb" structure was observed in any grain, probably due to the fine grain size.

Virtually by default, most of the quartz component of the samples falls into the category of strained "common (plutonic)". Vein quartz, chert and polycrystalline quartz varieties practically disappear in the finer size fraction, below about 80 microns. A relatively small percent of the grains actually fit the textbook description of straight to slightly undulose

extinction supposedly common or typical of igneous quartz. In any event Blatt and Christie (1963) and Blatt (1967) demonstrated the shaky nature of genetic quartz classification based on extinction habit. I feel that coarse silt to fine sand modes of the Cat Creek samples preclude a better breakdown of quartz varieties. It is unfortunate that the preponderance of grains fall into such a nondefinitive category. All that can be said of "common" quartz component is that it could be either igneous or metamorphic, and that from other lines of evidence is probably recycled (sedimentary).

Modal analyses of Cat Creek sandstones showed 6 to 12 percent of K-Na rich feldspar. Total feldspar is treated as one component in the present discussion. Feldspar was invariably smaller in grain size than the mean for quartz in the samples although this determination was qualitative. No feldspathic rock fragment was observed, probably due in part to the fine to very fine modes of the sandstones as determined by mechanical grain size analysis. Alkalic feldspar, in any event, is good evidence for feldspathic plutonic rock somewhere in the genesis of the terrigenous sediment.

Nearly if not all feldspar grains showed some degree of alteration, and approximately 20 percent were severely altered. The great range of "weathering" effects exhibited by this component is possibly the most important point to note. If a granite-like igneous or metamorphic parent rock is assumed in the source terrane, then, mechanical weathering and erosion, coincident with near vertical downcutting of stream channels, would have yielded fresh feldspar while chemically altered grains were produced in soil profiles on the broad relatively flat lying divides. It might be logically argued, as an extension to the above, that feldspar grains in transit could have been held up for millions of years, for example on terraced floodplains, before continuing on



their journey, thus having been exposed to repeated chemical attack. Finally, the possibility exists that the "differential weathering" of feldspar observed in Cat Creek sandstones could represent local deuteritic or metasomatic alteration of the granite-like parent rock. More study concerning the processes of vacuolization and sericitization of feldspar is necessary before a final conclusion can be drawn.

On the other hand, studies of the durability and stability of feldspar and its ability to survive more than one cycle of weathering, erosion, transport, deposition and lithification are not documented. One may infer from the literature that this component is not ordinarily a product of older sedimentary rocks. Blatt (1967) takes exception to this inference, feeling that the ground has barely been broken in such studies of mineral survivability. Thus for feldspar, as with quartz varieties, the important question of sediment recycling may be impossible to answer at this time.

Because rock fragments are polymineralic pieces of the source rocks they are particularly useful in provenance determinations. Relatively high percentages of soft, fine sand-size grains of older sedimentary and metamorphic origin may also indicate gentle currents insufficient to effect abrasion in the depositional environments. Probably, clay pellets and some shale fragments represent reworked penecontemporaneous channel fill.

As stated earlier, objective criteria for distinguishing between argillaceous sedimentary and low rank metamorphic rock fragments were practically limited to the degree of foliation of platy minerals, indicating recrystallization. For convenience all clayey and micaceous rock fragments are lumped together. Cherty quartz must also be considered as a type of rock fragment.



Unfortunately, the above lumping of all rock fragments does not allow for more than a qualitative estimate of MRF: SRF ratio in the samples; I estimated this ratio to be roughly 2:3. More than half of all rock fragments were shale and clay-ironstone. These reflect upstream lithologies through which channels were being cut. While no carbonate clasts were noted (preserved?) in any sample, the cherty quartz was likely shed from an older chert-bearing carbonate section.

The remainder of rock fragments encountered included grains of slate and phyllite. Textures reflecting the character of source rocks are preserved to a limited degree in the mostly fine sand-size fraction. It is not possible to be more definite about the source of these MRF's other than to say that it was low to possibly medium rank metamorphic and that the pre-metamorphosed rock was argillaceous. Based on the total proportion of feldspar and rock fragments one could presume 'Cat Creek' sands to be first-cycle. However, the ability of these components to survive long or repeated erosion and transport is largely unknown.

Micaceous rock components occur both as constituents of RF's and as discrete flakes. Muscovite, biotite and chlorite mega-mica were probably shed by the same ultimate source as that which contributed the low to medium rank metamorphic rock fragments. In the case of this component, however, the potential for recycling of mica flakes must be much greater than for RF's in general.

Nonopaque, nonmicaceous heavy minerals present in the samples, consisting essentially of zircon, tourmaline, garnet and rutile, are physically and chemically very stable. The ZTR index of 91, together with the frequency of rounded grains suggests recycling and modification of the original suite.

Based on the occurrence of garnet and staurolite the ultimate source for the suite includes high rank metamorphic rocks. Illmenite and magnetite among the opaque fraction point to a plutonic contribution.

Thin section petrography and heavy mineral study of Cat Creek sandstones indicate a combination of sources in the overall picture of provenance. This study suggests an older (pre-Virgil) sedimentary terrane composed of sandstone, siltstone, shale and cherty carbonate rocks was the likely immediate source of sediment for the blanket and channel-sand accumulations. Composition of the primary source rocks from which this older sedimentary terrane was apparently derived include 1) silicic plutonic rocks, 2) pegmatites and hydrothermal veins, 3) low-medium rank metamorphic rocks and 4) high rank metamorphic rocks.

A silicic plutonic source (granitic and/or gneissic) ultimately contributed most of the monocrystalline common quartz, alkali feldspar, and, zircon, tourmaline, rutile and opaque heavy minerals. Associated with the above plutonic rocks were pegmatites and hydrothermal veins, as inferred by certain blue tourmaline and quartz grains containing abundant inclusions of liquid and chlorite. Low-medium rank metamorphic rocks in this primary source terrane are evidenced by slate-phyllite fragments and chlorite mega-mica flakes. High rank metamorphic rocks shed some of the polycrystalline quartz, most of the muscovite and biotite mega-mica, and probably all of the garnet and staurolite.

Thus it seems reasonable to conclude that Cat Creek sandstones are at least largely derived from pre-existing sediments; i.e. the detritus has likely gone through more than one cycle of sedimentation. Evidence, further, points to a primary source terrane made up of a series of rock types ranging from plutonic to high and low rank metamorphics. The nearest and probably the only major source of such rocks exposed during the Late Paleozoic Era was the Precambrian Canadian Shield (Eardley, 1962).

## SUMMARY AND CONCLUSIONS

The local stratigraphic section exhibits cycles of sedimentation typical of the Wabaunsee and Admire Groups. The Willard Shale contains a widespread blanket-sand which is commonly found in the upper part of the formation and which is the initial or basal sandy phase of a cycle. Such sand accumulation has been considered to be a shallow-water, delta front, deposit elsewhere in the Late Pennsylvanian section of the northern midcontinent (Potter and Pryor, 1961).

Late Pennsylvanian and Early Permian formations of northeast Kansas show many local unconformities marked by channel development. These channels range from shallow structures contained within blanket-sands to deep channels that cut into and through underlying formations. The channels are thought to have been eroded subaerially, and the fill of most of them is considered to be non-marine (Mudge, 1956).

Both blanket and channel sandstones are exposed in the recent stream cut just west of Wamego, Kansas. The blanket sandstone of the Willard Shale has not been reported this far south. The channel sandstone, earlier reported to be the Indian Cave Sandstone (marking the systemic boundary) and more recently of Pony Creek or Pillsbury age, cannot be identified with certainty at this time. Mudge's Pony Creek age seems reasonable.

This study produced no evidence by which a sure distinction could be made between the sandstone bodies of Cat Creek other than by geometry. A combination of sources is indicated in the provenance of the terrigenous sediment. An older sedimentary terrane was the likely immediate source, but the primary source from which this terrane was derived is probably the Canadian Shield.

## REFERENCES CITED

- Armstrong, R.L., in Schaeffer, O.A., and Zahringer, J., 1966, Potassium Argon Dating: New York, Springer-Verlag Inc., 234 p.
- Blatt, Harvey, 1967a, Original characteristics of clastic quartz grains: Jour. Sed. Petrology, v. 37 no. 2, p. 401-424.
- 1967b, Provenance determinations and recycling of sediments: Jour. Sed. Petrology, v. 37, no. 4, p. 1031-1044.
- Blatt, Harvey, and Christie, J.M. 1963, Undulatory extinction in quartz of igneous and metamorphic rocks and its significance in provenance studies of sedimentary rocks: Jour. Sed. Petrology, v. 33, p. 559-579.
- Brookins, D.G., and Voss, J.D., 1970, Age dating of muscovites from Pennsylvanian sandstones near Wamego, Kansas: Amer. Assoc. Petrol. Geol. Bull., v. 54, no. 2, p. 353-356.
- Chayes, Felix, 1954, Petrographic modal analysis; an elementary statistical appraisal: New York, Wiley, 113 p.
- Eardly, A.J., 1962, Structural geology of North America: New York, Harper and Brothers, 2nd ed., 743 p.
- Fenneman, N.M., 1931, Physiography of western United States: New York, McGraw-Hill Book Co., Inc., 534 p.
- Folk, R.L., 1968, Petrology of sedimentary rocks: Austin, Texas, Hemphill's, 170 p.
- Folk, R.L., and Ward W.C., 1957, Brazos River Bar: A study in the significance of grain size parameters: Jour. Sed. Petrology, v. 27, no. 1, p. 3-26.
- Frye, J.C., and Swineford, Ada, 1949, The Plains Border physiographic section: Kansas Geol. Survey Bull. 70, pt. 3, p. 29-52.
- Harned, C.H., and Chelikowsky, J.R., 1945, The stratigraphic range of the Pennsylvanian-Permian disconformity in Pottawatomie County, Kansas: Kansas Acad. Sci. Trans., v. 48, no. 3, p. 355-358.
- Hower, John, 1967, Order of mixed-layering in illite/ montmorillonites: in Clays and Clay Minerals, Proc., 15th Natl. Conf., p. 63-74.
- Hubert, John F., 1962, A zircon-tourmaline-rutile maturity index and the interdependence of the composition of heavy mineral assemblages with the gross composition and texture of sandstones: Jour. Sed. Petrology, v. 32, no. 3, p. 440-450.

- Jewett, J.M., 1933, Evidence of cyclic sedimentation in Kansas during the Permian period: *Kansas Acad. Sci. Trans.* v. 36, p. 137-140.
- \_\_\_\_\_, 1951, Geologic structures in Kansas: *Kansas Geol. Survey Bull.* 90, pt. 6, 172 p.
- Krumbein, W.D., and Pettijohn, F.J., 1938, *Manual of sedimentary petrography*: New York, D. Appleton-Century Company, Inc., 549 p.
- Lee, Wallace, 1943, The stratigraphy and structural development of the Forest City Basin in Kansas: *Kansas Geol. Survey Bull.* 51, 142 p.
- Moore, R.C., 1934, Relation of cyclic depositional units to the classification of the Pennsylvanian and Permian of the northern mid-continent area: *Tulsa Geol. Soc. Digest*, p. 18-20.
- \_\_\_\_\_, 1935, Correlation of phases in sedimentation cycles in Pennsylvanian and "Permian" rocks in Kansas (abs.): *Geol. Soc. of America Proc.* 1934, p. 100.
- \_\_\_\_\_, 1936, Stratigraphic classification of the Pennsylvanian rocks of Kansas: *Kansas Geol. Survey Bull.* 22, 256 p.
- \_\_\_\_\_, 1940, Carboniferous-Permian boundary: *Amer. Assoc. Petrol. Geol. Bull.*, v. 24, no. 2, p. 282-336.
- \_\_\_\_\_, 1949, Divisions of the Pennsylvanian system in Kansas: *Kansas Geol. Survey Bull.* 83, 203 p.
- Moore, R.C., and Condra, G.E., 1932, *Geologic Map of Eastern Kansas*: *Kansas Geol. Soc. Guidebook* 6th Ann. Field Conf.
- Moore, R.C., Elias, M.K., and Newell, N.D., 1934, Stratigraphic sections of Pennsylvanian and "Permian" rocks of Kansas River Valley: *Kansas Geol. Survey chart*, issued Dec.
- Moore, R.C., Frye, J.C., Jewett, J.M., Lee, Wallace and O'Connor, H.G., 1951, The Kansas rock column: *Kansas Geol. Survey Bull.* 89, 132 p.
- Moore, R.C., and Moss, R.G., 1934, Permian-Pennsylvanian boundary in the northern mid-continent area (abs.): *Geol. Soc. of America Proc.*, 1933, p. 120.
- Moore, R.C., and Mudge, M.R., 1956, Reclassification of some Lower Permian and Upper Pennsylvanian strata in northern mid-continent: *Amer. Assoc. Petrol. Geol. Bull.*, v. 40, no. 9, p. 2271-2278.
- Mudge, M.R., 1956, Sandstones and channels of the Upper Pennsylvanian and Lower Permian in Kansas: *Amer. Assoc. Petrol. Geol. Bull.* v. 40, no. 4, p. 654.

- Mudge, M.R., 1957a, Permian-Pennsylvanian boundary in Kansas: Kansas Geol. Soc. Guidebook 21st Ann. Field Conf., p. 113-117.
- 1957b, Lithologic variations in exposed Upper Pennsylvanian and Lower Permian rocks in Kansas: Kansas Geol. Soc. Guidebook 21st Ann. Field Conf., p. 105-112.
- Mudge, M.R., and Burton, R.H., 1959, Geology of Wabaunsee County, Kansas: U.S. Geol. Survey Bull. 1068, 210 p.
- Mudge, M.R., Walters, C.P., and Skoog, R.E., 1959, Geology and Construction-Material Resources of Nemaha County, Kansas: U.S. Geol. Survey Bull. 1060-D, 256 p.
- Mudge, M.R., and Yochelson, E.L., 1962, Stratigraphy and Paleontology of the Uppermost Pennsylvanian and Lowermost Permian rocks in Kansas: U.S. Geol. Sur., Prof. Paper 323, 213 p.
- O'Connor, H.G., 1953, Geology, mineral resources, and groundwater resources of Lyon County, Kansas: Kansas Geol. Survey Bull., v. 12, pt. 1, p. 5-24.
- Pierce, J.W., and Siegal, F.R., 1969, Quantification of clay mineral studies of sediments and sedimentary rocks: Jour. Sed. Petrology, v. 39, no. 1, p. 187-193.
- Potter, P.E., and Pryor, W.A., 1961, Dispersal centers of Paleozoic and later clastics of the Upper Mississippi Valley and adjacent areas: Geol. Soc. American Bull. 72, p. 1195-1250.
- Scott, G.R., Foster, F.W., Crumpton, C.F., 1959, Geology and Construction-Material Resources of Pottawatomie County, Kansas: U.S. Geol. Survey Bull. 1060-C, 178 p.
- Tomlinson, C.W., Moore, R.D., Dott, R.H., Cheney, M.G., and Adams, J.E., Classification of Permian rocks: Amer. Assoc. Petrol. Geol. Bull., v. 24, no. 2, p. 337-358.
- Walters, K.L., 1953, Geology and ground-water resources of Jackson County, Kansas: Kansas Geol. Survey Bull. 101, 90 p.
- 1954, Geology and ground water resources of Marshall County, Kansas: Kansas Geol. Survey Bull. 106, 116 p.
- Wanless, H.R., Tubb, J.B., Jr., Gednetz, D.E., and Weiner, J.L., 1963, Mapping sedimentary environments of Pennsylvanian cycles: Geol. Soc. America Bull., v. 74, p. 437-486.

——— and Weller, J.M., 1932, Correlation and extent of Pennsylvanian cyclothems: Geol. Soc. America Bull., v. 43, no. 4, p. 1003-1016.

Weller, J.M., 1930, Cyclical sedimentation of the Pennsylvanian Period and its significance: Jour. Geology, v. 38, p. 97-135

Zeller, D.E., 1968, The Stratigraphic Succession in Kansas: Kansas Geol. Survey Bull. 189, 81 p.

## Appendix I

### Cumulative Frequency Curves of Representative Samples



# ILLEGIBLE DOCUMENT

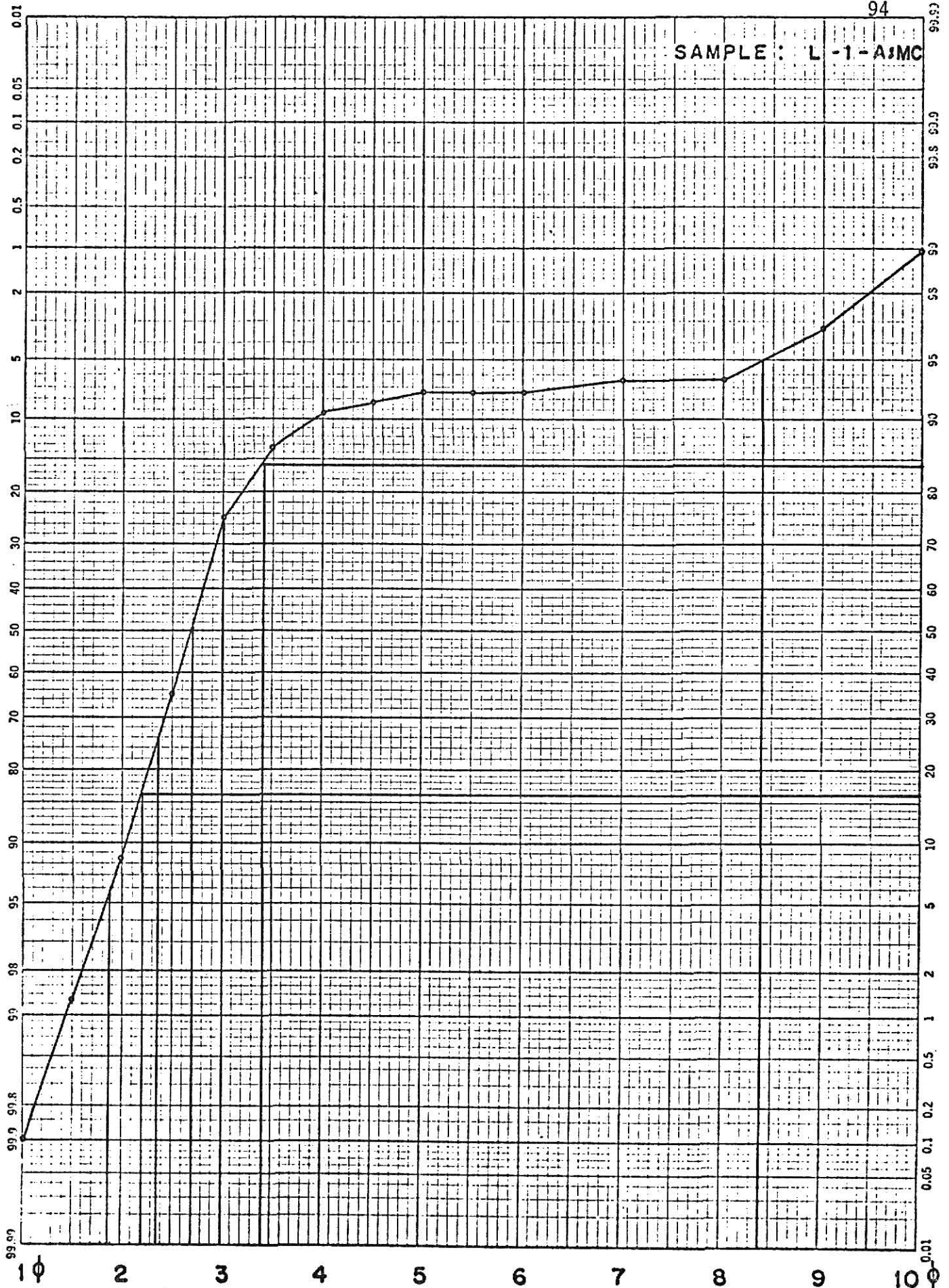
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POOR LEGIBILITY IN  
THE ORIGINAL

THIS IS THE BEST  
COPY AVAILABLE

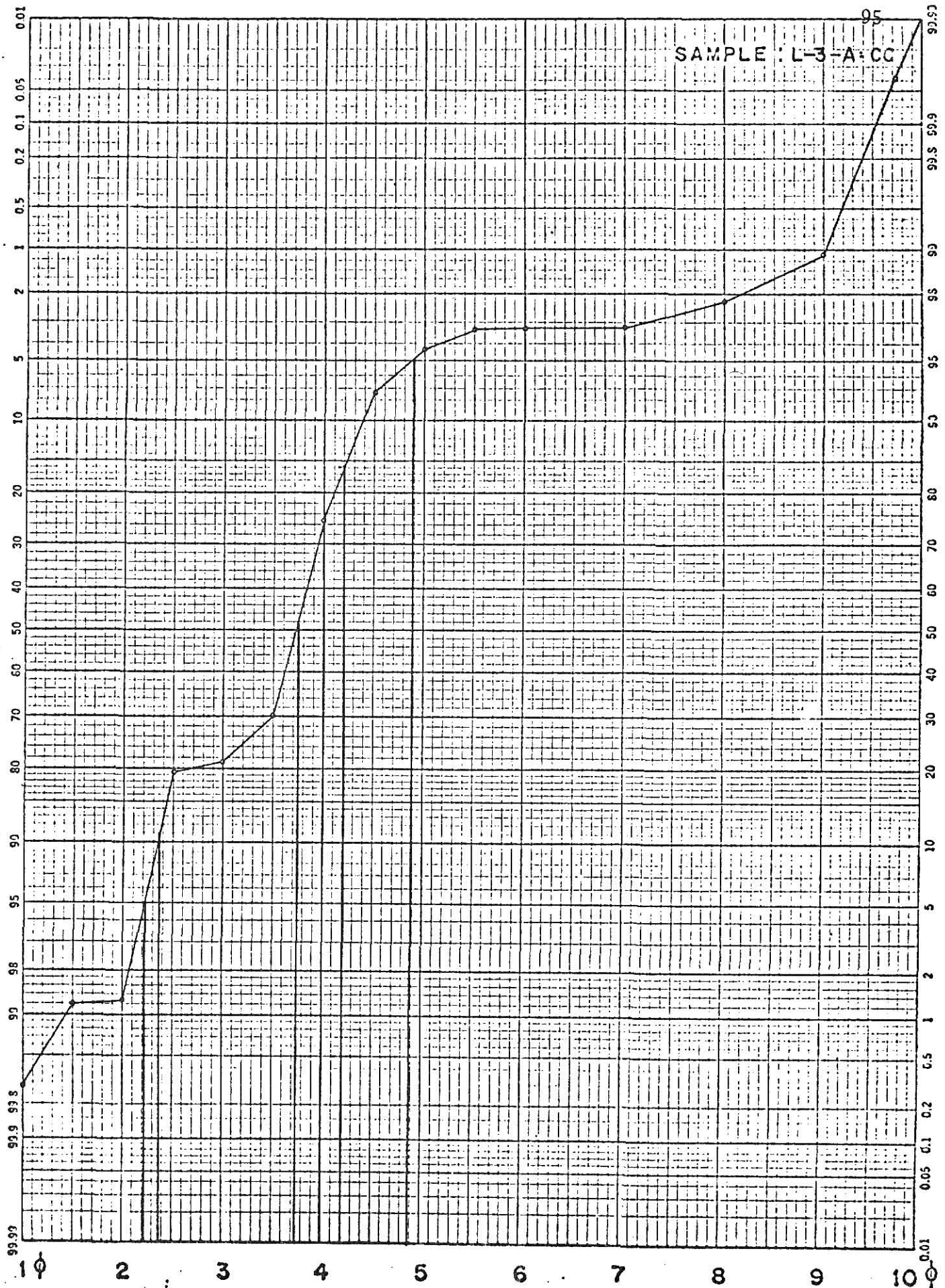
# CUMULATIVE FREQUENCY CURVE

94

SAMPLE : L - 1 - A JMC



# CUMULATIVE FREQUENCY CURVE

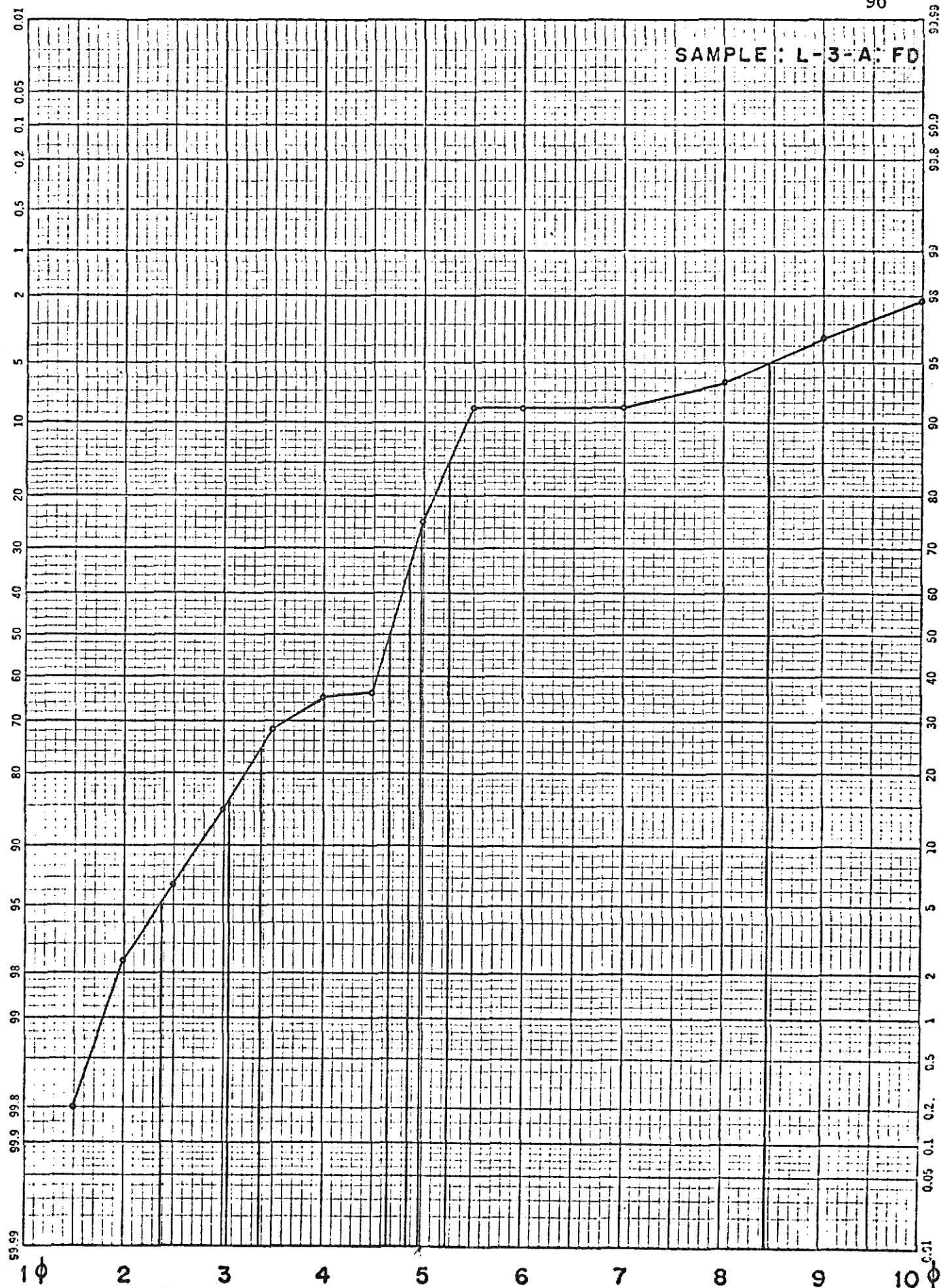




# CUMULATIVE FREQUENCY CURVE

96

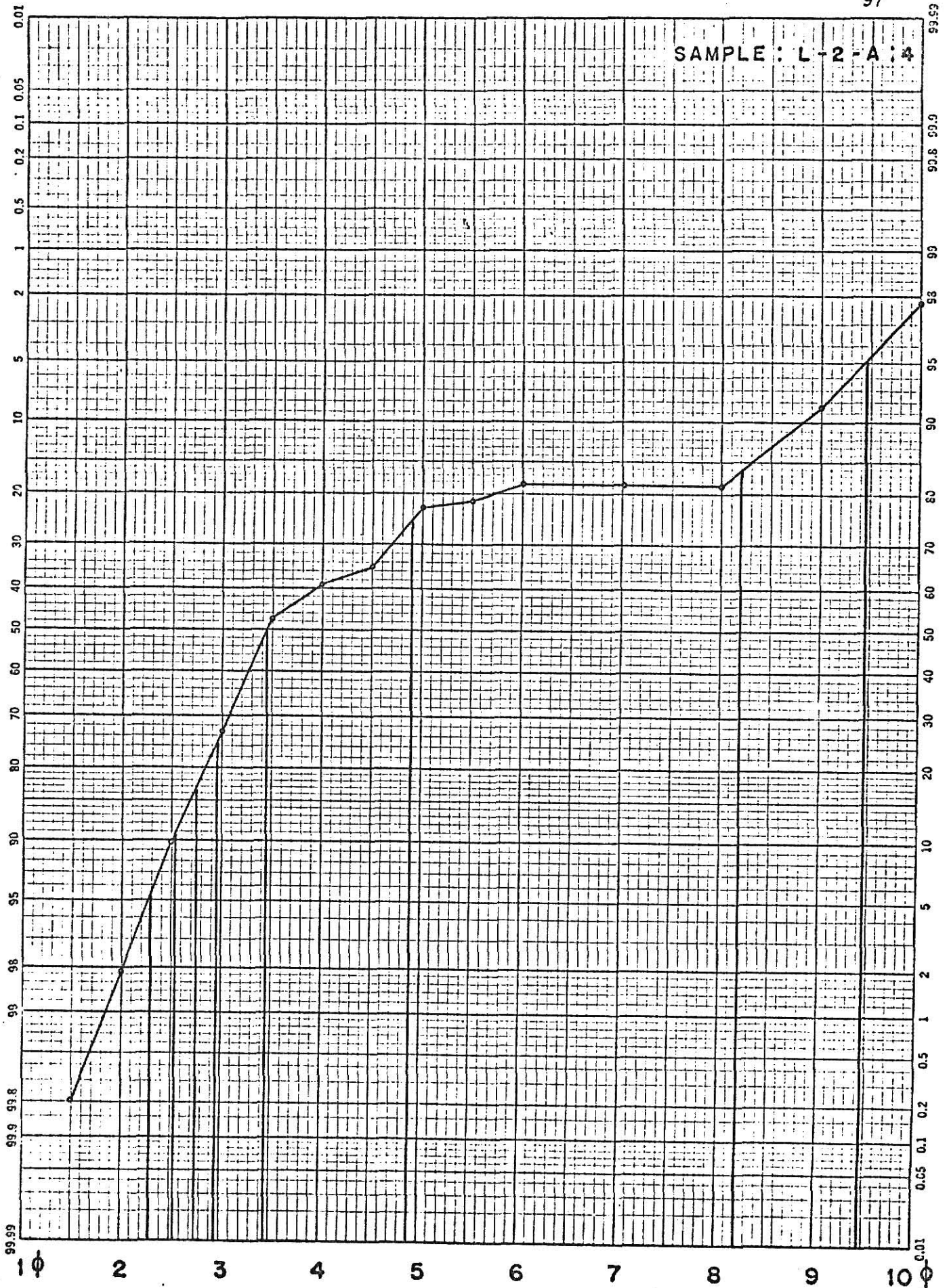
SAMPLE : L-3-A: FD



# CUMULATIVE FREQUENCY CURVE

97

SAMPLE: L-2-A:4

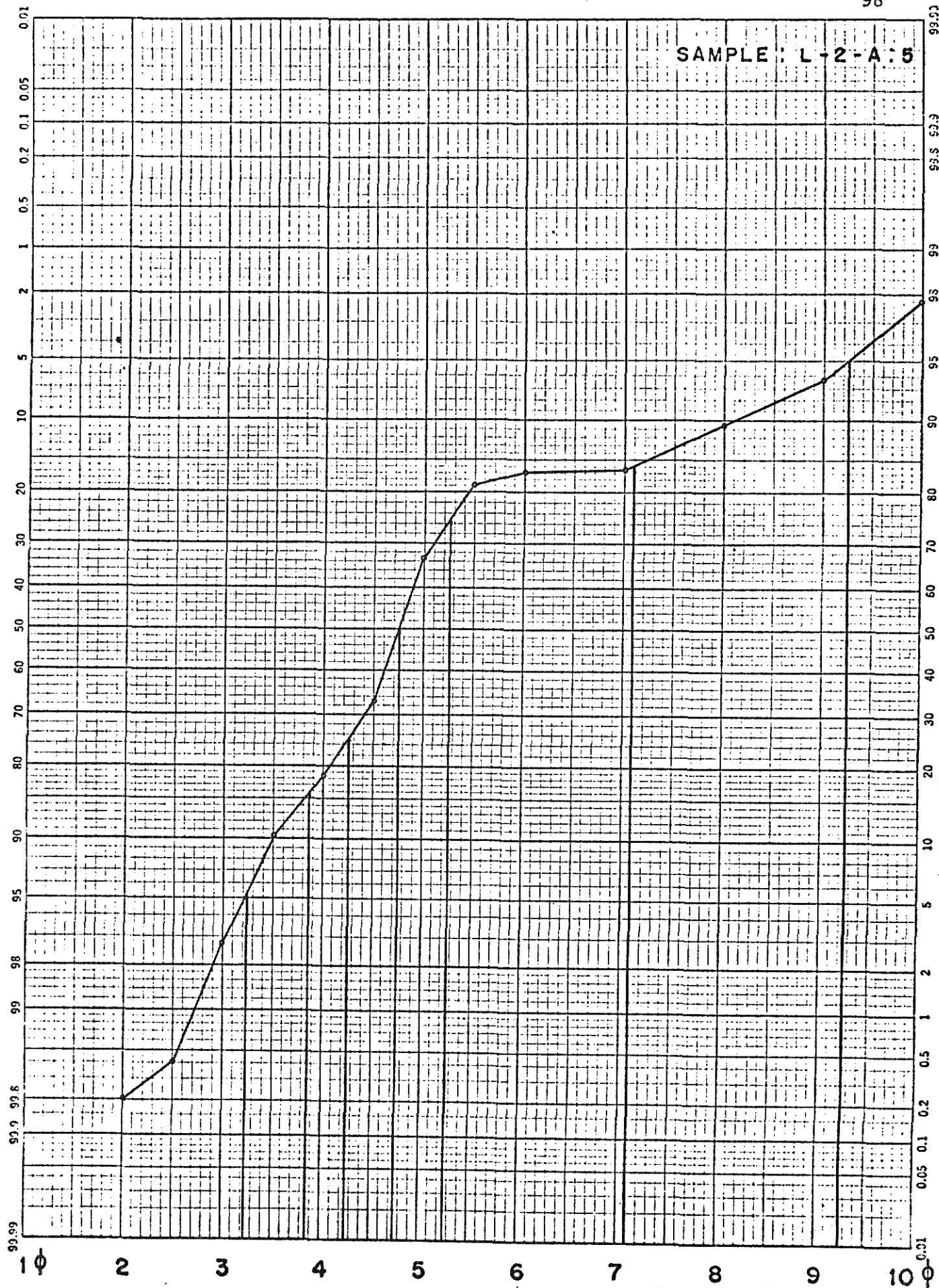




# CUMULATIVE FREQUENCY CURVE

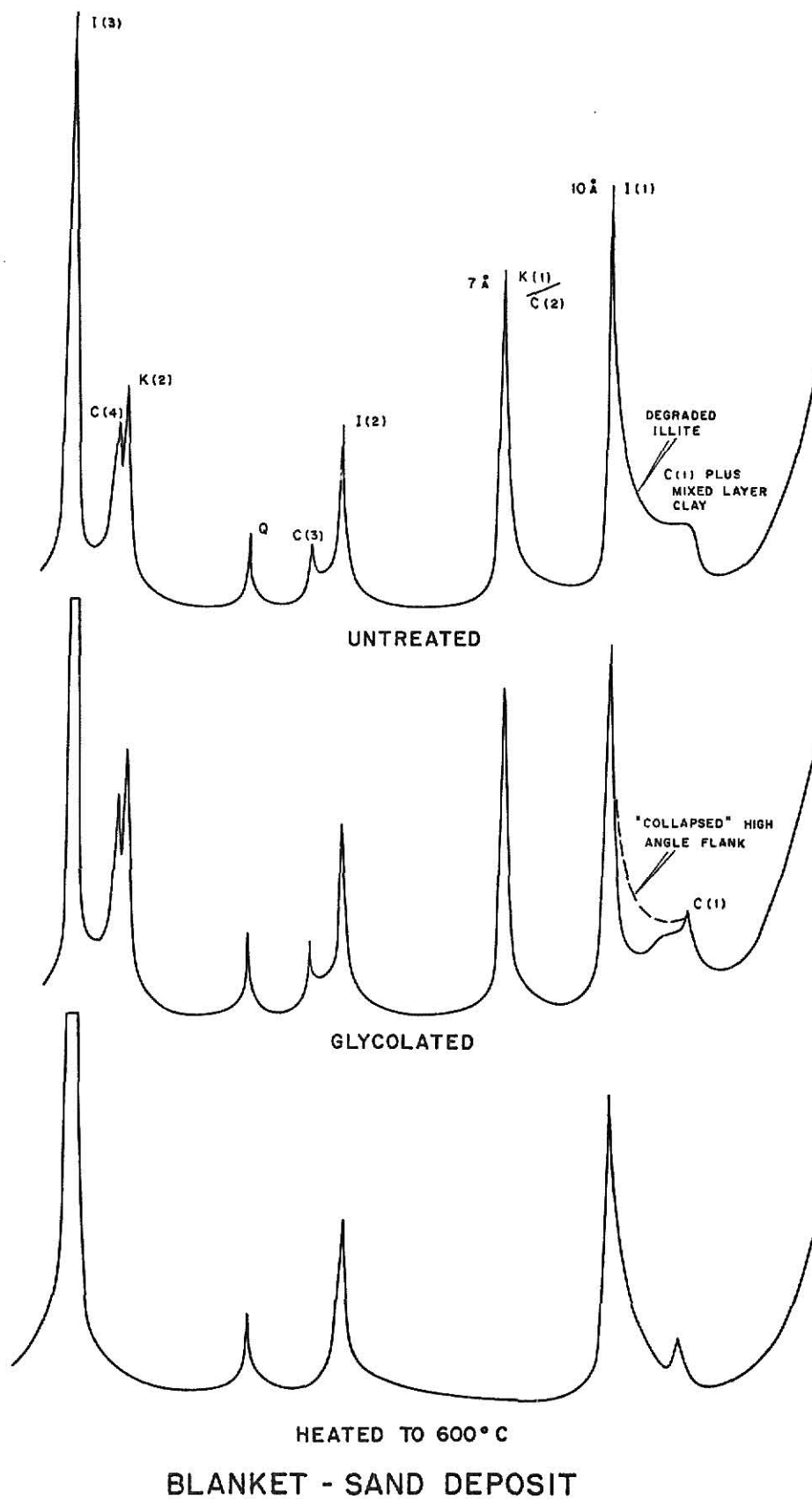
98

SAMPLE : L-2-A:5

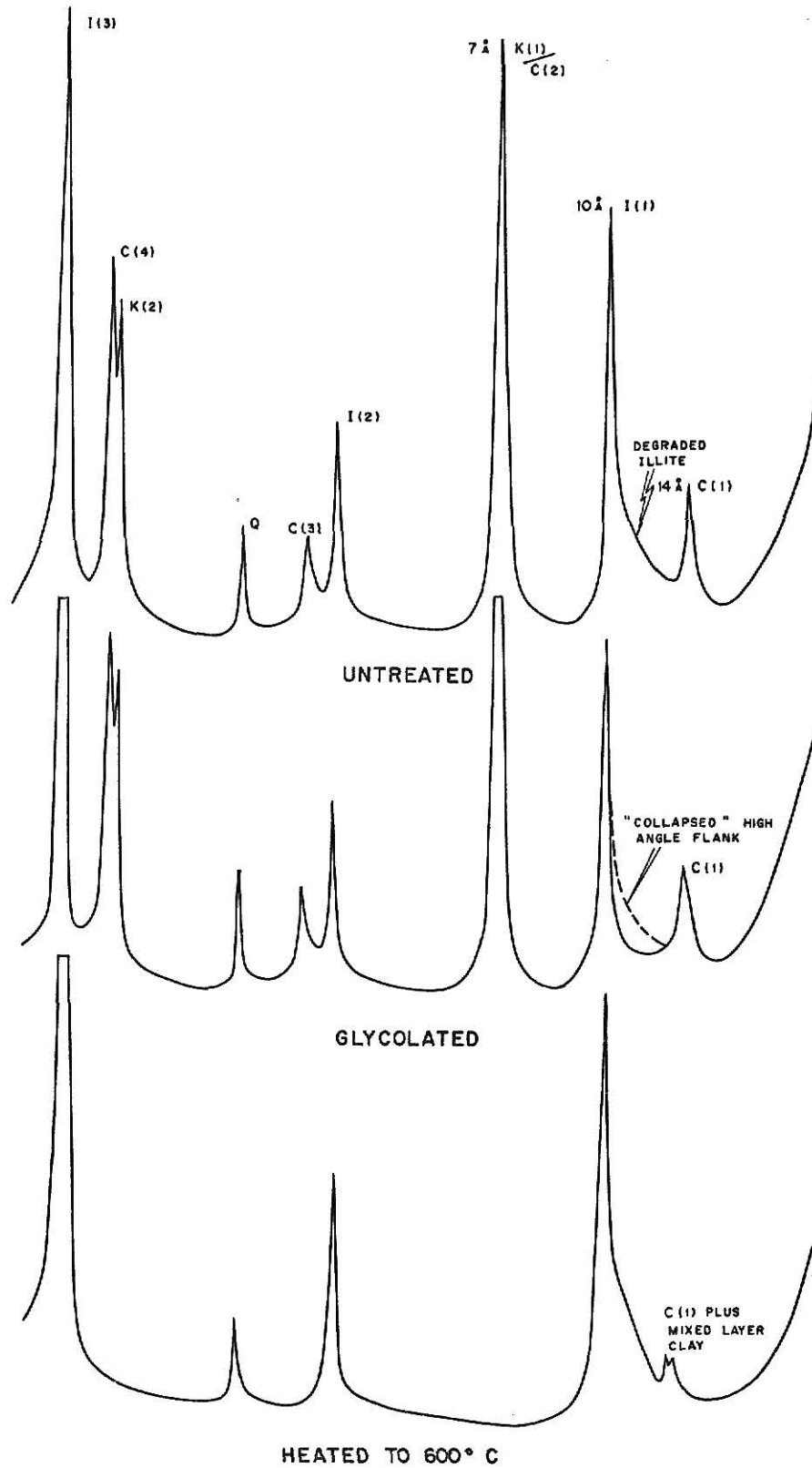


## Appendix II

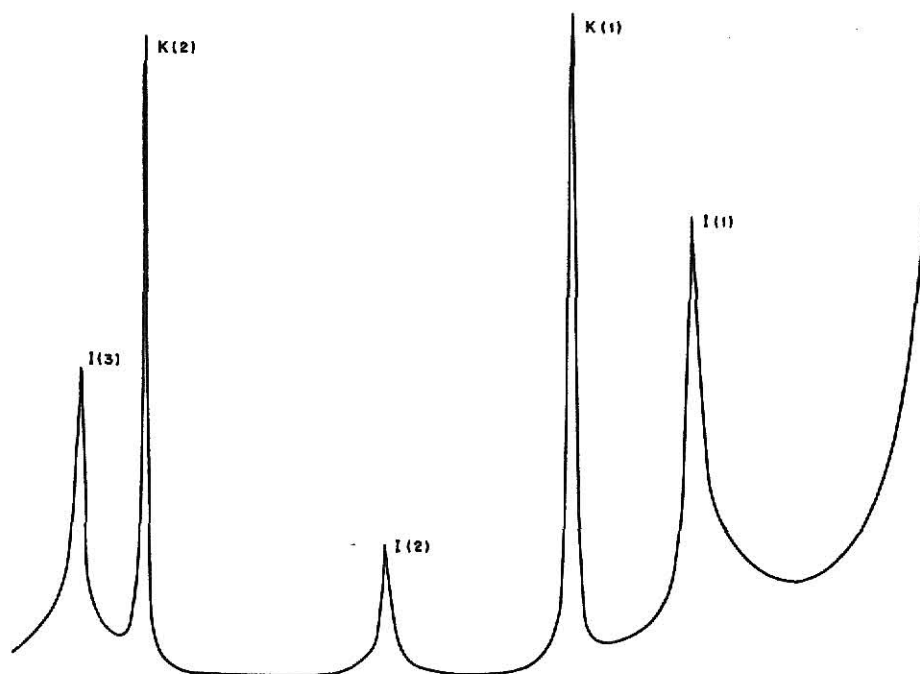
### Diffractograms of Clay Mineral Assemblage



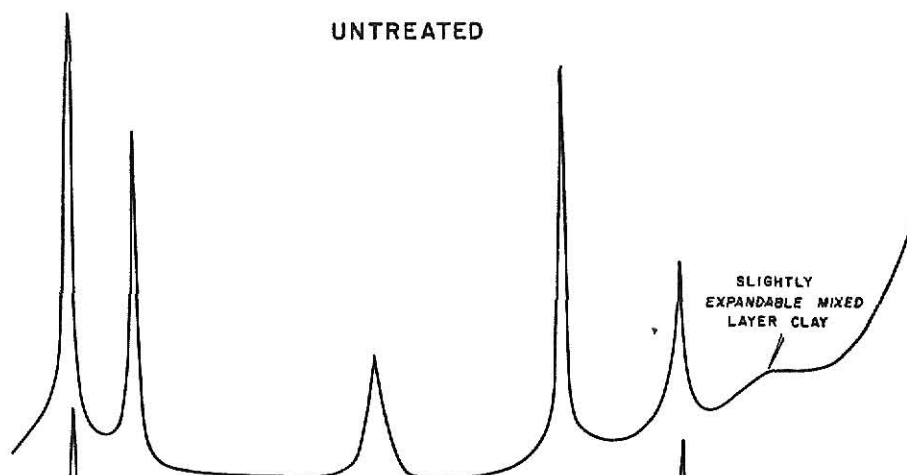




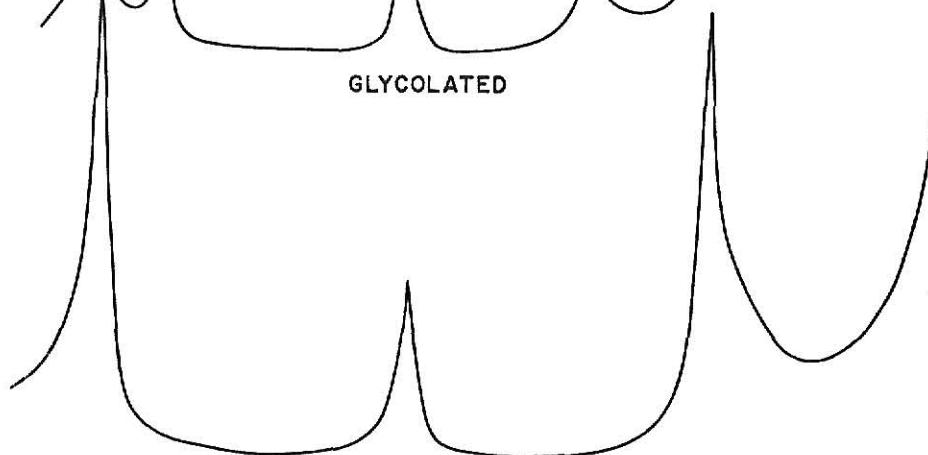
CHANNEL - SAND DEPOSIT ("FINE-DIRTY FACIES")



UNTREATED



GLYCOLATED



HEATED TO 600° C

CHANNEL - SAND DEPOSIT ( COARSE - CLEAN FACIES )

## Appendix III

## Detailed Results of Thin Section Modal Analyses

<u>Sample</u>	<u>Category</u>										
	Q <sub>1</sub>	Q <sub>2</sub>	Q <sub>3</sub>	Q <sub>4</sub>	F <sub>1</sub>	F <sub>2</sub>	F <sub>3</sub>	F <sub>4</sub>	RF <sub>1</sub>	RF <sub>2</sub>	M
L-1-A: MC	28	769	113	28	56	29	19	50	168	68	112
L-3-A: CC	9	42	8	3	2	2	0	2	7	6	19
L-3-A: FD	11	49	9	2	2	1	0	2	3	5	16
L-2-A: 5	7	60	3	0	1	0	1	1	7	2	18
L-2-A: 4	34	795	102	33	41	34	12	45	32	10	142
L-2-A: 3	3	56	10	2	3	1	1	2	8	4	10

# Appendix IV

## Detailed Results of Heavy Mineral Counts

<u>Mineral</u>	<u>Sample</u>							
	L-1-A:MC	L-3-A:CC	L-3-A:FD	L-2-A:5	L-2-A:4	L-2-A:3	L-2-A:2*	L-2-A:1
Zircon	137	120	110	101	133	117	83	90
Tourmaline	36	94	136	152	79	105	173	182
Garnet	98	32	20	18	37	25	19	4
Rutile	18	29	17	3	41	20	2	0
Staurolite	5	8	0	2	3	11	0	0
Apatite	1	5	0	0	1	2	0	0
Miscellaneous	4	12	17	24	6	20	23	34

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\* Mudstones

GEOLOGY OF ANCIENT BLANKET AND CHANNEL DEPOSITS  
EXPOSED NEAR WAMEGO, KANSAS

by

JAMES D. VOSS

B. A., Lawrence University, Wisconsin, 1965

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AN ABSTRACT OF A THESIS

submitted in partial fulfillment of the  
requirements for the degree

MASTER OF SCIENCE

Department of Geology  
KANSAS STATE UNIVERSITY  
Manhattan, Kansas

1972

## ABSTRACT

This study describes an occurrence of blanket and channel sandstones stratigraphically near the Pennsylvanian-Permian boundary in south-central Pottawatomie County, Kansas. Field investigation documents the existence of typical Wabaunsee cyclic sedimentation, and, with drilling records, establishes the existence of a blanket sandstone cut by a channel, the fill of which is also sandstone. The blanket sandstone of the Willard Shale, Wabaunsee Group, Upper Pennsylvanian Series, has not been reported this far south. The channel is of undetermined age but may be associated with a Pony Creek channel system nearby, and also of Upper Pennsylvanian age.

Petrologic study indicates lithologic types contained within both sandstone bodies are restricted to feldspathic litharenite and sublitharenite; individual mineral component abundances among samples are a function of mean grain size. All samples are carbonaceous and micaceous and with the exception of one channel facies are possessed of a clay-iron oxide 'binder'. Framework components of the samples are notably stable, while the nonopaque, nonmicaceous heavy mineral fractions are ultra stable. Texturally the samples are slightly clayey, silty to very fine grained, poorly sorted sandstones. The same clay minerals are present in both sandstone bodies; they are illite, a chlorite-group mineral, illite-mixed-layer or interstratified clay, and kaolinite. Post-depositional diagenetic alteration and authigenic development have altered the original state of the clay mineral assemblages.

K-Ar dates on the muscovite component separated from both sandstones are  $389 \pm$  million years for the blanket sandstone and  $377 \pm 11$  million years for the channel sandstone; Rb-Sr dates on muscovite are  $401 \pm 20$  million years from the blanket and  $368 \pm 20$  million years from the channel. Thin section petrography and heavy mineral study of the sandstones indicate a combination

of sources in the provenance of the terrigenous sediment. An older (pre-Virgilian) sedimentary terrain was the likely immediate source of sediment for both sandstones. Composition of the primary source from which this older sedimentary terrain was derived include acid plutonic rocks, pegmatites and hydrothermal veins, low rank metamorphic and high rank metamorphic rocks. The ultimate source for most of the terrigenous sediment seems to have been the Canadian Shield, but that does not explain the Lower to Middle Devonian age of the muscovite.