PETROLOGY OF PART OF THE WEWOKA FORMATION
(PENNSYLVANIAN) IN HUGHES COUNTY, OKLAHOMA

by

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INTRODUCTION

Purpose of Investigation

This investigation is a petrologic study of a thin stratigraphic interval of Desmoinesian rocks in Hughes County, Oklahoma, and was undertaken to investigate the relation between sedimentary rocks, their contained fossil assemblages, and depositional environments. These latter two aspects have been previously studied by West (1970). Grain size, clay mineral, and paleo-salinity analyses were made on part of the Wewoka Formation in a small geographic area. From these data the following interpretations were made: (1) relationship among grain size, clay mineralogy, and paleosalinity, (2) source area and environments of deposition as reflected by the sedimentary rocks, and (3) relationship between sedimentary rocks and benthic marine communities.

Location

The area of investigation is in Sec. 33, T. 7 N., R. 9 E., of Hughes County, Oklahoma, and is southeast of Holdenville, on the northwest side of Lake Holdenville (fig. 1). A stream draining the overflow from Lake Holdenville dissects the area and has made extensive exposures of portions of the strati-graphic interval studied. Additional outcrops are in small gullies and open glades on steep hillsides.

Previous Investigations

The Wewoka Formation was originally described by Taff (1901), and named after the town of Wewoka in east-central Seminole County. Weaver (1954) mapped the geology of Hughes County and measured sections. Detailed mapping and stratigraphic studies of the study area by West (1970) provided the basic framework for this investigation.
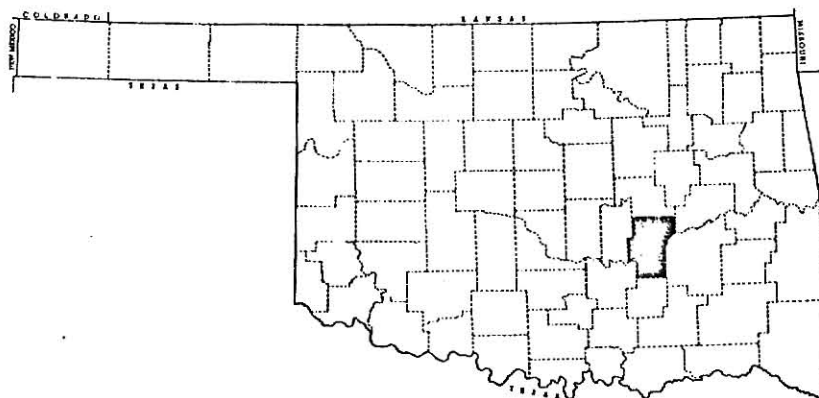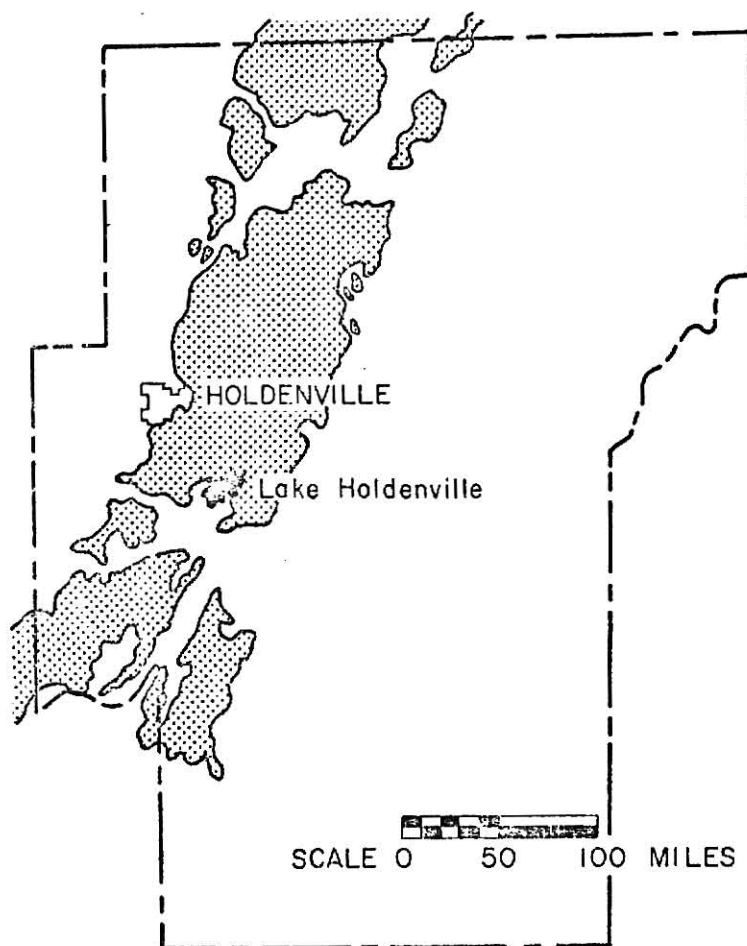
Fig. 1. Outcrop pattern of the Wewoka Formation in Hughes County, Oklahoma (after Miser, et. al., 1954).

GEOLOGIC SETTING AND STRATIGRAPHY

Tectonically, the study area is on the northwest edge of the Arkoma (McAlester) Basin and the extreme southwest corner of the Cherokee Basin (fig. 2). Immediately west is the Hunton-Tishomingo Uplift and the Nemaha Ridge with the Ouachita structural complex to the south and southeast.

The Wewoka Formation is in the upper part of the Des Moines Series (Marmaton Group) of the Pennsylvanian System. It crops out from east-central Pontotoc County northeastward through Hughes, Okfuskee, Okmulgee, and Tulsa Counties to the Arkansas River (Miser, et. al., 1954).

The following information about the Wewoka Formation in Hughes County was obtained from Weaver (1954). Exposures of the Wewoka occur in a broad belt about seven miles wide that trends northeastward across the west-central and north-central part of the county. Strike is approximately N. 25° E. and dip is about one degree northwest. The Wewoka lies conformably on the Wetumka Shale and is overlain conformably by the Holdenville Shale (fig. 3). Four massive to thin-bedded sandstone units separated by thick, interbedded and intertonguing shales constitute the Wewoka. Weaver designated the sandstone units Pwk-1 to Pwk-4 in ascending order and the shales as Pwk (fig. 4).

The sandstones are fine-grained but conglomeratic beds occur near the base of some sandstone units. These sands are generally friable and light brown to reddish brown and orange. Shales are bluish gray to yellowish gray-brown, sandy, silty, and fossiliferous.

The average thickness of the formation is 680 feet in Hughes County (Weaver, 1954). North of Hughes County the thickness is consistent; however, shales thicken and sandstones become thinner and more abundant (West, 1970). North of the Arkansas River, equivalents of the Wewoka Formation are limestones and shales (Oakes, 1951).

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POSITIVE FEATURES

NEGATIVE FEATURES

WEWOKA OUTCROP

Ozark Uplift

Cherokee Basin

Arkoma Basin

Ouachita Mtns.

Anadarko Basin

Amarillo-Wichita Mtns.

HOLDENVILLE

Lake Holdenville

SCALE 0   50   100 MILES
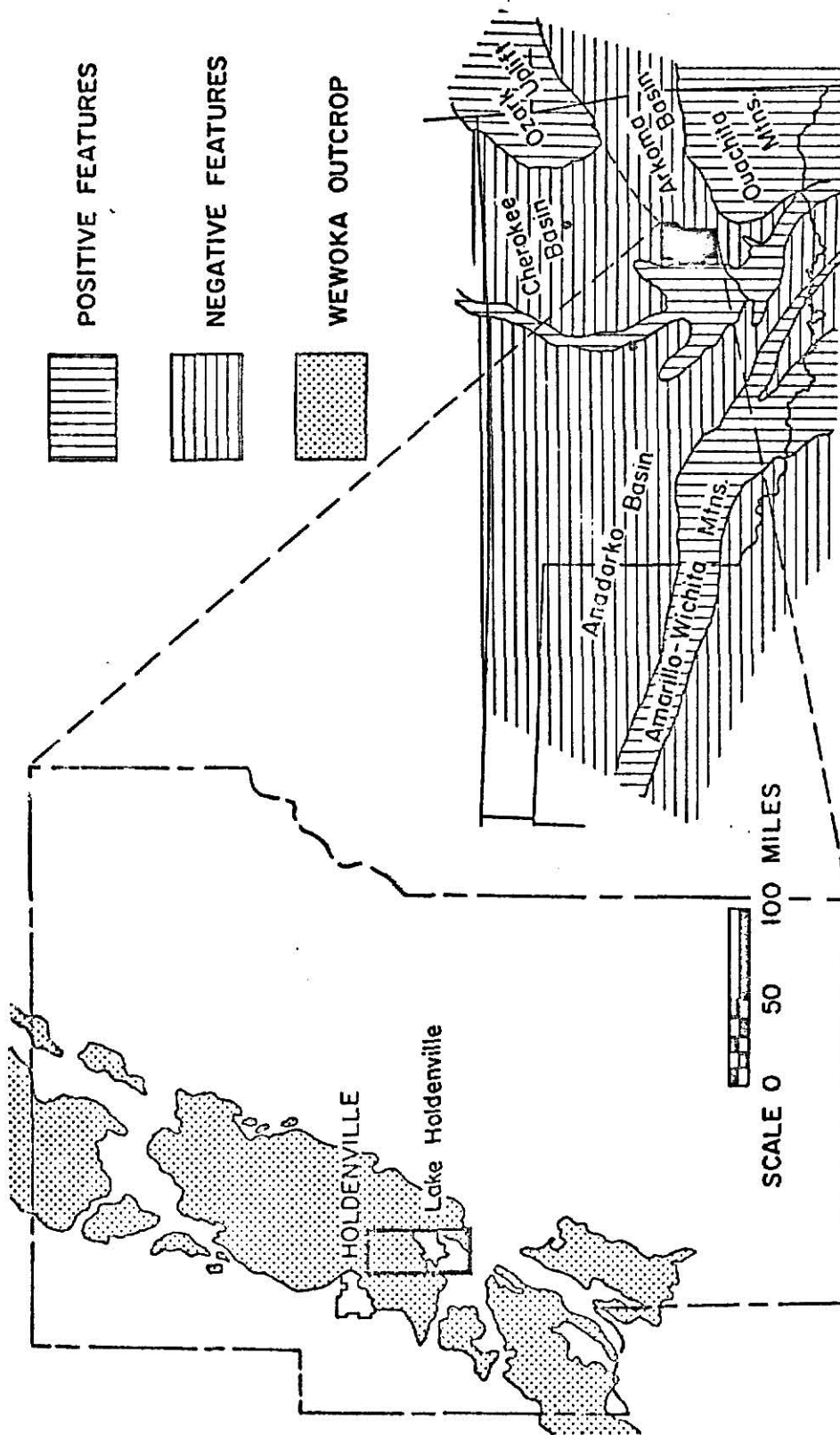
Fig. 2. Geologic setting of the study area (after West, in press).

KANSAS AND NEBRASKA	CENTRAL OKLAHOMA & ARKANSAS VALLEY	MID CONT.
Marmaton group — Lenapah ls.; Altamont ls.; Laberdie ls.; Myrick Sta.; Labette shale; Higginsville; Summit coal; Blackjack ls.; Mulky coal	Holdenville; Wewoka fm.; Wetumka fm.	DES MOINES SERIES
Cherokee shale — Bevier coal; Ardmore ls.; Mineral coal; Bluejacket ss.	Calvin ss.; Senora fm.; Stuart sh.; Thurman ss.; **Boggy fm.** — Tiawah ls.; Inola ls.; Bluejacket ss.; **Savanna fm.** — Spaniard Cr.; Tamaha ss.	

Fig. 3. Stratigraphic sections of rocks of the Des Moines Series in Oklahoma, Kansas, and Nebraska (after West, 1970).

Fig. 4. Pennsylvanian (Wewoka) geology and localities of shale and mudstone exposures studied in Hughes County, Oklahoma (modified from West, 1970).

The stratigraphic interval under study is the shale and mudstone above sandstone Pwk-2 through part of sandstone Pwk-3a (fig. 4). Maximum thickness of the shale and mudstone interval in the study area is 128 feet (West, 1970), but only 82 feet are exposed.

Lithology

Shale and mudstone with many irregular, laterally non-persistent beds of calcareous and ironstone nodules compose the interval. Shale composes the lowest part of the interval and the overlying mudstone can be divided into three units on subtle lithologic differences (West, 1970). The terms shale and mudstone are used to describe rocks composed of predominantly silt and clay in which neither component exceeds a 2:1 ratio (Folk, 1968). Shale is used to denote fissility whereas mudstone lacks this property (Pettijohn, 1957). The upper 2.9 feet consist of interbedded mudstone and siltstone in gradational contact with sandstone Pwk-3a.

Shale.--Shale is assumed to be in contact with the underlying sandstone Pwk-2 although this contact was not observed. The shale is dark gray to black, hard, platy to fissile, and pyritic. The following information was obtained from West (1970). Calcareous nodule horizons occur in the shale, as well as "phosphatic" nodules randomly scattered and in layers. One of the calcareous nodular beds contains abundant marine invertebrates. Dominant fossils are plant debris, conularids, orbiculoids, some foraminifers, pyrite filled burrows?, conodonts, scolecodonts, ostracodes, fish debris, some goniatites, and fecal pellets. Most fossils are partially or completely replaced by pyrite.

Lower Mudstone.--The lower mudstone unit has a gradational contact with the shale below and is about 47 feet thick. It is yellowish brown, platy to blocky, slightly calcareous, and contains ironstone (sideritic) nodules.

These nodules are in discontinuous beds and are also randomly scattered throughout the unit. A molluscan fossil assemblage is dominant in this unit (West, 1970).

Middle Mudstone.--Overlying the lower mudstone gradationally is the middle mudstone unit, approximately 21 feet thick. It is platy to blocky, calcareous, and olive gray to bluish gray. Ironstone (sideritic) nodules are less abundant than in the unit below; small, irregular calcareous nodules also occur. Brachiopods, horn corals, bryozoans, trilobites, crinoid debris and fusulinids are the primary biotic elements in this unit (West, 1970).

Upper Mudstone.--The contact of the upper mudstone is gradational with the unit below and is approximately 36 feet thick, platy to blocky, and yellowish to orangish brown and brownish yellow. It contains many discrete ironstone (sideritic) nodules and nodular beds. Grain size increases in the upper part; contact with the overlying sandstone is gradational. Thin beds of sandstone are interbedded with silty, sandy mudstone in the upper 2.9 feet of this unit. Beds of sandstone become thicker until the base of a massive sandstone is encountered. Arenaceous foraminifers, ostracodes, and plant debris dominate this upper mudstone unit (West, 1970).

Sandstone.--Overlying the mudstone interval is sandstone Pwk-3a that is moderately soft, friable, thick- to medium-bedded and cross-bedded. The unit is a ferruginous, moderately well-sorted very fine quartz sandstone and ranges from reddish brown to orange brown and brownish yellow. Northeast of the study area at locality J, the sandstone is finer and contains more clay and silt. Trace fossils and plant fragments of *Lepidodendron*, *Stigmaria*, and *Calamites* are in the unit (West, 1970).

Cyclicity

West (1970) examined two other shale and mudstone units within the Wewoka

Formation and found them to be similar to this interval. A definite repetition of the fossil assemblages, lithologies, and color changes were observed in shale and mudstone intervals below sandstones Pwk-2 and Pwk-3b. In general, my field observations support this proposed cyclicity. Figure 5 is a graphic representation inferred from West's observations of the three intervals of mudstone. More detailed work would be necessary to firmly establish this repetition.

METHODS OF INVESTIGATION

Field Procedure

Collection of samples was greatly facilitated by available detailed topographic maps and measured sections (West, 1970). West collected 19 samples for his detailed fossil analysis and statistically grouped them into four benthic communities. The 30 samples collected for this study are distributed as follows: 5 from the interval below the Glabrocingulum Community, 12 from the Glabrocingulum Community, 2 from the Transitional Community, 2 from the Cleiothyridina Community, 1 from the Mesolobus Community, and 5 (2 are sandstones) above the Mesolobus Community (fig. 6). An almost complete section was exposed at locality E at which 11 samples were collected; lateral equivalents were obtained where possible at localities G, C, F, H, and A (fig. 7). Although outside this area, three additional samples were collected at locality J (fig. 4) because of the well-exposed contact between the sandstone and underlying mudstone.

Laboratory Procedure

Grain Size Analysis.--Measurement of sediment grain size enables one to understand processes which result in rock formation and to reconstruct

LITHOLOGY	AGE	CONTACTS	BIOTIC ELEMENTS	DEPOSITIONAL ENVIRONMENTS
	Pwk-3b			
	Pwk (M F)	Gradational	Brachiopods Crinoids	
			Cephalopods Pelecypods Gastropods	
	Pwk-3a (A)	Sharp	*Stigmaria* sp. *Lepidodendron* sp.	
			Ostracodes Arenaceous Foraminifers	
	Pwk (K O W)	Gradational	Brachiopods Crinoids	
		Gradational	Cephalopods Pelecypods Gastropods	
		Gradational	Plant Debris Conularids	
	Pwk-2 (E)			
			Plant Debris	
	Pwk (W)	Gradational	Ostracodes Arenaceous Foraminifers	
			Brachiopods Crinoids	

Fig. 5. Cyclicity of depositional environments in the Wewoka Formation (after West, 1970).
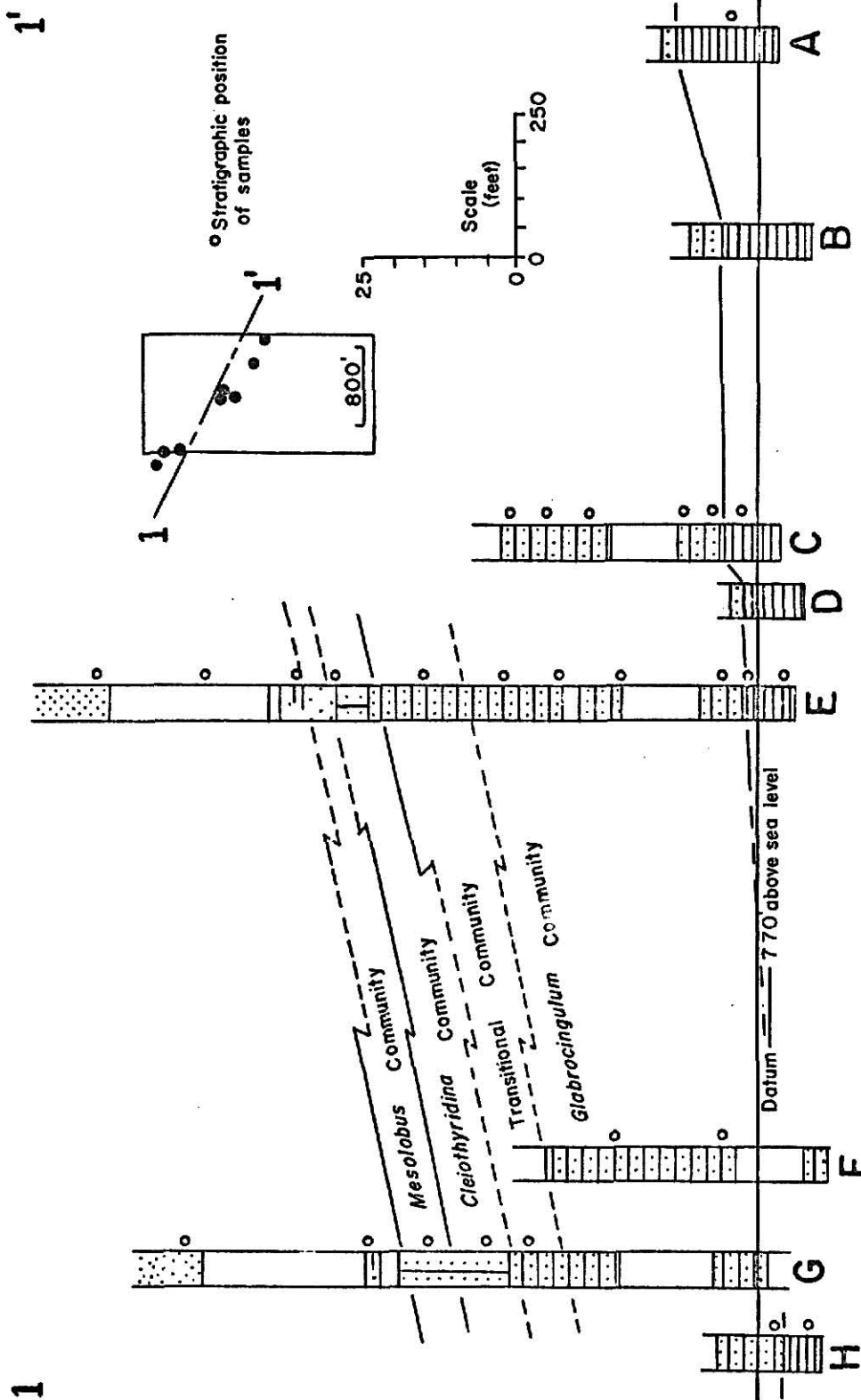
Fig. 6. Location of samples with respect to benthic marine communities proposed by West (1970).
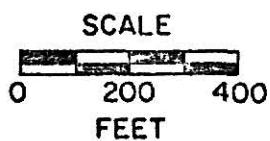
Fig. 7. Location of measured sections (after West, 1970).

depositional environments.

The grain size scale used in this study is taken from Folk (1968) as modified by Twiss (1972, personal communication) and is shown in Table 1. Particle size limits are often expressed in terms of U.S. Standard sieve mesh numbers, phi-notation, or in metric units of the Wentworth (1922) scale. The Wentworth scale is a logarithmic scale in that each grade limit is twice as large as the succeeding grade limit. It can be expressed as the function:

$$\text{Particle Diameter in mm.} = 2^{\pm\phi}$$

where ϕ is an integral exponent (Royse, 1970). Krumbein (1934) observed that Wentworth values could be expressed as the exponent "phi" and proposed a phi-notation based on the logarithm to the base 2 of the particle diameter. This notation takes the following form:

$$\phi = -\log_2 (\text{diam. in mm.})$$

There are two main advantages in using the phi-notation: (1) use of small, whole numbers simplifies evaluation and presentation of data, and (2) results may be plotted on graph paper with an arithmetic ordinate.

No single technique can be satisfactorily adopted for analysis of sediments with a wide range in particle size. Consequently, two separate procedures were used depending on rock type, as indicated by the flow sheet (fig. 8).

Pipette analysis.--Pipette sedimentation was used for analyzing the less than 62.5 micron fraction, after separation from the coarse fraction (fig. 8). Because of very small size, particles in the fine fraction cannot be measured by sieving.

The fine fraction was obtained from shales and mudstones by wet sieving through a 62.5 micron screen and from sandstones by saving the pan fraction after dry sieving the entire sediment. This fraction was then suspended in

Table 1

Grain Size Scales for Sediments (After Folk, 1968)

U.S. Standard Sieve Mesh #	Millimeters	Phi	Wentworth Size Class
	4096	-12	
	1024	-10	Boulder
	256	- 8	
	64	- 6	Cobble
	16	- 4	Pebble
5	4	- 2	
6	3.36	- 1.75	
7	2.83	- 1.5	Granule
8	2.38	- 1.25	
10	2.00	- 1.0	
12	1.68	- 0.75	
14	1.41	- 0.5	Very coarse sand
16	1.19	- 0.25	
18	1.00	0.0	
20	0.84	0.25	
25	0.71	0.5	Coarse sand
30	0.59	0.75	
35	0.50	1.0	
40	0.42	1.25	
45	0.35	1.5	Medium sand
50	0.30	1.75	
60	0.25	2.0	
70	0.210	2.25	
80	0.177	2.5	Fine sand
100	0.149	2.75	
120	0.125	3.0	
140	0.105	3.25	
170	0.088	3.5	Very fine sand
200	0.074	3.75	
230	0.0625	4.0	
270	0.053	4.25	
325	0.044	4.5	Very coarse silt
	0.037	4.75	
	0.031	5.0	
	0.0156	6.0	Coarse silt
	0.0078	7.0	Medium silt
	0.0039	8.0	Fine silt
	0.0020	9.0	Very fine silt
	0.00098	10.0	
	0.00049	11.0	
	0.00024	12.0	Clay
	0.00012	13.0	
	0.00006	14.0	

```
        ┌─────────────┐                              ┌─────────────────────┐
        │ Sandstone   │                              │ Shale and mudstone  │
        └─────────────┘                              └─────────────────────┘
               │                                              │
     ┌──────────────────────┐                        ┌──────────────────┐
     │   Disaggregation     │                        │   Raw sample     │
     │ with mortar and pestle│                       │   15-20 gm.      │
     └──────────────────────┘                        └──────────────────┘
               │                                              │
     ┌──────────────────┐                           ┌──────────────────────┐
     │  Sample split    │                           │       Crush          │
     │ to approx. 100 gm.│                          │  Mix in blender      │
     └──────────────────┘                           │ with Calgon solution*│
               │                                     └──────────────────────┘
     ┌───────────────────────┐                               │
     │   Sieve on Ro-Tap     │                     ┌──────────────────────┐
     │1/4 phi intervals, 15 min.│                  │     Wet sieve        │
     └───────────────────────┘                     │ with Calgon solution*│
               │                                    └──────────────────────┘
```

Sandstone path:
- Disaggregation with mortar and pestle
- Sample split to approx. 100 gm.
- Sieve on Ro-Tap 1/4 phi intervals, 15 min.
  - Coarse fraction > 62 u → Weigh each sieve fraction
  - Fine fraction < 62 u → Hydrometer jar

Shale and mudstone path:
- Raw sample 15-20 gm.
- Crush, Mix in blender with Calgon solution*
- Wet sieve with Calgon solution*
  - Fine fraction < 62 u → Hydrometer jar
  - Coarse fraction > 62 u → Dry → Sieve, 5 min. 1 phi intervals → Weigh each sieve fraction

Hydrometer jar branch:
- Hydrometer jar Fill to 1000 ml. with Calgon solution*
- Pipette analysis 1 phi intervals
- Dry and weigh beakers
- Compute aliquot weights less Calgon dispersant
- Compute weight in each phi class interval

* Concentration of Calgon solution 5.5 gm./liter.

Fig. 8. Flow sheet for grain size analysis.

a hydrometer jar filled to 1000 ml. with a dispersing solution. After thorough mixing the jar was placed in a Magni Whirl hydrometer jar bath, set at a constant temperature of 24° C. A waiting period of two to four hours allowed the suspension to reach thermal equilibrium with the water in the bath. The suspension was then mixed thoroughly using a stirring rod. Pipette samples of 20 ml. were taken from the suspension at fixed times and depths indicated in Table 2. These 20 ml. aliquots were emptied into pre-weighed beakers and evaporated to dryness. After cooling the beakers were weighed to the nearest 0.001 gram.

Weight of the dried aliquot minus the amount of dispersant represents 1/50 of the weight of sediment present at the fixed depth at a fixed time. The difference between the weights of successive withdrawals, multiplied by 50, represents the amount of sediment present in each phi class.

Wadell's (1936) modification of Stokes' law was used to calculate settling velocities because the particles are intermediate in shape between a disc and a sphere and the percentage of clay particles is high. Stokes' equation assumes the particles to be spheres. Wadell's equation is expressed as:

$$Vp = Kr_p^2; \text{ where } K = \frac{(d_1 - d_2)}{7n}$$

Vp is practical settling velocity, r_p is practical settling radius, $(d_1 - d_2)$ is the difference in fluid particle density, g is the gravitational constant, and n is the viscosity of water. For particles with a specific gravity of 2.65 in fluid medium at 24° C., $K = 2.515 \times 10^4$. The withdrawal times and depths in Table 2 were calculated from the above equation.

Sources of error in the analysis include incomplete initial homogenization, turbulence created during aliquot withdrawal, fluctuations in water temperature, and incomplete dispersion. The first two factors can be

minimized by practicing good technique, and the third by use of a water bath
or closely controlled room temperature. Incomplete dispersion is probably the
major source of inaccurate results. Trial analyses in this study were charact-
erized by floculation of the particles. To obtain a well-dispersed suspension,
a dispersing agent, sodium hexametaphosphate (Calgon) was used. Such a disper-
sing agent establishes a molecular layer around the particles causing mutual
particle repulsion. Preliminary experiments were conducted to select the
optimal concentration of Calgon to obtain maximum dispersion. Calgon solutions
of 0.5 gram/liter, 2.5 gram/liter, and 5.5 gram/liter were used in testing
several samples. Maximum dispersion was obtained using a 5.5 gram/liter
concentration, and it was used for all pipette analyses.

Table 2

Settling Times Computed According to Wadell's Modification
of Stokes' Law at 24° C.

Diameter (phi)	(mm.)	Depth (cm.)	Settling Times (hours)	(minutes)	(seconds)
4	1/16	20	0	1	00
5	1/32	20	0	5	26
6	1/64	20	0	21	47
7	1/128	10	0	43	30
8	1/256	10	2	45	--
9	1/512	7	8	00	--
10	1/1024	5	22	57	--
11	1/2048	5	88	27	--

Sieve Analysis.--Sand from both sandstone and shale and mudstone samples was separated into classes using U.S. Standard screens (fig. 8). The coarse fraction of the shale and mudstone samples was shaken for 5 minutes in a stack of 3 inch, 1 phi interval sieves. All sandstone samples were sieved using 8 inch, $\frac{1}{4}$ phi interval sieves on a Tyler Ro-Tap for 15 minutes. Each fraction was weighed to the nearest 0.001 gram on an analytical balance, and the pan fraction saved for pipette analysis.

The weights of each fraction derived from sieve analysis and from pipette analysis were combined for each sample. Cumulative weight percentages were computed for the entire sample.

Clay Mineral Analysis.--General laboratory procedure for clay mineral analysis is shown in the flow sheet (fig. 9).

Fractionation of Clay Minerals.--About 20 grams of air-dried sample was crushed to pea-size chunks and smaller. The sample was transferred to a blender and mixed for 10 minutes with about 600 ml. of distilled water. Sand was removed by wet-sieving through a 230-mesh screen and then washed until the clay remained in suspension by: (1) centrifuging, (2) decanting the clear liquid, and (3) adding distilled water.

The washed slurry was placed in a 1000 ml. cylinder, filled to volume with distilled water and mixed. After eight hours of settling, the < 2 micron fraction was removed by pipette and centrifuged to fractionate the < 1 micron size clays which were used for all analyses.

Oriented Slides.--A 2 ml. portion of the less than 1 micron slurry was placed on glass slides and allowed to air dry. One untreated slide was X-rayed, the other slides saved for treatments.

Heat Treatment.--Behavior upon heating is a useful method in identification of clay minerals. Kaolin minerals dehydrate and lose their crystallinity
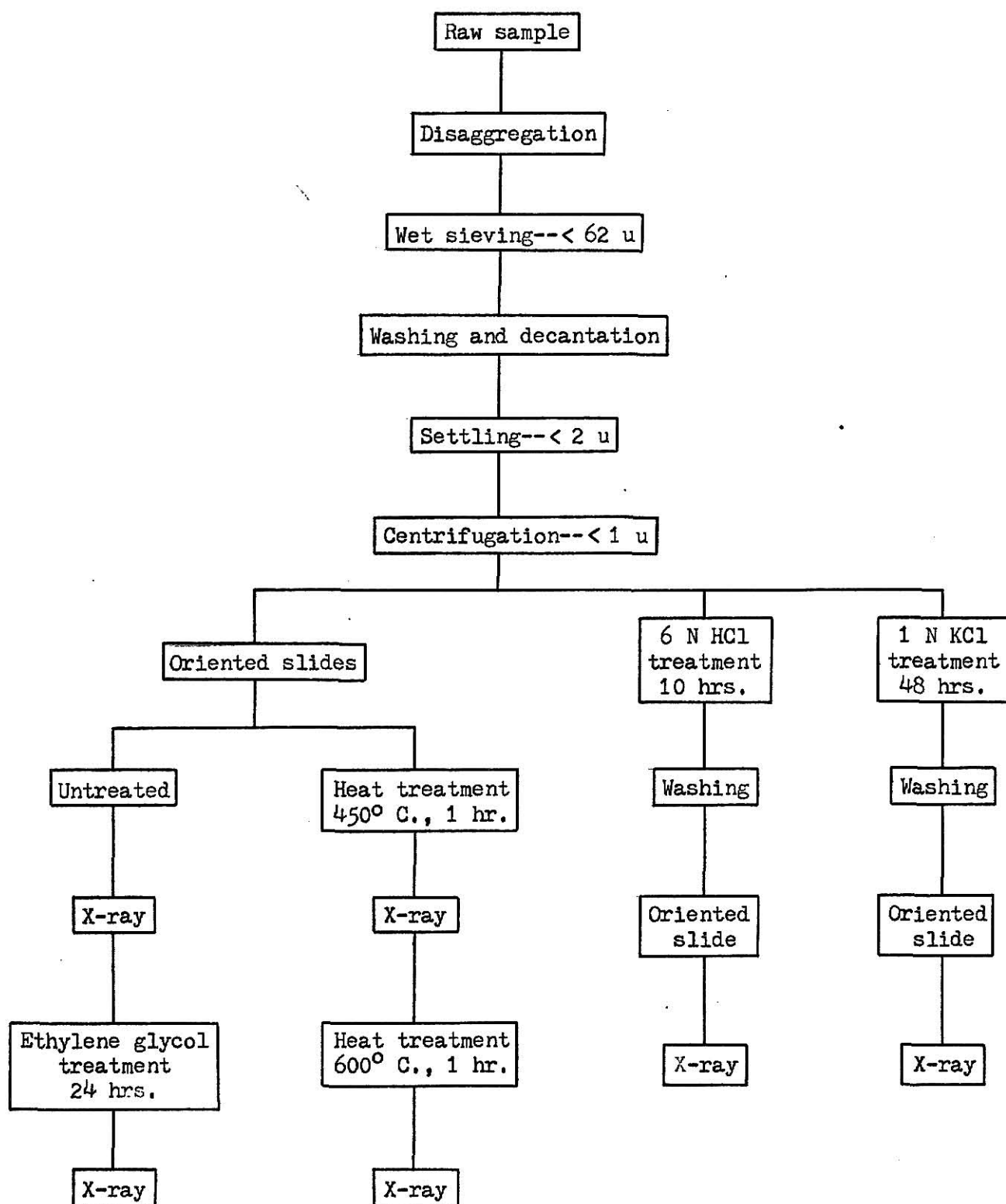
Fig. 9. Flow sheet of procedure used in clay mineral analysis.

at 550-600° C. (Brindley, 1961a, p. 84). Heating montmorillonite at 300° C. removes interlayer water and collapses the structure to 10 A.U. (Carroll, 1970). Vermiculite loses interlayer water when heated, but quickly rehydrates (Walker, 1961). Chlorite is unaffected by heat up to 600° C.; however, poorly crystalline types decompose at temperatures as low as 450° C. (Brindley, 1961b). Illite is not affected significantly below 600° C.

Oriented slides were heated for one hour at 450° C. and 600° C. in a muffle furnace and X-rayed immediately.

HCl Treatment.--Destruction of some clay minerals by HCl treatment serves as a means of identification. MacEwan (1961) reported that montmorillonite is soluble upon treatment by warm HCl. Lee (1972) stated that vermiculite is not resistant to the treatment. Carroll (1970) stated that chlorite is soluble in HCl.

About 25 ml. of slurry was treated with 25 ml. of 6 N HCl for 10 hours. The slurry was then washed until a pH of 7 was approached. Approximately 5 ml. of ethyl alcohol was added to prevent curling of the oriented layer as it dried on the glass slide.

Glycolation.--Certain clay minerals when treated with organic liquids expand the basal spacing as much as 3 A.U. Clay minerals that undergo this expansion include montmorillonite, mixed-layer clays with an expandable component, and some varieties of chlorite and vermiculite (Carroll, 1970). Oriented slides were placed in a dessicator containing ethylene glycol for at least 24 hours, then X-rayed immediately after removal.

Ion Exchange Treatment.--Ion exchange capacity provides information on the interlayer charge of a mineral; and according to Weaver (1958a), this property is applicable for differentiating the origin of some minerals. For example, montmorillonite derived from a pre-existing illite has a high

interlayer charge; montmorillonite formed by alteration of volcanic ash has a low charge (Weaver, 1958a).

Four samples containing illite and interlayered illite and montmorillonite were treated with 1 N potassium chloride solutions. About 20 ml. of the chloride salt solution was added to 25 ml. of the slurry and allowed to stand for 48 hours with stirring at intervals of a few hours. Samples were then washed, centrifuged, and oriented slides prepared.

X-ray Diffraction.--Oriented slides were analyzed using a Norelco Wide Range Diffractometer with the following settings: Ni filtered Cu K-alpha radiation, with 35 kilovolts and 18 milliamperes, scanning speed of 1°/min., chart speed 20 inches/hr., time constant of 2 seconds, and proportional counter detector. The pulse height analyzer was set at a level of 5.04 volts with a window of 2.20 volts; the detector voltage was 1.62 kilovolts. The goniometer slit system consisted of divergent and antiscatter slits of one degree, and a 0.003 inch receiving slit.

Untreated slides were scanned from 62 to $1\frac{1}{2}$ degrees (two theta). All treated slides were run from 30 to $1\frac{1}{2}$ degrees (two theta).

Paleosalinity Determinations.--Paleosalinity estimations were made on shale and mudstone samples using the sedimentary phosphate method proposed by Nelson (1967). The method is based on the discovery that both recent and ancient argillaceous sediments contain small quantities of sedimentary phosphate that are widely distributed in sediments from different depositional environments (Nelson, 1967). This phosphate can be extracted selectively from the sediment and differentiated into fractions whose relative proportions are sensitive to the salinity of the water at the site of deposition. These phosphate fractions are interdependent variables affected by salinity, and the ratio between them is independent of their absolute abundance in the sediment.

Sediments serve as a reservoir for phosphorous and contain higher concentrations of phosphorous than is contained in natural waters (Nelson, 1967). Studies of lakes (Mortimer, 1941 and 1942) and of estuaries and marine waters by Rochford (1951), Jitts (1959), and Pomeroy, et. al. (1965), indicated that exchange of phosphate takes place between the muddy bottom and overlying water. Nelson (1967) stated that the dominant sedimentary phosphate in rivers and lakes is iron phosphate, whereas marine sediments contain calcium phosphate almost exclusively. In recent sediments, ranging from freshwater to open marine, Nelson (1967) found a direct relationship between salinity and the ratio of Ca-phosphate to Fe-phosphate plus Ca-phosphate. In the transition from freshwater to marine sediments, the chemical activity of iron decreases, but the activity of calcium increases with an increase in salinity (Nelson, 1967). Absence of iron phosphate where the water is more saline is caused by the combination of Ca^{2+} and PO_4^{3-}, under conditions of higher Ca^{2+} content in the water, reaching saturation sooner than the combination of PO_4^{3-} and Fe^{2+}, because the content of Fe^{2+} is lower in the interstitial water of sediments in the sea (Strokhov, 1969).

Fractionation of Sedimentary Phosphates.--Phosphates of aluminum, iron, and calcium are dominant phosphorous compounds in sediments. Each form can be extracted selectively by a fractionation procedure proposed by Chang and Jackson (1957) for soil phosphorous. The most common phosphorous compounds in soils are variscite, $AlPO_4 \cdot 2H_2O$; strengite, $FePO_4 \cdot 2H_2O$; and hydroxylapatite, $Ca_{10}(PO_4)_6(OH)_2$; each of which is very insoluble (Chang and Jackson, 1957). Each compound can be selectively removed by reacting in sequence with 0.5 N NH_4F (for Al-phosphate), 0.1 N NaOH (for Fe-phosphate), and 0.5 N H_2SO_4 (for Ca-phosphate).

Samples were finely ground using a Spex Industries Mixer/Mill for 10 to

15 minutes. Each sample was treated according to the following fractionation procedure (fig. 10) adapted from Chang and Jackson (1957) and Nelson (1967):

Extraction of Aluminum Phosphate. A 0.50 gram sample was placed in a 100 ml. centrifuge tube and shaken with 25 ml. of 1 N NH_4Cl for 30 minutes on a shaker which reciprocates about 250 times a minute. This process removed water soluble and loosely bound phosphorous as well as exchangeable calcium. The suspension was centrifuged and the supernatant liquid descarded.

To the sample in the centrifuge tube, 25 ml. of neutral 0.5 N NH_4F was added and the suspension extracted for 1 hour on the shaker. The suspension was centrifuged and the clear supernatant decanted and discarded because determinations were not performed on the aluminum phosphate fraction. This sediment sample was saved for extraction of iron phosphate.

Extraction of Iron Phosphate. The sediment sample saved after extraction of aluminum phosphate was washed twice with 15 ml. portions of saturated NaCl solution. It was then extracted with 25 ml. of 0.1 N NaOH on the shaker for 17 hours. The suspension was centrifuged at 2100 rpm for 20 minutes to obtain a clear solution, which was decanted into another centrifuge tube. The sediment sample was saved for extraction of calcium phosphate. If the decanted solution was highly colored with organic matter, 2 ml. of 2 N H_2SO_4 was added, followed by 1 or 2 drops of concentrated H_2SO_4. The suspension was centrifuged and the clear solution saved for analysis of phosphorous (fig. 11).

Extraction of Calcium Phosphate. The sediment sample saved after extraction of iron phosphate was washed twice with 15 ml.
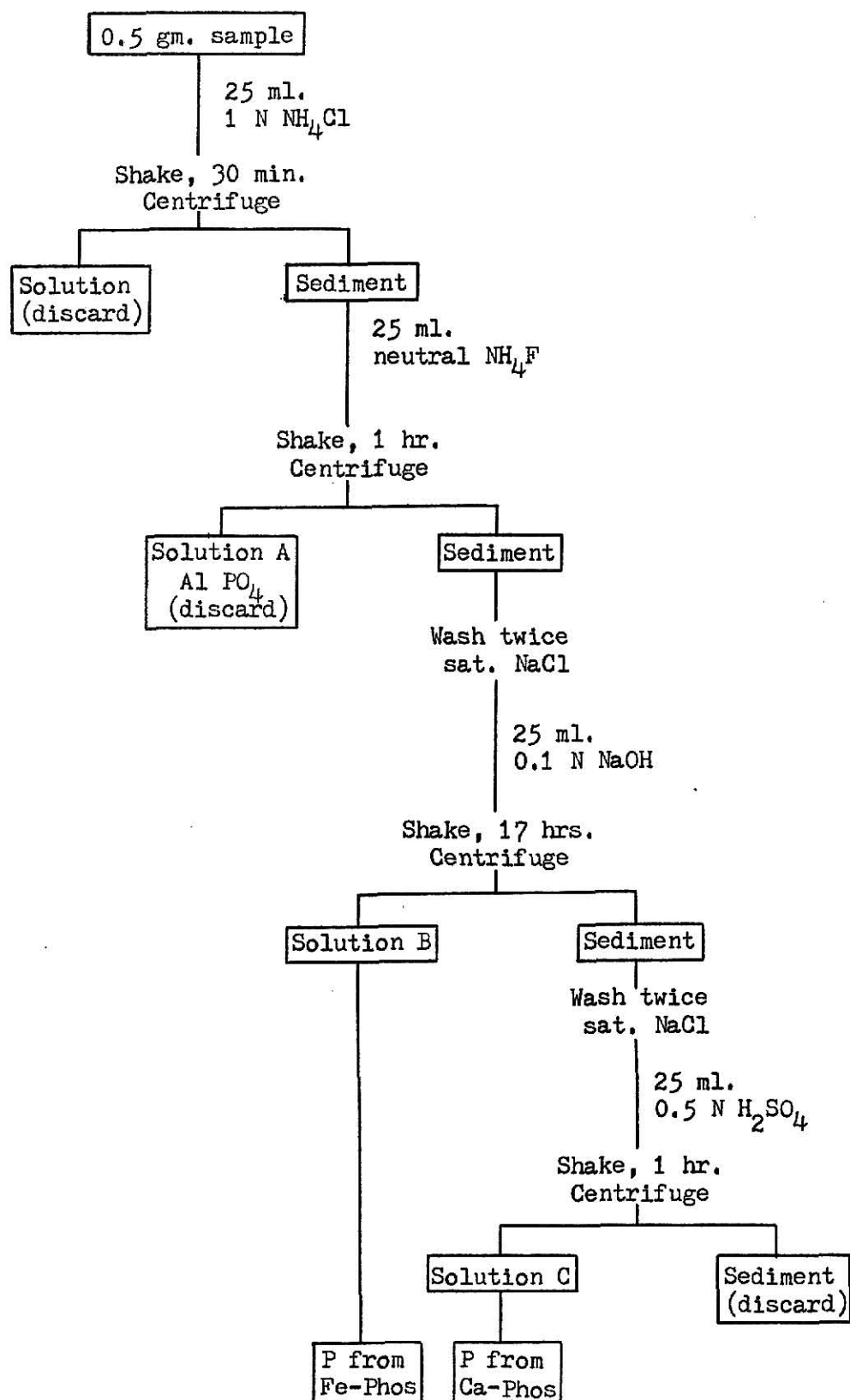
Fig. 10. Flow sheet of sedimentary phosphate fractionation procedure.
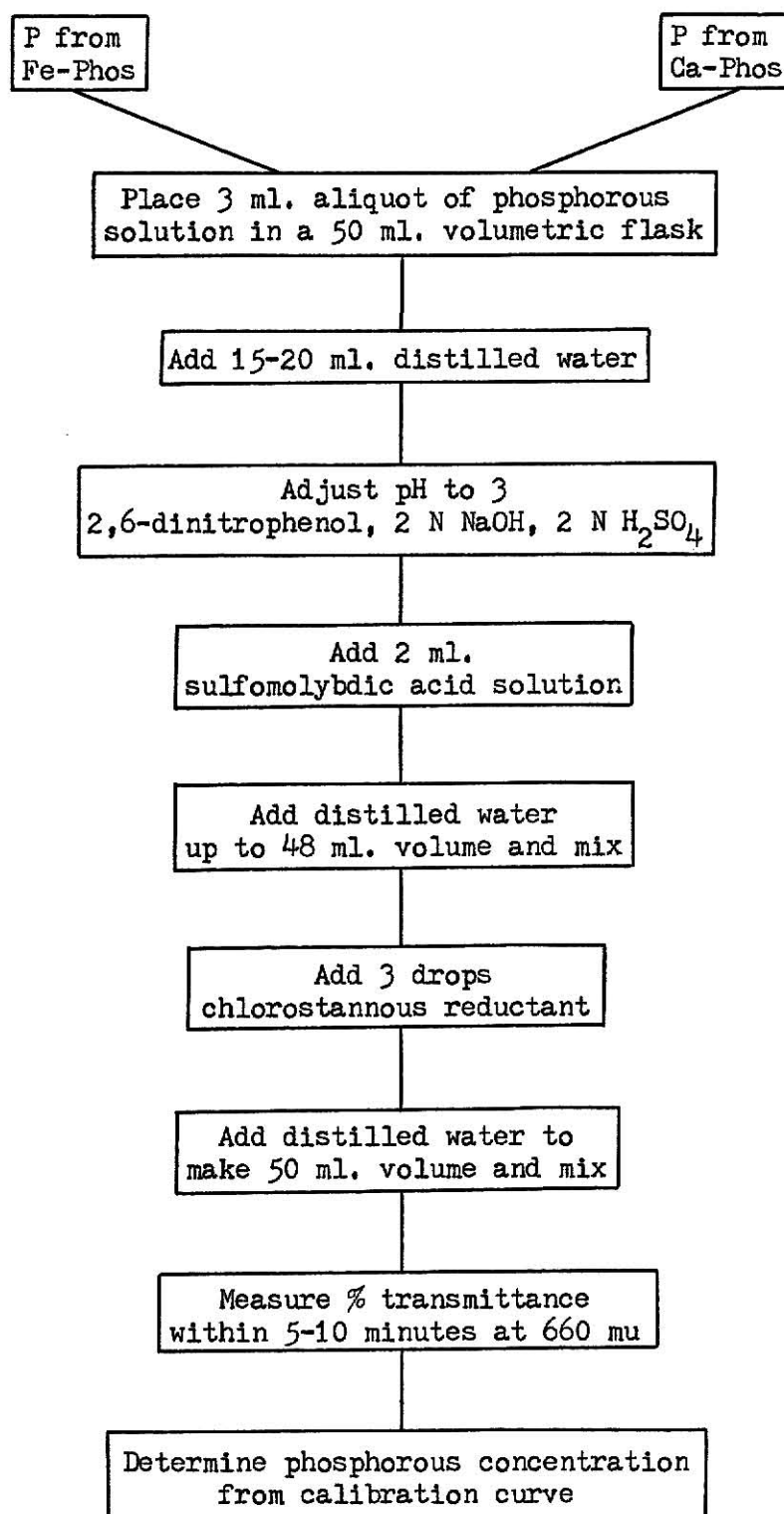
Fig. 11. Flow sheet of procedure used in spectrophotometric determinations of phosphorous.

portions of saturated NaCl solution. A 25 ml. volume of 0.5 N H_2SO_4 was added and the suspension extracted for 1 hour on the shaker, suspension centrifuged, sediment discarded, and the clear solution saved for analysis of phosphorous (fig. 11).

Spectrophotometric Determinations of Phosphorous.--Phosphorous concentrations of the clear liquids obtained from the extraction procedure (fig. 10) were determined by spectrophotometry. The method of phosphorous determination was a modification of the Osmond (1887) method, involving the molybdo-phosphoric blue produced by selective reduction of the heteropoly molybdo-phosphoric acid, in a sulfuric acid system (Jackson, 1958). The heteropoly complexes are believed to be formed by coordination of molybdate ions, with phosphorous as the central coordinating atom and the substitution of oxygen of the molybdate radicals for PO_4^{3-}:

$$H_3PO_4 + 12\ H_2MoO_4 \longrightarrow H_3P(Mo_3O_{10})_4 + 12\ H_2O$$
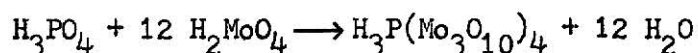
Ions besides (P^{5+}), which may act as the central coordinating atom to form 12-fold heteropoly acids with molybdate, include arsenic (As^{5+}), silicon (Si^{4+}), germanium (Ge^{4+}), and under certain conditions molybdenum (Mo^{6+}) and boron (B^{3+}). The method used provides a working range from 0.02 to 1.00 ppm of phosphorous, and has the highest sensitivity per unit of phosphorous. It provides for noninterference of Si in solution up to 200 ppm, Fe^{2+} up to 100 ppm, Fe^{3+} up to 2 ppm, Ti up to 20 ppm, Ca and Mg up to 500 ppm, Cl up to 250 ppm, and SO_4 up to 1000 ppm; however, it includes arsenate in chemical equivalence to phosphorous.

Phosphorous determinations were made on a Coleman Model 14 Universal Spectrophotometer set at a wavelength of 660 mu. A calibration curve was prepared by determining percent transmittance on five standard phosphorous solutions ranging in concentrations from 0.04 to 0.50 ppm phosphorous (fig. 12).
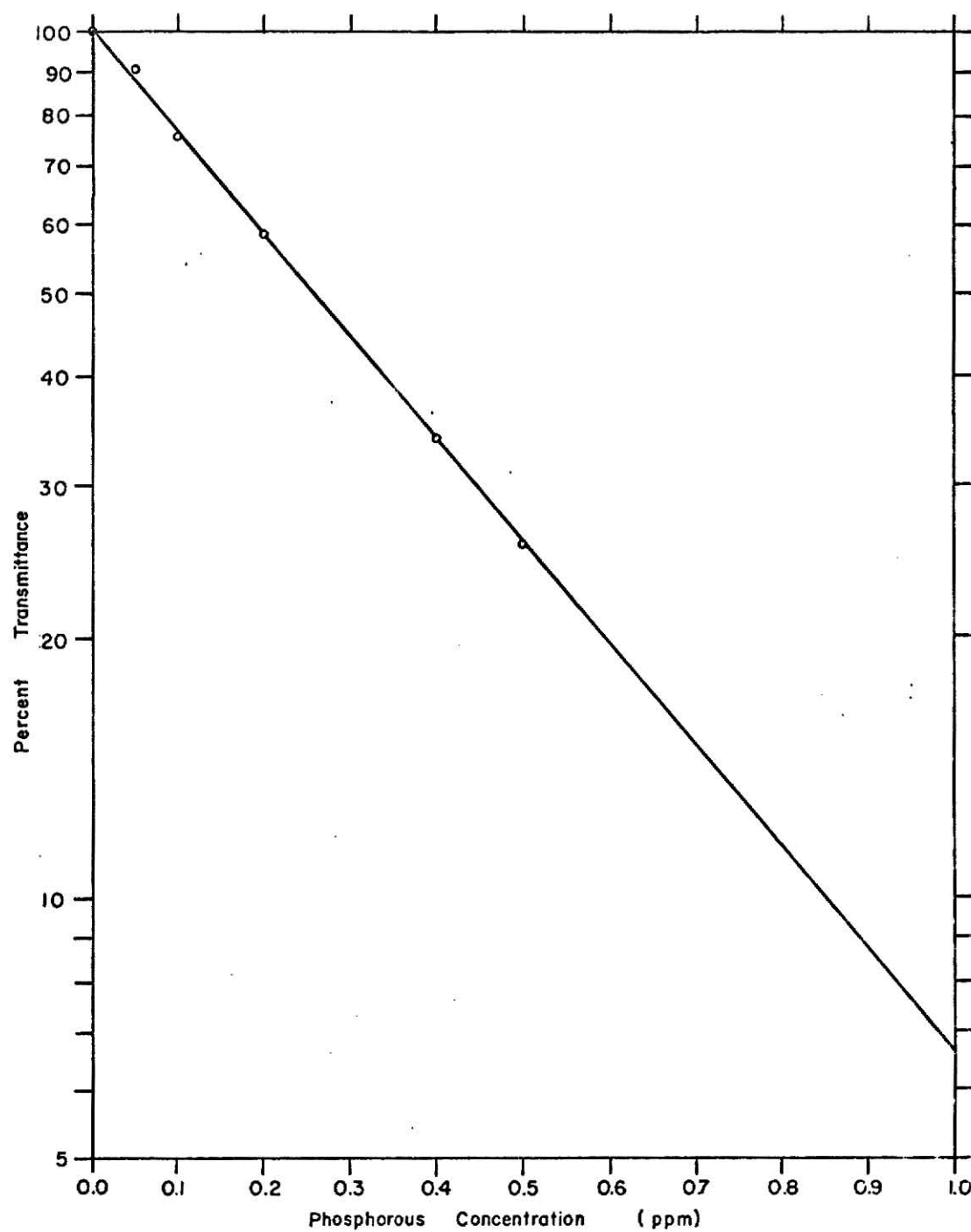
Fig. 12. Concentration-transmittance calibration curve.

From this calibration curve concentrations of test solutions were determined from the percent transmittance observed on the spectrophotometer. Reagents used in the sample processing were included in the standard phosphorous solutions and in the blanks to take into account the influence of extraneous ions and impurities which might affect the transmittance of the solutions.

Phosphorous determinations were made using the following procedure (fig. 11) proposed by Jackson (1958) and modified by Nelson (1967).

A 3 ml. aliquot of phosphorous solution was transferred by pipette to a 50 ml. volumetric flask and diluted with distilled water to about 20 ml. The pH of the solution was adjusted to about 3 by addition of 2 N NaOH until 2,6-dinitrophenol indicator turned yellow. Dropwise, 2 N H_2SO_4 was added until the solution became colorless, followed by the addition of 2 ml. of sulfomolybdic acid solution by pipette. Distilled water was added to a volume of about 48 ml. and the solution mixed. Three drops of chlorostannous reductant were added to develop the color. Distilled water was added to make up the 50 ml. volume and the solution mixed. The color was read on the spectrophotometer within a 5 to 10 minute interval at 660 mu. Phosphorous concentrations were obtained from the calibration curve (fig. 12). Samples which had little or no blue (greater than 95% transmittance) were rerun substituting a 9 ml. aliquot for the initial 3 ml. aliquot. Concentrations obtained were then divided by three.

Details of the reagents and apparatus needed for both the fractionation procedure and the phosphorous determinations are in Appendix IV.

INTERPRETATION OF LABORATORY DATA

Grain Size Analysis

Individual grain size weights were used to calculate class percentages,
cumulative weights, and cumulative weight percentages (Appendix II). Cumula-
tive curves were constructed by plotting cumulative weight percentages against
grain size in $\emptyset$ (phi) units on arithmetic probability paper.

Statistical Grain Size Parameters.--The following statistical parameters
of Folk and Ward (1957) were determined graphically from probability cumulative
curves:

Median (Md).--The median is the phi diameter that corresponds to the 50th
percentile of the cumulative curve. Half of the particles by weight are
coarser than the median, and half are finer. It is the most commonly used
measure and the easiest to determine; however, it does not reflect the overall
size of the sediment as it is not affected by the extremes of the curve.

Graphic Mean (M_z).--Graphic mean is the best measure for determining
overall size and is defined as:

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

Because it is based on three points, it is superior to the median and gives
a better overall picture. This measure includes the central 68 percent of
the size distribution curve.

Inclusive Graphic Standard Deviation (σ_I).--Inclusive graphic standard
deviation is given by the formula:

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

This is the best overall measure of sorting and includes 90 percent of the
grain size distribution. The verbal classification scale for sorting as
suggested by Folk (1968) is as follows:

σ_I under 0.35ϕ, very well sorted
0.35ϕ to 0.50ϕ, well sorted
0.50ϕ to 0.71ϕ, moderately well sorted
0.71ϕ to 1.00ϕ, moderately sorted
1.00ϕ to 2.00ϕ, poorly sorted
2.00ϕ to 4.00ϕ, very poorly sorted
over 4.00ϕ, extremely poorly sorted

Inclusive Graphic Skewness (Sk_I).--Inclusive graphic skewness is a measure
of the degree of asymmetry of the grain size distribution and is given by
the formula:

$$Sk_I = \frac{\phi16 + \phi84 - 2\phi50}{2(\phi84 - \phi16)} + \frac{\phi5 + \phi95 - 2\phi50}{2(\phi95 - \phi5)}$$

This measure includes 90 percent of the curve and is thus sensitive to the
"tails" of the curve as well as the central portion.

Symmetrical curves have Sk_I = 0.00; those with excess fine sediment have
a tail to the right (positive skewness), and those with excess coarse sediment
have a tail to the left (negative skewness). Verbal limits of skewness
suggested by Folk (1968) are:

+1.00 to +0.30, strongly fine-skewed
+0.30 to +0.10, fine-skewed
+0.10 to -0.10, near-symmetrical
-0.10 to -0.30, coarse-skewed
-0.30 to -1.00, strongly coarse-skewed

Graphic Kurtosis (K_G).--Kurtosis describes the departure from normality
of a grain size distribution curve. In a normal probability curve the spread
between $\phi5$ and $\phi95$ should be exactly 2.44 times the spread between $\phi25$ and
$\phi75$. It is expressed by the formula:

$$K_G = \frac{\phi95 - \phi5}{2.44(\phi75 - \phi25)}$$

This expression measures the ratio between the sorting in the "tails" of
the curve and that in the central portion. If the central portion is better
sorted than the "tails", the curve is said to be peaked or leptokurtic; if

the tails are better sorted than the central portion, the curve is flat-peaked

or platykurtic. Folk (1968) suggested the following verbal limits for kurtosis:

under 0.67, very platykurtic
0.67 to 0.90, platykurtic
0.90 to 1.11, mesokurtic
1.11 to 1.50, leptokurtic
1.50 to 3.00, very leptokurtic
over 3.00, extremely leptokurtic

The phi percentile values obtained graphically from the cumulative curves

are shown in Table 3; from these values statistical parameters shown in Table 4

were calculated.

Precision of Pipette Method.--Accuracy of any mechanical analysis of

sediment size cannot be measured because the true particle size distribution

is not known (Royse, 1970), but precision or the reproducibility of the

technique can be determined. Sternberg and Creager (1961) reported pipette

analyses of nine subsamples of identical composition where the concentration

of suspensions ranged from 3 to 25 grams per liter. Their results showed that

the median diameter (about $6\emptyset$) is reproducible at the 95 percent level within

about ±0.4 phi-units. Royse (1970) suggested careful analysis will result in

median values reproducible within ±0.2 phi-units. Although precision of the

method was not part of the study, two subsamples of each of two samples were

analyzed to get an idea of the reproducibility of the method. These results

in terms of grain size distribution and phi statistical parameter values are

in Table 5.

Evaluation of Data.--Grain size distributions were characterized by very

small differences within specific lithologies and form three basic patterns

which reflect the different lithologies of the samples (fig. 13). The three

patterns reflect the spread of grain size distribution curves for (1) the

shale, lower mudstone, middle mudstone, and lower part of the upper mudstone;

(2) the sandstone unit; and (3) the upper part of the upper mudstone in which

Table 3

Phi Percentile Values

Sample No.	5%	16%	25%	50%	75%	84%	95%
E-Sand	2.40	2.60	2.67	3.00	3.25	3.55	4.75
E-26-1	4.95	5.70	6.10	7.90	10.10	11.05	11.75
E-25'	5.40	6.30	6.90	8.90	10.70	11.20	11.90
E-25	4.90	6.30	7.20	9.40	11.05	11.35	12.00
E-23	4.20	5.50	6.45	8.40	10.30	11.05	11.75
E-22	5.45	6.60	7.20	8.80	10.30	11.00	11.70
E-20	5.10	6.30	6.95	8.70	10.35	11.10	11.75
E-16	5.10	6.30	7.00	8.80	10.60	11.15	11.85
E-12	5.65	6.65	7.25	8.75	10.30	11.05	11.75
E-7	5.80	6.95	7.60	9.10	10.50	11.10	11.80
E-4	5.70	7.00	7.50	8.80	10.40	11.10	11.80
G-Sand	2.55	2.70	2.85	3.15	3.53	3.90	5.15
G-20'	5.10	5.85	6.50	8.45	10.50	11.20	11.85
G-20	4.75	5.70	6.35	8.40	10.50	11.15	11.85
G-14	5.05	6.10	6.80	8.80	10.60	11.15	11.85
G-12	4.65	5.85	6.65	8.60	10.55	11.15	11.95
C-17'	4.95	6.15	6.90	8.85	11.00	11.30	12.00
C-17	4.90	6.30	7.00	8.90	10.90	11.35	12.05
C-15	5.10	6.35	7.10	9.05	10.90	11.30	11.90
C-10	5.80	6.60	7.20	8.90	10.75	11.25	11.90
C-8	5.80	6.80	7.45	9.10	10.90	11.25	11.90
C-3	6.10	7.05	7.55	8.75	10.20	10.95	11.70
H-6	4.90	5.95	6.70	8.55	10.30	11.05	11.75
H-4	5.25	6.40	7.05	8.60	10.20	11.00	11.70
F-18	5.35	6.60	7.30	9.00	10.85	11.25	11.90
F-6	5.20	6.45	7.20	8.90	10.70	11.30	12.00
J-Sand	3.33	3.55	3.68	3.90	4.25	4.80	7.75
J-1	3.95	4.80	5.50	7.70	10.10	11.05	11.75
J-2	4.45	4.90	5.30	7.20	9.80	11.10	11.75
A-6	6.40	7.40	7.90	9.30	10.90	11.30	11.90

Table 4

Phi Statistical Parameter Values

Sample No.	M_z	Md	I	Sk_I	K_G
E-Sand	3.05	3.00	0.59	+0.32	1.66
E-26-1	8.22	7.90	2.37	+0.16	0.70
E-25'	8.80	8.90	2.22	-0.07	0.70
E-25	9.02	9.40	2.34	-0.25	0.76
E-23	8.32	8.40	2.53	-0.05	0.80
E-22	8.80	8.80	2.05	-0.04	0.83
E-20	8.70	8.70	2.21	-0.04	0.80
E-16	8.75	8.80	2.24	-0.06	0.77
E-12	8.82	8.75	2.02	+0.01	0.82
E-7	9.05	9.10	1.96	-0.07	0.85
E-4	8.97	8.80	1.95	+0.05	0.86
G-Sand	3.25	3.15	0.69	+0.39	1.57
G-20'	8.50	8.45	2.36	+0.02	0.69
G-20	8.42	8.40	1.44	-0.01	0.70
G-14	8.68	8.80	2.29	-0.09	0.73
G-12	8.53	8.60	2.43	-0.06	0.77
C-17'	8.77	8.85	2.36	-0.08	0.71
C-17	8.85	8.90	1.34	-0.07	0.75
C-15	8.90	9.05	2.27	-0.13	0.73
C-10	8.92	8.90	2.08	0.00	0.70
C-8	9.05	9.10	2.03	-0.06	0.72
C-3	8.92	8.75	1.82	+0.09	0.87
H-6	8.52	8.55	1.32	-0.04	0.78
H-4	8.67	8.60	2.13	0.00	0.84
F-18	8.93	9.00	2.15	-0.07	0.76
F-6	8.87	8.90	2.24	-0.05	0.80
J-Sand	4.08	3.90	0.98	+0.59	3.18
J-1	7.85	7.70	2.75	+0.06	0.70
J-2	7.73	7.20	2.66	+0.25	0.67
A-6	9.33	9.30	1.81	-0.01	0.75

Table 5

Result of Duplicate Pipette Analysis of Two Samples

Grain Size Distribution
(Cumulative Percent)

Class Interval (Phi Units)	Sample E-20		Sample E-25'	
	Run 1	Run 2	Run 1	Run 2
4.0- 5.0	3.63	3.80	1.60	1.78
5.0- 6.0	14.28	12.35	12.81	12.24
6.0- 7.0	25.36	25.29	26.98	26.28
7.0- 8.0	35.00	38.53	39.78	39.80
8.0- 9.0	55.36	54.41	53.95	54.34
9.0-10.0	70.00	69.71	68.67	70.41
10.0-11.0	80.00	82.65	79.29	83.16
> 11.0	100.00	100.00	100.00	100.00

Phi Statistical Parameter Values

Statistical Parameters	Sample E-20		Sample E-25'	
	Run 1	Run 2	Run 1	Run 2
Graphic Mean (M_z)	8.69	8.69	8.72	8.68
Median (Md)	8.72	8.72	8.73	8.70
Standard Deviation (σ_I)	2.27	2.19	2.22	2.15
Skewness (Sk_I)	-.034	-.040	-.007	-.013
Kurtosis (K_G)	.78	.80	.713	.76

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Fig. 13. Grain size distribution patterns of the lithologic units.
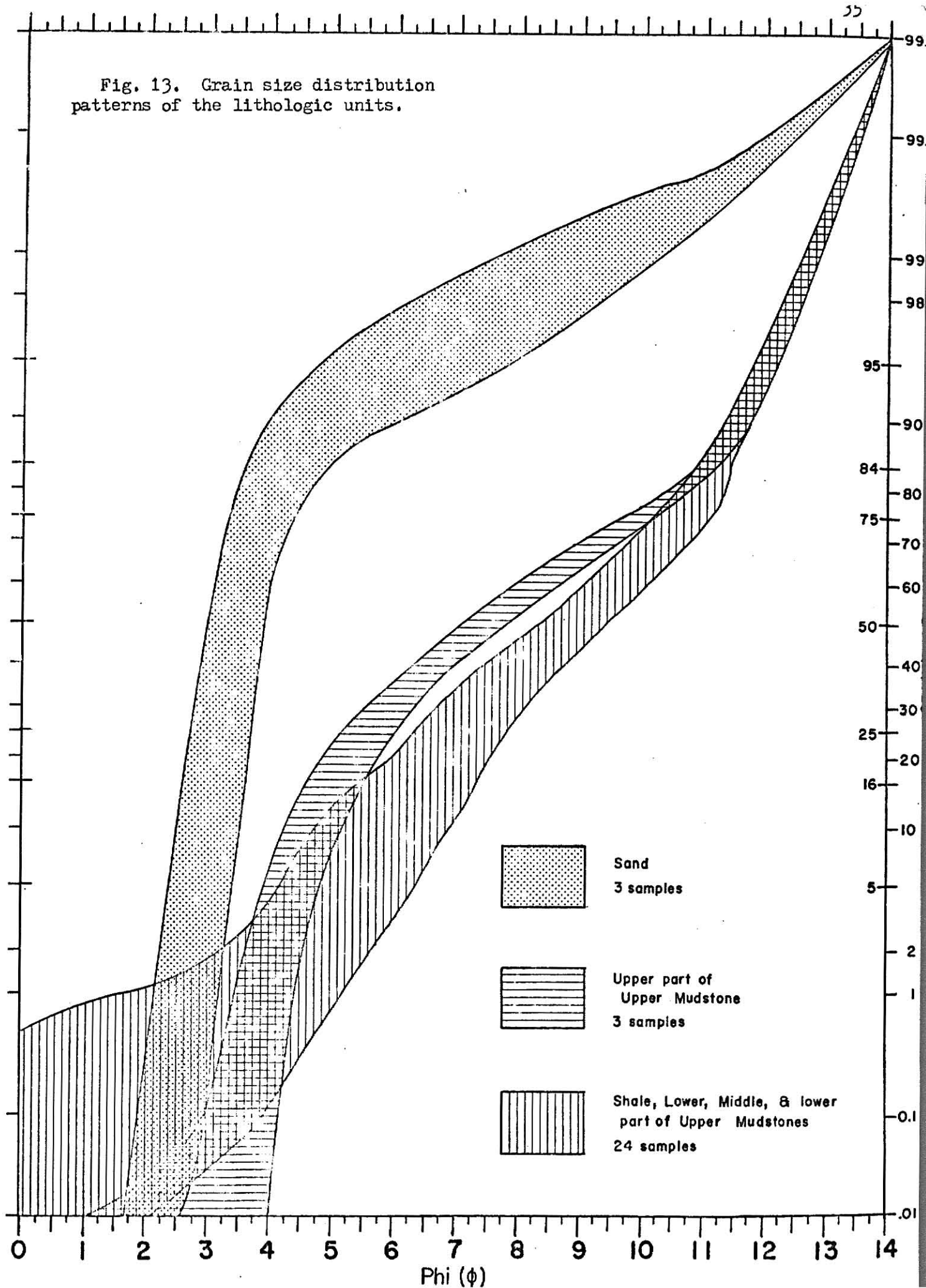
sediment becomes coarser near the contact with the overlying sandstone. A binary plot (fig. 14) of mean grain size versus skewness shows this same lithologic separation.

Shale and mudstone samples range in mean grain size from 7.73ø to 9.33ø, are poorly to very poorly sorted, and are platykurtic. The majority (23) of the samples are near-symmetrical; of the remaining four, two are fine-skewed and two are coarse-skewed. Sandstone samples range from very fine to silty very fine sandstone, moderately sorted to moderately well-sorted, strongly fine-skewed, and very leptokurtic to extremely leptokurtic.

Lateral and vertical variations in grain size of the shale and mudstone samples are slight. Significant vertical changes in grain size occur at the contact of the black shale with the overlying lower mudstone, in the middle mudstone unit, and in the upper part of the upper mudstone near the contact with the overlying sandstone (fig. 15). Laterally, a general decrease in grain size occurs in an easterly direction. This is supported by an analysis of variance of the mudstone samples from localities G, E, and C (Table 6). The mudstone samples from these localities are statistically different at the 90 percent level. Mean grain size of black shale samples from west to east are as follows: H-4, 8.67ø; E-4, 8.97ø; C-3, 8.92ø; A-6, 9.33ø. Sandstone samples at localities G and E have a mean grain size of 3.25ø and 3.05ø, respectively, while the sandstone at locality J (1.75 miles northeast) has a mean grain size of 4.08ø. Because of the small number of samples it is not possible to statistically test the shale and sandstone values (personal communication, Nassar, 1970), but this is supported by inspection of the mean grain size values (Table 7).

Comparison of some statistical measures from sandstone samples with those made by Friedman (1961) on recent river sands show a very close relationship.
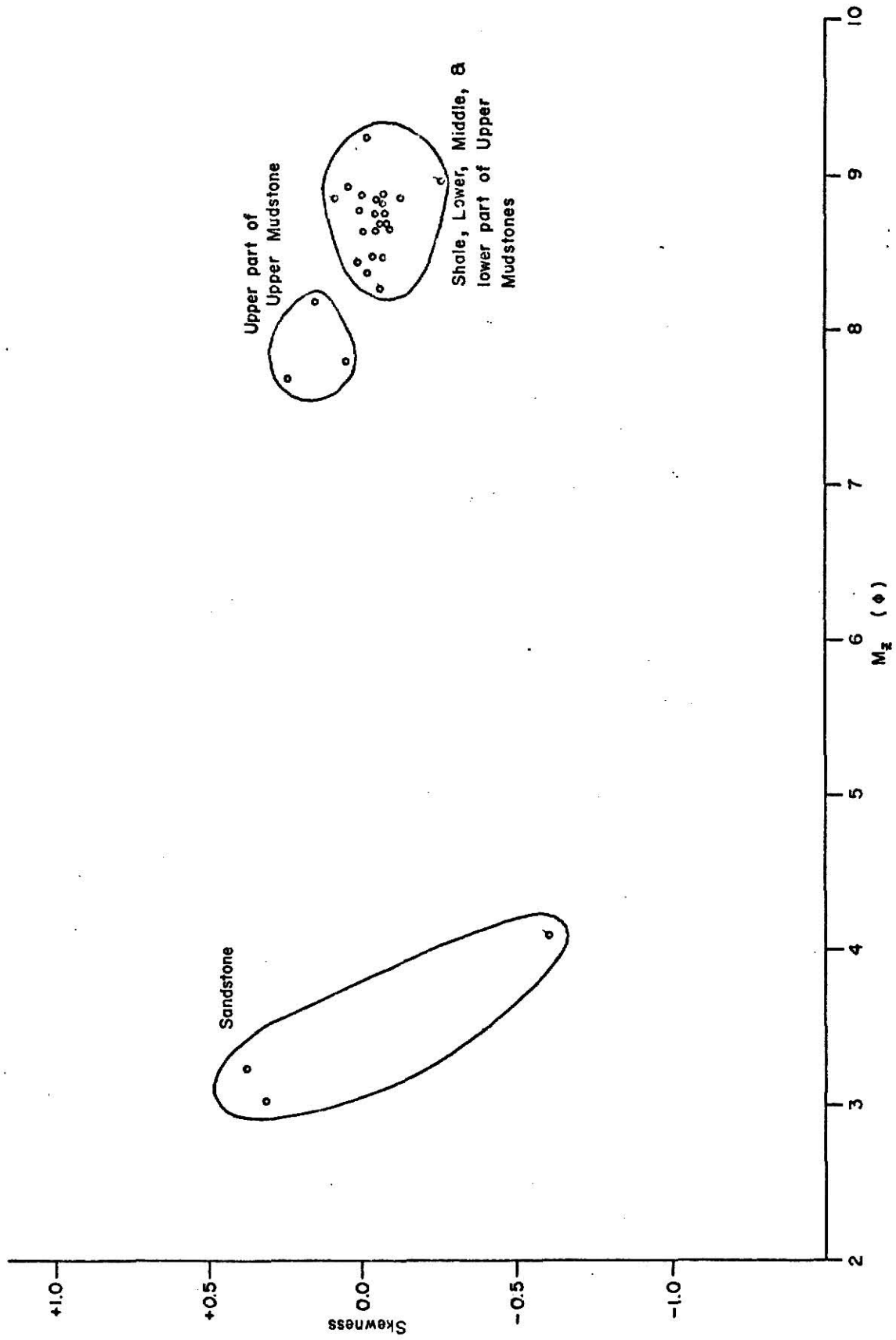
Fig. 14. Binary plot of mean grain size versus skewness.
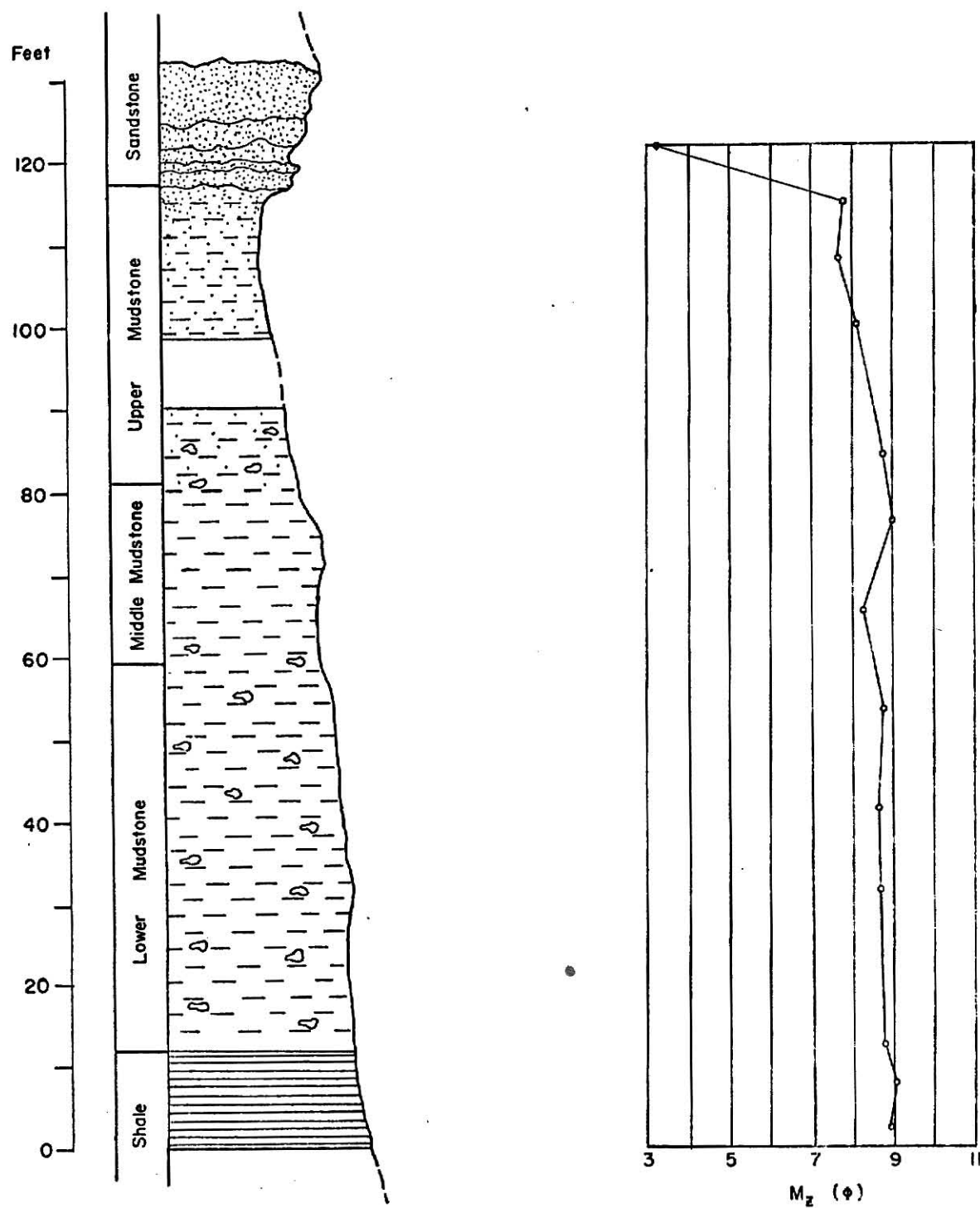
Fig. 15. Vertical changes in mean grain size (composite of localities E and J).

Table 6

One-Way Analysis of Variance of Lateral Variation
in Mean Grain Size of the Mudstone Interval

Mean Grain Size Values (∅ Units)

Locality G	Locality E	Locality C
8.50	8.22	8.77
8.42	8.80	8.85
8.68	9.02	8.90
8.53	8.32	8.92
	8.80	9.05
	8.70	
	8.75	
	8.82	

	Locality G	Locality E	Locality C
ΣY	34.13	69.43	44.49
ΣY^2	291.249	603.075	395.915
$\overline{Y}$	8.53	8.68	8.90
n	4	8	5

	Sum of Squares	D. F.	Mean Square	F-Test
Total	0.899	16		
Between Sections	0.312	2	0.156	3.714*
Within Sections	0.587	14	0.042	

* Significant at 10% level.

Table 7

Lateral Variation in Mean Grain Size of Shale and Sandstone Samples

Lithologic Unit	Black Shale			Sandstone		
Sample	H-4	E-4	A-6	G-Sand	E-Sand	J-Sand
M_z (∅)	8.67	8.97	9.33	3.25	3.05	4.08
σ_I	2.13	1.95	1.81	0.69	0.59	0.98

Friedman (1961) was able to distinguish dune, beach, and river sands using mean, standard deviation (sorting), skewness, and kurtosis. By plotting skewness against kurtosis, river and dune sands can be distinguished from beach sands. River and dune sands are generally positively-skewed whereas beach sands are generally negatively-skewed. Kurtosis is not environment sensitive; it is employed to provide a second dimension to the plot. To distinguish dune and river sands (both positively-skewed), plots can be made of skewness against standard deviation (sorting). Beach sands tend to be better sorted (lower numerical standard deviation values) than river sands (Friedman, 1961). The sandstone samples analyzed have sorting, skewness, and kurtosis values similar to the recent river sands analyzed and fall within the field of river sands on the plots by Friedman.

Clay Mineral Analysis

Identification of Clay Minerals.--Clay minerals were identified by routine examination of X-ray diffractograms obtained from untreated, glycolated, heat treated, and acid treated oriented samples.

Illite.--Basal spacings of 10 A.U., 5 A.U., 3.3 A.U., and others were observed in all samples. Heating, glycolation, and HCl-treatments did not significantly affect the spacings; however, heat treated slides usually showed a sharpening of the 001 reflection.

Illite-Montmorillonite.--Mixed layers of illite and montmorillonite were indicated by a broad diffuse peak on the low angle side of the 10 A.U. illite reflection. A reflection at about 11 A.U. was on untreated samples; glycolation shifted the peak to about 13 A.U. Contraction of the structure to 10 A.U. by heating and by potassium treatment suggests this mixed-layer clay is a degraded form of illite.

Chlorite.--Basal spacings of 14 A.U., 7 A.U., 4.7 A.U., and 3.5 A.U. were attributed to chlorite and mixed-layer chlorite. Chlorite was identified by the stability of the basal spacing after heating and glycolation, and by destruction of the structure with acid treatment.

Mixed-Layer Chlorite.--Random mixed layers of chlorite and vermiculite and vermiculite and chlorite were identified through behavior of the d-spacing after glycolation and heating. Heat treatments reduced the 001 spacing by less than one A.U. and glycolation produced a slight expansion of about 0.5 A.U.

Kaolinite.--Kaolinite was observed in all samples with sharp reflections at 7.2 A.U. (001) and 3.58 (002). Peak intensities were reduced by heating to 450° C. and complete disappearance of the peak was observed at 600° C. Glycolation and acid treatment had no effect on basal spacings.

Quantification of Data.--Following the suggestion of Pierce and Siegel (1969), areas of first order peaks were measured to show relative abundance of the various clay minerals. For purposes of data quantification, chlorite and mixed-layer chlorite were grouped together. Areas of 001 reflections for illite, mixed-layer chlorite and chlorite, and kaolinite were measured directly on glycolated patterns. By superimposing untreated and glycolated diffracto-grams, the area of interlayered illite and montmorillonite was obtained. Relative proportions of the clay mineral types are shown in Figure 16 and in Appendix III.

A consistent laboratory procedure was adopted for preparation and treat-ment of samples to minimize the factors affecting a quantitative estimation of clay minerals.

Evaluation of Data.--Differences in clay mineralogy seem to reflect lithologic associations. Only minor differences in abundance of illite, illite-montmorillonite, kaolinite, and mixed-layer chlorite were observed (fig. 17).
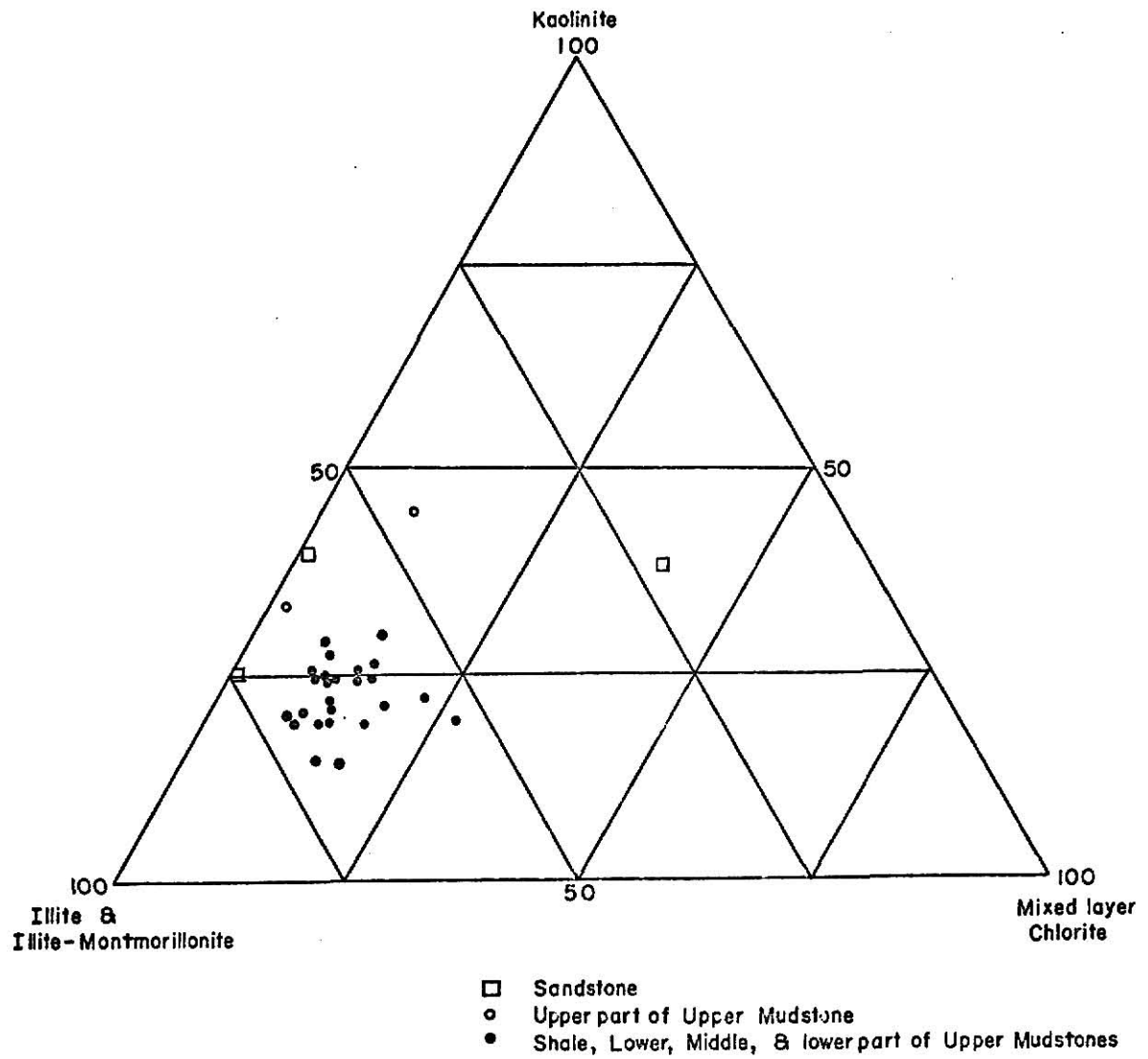
Fig. 16. Clay mineral compositions.
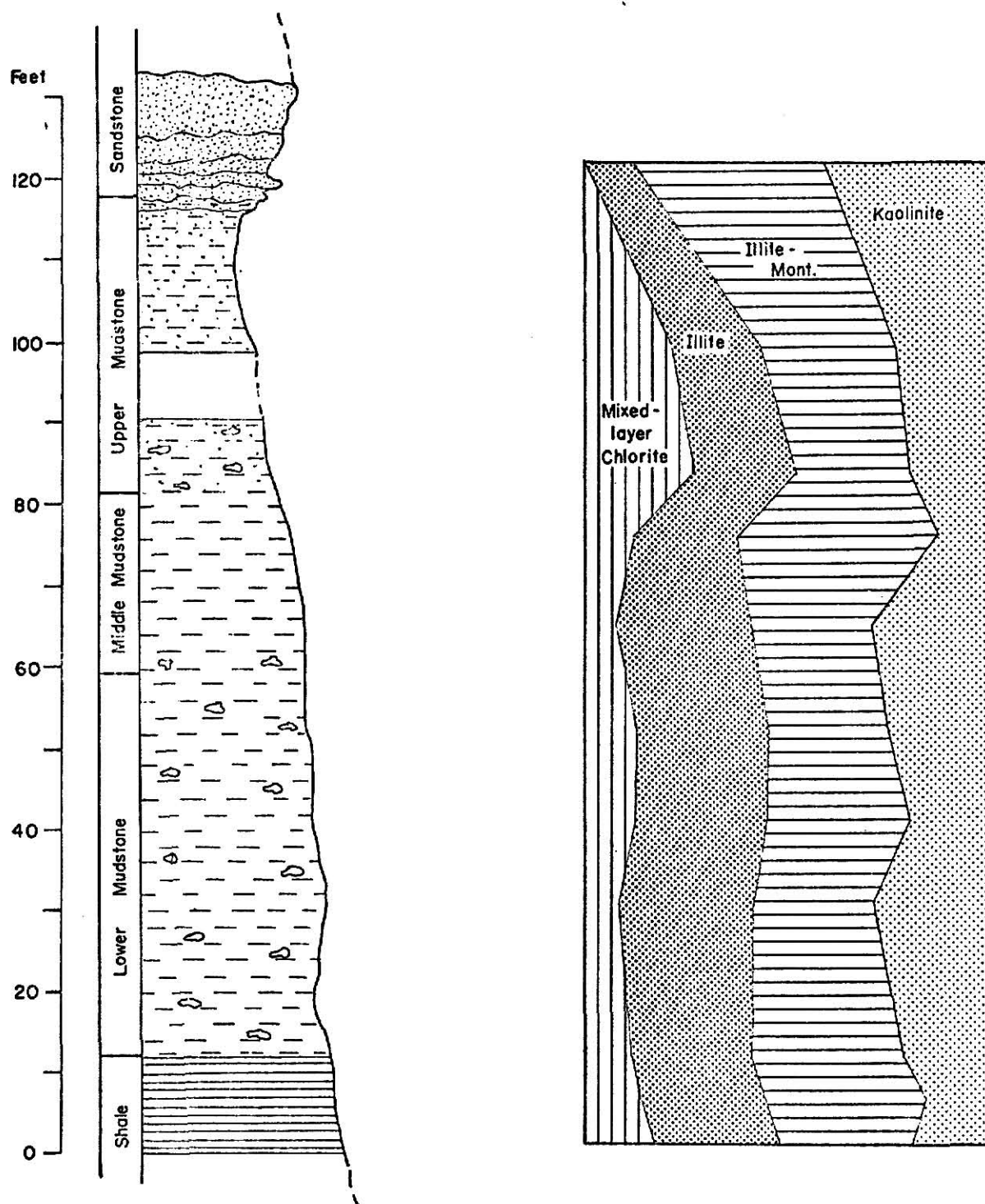
Fig. 17. Vertical changes in clay mineralogy at locality E.

EXPLANATION OF PLATE I

Sample E-4 contains illite (10 A.U.), illite-montmorillonite (11-12 A.U.), mixed-layer chlorite (14.3 A.U.), and kaolinite (7.2 A.U.). Upon glycolation mixed-layer chlorite expanded to 14.5 A.U. and illite-montmorillonite to about 14 A.U. KCl treatment caused the structural collapse of illite-montmorillonite to 10 A.U. indicating it is a degraded illite.

PLATE I
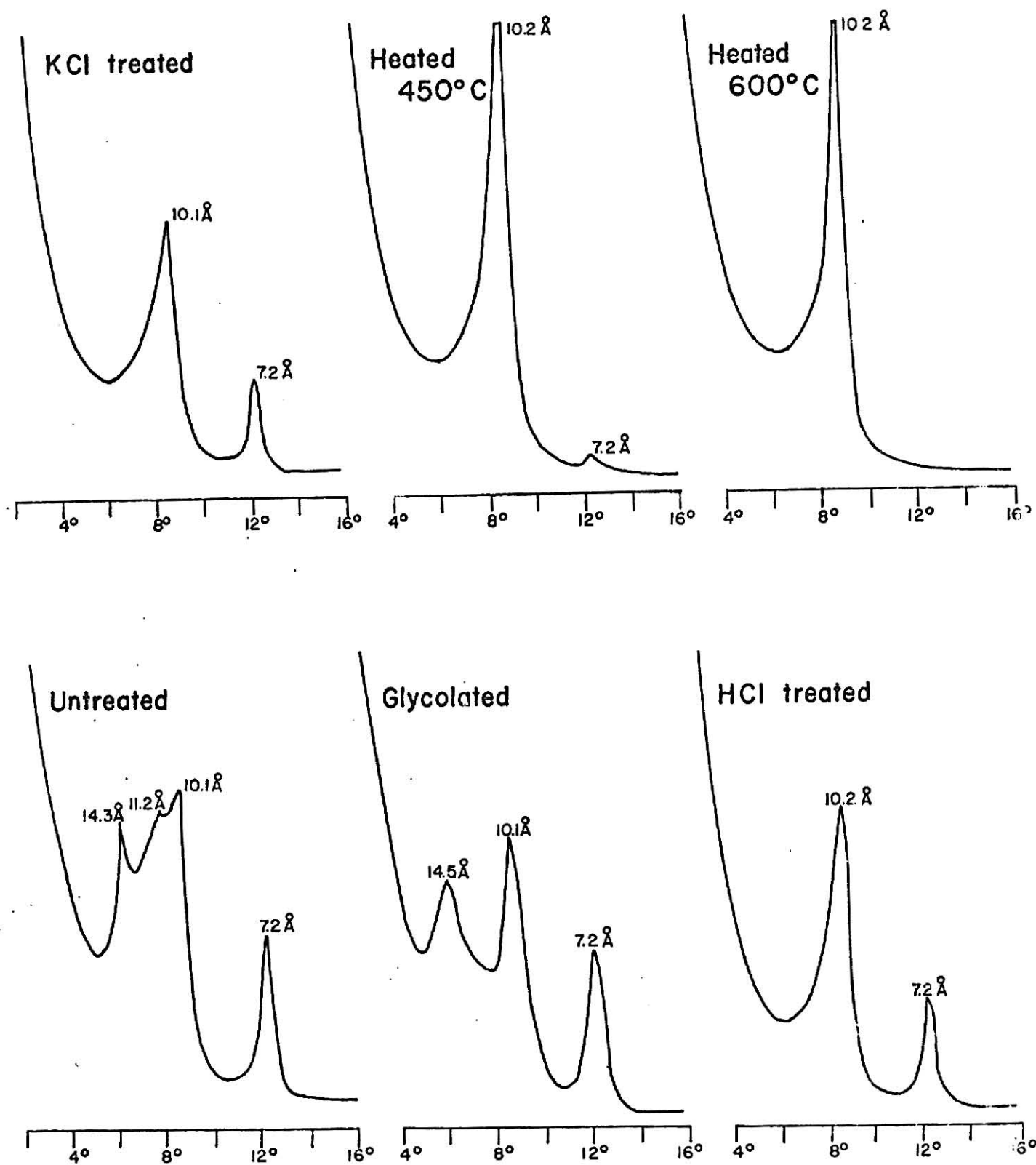
X-RAY DIFFRACTOGRAMS OF SAMPLE E-4

EXPLANATION OF PLATE II

Sample G-sand contains illite (10 A.U.), illite-montmorillonite
(10-11 A.U.), and kaolinite (7.2 A.U.). Glycolation caused expansion of
illite-montmorillonite to about 13 A.U. The 7.2 A.U. peak is sharp and
intense, indicating presence of authigenic kaolinite.

PLATE II
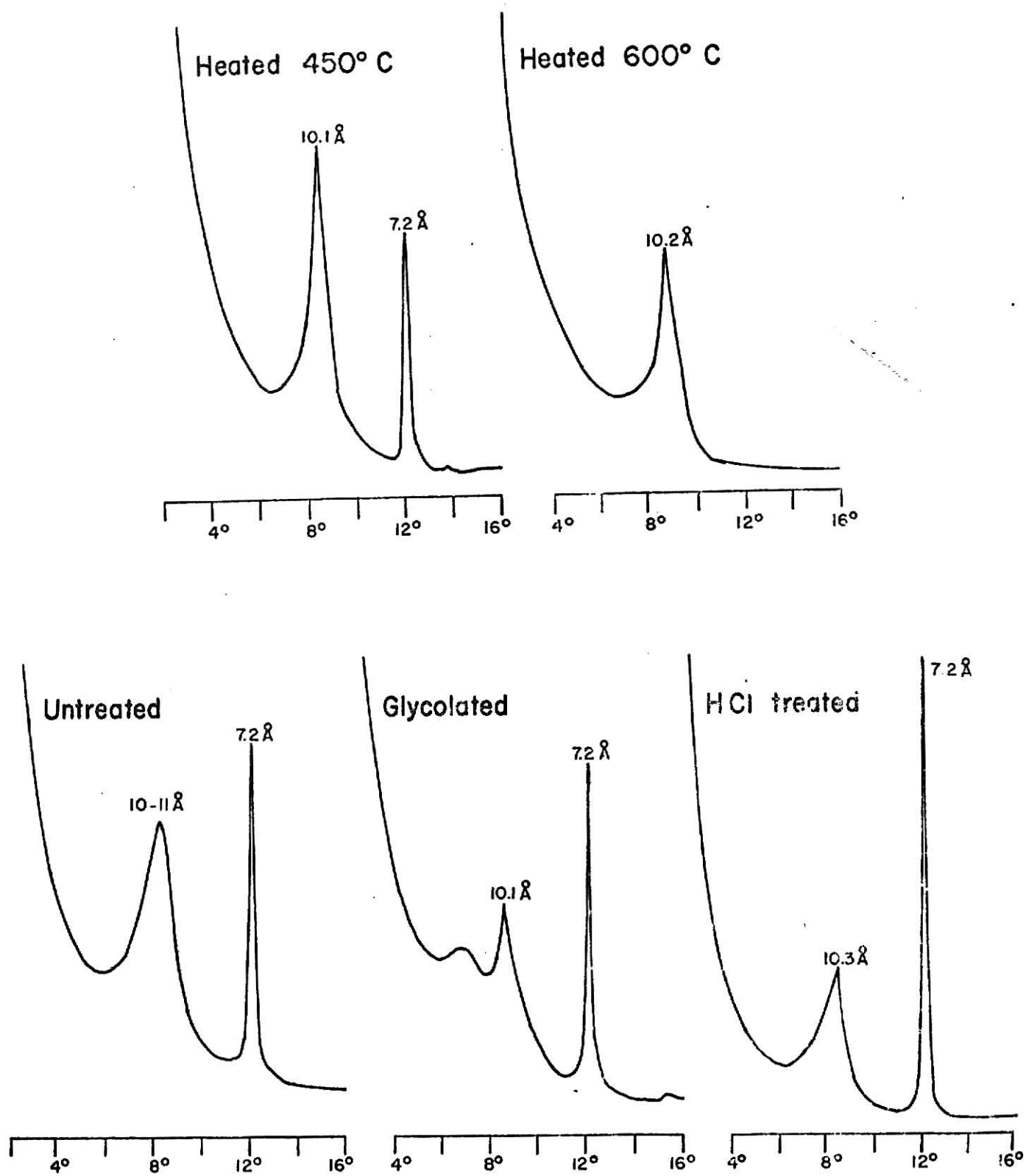
X-RAY DIFFRACTOGRAMS OF SAMPLE G-SAND

Sandstone samples at localities E and G differed from the underlying shale and mudstone in that they lacked mixed-layered chlorite and contained higher concentrations of kaolinite. The sandstone at locality J also contained a higher proportion of kaolinite as well as abundant mixed-layer chlorite. This change in the clay mineral assemblage of the sandstone from localities E and G to locality J seems to be the only significant lateral variation.

The higher proportion of kaolinite in the sandstones is probably due, in part, to authigenic formation of kaolinite in interstitial pore spaces. X-ray diffractograms show a sharper, more intense 7.2 A.U. peak for sandstones than for shales and mudstones. Thin section examination of sandstones revealed kaolinite occurring in large crystals, some exhibiting an accordion-like structure. Similar occurrences of kaolinite in DesMoinesian sands in Oklahoma have been reported by Bucke and Mankin (1971).

Paleosalinity Analysis

In his study of recent sediments, Nelson (1967) found a direct relation-ship between salinity and the ratio of calcium phosphate to calcium phosphate plus iron phosphate. This ratio will be referred to as the calcium-phosphate fraction. The relation between the calcium-phosphate fraction and bottom water salinity as indicated by Nelson (1967) is in Figure 18. The line of best fit is defined by the equation: calcium-phosphate fraction = .09 + .026 (salinity). The correlation coefficient is 0.97, and the dashed lines on the figure represent 95 percent confidence limits, or ± 4 0/00 (parts per thousand) (Nelson, 1967).

Concentrations of the calcium- and iron-phosphate fractions are tabulated in Table 8. From these values, the calcium-phosphate fraction (Ca/Ca + Fe) was calculated for each sample. Paleosalinity estimations were determined from Figure 18.
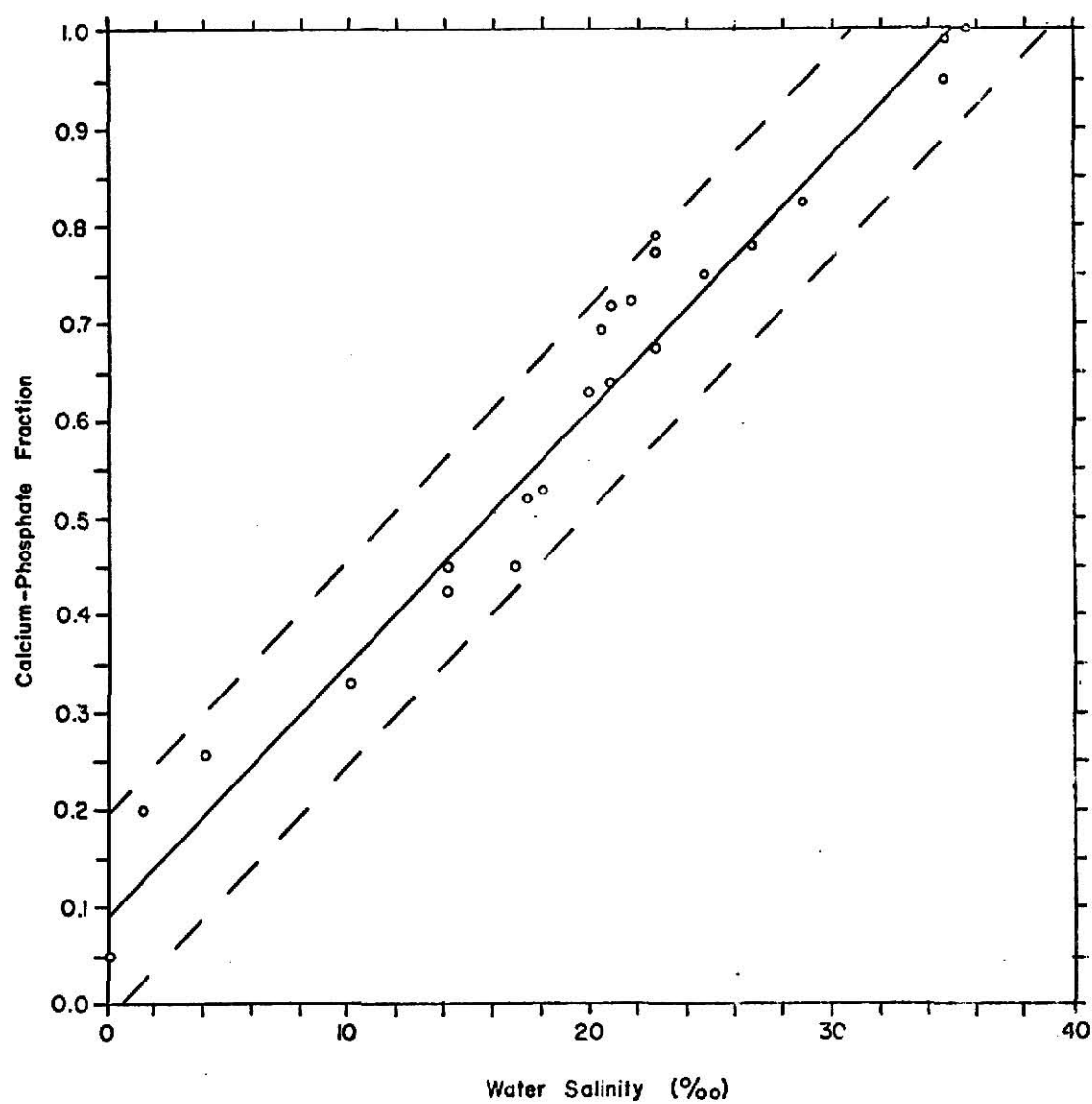
Fig. 18. Relation between calcium-phosphate fraction and bottom water salinity (after Nelson, 1967).

Table 8

Paleosalinity Estimates Based on Sedimentary Phosphates

Sample No.	Ca-PO$_4$ Conc. (ppm)	Fe-PO$_4$ Conc. (ppm)	$\dfrac{Ca}{Ca + Fe}$	Salinity** 0/00
E-26-1	.266	.031*	.896	31.0
E-25'	.315	.014*	.957	33.3
E-25	.277	.004*	.986	34.4
E-23	.515	.010*	.981	34.2
E-22	.385	.010*	.975	34.0
E-20	.455	.009*	.981	34.2
E-16	.310	.008*	.975	34.0
E-12	.345	.020*	.945	32.9
E-7	.164	.108	.603	19.7
E-4	.105	.271	.279	7.3
G-20'	.254	.031*	.891	30.8
G-20	.494	.008*	.984	34.4
G-14	.396	.004*	.990	34.6
G-12	.338	.005*	.985	34.4
C-17'	.880	.007*	.992	34.7
C-17	.564	.006*	.989	34.6
C-15	.412	.008*	.981	34.2
C-10	.293	.007*	.977	34.1
C-8	.386	.013*	.967	33.7
C-3	.200	.113	.639	21.1
H-6	.435	.007*	.984	34.4
H-4	.844	.006*	.993	34.7
F-18	.423	.006*	.986	34.4
F-6	.424	.004*	.991	34.6
J-1	.005	.027	.156	2.5
J-2	.131	.077	.630	20.7
A-6	.102	.180	.362	10.4

* Values obtained from 9 ml. aliquot (for explanation, see text, p. 28).

** Paleosalinities estimated from Figure 18.

Precision of the Sedimentary Phosphate Method.--The level of uncertainty presently existing in the calcium-phosphate/salinity relationship is indicated in Figure 18 by the separation of the 95 percent confidence limit lines. Hopefully, future work will refine this relationship and the phosphate method.

While testing precision of the method was not part of this study, seven subsamples from each of two samples were analyzed to check the reproducibility of the method. Although a large variation in the absolute abundances of the phosphate fractions exists, the Ca-phosphate ratios and salinity values are very consistent in the seven runs (Table 9).

Evaluation of Data.--Paleosalinity estimates of the shale and mudstone sequence range from freshwater to marine (Table 8). As indicated in Figure 19, salinity values are low in the black shale (7.3 to 21.1 0/00) and increase to normal marine salinity (about 34 0/00) through the lower and middle mudstones. Maximum salinity occurs in the middle mudstone unit, then decreases throughout the upper mudstone. A still further decrease in salinity (20.1 to 2.5 0/00) is observed just below the contact of the upper mudstone with the overlying sandstone at locality J. Because of the limited geographic area of this study, no lateral salinity variations were detected.

Summary of Data

There seems to be little relationship between grain size, clay mineralogy and salinity within the shale and mudstone interval. Scatter plots of mean grain size against percent kaolinite and percent chlorite are shown in Figure 20. No definite conclusions can be drawn about the relationship between mean grain size and clay mineralogy; however, an apparent increase in kaolinite and a decrease in chlorite with coarser mean grain size exists.

Scatter plots of salinity against percent kaolinite and percent chlorite

Table 9

Results of Paleosalinity Method Replications

Sample E-7

Run #	Fe-phos. (ppm)	Ca-phos. (ppm)	$\frac{Ca}{Ca + Fe}$	Salinity (0/00)
1	0.117	0.162	0.581	18.9
2	0.103	0.163	0.613	20.1
3	0.107	0.167	0.614	20.2
4	0.083	0.120	0.597	19.5
5	0.083	0.122	0.595	19.4
6	0.085	0.138	0.619	20.4
7	0.086	0.110	0.561	18.0

Mean $(\overline{X})$ 19.50
Variance (S^2) 0.714
Standard Error of Mean $(S_{\overline{X}})$ 0.345

Sample E-4

Run #	Fe-phos. (ppm)	Ca-phos. (ppm)	$\frac{Ca}{Ca + Fe}$	Salinity (0/00)
1	0.265	0.107	0.288	7.6
2	0.270	0.105	0.280	7.3
3	0.276	0.105	0.276	7.1
4	0.200	0.087	0.303	8.1
5	0.230	0.083	0.265	6.7
6	0.180	0.085	0.321	8.8
7	0.188	0.093	0.331	9.2

Mean $(\overline{X})$ 7.83
Variance (S^2) 0.842
Standard Error of Mean $(S_{\overline{X}})$ 0.375
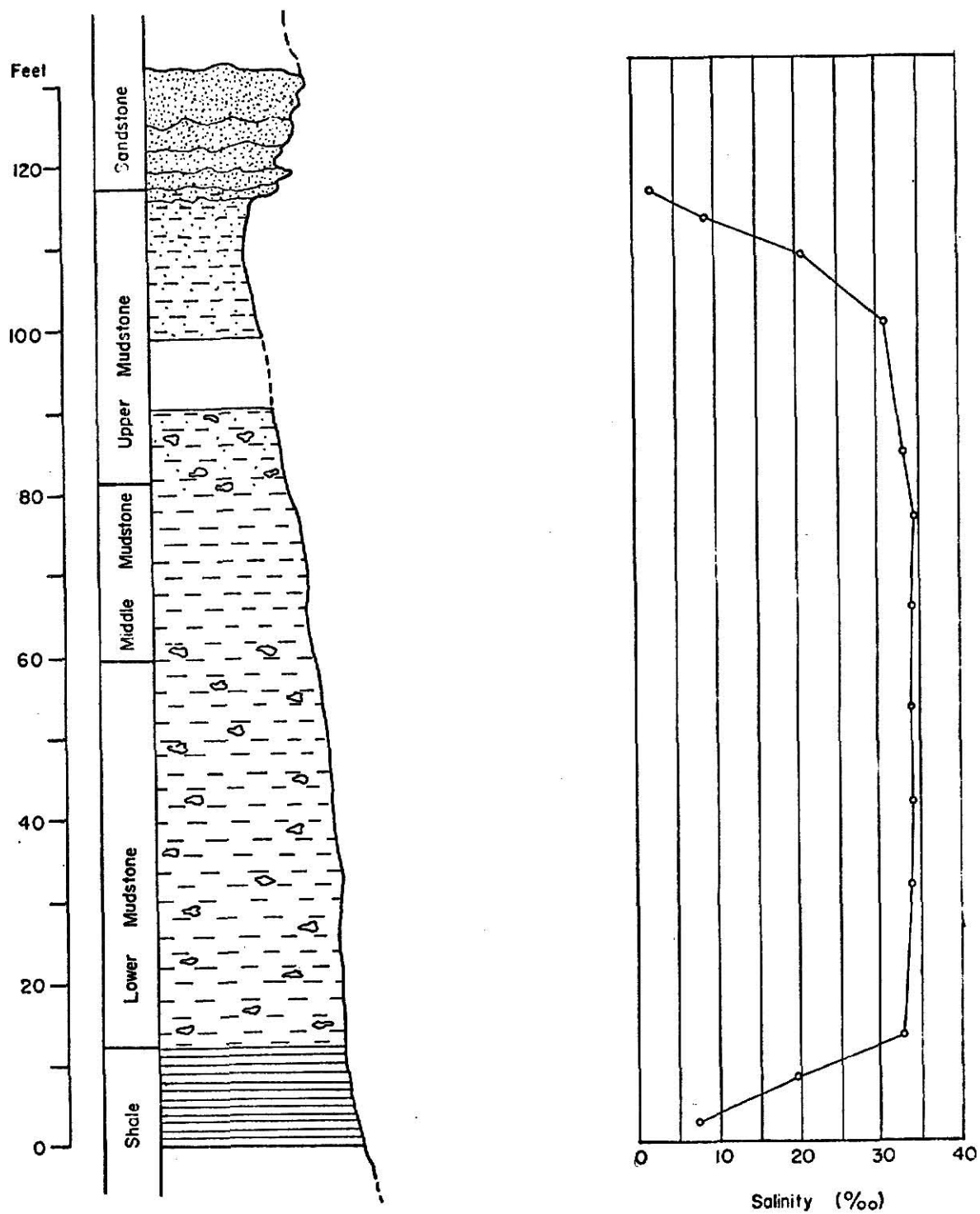
Fig. 19. Vertical changes in paleosalinity estimates (composite of localities E and J).
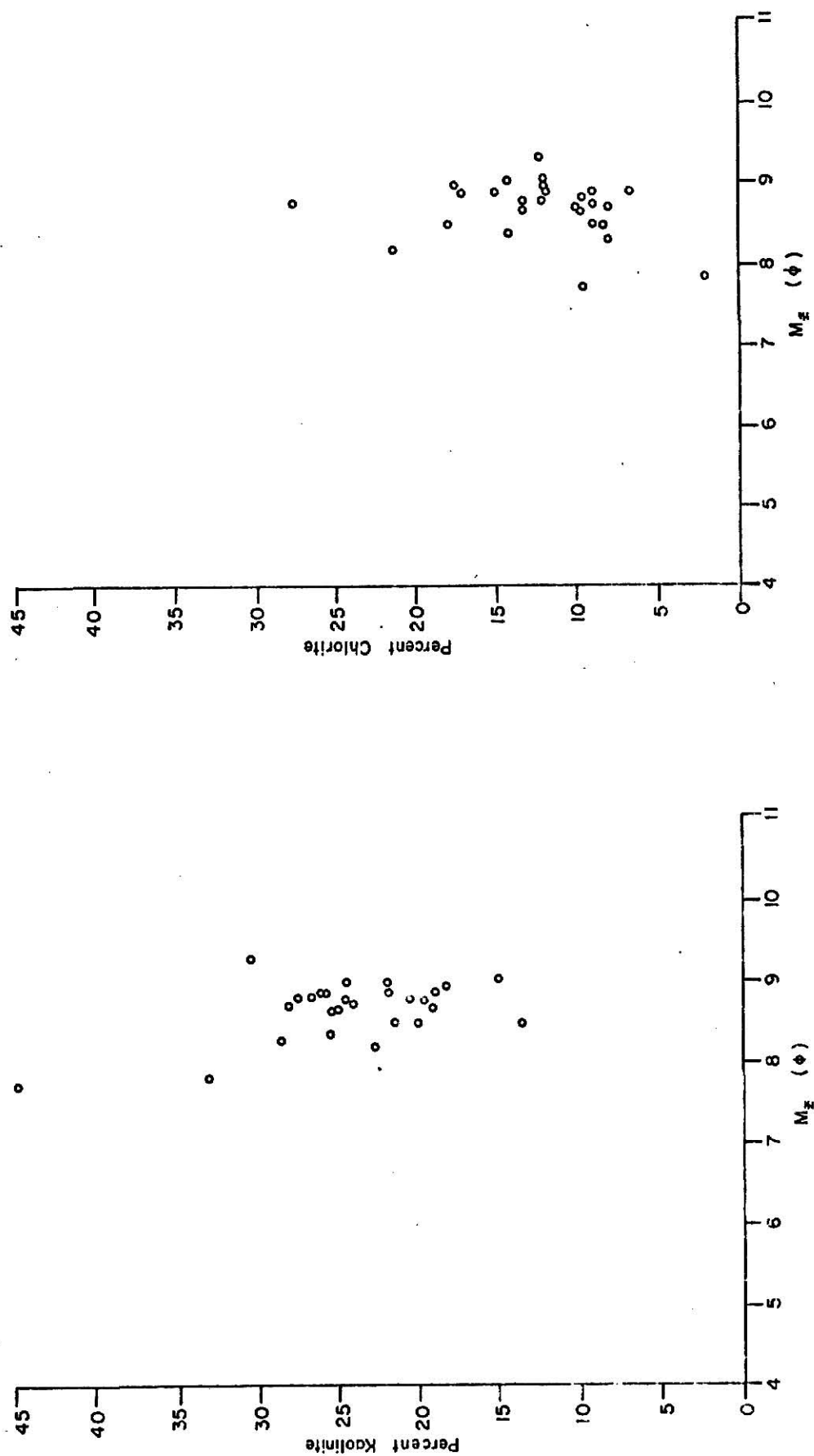
Fig. 20. Relation between mean grain size and proportions of kaolinite and chlorite.

also are inconclusive (fig. 21). A weak relationship of decreasing amounts of kaolinite and increasing chlorite with an increase in salinity appears to exist.

No direct correlation between mean grain size and salinity was observed in the shale and lower and middle mudstones; however, in the upper mudstone an increase in mean grain size was accompanied by a decrease in salinity.

ENVIRONMENT OF DEPOSITION AND SOURCE

Previous investigations indicate that the Wewoka Formation was deposited in a deltaic environment (Weaver, 1954; West, 1970). This interpretation is compatible with the information obtained in this study.

West (1970) proposed depositional environments for each of the lithologic units of the interval studied. In ascending order they are, (1) marshy subtidal to tidal flat represented by black, fossiliferous shale, (2) shallow nearshore subtidal (delta front) represented by molluscan mudstone, (3) offshore subtidal (prodelta) represented by brachiopodal mudstone, (4) nearshore subtidal (outer delta plain) represented by silty, foraminiferal mudstone, and (5) deltaic sand deposition (distributary system) represented by crossbedded sandstones containing large plant fragments. This vertical sequence of sedimentary environments and lithologies fits well the vertical sequence of modern prograding deltas (fig. 22). Within this shale and mudstone interval, West (1970) defined four different benthic marine communities which are, in ascending order, (1) Glabrocingulum Community of the inner delta front environment, (2) Transitional Community of the outer delta front to inner prodelta environment, (3) Cleiothyridina Community of the inner to middle prodelta environment, and (4) Mesolobus Community of the inner prodelta and outer delta plain environment. Lithologies, depositional environments, and contained biotic elements and communities are shown in Figure 23.
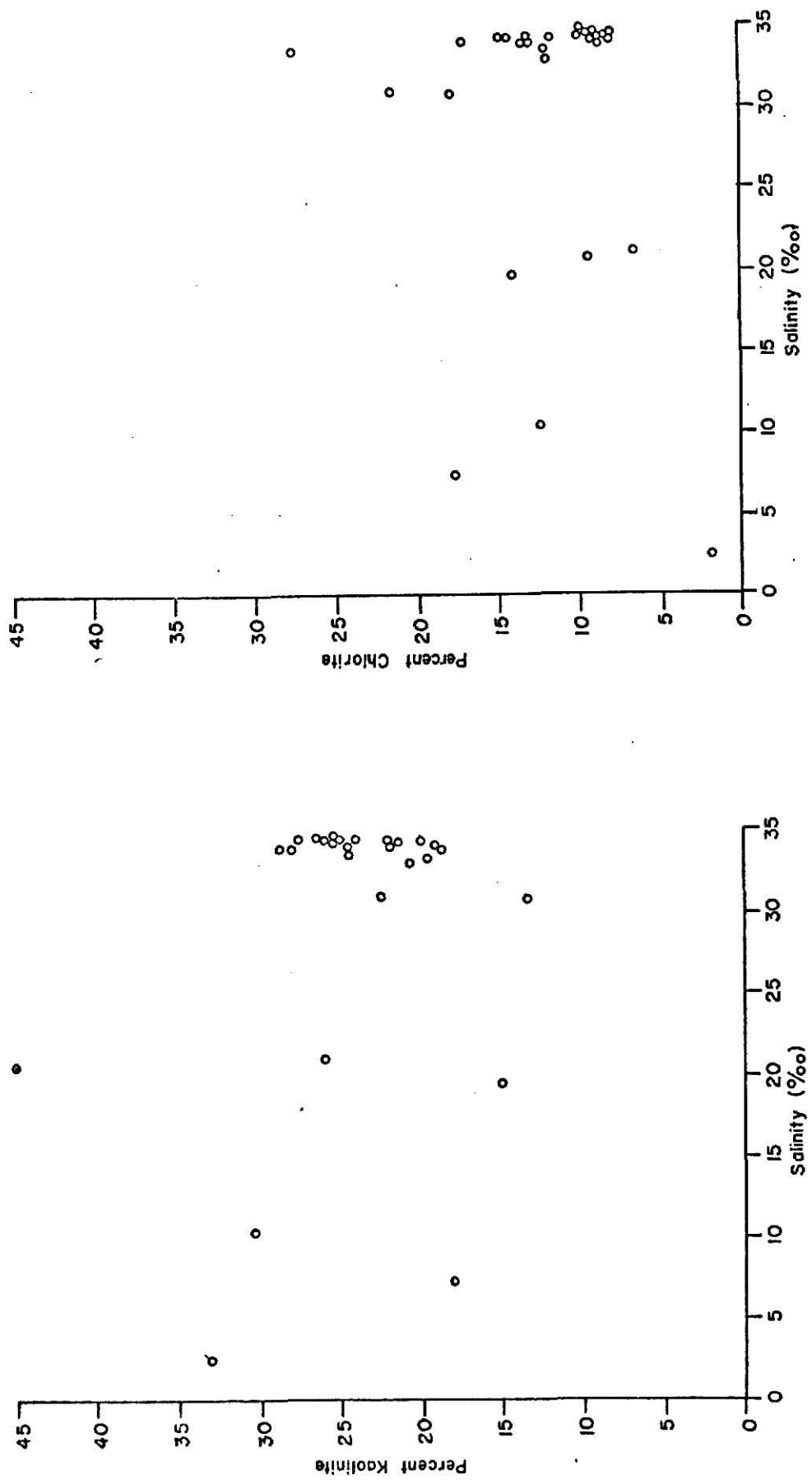
Fig. 21. Relation between salinity estimates and proportions of kaolinite and chlorite.
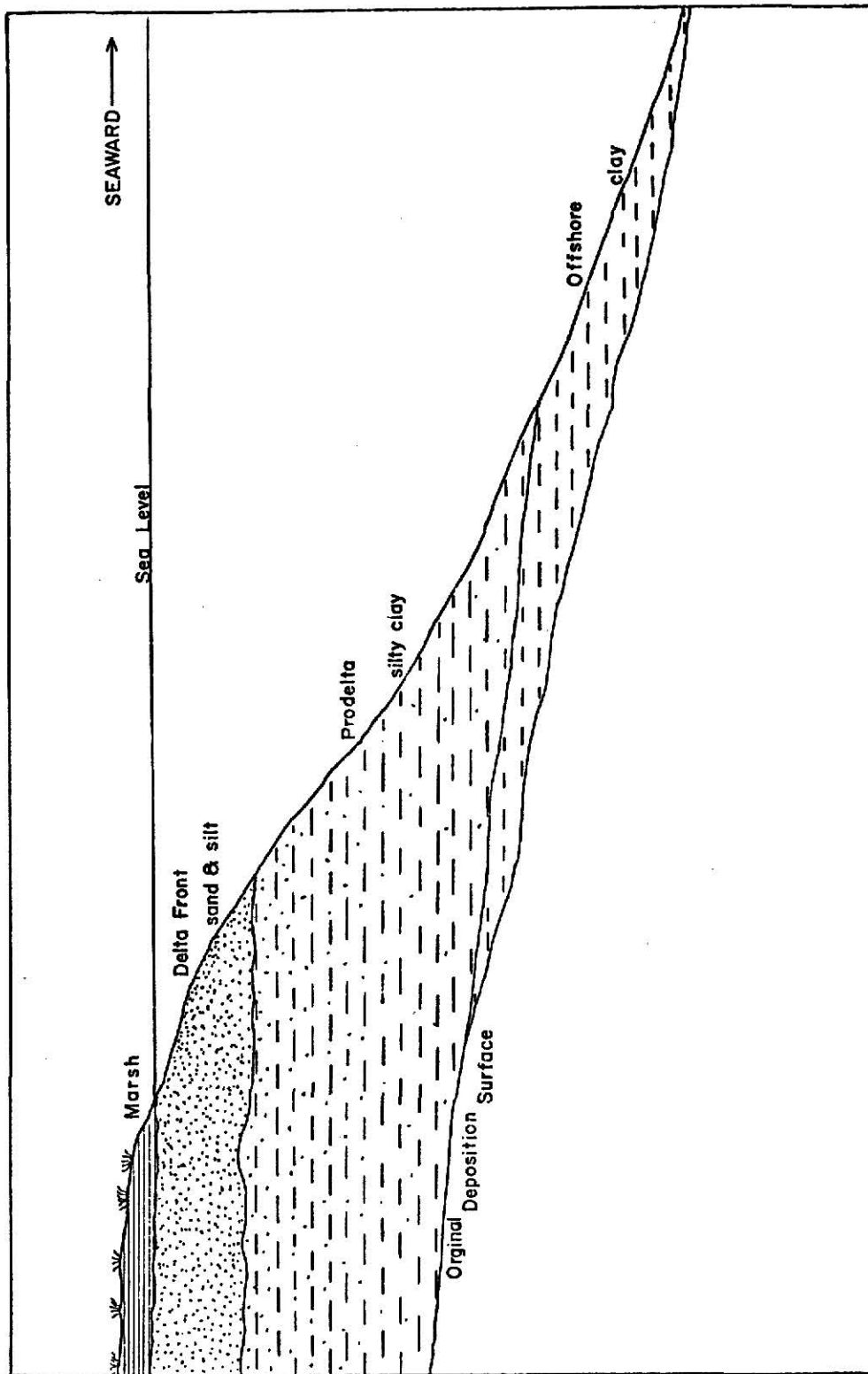
Fig. 22. Sequence of sediments in a modern prograding delta (modified from Scruton, 1960).

Depositional Environment	Biotic Elements	Color	Communities	Unit	Lithology
Delta Plain	*Stigmaria* sp.	Yellowish Grey to Orange		IPwk-3a	
Outer Delta Plain or Restricted Bay to Marsh	Ostracodes, Arenaceous Foraminifera	Yellowish Brown	*Mesolobus*	IPwk	
Outer Delta Front to Prodelta	Brachiopods, Crinoids	Blue Grey	*Cleiothyridina*		
Inner Delta Front	Gastropods, Cephalopods, Bivalves	Yellow to Brown	Transitional / *Glabrocingulum*		
Tidal Flat to Marsh	Plant Derbis	Black			
Delta Plcin				IPwk-2	

Formation: Wewoka

Legend: Sandstone, Silty Mudstone, Mudstone, Shale, Ironstone Nodules

Fig. 23. Lithologies, depositional environments, biotic elements, and communities of the interval studied (modified from West, 1970).

Paleosalinity and grain size data obtained in this investigation support the depositional environments and communities proposed by West (1970). Paleosalinity estimates are shown in Figure 24, along with inferred depositional environments. An excellent correlation between salinity values and inferred depositional environment with respect to shore exists; maximum salinity values are in the Cleiothyridina Community which was interpreted as being most marine. Existence of different communities is supported by grain size data. An analysis of variance (Table 10) shows that the grain size variation within communities is less than variation between communities. Paleosalinity determinations do not statistically support the proposed communities (Table 11). This could be due to inadequate sampling and/or the fact that most values are near normal marine salinity (35 0/00). Paleosalinity values in the mudstone interval ranged from 32.9 to 34.7 0/00. In the Transitional, Cleiothyridina, and Mesolobus Communities there are only two determinations for each, while there are twelve from the Glabrocingulum Community. However, it should be recalled that the vertical paleosalinity profile (fig. 19) shows a maximum paleosalinity value for the sample within the Cleiothyridina Community as proposed by West (1970).

Factors influencing the Cleiothyridina and Mesolobus Communities seem to be mean grain size and salinity. The Cleiothyridina Community was interpreted by West (1970) as representing the farthest offshore community. This is reflected by the maximum salinity values recorded in the entire interval studied, and the finest mean grain size in the mudstone interval. The Mesolobus Community was interpreted as a return to nearshore conditions (West, 1970). This environmental change is reflected by a decrease in salinity and coarser mean grain size.
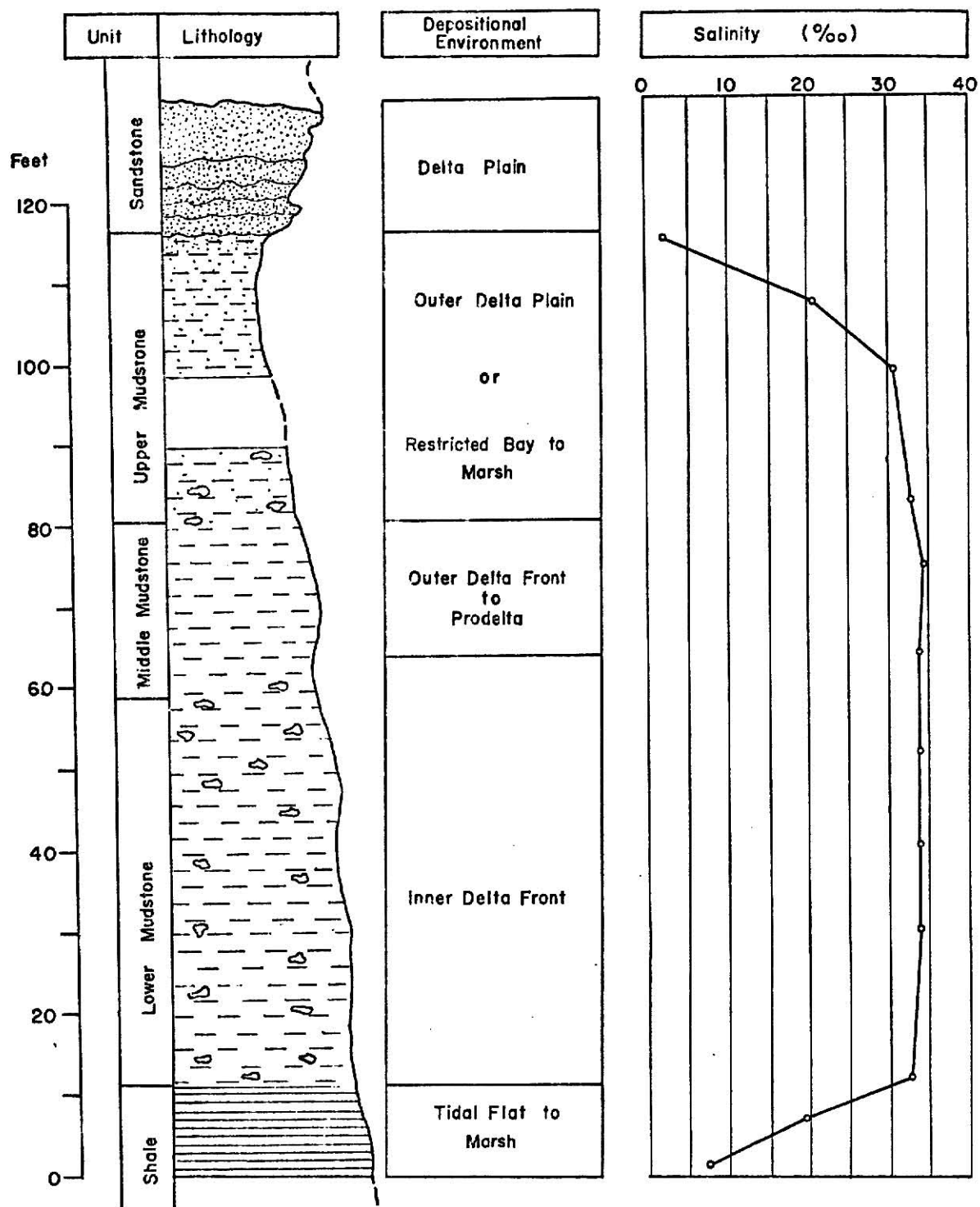
Fig. 24. Vertical changes in salinity estimates and inferred depositional environments (composite of localities E and J).

Table 10

One-Way Analysis of Variance
of Mean Grain Size Data from the Communities

Mean Grain Size Values (∅ Units)

	Glabrocingulum Community	Transitional Community	Cleiothyridina Community	Mesolobus Community
	8.52	8.53	8.68	8.42
	8.87	8.32	9.02	8.80
	8.93			
	8.82			
	8.75			
	8.70			
	8.80			
	9.05			
	8.92			
	8.90			
	8.85			
	8.75			
ΣY	105.86	16.85	17.70	17.22
ΣY^2	934.061	141.983	156.703	148.336
$\bar{Y}$	8.82	8.43	8.85	8.61
n	12	2	2	2

	Sum of Squares	D. F.	Mean Square	F-Test
Total	0.682	17		
Between Communities	0.329	3	0.110	4.40*
Within Communities	0.353	14	0.025	

* Significant at 10% and 5% levels.

Table 11

One-Way Analysis of Variance
of Paleosalinity Determinations from the Communities

Paleosalinity Estimates (0/00)

	Glabrocingulum Community	Transitional Community	Cleiothyridina Community	Mesolobus Community
	34.4	34.4	34.6	34.4
	34.6	34.2	34.4	33.3
	34.4			
	32.9			
	34.0			
	34.2			
	34.0			
	33.7			
	34.1			
	34.2			
	34.6			
	34.7			
ΣY	409.8	68.6	69.0	67.7
ΣY^2	13997.32	2353.00	2380.52	2292.25
$\overline{Y}$	34.15	34.3	34.5	33.85
n	12	2	2	2

	Sum of Squares	D. F.	Mean Square	F-Test
Total	3.76	17		
Between Communities	0.47	3	0.157	0.668
Within Communities	3.29	14	0.235	

Not significant at 10%, 5%, or 1% levels.

Clay minerals in the interval studied are interpreted to be largely detrital in origin, with the exception of some authigenic kaolinite in the sandstone. Relative abundances of clay minerals reflect very little, if anything, about depositional environments. This is in contrast to observations by Whitehouse and others (1960), and Pryor and Glass (1961) in which kaolinite is in greater abundance nearshore, due to preferential floculation upon entering saline waters. Possibly the magnitude of environmental changes is not great enough in the interval studied to reflect a segregation of clay minerals.

As previously mentioned, beds of sandstone are interpreted as having a fluvial origin; and are believed to represent a migrating distributary channel of a delta system. Associated with this distributary are the underlying and adjacent siltstone and mudstone units that represent low energy deposition seaward or laterally in an interdistributary bay. The study area is interpreted as being in an interdistributary bay, near the margin of a distributary channel. A decrease in mean grain size to the east and the intertonguing of the sandstone with siltstone and mudstone east of the area indicate the proposed distributary channel was to the west or southwest.

The most likely source area is the Ouachita Mountain system of southern Oklahoma. Deformation of the Ouachita system began during Atoka time and continued concurrently with the downwarping of the Arkoma (McAlester) Basin through Des Moines time (Flawn, et. al., 1961). The Arbuckle Mountains to the southwest were probably not a significant sediment source as deformation occurred there during the Late Pennsylvanian (Virgil) (Ham, 1956). Thick sequences of Upper Mississippian and Lower Pennsylvanian clastic strata comprise a major part of the Ouachita fold belt (Eardley, 1962). A thickness of 18,950 feet was reported by Cline and Moretti (1956) for the Stanley,

Jackfork, and Johns Valley formations; and the Atoka sequence is reported to be 17,000 feet thick (Hendricks, et. al., 1936). A source consisting of this pre-existing sandstone and shale sequence is plausible in light of clay mineral studies of these formations by Weaver (1958b). Post-Lower Mississippian Stanley, Jackfork, Johns Valley, and Atoka formations consist of illite, chlorite, kaolinite, and mixed-layer illite-montmorillonite (Weaver, 1958b). The existence of the same basic clay mineral assemblage in the Wewoka Formation strengthens the Ouachita source area concept.

ACKNOWLEDGEMENTS

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Appendix I

Location of Measured Sections and Samples

Section A

Measured section A is near the center of NE$\frac{1}{4}$, NE$\frac{1}{4}$, SW$\frac{1}{4}$, NE$\frac{1}{4}$, Sec. 33, T. 7 N., R. 9 E., Hughes County, Oklahoma.

Sample No.	No. Feet Above Base of Measured Section A (West, 1970).
A-6	9

Section C

Measured section C starts near NE cor. SE$\frac{1}{4}$, SW$\frac{1}{4}$, NW$\frac{1}{4}$, NW$\frac{1}{4}$, Sec. 33, T. 7 N., R. 9 E., Hughes County, Oklahoma.

Sample No.	No. Feet Above Base of Measured Section C (West, 1970).
C-17'	43
C-17	29
C-15	34
C-10	16
C-8	13
C-3	6

Section E

Measured section E starts 10 ft. W. of C. of E. line of E$\frac{1}{2}$, NW$\frac{1}{4}$, SE$\frac{1}{4}$, NE$\frac{1}{4}$, SW$\frac{1}{4}$, NW$\frac{1}{4}$, NW$\frac{1}{4}$, Sec. 33, T. 7 N., R. 9 E., Hughes County, Oklahoma.

Section E (Cont.)

Sample No.	No. Feet Above Base of Measured Section E (West, 1970).
E-Sand	117
E-26-1	99
E-25'	83
E-25	75
E-23	64
E-22	52
E-20	41
E-16	31
E-12	12
E-7	8
E-4	2

Section F

Measured section F starts 15 ft. N. of C. of W. line of SW$\frac{1}{4}$, NW$\frac{1}{4}$, NW$\frac{1}{4}$, NW$\frac{1}{4}$, Sec. 33, T. 7 N., R. 9 E., Hughes County, Oklahoma.

Sample No.	No. Feet Above Base of Measured Section F (West, 1970).
F-18	33
F-6	18

Section G

Measured section G starts 10 ft. S. of C. of E. line of NE$\frac{1}{4}$, SE$\frac{1}{4}$, NE$\frac{1}{4}$, NE$\frac{1}{4}$, NE$\frac{1}{4}$, NE$\frac{1}{4}$, Sec. 32, T. 7 N., R. 9 E., Hughes County, Oklahoma.

Section G (Cont.)

Sample No.	No. Feet Above Base of Measured Section G (West, 1970).
G-Sand	102
G-20'	70
G-20	61
G-14	52
G-12	39

Section H

Measured section H starts 9 ft. W. and 5 ft. S. of the C. of N. line, NE$\frac{1}{4}$, SE$\frac{1}{4}$, NE$\frac{1}{4}$, NE$\frac{1}{4}$, NE$\frac{1}{4}$, NE$\frac{1}{4}$, Sec. 32, T. 7 N., R. 9 E., Hughes County, Oklahoma.

Sample No.	No. Feet Above Base of Measured Section H (West, 1970).
H-6	10
H-4	4

Section J

Locality J is in SE$\frac{1}{4}$, SE$\frac{1}{4}$, SE$\frac{1}{4}$, NE$\frac{1}{4}$, Sec. 21, T. 7 N., R. 9 E., Hughes County, Oklahoma.

Sample No.	Stratigraphic Position
J-Sand	Lower 1 Ft. of Sandstone Pwk-3a
J-1	1.5 Ft. Below Base of Sandstone Pwk-3a
J-2	4.5 Ft. Below Base of Sandstone Pwk-3a

Appendix II

Grain Size Data

E-Sand

Class Interval (Phi Units)	Class Weight (gm.)	Weight Percent	Cumulative Weight (gm.)	Cumulative Percent
1.50- 1.75	0.024	0.024	0.024	0.024
1.75- 2.00	0.346	0.359	0.370	0.384
2.00- 2.25	1.977	2.052	2.347	2.436
2.25- 2.50	6.230	6.467	8.577	8.904
2.50- 2.75	25.121	26.079	33.698	34.983
2.75- 3.00	13.536	14.052	47.234	49.036
3.00- 3.25	24.582	25.519	71.816	74.555
3.25- 3.50	8.470	8.793	80.286	83.349
3.50- 3.75	2.686	2.788	82.972	86.137
3.75- 4.00	4.189	4.348	87.161	90.486
4.00- 5.00	5.170	5.366	92.331	95.837
5.00- 6.00	1.720	1.785	94.051	97.623
6.00- 7.00	0.900	0.934	94.951	98.557
7.00- 8.00	0.550	0.570	95.501	99.128
8.00- 9.00	0.350	0.363	95.851	99.491
9.00-10.00	0.210	0.217	96.061	99.709
10.00-11.00	0.070	0.072	96.131	99.782
> 11.00	0.210	0.217	96.341	100.000

E-26-1

Class Interval (Phi Units)	Class Weight (gm.)	Weight Percent	Cumulative Weight (gm.)	Cumulative Percent
3.00- 4.00	0.001	0.006	0.001	0.006
4.00- 5.00	1.000	6.390	1.001	6.400
5.00- 6.00	2.550	16.290	3.551	22.690
6.00- 7.00	2.500	15.970	6.051	38.660
7.00- 8.00	2.000	12.780	8.051	51.440
8.00- 9.00	1.650	10.540	9.701	61.980
9.00-10.00	1.800	11.500	11.501	73.480
10.00-11.00	1.550	9.900	13.051	83.390
> 11.00	2.600	16.610	15.651	100.000

E-25'

Class Interval (Phi Units)	Class Weight (gm.)	Weight Percent	Cumulative Weight (gm.)	Cumulative Percent
1.00- 2.00	0.003	0.016	0.003	0.016
2.00- 3.00	0.008	0.043	0.011	0.059
3.00- 4.00	0.011	0.059	0.022	0.119
4.00- 5.00	0.450	2.440	0.472	2.560
5.00- 6.00	1.750	9.500	2.222	12.060
6.00- 7.00	2.650	14.380	4.872	26.450
7.00- 8.00	2.250	12.210	7.122	38.660
8.00- 9.00	2.450	13.300	9.572	51.960
9.00-10.00	2.850	15.470	12.422	67.430
10.00-11.00	2.050	11.130	14.472	78.560
>11.00	3.950	21.440	18.422	100.000

E-25

Class Interval (Phi Units)	Class Weight (gm.)	Weight Percent	Cumulative Weight (gm.)	Cumulative Percent
-1.00- 0.00	0.086	0.536	0.086	0.536
0.00- 1.00	0.044	0.274	0.130	0.811
1.00- 2.00	0.052	0.324	0.182	1.136
2.00- 3.00	0.061	0.380	0.243	1.520
3.00- 4.00	0.072	0.449	0.315	1.970
4.00- 5.00	0.550	3.430	0.865	5.400
5.00- 6.00	1.250	7.810	2.115	13.210
6.00- 7.00	1.650	10.300	3.765	23.510
7.00- 8.00	1.050	6.560	4.815	30.070
8.00- 9.00	2.250	14.050	7.065	44.110
9.00-10.00	2.400	14.990	9.465	59.100
10.00-11.00	2.350	14.670	11.815	73.770
>11.00	4.200	26.230	16.015	100.000

E-23

Class Interval (Phi Units)	Class Weight (gm.)	Weight Percent	Cumulative Weight (gm.)	Cumulative Percent
-2.00- -1.00	0.015	0.096	0.015	0.096
-1.00- 0.00	0.034	0.218	0.049	0.315
0.00- 1.00	0.041	0.264	0.090	0.579
1.00- 2.00	0.055	0.354	0.145	0.933
2.00- 3.00	0.132	0.850	0.277	1.780
3.00- 4.00	0.302	1.940	0.579	3.730
4.00- 5.00	1.300	8.370	1.879	12.100
5.00- 6.00	1.250	8.050	3.129	20.150
6.00- 7.00	1.950	12.560	5.079	32.710
7.00- 8.00	1.900	12.240	6.979	44.940
8.00- 9.00	1.950	12.560	8.929	57.500
9.00- 10.00	2.200	14.170	11.129	71.670
10.00- 11.00	1.850	11.910	12.979	83.580
>11.00	2.550	16.420	15.529	100.000

E-22

Class Interval (Phi Units)	Class Weight (gm.)	Weight Percent	Cumulative Weight (gm.)	Cumulative Percent
-1.00- 0.00	0.017	0.104	0.017	0.104
0.00- 1.00	0.014	0.086	0.031	0.191
1.00- 2.00	0.015	0.092	0.046	0.283
2.00- 3.00	0.021	0.129	0.067	0.413
3.00- 4.00	0.037	0.228	0.104	0.641
4.00- 5.00	0.350	2.160	0.454	2.800
5.00- 6.00	1.050	6.480	1.504	9.280
6.00- 7.00	2.050	12.650	3.554	21.930
7.00- 8.00	2.400	14.810	5.954	36.740
8.00- 9.00	2.750	16.970	8.704	53.720
9.00-10.00	2.700	16.660	11.404	70.380
10.00-11.00	2.200	13.580	13.604	83.950
>11.00	2.600	16.040	16.204	100.000

E-20

Class Interval (Phi Units)	Class Weight (gm.)	Weight Percent	Cumulative Weight (gm.)	Cumulative Percent
-1.00- 0.00	0.021	0.122	0.021	0.122
0.00- 1.00	0.020	0.116	0.041	0.238
1.00- 2.00	0.023	0.134	0.064	0.373
2.00- 3.00	0.034	0.198	0.098	0.571
3.00- 4.00	0.058	0.338	0.156	0.909
4.00- 5.00	0.650	3.790	0.806	4.700
5.00- 6.00	1.450	8.450	2.256	13.150
6.00- 7.00	2.200	12.820	4.456	25.970
7.00- 8.00	2.250	13.110	6.706	39.090
8.00- 9.00	2.700	15.740	9.406	54.830
9.00-10.00	2.600	15.160	12.006	69.980
10.00-11.00	2.200	12.820	14.206	82.800
>11.00	2.950	17.200	17.156	100.000

E-16

Class Interval (Phi Units)	Class Weight (gm.)	Weight Percent	Cumulative Weight (gm.)	Cumulative Percent
0.00- 1.00	0.002	0.012	0.002	0.012
1.00- 2.00	0.016	0.099	0.018	0.112
2.00- 3.00	0.031	0.193	0.049	0.305
3.00- 4.00	0.037	0.230	0.086	0.536
4.00- 5.00	0.600	3.740	0.686	4.280
5.00- 6.00	1.350	8.420	2.036	12.700
6.00- 7.00	1.950	12.160	3.986	24.860
7.00- 8.00	2.200	13.720	6.186	38.580
8.00- 9.00	2.400	14.970	8.586	53.540
9.00-10.00	2.200	13.720	10.786	67.260
10.00-11.00	2.050	12.780	12.836	80.040
>11.00	3.200	19.960	16.036	100.000

E-12

Class Interval (Phi Units)	Class Weight (gm.)	Weight Percent	Cumulative Weight (gm.)	Cumulative Percent
-1.00- 0.00	0.019	0.110	0.019	0.110
0.00- 1.00	0.005	0.030	0.024	0.140
1.00- 2.00	0.013	0.075	0.037	0.220
2.00- 3.00	0.036	0.210	0.073	0.430
3.00- 4.00	0.039	0.230	0.112	0.650
4.00- 5.00	0.250	1.460	0.362	2.120
5.00- 6.00	1.000	5.840	1.362	7.960
6.00- 7.00	2.300	13.440	3.662	21.400
7.00- 8.00	2.650	15.490	6.312	36.890
8.00- 9.00	2.950	17.240	9.262	54.130
9.00-10.00	2.750	16.070	12.012	70.200
10.00-11.00	2.250	13.150	14.262	83.350
>11.00	2.850	16.650	17.112	100.000

E-7

Class Interval (Phi Units)	Class Weight (gm.)	Weight Percent	Cumulative Weight (gm.)	Cumulative Percent
0.00- 1.00	0.034	0.190	0.034	0.190
1.00- 2.00	0.028	0.150	0.062	0.340
2.00- 3.00	0.032	0.180	0.094	0.520
3.00- 4.00	0.035	0.190	0.129	0.710
4.00- 5.00	0.250	1.380	0.379	2.100
5.00- 6.00	0.750	4.150	1.129	6.240
6.00- 7.00	1.850	10.230	2.979	16.480
7.00- 8.00	2.850	15.760	5.829	32.240
8.00- 9.00	2.650	14.660	8.479	46.900
9.00-10.00	3.700	20.470	12.179	67.370
10.00-11.00	2.600	14.380	14.779	81.750
>11.00	3.300	18.250	18.079	100.000

E-4

Class Interval (Phi Units)	Class Weight (gm.)	Weight Percent	Cumulative Weight (gm.)	Cumulative Percent
0.00- 1.00	0.001	0.005	0.001	0.005
1.00- 2.00	0.031	0.174	0.032	0.179
2.00- 3.00	0.108	0.606	0.140	0.786
3.00- 4.00	0.105	0.590	0.245	1.380
4.00- 5.00	0.300	1.685	0.545	3.060
5.00- 6.00	0.550	3.090	1.095	6.150
6.00- 7.00	1.800	10.120	2.895	16.270
7.00- 8.00	3.200	17.980	6.095	34.250
8.00- 9.00	3.500	19.670	9.595	53.920
9.00-10.00	2.750	15.450	12.345	69.370
10.00-11.00	2.350	13.210	14.695	82.580
>11.00	3.100	17.420	17.795	100.000

G-Sand

Class Interval (Phi Units)	Class Weight (gm.)	Weight Percent	Cumulative Weight (gm.)	Cumulative Percent
1.00- 1.25	0.002	0.001	0.002	0.001
1.25- 1.50	0.003	0.003	0.005	0.005
1.50- 1.75	0.009	0.008	0.014	0.013
1.75- 2.00	0.104	0.103	0.117	0.117
2.00- 2.25	0.679	0.679	0.796	0.796
2.25- 2.50	2.737	2.738	3.533	3.535
2.50- 2.75	16.609	16.618	20.142	20.153
2.75- 3.00	13.320	13.327	33.462	33.481
3.00- 3.25	27.407	27.422	60.869	60.903
3.25- 3.50	13.232	13.239	74.101	74.143
3.50- 3.75	6.135	6.138	80.236	80.281
3.75- 4.00	6.423	6.426	86.659	86.708
4.00- 5.00	7.850	7.854	94.519	94.567
5.00- 6.00	2.060	2.061	96.579	96.628
6.00- 7.00	1.170	1.170	97.749	97.798
7.00- 8.00	0.690	0.690	98.439	98.489
8.00- 9.00	0.480	0.480	98.919	98.969
9.00-10.00	0.410	0.410	99.329	99.379
10.00-11.00	0.410	0.410	99.739	99.789
>11.00	0.210	0.210	99.949	100.000

G-20'

Class Interval (Phi Units)	Class Weight (gm.)	Weight Percent	Cumulative Weight (gm.)	Cumulative Percent
2.00- 3.00	0.002	0.012	0.002	0.012
3.00- 4.00	0.006	0.037	0.008	0.049
4.00- 5.00	0.650	4.050	0.658	4.100
5.00- 6.00	2.400	14.950	3.058	19.040
6.00- 7.00	2.250	14.010	5.308	33.060
7.00- 8.00	1.900	11.830	7.208	44.890
8.00- 9.00	1.850	11.520	9.058	56.410
9.00-10.00	2.050	12.770	11.108	69.170
10.00-11.00	1.750	10.900	12.858	80.070
>11.00	3.200	19.930	16.058	100.000

G-20

Class Interval (Phi Units)	Class Weight (gm.)	Weight Percent	Cumulative Weight (gm.)	Cumulative Percent
1.00- 2.00	0.019	0.117	0.019	0.117
2.00- 3.00	0.052	0.320	0.071	0.437
3.00- 4.00	0.065	0.400	0.136	0.837
4.00- 5.00	1.250	7.700	1.386	8.536
5.00- 6.00	1.850	11.390	3.236	19.930
6.00- 7.00	2.300	14.170	5.536	34.100
7.00- 8.00	1.750	10.780	7.286	44.880
8.00- 9.00	1.950	12.010	9.236	56.890
9.00-10.00	1.900	11.700	11.136	68.590
10.00-11.00	1.950	12.010	13.086	80.600
>11.00	3.150	19.400	16.236	100.000

G-14

Class Interval (Phi Units)	Class Weight (gm.)	Weight Percent	Cumulative Weight (gm.)	Cumulative Percent
0.00- 1.00	0.007	0.036	0.007	0.036
1.00- 2.00	0.034	0.175	0.041	0.212
2.00- 3.00	0.063	0.326	0.104	0.538
3.00- 4.00	0.066	0.341	0.170	0.879
4.00- 5.00	0.700	3.620	0.870	4.503
5.00- 6.00	2.050	10.610	2.920	15.110
6.00- 7.00	2.400	12.420	5.320	27.540
7.00- 8.00	2.250	11.650	7.570	39.180
8.00- 9.00	2.550	13.200	10.120	52.380
9.00-10.00	2.850	14.750	12.970	67.130
10.00-11.00	2.500	12.940	15.470	80.070
>11.00	3.850	19.930	19.320	100.000

G-12

Class Interval (Phi Units)	Class Weight (gm.)	Weight Percent	Cumulative Weight (gm.)	Cumulative Percent
0.00- 1.00	0.006	0.036	0.006	0.036
1.00- 2.00	0.045	0.274	0.051	0.311
2.00- 3.00	0.101	0.616	0.152	0.928
3.00- 4.00	0.176	1.074	0.328	2.000
4.00- 5.00	0.950	5.800	1.278	7.800
5.00- 6.00	1.600	9.770	2.878	17.570
6.00- 7.00	1.950	11.910	4.828	29.480
7.00- 8.00	2.100	12.820	6.928	42.300
8.00- 9.00	2.050	12.520	8.978	54.820
9.00-10.00	2.150	13.130	11.128	67.940
10.00-11.00	2.050	12.520	13.178	80.460
>11.00	3.200	19.540	16.378	100.000

C-17'

Class Interval (Phi Units)	Class Weight (gm.)	Weight Percent	Cumulative Weight (gm.)	Cumulative Percent
0.00- 1.00	0.004	0.030	0.004	0.027
1.00- 2.00	0.026	0.180	0.030	0.203
2.00- 3.00	0.018	0.120	0.048	0.325
3.00- 4.00	0.038	0.260	0.086	0.583
4.00- 5.00	0.750	5.100	0.836	5.670
5.00- 6.00	1.350	9.200	2.186	14.830
6.00- 7.00	1.750	11.900	3.936	26.710
7.00- 8.00	1.950	13.200	5.886	39.940
8.00- 9.00	1.800	12.200	7.686	52.160
9.00-10.00	1.750	11.900	9.436	64.030
10.00-11.00	1.500	10.200	10.936	74.210
>11.00	3.800	25.800	14.736	100.000

C-17

Class Interval (Phi Units)	Class Weight (gm.)	Weight Percent	Cumulative Weight (gm.)	Cumulative Percent
-1.00- 0.00	0.022	0.126	0.022	0.126
0.00- 1.00	0.019	0.109	0.041	0.236
1.00- 2.00	0.023	0.132	0.064	0.368
2.00- 3.00	0.032	0.184	0.096	0.553
3.00- 4.00	0.052	0.299	0.148	0.853
4.00- 5.00	0.850	4.900	0.998	5.750
5.00- 6.00	1.250	7.210	2.248	12.960
6.00- 7.00	2.150	12.390	4.398	25.350
7.00- 8.00	2.200	12.680	6.598	38.030
8.00- 9.00	2.300	13.260	8.898	51.290
9.00-10.00	2.250	12.970	11.148	64.260
10.00-11.00	2.050	11.820	13.198	76.080
>11.00	4.150	23.920	17.348	100.000

C-15

Class Interval (Phi Units)	Class Weight (gm.)	Weight Percent	Cumulative Weight (gm.)	Cumulative Percent
-1.00- 0.00	0.005	0.027	0.005	0.027
0.00- 1.00	0.016	0.088	0.021	0.116
1.00- 2.00	0.025	0.138	0.046	0.254
2.00- 3.00	0.027	0.149	0.073	0.404
3.00- 4.00	0.045	0.249	0.118	0.653
4.00- 5.00	0.700	3.870	0.818	4.530
5.00- 6.00	1.500	8.300	2.318	12.830
6.00- 7.00	1.950	10.790	4.268	23.620
7.00- 8.00	2.150	11.900	6.418	35.520
8.00- 9.00	2.500	13.840	8.918	49.360
9.00-10.00	2.550	14.110	11.468	63.470
10.00-11.00	2.300	12.730	13.768	76.200
>11.00	4.300	23.800	18.068	100.000

C-10

Class Interval (Phi Units)	Class Weight (gm.)	Weight Percent	Cumulative Weight (gm.)	Cumulative Percent
0.00- 1.00	0.001	0.006	0.001	0.006
1.00- 2.00	0.003	0.019	0.004	0.026
2.00- 3.00	0.009	0.059	0.013	0.085
3.00- 4.00	0.012	0.079	0.025	0.165
4.00- 5.00	0.350	2.310	0.375	2.480
5.00- 6.00	1.100	7.270	1.475	9.750
6.00- 7.00	1.900	12.560	3.375	22.310
7.00- 8.00	2.200	14.550	5.575	36.860
8.00- 9.00	2.250	14.880	7.825	51.740
9.00-10.00	2.100	13.880	9.925	65.620
10.00-11.00	1.850	12.230	11.775	77.850
>11.00	3.350	22.150	15.125	100.000

C-8

Class Interval (Phi Units)	Class Weight (gm.)	Weight Percent	Cumulative Weight (gm.)	Cumulative Percent
2.00- 3.00	0.009	0.057	0.009	0.057
3.00- 4.00	0.025	0.159	0.034	0.217
4.00- 5.00	0.250	1.600	0.284	1.820
5.00- 6.00	0.700	4.480	0.984	6.290
6.00- 7.00	1.950	12.470	2.934	18.770
7.00- 8.00	2.250	14.390	5.184	33.160
8.00- 9.00	2.400	15.350	7.584	48.510
9.00-10.00	2.350	15.030	9.934	63.540
10.00-11.00	2.050	13.110	11.984	76.650
>11.00	3.650	23.350	15.634	100.000

C-3

Class Interval (Phi Units)	Class Weight (gm.)	Weight Percent	Cumulative Weight (gm.)	Cumulative Percent
2.00- 3.00	0.005	0.031	0.005	0.031
3.00- 4.00	0.012	0.074	0.017	0.105
4.00- 5.00	0.150	0.930	0.167	1.040
5.00- 6.00	0.550	3.410	0.717	4.450
6.00- 7.00	1.800	11.170	2.517	15.620
7.00- 8.00	3.000	18.610	5.517	34.230
8.00- 9.00	3.400	21.100	8.917	55.330
9.00-10.00	2.750	17.060	11.667	72.390
10.00-11.00	1.950	12.100	13.617	84.490
>11.00	2.500	15.510	16.117	100.000

H-6

Class Interval (Phi Units)	Class Weight (gm.)	Weight Percent	Cumulative Weight (gm.)	Cumulative Percent
0.00- 1.00	0.001	0.006	0.001	0.006
1.00- 2.00	0.003	0.018	0.004	0.025
2.00- 3.00	0.015	0.094	0.019	0.119
3.00- 4.00	0.028	0.176	0.047	0.295
4.00- 5.00	0.090	5.660	0.947	5.960
5.00- 6.00	1.750	11.010	2.697	16.970
6.00- 7.00	1.950	12.270	4.647	29.230
7.00- 8.00	2.000	12.580	6.647	41.810
8.00- 9.00	2.450	15.410	9.097	57.220
9.00-10.00	2.300	14.470	11.397	71.690
10.00-11.00	1.750	11.010	13.147	82.700
>11.00	2.750	17.300	15.897	100.000

H-4

Class Interval (Phi Units)	Class Weight (gm.)	Weight Percent	Cumulative Weight (gm.)	Cumulative Percent
1.00- 2.00	0.008	0.041	0.008	0.041
2.00- 3.00	0.026	0.136	0.034	0.178
3.00- 4.00	0.053	0.277	0.087	0.455
4.00- 5.00	0.650	3.410	0.737	3.860
5.00- 6.00	1.300	6.810	2.037	10.670
6.00- 7.00	2.650	13.880	4.687	24.560
7.00- 8.00	3.100	16.240	7.787	40.800
8.00- 9.00	3.150	16.500	10.937	57.300
9.00-10.00	2.900	15.190	13.837	72.490
10.00-11.00	2.300	12.050	16.137	84.540
>11.00	2.950	15.460	19.087	100.000

F-18

Class Interval (Phi Units)	Class Weight (gm.)	Weight Percent	Cumulative Weight (gm.)	Cumulative Percent
0.00- 1.00	0.011	0.062	0.011	0.062
1.00- 2.00	0.019	0.107	0.030	0.170
2.00- 3.00	0.033	0.187	0.063	0.358
3.00- 4.00	0.032	0.181	0.095	0.539
4.00- 5.00	0.450	2.560	0.545	3.100
5.00- 6.00	1.300	7.390	1.845	10.490
6.00- 7.00	1.900	10.800	3.745	21.280
7.00- 8.00	2.450	13.920	6.195	35.210
8.00- 9.00	2.600	14.780	8.795	49.990
9.00-10.00	2.450	13.920	11.245	63.910
10.00-11.00	2.300	13.070	13.545	76.980
>11.00	4.050	23.020	17.595	100.000

F-6

Class Interval (Phi Units)	Class Weight (gm.)	Weight Percent	Cumulative Weight (gm.)	Cumulative Percent
0.00- 1.00	0.002	0.010	0.002	0.010
1.00- 2.00	0.020	0.109	0.022	0.120
2.00- 3.00	0.029	0.159	0.051	0.279
3.00- 4.00	0.037	0.202	0.088	0.482
4.00- 5.00	0.650	3.560	0.738	4.050
5.00- 6.00	1.350	7.400	2.088	11.450
6.00- 7.00	1.950	10.690	4.038	22.140
7.00- 8.00	2.550	13.980	6.588	36.120
8.00- 9.00	2.850	15.630	9.438	51.750
9.00-10.00	2.550	13.980	11.988	65.730
10.00-11.00	2.250	12.340	14.238	78.070
>11.00	4.000	21.930	18.238	100.000

J-Sand

Class Interval (Phi Units)	Class Weight (gm.)	Weight Percent	Cumulative Weight (gm.)	Cumulative Percent
2.00- 2.25	0.003	0.005	0.003	0.005
2.25- 2.50	0.003	0.005	0.006	0.010
2.50- 2.75	0.014	0.025	0.020	0.035
2.75- 3.00	0.204	0.366	0.224	0.402
3.00- 3.25	1.202	2.157	1.426	2.560
3.25- 3.50	5.735	10.296	7.161	12.857
3.50- 3.75	8.399	15.078	15.560	27.936
3.75- 4.00	18.839	33.822	34.399	61.760
4.00- 5.00	13.442	24.132	47.841	85.895
5.00- 6.00	2.706	4.858	50.547	90.753
6.00- 7.00	1.397	2.508	51.944	93.261
7.00- 8.00	1.222	2.193	53.166	95.455
8.00- 9.00	1.135	2.037	54.301	97.493
9.00-10.00	0.698	1.253	54.999	98.746
10.00-11.00	0.436	0.782	55.435	99.529
>11.00	0.262	0.470	55.697	100.000

J-1

Class Interval (Phi Units)	Class Weight (gm.)	Weight Percent	Cumulative Weight (gm.)	Cumulative Percent
1.00- 2.00	0.003	0.020	0.003	0.020
2.00- 3.00	0.009	0.062	0.012	0.083
3.00- 4.00	0.789	5.500	0.801	5.580
4.00- 5.00	1.950	13.590	2.751	19.170
5.00- 6.00	1.750	12.190	4.501	31.360
6.00- 7.00	1.650	11.500	6.151	42.860
7.00- 8.00	1.600	11.150	7.751	54.010
8.00- 9.00	1.850	12.900	9.601	66.900
9.00-10.00	1.000	6.970	10.601	73.870
10.00-11.00	1.250	8.710	11.851	82.580
>11.00	2.500	17.420	14.351	100.000

J-2

Class Interval (Phi Units)	Class Weight (gm.)	Weight Percent	Cumulative Weight (gm.)	Cumulative Percent
1.00- 2.00	0.001	0.005	0.001	0.005
2.00- 3.00	0.004	0.023	0.005	0.029
3.00- 4.00	0.184	1.077	0.189	1.106
4.00- 5.00	3.110	18.209	3.299	19.316
5.00- 6.00	2.610	15.281	5.909	34.598
6.00- 7.00	2.220	12.998	8.129	47.596
7.00- 8.00	1.890	11.066	10.019	58.662
8.00- 9.00	1.780	10.422	11.799	69.084
9.00-10.00	1.220	7.143	13.019	76.228
10.00-11.00	1.220	7.143	14.239	83.371
>11.00	2.840	16.628	17.079	100.000

A-6

Class Interval (Phi Units)	Class Weight (gm.)	Weight Percent	Cumulative Weight (gm.)	Cumulative Percent
1.00- 2.00	0.003	0.019	0.003	0.019
2.00- 3.00	0.016	0.102	0.019	0.121
3.00- 4.00	0.044	0.280	0.063	0.402
4.00- 5.00	0.100	0.638	0.163	1.040
5.00- 6.00	0.300	1.920	0.463	2.960
6.00- 7.00	1.200	7.660	1.663	10.620
7.00- 8.00	2.700	17.240	4.363	27.860
8.00- 9.00	2.700	17.240	7.063	45.090
9.00-10.00	2.800	17.880	9.863	62.970
10.00-11.00	2.100	13.410	11.963	76.380
>11.00	3.700	23.620	15.663	100.000

Appendix III

Relative Percentages of Clay Minerals
Based on Peak Areas from Glycolated Patterns

Sample No.	Mixed-Layer Chlorite	Illite	Illite-Mont.	Kaolinite
E-Sand	--	22.0	37.4	40.7
E-26-1	21.5	22.2	33.5	22.7
E-25'	27.7	24.9	27.7	19.6
E-25	12.0*	26.3	39.8	21.9
E-23	8.0*	33.5	29.7	28.7
E-22	13.3*	32.6	29.6	24.6
E-20	13.3*	32.5	35.1	19.2
E-16	9.0*	33.3	29.7	28.0
E-12	12.2	29.6	37.7	20.6
E-7	14.3	31.0	39.7	15.0
E-4	17.7	31.1	33.0	18.3
G-Sand	--	48.4	26.1	25.5
G-20'	18.1	31.1	37.0	13.7
G-20	14.3*	21.2	39.0	25.4
G-14	10.1*	31.1	33.7	25.1
G-12	9.0*	36.6	32.9	21.5
C-17'	9.9*	35.7	30.3	24.1
C-17	9.5*	33.8	29.1	27.5
C-15	17.2*	32.6	28.4	21.8
C-10	9.2*	38.2	33.5	19.0
C-8	11.9	37.6	26.1	24.5
C-3	6.6*	38.1	29.0	26.2
H-6	8.3*	43.8	27.6	20.2
H-4	8.0*	33.4	33.3	25.3
F-18	11.7*	38.8	23.6	25.9
F-6	14.9*	38.6	20.0	26.5
J-Sand	39.2*	9.4	13.0	38.3
J-1	2.0	42.9	22.0	33.2
J-2	9.6*	25.8	19.5	45.1
A-6	12.4	31.3	26.0	30.3

* Discrete Chlorite

Appendix IV

Reagents and Apparatus for Phosphate Determinations

Reagents used in the procedure were prepared as follows:

1) 1 N NH_4Cl. 53.5 gm. solid dissolved in distilled water and diluted to a 1 liter volume.

2) 0.5 N NH_4F. 18.5 gm. solid dissolved in 1 liter of distilled water. Adjust pH to 7.0 with 4 N NH_4OH added dropwise.

3) 0.1 N NaOH. A 0.1 N volumetric standard was used in this study.

4) 0.5 N H_2SO_4. A 0.5 N volumetric standard was used in this study.

5) Saturated NaCl solution. 400 gm. NaCl suspended in 1 liter of distilled water.

6) Standard phosphorous solutions. 21.95 gm. of KH_2PO_4 is dissolved in distilled water and diluted to a 1 liter volume. 10 ml. of this solution is diluted to a volume of 1 liter to make a 50 ppm solution. Less concentrated solutions may be prepared as needed by further dilution of this 50 ppm stock solution.

7) Chlorostannous reductant. 25 gm. of $SnCl_2 \cdot 2H_2O$ is dissolved in 100 ml. concentrated HCl, diluted to 1 liter and stored in a brown bottle with a siphon under a 10 mm. layer of mineral oil.

8) Sulfomolybdic acid solution. 25 gm. of $(NH_4)_6Mo_7O_{24} \cdot 4H_2O$ is dissolved in 200 ml. of distilled water, heated to 60° C., and filtered if cloudy. Then 275 ml. of phosphorous-free and arsenic-free concentrated sulfuric acid (35 to 36 N) is diluted to 750 ml. with distilled water. After both solutions have cooled, the ammonium molybdate solution is added slowly, with stirring, to the sulfuric acid solution.

The combined solution is then diluted to exactly 1000 ml. with
distilled water.

9) 2,6-dinitrophenol (or 2,4-dinitrophenol). 0.25% by weight in distilled
water.

Apparatus needed for the procedure consists of 2 ml. and 3 ml. pipettes;
a buret; 100 ml. centrifuge tubes; 50 ml. volumetric flasks; eye droppers;
stirring rods; 20 ml., 100 ml., and 1000 ml. graduated cylinders; and an array
of various size beakers.

The glassware used must be free from contamination of phosphorous (or
arsenic which gives the same test). Because Pyrex glass contains 0.7 percent
arsenic oxide, it must be weathered before use by treatment with a warm sul-
furic acid-dichromate solution for at least 24 hours (Jackson, 1958). This
solution can be prepared as outlined by Skoog and West (1965):

Mix 10 to 15 grams of potassium dichromate with about 15 ml.
of distilled water in a 500 ml. heat resistant conical flask. Add
concentrated sulfuric acid slowly, swirling between increments.
Contents of the flask will become a semisolid red mass; add just
enough sulfuric acid to bring the mass into solution. Allow the
contents to cool before transferring to a soft glass bottle. This
solution may be reused until it acquires the green color of chromium
(III) ion, at which time it must be discarded.

Washing soaps which contain phosphorous must be completely removed by
cleaning in strong acid. The glassware is dipped in 6 N HCl, rinsed several
times with tap water, then rinsed 3 times with distilled water. Other sources
of phosphorous contamination include dust, saliva, perspiration, and tobacco
ashes (Jackson, 1958).

PETROLOGY OF PART OF THE WEWOKA FORMATION
(PENNSYLVANIAN) IN HUGHES COUNTY, OKLAHOMA

by

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B. S., Kansas State University, 1970

AN ABSTRACT OF A MASTER'S THESIS

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ABSTRACT

A petrologic study of part of the Wewoka Formation in Hughes County, Oklahoma, was undertaken to determine (1) relationship among grain size, clay mineralogy, and paleosalinity, (2) source area and depositional environments, and (3) relationship between these sedimentary rocks and benthic marine communities.

Lithologies in this interval are, in ascending order, (1) shale, (2) mudstone (subdivided into lower, middle, and upper), and (3) sandstone. Only minor differences in mean grain size were observed in the shale and lower two-thirds of the mudstone. Mean grain size increases in the upper mudstone as the contact with the sandstone is approached. A decrease in mean grain size to the east was observed in both the shale and mudstone sequence and the sandstone. The clay mineral assemblage consists of illite, illite-montmorillonite, chlorite, mixed-layer chlorite, and kaolinite, with only minor variations in relative abundance. Potassium treatment causes structural collapse of illite-montmorillonite, indicating it is a degraded illite. Sandstone beds contain more kaolinite and less chlorite and mixed-layer chlorite than the underlying shale and mudstone interval. Paleosalinity estimates of the shale and mudstone interval range from 2.5 0/00 (freshwater) to 34.7 0/00 (normal marine). In general, low paleosalinity values were observed in the shale and in the upper mudstone, and normal marine values in the interval between.

Grain size and paleosalinity data support the deltaic depositional environments proposed by West (1970) which are, in ascending order, (1) marshy subtidal to tidal flat represented by black, fossiliferous shale, (2) shallow nearshore subtidal (delta front) represented by molluscan mudstone, (3) off-shore subtidal (prodelta) represented by brachiopodal mudstone, (4) nearshore

subtidal (outer delta plain) represented by silty, foraminiferal mudstone, and (5) deltaic sand deposition (distributary system) represented by crossbedded sandstones containing large plant fragments. The sediment was probably derived from the Ouachita Mountains which were deformed during Atoka and Des Moines time. This fold belt contains a thick sequence of Upper Mississippian-- Lower Pennsylvanian clastic strata with the same clay mineral assemblage as the interval studied. Grain size and paleosalinity data support the benthic marine communities proposed by West (1970).