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A stratigraphic and sedimentologic analysis of the Tongue River and Sentinel Butte Formations (Paleocene), western North Dakota

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A STRATIGRAPHIC AND SEDIMENTOLOGIC ANALYSIS OF THE TONGUE

RIVER AND SENTINEL BUTTE FORMATIONS (PALEOCENE),

WESTERN NORTH DAKOTA

by

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This dissertation submitted by Chester F. Royse, Jr. in partial fulfillment of the requirements for the Degree of Doctor of Philosophy in the University of North Dakota is hereby approved by the Committee under whom the work has been done.

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iii

ACKNOWLEDGMENTS

TABLE OF CONTENTS

CONTENTS (cont'd)

CONTENTS (cont'd)

LIST OF TABLES

TABLES (cont'd)

x

LIST OF ILLUSTRATIONS

ILLUSTRATIONS (cont'd)

ILLUSTRATIONS (cont'd)

xv

ILLUSTRATIONS (cont'd)

ABSTRACT

The Tongue River-Sentinel Butte contact has been regarded by many workers as a vague color boundary of minor extent within a relatively homogeneous sequence of Paleocene strata. Consequently, the Sentinel Butte has come to be regarded as a subordinate unit of the "Tongue River Formation". As defined in this report, the contact is a distinctive horizon between two discrete lithogenetic units. It is characterized by three criteria: a lignitic horizon (HT Butte bed) at the top of the Tongue River sequence; a basal sandy unit in the Sentinel Butte sequence; and a marked change in color between buff-yellow Tongue River sediments below and somber gray Sentinel Butte sediments above.

This contact has been mapped on a scale of 1:250,000 throughout the badlands of the Little Missouri River, and along the Missouri River from the Montana-North Dakota border to the mouth of the Little Missouri River. The contact is concealed in the central part of the Williston basin, but crops out on the eastern flank of the basin about 60 to 80 miles east of the area mapped. The extent of the contact along the eastern margin of the basin has not been determined, but outcrops in Morton County display lithologic relationships similar to those which distinguish the contact farther west. No evidence was found in support of the Tongue River-Sentinel Butte facies relationship postulated by previous investigators.

xvii

Recognition of distinctive stratigraphic relationships at the Tongue River-Sentinel Butte contact and documentation of their regional persistence demonstrate that the Sentinel Butte sequence is a mappable lithostratigraphic unit. It is therefore recommended that in western North Dakota and adjacent areas the Sentinel Butte sequence be assigned formational rank. The name Tongue River Formation should be applied only to beds underlying the Sentinel Butte Formation.

Granulometric analysis of nearly 500 sediment samples from 11 stratigraphic sections show that Tongue River sediments are finer grained and less well sorted than those of the Sentinel Butte Formation. Median diameter and skewness are environmentally sensitive particle-size statistics. CM patterns illustrate the fluvial origin of these Paleocene deposits and are used to differentiate sediment transport types and depositional environments; channel, floodplain, and backswamp facies are recognized. Significant differences in fluvial regimes are indicated by the relative abundances of floodplain and backswamp sediments deposited by Tongue River and Sentinel Butte streams. CM patterns give values for maximum suspended-load and minimum bed-load particle sizes which can be used with Hjulström-type diagrams to approximate paleocurrent velocities. Sentinel Butte streams had higher velocities than those of Tongue River time, but the magnitude of both was small and maximum and mid-depth velocities of 40 to 50 centimeters per second are estimated.

Evaluation of stratigraphic, lithologic, and sedimentologic relationships, types and occurrences of primary sedimentary structures, and carbonate contents of Tongue River and Sentinel Butte

strata permit formulation of a sedimentation model for each sequence. Tongue River strata were dispersed eastward across the North Dakota portion of the Williston basin by slow moving streams which drained a low-lying source area to the west. The gradient of the paleoslope was low and sediments were transported primarily in suspension. The fluvial system was stable and protected backswamps developed in which extensive deposits of locally derived organic material accumulated. Basinal subsidence was uniform and controlled the rate of sedimentation during most of the episode. Sediment characteristics indicate that western North Dakota was near base-level during Tongue River time. Near the close of the episode, the elevation of the source area was reduced, basinal subsidence exceeded sedimentation, and swamp conditions prevailed throughout much of western North Dakota.

The episode of Sentinel Butte deposition was initiated by an influx of coarse, basal sediment which spread eastward and southeastward across the late Tongue River swamp. Streams had slightly greater energies than those which previously crossed the basin, but sediment transport was still primarily by suspension. The paleoslope appears to have been variable, both in magnitude and direction, and may reflect changing or multiple sediment source areas created by late Laramide activity to the west and northwest. The elevation of western North Dakota above base-level increased during Sentinel Butte time, probably as a result of rapid deposition (in excess of basinal subsidence), vertical accretion, and eastward overstepping of the Sentinel Butte sequence.

INTRODUCTION

Scope and objectives

The principle motive for initiating a study of the Tongue River and Sentinel Butte Formations in western North Dakota stems from the writer's conviction that detailed sedimentological study can contribute significantly to paleogeographic and paleoecologic reconstruction. Paleontological study provides, perhaps, a more direct approach to such reconstruction, but detailed investigation of the Tongue River and Sentinel Butte fauna and flora have yet to be undertaken. In addition, paleontologic study of the Paleocene Series in North Dakota has been handicapped by three significant factors: (1) the lack of adequate criteria for determining stratigraphic position in the Tongue River-Sentinel Butte sequence, (2) the paucity of vertebrate remains throughout the sequence, and (3) a need of taxonomic revision of the Paloecene invertebrate fauna. Much preliminary investigation will be required before invertebrate fossils yield detailed ecologic information. The composition and ecology of the Paleocene flora of the Great Plains have been summarized (Brown, 1962), but the summary is general and the Tongue River and Sentinel Butte elements cannot be divorced from the synthesis. These factors make sedimentological reconstruction of the Tongue River and Sentinel Butte particularly meaningful and the loosely-consolidated character of the strata makes this approach feasible.

1

This study has been approached on three orders of magnitude. Stratigraphic investigations are broad in scope and are concerned primarily with establishing the regional extent of the Tongue River-Sentinel Butte contact. Of lesser magnitude is the study of selected stratigraphic sections and outcrops, from which sediment samples and directional data were obtained. The most detailed investigations involved precise laboratory analysis of sediments. The study is not a reconnaissance, but its scope and objectives are broad and the questions for which answers are sought are general. Sediments of the Paleocene Series are extremely heterogeneous, and an attempt has been made to focus on the "forest" and disregard the "trees". Uniformity, in the form of regional trends and significant similarities and differences of measured parameters, has been sought in this heterogeneity. During the course of investigation, the writer repeatedly became entangled in the "underbrush" of this "forest", as it has many interesting aspects, but a fundamental objective of this report is to establish a broad framework within which detailed studies can be sensibly defined. An effort has been made to bear this in mind and free the discussions of unnecessary "shrubbery".

Specific objectives of this report include the following:

(1) To describe the characteristics of the Tongue River-Sentinel Butte contact and to delimit its extent throughout a large portion of western North Dakota,

(2) To determine the direction of the source areas from which sediments were derived, and their dispersion patterns within the Paleocene Williston basin,

(3) To determine major similarities and differences between Tongue River and Sentinel Butte strata, and

(4) To reconstruct the fluvial and geographic conditions extant during Tongue River and Sentinel Butte time.

Fulfillment of the first objective should illustrate that the Sentinel Butte is a distinctive and mappable stratigraphic unit. In anticipation of such fulfillment, the writer freely refers to the Sentinel Butte as a formation. Other terminology, except that used in the context of previous investigators, is that currently accepted by the North Dakota Geological Survey. The lithostratigraphic nomenclature applied in this report to beds in the Paleocene Series in western North Dakota is given below:

Fort Union Group

Sentinel Butte Formation

Tongue River Formation

Ludlow and Cannonball Formations

Methods of Investigation

Field observations were made during the summers of 1965 and 1966. The Tongue River-Sentinel Butte contact was delimited (Figure 1) by continuity throughout much of the study area, but similarity of stratigraphic sequence was utilized in correlation across broad expanses where the contact is concealed. The contact was inspected at numerous localities, its elevation determined, and the character of adjacent beds recorded. Samples were taken 6 to 8 feet above and below the

contact at many stations. Field locations were accurately plotted on county road maps (scale = 1/62,500) and later transferred to topographic sheets (scale = 1/250,000). These points, supplemented with additional data from published reports, were used to extrapolate the contact throughout the drainage of the Little Missouri and Missouri Rivers.

Sediment samples were collected from widely separated, measured stratigraphic sections. Samples were collected from all units greater than about one foot in thickness and in many instances from thinner beds. As collected, samples should provide a proportional representation of the stratigraphic units present. Precautions were taken not to sample across boundaries of sedimentation units. In very-thinly bedded and laminated lithologies, a number of discrete units constitute a sample; however this number was held to a practical minimum. An attempt was made to obtain fresh samples, but few if any samples are entirely unweathered. The rapid rate of erosion in the badlands probably permits time for little more than oxidation of a few secondary minerals; clastic grains generally appear fresh and unaltered under the microscope.

Stratigraphic sections were measured by rod and hand level. Field procedure consisted of first rodding an entire section in 5-foot intervals and labeling each station with a numbered card fixed to the outcrop with a nail. The section was then studied, logged, and sampled.

Laboratory analyses were conducted in the Department of Geology at the University of North Dakota; procedures are described in appropriate sections of the text.

Previous Investigations

Many of the surface geologic studies of Paleocene strata in western North Dakota involved classification of coal lands and are found in the Bulletins of the U. S. Geological Survey. Most of these investigations were conducted between 1900 and 1930, but an increasing potential of lignite for generation of electric power and the discovery of uranium compounds in lignitic strata has renewed economic interest in these beds. Extensive seismic and other subsurface geophysical surveys have been made by various oil companies, but results of these studies are not generally available to the public. Several recent studies involving the Paleocene Series in western North Dakota can be found among the publications of the North Dakota Geological Survey. Among these, Royse (1967) has discussed the character and extent of the Tongue River-Sentinel Butte contact. Other relevant studies are cited in the text of this dissertation and additional references are included in the bibliography.

The Conservation Branch of the U. S. Geological Survey is presently mapping a number of quadrangles in Morton and Grant Counties, but the greatest portion of the study area (Figure 1) has not been mapped at a scale greater than 1/250,000 or a contour interval of less than 100 feet.

The recent emphasis by sedimentologists on studies of primary sedimentary structures and their hydrodynamic interpretations and the environmental interpretation of sediment textural parameters have aided in evaluation of the data of this investigation. Of particular significance for the interpretation of primary sedimentary structures

the publications by Middleton (ed., 1965) and Allen (1963b, 1965c).
Studies by Fisk (1947), Sundborg (1956), Passega (1957, 1964), Schumm
1960, and Allen (1965c), among others, have provided a basis for
genetic classification of sediments. The comprehensive synthesis of
paleocurrent studies and methods of analysis presented by Potter and
Pettijohn (1963) provided a foundation, as well as stimulus, for the
study of directional data. Studies by Hjulström (1939), Sundborg
1956), Inman (1949), Menard (1950), Leopold and others (1964),
Passega (1957), Friedman (1962), to cite but a few, have aided in
defining the relevant parameters of fluid particle transport and the
"fingerprint" which this mechanism leaves of sedimentary deposits.
Collectively, these studies make it possible to bridge the gap between
the sedimentary deposits themselves and their source, mode of trans-
port, and environment of deposition. Without these previous inves-
tigations, the present study would not be feasible.

GENERAL STRATIGRAPHY

Regional Setting

General statement

Strata of Paleocene age are widespread throughout the northern Great Plains. They conformably overlie the Hell Creek Formation of Cretaceous age and are unconformably overlain by the Golden Valley (Eocene) and White River (Oligocene) Formations and by late Tertiary gravels and assorted Pleistocene deposits. Collectively, beds of the Paleocene Series form a stratigraphic unit known as the Fort Union Group, which extends in continuous outcrop over much of western North and South Dakota, eastern Montana, and across the Powder River Basin of Wyoming. Fort Union beds are also recognized in northwestern Colorado.

In North Dakota, Fort Union beds are widespread within the Williston basin. Major outcrops, however, are largely restricted to the non-glaciated area (and adjacent glaciated areas of thin drift) south and west of the Missouri River. Excellent exposures are present in the highly dissected badlands of the Little Missouri River and along the northern reaches of the Missouri River. The Turtle Mountains, in north-central North Dakota, are an outlier of Paleocene strata.

The Tongue River and Sentinel Butte Formations constitute the

greatest Paleocene outcrop area within the state; the contact between the two is nearly continuous throughout the Little Missouri badlands. Exposures reach 300 to 500 feet, affording excellent opportunity for observation of stratigraphic relationships. Within the area here discussed (Figure 1), the base of the Tongue River Formation crops out only south of the vicinity of Bullion Butte where it overlies the Ludlow Formation. Elsewhere in western North Dakota it lies in the subsurface, except along the eastern flank of the Tertiary Williston basin where it appears above the Cannonball Formation. Much of this eastern area is mantled with drift, and the contact is largely concealed. Although Sentinel Butte strata are widespread in western North Dakota, the upper beds of the sequence have been widely removed by erosion and can be observed at relatively few localities.

Key beds

Tongue River Formation.--Lignite beds are the only good marker horizons in the Tongue River Formation. Several of these have remarkable persistence, but the mapping utility of most of them is limited because they occur low in the section and are exposed in outcrop only in the southern portion of the study area. The H, Hanson, and Harmon beds (Figure 2), have been mapped in the Marmarth lignite field by Hares (1928). They are persistent within the Marmarth field but, northward, the regional dip carries them into the subsurface.

The Garner Creek bed can be traced as it descends from the vicinity of Bullion Butte, northward. Its dip carries it into the stratigraphic interval exposed along the Little Missouri River about 8 miles south of Medora, from whence it can be traced northward in

Group	Fm.	Position	Key bed and outcrop area
Fort Union Group	Sentinel Butte Formation 380 to 620 feet thick		Upper sand; parts of western McKenzie Co. and Billings Co., western Dunn Co.
			Bullion Butte lignite; southern Billings Co. and Golden Valley Co., northern Slope Co.
			Upper "yellow" bed; McKenzie Co.
			Lower "yellow" bed; McKenzie Co.
			"Blue" bed; McKenzie Co.
			Basal sand; throughout area of this report
	Tongue River Formation 315 to 520+ feet thick		HT Butte bed; throughout area of this report
			Meyer lignite; northern Slope Co., ?southern Billings Co. and Golden Valley Co.
			Garner Creek lignite; northern Slope Co. to northern Billings Co.
			Harmon lignite ⎫
			Hanson lignite ⎬ Exposed only in northern Slope and southern Billings Co. and Golden Valley Co.
			H lignite ⎭
			Basal sand; Slope Co. and southern Golden Valley Co.

Figure 2.--Generalized stratigraphic section indicating relative positions of key beds in the Tongue River and Sentinel Butte Formations.

nearly continuous outcrop. In the vicinity of Medora and the South Unit of Roosevelt Park, the Garner Creek bed is equivalent to Bed C of Leonard and Smith (1909) and occurs about 40 feet below lignite Bed D, which is not recognized in the Marmarth field. North of Medora, the component of dip parallel to the Little Missouri River is nearly the same as the gradient of the stream, and the Garner Creek bed maintains a relatively constant stratigraphic position several tens of feet above the river floodplain. This lignite constitutes the best marker bed within the Tongue River Formation between the Marmarth field in the south and the locality of its disappearance beneath the Little Missouri floodplain somewhat north of the mouth of Blacktail Creek.

The Meyer lignite, recognized near the top of the Tongue River section in the Marmarth field, cannot be correlated with certainty to the north. It is probably equivalent to Bed E of Leonard and Smith, which is about 7 feet thick where it occurs at the surface near the village of Sentinel Butte. The extent of all lignite beds mentioned above has been discussed by Hares (1928) and Leonard and Smith (1909).

The best and most widely exposed marker bed in the Tongue River Formation is the HT Butte lignite bed, and its regional extent and relationship to the Tongue River-Sentinel Butte contact are discussed in the next section.

Sentinel Butte Formation.--Lignite beds are less well developed in the Sentinel Butte than in the Tongue River Formation and none have been recognized as useful in correlation. The Bullion Butte lignite bed, named by Hares (1928) in the Marmarth field, occurs in the upper part of the section. This bed may have considerable persistence but,

because upper Sentinel Butte strata have been so widely removed by erosion in western North Dakota, the bed has little value in correlation. It is probably present at Sentinel Butte where it has partially burned to produce the red, baked "scoria" on the northwest flank of the butte.

Several other distinctive lithologies are present in the Sentinel Butte formation (Figure 2) which permit limited correlation within the unit. From the base upward these are: (1) a basal sand, (2) a "blue" bed, (3) a lower "yellow" bed, (4) an upper "yellow" bed, and (5) an upper sand (Figure 19). The first three of these are most useful because the lower beds of the Sentinel Butte are most widespread; the latter have been removed by erosion throughout most of the area studied.

The extent of the basal sand, its relationship to the Tongue River-Sentinel Butte contact and its genetic significance are discussed in following sections. It is the only marker bed studied in detail for this report.

The "blue" bed is a montmorillonitic clay unit strikingly developed in and near the North Unit of Roosevelt Park. Its potential value as a key bed for mapping and correlation has been recognized (Benson, 1954; Fisher, 1953; and others) but its areal extent has not been defined. From the North Unit of Roosevelt Park, it is said (Benson, 1954, p. 15) to extend northward nearly to the Missouri River, and the writer has traced it westward to Sheep Buttes and southward in the bluffs of the Little Missouri drainage to the vicinity of Beicegel Creek (Figure 1). Twenty miles eastward, near Lost Bridge, a bentonitic bed of probable

equivalence is present in the bluffs both north and south of the Little Missouri River. The maximum extent of the "blue" bed has yet to be determined, but observations during this investigation suggest it is much greater than is generally suspected. For example, a bentonitic unit with the same tri-partite character (three distinct horizons occur within the unit in the North Unit of Roosevelt Park) as the "blue" bed, and occupying a similar stratigraphic position, is present at Sentinel Butte. It can be seen to greatest advantage on the eastern flank of the butte just above the saddle which joins the main butte with a small, rounded outlier. The stratigraphic interval which might contain this bed is absent across most of the traverse northward from Sentinel Butte to known exposures of the "blue" bed near Beicegel Creek and, although the resemblance is more than superficial, identification of the "blue" bed this far south is quite tenuous. A possible correlation of the bentonite unit on Sentinel Butte with the "blue" bed should, however, be kept in mind in the event that future investigations develop criteria by which equivalence can be tested.

The lower "yellow" bed (Fisher, 1953) is well exposed in the North Unit of Roosevelt Park where it occurs about 210 feet above the floodplain and 30 feet above the "blue" bed with which it appears to be coextensive. It has been recognized above the "blue" bed throughout the area outlined above. At Sentinel Butte a thick, silty "yellow" unit rests directly upon the "blue" unit and is separated from overlying strata by a thick (6 to 8 feet) sequence of lignitic shale. The same reservations apply to correlation of the "yellow" bed at Sentinel Butte as were mentioned for the "blue" bed, but their mutual

relationship adds merit to considerations of equivalence.

The "upper" yellow bed (Fisher, 1953) is present 430 feet above the floodplain in the North Unit of Roosevelt Park and a probable correlative can be seen high in the bluffs at Lost Bridge. Northward, westward, and southward, however, this stratigraphic interval has been removed by erosion. At Sentinel Butte, a second "yellow" bed is present above that mentioned above, and is separated from it only by 6 to 8 feet of lignitic shale. To postulate an equivalence of both yellow zones on Sentinel Butte with the upper and lower "yellow" beds in the North Unit of Roosevelt Park requires that the 220 foot stratigraphic interval separating the latter be equivalent to 8 feet of lignitic shale at Sentinel Butte. The possibility of such equivalence appears enhanced by the character of the lignitic shale. It contains many clay and silt stringers, is extremely pyritic (or marcasitic), and appears to constitute a significant hiatus. Other lignitic shales, even when quite thick, are not similarly developed. The fact that most shales reflect slow sedimentation and that lignitic shales reflect considerable quiescence is probably beyond debate; the question here is temporal magnitude and whether non-deposition intervened with deposition. Data are insufficient to present a firm argument for a hiatus in the section at Bullion Butte, but the significance of the question will be pursued again elsewhere.

Attention was drawn to a medium-grained, cross-bedded sand in the upper Sentinel Butte Formation (Figure 19-D) during field study of sedimentary structures. The unit appears to have a wide areal extent east of the Little Missouri badlands where upper Sentinel Butte strata have been preserved from erosion. Demonstration of physical

...valence is difficult, because exposures are limited to road cuts
...a few natural outcrops. The unit is very distinctive (cross-bedded,
...erately-well sorted, medium-grained, and usually oxidized) and un-
...any other lithology observed in the Sentinel Butte interval.
...can be seen: (1) along North Dakota Highway 22 between Killdeer
...Lost Bridge (particularly just south of the "breaks" at Lost
...ridge), (2) along North Dakota Highway 22 between Lost Bridge and
...vicinity of Mandaree, and (3) along North Dakota Highway 85
...tween Grassy Butte and the Little Missouri River. The sands above
...uraniferous lignite in the Union Carbide pits several miles north
...Belfield and the Susquehana pit near Gorham are believed to be
...rrelative. A great portion of the soil north and east of Belfield
...a sand loam and is probably developed, in large part, upon this
...and unit.

The precise stratigraphic position (and hence the equivalence)
...f the upper Sentinel Butte sand is difficult to determine because,
...re found, it generally constitutes the uppermost exposed stratum.
...ts proximity to the top of the Sentinel Butte section is assured
...rth of Lost Bridge and near Grassy Butte where Eocene beds of the
...lden Valley Formation occur nearby. It is certain that the unit
...not part of the Eocene Series (as presently recognized) and that it
...curs very near the top of the Sentinel Butte sequence. Its dis-
...imilarity to underlying strata merits emphasis; the significance of
...he upper sand is discussed in later sections.

The key lithologies discussed above are useful in local corre-
...ation, but the most widely exposed, distinctive, and useful key hor-
...zon is the contact between the Tongue River and Sentinel Butte

Formations. It has the greatest utility of any horizon recognized in the study area, and is therefore described in detail in a subsequent section.

Formational thickness

Considerable ambiguity exists in published values for the total thickness of the Tongue River and Sentinel Butte Formations. Three major factors account for the greatest part of these discrepancies: (1) the Tongue River and Sentinel Butte are not constant in thickness, (2) the limits or bounds of stratigraphic intervals loosely designated as Tongue River, Sentinel Butte, Fort Union, or "lignitic strata" have not always been explicitly defined, and (3) indiscriminant adoption of thicknesses reported for one area to other areas. The total thickness of the Tongue River or the Sentinel Butte can be accurately measured at few localities because the base of the first is seldom exposed at the surface and the top of the second has been removed by erosion throughout most of western North Dakota. Furthermore, the base of the Tongue River cannot be "picked" with certainty from well cuttings or logs, and its total thickness is virtually unknown throughout most of the Williston basin.

Dozens of citations of stratigraphic thicknesses for the Tongue River, Sentinel Butte, and Fort Union were tabulated from the literature by the writer in anticipation of isopaching these units in western North Dakota. Field experience and, in many instances, specific field checks, indicate that the greatest number of reported measurements are unreliable or do not apply to the stratigraphic intervals presently recognized as Tongue River and Sentinel Butte. A discouragingly

large number of them are repetitions of values reported in previous publications. Without intent to perpetuate them in the literature, a few of these values are offered below as examples.

Leonard and Smith (1909, p. 21) cited an exposed thickness for the "Fort Union Formation" of 900 feet and suggested that an additional 820 feet of lignite-bearing rocks (penetrated by a well at Medora) in the subsurface belong to the Fort Union. Their total thickness of 1720 feet for the Fort Union in western North Dakota is a widely cited value. This value not only includes the Ludlow Formation, but also the thick sandstone of the White River Formation which caps Sentinel Butte. The total thickness is excessive and the thickness of the Tongue River interval is indeterminant. The thickness of the Sentinel Butte "group" is not given but, as estimated from their generalized stratigraphic column (Plate II), it is about 365 feet.

Thom and Dobbin (1928, p. 487-488) interpreted values for the thickness of Paleocene and related units in eastern Montana and Wyoming and the western Dakotas. Within the Williston basin, values for the Tongue River "member" are given as 550 to 800 feet between Williston and Minot, 700 feet at Sentinel Butte, and 420 feet in the Cannonball lignite field. Adjacent areas in Montana have recorded thicknesses of about 600 to 650 feet at Culbertson and Plentywood, and about 730 feet at Sidney. Values for the Sentinel Butte Formation are cited as 500 feet between Williston and Minot, 700 feet at Sentinel Butte, and 420 feet in the Cannonball field; adjacent areas of Montana have thicknesses of 275 to 280 feet at Culbertson and Plentywood, and about 200 to 250 feet at Sidney. The values for Sentinel Butte were extrapolated from the report of Leonard and Smith (1909). Values reported

for North Dakota are excessively large.

In his study of the Marmarth lignite field, Hares (1928, p. 39, 47) reported a general thickness of 600 feet for the Tongue River and 350 feet for the Sentinel Butte "members". The first of these is certainly in error. Altimeter checks between the base of the Tongue River (just above the Little Missouri floodplain) and the HT Butte Lignite in the Red Hills (southwest of Bullion Butte) gave values only slightly greater than 300 feet. Crawford (1967, p. 8) reported 313 feet of Tongue River strata near this locality. Hares' reported value of Sentinel Butte thickness is a good approximation but is somewhat less than the writer determined by altimeter. Crawford (1967, p. 10) cited a thickness of about 450 feet for this unit, a value which appears slightly large. A portion of the discrepancy for Sentinel Butte thickness at Bullion Butte results from the indistinctness and poor exposure of the upper contact. This cannot account entirely for the disagreement, however, for Hares (p. 65) measured 325 feet of strata between the HT Butte and Bullion Butte lignite beds and Crawford (1967, Plate II) assigned a thickness of about 390 feet to the same interval. The writer accepts a thickness of slightly less than 400 feet for the Sentinel Butte Formation at Bullion Butte.

Hennen (1943) reported a thickness of 765 feet for Tongue River strata at Medora. The base of the unit was picked between two lignites (10 and 11) recorded in a deep water well. As discussed later in this report, Hennen included a portion of the Sentinel Butte Formation in his Tongue River interval and his reported value for Tongue River thickness is too large. The cited value for Sentinel Butte thickness is less than measured by the writer, but the difference is accounted

for by Hennen's misplacement of the basal contact of this unit. The general eastward thinning of stratigraphic units between Sentinel Butte and the Hebron-Glen Ullin area, shown schematically by Hennen (Figure 1) is probably a valid approximation.

The stratigraphic thicknesses of both the Tongue River and Sentinel Butte Formations appear to have been controlled by subsidence within the Williston basin during Tertiary time. These units are generally thin along the basin flanks and thicken toward its center. This relationship is more easily demonstrated for Sentinel Butte than for Tongue River strata. Approximate total Sentinel Butte thicknesses recorded for the basin margin are 380 feet at Sentinel Butte and Bullion Butte (southern Golden Valley County), 200 feet near Richardton (eastern Stark County), 300 feet near Newtown (southern Mountrail County), and 170 feet in the northern part of the White Earth valley (northern Mountrail County). Central basinal values are much greater, are about 500 feet at Lost Bridge (northern Dunn County), greater than 550 feet at the North Unit of Roosevelt Park and 650 feet (Meldahl, 1956) near Grassy Butte (south-central McKenzie County). These examples illustrate the basinal control on sediment accumulation, but available data are too sparse for accurate illustration of thickness distribution throughout the Tertiary basin.

The total thickness of Tongue River strata can be demonstrated by surface exposures only in the southern portion of the Williston Basin. The formation is about 300 feet thick and rests on the Ludlow formation southwest of Bullion Butte and about 300 feet thick in the vicinity of Dengate and Altmont in Morton County (C. S. V. Barclay, oral communication, 1966) where it overlies the Cannonball Formation.

A general northward thickening of the unit can be inferred by comparison of thicknesses at Bullion Butte and Medora. About 250 feet of Tongue River strata are exposed near Medora; if to this is added the 120 foot interval between the floodplain and the subsurface position of the Harmon lignite (Smith and Leonard, 1909, p. 25) and a conservative estimate of 100 feet for the distance between the Harmon bed and the base of the Tongue River (Hares, 1928, p. 48-49), a total thickness of about 470 feet is obtained. Thus the Tongue River increases in thickness by about 170 feet between Bullion Butte and Medora; a distance of about 20 miles.

The Sentinel Butte Formation is conformable upon Tongue River strata and the character of the contact suggests that deposition was continuous across this boundary. Beds above the Sentinel Butte, however, are of both Eocene and Oligocene age and the contact of these beds with the Sentinel Butte is disconformable, suggesting post-Sentinel Butte erosion and non-deposition. This is particularly evident at Sentinel Butte where the upper Paleocene strata are leached and incised by channels filled with Oligocene sandstone. The question arises whether Sentinel Butte beds along the margin of the Williston basin are thin as a result of lesser sediment accumulation or because a significant portion of the strata were removed by erosion prior to deposition of Eocene and Oligocene units. This question cannot be answered with certainty, but several lines of evidence suggest that the marginal thinning is primary.

(1) The circumstantial evidence favoring truncation is perhaps greatest at Sentinel and Bullion Buttes which are situated distally on the northeast flank of the Cedar Creek anticline. Post-Sentinel

Butte movement on this structure may have elevated this area thus facilitating erosion. However, similar uplift cannot be postulated for the rest of the basin margin, along which the Paleocene Series is also thin.

(2) The Paleocene sequence on Sentinel Butte is thin bedded throughout in comparison with that in the North Unit of Roosevelt Park. The general inference is that the Sentinel Butte interval near the center of the Williston basin thickens in response to thickening of individual beds. Likewise, the interval at Sentinel Butte is thinner as a result of thin sedimentation units, not because of erosional truncation.

(3) The thick lignitic shale, discussed above, in the section at Sentinel Butte may represent a hiatus, reflecting a significant period of non-deposition in this portion of the basin margin.

(4) The comparable thickening of the Tongue River Formation, which is conformable beneath Sentinel Butte strata, toward the center of the Williston basin, suggests that basinal control of Sentinel Butte deposits resulted from a pre-established mechanism.

Some erosion of Sentinel Butte beds, preceding and accompanying the deposition of Eocene and Oligocene strata, occurred, but the magnitude of this erosion was apparently slight. Further consideration is given this question later in a discussion of sediment dispersion.

The Tongue River-Sentinel Butte Contact

Definition of the contact

In locating and tracing the Tongue River-Sentinel Butte contact

in western North Dakota, it was found that it can be distinguished on the basis of three criteria. These are a marked change in gross color, the presence of a lignitic horizon in the uppermost part of the Tongue River Formation, and the presence of a sandy basal Sentinel Butte unit.

Color.--The first of these criteria, a distinctive color difference, is embodied in the original definition of the Sentinel Butte Formation given by Leonard and Smith (1909, p. 18) in their report on the Sentinel Butte lignite field.

> There is a very noticeable difference between the lower Fort Union beds, which outcrop in the bluffs bordering Little Missouri River, and the upper beds, occurring in the tops of the higher ridges, divides, and buttes, usually back some distance from the river. The lower member is composed of buff and light ash-gray clays and sands in alternate layers. The upper member is formed of strata considerably darker in appearance, mostly dark gray, with many brown, ferruginous, sandy nodules and concretions. The contrast between these members is so well marked and their contact so clearly defined that it can be readily distinguished at a distance and traced without difficulty wherever it is exposed. Over most of the eastern half of the field a thick bed of lignite or a layer of red clay formed by the burning of the lignite occurs just at the contact of the upper and lower members. But even where the coal or burnt-clay bed is wanting, the line of separation is readily discernible.

Leonard (1911, p. 534), in a discussion of the stratigraphy of North Dakota, again emphasized the marked contrast in color and the clarity of the contact between Tongue River and Sentinel Butte strata.

> In Billings County, North Dakota, an upper member [= Sentinel Butte] of the formation appears in the tops of the higher ridges, divides, and buttes, and resembles somewhat the Lance beds in its dark color and its many brown ferruginous, sandstone concretions. The lower member [= Tongue River] constitutes the typical yellow and light gray Fort Union and this is the only one present over most of the region. Where both occur, the contrast between the upper and lower members is so well marked and their contrast so clearly defined that it can be readily distinguished even at a distance and traced without difficulty, wherever it is exposed.

Although the color contrast between these stratigraphic units

is real and persists regionally, it may fail locally as a sole means of distinguishing the contact. The lower Sentinel Butte beds, as discussed below, are rather uniform in both color and lithology. The Tongue River beds below the contact exhibit considerable variation in texture and are locally variable in color. Where fine-grained, drab beds are present in the uppermost Tongue River the color contrast with the Sentinel Butte is reduced (Figures 6-C and 7-A). Because light-colored beds invariably dominate any weathered section of Tongue River strata, the contact is most discernible where it occurs above a substantial section of Tongue River strata.

It must by emphasized that the light, buff-yellow color of Tongue River sediments is largely, if not entirely, a weathering phenomenon. Locally, as in steep bluffs along rivers (Figure 8-B), where erosion proceeds rapidly, the Tongue River beds appear far more somber than in areas where oxidation has had ample time to operate. In fresh outcrops or in the subsurface, no color distinction can be made between these units. Despite these limited drawbacks, the color contrast remains perhaps the most useful single factor in field recognition of the Tongue River-Sentinel Butte contact in North Dakota.

HT Butte bed.--A lignitic unit is present at the Tongue River-Sentinel Butte contact in virtually all localities visited by the writer, but it is frequently concealed in outcrop by slumping of overlying material. With the exception of Hares' (1928) term "HT Butte lignite", terms formerly or presently applied to this unit are not stratigraphic binomials. It is therefore recommended that the terminology of Hares (1928) be exclusively retained and applied informally to this stratigraphic interval in North Dakota. As understood

and applied in the present report, the name HT Butte bed applies to a carbonaceous zone in the uppermost Tongue River Formation which may be represented by lignite, lignitic shale, or both, ranging in thickness from several inches to several tens of feet. Because of its great regional extent and distinctive stratigraphic relationships, this bed has great value in mapping.

The association of lignite with the contact has been noted by many workers. Taff (1909) placed the upper contact of his "Tongue River coal group" above the Roland coal bed. The likely persistence and great areal extent of this lignite was recognized by Thom and Dobbin (1924, p. 496).

> In northern Wyoming and southern Montana, and perhaps in Dakota areas as well, the base of the Sentinel Butte shale is marked by the Roland coal bed, which in thickness, persistence, and general genetic relationships resembles the Big Dirty coal of the Lebo.

In North Dakota this lignitic unit has received many designations, the most important of which are included in the synonymy of Table 1. Although an equivalence appears probable and the temptation to correlate is great, it is considered unwise to apply the term Roland coal in North Dakota until such correlation is more firmly established than it appears to be at present. Should definite correlation be established with the Roland coal bed of the Sheridan field in Wyoming, the term "HT Butte" should be replaced by the term "Roland", which has priority.

A note of explanation is necessary regarding consideration in this report of both the "F and G beds" of Leonard and Smith (Table 1) as a single stratigraphic unit. As originally stated by Leonard and Smith (1909, p. 31),

The second member of the group, bed G, from 25 to 50 feet above the lowest member [which is bed F], shows to better advantage in the south-central part of the surveyed area, in the base of the higher buttes, where its outcrop is marked by a fringe of clinker. Both the lower members become thin and disappear toward the northwest. These beds have been so generally burned that few exposures showing their whole thickness can be found.

TABLE 1.--Synonymy of terms applied to the lignitic interval at the Tongue River-Sentinel Butte contact.

Author	Nomenclature	Publication
Leonard (1908)	R	5th Bien. Rept. N. D. G. S.
Leonard and Smith (1909)	F and G	U. S. G. S. Bull. 341-A
Stebinger (1912)	K	U. S. G. S. Bull. 471
Hares (1928)	HT Butte	U. S. G. S. Bull. 775
Fisher (1953, 1954)	L	N. D. G. S. Rept. Inv. 11 & 15
Hanson (1955)	L	N. D. G. S. Rept. Inv. 18
Meldahl (1956)	L	N. D. G. S. Rept. Inv. 26

It appears that bed G is known with certainty to occur only at the base of Sentinel Butte where it was extensively mined in former years. Field inspection on the northeast flank of Sentinel Butte, at the site of the old Mammoth mine, indicates that bed F is about 6 feet thick and is separated from bed G by 18 feet of silty clay which constitutes a single stratigraphic unit. Bed G exceeds 20 feet in thickness and is overlain by a thick sequence of clayey sand.

Investigations by many workers since 1909 have resulted in the recognition and extension of bed F far beyond the limits of the Sentinel Butte field. Bed G, however, has not received such recognition.

This writer feels that, although outcrop exposures are inadequate for demonstration, it is most probable that the F and G beds comprise a single genetic unit parted by a wedge of clastic sediment. Correlation of the G bed with the lignite which burned to form the prominent red clinker capping ridges and buttes north of the village of Sentinel Butte (Leonard and Smith, 1909; Hennen, 1943) appears to be in error. The contact in this area is marked by a distinct color change (as can be seen on the northeast flank of Camel Hump Butte and near the center of sec. 4, T. 140 N., R. 104 W., Figure 5-C) associated with a lignitic zone and a basal Sentinel Butte sand, and underlies the clinker horizon by about 50 feet. The implications involving miscorrelation of the G bed are discussed in the following section.

Taff (1909) originally considered the top of the Roland coal as marking the top of his Tongue River coal group. Subsequent workers (Leonard and Smith, 1909; Hares, 1928; Fisher, 1953; and others) have arbitrarily included this bed in the Sentinel Butte Formation, perhaps because its dark color contrasts less with this unit than with the underlying Tongue River Formation. It appears, however, that the HT Butte bed represents the culmination of a sequential accumulation of fine clastic material in which development of thick lignites was fairly common. As discussed below, the Sentinel Butte was introduced by an influx of "basal" sand which spread across the "HT Butte swamps". Thus, the HT Butte bed is here considered a genetic unit of the Tongue River Formation.

The HT Butte bed is so variable in thickness that only general statements regarding thickness appear to have validity. As an example in point, it can be demonstrated that the thickness of the HT Butte

bed decreases northward from more than 10 feet in the South Unit of
Roosevelt Park to about 1 foot, 10 miles northward on the divide south
of Mikes Creek (Figure 6-C). A similar thinning occurs westward toward
Twin Buttes (Figure 5-D), where the HT Butte bed consists of a few
inches of lignitic shale. The thickness of lignites appears to be a
relatively local phenomenon which has little bearing on their regional
persistence and only minor significance regarding the regional con-
ditions which favor their development. Field experience has demon-
strated to the writer's satisfaction that lignites cannot and should
not be correlated solely on the basis of thickness. Thus, thickness
is considered a subordinate factor in recognition of the HT Butte bed.

Basal Sentinel Butte sand.--Recognition of a persistent basal
unit in the Sentinel Butte Formation has aided significantly in rec-
ognition of the Tongue River-Sentinel Butte contact. In its "typical"
or "maximum" state of development, this basal unit is silty, cross-
bedded fine sand ranging from several tens of feet to over 100 feet in
thickness (Figures 3 and 4). Cross-stratified sets range from several
inches to 3 feet or more in thickness, the average being about 18 or
20 inches, and are generally planar and wedge-shaped (Figures 3-A and
3-B). Lignite clasts are commonly concentrated in cross-laminae and
emphasize cross-bed sets (Figures 3-A and 3-C). Co-sets are often
bounded by ferruginous concretions of nodular or planar character
(Figures 3-D, 4-A, and 4-B) with associated plant-stem molds and des-
iccation features which indicate the diastemic nature of the bedding
planes. In many outcrops, marcasitic or limonitic concretions are
randomly scattered throughout the unit. Rarely, the clay-silt content
is reduced and the basal sand unit is fairly well sorted and loosely

FIGURE 3

A. Basal sand of the Sentinel Butte Formation in upper Blacktail Creek drainage. Cross-beds are
    emphasized by concentrations of lignite fragments along bedding planes; man in foreground in-
    dicates scale.
    Location: SE¼ sec. 10, T. 143 N., R. 101 W., Billings County, North Dakota.

B. Cross-bedded basal Sentinel Butte sand on West River road about 3 miles southwest of Medora.
    Sand is loosely cemented with iron oxides; hammer indicates scale.
    Location: SW¼ sec. 31, T. 140 N., R. 102 W., Billings County, North Dakota.

C. Cross-bedding in fine basal Sentinel Butte sand along fire-guard trail south of Bear Creek.
    Cross-bed sets are emphasized by lignite fragments concentrated along bedding planes. En-
    trenching shovel indicates scale.
    Location: SW¼ sec. 7, T. 137 N., R. 101 W., Billings County, North Dakota.

D. Concretionary zones developed along bedding-planes in basal Sentinel Butte sand about 5 miles
    southwest of Medora. Bedding planes are diastems and illustrate the periodic mode of accumu-
    lation of this unit; note similar structures in Figures 4-A and 4-B.
    Location: SW¼ sec. 11, T. 139 N., R. 103 W., Billings County, North Dakota.

A   B   C   D
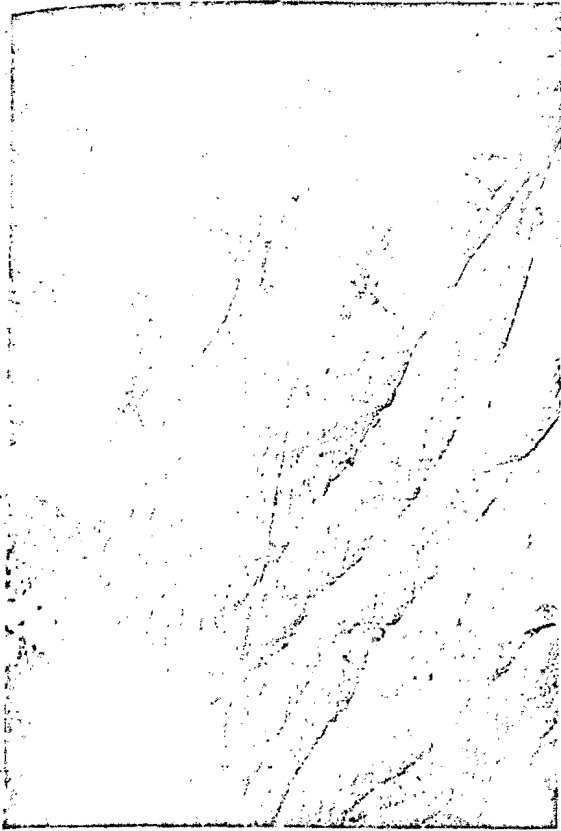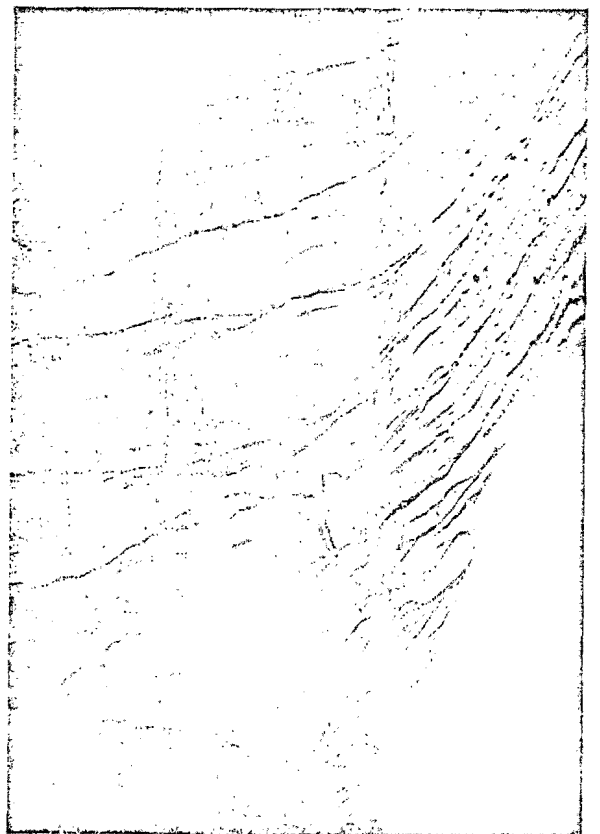
FIGURE 4

A. Bedding planes, emphasized by zones of concretionary iron oxide, show primary dip (note
    horizontal beds near top) in basal Sentinel Butte sand about 5 miles southwest of Medora.
    Fluted weathering reflects the high silt-clay content of this unit.
    Location: SW¼ sec. 11, T. 139 N., R. 103 W., Billings County, North Dakota.

B. Concretionary zones in basal Sentinel Butte sand near the entrance to Squaw Creek campground,
    North Unit of Roosevelt Park.
    Location: NE¼ sec. 31, T. 148 N., R. 99 W., McKenzie County, North Dakota.

C. Large clasts of loosely consolidated siltstone in clayey matrix of basal Sentinel Butte
    "sand" about 8 miles southeast of Medora.
    Location: NE¼ sec. 36, T. 139 N., R. 102 W., Billings County, North Dakota.

D. Petrified wood characteristic of the HT Butte bed of the Tongue River Formation adjacent to
    the road on the divide south of Mikes Creek.
    Location: NE¼ sec. 36, T. 143 N., R. 102 W., Billings County, North Dakota.
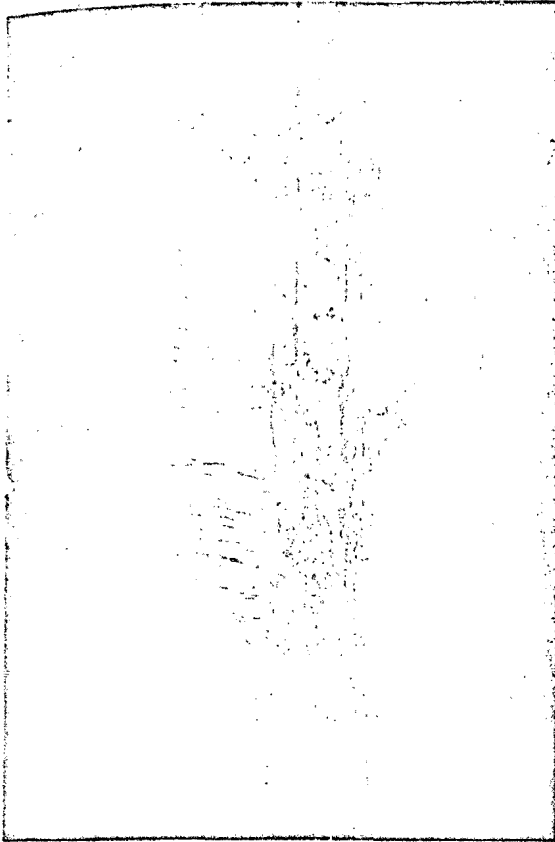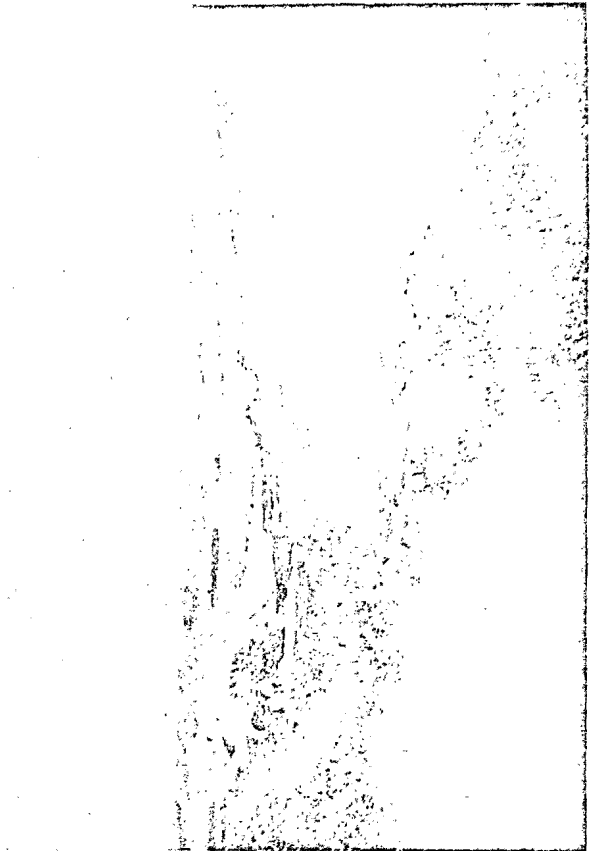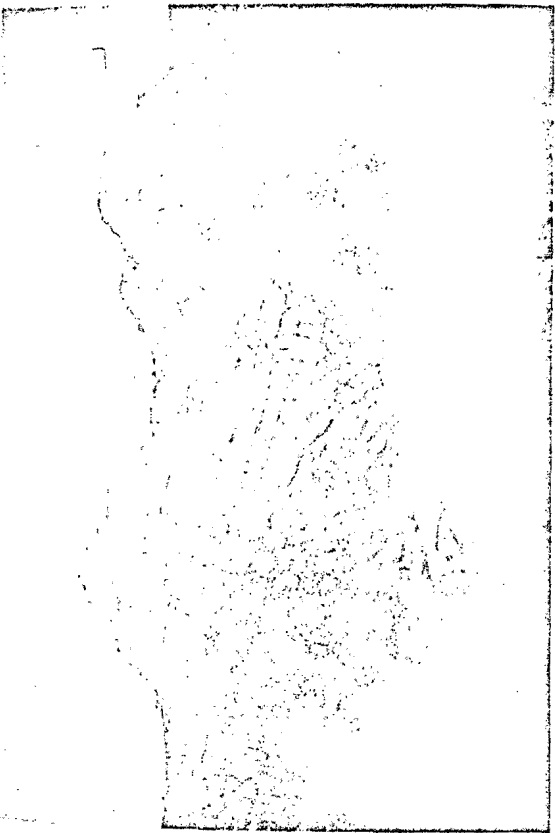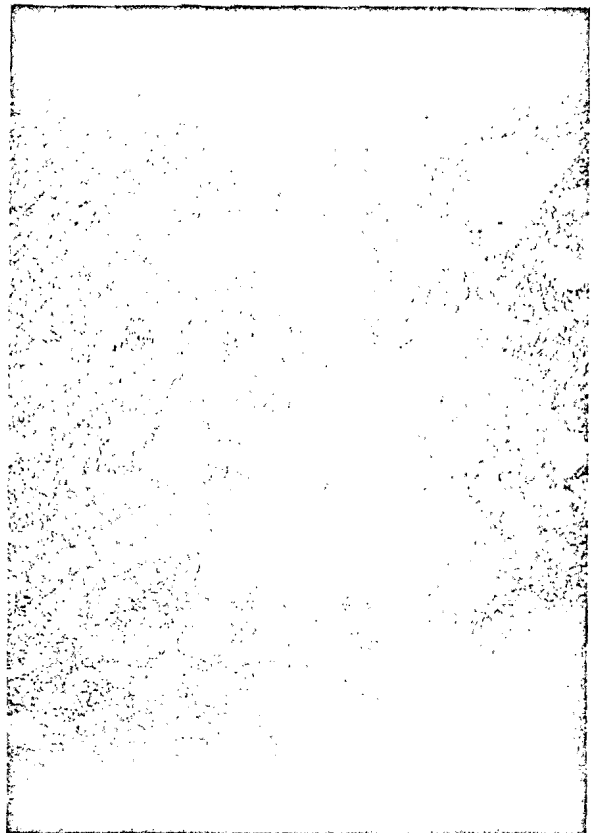
consolidated.

Fine-grained equivalents of the basal unit exist, but appear to be less extensive than the sandy facies. These "fine" facies are typically thin-bedded sandy silt and silt (rarely clayey silt) (Figures 3-C and 5-C) which often grade upward into coarser sediment. Cross-bedding occurs but is of the "small-scale" type and is usually obscured in exposed outcrops due to the alternate swelling and shrinking of clay components. Fine-grained facies of the basal unit invariably coarsen laterally, usually in a relatively short distance. Thus, except in areas of extremely limited outcrops, the validity of the textural relationships suggested here can be readily checked in the field. In deference to the dominant facies, the unit is referred to here as the basal sand of the Sentinel Butte Formation.

Occasionally the basal sand is separated from the HT Butte bed by a wedge of dark gray clay ranging in thickness from a few inches to as much as 4 or 5 feet. This clay is represented by dark horizons above the contact in Figures 5-D and 8-D. Both coarse- and fine-grained facies of the basal unit have been observed above and filling channels in this clay. Apparently the clay was widespread prior to deposition of the basal sand, and the latter may have incorporated much of this clay.

That the transport energies were high even for the finer-grained basal sediments is indicated by the presence of clay galls in many outcrops. These galls or clasts often swell or "check" on weathered surfaces and their character is not always clearly evident. Occasionally, clasts of coarser material were observed in a clay matrix, an example of which is shown in Figure 4-C.

With the possible exception of Hennen (1943), it appears that the persistence and correlative significance of the basal sand of the Sentinel Butte Formation has not been previously recognized. Hennen's observations appear to suffer from at least two errors. Hennen recognized a persistent marker bed in western North Dakota which he called "Sandstone 21" and which he described as follows (p. 1569):

> A persistent "marker bed" for correlation has been recognized in the Fort Union formation by the writer. It is grayish white, flaggy to shaly sandstone, apparently containing a mixture of volcanic ash, with silicified fossil plant stems in abundance, and here and there silicified stumps of trees 3-5 feet in diameter . . . it is ordinarily less than 5 feet in thickness but westward at Sully Springs, it is more than 40 feet thick but still is grayish white to ash-gray, with the silicified tree zone at the top. It is believed that a great outpouring of volcanic ash took place at the time of its deposition. . . . It is in this zone that the "Petrified Forest" occurs on the valley floor of Andrews Creek [Hennen means Sully Creek], 1.5 miles southwest of Sully Springs railway station. This zone may be observed also, in typical development, at the entrance gate to Roosevelt Park on Highway 10, 5 miles east of Medora.

In reference to thick occurrences in the vicinity of Sully Springs and the east gate of the South Unit of Roosevelt Park, Hennen's "Sandstone 21" is synonymous with the basal sand of this report. Hennen, however, places his "marker bed" in the Tongue River "member" about 70 feet below the horizon which he indicates as its upper contact. In order to resolve this discrepancy, it is necessary to consider how Hennen placed his "marker bed" in the Paleocene Series; this he elaborates in reference to his Sentinel Butte section (p. 1575-1576).

> At the point where the section was measured, formations were concealed directly below this lignite bed [20 feet thick] so that it was not possible here to determine its interval above Sandstone 21. However, immediately northeastward and northward at many places this lignite bed forms "scoria" at an elevation of 2,910 feet at the base, slightly more than a mile north of Sentinel Butte railway station . . . Here the top of Sandstone 21 with its characteristic silicified trees

is 70 feet by hand-level lower in the measures, or at prac-
tically the same interval (75 feet) as at point 2 [Medora]
below Lignite 22. Likewise, here a thin lignite bed imme-
diately overlies Sandstone 21, as at the Sully Springs
section . . .

The lignite is bed G of Leonard and Smith (1909) and, as stated
in the previous section, the correlation with the "scoria" to the north
and northeast appears invalid. Herein appears to lie the source of
Hennen's first error. He correctly identified the basal sand north
of Sentinel Butte, but miscorrelated the HT Butte bed. Thus, he was
led to believe that the basal sand on Sentinel Butte was concealed in
the subsurface below the F bed. In reality, it is well exposed and
overlies the G bed.

A second error occurred as Hennen carried his marker bed east-
ward toward Medora (his point 2). Very few beds resembling the basal
sand are present in the Tongue River Formation but, from about the
Billings-Golden Valley County line to Medora and northward into the
South Unit of Roosevelt Park, a locally persistent clayey sand bed
does exist in the upper Tongue River section. This bed occurs about
70 to 80 feet below the Tongue River-Sentinel Butte contact and is
about 5 feet thick along U. S. Highway 10 several miles west of Medora.
It can be traced along the highway to Medora and is prominent in the
west bluffs of the Little Missouri which extend northward into the
park. The unit thickens considerably as it enters the park, as can
be seen along the park road as it descends from Johnson Plateau to
the valley floor. This unit Hennen confused with the "marker bed"
of the Sentinel Butte locality. The stratigraphic occurrence of
this sand bed is unfortunate, for it allowed Hennen to justify his
first error with a second. The paradox is even more apparent when

one realizes that clayey-sand beds are quite uncommon among Tongue
River strata. Hennen's second error was recognized by Brown (1948a,
p. 1269) who concluded,

> . . . It would seem that, between Sentinel Butte and
> Sully Springs, Hennen confused two silicified zones in an
> interval of 100-125 feet.

It is unfortunate that Hennen's study recieved so little
acceptance, for closer inspection of his "Sandstone 21" might have
aided in an earlier recognition of the basal Sentinel Butte sand.
The writer confesses his own skepticism of Hennen's work during
initial stages of field investigation. Only after the partial equiv-
alence of Hennen's "marker bed" with the basal sand at Sully Springs
was realized was an attempt made to resolve the conflicts which ex-
isted in his cross-section between Sentinel Butte and Medora. Whether
Hennen's "Sandstone 21" is equivalent to the basal sand elsewhere in
western North Dakota is not readily apparent. The two appear to be
co-extensive as will be discussed presently.

Regional extent of the contact

The extent of the Tongue River-Sentinel Butte contact in a
significant portion of western North Dakota is indicated in Figure 1.
The contact is essentially a line of best approximation connecting
points at which the character and elevation of the contact was estab-
lished in the field. The writer has utilized available literature in
facilitating extrapolations through areas for which his field obser-
vations are limited. In this regard, reports of Leonard and Smith
(1909), Hares (1928), Fisher (1953, 1954), and unpublished data of

Clayton (in preparation) were of particular value. The reliability of all published sections and datum points utilized in establishing the contact was verified by a thorough field check. During the course of six months spent in the field, the writer visited nearly every township in which the contact is indicated to be present. However, the probability exists that some outliers containing the contact have been overlooked and, to the extent that this is true, Figure 1 is incomplete. It is expected that future detailed mapping will correct these omissions; if the feasibility of such mapping is demonstrated by Figure 1, it has served its purpose.

Little Missouri badlands.--The Tongue River-Sentinel Butte contact is essentially continuous throughout the badlands east of the Little Missouri River from northern Slope County to southern McKenzie County. West of the river, the contact is discontinuous and defines detached remnants of Sentinel Butte strata which form divides or buttes which rise above the regional level. This distribution is an expression of the regional dip of these beds toward the structural axis of the Williston basin (syncline) which lies to the east and northeast. For many miles east of the east "breaks" of the Little Missouri badlands, topography is developed almost entirely upon strata of "Sentinel Butte" and younger age. In the extreme southwest corner of the map area, all Paleocene and younger strata have been removed by erosion from the northeast flank of the Cedar Creek anticline.

Both time limitations and difficulties imposed by the gently rolling topography and paucity of outcrops prevented tracing of the contact south of Amidon and, with the exception of HT Butte, this

locale constitutes the southern limit of investigation. Between Amidon and Medora the contact is readily apparent and can be inspected at many localities. The HT Butte bed and the basal sand are generally well developed but locally the HT Butte bed thins and the basal sand becomes fine grained. The HT Butte bed has burned throughout much of this area, as can be readily seen from the road into the "Burning Coal Vein", northwest of Amidon, which follows the divide westward across the center of T. 136 N., R. 101 W. Outcrops of the contact along this divide (Figure 5-A) show the basal sand to be fine grained and the HT Butte bed to be rather thin.

Northward, on the divide south of Bear Creek the color contrast is marked and the contact is evident from a distance. At this locality the HT Butte bed is about 60 inches thick and the basal sand is well developed (Figure 5-B). The basal Sentinel Butte unit is silty above the HT Butte bed but coarsens upward, becoming sandy within a vertical interval of 6 feet.

On the west side of the Little Missouri, the contact is prominent on Bullion Butte and occurs in the bases of Sentinel and Square (Flat Top) Buttes. The contact dips eastward at Sentinel Butte and passes into the subsurface along U. S. Highway 10 (Interstate 94) about three miles east of Medora. The HT Butte bed is burned along most of this traverse and its descent into the subsurface east of Medora is marked by a fringe of red clinker, but a minimum thickness of 7 feet was measured for the bed at a partial exposure in Sheep Creek. The basal sand is exposed on the northeast flank of Sentinel Butte and can be viewed along the "West River road" in the northeast portion of T. 139 N., R. 103 W., near Sully Springs, and just west

FIGURE 5

A. Tongue River-Sentinel Butte contact (arrow) near road on the divide south of Second Creek, about 7 miles northwest of Amidon. The HT Butte bed measures 30 inches but is poorly exposed.
Location: NE¼ sec. 20, T. 136 N., R. 101 W., Slope County, North Dakota.

B. Tongue River-Sentinel Butte contact (arrow) near fire-guard trail about midway between Amidon and Medora. Forty inches of poorly exposed HT Butte bed underlies a thick sequence of basal Sentinel Butte sand.
Location: SW¼ sec. 7, T. 137 N., R. 101 W., Billings County, North Dakota.

C. Tongue River-Sentinel Butte contact (arrow) about 4 miles north of the village of Sentinel Butte. The basal unit is fine grained and conspicuously banded, the HT Butte bed is thin, but the color contrast above and below the contact is marked.
Location: NW¼ sec. 4, T. 140 N., R. 104 W., Golden Valley, North Dakota.

D. Tongue River-Sentinel Butte contact (arrow) in the vicinity of Twin Buttes. The dark bed above the contact is a dense clay which locally separates the basal sand and the HT Butte bed.
Location: E½ sec. 16, T. 141 N., R. 103 W., Golden Valley County, North Dakota.

A

B

C

D
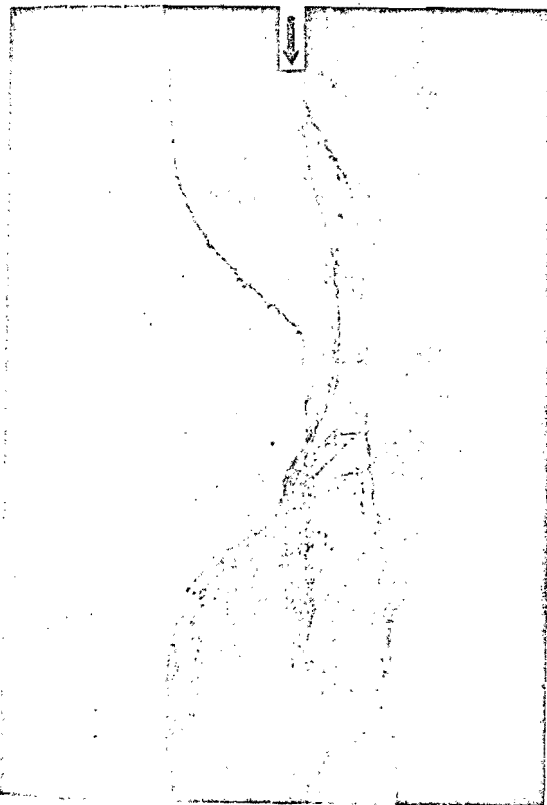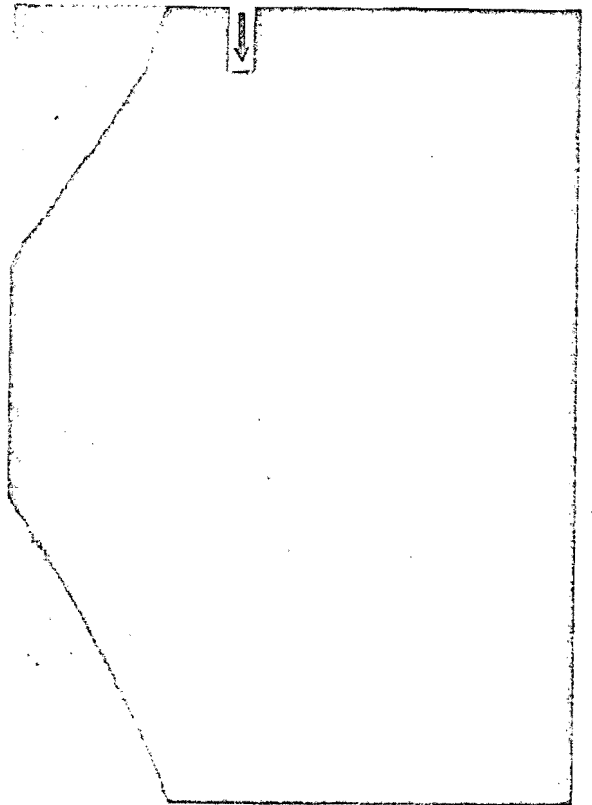
of the east entrance to Roosevelt Park.

Within the South Unit of Roosevelt Park, the contact is present high in the bluff on the west side of the Little Missouri River across from Cottonwood campground. Here the HT Butte bed exceeds 9 feet in thickness and is overlain by a thick sequence of basal sand. The contact can also be seen in the vicinity of "Scoria Point", a scenic stop within the park. The HT Butte bed has largely burned to produce a spectacular red clinker, but an unburned remnant, nearly 12 feet in thickness, can be seen in the gully below the overlook. The so-called "Burning Coal Mine" in the park is in the HT Butte bed and clinker produced by earlier burns is widespread; good outcrops occur adjacent to the road near the park boundary north of Wind Canyon.

North of the village of Sentinel Butte, near Twin Buttes, the contact is exposed on numerous small buttes and divides (Figure 5-D). The HT Butte bed is represented by only 6 to 8 inches of lignitic shale, but the contrast in color between the formations is exceedingly good. This contrast is persistent northward and can be seen near the entrance to Techer's ranch (Figure 6-A), on the divide above the historic Elkhorn Ranch site. Throughout much of this area the basal Sentinel Butte sand is rather fine grained and at several localities it is separated from the HT Butte bed by as much as 4 feet of dark clay. At these localities, however, the clay grades upward and laterally into more "typical" basal sand.

Three localities on the east side of the Little Missouri north of the South Unit of Roosevelt Park appear representative of the contact. The first of these is a prominent bluff on the east side of the river road about 3 miles north of the park boundary (Figure 6-B). The

FIGURE 6

A. Tongue River-Sentinel Butte contact (arrow) near the entrance to Techer's Ranch, about 13 miles north of Twin Buttes. The color contrast above and below the contact is very pronounced. Location: NE¼ sec. 1, T. 143 N., R. 103 W., Golden Valley County, North Dakota.

B. Tongue River-Sentinel Butte contact (arrow) on the river road about 3 miles north of the South Unit of Roosevelt Park. The HT Butte bed is largely covered but exceeds 13 feet in thickness. Location: NW¼ sec. 8, T. 141 N., R. 103 W., Billings County, North Dakota.

C. Tongue River-Sentinel Butte contact (arrow) on the river road 13 miles north of South Roosevelt Park. The basal sand of the Sentinel Butte Formation is fine grained and the color contrast above and below the contact is subdued by dark clays in the upper portion of the Tongue River Formation. Location: NE¼ sec. 36, T. 143 N., R. 102 W., Billings County, North Dakota.

D. Tongue River-Sentinel Butte contact (arrow) in the valley of Blacktail Creek about 17 miles north of the South Unit of Roosevelt Park. The basal Sentinel Butte sand is "typically" developed with large-scale cross-bed sets. Location: SE¼ sec. 10, T. 143 N., R. 101 W., Billings County, North Dakota.

B
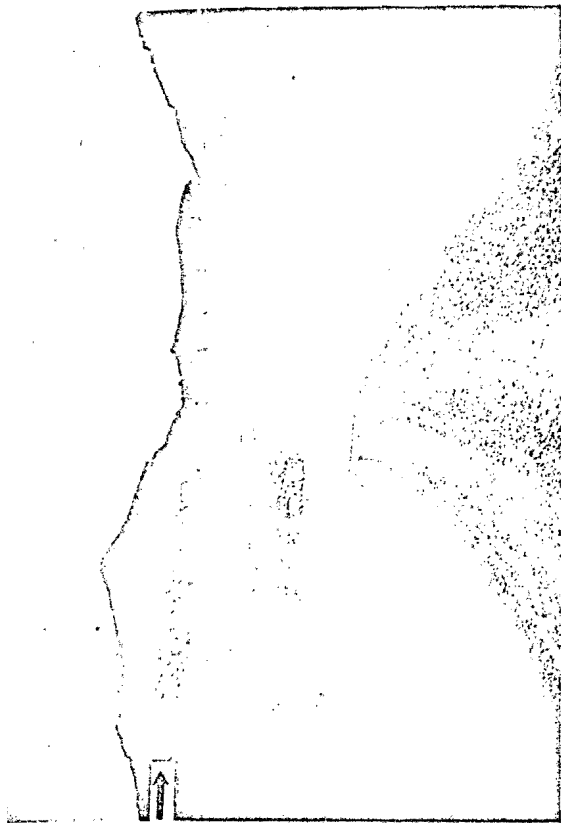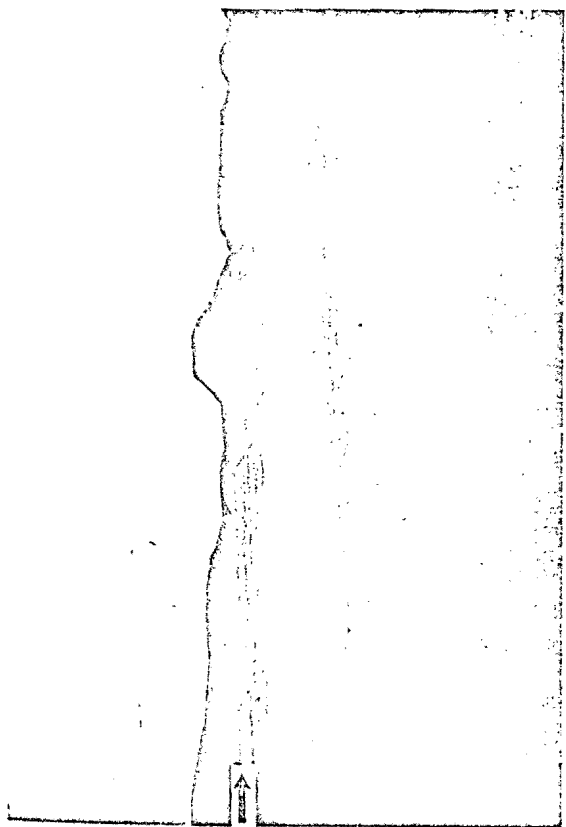
A

C

HT Butte bed is well developed, measuring about 13.5 feet in thickness. The basal sand consists of 6 to 8 feet of rather clayey silt which grades upward into 20 feet of clayey sand. About 10 miles north of this outcrop, the contact is accessible near the road at the summit of the divide south of Mikes Creek (Figure 6-C). The HT Butte bed is only 16 to 18 inches thick and the lower portion of the basal sand is thinly bedded and fine grained. Despite its overall fine texture, the basal sand contains pods and lenses of medium sand and large clasts or "galls" of clay. Silicified wood (Figure 3-D) is particularly abundant at this locality.

The river road north of Medora terminates, after 30 scenic miles, at the ranches of Les and Jack Connel; exit from the badlands is gained along the Blacktail Creek drainage eastward to Gorham. Along the Blacktail Creek road occur some of the best examples of "typically" developed basal sand. The contact is conspicuous and nearly continuous along the north wall of the creek valley for 5 or 6 miles up Blacktail Creek from its mouth. Where the contact passes beneath the valley floor, erosional remnants of the resistant basal sand form numerous buttes which project above the valley alluvium (Figure 6-D). Here, the HT Butte bed is generally thin, averaging 12 to 20 inches thick.

The basal sand is well developed north of the Blacktail drainage and was observed on the divide between Whitetail and Magpie Creeks and in the Magpie Creek valley. Excellent exposures also occur in the Belcegel and Sand Creek drainages, but the upper Tongue River beds become somewhat clayey and the color contrast with the Sentinel Butte Formation is less pronounced (Figure 7-A). The basal sand

FIGURE 7

    A.   Tongue River-Sentinel Butte contact (arrow) along Sand Creek about 13 miles west of Grassy
            Butte. The basal sand of the Sentinel Butte Formation is well developed, but the color con-
            trast above and below the contact is somewhat subdued by gray clay beds in the upper Tongue
            River Formation.
            Location: sec. 10, T. 145 N., R. 101 W., McKenzie County, North Dakota.

    B.   Tongue River-Sentinel Butte contact (arrow) near the road on the divide above the Beicegel
            Ranch about 16 miles west of Grassy Butte. The basal Sentinel Butte sand greatly resembles
            that in outcrops to the south along Blacktail Creek (Figure 6-D)
            Location: SE¼ sec. 6, T. 145 N., R. 101 W., McKenzie County, North Dakota.

    C.   Tongue River-Sentinel Butte contact (arrow) in the Bowline Creek drainage about 9 miles south-
            east of Sheep Buttes. The HT Butte bed is 6 to 7 feet thick and partially concealed by slumping
            of the basal Sentinel Butte sand.
            Location: NW¼ sec. 18, T. 147 N., R. 101 W., McKenzie County, North Dakota.

    D.   Tongue River-Sentinel Butte contact (arrow) about 2 miles southwest of Sheep Buttes. The HT
            Butte bed is concealed but measures about 4 feet and is overlain by about 20 feet of silty
            basal Sentinel Butte sand.
            Location: SW¼ sec. 21, T. 148 N., R. 103 W., McKenzie County, North Dakota.

A

B

C

D
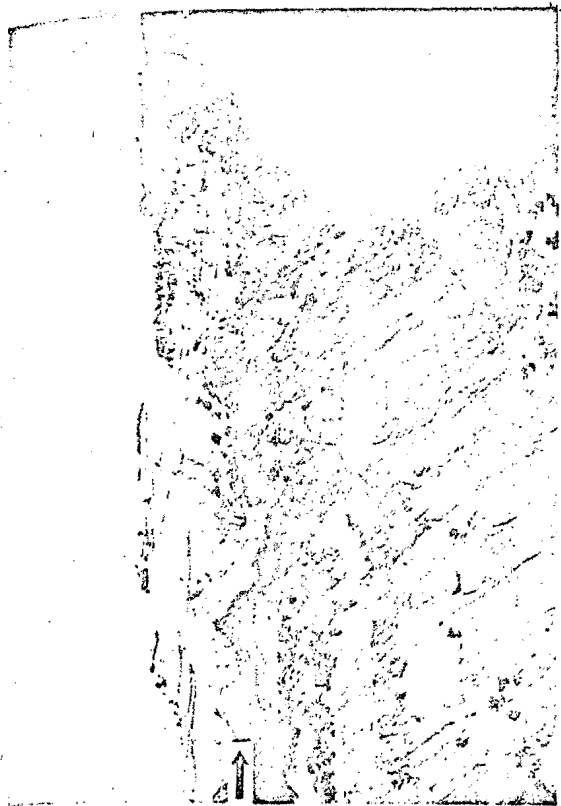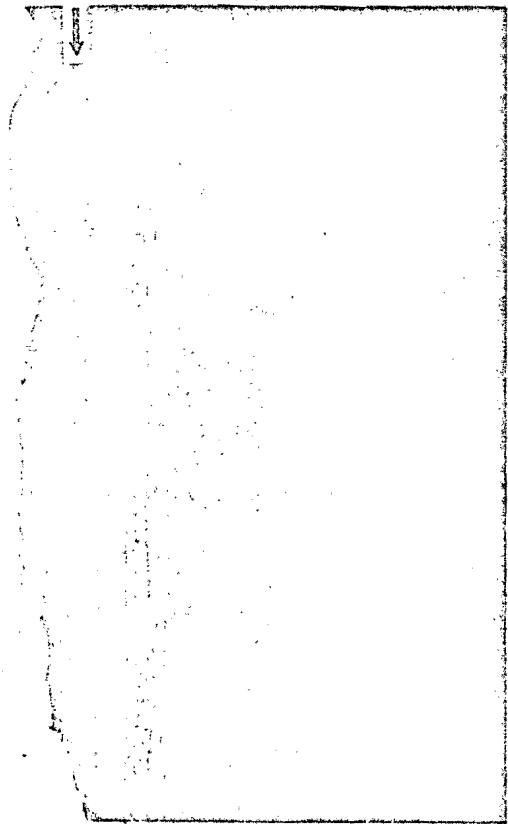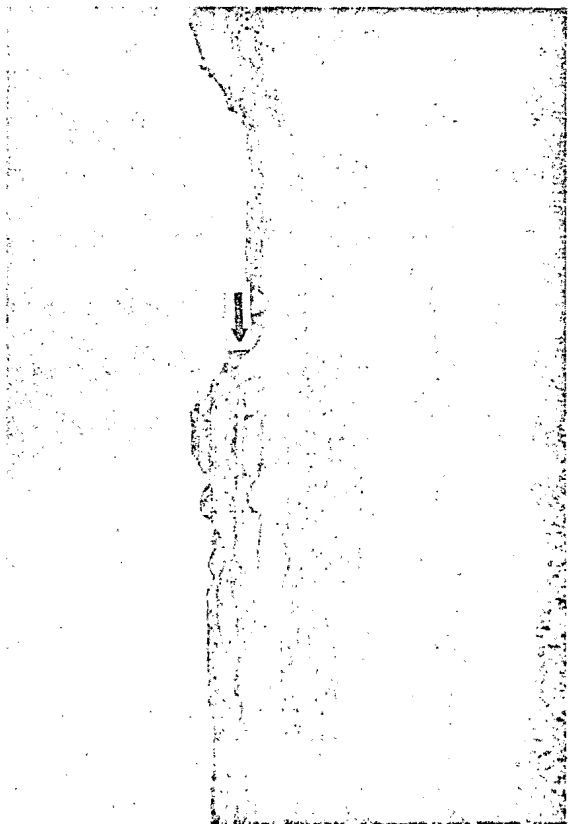
reaches thicknesses in excess of 100 feet in the upper reaches of Sand Creek.

At the summit of the road above the Deicegel Ranch, the basal sand is well exposed (Figure 7-B) and greatly resembles outcrops in the Blacktail Creek area. The HT Butte bed is generally thin along Sand Creek but thickens northward, as measured in a section near the Nelson Ranch (SW¼, sec. 18, T. 146 N., R. 101 W.), the bed is 7 feet thick.

Farther north, the contact can be seen in the bluffs of the Little Missouri in the vicinity of sec. 28, T. 147 N., R. 101 W., but it passes beneath slump debris and valley alluvium somewhere in the vicinity of the southern boundary of the North Unit of Roosevelt Park. The contact has not been observed within the park but its presence at shallow depths in the subsurface is indicated by the thick interval of basal sand which can be seen at many localities within the park, the most accessible of which are adjacent to the entrances to the Squaw Creek campground (Figure 4-B).

The northern limit of the contact within the north-south reach of the Little Missouri badlands appears to be in the Bowline Creek drainage (Figure 7-C). Here the contact is again distinct, despite the presence of a gray bentonite bed in the uppermost part of the Tongue River Formation. The basal sand is silty near the base and coarsens upward in the unit. The HT Butte bed is 6 to 7 feet thick. Additional outcrops occur along the road several miles south of this locality in the east half of sec. 25, T. 147 N., R. 102 W.

North of the badlands.--The area north of the Little Missouri badlands of western North Dakota has been glaciated, the topography

is rather subdued, and bedrock is well exposed only in the deeper drainages. The contact can be extrapolated northwestward from Bowline Creek to the vicinity of Sheep Buttes. The "big blue" clay bed, which is so prominent in the North Unit of Roosevelt Park, aids correlation across this area of limited bedrock exposure. The contact is exposed about 2 miles southwest of Sheep Buttes (Figure 7-D) at the location of Fisher's (1953) "section 3". The HT Butte bed here is 4 feet thick and overlain by 20 feet of rather silty basal Sentinel Butte sand. Northward, the contact can be seen in the more prominent slopes of the Horse Creek drainage, particularly in the vicinity of Horse Creek school. Fisher (1953) has noted the HT Butte bed in this area which he designated as "L" in his "section 2".

The Sentinel Butte Formation appears to have limited extent in Montana, but it can be viewed at Blue Mountain in northern Wibaux County, in the east bluffs of the Yellowstone River northeast of Sidney, and at the Snowden railway siding on the Missouri River near the Montana-North Dakota state line. The latter localities are of particular interest because they lie within the general type area of the Fort Union Group. On the "river road" about 8 miles southwest of Cartwright, North Dakota, the contact is marked by a 5-foot thickness of HT Butte bed and a marked color change. The basal sand is typical and ranges in thickness between 25 and 40 feet (Figure 8-A). The contact in this area is so distinct that it can be picked with ease from aerial photographs. Similar conditions exist at the contact 0.8 miles northwest of the road junction at Snowden, Montana, except that the HT Butte bed is represented by 40 inches of lignitic shale. Here 52 feet of Sentinel Butte strata overlie about 250 feet of the

FIGURE 8

A. Tongue River-Sentinel Butte contact (arrow) in bluffs of Yellowstone River about 8 miles south-
    west of Cartwright. The contact here is very distinct and lies within the type area of the
    Fort Union Group.
    Location: SE¼ sec. 31, T. 150 N., R. 104 W., McKenzie County, North Dakota.

B. Tongue River-Sentinel Butte contact (arrow) near Garrison Reservoir about 7 miles northwest of
    Newtown. The basal Sentinel Butte sand stands in high relief above less resistent Tongue River
    beds.
    Location: Near center sec. 26, T. 153 N., R. 103 W., Mountrail County, North Dakota.

C. Tongue River-Sentinel Butte contact (arrow) along Garrison Reservoir about 8 miles northwest
    of Newtown. The HT Butte bed is about 9 feet thick and is overlain by about 50 feet of basal
    Sentinel Butte sand.
    Location: SE¼ sec. 22, T. 153 N., R. 93 W., Mountrail County, North Dakota.

D. Tongue River-Sentinel Butte contact (arrow) about 2 miles southwest of Glen Ullin. The dark
    horizon above the contact is a dense clay; note the similarity of this outcrop with that of
    Figure 5-D.
    Location: NE¼ sec. 2, T. 138 N., R. 89 W., Morton County, North Dakota.
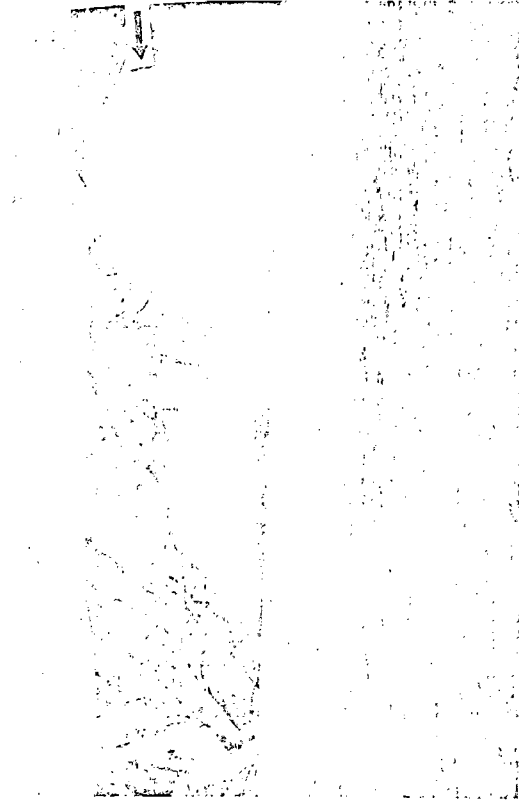
A
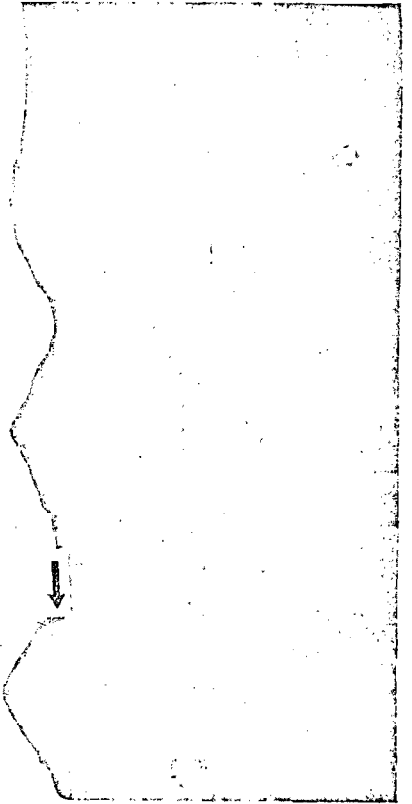
B
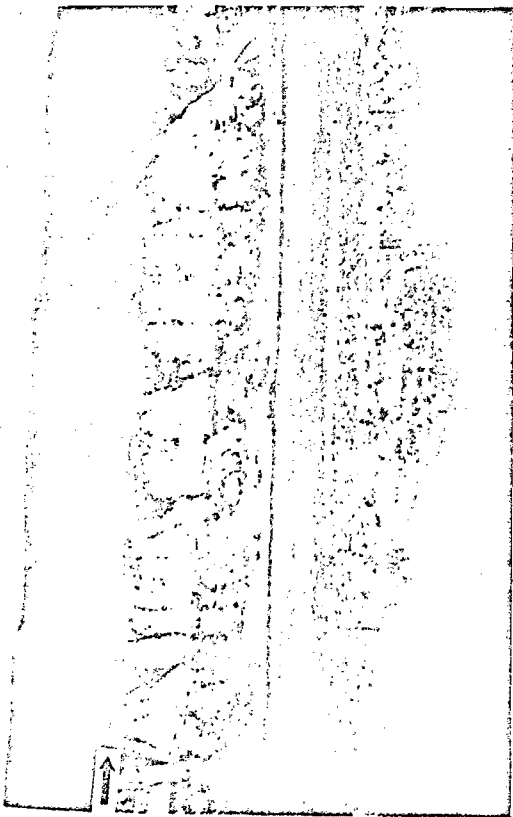
C

D
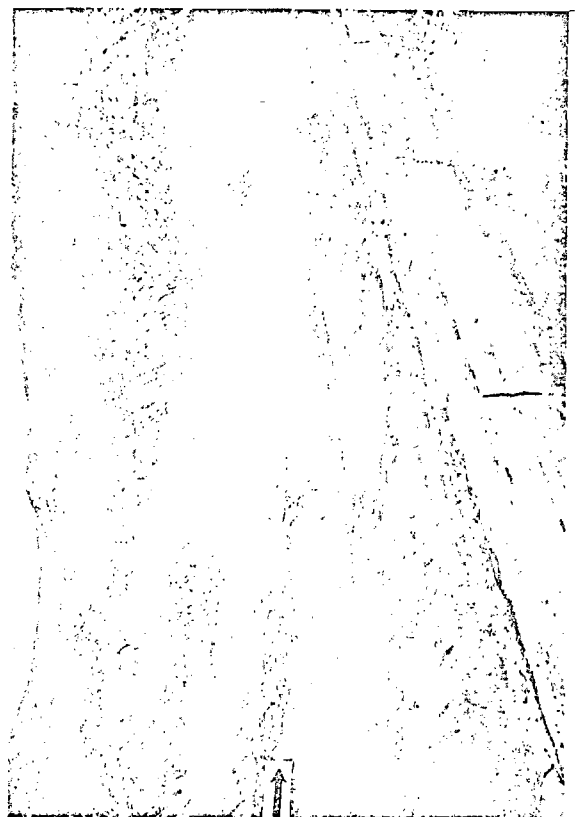
Tongue River Formation. The basal sand is typically developed and silicified wood and stumps are abundant along the contact.

East of the Snowden-Buford area, the contact dips below the Missouri River and is believed to remain in the subsurface across most of southern Williams County. Near the Williams-Mountrail County line it rises to the surface along the west flank of the Nesson anticline. Good exposures can be seen in the bluffs along Garrison Reservoir just east of the Mountrail County line (Figure 8-B). An outcrop, accessible by car, occurs about 7 miles northwest of Newtown (Figure 8-C) where about 9 feet of lignite, lignitic shale, and carbonaceous clay constitute the HT Butte bed and are overlain by 40 feet of basal sand. The lower portion of the basal sand is better sorted than is "typical", but the clay-silt content increases upward in the unit.

The contact can be extrapolated up the valley of the White Earth River in western Mountrail County to its terminus near the Burke County line. East of the mouth of the White Earth valley, the contact can be traced in discontinuous outcrops along Garrison Reservoir to the Four Bears Bridge, west of Newtown, where it is well exposed at an elevation slightly above the bridge abutments. The contact cannot be traced beyond a sag filled with post-Paleocene sediments (Clayton, oral communication) about 6 miles south of Newtown. Sentinel Butte strata only are present above the reservoir level for several miles south of the sag, and it is inferred that the contact has been displaced downward along a northwest-trending fault (Clayton, in preparation). The writer has not inspected the bluffs along the reservoir beyond the Mountrail-Dunn County line, but

Clayton (oral communication, 1967) has observed what he believes is the Tongue River-Sentinel Butte contact in the bluffs along the north shore of the reservoir opposite the mouth of the Little Missouri River. This occurrence seems plausible, because the contact is thought to occur due west of this locality in the vicinity of Lost Bridge.

At Lost Bridge, strata believed to contain the contact occur near flood-plain level where bedrock crops out adjacent to the river. Caution is required in evaluating these exposures, for many slump blocks (not all of which have been rotated) are present along the base of the high bluffs. The contact is believed to be present just west of the north abutment of the bridge. The HT Butte bed is locally burned but a single measurement indicates that it is thin, and probably averages less than 3 feet in thickness. The basal sand is present above the lignite but its stratigraphic position is locally occupied by floodplain and alluvial-fan debris and its total thickness is undetermined. The absence of a well exposed section of Tongue River strata makes it difficult to demonstrate the validity of the contact at Lost Bridge. Supporting evidence is contained in the 450 feet of Sentinel Butte beds which extend above the presumed contact. This section contains marker beds (a "blue" bed and upper and lower "yellow" beds) which appear correlative with similar beds in the North Unit of Roosevelt Park. If the correlation of these beds is correct, and if their relative stratigraphic positions are constant, the contact should exist near river level at Lost Bridge.

Eastward extent of contact.--The area of Figure 1 south of the Little Missouri River and east of North Dakota State Highway 85, which includes most of Dunn and Stark Counties, is not specifically

included in the scope of this report. However, the writer has traveled most of the major roads of this region and is of the opinion that nearly all of the exposed strata are of Sentinel Butte age and younger. This observation is in accord with regional structure, for the axis of the Williston basin (syncline) of North Dakota extends north-south through this area. This is demonstrated, for example, by beds of Tongue River and older age which are concealed by younger strata along U. S. Highway 10 (Interstate 94) between the east "breaks" of the badlands and the Glen Ullin-New Salem area, 60 miles to the east.

Success in delimiting the Tongue River-Sentinel Butte contact throughout the areas discussed above leads to an important query -- can the contact be delimited with equal facility farther east along the truncated flank of the Williston basin? Difficulties are imposed in this area by rolling terrain mantled with vegetation and glacial debris which conceal the bedrock. The composite thickness of Paleocene strata is considerably less in this area than in the badlands and greater altimetric control is necessary to correlate between the isolated outcrops. Questions concerning the differentiation of Tongue River and Sentinel Butte strata in this region will ultimately be answered by detailed geologic mapping of the units, an initial stage of which has already begun.

During the fall of 1966, the writer held a field conference with U. S. Geological Survey geologists[1] involved in surface mapping in

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[1] U. S. Geological Survey geologists were C. S. V. Barclay, G. D. Mowat, and K. Soward; the writer was accompanied by C. G. Carlson of the North Dakota Geological Survey.

Morton and Grant Counties. The contact, as defined by the writer,
was inspected at many localities in Billings and Golden Valley
Counties and compared with a persistent "marker" horizon in Morton
County. Although the HT Butte bed is thin and poorly developed and
the basal Sentinel Butte sand is fine grained, the writer (and ap-
parently his companions; the writer expresses no formal commitment
on their part) concluded that the "marker" horizon was in fact the
Tongue River-Sentinel Butte contact. In regard to this horizon in
Morton and Grant Counties, Barclay (written communication, January,
1967) has stated:

> I am convinced that the horizon which you showed me on
> November 4 [1966] in the South Unit of the Theodore Roosevelt
> National Park and which you map as the Sentinel Butte/Tongue
> River contact is the same horizon I showed you on the follow-
> ing day in the Glen Ullin and Dengate Quadrangles, which I
> had mapped as a marker between two major lignite zones. I
> have seen the same horizon in the White Butte, Clark Butte,
> and the North Almont Quadrangles. I'm sure it is present in
> the Heart Butte and Heart Butte NW Quadrangles.
>
> In the Glen Ullin and Dengate Quadrangles, the contact
> is marked by a dark olive to greenish gray montmorillonitic,
> locally silty to sandy claystone above, and a yellowish gray
> sandstone and siltstone sequence below. There is commonly
> a [thin] lignitic zone at the base of the clay [which may be]
> an HT Butte lignite equivalent. You stated, or at least im-
> plied, that the montmorillonitic claystone, with its locally
> high proportion of coarser material, is, at least in part,
> a lateral equivalent of the basal clayey sandstone [present
> in the Little Missouri badlands]. I concur in this also,
> except I tend to regard the montmorillonitic claystone
> with the characteristically high admixtures of coarser mat-
> erial as the "normal" contact and the clayey sandstone as
> the result of local emphasis on one aspect of sedimentologi-
> cal conditions during earliest Sentinel Butte time. Of course
> this local emphasis becomes more general as the source area
> for the coarser material is approached . . .
>
> I also believe that this "local" emphasis occurred in the
> Dengate-Glen Ullin area. Actually, I include 13 to 15 feet of
> sediment -- the interval from the lignitic zone below the
> montmorillonitic clay to the base of the next lignitic zone --
> in a basal zone of the Sentinel Butte, the uppermost third or
> so of which is not uncommonly a clayey or silty sandstone to
> sandstone. As a matter of fact, there is a sandstone at least

40 feet thick above the contact that is exposed in a railroad
cut in the Dengate Quadrangle [NE¼, sec. 21, T. 139 N., R. 87 W.].
This sandstone body is not well exposed but is of limited areal
extent. Its outcrop pattern and primary dips on either side of
its long axis indicate it is a "channel" sand.

The writer is in essential agreement with Barclay's deductions.
It appears that the basal Sentinel Butte "sand" contains greater ad-
mixtures of fine silt and clay, particularly near its base, in this
eastern region and its dominant texture may be silty clay or clayey
silt. The contact is mappable, however, and the criteria which aid
in its recognition are essentially the same as those recognized far-
ther west. Figure 8-D illustrates the contact in the Glen Ullin Quad-
rangle.

Previous observations of the contact

Numerous statements regarding the character and extent of the
Tongue River-Sentinel Butte contact appear in the geological litera-
ture. Many of these are restatements of opinions expressed by earlier
workers and most are intended to apply to relatively small study areas.
Individually, they add testimony to the persistence and character of
the contact and, collectively, they appear to support the general con-
clusions of this report. A few of these statements have already been
cited, others which relate to western North Dakota are reviewed below.

The most comprehensive and concise statement regarding the re-
gional extent of the Sentinel Butte Formation noted by this writer, is
given by Seager, and others (1942, p. 1417).

> The best exposures of Sentinel Butte are found in the bad-
> lands of the Little Missouri River in the vicinity of North
> Roosevelt Park, McKenzie County, North Dakota. In this local-
> ity, near the axis of the Williston Basin syncline, the unit

as a whole is flat, and may exceed 550 feet in thickness
Its position in the syncline preserved it from pre-Oligo-
cene erosion. The Sentinel Butte is the surface rock in
most of McKenzie, Billings, Dunn, and Stark Counties, in
eastern Slope County and in parts of Mercer and Morton
Counties. It crops out along the Missouri and Little Miss-
ouri rivers as far east as Sanish and Elbowoods, and also
may be observed in the drainage of the Knife River near
Hebron . . .

The Tongue River member of the Paleocene Fort Union For-
mation conformably underlies the Sentinel Butte. A clinker
resulting from the burning of a lignite bed marks the contact
of the Tongue River and Sentinel Butte members in many places.
Numerous clinker beds occur both above and below the contact
clinker. Thus, the presence of clinker should not be used in-
discriminantly as the criterion for separating the two members.

Regarding the distribution of the Tongue River Formation, these wri-

ters stated (p. 1417):

The Tongue River . . . crops out extensively in the bad-
lands of the Little Missouri River from the vicinity of Mar-
marth, North Dakota, to a point 100 miles north. At the latter
locality, the general northeast dip of the strata into the Wil-
liston Basin syncline carries the member below river level.
The member is exposed over a broad area along the Montana-North
Dakota boundary, from northern Slope County at least as far
north as the Missouri River. It reappears on the crest of the
Nesson anticline in southern Williams County, and is exposed
along the Missouri River on the east side of the Williston
Basin syncline.

These statements are in essential agreement with the distribution of

Paleocene strata as recognized by the writer. Although Seager and

others, alluded to the HT Butte bed of the Tongue River Formation, no

mention was made of the basal Sentinel Butte sand.

Hennen (1943) is apparently the only person who has attributed

regional persistence to a sandstone bed. As discussed above, the

"Sandstone 21" of Hennen is equivalent in part to the basal Sentinel

Butte sand of this report and, although Hennen placed it within the

Tongue River Formation, its persistence suggests it may be largely

synonymous with the basal sand of the Sentinel Butte. Regarding the

distribution of his "Sandstone 21", Hennen (p. 1570) wrote:

> It is persistent and widespread in the Dakota basin, as
> evidenced by exposures extending from the vicinity of Sentinel
> Butte, Golden Valley County, eastward to the vicinity of
> Almont, Morton County; from a point on the east bank of North
> Fork of Cannonball River, 10 miles northeast of Amidon, in
> eastern Slope County, northward to the steeply pitching flanks
> of the Nesson anticline in southern Williams County; and
> thence southeastward along the valley of the Missouri River
> to the vicinity of Coleharbor . . .
>
> Marker-bed SS_{21} is typically developed on both flanks of
> the Nesson anticline in southern Williams County with the same
> abundance of silicified plant stems and here and there a sil-
> icified tree stump.

With the exception of sections figured in Hennen's east-west cross-
section from Sentinel Butte to Kidder County, locations given for
"Sandstone 21" are too general for accurate field checks and the ex-
tent to which it is equivalent to the basal sand of this report has
not been determined.

In reference to the distribution and stratigraphic relationships
of Fort Union strata, Brown (1948a, p. 1270-1271) made the following
remarks:

> The dark Sentinel Butte shale, according to Hennen extends
> eastward across the Little Missouri River as far as Almont,
> about 115 miles from Sentinel Butte. Northward it comprises
> the higher strata of the badlands along the Little Missouri
> River and is part of the type section of the Fort Union for-
> mation on the north side of the Missouri River opposite the
> mouth of the Yellowstone River. Its color in these farther
> areas, however, is relatively light, so that in this respect
> it is practically indistinguishable from the underlying Tongue
> River member . . .
>
> Southwest of Broadus, Montana, a considerable dark se-
> quence, near the top of the Tongue River but beneath lignitic
> strata containing Wasatch fossils appears to the writer to be
> correlatable northeastward with the dark Sentinel Butte shale
> and its lateral equivalents.
>
> The Tongue River member of the Fort Union in the type ex-
> posures along Tongue River in Wyoming and Montana is essentially
> a light-colored zone of sandstones, shales, clays and coals.

Duller colors, however, prevail in its southwestern and north-
eastern extensions, and lenses or bands of dark-colored por-
tions come and go both vertically and laterally so that its
boundaries, except locally, are very definite, accounting per-
haps for many of the variations in thickness attributed to the
member . . .

In some areas . . . the variation in thickness [of the
Tongue River member] is caused by the lateral transition of
light-colored into darker strata and vice versa which moves
the color boundaries up and down in the section.

In brief, the color changes match the equally great var-
iations in lithologic composition, vertically and laterally,
in the Paleocene sequence east of the Rocky Mountains, and
render the definition and mapping of its several so-called
members difficult or impossible, except locally. No reliance
can be placed on distant lateral correlations made on this
basis.

These statements appear to be, by and large, undocumented

statements of opinion and intuition which may possibly have prejudiced

concepts of the Tongue River-Sentinel Butte contact in North Dakota.

Field observations upon which the present report is based do not

support interpretation of a facies relationship between Tongue River

and Sentinel Butte strata in western North Dakota. Brown's state-

ment regarding the Sentinel Butte beds as "practically indistinguish-

able" from the Tongue River "member" near the mouth of the Yellowstone

River appears questionable. As Figure 8-A illustrates, the color con-

trast across the contact is as marked here as can be observed any-

where in North Dakota.

The great variation in thickness recorded for the Tongue River

"member" probably results more from differing opinions regarding its

bounds than from lateral transition of light-colored into darker

strata as suggested above by Brown. For example, Leonard (1911,

p. 540) stated:

> Where the uppermost beds of the [Fort Union] formation
> are found, as on the top of such high buttes as Sentinel,
> Flat Top, Bullion, and Black, they are seen to consist of a
> rather hard sandstone 80-100 feet thick . . . The White River
> beds are seen resting directly on this uppermost sandstone of
> the Fort Union.

This "uppermost" sandstone has since yielded fossils which reveal its

true age as Oligocene (Brown, 1948a). Thus one must deduct 80 to 100

feet from the composite thickness cited for the Fort Union Group (or

for the Sentinel Butte Formation) by Leonard. An error of similar

magnitude is apparent in a later statement by Leonard (Leonard, and

others, 1925, p. 35).

> The top of Sentinel Butte is 1163 feet above the bottom
> of the Little Missouri River valley at Medora so that in going
> from the river to the top of that butte it is possible to
> determine the number of coal beds present in this vertical
> section of over 1100 feet of strata.

This statement tacitly assumes that the strata are horizontal, an

assumption which is good only as a "first" approximation. The east-

ward component of dip between Sentinel Butte and Medora is about 0.3

or 0.4 degree eastward. This dip carries the HT Butte bed downward

from the base of Sentinel Butte into the subsurface about 3 miles

east of Medora, and the apparent composite is reduced accordingly.

Thus the composite section along this traverse is considerable less

than 1100 feet, probably on the order of 650 to 700 feet. Many sim-

ilar errors are present in the literature and citations of aggregate

or composite thicknesses of Paleocene strata require careful evalua-

tion.

That Paleocene units do vary in thickness, however, appears

certain. For example, the thickness of the Sentinel Butte Formation

increases from about 350 feet at Bullion Butte to 400 feet at Sentinel

... attains a maximum recorded thickness near the North Unit

... velt Park of about 600 feet. In the writer's opinion, such

... in thickness reflects primary depositional control and,

... with directional data, will eventually aid in evaluating both

... structural character of the Tertiary basin of accumulation and the

... of Paleocene sediments. This will be achieved, however, only

... the stratigraphic units have been adequately differentiated.

... Brown (1948a) does not stand alone in his contention that the

... boundary between the Tongue River and Sentinel Butte Formations

... history. Benson (1952, p. 41-43) summarized his investigations

... with Brown:

> At various times during the summers of 1947 through 1949
> Brown and I together examined the Paleocene and Eocene forma-
> tions in western North Dakota in an attempt to determine what
> happens to the Tongue River-Sentinel Butte contact east of
> Sentinel Butte and the Little Missouri River. We reached
> the following tentative conclusions:
>
> (1) The contact between the Tongue River and Sentinel
> Butte shale members of the Fort Union Formation is essentially
> a color boundary, with little lithologic difference between
> the two members.
>
> (2) This contact cannot be traced directly east because
> it dips in that direction into the Williston Basin and is con-
> cealed by younger formations. It can, however, be traced
> along the Little Missouri River north and south from the type
> locality of the Sentinel Butte shale near Medora. To the
> south, the Sentinel Butte shale can be identified as far as
> the Marmarth coal field (Hares, 1928), beyond which area
> erosion has removed all the late Paleocene beds. To the north,
> the color contact can be followed, at or near the same strat-
> igraphic horizon, as far as southern McKenzie County, where
> the dip into the Williston Basin carries it below the floor
> of the Little Missouri Valley.
>
> (3) Beds representing the approximate stratigraphic hor-
> izon of the Tongue River-Sentinel Butte contact reappear at the
> surface on the east side of the Williston Basin in eastern
> McKenzie, northeastern Dunn and western Mercer counties. In
> this area, however, there is no color change. The section as

a whole is dark, resembling the type Sentinel Butte shale;
but it also contains numerous light beds that resemble the
Tongue River.

(4) The eastward darkening of the section is probably
due to eastward thinning of the Fort Union formation, especially
the Tongue River member. Near Medora the combined thickness
of the Tongue River and Sentinel Butte members is between
1,000 and 1,500 feet and sand comprises about half of the
section. In Mercer County, the thickness of the Tongue River-
Sentinel Butte beds is probably less than 800 feet, and the
section is 60 to 65% gray shale. Also, as the total volume
of sediments decreases, the relative abundance of carbona-
ceous material increases, causing a darkening of the color.
It is not surprising that the color contrast between the Sen-
tinel Butte shale member and the Tongue River member does not
persist as far east as the Knife River area.

(5) The Sentinel Butte shale, therefore, is mappable as
a separate member of the Fort Union formation only near its
type locality in western North Dakota. To the east it appears
to inter-tongue, both laterally and vertically, with the Tongue
River member. We therefore suggest that the name "Sentinel
Butte" be used only in western North Dakota; and that beds
of equivalent age in the central part of the state be included
in the Tongue River member of the Fort Union formation.

As interpreted in this report, the Tongue River-Sentinel Butte

contact is not just a color boundary, it is a lithogenetic break be-

tween two rock stratigraphic units, the uppermost of which transgressed

the lower. Evaluation of analyses of nearly 500 stratigraphic samples

demonstrates that these units are distinct in both texture and compo-

sition and that they record two different episodes of Paleocene his-

tory. Thus, statements regarding Tongue River and Sentinel Butte

lithologies as "indistinct" appear to be questionable.

Benson's failure to distinguish the Tongue River-Sentinel Butte

contact within the Knife River drainage suggests to this writer that

it is not exposed in much of this area. The contact is distinct south

of Benson's map area in Morton County and efforts are presently

underway to carry it northward (C. G. Carlson, in progress). The

presence of light-colored horizons within the Sentinel Butte Formation is not denied. "Yellow" beds can be seen in the upper half of the section near the North Unit of Roosevelt Park and correlative strata appear to exist westward to Sheep Buttes, eastward to Lost Bridge, and southward at least as far as the Blacktail-Whitetail Creek divide. A light-colored bed occurs high in the local section just west of Fryburg, Billings County, which has considerable persistence and might correlate with one of the "yellow" beds mentioned above. The writer considers these beds similar to Tongue River strata and suggests they may represent a brief "return to Tongue River conditions"; however, no evidence exists to imply that they have physical continuity with the bulk of strata in the underlying Tongue River Formation.

The influence of Benson and Brown is evident in the reports of subsequent investigations. For example, Fisher (1953) made the statement,

> The Sentinel Butte sediments are generally more somber than those below. Brown (1948), in his review of the Paleocene rocks of westcentral North Dakota, has shown them to be a facies of the Tongue River formation; a color change that moves vertically across the section. A similar condition is indicated in McKenzie County for the upper part of the river bluffs in the northwestern portion of the county contain beds which are probably high in the [Fort Union] section, but are chiefly buff in color. The writer cannot be certain of this fact because correlations were not carried into that area.

Fisher's uncertainty is justified by the writer's field check of the bluffs along the river north of the Nelson Bridge east of Fairview, Montana, which contain only Tongue River strata.

Fisher's success in tracing the HT Butte bed is of greater concern than his comments regarding facies. In regard to this unit,

which he designated as the L bed or "scoria", he stated:

> The L lignite of this report can be traced over 30 miles southeast from the bend of the Yellowstone River [in north-western McKenzie County].

> The L scoria forms the rimrock in much of the western half of the area. It is the thickest single scoria in the area ranging up to 45 feet although usually less than half that thick.

In a southward continuation of his structural study in west-central McKenzie County, Fisher (1954) again used the L bed as a datum.

> It was thought desirable to follow out the extensive L scoria which served as contour datum in that report [Fisher, 1953], and to locate the position of this bed in the sections measured by Leonard along the Little Missouri River.

> In McKenzie and northern Golden Valley counties at least, this scoria marks the contact between the light colored standard Tongue River sediments and the overlying somber Sentinel Butte facies.

Fisher's structural mapping was followed by similar studies to the southeast (Hanson, 1955) and east (Meldahl, 1956). In regard to the contact within the "Elkhorn Ranch area" Hanson (1955) commented:

> The contact between the Sentinel Butte member and the underlying beds of the Tongue River formation is quite pronounced because it is picked at a color change; dark brown Sentinel Butte shale is found resting on gray to tan Tongue River beds.

> In the southern part of the area a prominent clinker bed exists which has been designated by the writer by the letter "L". This clinker bed extends for about three miles north of the southern boundary of the area, and caps all the buttes in that vicinity. Although this clinker bed is not very extensive, and is much thicker than the clinker bed in the Skaar-Trotter area, it was determined that it is the same bed described by Fisher (1954) in the Skaar-Trotter area. The base of clinker bed "L" was used for the datum plane in structure contouring.

Although Hanson's report adds testimony to the color contrast between the Tongue River and Sentinel Butte Formations, his mapped contact between them does not agree well with Figure 1 of this report.

The following year, Meldahl (1956) mapped the "Grassy Butte area" which constitutes a northward extension of Hanson's and an eastward extension of Fisher's investigations. In reference to the character of the contact, Meldahl stated:

> The contact of the Sentinel Butte member with the lower part of the Tongue River formation is essentially a color boundary with little lithologic difference. As previously described, the lower Tongue River strata are buff, light tan, and light gray in color. The Sentinel Butte member is generally darker and more somber in color, usually being dark to light gray. The color difference between the Sentinel Butte member and the rest of the Tongue River formation usually appears quite distinct from the distance, but is actually gradational and indefinite.

Such skepticism regarding recognition of the contact would presumably preclude its use as a structural datum, but Meldahl had success comparable to that of Fisher (1953, 1954) in tracing the "L bed":

> . . . The base of the Sentinel Butte member is marked by the "L bed" in this area, in the adjacent areas to the north, west, south, and in the South Unit of Theodore Roosevelt National Park. In those areas the "L Bed" is usually a prominent scoria, quite thick in the Park, and north of the Grassy Butte area, but generally only about four feet thick to the west of the Grassy Butte area and in the Elkhorn area to the south. In the northern half of this [Grassy Butte?] area the "L bed" is lignite, four feet thick, and only locally has it burned to produce scoria. In the southern half of the Grassy Butte area the lignite thins and in places is entirely absent. Here the "L bed" consists of bentonitic clay which in places is underlain by the lignite. Both the bentonitic clay and the lignite in general contain petrified logs. Hanson (1955) also picked the color change at this stratigraphic horizon in the northern part of the Elkhorn Ranch area to the south.

Meldahl's reference to replacement of the "L bed" by a "bentonitic" clay merits comment. This unit is a local wedge of fine material between the HT Butte bed and the basal Sentinel Butte sand. Where it was observed in Meldahl's and Hanson's map areas, it is discontinuous and ranges in thickness from a "feather edge" to 4 or 5 feet. It is distinct from, but usually grades abruptly into, the

basal sand. It may have (in its original extent) been the source of clay in the basal sand.

As a final example of previous observations of the Tongue River-Sentinel Butte contact, brief consideration is given to Nevin's (1946) comments regarding the contact in the Keene dome area of eastern McKenzie County.

> Although the Sentinel Butte is conformable with the underlying Tongue River, and although the environment of sedimentation was very similar for both formations, it is possible to map them separately . . . Since the contact of the Sentinel Butte and Tongue River is completely gradational, some arbitrary horizon must be selected for the boundary. Seager (1942) states that a lignite or a burned clinker bed marks the contact in many places. Hennen places the contact at the top of lignite 22, a bed 20 feet thick, that is being mined on the north face of Sentinel Butte. If no mistake has been made in correlation, this horizon is equivalent to JK of the stratigraphic section, figured in this report.

Nevin, however, considered a more "logical" contact (his bed L which he designated as the approximate top of the Tongue River) to exist about 200 feet stratigraphically higher than the JK bed. Spot checks of Nevin's datum points between Charlson and the Missouri River, where the contact (as defined by criteria of this paper) is known to exist, indicate to the writer that Nevin erred in his regional correlation of the contact by at least 200 feet. This error has no direct bearing on his local correlation and should not influence his structural interpretations. Nevin's failure to include key marker beds (such as the "blue bed" and the "upper and lower yellow beds" of Fisher, 1953) which are believed to be present in his map area, limit the utility of his generalized stratigraphic section.

Stratigraphic Nomenclature

In any penetrating study of early Tertiary continental deposits of the western interior, the geologist will find himself drawn into a voluminous literature full of nomenclatorial ambiguity and uncertainty. Few stratigraphic intervals in the United States have been subject to greater argument, debate, and disagreement than has the late Cretaceous-early Tertiary continental sequence of the Western Interior. The roots of controversy extend back to the first comprehensive geological studies by the Territorial Surveys; duplication and confusion accompany and characterize the history of subsequent study. Only recently has our knowledge reached the degree of completeness necessary for clarification of the stratigraphic nomenclature. A brief resume of uses (and misuses) of stratigraphic terms applied to the Cretaceous-Tertiary sequence appears desirable here in order to place the Tongue River and Sentinel Butte units in proper nomenclatorial perspective.

Early Nomenclature

Early geological reports (1852 to 1876 and later) referred to the Lignite (Lignitic) Group, now known to contain strata which range in age from late Cretaceous to early Tertiary. Meek and Hayden

(1862) supplanted the "Lignitic Group"[2] of older reports with the "Fort Union Group" or the "Great Lignitic Group". Apparently, no need for consistent usage was felt and the terms were used interchangeably by Hayden during the following decade. A seed of synonymy had, however, been sown, for the term "Lignitic Group" was an abstraction applicable to carbonaceous strata anywhere; "Fort Union" was specific and applied to a definite sequence of strata with a designated type locality. The two were in no way entirely equivalent.

The term "Lignitic Group" was also replaced by the term "Laramie Group" in the vicinity of the fortieth parallel by King (1876). This duplication of terminology was soon recognized, and Hayden and King together agreed to replace the descriptive term "Lignitic" with the geographic term "Laramie". They included within the "Laramie Group" all strata between the "Fox Hills Sandstone" and "Vermillion Creek" (of King) or "Wasatch" (of Hayden) Group. It is not entirely evident that Hayden ever intended to replace the term Fort Union with Laramie; it would seem, rather, that he temporarily revised its age, considered it "Wasatch", and preserved its identity. Hayden (1878, p. iv) stated,

> If objection is made to the use of Lignitic group I would say that in this work it is restricted to a series of coal-bearing strata lying above the Fox Hills group, or Upper Cretaceous, and these are embraced in the Laramie and Fort Union groups . . . It is also probable that the brackish-water beds on the upper Missouri must be correlated with the Laramie,

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[2]Formal stratigraphic terms, used in the context of previous workers, which are considered to embrace different stratigraphic intervals than current usage permits are placed in quotes. Likewise, obsolete rank terms are placed in quotes. Quotes are omitted for terms currently accepted by the North Dakota Geological Survey and the writer, and for terms used in general context without explicit stratigraphic connotation.

and that the Wasatch group as now defined and Fort Union group are identical as a whole, or in part at least.

If King and Hayden ever agreed on the usage of Laramie, it is certain that they never agreed on its age. Controversy is apparent in King's (1878, p. 298) statement regarding the "Laramie Group" as the last of the conformable marine strata and equivalent to the "Lignitic series" of Meek and Hayden (1862) in the upper Missouri section:

> Dr. Hayden has successively considered these rocks as Tertiary and as transitional between Cretaceous and Tertiary . . . That there might be no misunderstanding as to stratigraphic position and nature of the rocks themselves, Dr. Hayden and I mutually agree to know them thereafter as the Laramie group, and to leave their age for present as debatable ground, each referring them to the horizon which the evidence seems to him to warrant. The result of our investigations leads me to the distinct belief of their Cretaceous age.

Hayden (1876, p. 26-27) was no less emphatic in his viewpoint:

> I still regard the lignitic group proper as transitional or Lower Eocene, and shall so regard its age until evidence to the contrary is much stronger than any which has been presented up to present time. When, however, the proof is sufficient to decide the Cretaceous age of the group I shall accept the verdict without hesitation. It is somewhat doubtful whether the age will ever be decided positively to the satisfaction of all parties.

In retrospect we realize that both men were largely correct, that the lignitic sequence in question contains strata of both Cretaceous and Tertiary age, and that King probably saw more of the former and Hayden more of the latter. That Hayden had the better perspective is indicated by his lack of dogmatism and by his statement (Hayden, 1878, p. iv) that

> . . . Those who worked from the south and southwest toward the north have been thoroughly impressed with the Cretaceous age of the "Lignitic group", while those who have studied the deposits from the north and northwest toward the interior basin received their first impressions they were of Tertiary age.

Thus at the close of the Territorial surveys (1878) the term "Lignitic group" was passing into disuse and uncertainty existed as to the meaning and age of the terms Fort Union and Laramie. By 1900, the age, definition, and extent of the "Laramie Formation" was becoming a major issue (the Laramie Problem) in the burning debate over placement of the Cretaceous-Tertiary boundary in the Western Interior. As detailed studies were completed, additional terminology was introduced, older terms were revised and restricted, and the stratigraphic nomenclature rapidly attained a complexity capable of wearying the casually interested and frustrating the seriously involved geologist.

Weed (1893) made the first major subdivision of the "Fort Union" near Livingstone, Montana, in which he restricted the term "Fort Union Group" to an upper sequence of rather massive cross-bedded sandstones with gray silty shales and local lenses or impure limestone which he (p. 35)

> . . . Believed to be a distinct formation, corresponding in lithology, stratigraphic position, and fossil contents to beds exposed along the Missouri River at the mouth of the Yellowstone, so long known in geological literature as Fort Union beds.

Beneath this "Fort Union" he recognized the "Livingstone beds" which unconformably overlay a thick sequence he regarded as equivalent to the Cretaceous "Laramie beds" of King and others. This appears to be the first clear recognition of the temporal and stratigraphic distinction between the "Laramie" and "Fort Union" formations. Subsequent work in adjacent localities resulted in further subdivision of these strata in which "Fort Union" was restricted to the youngest strata underlying the "Wasatch formation" and its equivalents.

Strata beneath the "Fort Union beds" received various new terms.

In Converse County, Wyoming, the late Cretaceous sequence equivalent to the widespread dinosaur-bearing beds (Ceratops beds) between the "Fox Hills" and "Fort Union" formations were named "Lance Creek beds" (Hatcher, 1903); similar strata in eastern Montana were named "Hell Creek beds" (Brown, 1907) and subsequently became known as the "Hell Creek member of the Lance formation" (Thom and Dobbin, 1924).

Just as the term Fort Union became restricted to the upper portion of the lignitic strata of the Great Plains, the term Lance received wide application to the lower interval. From its inception, the term was equivalent in part to the "Laramie formation" of King and others. As a result of the uncertainty which attended usage of "Laramie formation" the U. S. Geological Survey, in 1910, restricted the use of Laramie to rocks of the Denver basin. As a result, "Lance formation" was extended to include strata throughout Wyoming and adjacent portions of Colorado, Montana, North Dakota, and South Dakota. Brown (1943) proposed that the term Laramie be expanded to include the "Arapahoe conglomerate" and the Cretaceous portion of the "Denver formation", thus making the "Laramie formation" equivalent to the typical "Lance" and "Hell Creek" formations.

The upper contact of the Lance Formation is gradational with younger beds of variable character, many of which have been treated as members of the Lance Formation and considered to be of late Cretaceous age. In eastern Montana such units included the "Tullock member" (Rogers and Lee, 1923) and the "Lebo shale" (Stone and Calvert, 1910) and in adjacent North and South Dakota the "Ludlow lignitic member" (Lloyd, 1914). The Paleocene age of each of these units has subsequently been recognized and they are now considered to be

subordinate units within the Fort Union sequence (Keroher, 1966).

Because of the uncertain age relationship between the Lance and Laramie strata (the latter of which was considered to be of established Cretaceous age), the U. S. Geological Survey in 1935 elevated the Hell Creek and Tullock "members" to formational rank and restricted the age designation of the Lance to "Cretaceous" except where beds of demonstrated Tertiary age exist above those of Cretaceous age, in which case the age designation might be "Upper Cretaceous and Eocene". In North Dakota, the Ludlow and Cannonball continued to be considered members of the "Lance" (Wilmarth, 1938), their Paleocene affinities not yet having been demonstrated.

Tongue River and Sentinel Butte Formations

The "Fort Union" also underwent subdivision during the early part of the century, largely as a result of the many "coal surveys" of the U. S. Geological Survey. Taff (1909) divided the "DeSmet formation" (equivalent in part to the Fort Union) of Darton (1906) in the Sheridan coal field, Wyoming, into three groups. In descending order, these were the Ulm, Intermediate, and Tongue River coal "groups". The Tongue River coal "group" was named for exposures along the northward flowing river of that name, and its upper contact was defined by the top of the Roland coal bed. On the basis of fossil plants and shells collected from the Tongue River "group" upward, Taff considered the coal-bearing rocks of the Sheridan field to be of "Fort Union" age; that is lower "Eocene" or "basal" Tertiary.

About the same time, Leonard (1908) and Leonard and Smith (1909) divided strata of the Sentinel Butte coal field of western North Dakota

into an upper Sentinel Butte coal "group" and a lower Medora coal "group". Leonard (1908) is properly credited with the first stratigraphic application of the term "Sentinel Butte"; however, the stratigraphic interval assigned to the Sentinel Butte group in 1908 differed from that of Leonard and Smith the following year. In 1908, the Sentinel Butte coal "group" was recognized as containing, in its lower portion, lignite beds Q, R, and S. Bed Q marked the base of the group. In 1909, only two beds, F and G, were assigned to the lower part of the Sentinel Butte coal "group", and bed F constituted its base. The equivalence of beds S and G is certain, both being reported as 20 feet in thickness. It is also certain that bed R equals F; thus the Q-R interval of the "1908" Sentinel Butte "group" was omitted from the 1909 section, apparently being relegated to the underlying Medora "group". Subsequent applications of the name "Sentinel Butte" appear to follow the revision of Leonard and Smith (1909).

Leonard's use of "Medora group" merits additional comment. In 1908 Leonard recognized the Beaver Creek and Medora coal "groups" as underlying the Sentinel Butte group of lignite beds. The partial equivalence of lignite beds of the Beaver Creek and Medora "groups" is evident to this writer. Perhaps it was this equivalence which caused Leonard and Smith (1909) to omit the Beaver Creek "group" and apply the term Medora "group" to the entire lignitic sequence (exclusive of the Ludlow Formation) below the Sentinel Butte "group". This revised Medora "group", as shown by Leonard and Smith, contains fewer lignite beds than did the 1908 combined sequence of Medora plus Beaver Creek "group".

Leonard (1908) regarded the Sentinel Butte "group" as part of

the "Fort Union formation", and the entire sequence to be of early Eocene age (Eocene then included the Paleocene Epoch). Thom and Dobbin (1924) complied with the then current usage of the U. S. Geological Survey and treated it as Fort Union(?) although they stated that they regarded it to be of "Wasatch" age and equivalent to the Intermediate coal "group" (plus the Roland coal) of the Sheridan coal field in Wyoming. Likewise, Hares (1928) followed the same classification and expressed the same personal opinion as Thom and Dobbin. A subtle fact was becoming apparent, not only is the base of the Paleocene Series problematical but its upper boundary is also indistinct. The age of the Sentinel Butte Formation had become an issue.

Early opinions regarding the age of Sentinel Butte strata appear to result from two considerations; its relationship to the "Clark Fork beds" of the Big Horn Basin and to the Intermediate coal "group" and the "Kingsbury conglomerate" in the Powder River basin. Simpson (1929) tentatively correlated Sentinel Butte with Clark Fork strata which he considered (paleontologically) transitional between late Paleocene (Torrejon) and true "Wasatch". The paucity of fossil material and the uncertain stratigraphic position of key specimens allowed Simpson (p. 7-8) to formulate only the following tentative conclusion:

> If this distinctly Paleocene type of fauna does belong in the Sentinel Butte, it would be much more satisfactory from a faunal point of view to retain this member in the Fort Union Formation or Group, rather than to follow Thom and Dobbin in placing it in the Wasatch. Equivalence with the Clark Fork fauna does not necessitate inclusion in the Wasatch. The known Clark Fork fauna may be slightly later than the Bear Creek fauna, . . . but it is still essentially of final Paleocene type.

In 1930 Jepsen, on paleontologic grounds, assigned the "Clark Fork

formation" to the Fort Union and considered it to mark the summit of the Paleocene. Although Jepsen's study helped confirm the age of the "Clark Fork beds" their correlation with the Sentinel Butte Formation remained tenuous.

Darton (1906) named and described the "Kingsbury conglomerate" at Kingsbury Ridge on the east flank of the Big Horn Mountains in Wyoming and assigned it to the Cretaceous. In 1909, Knowlton, in his discussion of the Hell Creek, Ceratops, and Fort Union "beds", stressed the similarity of floras from the Kingsbury and the upper and lower "members" of the Fort Union, to which he considered the Kingsbury belonged. Likewise, Gale and Wegeman (1910) considered the "Kingsbury conglomerate" to be an upper member of their "Fort Union", although Wegeman (1917, p. 60) amended his views to the effect that:

> . . . It is the writer's opinion that the Kingsbury conglomerate is equivalent to part of the Wasatch, and that the unconformity at its base separates that formation, in the Kingsbury region at least, from all older rocks.

Apparently prompted by opinions of Thom and Dobbin (1924) and Hares (1928) favoring a "Wasatch" age for the Sentinel Butte "shale" and Intermediate coal "group" (which they correlated with the "Kingsbury conglomerate"), a number of subsequent workers followed suit and assigned the Sentinel Butte "shale" an Eocene age (Kline, 1942; Seager, and others, 1942; Laird and Mitchell, 1942; Hennen, 1943; Nevin, 1946; and others). It appears relevant to mention that Thom and Dobbin also correlated the Sentinel Butte "shale" with the "Clark Fork beds" of the Big Horn Basin which subsequently (as discussed above) have been regarded as uppermost Paleocene; thus the correlation of the two remains valid although the age assignments of both have undergone individual

change. In two related papers, Brown (1948a, 1948b) largely clarified the age relationships of the "Kingsbury conglomerate", Intermediate coal "group", and Sentinel Butte "shale". Faunal evidence has established the Eocene (Wasatch) age of the "Kingsbury conglomerate" but, as Brown (1948a, p. 1273) pointed out, although

> . . . The Kingsbury conglomerate . . . was said to occupy a position somewhat laterally of the Intermediate coal group with stringers into that group . . . neither Taff nor anyone else has succeeded . . . in establishing its stratigraphic level relative to the base of the Kingsbury conglomerate.

Thus the presumed correlation of the Intermediate coal "group" (and thus the Sentinel Butte Formation) with the "Kingsbury conglomerate" cannot be physically demonstrated. This relationship led Brown (1948a, p. 1273) to conclude:

> All the recent paleontologic and stratigraphic evidence points toward retention of the Sentinel Butte shale within the Fort Union formation of the Paleocene series. This evidence seems to be harmonious across the entire Paleocene-Eocene terrain east of the Rocky Mountains and permits the drawing of the Paleocene-Eocene boundary with reasonable assurance.

As previously mentioned, Taff (1909) divided the "DeSmet formation" (Darton, 1909) of the Sheridan coal field into upper and lower "members". The upper "member", in turn, was divided into (ascending) Tongue River, Intermediate, and Ulm coal "groups". The top of the Tongue River "group" was marked by (and included) the Roland coal bed; the base was (p. 127)

> . . . Distinguished by the relative quantities of sandstone and shale and by the general color of the rocks . . . and is marked approximately by the Carney coal bed . . . The rocks below the Carney coal are essentially all shale or are shaley in character and prevailingly dull drab, bluish, and brown in color.

In western North Dakota the same lithostratigraphic relationship exists. The top of the Tongue River Formation is defined by the HT Butte bed

and the base (where observable) is separated from the somber Ludlow Formation by a well developed basal sand. It is conformably overlain by the Sentinel Butte Formation and is a discrete rock-stratigraphic unit.

In early publications, the U. S. Geological Survey regarded the Tongue River as a "member" of the Fort Union "formation" and the Sentinel Butte as a "member" of the Fort Union(?) "formation" (Hares, 1928; Wilmarth, 1938). About the same time that it formally accepted Paleocene as an epoch-series term (June 12, 1939) the U. S. Geological Survey omitted the question mark and began to refer the Sentinel Butte "member" to the Fort Union "formation". This usage is still current.

North Dakota geologists have been less consistent in their assignment of stratigraphic rank to Sentinel Butte strata. Workers have variously referred to the "Sentinel Butte formation of the Wasatch group" (Nevin, 1946), "Sentinel Butte shale formation of Eocene (Wasatch) age" (Laird and Mitchell, 1942), "the Sentinel Butte member of the Wasatch formation" (Seager, and others, 1942; Kline, 1942; Hennen, 1943), or to the Sentinel Butte "member" of the Fort Union "formation". No sooner had the reassignment of the Sentinel Butte "shale" to the Paleocene (Brown, 1948a and 1948b) received general acceptance than its relationship to the underlying Tongue River began to be questioned. Two basic opinions developed; one considered the Sentinel Butte to be a "member" of the "Tongue River formation" and a second regarded the Sentinel Butte to be a facies of the "Tongue River formation". Neither of these opinions is supported in this report.

Classification of the Sentinel Butte as a subordinate interval (exclusive of a facies) within the Tongue River necessitates an extension

of the upper contact of the Tongue River (which has been firmly
placed at the Roland and HT Butte horizons) to include a greater
stratigraphic interval than originally defined, and subsequently
accepted, for the Tongue River. Such revision of lithostratigraphic
units (with retention of original names) is discouraged both by
precedent and by the accepted standards of the Stratigraphic Code
of Nomenclature (A. C. S. N., 1961, Article 14). Loose adherence
to this rule has made it increasingly difficult in recent years to
understand an author's meaning of "Tongue River", and whether he is
using original or modified terminology.

Consideration of the Sentinel Butte as an "upper member" of
the Tongue River Formation creates an unnamed "lower member" (Craw-
ford, 1967) occupying the interval formerly considered as Tongue
River. Reference to this "lower member" is commonly made with some
qualification. For example, Fisher (1953, 1954) refers alternately
to "typical", "usual", and "standard" Tongue River rocks in discussing
beds below the Sentinel Butte "member". Meldahl (1956) was forced
to allude to the "lower part" of the Tongue River "formation". Other
writers are equally vague about this stratigraphic interval which for
years was known as Tongue River.

Consideration of the Sentinel Butte as a "facies" of the Tongue
River Formation is even less acceptable to the writer than member
status discussed above. This usage appears to have entered the liter-
ature largely as a result of Brown's (1948a) cross-section correlating
lignitic strata between Sheridan, Wyoming, and Mandan, North Dakota,
which schematically expresses facies relationships between light and
dark strata. Benson (1952, 1954) regarded the ". . . Sentinel Butte

shale member as a facies of the Tongue River member." His motives
were apparently expressed by Brown (1948a, p. 1268):

> Benson, as a result of detailed mapping in the Knife
> River area in 1946 . . . found it impossible to distinguish
> one from another the sequences of strata that had there been
> called Tongue River member and Sentinel Butte shale.

As previously acknowledged, the writer has not thoroughly explored
Benson's map area, but structural relationships imply that sediments
of the Tongue River "member" should not be exposed throughout most of
the area. It is probable that the Tongue River-Sentinel Butte sequence
undergoes lithologic and textural change with increased distance
from its source, such is certainly the case in many post-orogenic
sequences. But evidence for a major facies relationship between Tongue
River and Sentinel Butte strata (if it ever existed) has been removed
by late Tertiary erosion and the relationship cannot be demonstrated
within remaining outcrop areas in western North Dakota.

Proposed revisions

Field investigation has provided criteria for recognition of
the Tongue River-Sentinel Butte contact and has documented its per-
sistence throughout much of western North Dakota. It is hoped that
differentiation of these units will encourage study of the lithogen-
etic and paleontologic aspects of the individual units. Such studies
should contribute significantly to a knowledge of Paleocene tec-
tonics, geography, and ecology of the Rocky Mountains and Great Plains.

The Sentinel Butte has been accepted as a lithostratigraphic
unit of sub-formational rank since originally defined by Leonard and
Smith (1909). The evidence appears to be unequivocal that the

stratigraphic sequence presently referred to as Sentinel Butte is a distinctive and mappable stratigraphic unit and deserves formational rank. It is therefore recommended that the following lithostratigraphic terminology be applied to the Paleocene Series in western North Dakota and adjacent areas:

Fort Union Group

Sentinel Butte Formation

Tongue River Formation

Ludlow and Cannonball Formation

SEDIMENTOLOGY

Presentation of Data

Sediment-size statistics

General statement.--Detailed study of 350 stratigraphic samples
from the Tongue River and Sentinel Butte Formations form the basis of
sedimentologic investigation. Samples were collected from widely
separated, measured sections between Bullion Butte in the south to
the type locality of the Fort Union Group (the Snowden-Buford area)
in the north (Figure 9). Sections are largely restricted to steep
bluffs in major drainages. Nine stratigraphic sections are repre-
sented, two of which (Bullion Butte and Beicegel Creek) contain
sediments of both Tongue River and Sentinel Butte age. Samples are
designated by letter and number, the first indicating the strati-
graphic section, and the second the stratigraphic position (number
one at the base) from which it was collected. Representative por-
tions of each sample have been placed on file in the reference col-
lections of the University of North Dakota Department of Geology.
The locations and thicknesses of the various sections are summarized
in Table 2.

In addition to stratigraphic samples from measured sections,
pairs of samples were collected 6 to 8 feet above and below the Tongue
River-Sentinel Butte contact at fifty-four localities for comparison

78

O Donnybrook

Snowden

O Yellowstone

Long Cross
O
O
Lost Bridge

O Beicegel Creek

NORTH   DAKOTA

Missouri River

Sentinel Butte
O O
   Medora

O Bullion Butte

0   20   50 miles
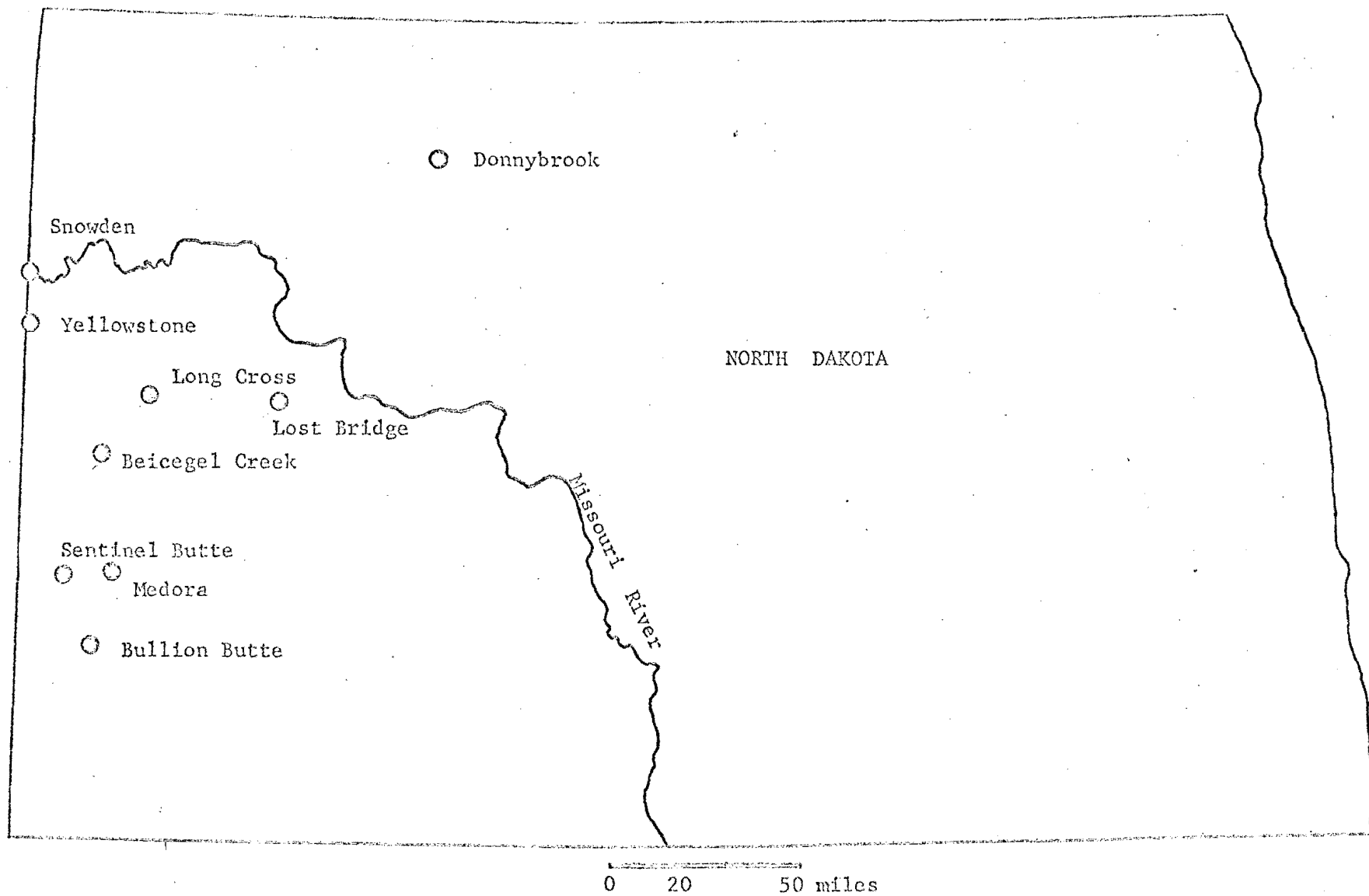
Figure 9.—Index to locations of stratigraphic sections sampled for this investigation.

TABLE 2.—Locations and local thicknesses of stratigraphic sections samples for this investigation.

Section	Thickness (feet)	Location
Bullion Butte	715	secs. 13, 28, and 33, T. 137 N., R. 103 W., Golden Valley County, North Dakota
Sentinel Butte	387	SE¼ sec. 5, NE¼ sec. 8, T. 139 N., R. 104 W., Golden Valley County, North Dakota
Medora	256	NE¼ sec. 27, SW¼ sec. 23, T. 140 N., R. 102 W., Billings County, North Dakota
Beicegel Creek	370	SE¼ sec. 13, T. 146 N., R. 102 W., McKenzie County, North Dakota
Long Cross	545	W½ secs. 1 and 12, T. 147 N., R. 99 W., McKenzie County, North Dakota
Yellowstone	285	SW¼ sec. 23, T. 151 N., R. 104 W., McKenzie County, North Dakota
Snowden	302	SW¼ sec. 2, T. 152 N., R. 59 E., Roosevelt County, Montana
Lost Bridge	504	NW¼ sec. 35, SW¼ sec. 26, T. 148 N., R. 95 W., Dunn County, North Dakota
Donnybrook	54	NE¼ sec. 16, T. 158 N., R. 87 W., Ward County, North Dakota

of the lithologic characteristics of the two horizons. Samples taken above the contact represent the sandy, basal unit of the Sentinel Butte Formation.

Size analysis.--All samples were pretreated for removal of reactive carbonate and analyzed for particle size according to conventional sieve and pipette procedures (details of analytical procedures are given in Appendix I). Size statistics of Folk and Ward (1957) and Inman (1952); sand, silt, and clay percentages; and other values were obtained by computer program. Moment measures were obtained only for samples for which the next to last accumulated percentage of class weights was greater than 99.5, and the number of such samples was insufficient to permit general use of moment measures. Folk and Ward statistics were computed for all samples and have been adopted for presentation of size data in this study.

Tongue River and Sentinel Butte sediments are well suited to
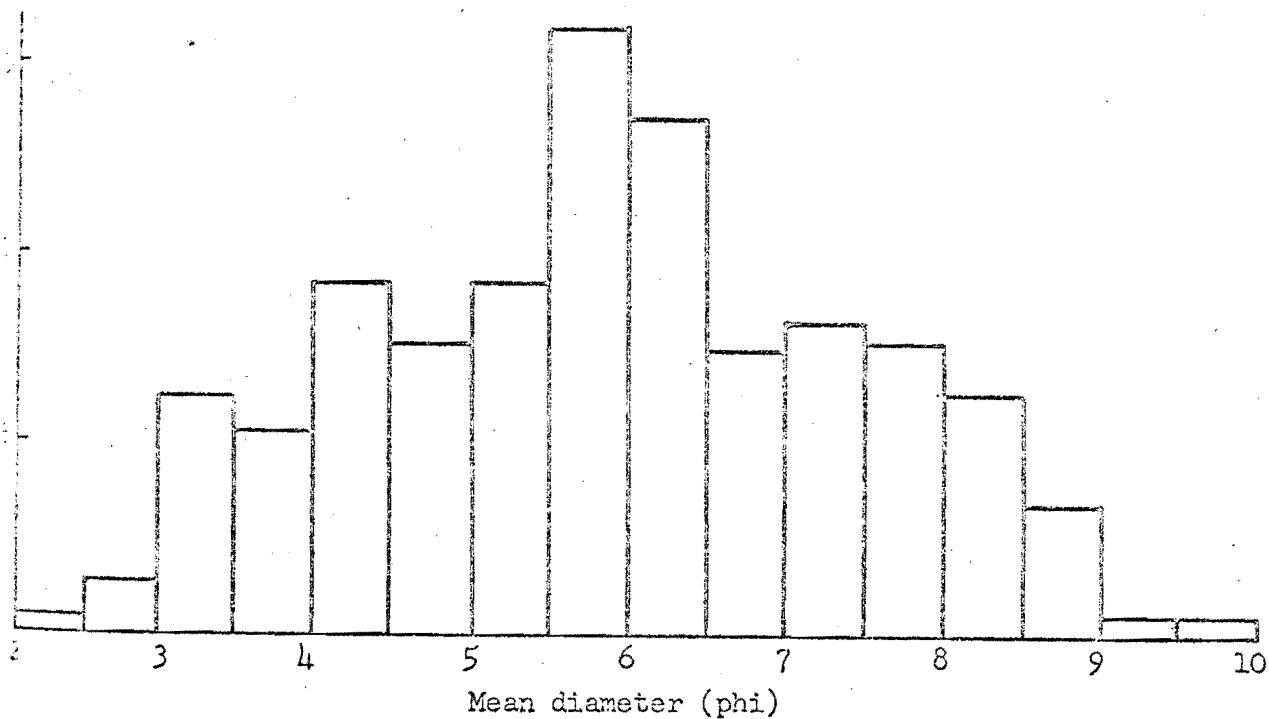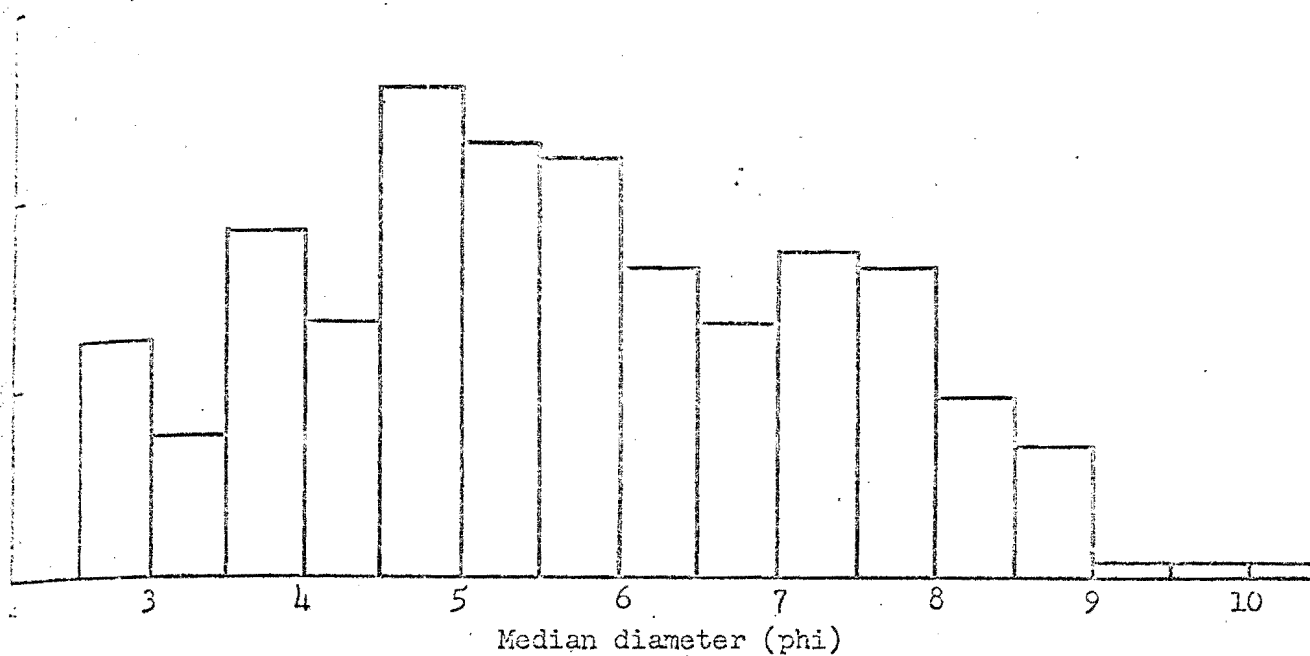
Figure 10.--Distribution median and mean diameters in stratigraphic samples from the Sentinel Butte Formation.
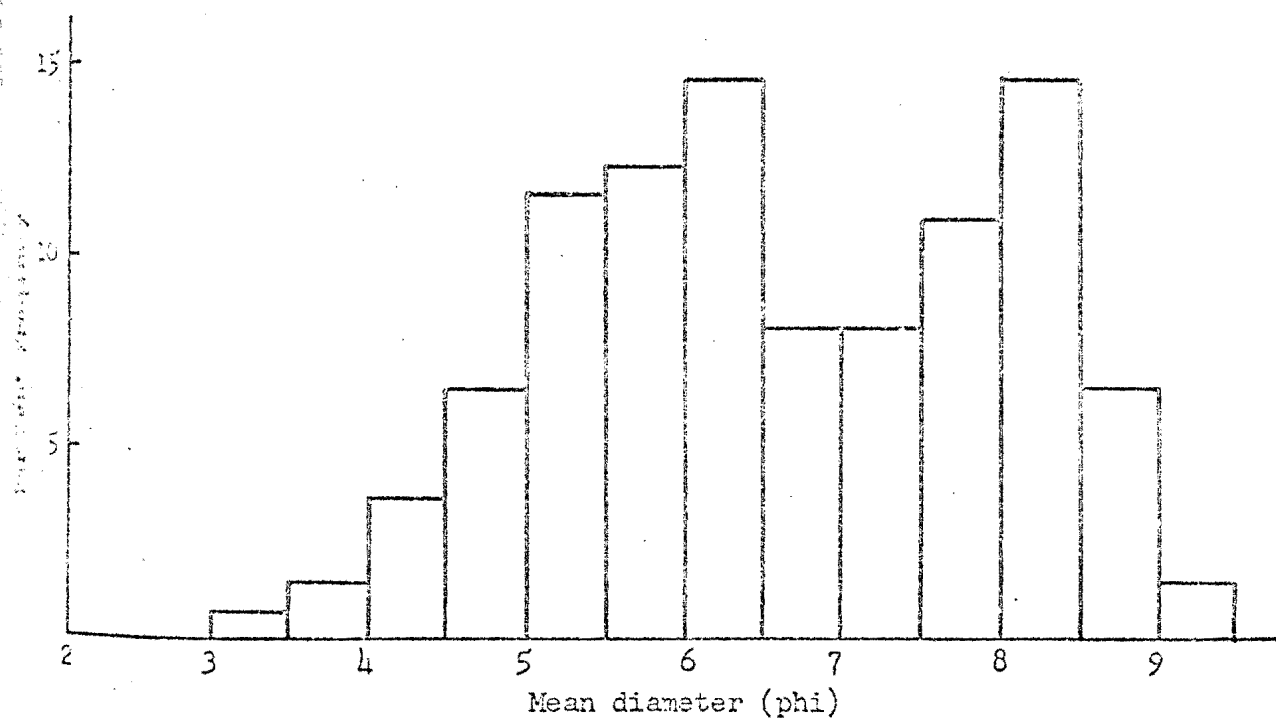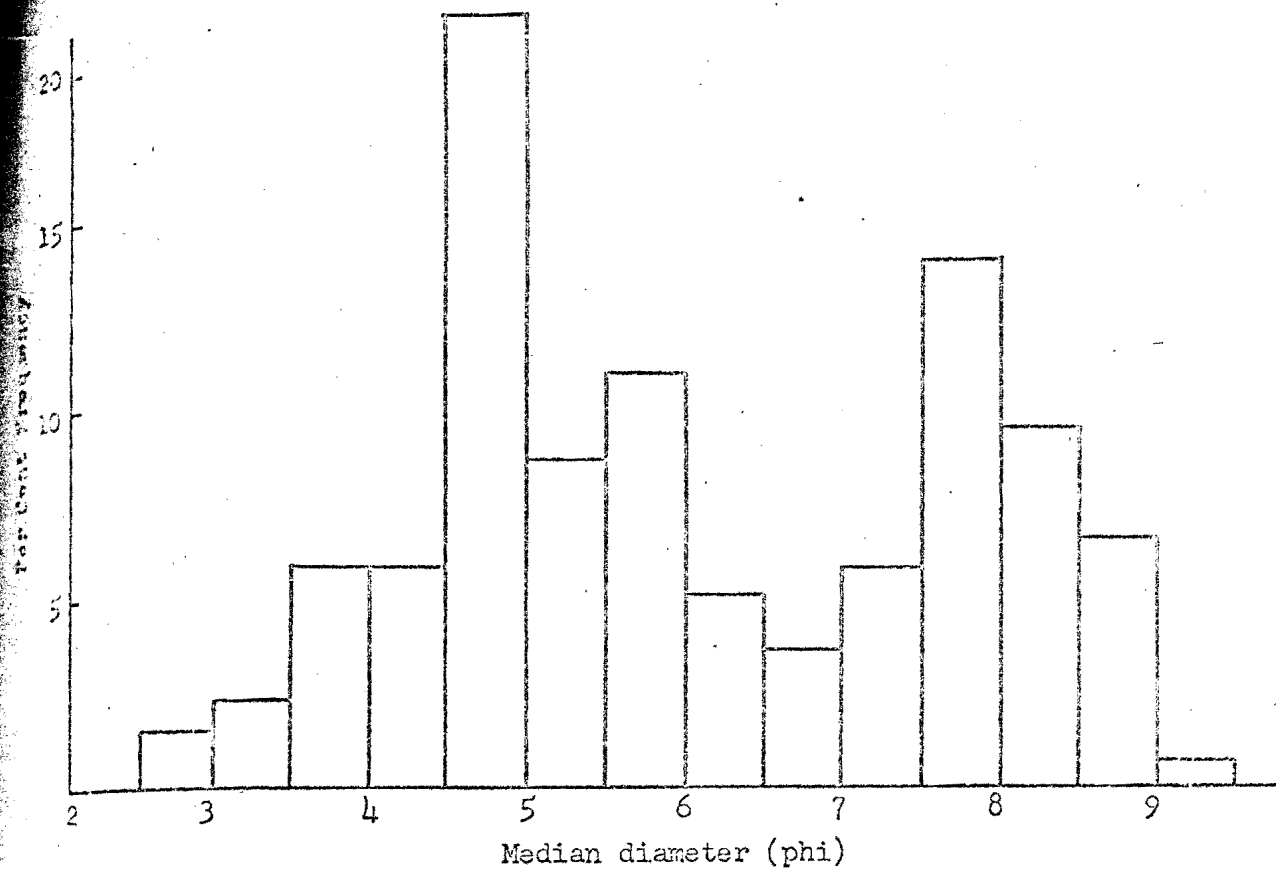
Figure 11.--Distribution of median and mean diameters in stratigraphic samples from the Tongue River Formation.

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tail of coarse values), those of the Sentinel Butte samples are more nearly symmetrically distributed. The average mean and median diameters of grouped data for Tongue River samples are 6.62 and 6.07 phi, those for Sentinel Butte samples are 5.87 and 5.76 phi, respectively. Because Tongue River data are bimodal, average values for this unit have less meaning than for the Sentinel Butte samples.

Sorting.--The distribution of Folk sorting coefficients for Tongue River and Sentinel Butte stratigraphic samples is shown in Figure 12. Sentinel Butte sediments are better sorted and have a more nearly symmetrical distribution of values than do Tongue River sediments. Samples from both formations have about the same range of values and are dominantly poorly sorted (1.0 to 2.0 phi-units). The greatest difference in sorting values of the two units is the greater percentage of very poorly sorted (2.0 to 4.0 phi-units) Tongue River samples, which causes that distribution to be weakly bimodal. Plots of mean diameter vs. sorting (Figures 13 and 14) show only a slight tendency to group; and the combination of these statistics appears to be of little value in differentiation of sediment types.

The distribution of sorting values, according to the textural classification of Folk, for samples from the various stratigraphic sections is given in Table 3. Plots of mean diameter vs. sorting for individual stratigraphic sections are given in Appendix II-A (Figures 52 to 62).

Skewness.--As shown in Figure 15, Folk skewness values of Tongue River and Sentinel Butte samples are nearly all positive and have approximately the same range. The distribution of Tongue River values is markedly bimodal. A slight tendency for higher skewness
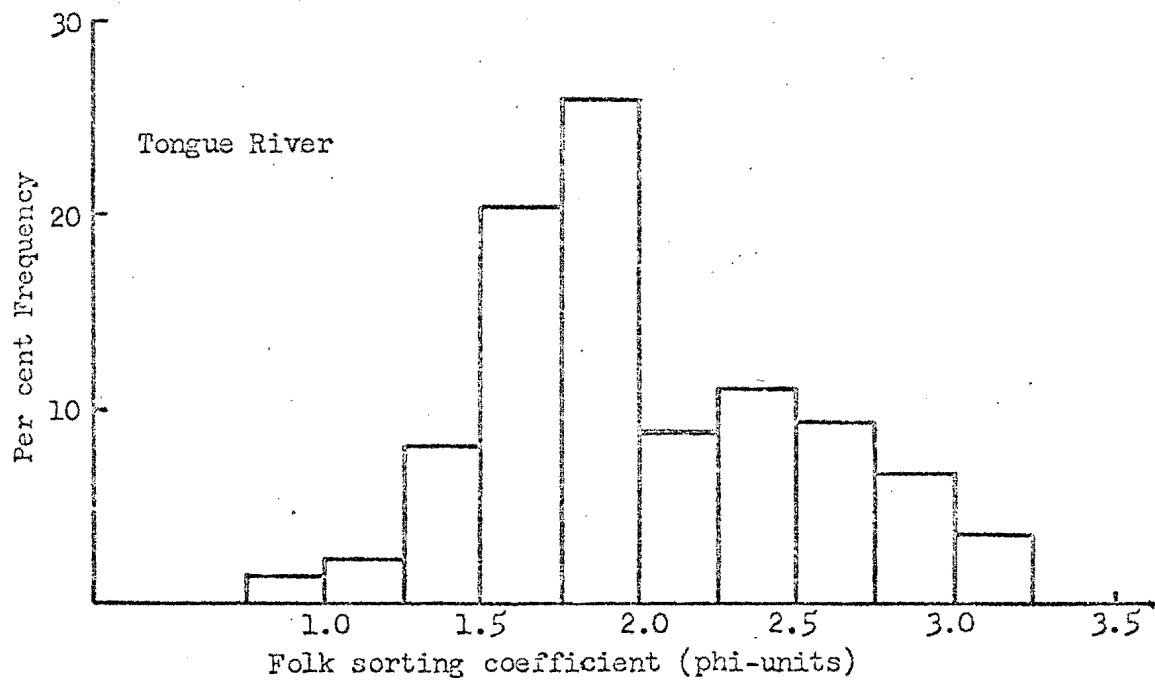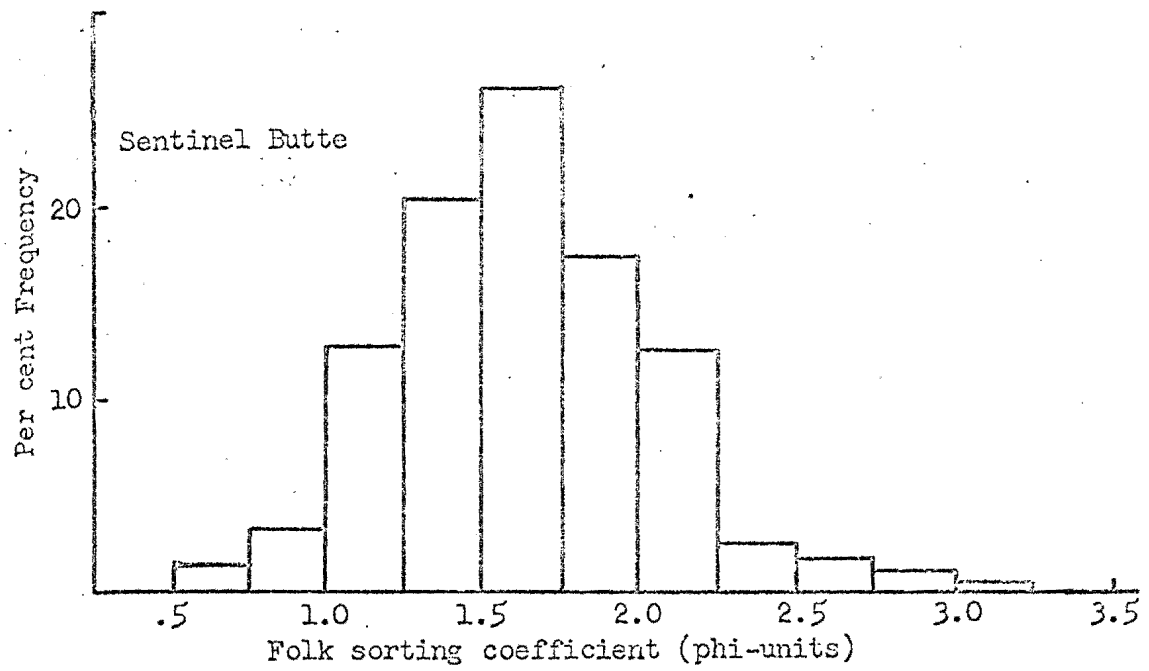
Figure 12.--Distribution of Folk sorting in stratigraphic samples from the Sentinel Butte and Tongue River Formations.
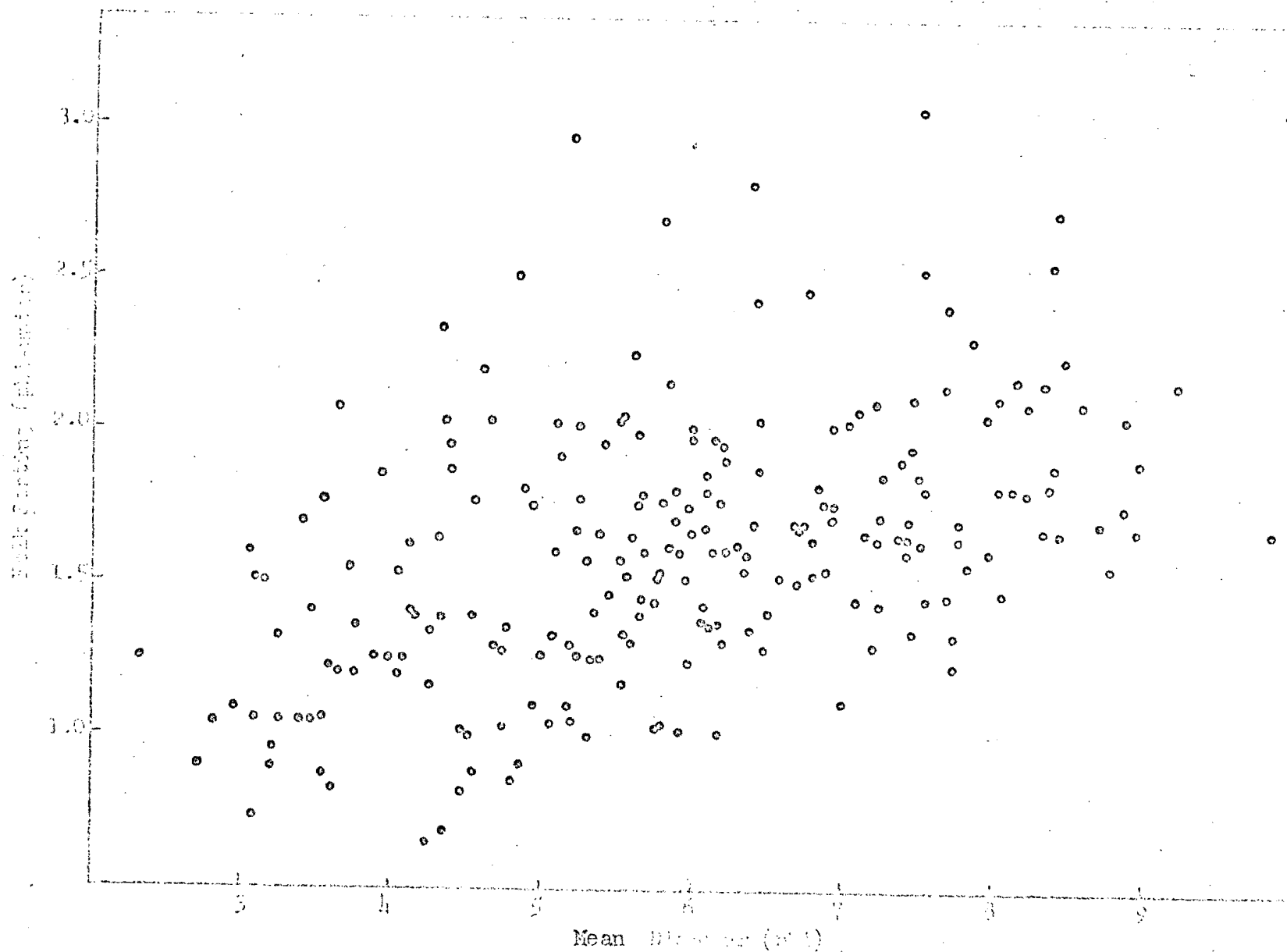
Figure 13.--Composite plot of Folk sorting vs. mean diameter for stratigraphic samples from the Sentinel Butte Formation.
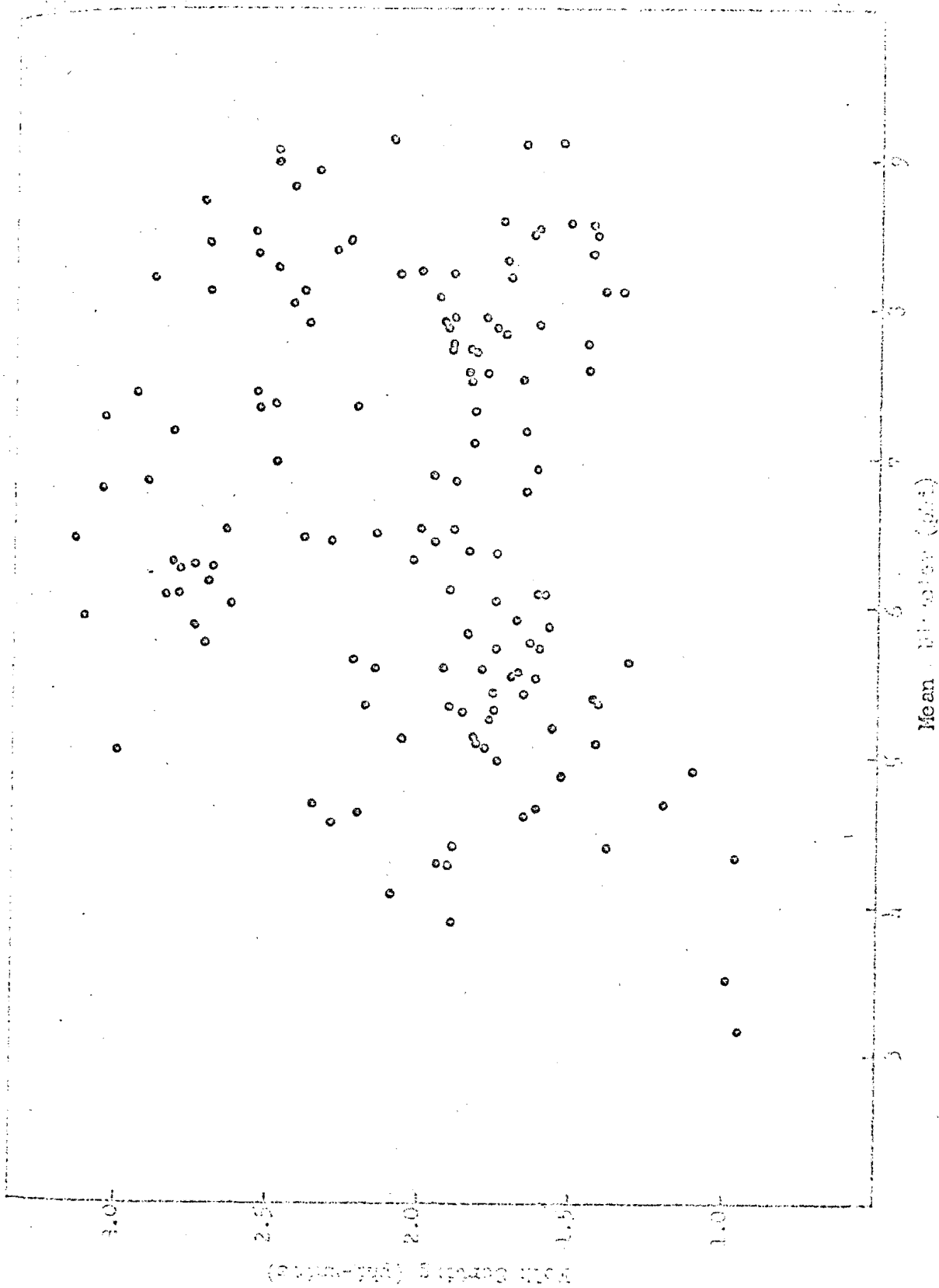
Figure 14.—Composite plot of Folk sorting vs. mean diameter for stratigraphic samples from the Tongue River Formation.
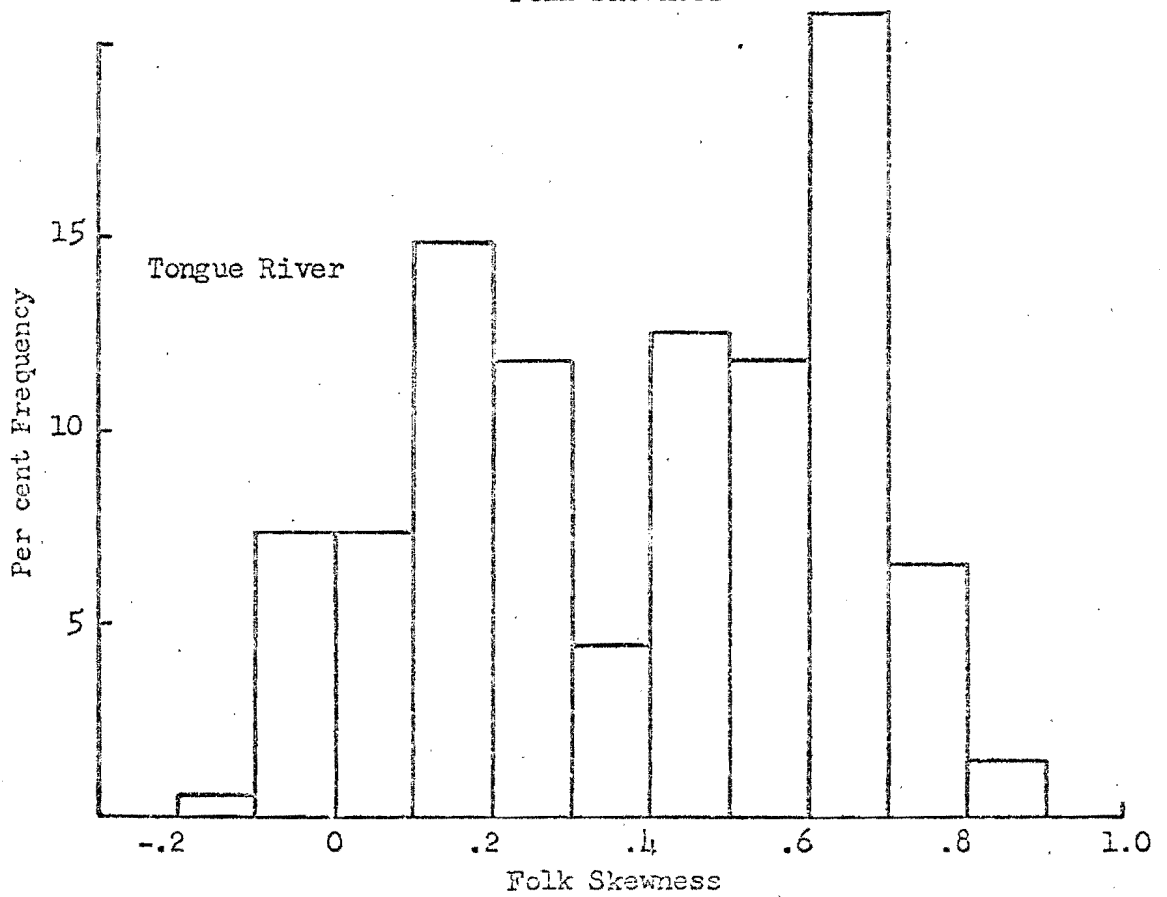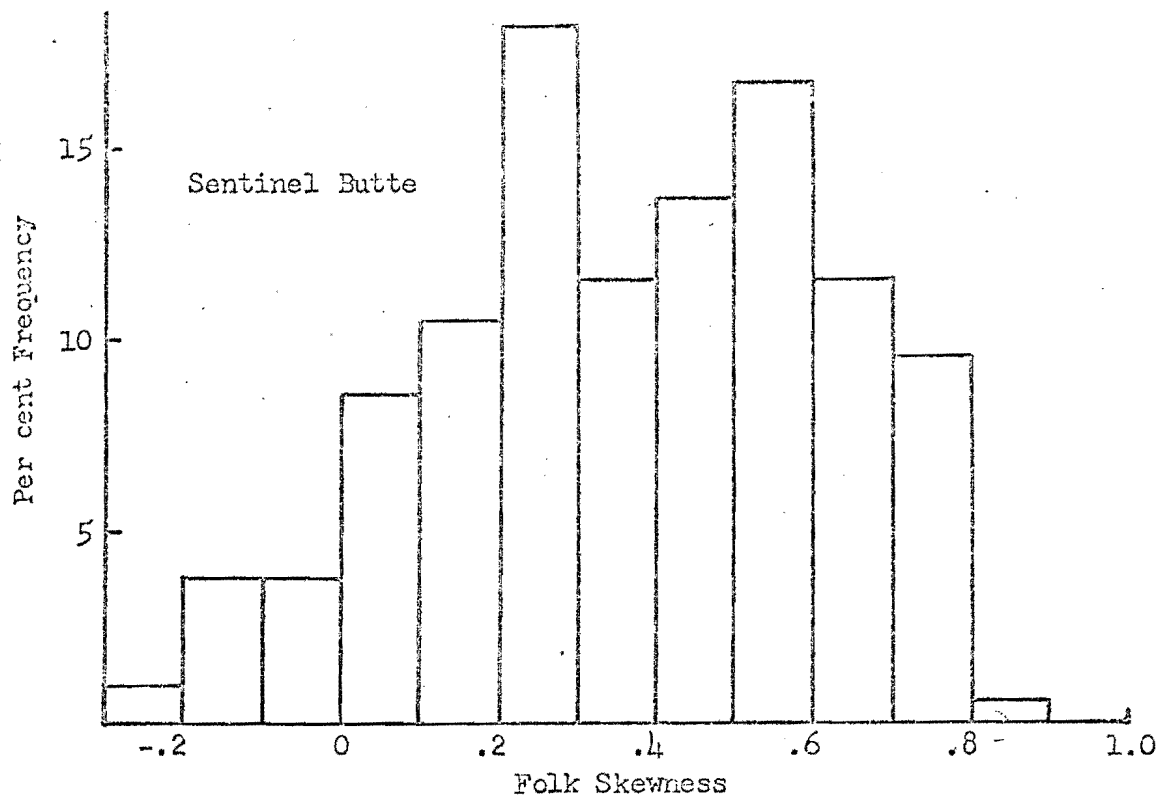
Figure 15.--Distribution of Folk skewness values for stratigraphic samples from the Tongue River and Sentinel Butte Formations.

TABLE 3.--Distribution of Folk sorting types in stratigraphic samples from the Tongue River and Sentinel Butte Formations.

Sections	Moderately Sorted	Moderately Poorly Sorted	Poorly Sorted	Very Poorly Sorted
Sentinel Butte				
Bullion Butte	-	1	33	4
Sentinel Butte	2	9	39	15
Beicegel Creek	-	-	10	4
Long Cross	-	1	48	6
Lost Bridge	-	-	35	5
Per cent	0.9	5.1	77.8	16.0
Tongue River				
Bullion Butte	-	1	28	1
Medora	-	-	3	33
Beicegel Creek	-	2	16	1
Yellowstone	-	-	29	1
Snowden	-	-	2	15
Donnybrook	-	-	5	2
Per cent	0.0	2.1	59.7	38.1

values exists in Tongue River sediments, as is manifested by the relative displacement of the average mean and median values given above (0.55 and 0.11 phi-units for the Tongue River and Sentinel Butte respectively). Over 50 per cent of the samples in both formations

are very-fine skewed, and an additional 25 per cent or more are fine
skewed. The relative percentages of skewness types for samples
from the two units are given in Table 4. Histograms of skewness

TABLE 4.--Distribution of Folk skewness types in stratigraphic samples
from the Tongue River and Sentinel Butte Formations.

Section	Strongly Fine Skewed	Fine Skewed	Nearly Symmetrical	Coarse Skewed
Sentinel Butte				
Bullion Butte	26	7	4	1
Sentinel Butte	25	26	10	4
Beicegel Creek	9	2	3	-
Long Cross	32	15	5	3
Lost Bridge	23	10	5	2
Per cent	54.2	28.3	12.7	4.7
Tongue River				
Bullion Butte	15	12	3	-
Medora	22	6	7	1
Beicegel Creek	11	8	-	-
Yellowstone	18	7	5	-
Snowden	9	3	4	1
Donnybrook	5	1	1	-
Per cent	57.5	26.6	14.3	1.4

distributions and plots of skewness vs. median diameter for strat-
igraphic sections are given in Appendices II-B and II-C.

Kurtosis.--Figure 16 compares the relative distribution kur-
tosis values in Tongue River and Sentinel Butte sediments. Sentinel
Butte samples display a greater range of values, are larger (on an
average), and have a weaker mode than do Tongue River samples. Both
distributions are strongly skewed toward high kurtosis values but
Sentinel Butte values have a higher degree of symmetry. The larger
kurtosis values for Sentinel Butte samples reflect the better sorting
of samples from this unit. The relative percentages of samples in
each of Folk's kurtosis classes is given in Table 5.

Sediment size components

Many systems of classification have been proposed for sedi-
mentary aggregates, none of which satisfactorily meet the needs of
all workers. Binary and ternary systems have been most widely used
and the latter have gained some favor in recent years. Robinson
(1949), Trefethen (1950), Folk (1954), Shepard (1954), Link (1966),
and many Government and commercial organizations have presented
ternary diagrams with end-members of sand, silt, and clay. Little
agreement exists regarding the limits of classes within these tri-
angular diagrams, but the classes of Shepard have gained common
acceptance and are adopted for use in this study. Plots of sand,
silt, and clay (as defined by Wentworth, 1922) relationships are
shown in Figures 17 and 18; data for individual sections are inclu-
ded in Appendix II-D (Figures 77 to 87). A summary of these data,
expressed in Folk's textural terms, is presented as supplementary
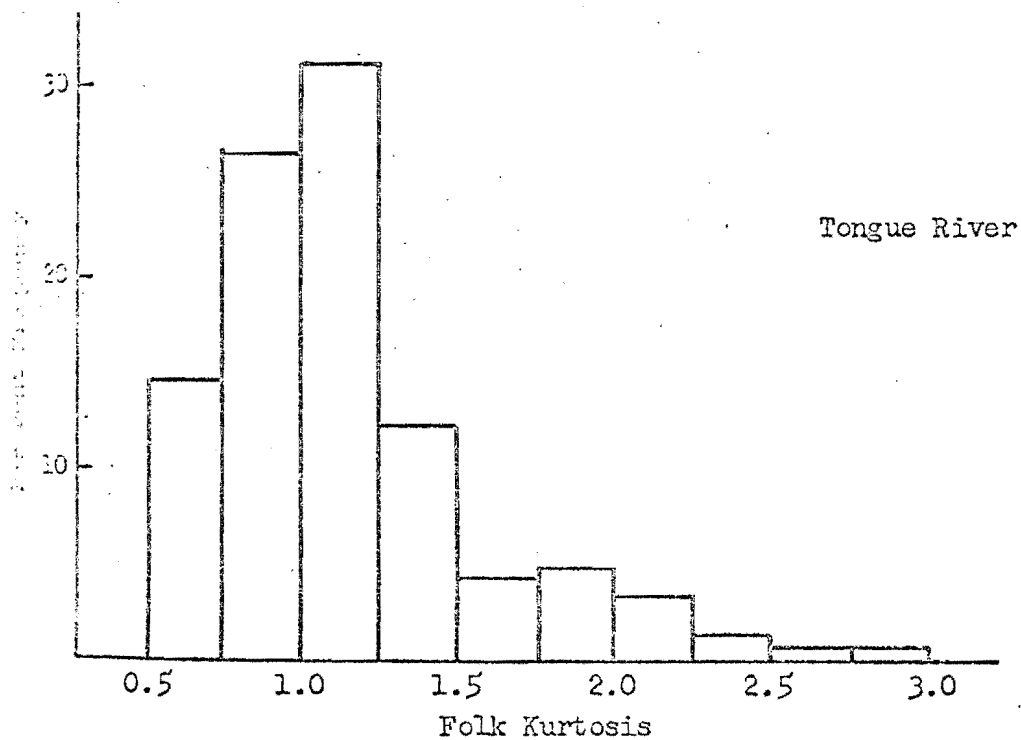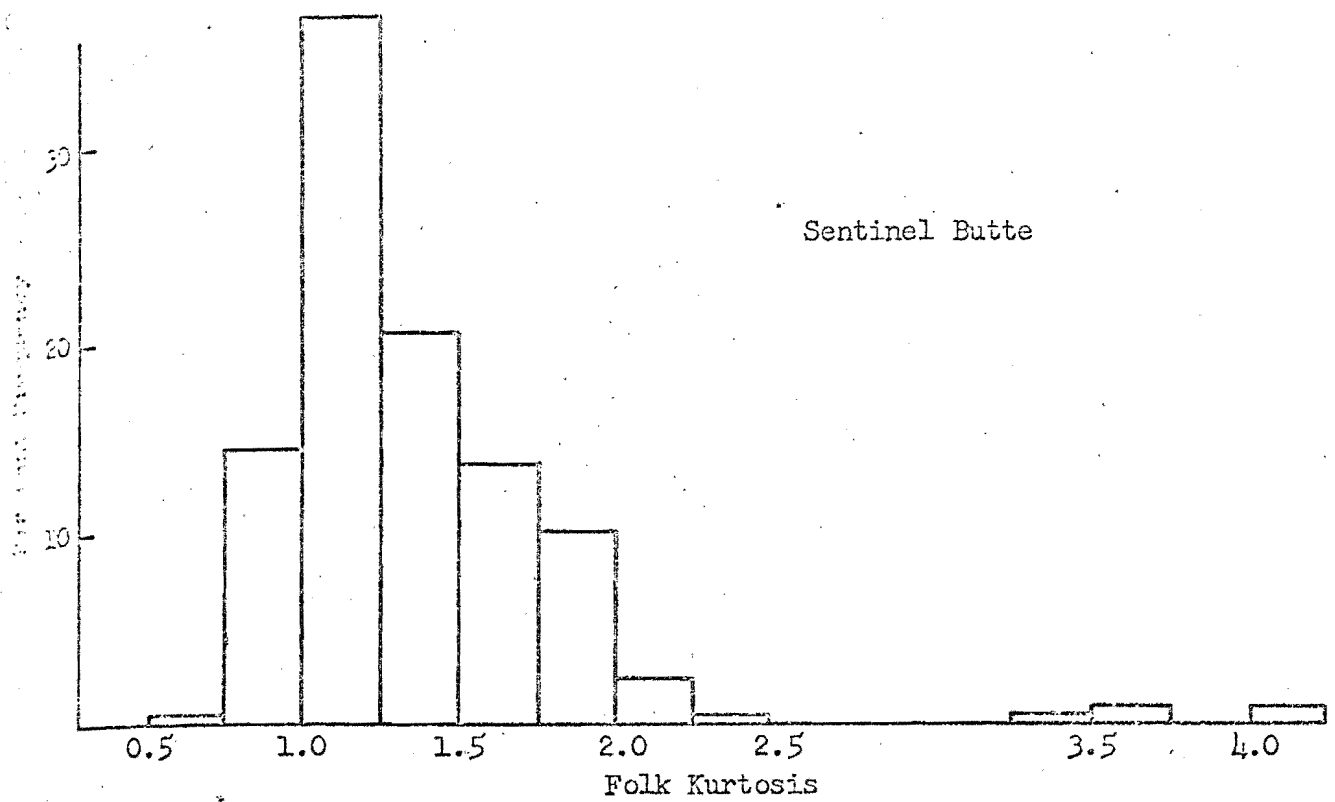
Figure 16.--Summary of kurtosis values in stratigraphic samples from the Tongue River and Sentinel Butte Formations.
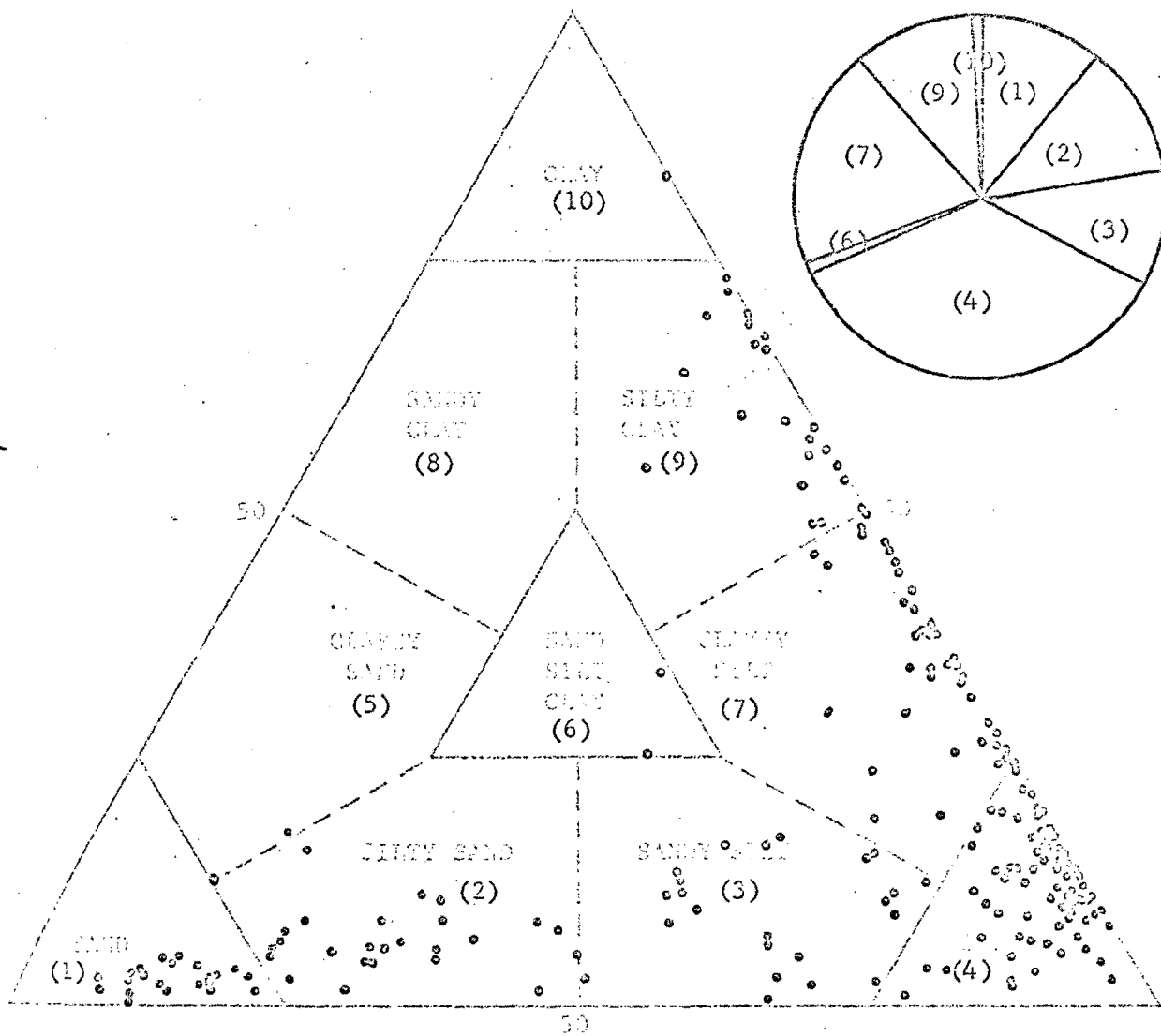
Figure 17.—Sand, silt, clay contents of stratigraphic samples from the Sentinel Butte Formation.
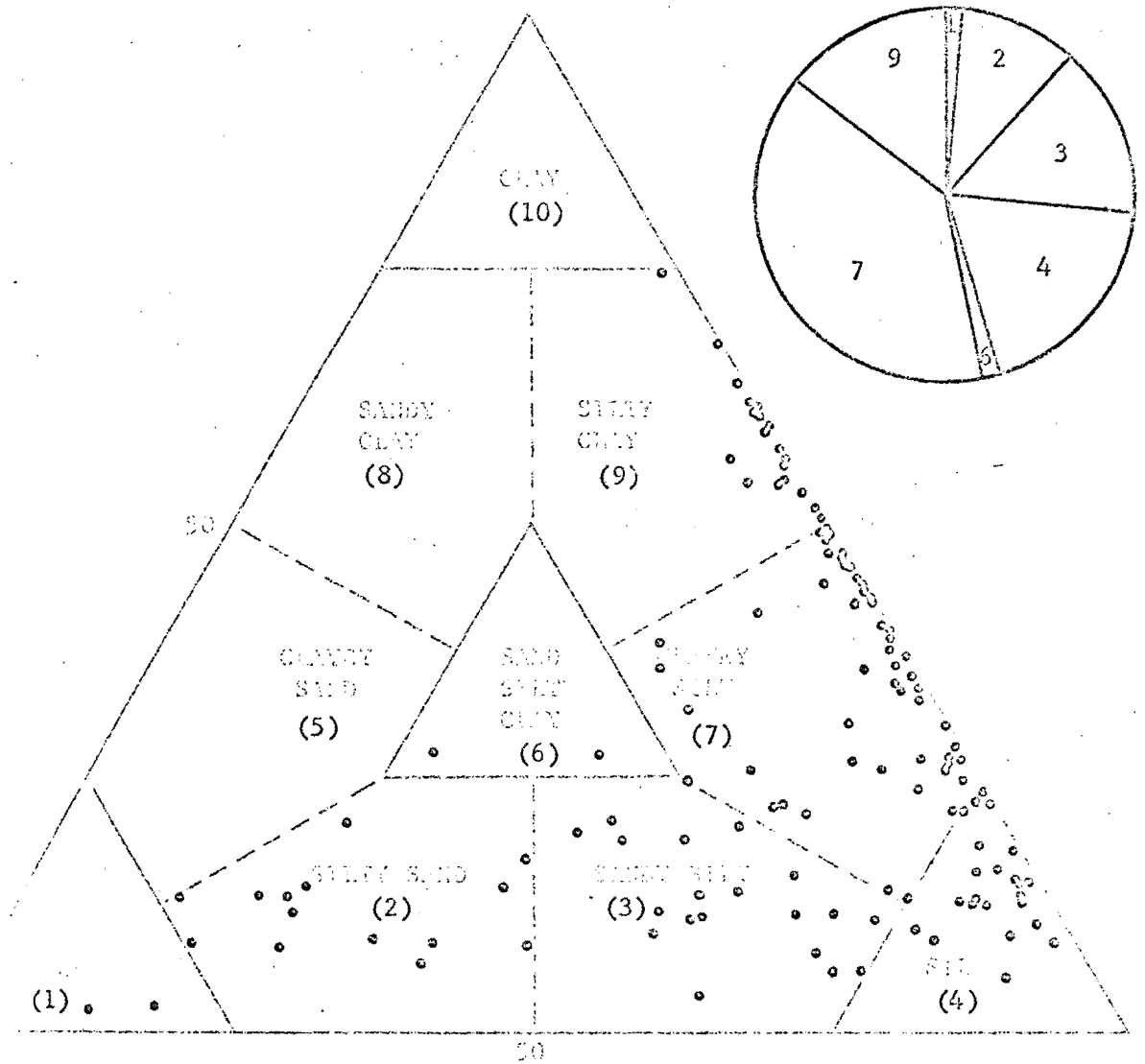
Figure 18.--Sand, silt, clay contents of stratigraphic samples from the Tongue River Formation.

TABLE 5.--Distribution of Folk kurtosis types in stratigraphic samples from the Tongue River and Sentinel Butte Formations.

Section	Extremely Lepto-kurtic	Very Lepto-kurtic	Lepto-kurtic	Meso-kurtic	Platy-kurtic	Very Platy-kurtic
Sentinel Butte						
Bullion Butte	5	13	11	7	2	-
Sentinel Butte	-	13	28	19	5	-
Beicegel Creek	-	2	5	6	1	-
Long Cross	-	13	23	18	1	-
Lost Bridge	-	11	15	10	4	-
Per cent	2.3	24.5	38.6	28.3	6.1	0.0
Tongue River						
Bullion Butte	-	7	10	13	-	-
Medora	-	3	8	6	16	3
Beicegel Creek	-	3	5	7	4	-
Yellowstone	-	7	11	8	4	-
Snowden	-	1	1	2	8	5
Donnybrook	-	-	5	2	-	-
Per cent	0.0	15.1	28.7	27.3	23.0	5.7

data in Table 6.

A comparison of Figures 17 and 18 shows that the range of sediment types is approximately the same for stratigraphic samples from the Tongue River and Sentinel Butte Formations. Both units contain

TABLE 6.—Summary of Folk's (1954) textural types in stratigraphic samples from the Tongue River and Sentinel Butte Formations.

Stratigraphic unit	Sand	Silty Sand	Sandy Silt	Silt	Mud	Sandy Mud	Clay	Muddy Sand
				Sentinel Butte				
Bullion Butte	–	15	5	11	6	–	1	–
Sentinel Butte	–	10	18	18	14	1	4	–
Beicegel Creek	–	3	1	6	3	–	–	1
Long Cross	–	7	4	33	9	1	1	–
Lost Bridge	–	6	6	18	5	2	3	–
Per cent	0.0	19.3	16.0	40.5	17.4	1.8	4.2	0.4
				Tongue River				
Bullion Butte	–	–	11	7	9	–	3	–
Medora	–	1	9	6	14	3	–	3
Beicegel Creek	–	2	3	7	7	–	–	–
Yellowstone	–	2	7	11	10	–	–	–
Snowden	–	1	1	2	10	3	–	–
Donnybrook	–	1	–	4	–	–	1	1
Per cent	0.0	5.0	22.3	26.6	35.9	4.3	2.8	2.8

silty clay, clayey silt, silt, sandy silt, silty sand, and sand; but the distribution of samples within these classes differs. Tongue River sediments have a strong mode in the silty clay and clayey silt classes; Sentinel Butte sediments are dominantly silts and clayey

silts with a strong mode in the sand class. The frequency rela-
tionships within the size classes are quantitatively summarized
in the pie diagrams which accompany the triangular diagrams.

Tongue River sediments display a greater dispersion from the
base of the triangle than do Sentinel Butte sediments; that is,
the coarser Tongue River sediments contain greater percentages of
clay. Conversely, Sentinel Butte samples have a slight tendency
to depart farther from the clay-silt boundary than do Tongue River
sediments. The first of these tendencies manifests the poorer
sorting of coarse Tongue River sediments, and, the second indicates
poorer sorting of fine grained Sentinel Butte sediments. Compared,
the patterns illustrate the poorer sorting of Tongue River sediments
relative to those of the Sentinel Butte.

Sedimentary structures

General statement.--A major objective during field study was
to obtain directional data from large-scale cross-stratified units.
Although the writer does not share Pettijohn's (1957, p. 166-167)
opinion that, "It now seems doubtful whether genetic types of
cross-bedding exist and whether the classification now used have any
genetic significance", he agrees that vectoral properties of these
structures are of greatest paleogeographic importance. Priority
was thus given to accumulating directional data. However, obser-
vations of other types of structures were recorded, and these permit
a qualitative discussion of the relative abundance and types of
primary sedimentary structures, and comments on several minor struc-
tures, in Tongue River and Sentinel Butte strata.

Sedimentary structures are present in nearly all lithologies of Tongue River and Sentinel Butte strata, but the alternate swelling and shrinking of clay components disrupts and masks bedding in many units, causing structures to appear less abundant than they actually are. The recent emphasis of studies concerning the hydrodynamic interpretation of primary sedimentary structures is providing information which may be effectively used to refine the results of the present investigation. Data are presented here in the hope of encouraging additional study of these features.

Classification.--Various systems have been proposed for the classification of cross-stratification (McKee and Wier, 1953; Potter and Pettijohn, 1963; Allen, 1963b). McKee and Wier proposed a classification based primarily on the character of the lower bounding surfaces of cross-strata sets, with secondary considerations involving: (1) the shape of the cross-strata set, (2) the attitude of the axis of the set (if present), (3) the symmetry of cross strata with respect to this axis, (4) the geometry of cross-strata boundaries, (5) inclination of cross strata, and (6) the length of individual cross-strata sets. Working from this classification, Allen (1963b) developed nomenclature for cross-stratified units on the basis of six criteria. As stated by Allen (p. 111) these are:

> (1) Whether the cross-stratified unit is a single set, or a coset formed of two or more similar sets, (2) the physical size of the set of cross-strata, (3) the character of the lower bounding surface of the set of cross-strata, (4) the shape of the lower bounding surface of the set of cross-strata, (5) the relation between the cross-strata in the set and the lower bounding surface of the set, and (6) the degree of lithological uniformity of the cross-strata.

Although Allen's classification is subject to some criticism (for example, Crook, 1965), it is considered the most functional system presently available, and is used in this study.

Sedimentary structures are discussed below under three categories: (1) horizontal stratification, (2) inclined stratification, and (3) other structures. These divisions are for purposes of discussion only, they are not classificatory or mutually exclusive. In regard to bed-thickness nomenclature, the terms of McKee and Wier (1953) are used. The terminology applied to other structures are considered to be in common use, most are listed by Pettijohn (1957, p. 157-196).

Horizontal stratification.--Most of the strata in the Tongue River and Sentinel Butte Formations are flat- (or nearly flat-) bedded. The bounding surfaces of major lithologic units are usually planar and discordance is evident only in small-scale bedding features.

Flat-bedding is present in sediments of all textures. Laminated to thin-bedded sandstones (including silty sands and sandy silts) are less common than cross-bedded varieties, but where observed they appear to have greater lateral persistence than other sandstones. Most large sandstone bodies are massive near the base and become both finer grained and more thinly bedded upward; lamination sometimes occurs in the upper part as shown in Figure 19-A. Flat-bedded sandstones appear to be most abundant in the Tongue River Formation.

Thin-bedded and laminated silt, silty clay, and clayey silt beds are nearly ubiquitous in both formations and constitute the

FIGURE 19

A. Thinly flat-bedded sandstones in the upper third of the Tongue River section at Medora.
Note how bedding develops upward in the unit.
Location: SW¼ sec. 23, T. 140 N., R. 102 W., Billings County, North Dakota.

B. Laminated, very friable siltstone from the upper third of the Sentinel Butte section near the
Long Cross Bridge.
Location: NW¼ sec. 12, T. 147 N., R. 99 W., McKenzie County, North Dakota.

C. Xi-cross-stratification in the lower third of the Tongue River Formation about 15 miles north
of the village of Sentinel Butte.
Location: NW¼ sec. 12, T. 142 N., R. 104 W., Golden Valley County, North Dakota.

D. Omikron-cross-stratification in upper Sentinel Butte sand along highway south of Lost Bridge.
Location: Near center sec. 16, T. 147 N., R. 95 W., Dunn County, North Dakota.
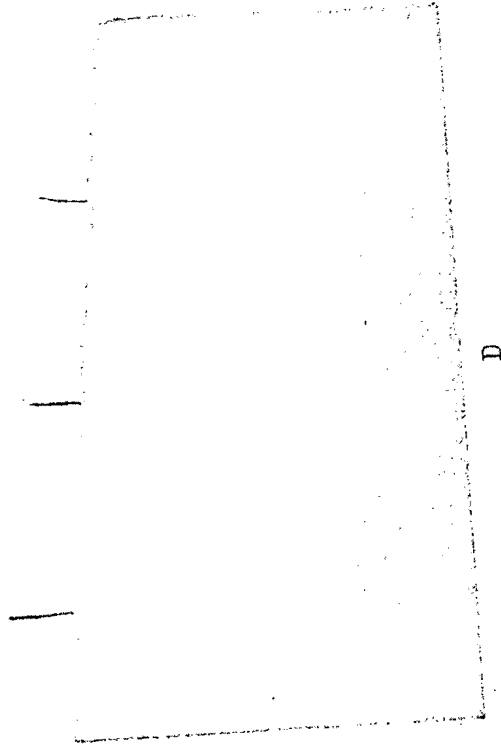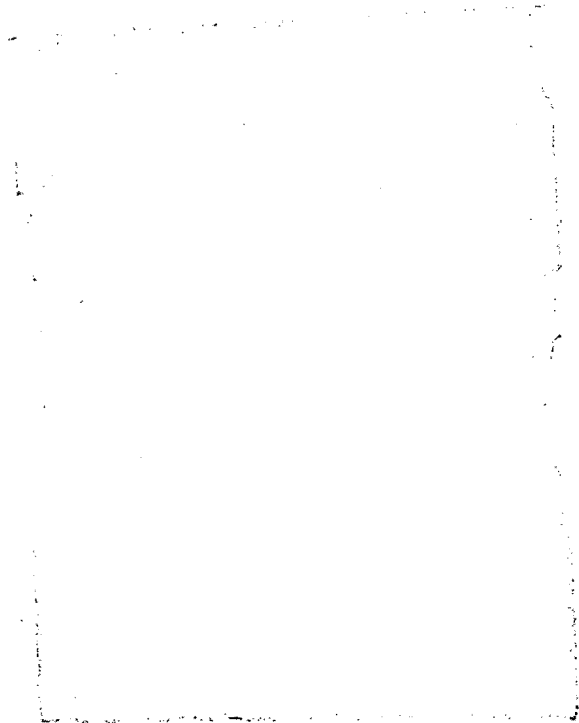
most common bedding type. Laminae vary in thickness but seldom exceed 0.5 centimeters; a very thin-laminated siltstone is illustrated in Figure 19-B.

Inclined stratification.--Measured in terms of volume, cross-stratified units are not abundant but, because they are commonly better consolidated, they are more prominent than other units. Both large- and small-scale cross-beds are present, but the occurrences of the latter are more numerous.

Large-scale cross-beds consist primarily of lithologically homogeneous, wedge-shaped groups (cosets) with erosional, planar lower boundaries which rest discordantly upon underlying sets (Figure 19-C). This type of unit has been termed xi-cross-stratification by Allen (1963b). Occasionally, wedges become elongate and tabular sets of Allen's omikron class (Figures 19-D and 20-A) develop. Pi-cross-stratification (large-scale trough-sets) was not observed.

Small-scale cross-beds are lithologically homogeneous cosets bounded by erosional or gradational surfaces. The lower boundaries of sets are both curved and planar and define the kappa and lambda types of Allen. Kappa-cross-stratification appears to predominate (Figures 20-B and 20-C). Nu-cross-stratification (festoon-bedding) is also found (Figure 20-D), but is less common than either kappa or lambda types. Ripple-marked surfaces of asymmetrical transverse and linguoid (cuspate) ripples (Figure 21-A) were observed, but sediment texture seldom favors preservation of these surfaces.

Large-scale cross-beds are found throughout the Tongue River Formation (Figure 19-C), but within the Sentinel Butte they are largely confined to the basal and upper sands (Figures 3-A, B, C,

FIGURE 20

A. Omikron-cross-stratification near middle of the Sentinel Butte Formation near the west boundary of the North Unit of Roosevelt Park (hammer indicates scale).
Location: SE¼ sec. 8, T. 147 N., R. 100 W., McKenzie County, North Dakota.

B. Kappa-cross-stratification in a large float boulder of concretionary sandstone at the base of Sheep Buttes (pencil indicates scale).
Location: NE¼ sec. 14, T. 148 N., R. 104 W., McKenzie County, North Dakota.

C. Kappa-cross-stratification in lithified silty sand in the upper third of the Tongue River Formation in the South Unit of Roosevelt Park. Note that cross-bedding passes upward into horizontal bedding.
Location: NE¼ sec. 23, T. 140 N., R. 102 W., Billings County, North Dakota.

D. Tangential section of nu-cross-stratification in lithified silty sand of the upper Tongue River Formation in the Beaver Creek drainage (pencil indicates scale).
Location: NE¼ sec. 20, T. 143 N., R. 105 W., Golden Valley County, North Dakota.

A

B

C

D
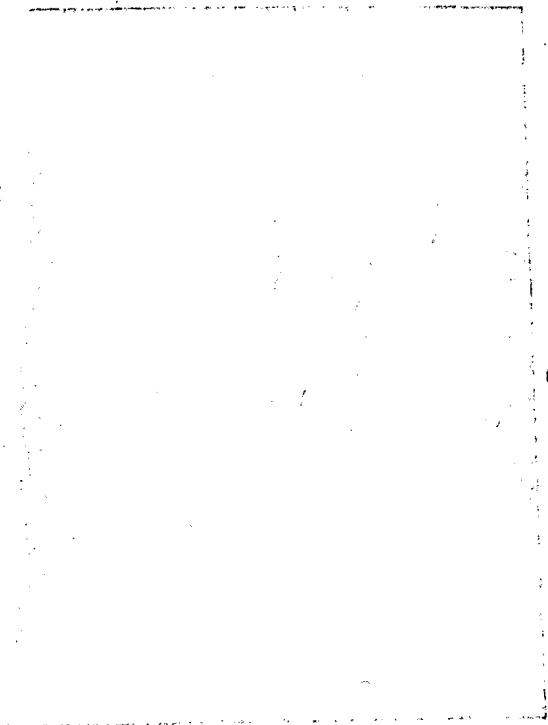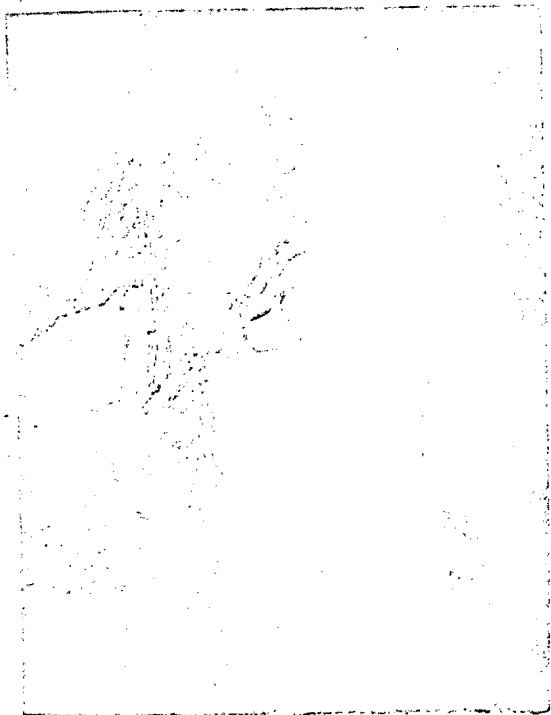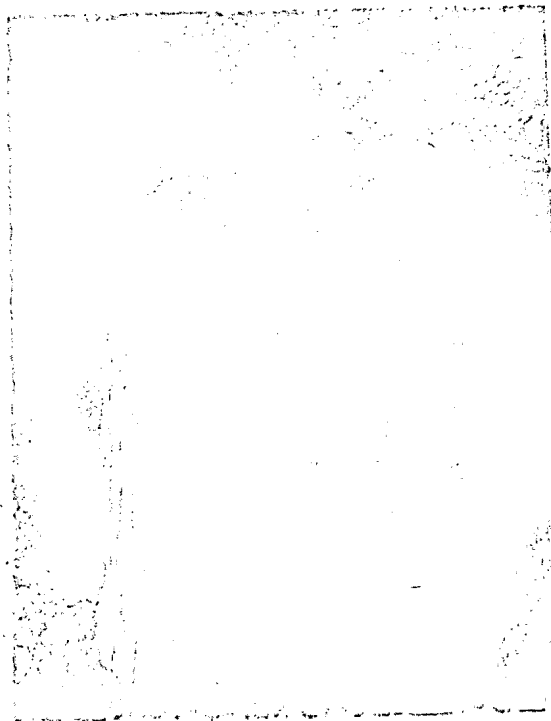
FIGURE 21

A. Asymmetrical transverse ripple marks in lithified silty sand in the upper third of the Tongue
    River Formation along Beicegel Creek road.
    Location: NE¼ sec. 33, T. 146 N., R. 101 W., McKenzie County, North Dakota.

B. Small channel-fill deposit in upper third of Sentinel Butte Formation along highway 85 about
    3 miles south of Little Missouri River. Note truncation on left (north) indicates lateral
    migration in that direction, flow was eastward.
    Location: S½ sec. 13, T. 147 N., R. 99 W., McKenzie County, North Dakota.

C. Desiccation-crack filling in fine-grained concretionary bedding-plane material of the basal sand
    of the Sentinel Butte Formation about 3 miles southwest of Medora.
    Location: SE¼ sec. 10, T. 139 N., R. 103 W., Golden Valley County, North Dakota.

D. Small pitted mounds on fine-grained concretionary bedding surface of the basal Sentinel Butte
    sand, about 3 miles southwest of Medora, presumed to be lithified gas bubbles. Cracks in the
    concretionary material may be primary structures.
    Location: SE¼ sec. 10, T. 139 N., R. 103 W., Golden Valley County, North Dakota.

A   B   C   D
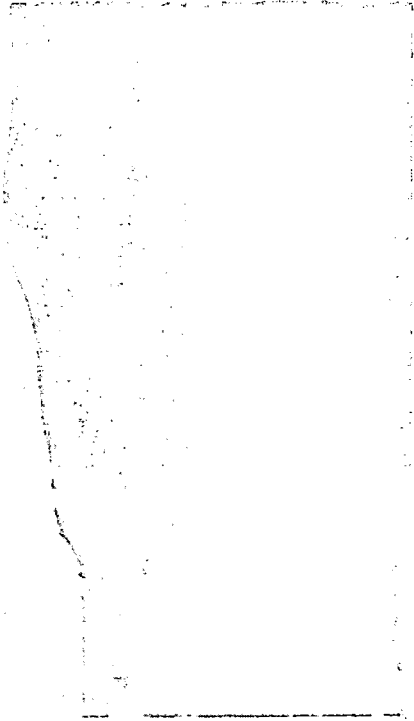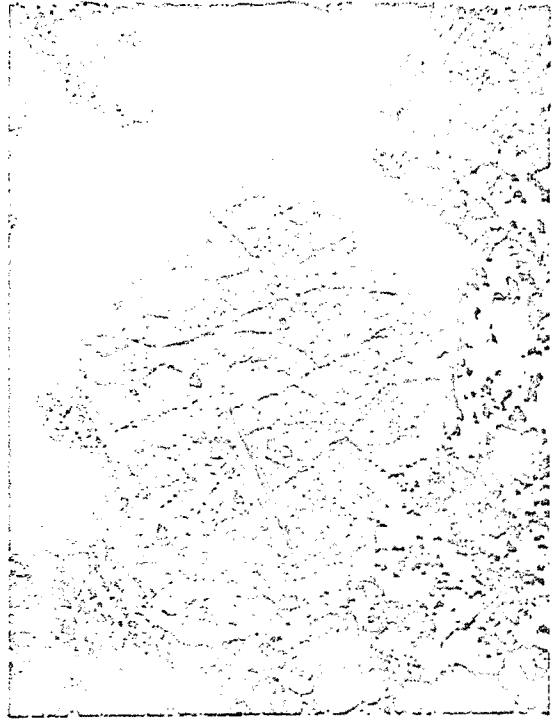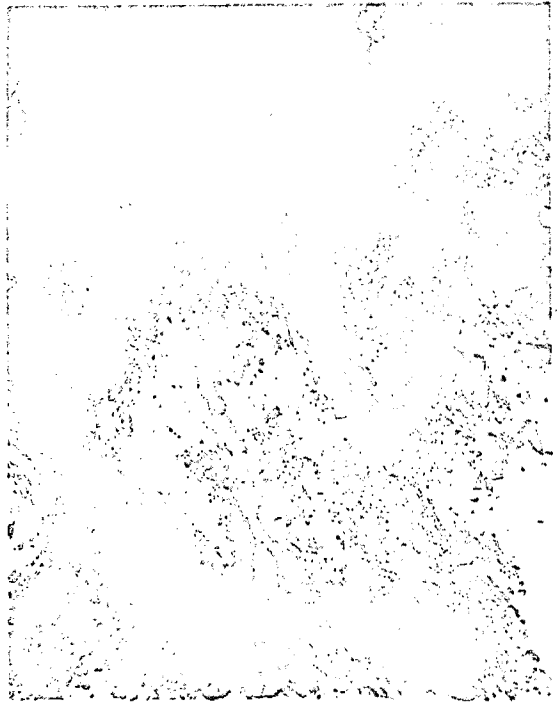
and 19-D). Xi-cross-stratification predominates in Tongue River strata, but there is a definite tendency for lower angle, broader wedges in Sentinel Butte beds, particularly in the upper sand. The relative abundance of large-scale structures is reflected in the number of directional readings recorded from each unit (Table 7).

Inclined strata of large magnitude were noted at a number of localities in the basal Sentinel Butte sand (Figure 4-A). In outcrop, these resemble rotated slump blocks, but their primary origin is substantiated by horizontal beds above and below the dipping strata. Individual beds are commonly several feet thick and separated by concretionary bedding "planes" which bear evidence of subaerial exposure. The sequence appears to be a rhythmic accumulation which resulted from periodic influxes of sediment.

Occasionally, channel-lag or channel-fill deposits can be identified within the Tongue River-Sentinel Butte sequence. Rarely, channel structures truncate underlying strata, but such evidence of erosion (however local) is relatively uncommon. Figure 21-B shows a small channel in the Sentinel Butte Formation which eroded underlying strata prior to being filled. Trough-sets are partly discordant and partly concordant with adjacent beds. A similar situation can be seen in strata of the Tongue River Formation in the road cut just south of the summit of Johnson Plateau in the South Unit of Roosevelt Park. Major channeling, such as that shown by Hares (1928, pl. 5-B), appears to have been restricted to the basal portion of the Tongue River Formation.

Miscellaneous structures.--Convolute bedding is a relatively rare phenomenon in Tongue River and Sentinel Butte strata, but was

observed in some fine-grained sediments and in freshwater limestones. Where studied, convolute beds occupy a narrow interval of a foot or so, maintain a uniform thickness, and are laterally continuous in outcrop. Beds above and below show little evidence of deformation. The origin of convolute bedding is not understood, but the occurrence cited here demonstrates that it is not restricted to turbidite sequences as believed by Sanders (1960, p. 419). Deformation due to loading and compaction is doubtful because of the lack of irregular boundaries (load casts) with adjacent units. The absence of faulting and rupture of the convolutions makes movement by sliding improbable. The most probable explanation of their origin appears to be that they result from slight differential movement of hydroplastic sediment during its accumulation.

A number of bedding-plane structures have been observed which suggest periods of subaerial exposure and desiccation. Foremost of these are mud-cracks, which were observed in concretionary bedding zones at several localities in the Sentinel Butte Formation. They are manifested by differentially cemented, fine-grained filling which weathers in relief forming polygonal ridges on exposed surfaces (Figure 21-C). At one locality in the basal Sentinel Butte sand, mud cracks were accompanied by small, conical structures with a pitted apex which resemble bubbles (Figure 21-D). It is inferred that these may be lithified gas bubbles formed by decomposition of organic-rich debris which accumulated between episodes of sand deposition. The former presence of this debris is documented by molds of leaves, seeds, and other vegetative material. The concretionary character of the bedding zones themselves suggest quiescent interludes during

which deposition of lithogenous sediment was slow and organic material formed a significant sediment component. The fixation of iron, which has altered the bedding surfaces to thin concretionary zones (Figures 3 and 4), probably resulted from redox reaction involving anoxic decomposition of organic matter. Iron reduced during this reaction was fixed as sulfides (or similar compounds) which were subsequently oxidized during weathering.

This mechanism probably accounts also for the origin of marcasite nodules which are so common in Tongue River strata (Figure 22-A). Large nodules of this type are commonly formed around plant debris as indicated by molds passing through the axis of the structures. Small, spherical nodules seldom contain visible organic structures, but the writer found a marcasite replica of a small snail in one such nodule. The occurrence of organic nuclei in many types of concretions and nodules is well documented, and it is suggested here that marcasite concretions in Tongue River strata formed largely in response to decomposition of organic material. The organic structures themselves are, most frequently, destroyed by the processes of replacement and crystallization.

Large, cannonball-like, calcareous concretions also occur and were noted principally in the Sentinel Butte Formation. Most of these structures are true septaria which, when the veins are filled and the sediment matrix removed, form boxwork structures (melikaria) similar to that shown in Figure 22-B. The origin of these structures is not known with certainty but, in the present instance, the volume reduction could be associated with dolomitization.

Log-like concretions (Figure 22-C) are found in both Tongue

FIGURE 22

A. Small spherical nodules of weathered iron sulfide in sandstone of the lower third of the Tongue River Formation about 6 miles northwest of Amidon. Note the vague stratification which becomes more prominent upward.
Location: SE¼ sec. 24, T. 136 N., R. 102 W., Slope County, North Dakota.

B. Boxwork structure (melikaria) in the basal sand of the section at Sentinel Butte, the vein fillings are calcium carbonate
Location: SE¼ sec. 5, T. 139 N., R. 104 W., Golden Valley County, North Dakota.

C. Log-like concretions in lower Tongue River strata along the West River Road about 5 miles north of Bullion Butte.
Location: NE¼ sec. 13, T. 138 N., R. 103 W., Golden Valley County, North Dakota.

D. Molds of worm trails on the base of argillaceous limestone slab from the upper half of the section at Sentinel Butte; note particularly the lower left corner of the slab.
Location: SE¼ sec. 5, T. 139 N., R. 104 W., Golden Valley County, North Dakota.

A

B

C

D
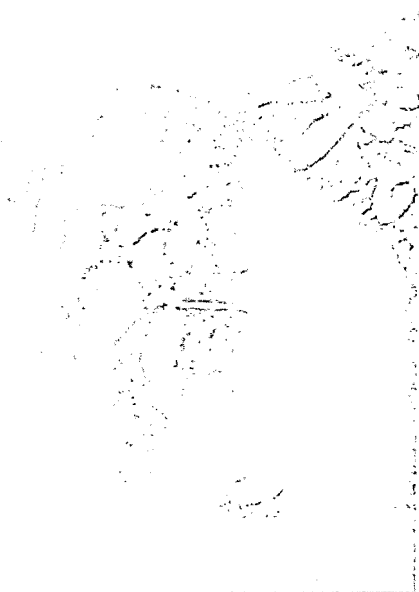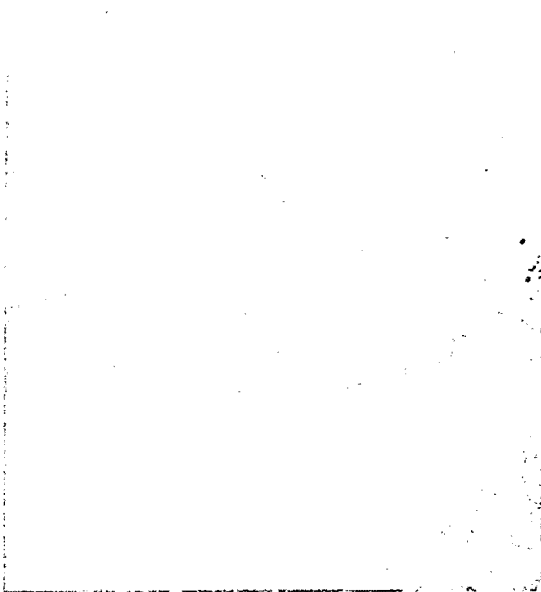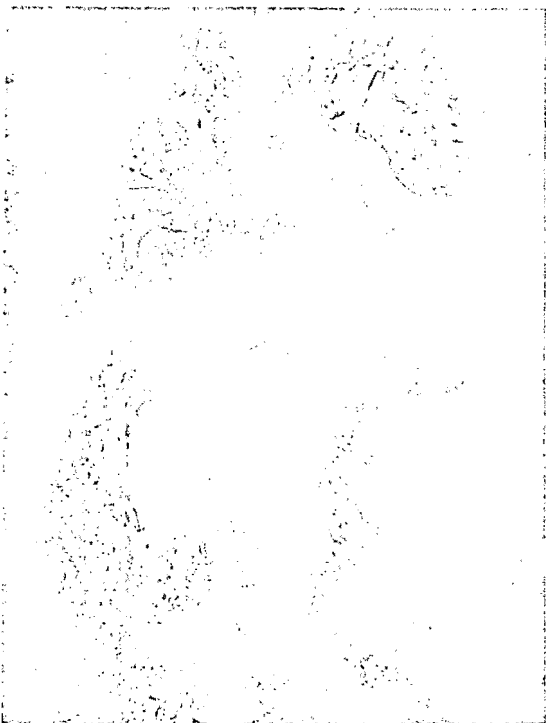
River and Sentinel Butte strata, but were noted most frequently
in the Tongue River Formation and in the basal Sentinel Butte sand.
Their formation is not understood, but it is probably controlled
largely by secondary factors and only in part by primary properties
of the sediments themselves.

A single occurrence of worm trails was observed (Figure 22-D)
on the base of a freshwater limestone slab from the Sentinel Butte
section. To the writer's knowledge, such structures have not pre-
viously been reported from the Sentinel Butte Formation and, although
the biologic affinities of the organisms which formed them are not
known, their presence is worthy of mention.

Paleocurrents

Field procedures.--Directional data were collected from large-
scale cross-beds wherever such structures were observed for compari-
son of the sediment dispersion patterns in Tongue River and Sentinel
Butte strata. The strike, dip, maximum bed-thickness, stratigraphic
position and location of structures were systematically recorded at
outcrops. One measurement of maximum dip and thickness was recorded
per bed, in vertical succession, for 15 to 20 beds at each locality.
Less measurements were made where cross-beds were few; no outcrop
was by-passed because it displayed a small number of cross-beds. The
attitude of all major bedding planes is nearly horizontal, and no
correction (Potter and Pettijohn, 1963, p. 259) was applied for bed
tilt.

Analysis.--No distinctive or persistent cross-bedded horizons
were recognized in the Tongue River Formation, and reported measurements

represent the total exposed thickness of the unit. Data for the Sentinel Butte Formation, however, can be segregated into three stratigraphic categories: a basal sand, an upper sand, and the intervening Sentinel Butte strata. It should be emphasized that the criteria for differentiation of "basal" and "upper" Sentinel Butte horizons is stratigraphic and sedimentologic, not directional.

Measurements from each locality were plotted on a circular diagram divided into 30-degree classes (Table 7). All readings within a single class were assigned the value of the mid-point azimuth. Vector means of the grouped data were calculated according to the formulas (Potter and Pettijohn, 1963, p. 256):

$$V = \sum_{i=1}^{n} n_i \cos x_i$$

$$W = \sum_{i=1}^{n} n_i \sin x_i$$

$$\bar{x} = \arctan W/V$$

where x_i is the mid-point azimuth of the ith class interval, $\bar{x}$ is the azimuth of the resultant vector, n_i the number of observations in each class, and n the total number of observations. Vector means for individual outcrops are shown, with rose diagrams and grand means, in Figures 23 to 26.

The grand means, variance, and standard deviations calculated for all observations from the Tongue River, basal and upper sands, and
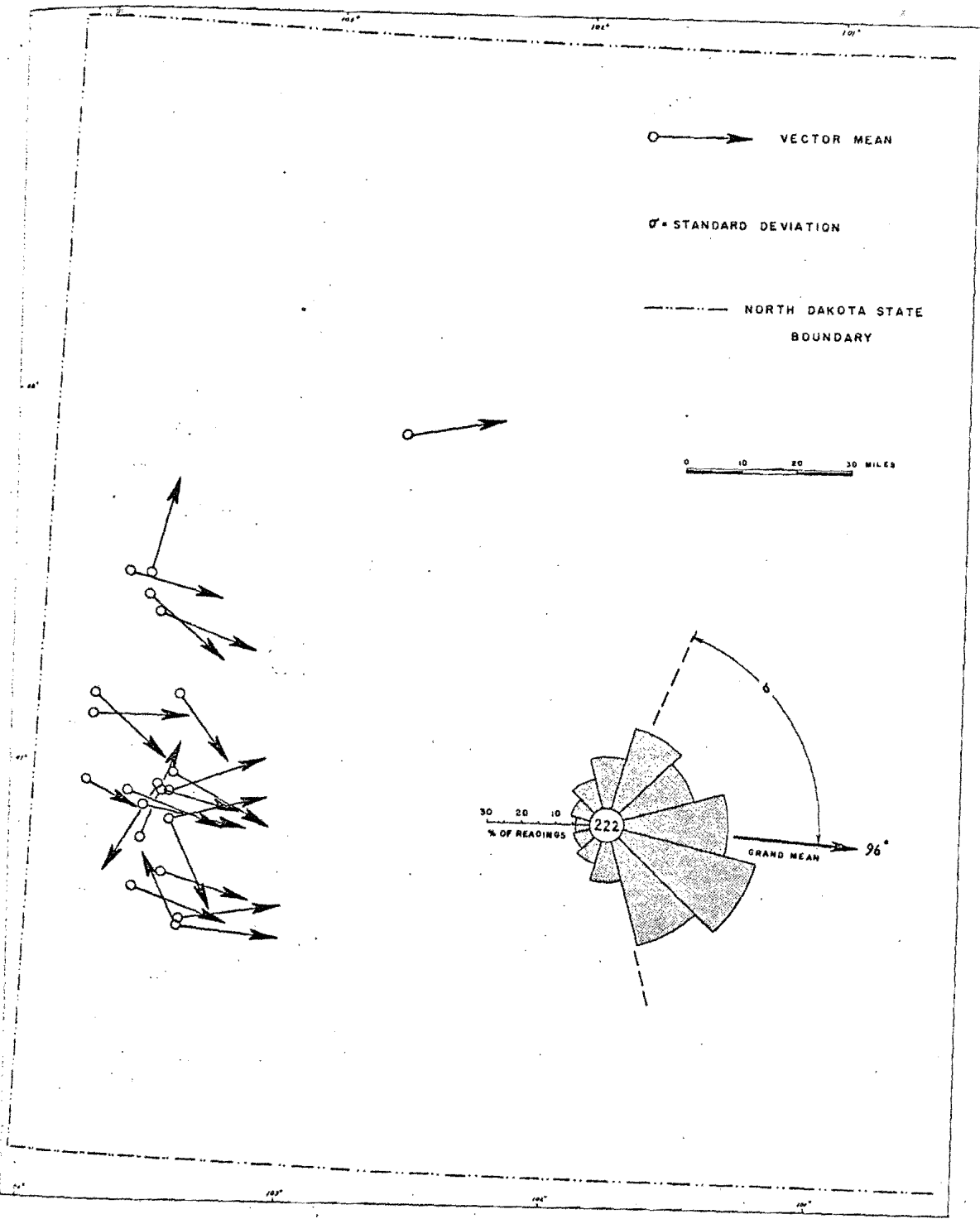
Figure 23.—Vector means for cross-bed measurements from outcrops in the Tongue River Formation. Readings are summarized in the rose diagram.
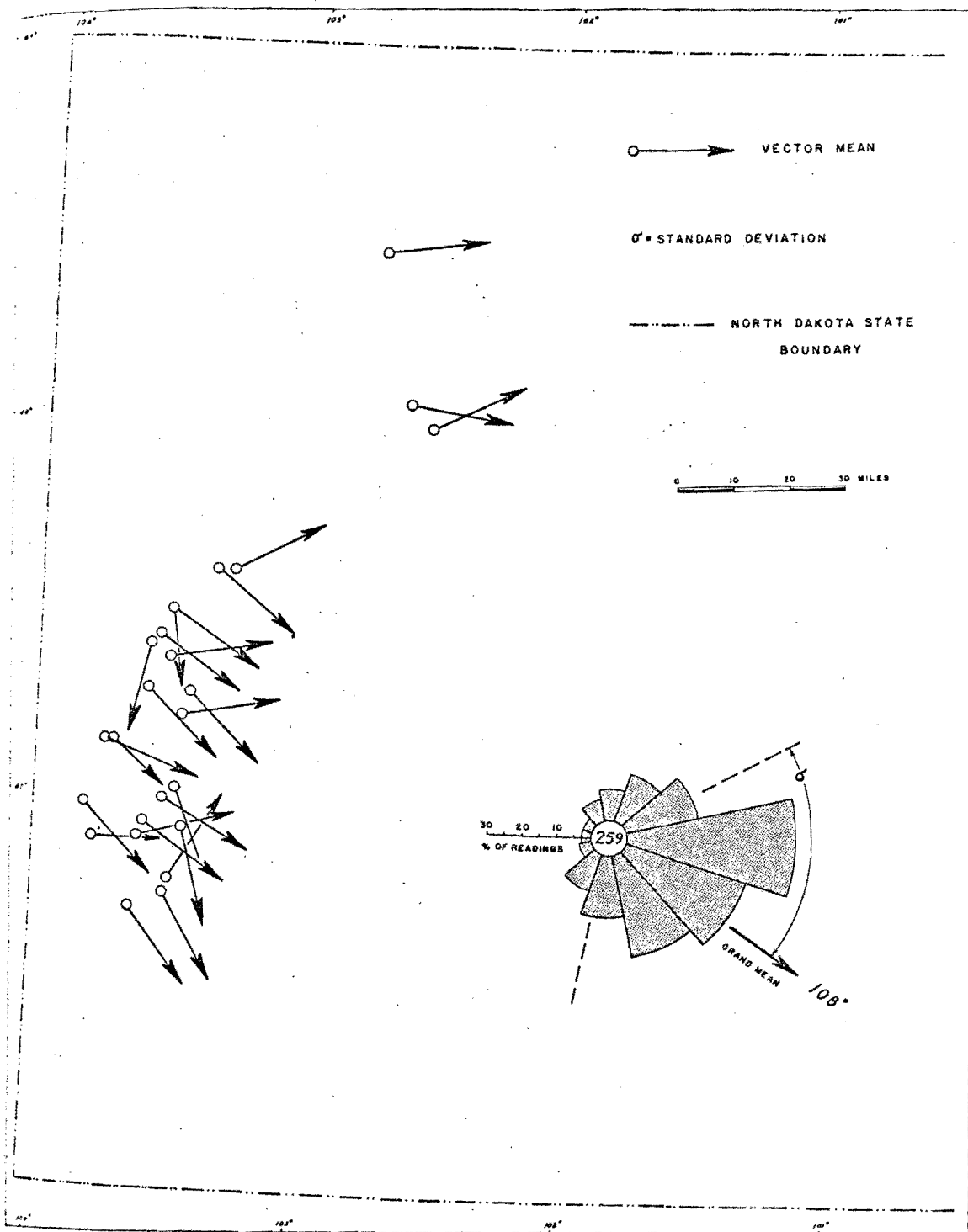
Figure 24.--Vector means for cross-bed measurements from outcrops of the basal Sentinel Butte sand. Readings are summarized in the rose diagram.
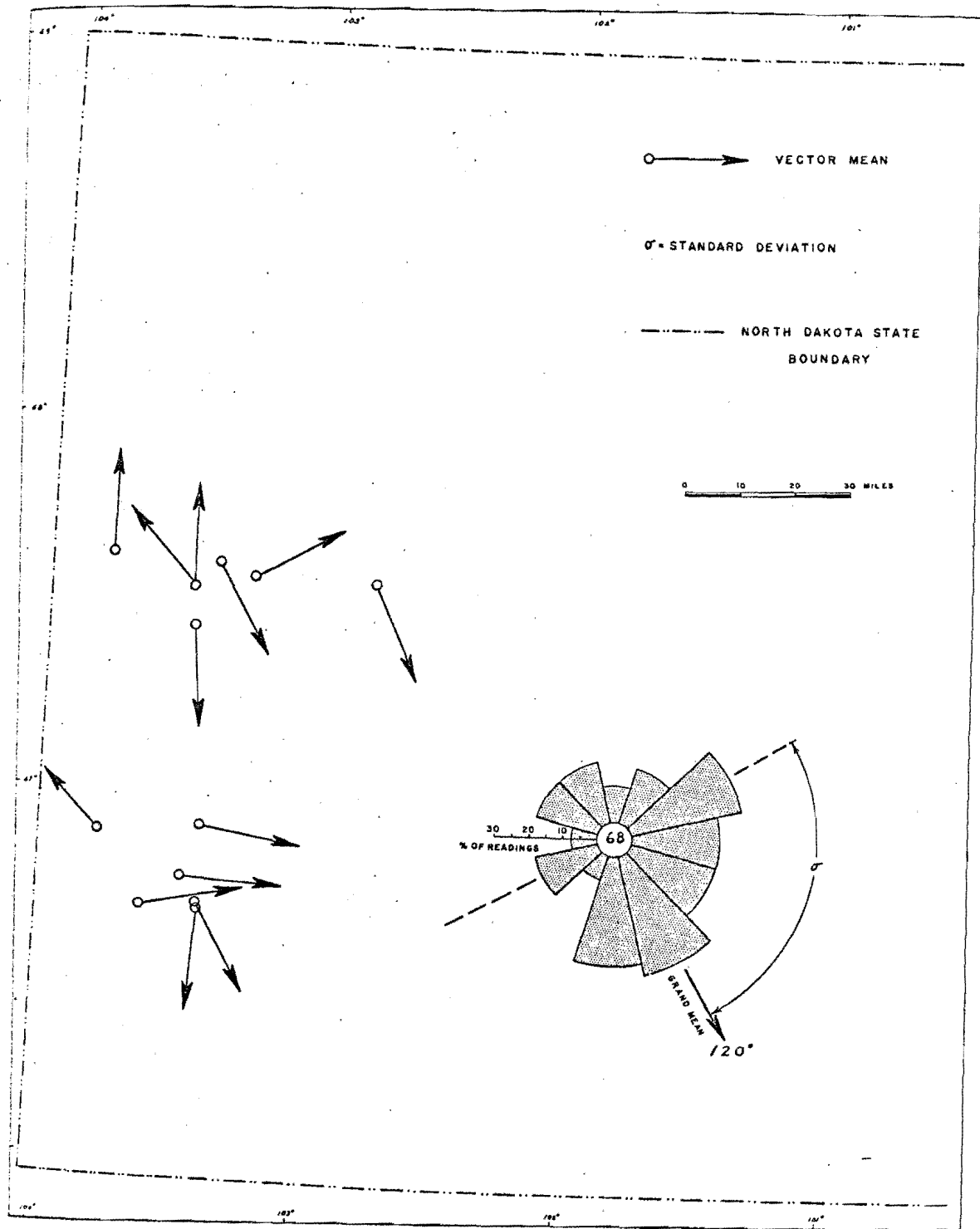
Figure 25.—Vector means for cross-bed measurements from outcrops between the basal and upper Sentinel Butte sands. Readings are summarized in the rose diagram.
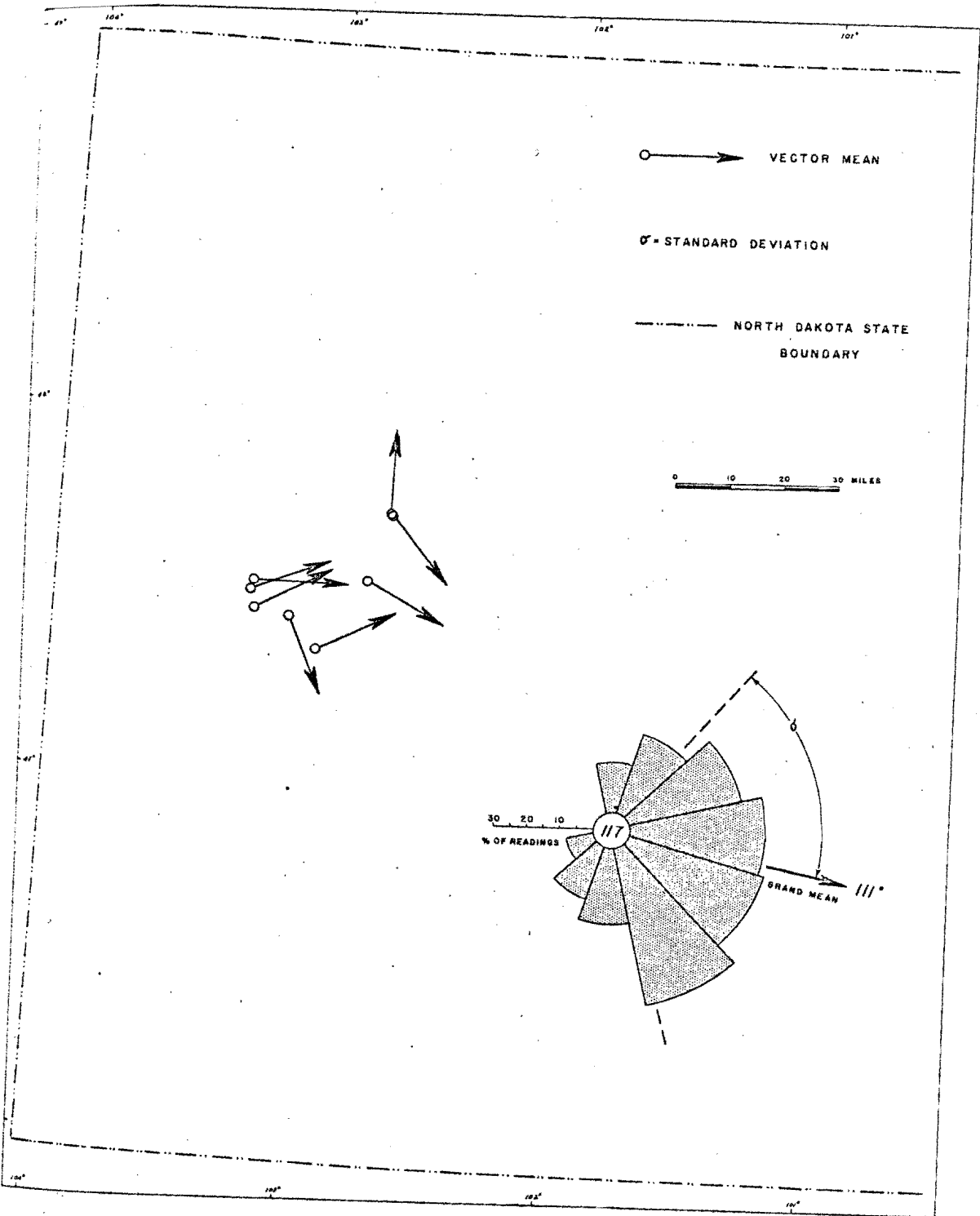
Figure 26.--Vector means for cross-bed measurements from outcrops of upper Sentinel Butte sand. Readings are summarized in the rose diagram.

TABLE 7.—Summary of large-scale cross-bed measurements from the Tongue River and Sentinel Butte Formations.

Stratigraphic unit	345 to 15	15 to 45	45 to 75	75 to 105	105 to 135	135 to 165	165 to 195	195 to 225	225 to 255	255 to 285	285 to 315	315 to 345	Total (n)	Grand mean (degrees)	Variance	Standard Deviation
						Azimuth Class										
Upper sand	7	12	16	19	17	23	11	8	4	-	-	-	117	111	3835	61.9
Sentinel Butte[a]	3	4	9	7	7	10	9	2	5	2	5	5	68	120	8285	91.0
Basal sand	12	19	27	55	46	43	23	14	4	3	3	8	257	109	4176	64.6
Tongue River	16	27	23	33	43	35	13	7	5	4	6	10	222	96	5136	71.7

[a]Sentinel Butte Formation exclusive of basal and upper sands.

intervening Sentinel Butte strata are included in Table 7.

A test to determine the level of significance of preferred orientation was conducted for the grand means. The ratio of the computed sample variance, s_o^2, to the variance of the uniform distribution, s_u^2, is called the F ratio and provides a test for the null hypothesis,

$$H_o : s_o^2 = s_u^2$$

The alternate hypothesis must be,

$$H_a : s_o^2 < s_u^2$$

The value of s_u^2 is computed by the method of Griffiths and Rosenfeld (1953, p. 212),

$$s_u^2 = \frac{a^2}{3}$$

where a^2 is the maximum range of the distribution. The degrees of freedom are the same for the numerator and denominator of F, and equal $n - 1$. All grand means except that for the Sentinel Butte have preferred orientation at the 99.95 per cent level of confidence, the Sentinel Butte is significant only at the 95.0 percentile. Results of orientation tests are tabulated in Table 8.

TABLE 8.—Summary of test data for preferred orientation of grand means of large-scale cross-bed measurements.

Stratigraphic unit	Vector-Mean (degrees)	$s_u^2/s_o^2 = F$	Degrees of freedom	Level of significance
Upper sand	111	2.82	110	.9995
Sentinel Butte	120	1.50	67	.950
Basal sand	109	2.59	256	.9995
Tongue River	96	2.27	221	.9995

A test for equality of means, using the Student's t test (Dixon and Massey, 1957, p. 123), was made to determine whether significant differences exist between grand means. The t statistic was computed according to the equation

$$t = \frac{(\bar{x}_1 - \bar{x}_2) - (u_1 - u_2)}{\sqrt{(s_1^2/n_1) + (s_1^2/n_1)}}$$

which, if normality can be assumed, has f degrees of freedom where

$$f = \frac{(s_1^2/n_1 + s_2^2/n_2)^2}{\dfrac{(s_1^2/n_1)^2}{n_1 + 1} + \dfrac{(s_2^2/n_2)^2}{n_2 + 1}} - 2$$

It was found that data for the Tongue River Formation differ significantly (97.5 per cent level) from those for the basal and upper sands and for the intervening Sentinel Butte strata. Differences between grand means of the stratigraphic intervals within the Sentinel Butte Formation are considerably less significant, and the hypothesis that they are equal can be rejected only with 60 to 80 per cent confidence. Results of these tests are given in Table 9.

CM relationships

Theory.--Passega (1957, 1964) presented plots of samples from known environments in which the smallest particle size in the coarsest one percentile (C) of the size frequency distribution was plotted as a function of the median grain size (M). The value of C is representative of the (minimum) competence of the transporting agent and M is a statistic characteristic of the total range of particle sizes

TABLE 9.--Summary of test data for equality of grand means of cross-bed data.

Test pair	t	df	Confidence level of rejection
Tongue River vs Sentinel Butte[a]	1.99	95	.975
Tongue River vs Basal sand	2.06	444	.975
Tongue River vs Upper sand	2.00	276	.975
Sentinel Butte vs Basal sand	0.94	88	.800
Sentinel Butte vs Upper sand	0.73	104	.700
Basal sand vs Upper sand	0.29	242	.600

[a]Sentinel Butte Formation exclusive of the basal and upper sands.

undergoing transport by this agent. The value C = M constitutes a limit for coordinates (C, M) and is approached for samples in which the coarse half of the sediment is well sorted; that is, when the first percentile and fiftieth percentile have nearly the same corresponding particle sizes. The relative displacement of plotted points

from the limit C = M, measured parallel to the M-axis and expressed
in phi-units, is an index to the sorting in the coarse half of sedi-
ment samples. For the segment of CM diagrams representing sediments
transported as graded suspension, Passega (1964, p. 834) has desig-
nated this displacement as an index of maximum sorting (I_m).

The fine fractions of samples can be represented on a CM
diagram by recording their per cent weight beside the plotted values
of (C, M). Passega regarded particle sizes less than 125 microns
(3 phi) to constitute the fine fraction, and illustrated it by
contour lines drawn for values of 25, 12, 6, 3, and 1.5 per cent
lutite.

Basic types of CM patterns are shown in Figure 27. Accord-
ing to Passega, (p. 1973),

> Pattern I is the typical pattern formed by rivers and
> by tractive currents in areas of low velocity. Very fine
> particles settle, mixed with intermediate-size particles
> which are placed in suspension in areas of maximum velocity.
> The maximum size of these intermediate particles is a lower
> limit of the value of C in the pattern. It is also an in-
> dication of the turbulence in the upper levels of the current.
> Pattern II is formed by turbidity currents. It may
> also be formed by tractive currents, under exceptional cir-
> cumstances, when these lose speed so gradually and uniformly
> that the suspension near bottom remains graded and adjusted
> to the velocity. Pattern II is parallel with the limit
> C = M.
> Pattern III represents sediments settling through quiet
> water. The pattern is commonly round; points are scattered.
> Conditions of deposition which are a combination of
> those described produce composite patterns. For instance,
> a sequence of locally swift tractive currents and slow uni-
> form currents would form a fan-shaped pattern of scattered
> points extending from Pattern I to Pattern II. A current
> making some deposits in quiet water would form a pattern
> composed of Patterns I and III or II and III.
> Rivers or tractive currents which have beds composed
> of particles of sand of the same size as those concentra-
> ted at the bottom of the suspension form Pattern IV (Fig.
> 12). This pattern is parallel with the limit C = M. The
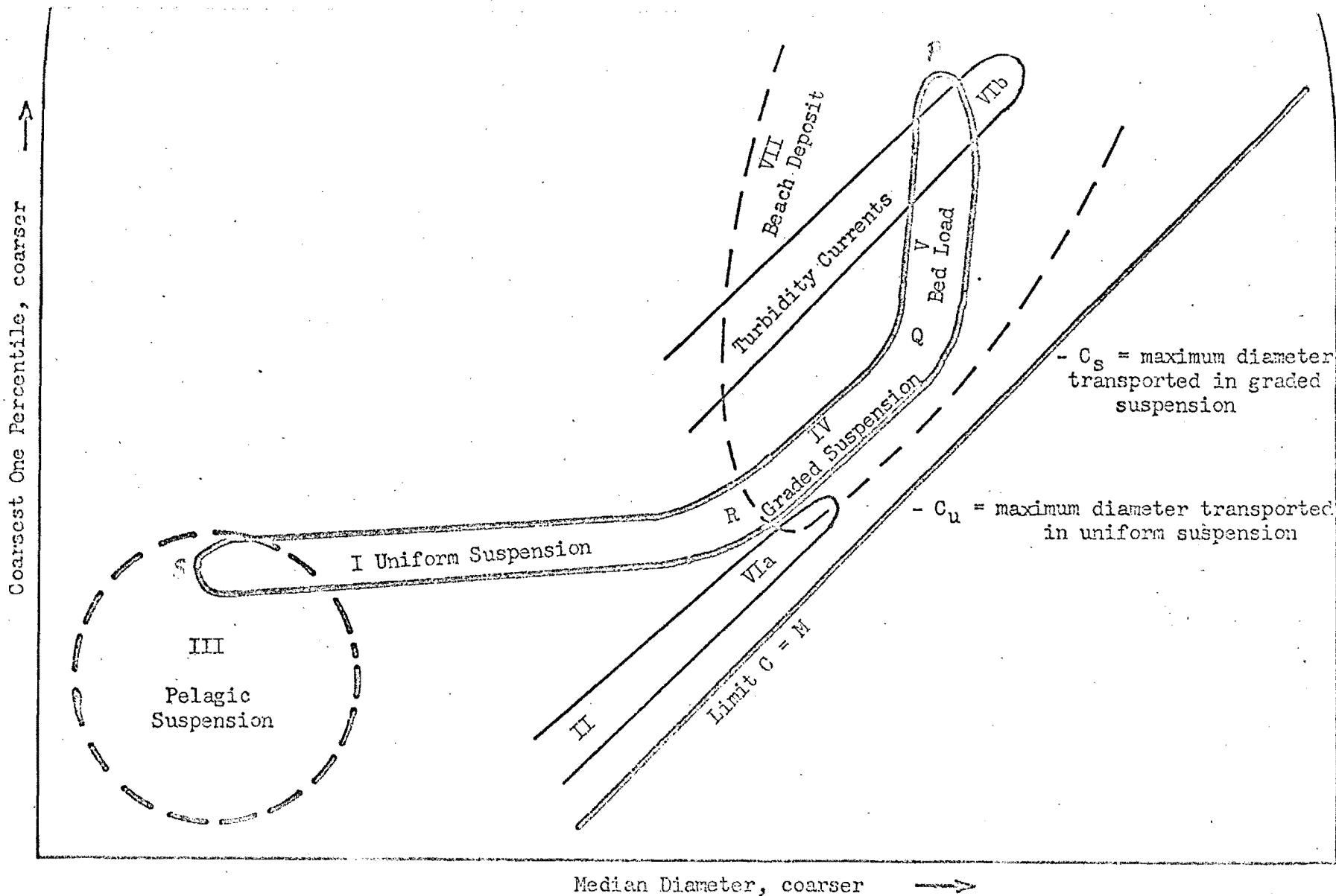
Figure 27.---Basic CM patterns, see text for explanation. (Modified from Passega, 1957)

maximum and minimum values of C in the pattern are an
indication of maximum and minimum turbulence at the bottom
of the current, provided material of all transportable
sizes are available to the current.

Pattern IV is generally continued on the fine side by
Pattern I, on the coarse side by Pattern V.

When rivers or tractive currents transport by traction
sands too coarse to be supported in suspension, their de-
posits form Pattern V. This pattern makes a small angle
with the ordinates. C may vary considerably with little
effect of the median. In the upper part of the pattern
points are scattered. The maximum value of C is a measure
of the competency of the current, the minimum value an
indication of the maximum turbulence at the bottom of the
current, provided all sizes transportable are available
to the current.

Turbidity currents form Pattern VI. This pattern is
parallel with the limit C = M. On the fine side it is
continued by Pattern II. Pattern VI is shown in two po-
sitions: VIa and VIb which represent deposits of two types
of turbidity currents. The distance between the pattern
and the limit C = M is a possible indication of the con-
centration of the evenly dispersed fine material in sus-
pension.

The composite pattern (I, IV, V) for river transported sediment
is of particular concern, because samples of Tongue River and Sen-
tinel Butte sediments form patterns similar to this composite pat-
tern. The interpretation of this pattern is well documented by
Passega (1957) by plots of samples collected from the Mississippi
River (U. S. Waterways Experimental Station, 1939), the Enoree
River (Einstein, and others, 1940), and other rivers. Conditions
of flow, discharge, concentration of suspended sediment and other
factors were recorded for stations from which samples were collected
and permit interpretation of CM patterns in terms of agents of trans-
port and environments of deposition.

The CM pattern for the Mississippi River (Passega, 1957, p. 1954)
is divisible into three segments (I, IV, V) which correspond to the
main channel, the subaqueous bank, and protected backwater. Samples

of the coarsest material from the main channel plot in group V, have C values greater than the maximum measured for sediment in suspension, and are considered to have been transported by traction only. Sediments from the subaqueous bank plot in group IV (parallel to C = M) and correspond in size to sediment measured in graded suspension in the lower part of the water column. Sediments from the protected backwater environment plot in group I and have values of C and M corresponding to sediment carried in uniform suspension.

Thus, Passega established the relationships between sediment textures, modes of transport, and depositional environments for a section of the Mississippi River near Mayersville, Mississippi. The value of C at the inflection of the CM pattern at point Q (Figure 27) is designated C_s and corresponds to the largest particle diameter which can be transported in graded suspension. Likewise, the value of C_u at point R is the coarsest particle which can be transported in uniform suspension.

Analytical precision.--C constitutes part of the sand fraction in most Tongue River and Sentinel Butte sediments and is easily measured. As noted by Inman (1952) the median diameter (M) is measured with the greatest precision of any size-distribution statistic. The influence of fluctuations of sampling and analysis on the size frequency distribution increases with distance from the 50th percentile, the relative standard error increasing rapidly in the tails of the distribution. Thus, M is determined with greater relative accuracy than is C. Although the relative standard error may be greater for C than for slightly larger percentiles, it is as reproducible as the limits of the phi-class in which it occurs

and the accuracy with which it is interpolated. In Tongue River and Sentinel Butte sediments, C occurs most often between 2 and 4 phi (which are sieve-size classes) and was obtained by the same method of interpolation as other percentiles used in computation of size statistics. It is reproducible within about 0.02 phi-units.

As discussed by Passega (1964, p. 844-845) samples for which C is determined must be free of non-terriginous (non-lithogenous) debris, such as shell fragments, and represent a single sedimentation unit. A pattern should consist of 20 to 30 samples which represent all sediment textures deposited by transport mechanisms active within a particular environment.

Previous applications.--Weller (1960, p. 323) reproduced Passega's (1957, p. 1973) basic CM diagram with an acknowledgment that CM relationships provide evidence which aid in the distribution of the mode of transport and depositional environment of sedimentary rocks. Bull (1962) presented CM patterns which differentiated mud-flow, stream-channel, braided-stream, and "intermediate" deposits on alluvial fans in western Fresno County, California. Warner (1966, p. 945-958) noted the relationships of CM patterns to contoured data of median diameter, Trask sorting coefficient, and porosity in the Duchene River Formation of the Uinta Basin, Utah. He concluded that CM patterns are useful tools in directing sedimentological study, but made no direct interpretations based upon them. His plots (p. 498, Figure 3) contain several points for which median values are larger than the coarsest particle size (which is physically impossible), and for this reason his data are considered suspect.

Proposed application.--Tongue River and Sentinel Butte sediments

are particularly well suited for textural analysis. They can be efficiently dispersed, contain little non-lithogenous material, and the bulk of most samples are composed of particles which fall within the size limits of accurate measurement (coarser than 10 phi). Data are well suited for CM representation.

It has long been assumed that the Tongue River and Sentinel Butte Formations are composed of fluvial deposits. Comments regarding this origin are not always explicit or well documented. The molluscan and vertebrate faunas and the flora of these units, combined with the lithology and morphology of stratigraphic units and primary sedimentary structures all appear to indicate stream transport and an aquatic environment. The CM patterns of stratigraphic samples given in Figures 28 and 29 are best interpreted as resulting from stream transport, and they add strong testimony to existing evidence for fluvial origin of Tongue River and Sentinel Butte strata.

Comment should be offered regarding the use of stratigraphic samples in formulating a CM pattern. Passega (1957) utilized stratigraphic data of Clark (1950) in identification of the depositional environment of Des Moines (Pennsylvanian) channel and blanket sands. The resulting pattern was compact and Passega (p. 1981) commented that,

> A remarkable feature of the pattern is that it indicates an extreme uniformity in the depositional process. Although deposition of the various sand was interrupted by long intervals during which other sediments were deposited, all the sands are of a single depositional environment.

Similar application was made of size data presented by Foreman and Thompson (1940) for the Berea Sandstone (Devonian or Mississippian) in Ohio. Stratigraphic data from cores was also utilized by Bull
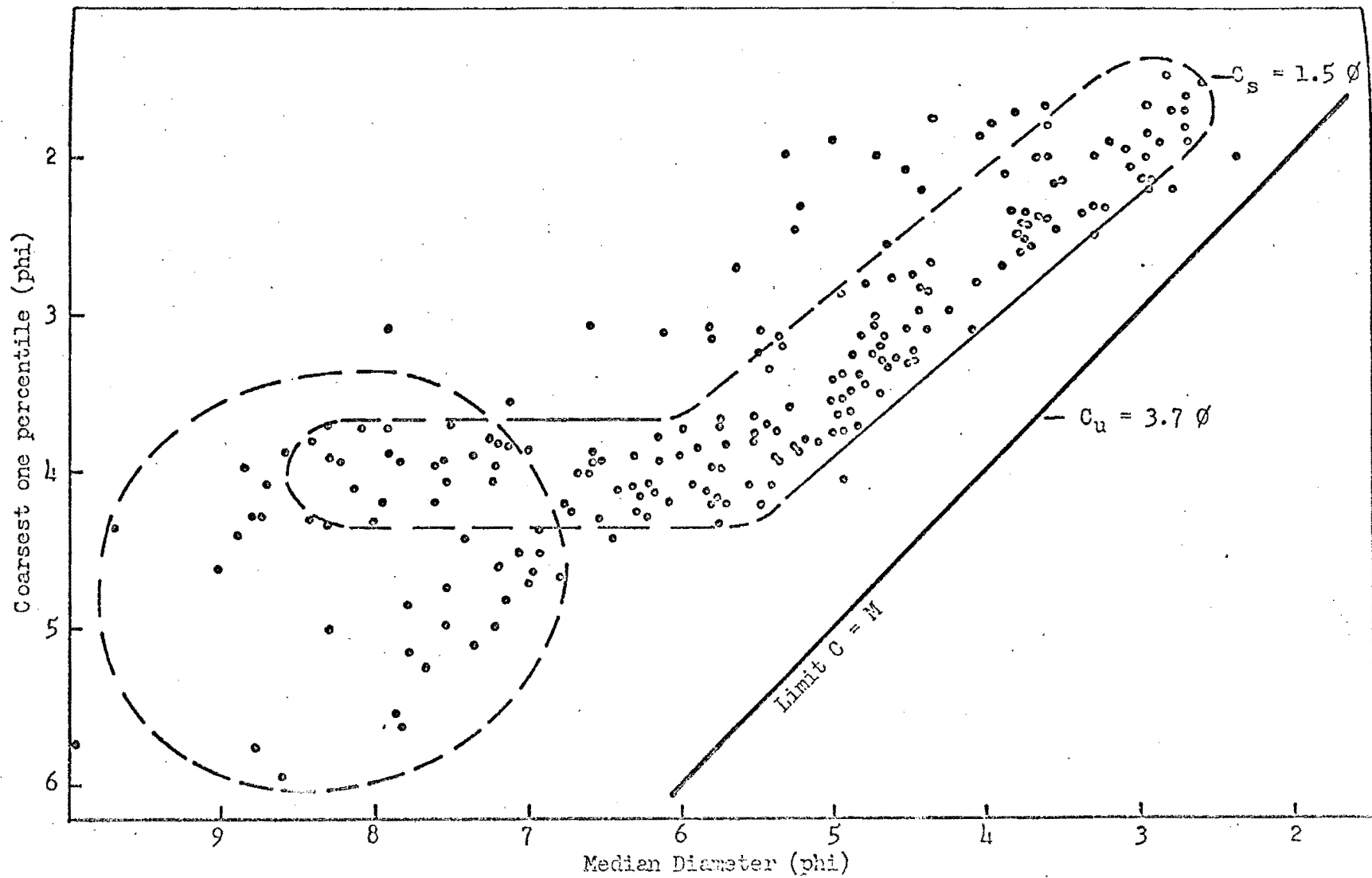
Figure 28.—Composite CM pattern of stratigraphic samples from the Sentinel Butte Formation.
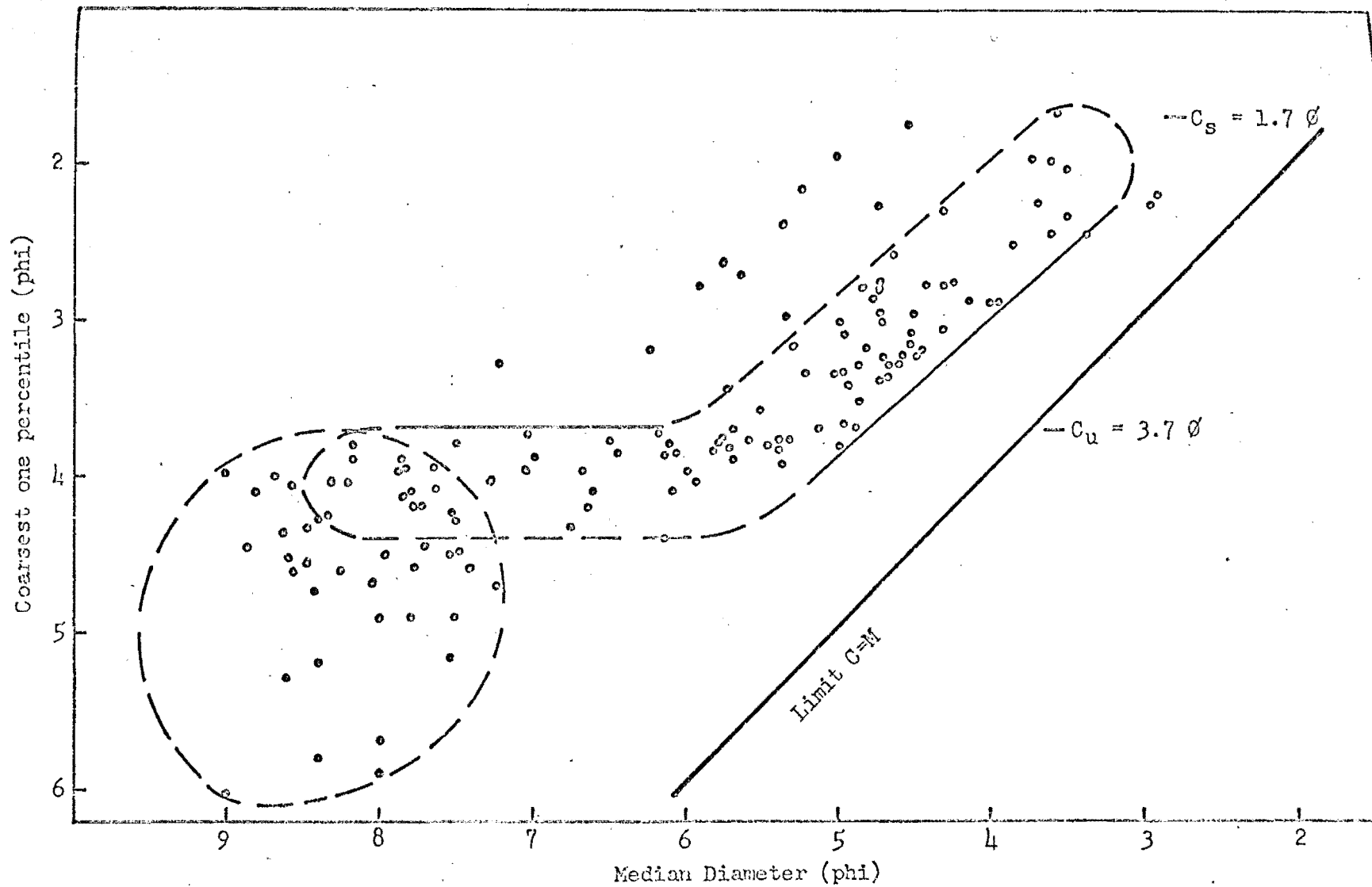
Figure 29.-- Composite CM pattern of stratigraphic samples from the Tongue River Formation.

(1962) for CM plots.

With the exception of samples of the basal Sentinel Butte sand, all data plotted on CM diagrams in this report are for samples distributed stratigraphically in various sections. Justification of such use involves the assumption that all environments (channel, levee, floodplain, floodbasin, etc.) of the fluvial regime are represented in the stratigraphic section. The resulting pattern is composite and must be assumed to represent an "average Tongue River" or an "average Sentinel Butte" stream. The amount of dispersion of points from the typical fluvial pattern may (excluding error due to sampling and analysis) represent the total amount of fluctuation in the streams which deposited the sediments. Because most sediment is transported and deposited during flood-stage, CM patterns for fluvial sediments should reflect conditions of maximum stream competence. A summary of CM data for stratigraphic samples from the Tongue River and Sentinel Butte Formations is given in Table 10. CM patterns for individual stratigraphic sections in western North Dakota are shown in Appendix II-E (Figures 88 to 98).

Classification of sediments

Previous classifications.--Fluvial sediments have been fundamentally differentiated by many workers as vertical and lateral accretion deposits (Fenneman, 1906; Melton, 1936; Mackin, 1937; Happ and others, 1940; Challinor, 1946; Fisk, 1947; Jahns, 1947; Wolman and Leopold, 1957, as cited by Allen, 1965c).

Fisk (1947) subdivided meander-belt sediments in the Mississippi

TABLE 10.--Summary of CM data for stratigraphic samples from the Tongue River and Sentinel Butte Formations.

Station	Im (Ø-units)	Cu (Ø)	Cs (Ø)
Sentinel Butte			
Bullion Butte	0.80	3.75	1.50
Sentinel Butte	0.80	3.70	1.60
Beicegel Creek	1.45	3.85	2.15
Long Cross	1.15	3.80	2.20
Lost Bridge	1.25	3.80	1.80
Contact	1.00	3.75	1.25
Average (exclusive of Contact)	1.09	3.98	1.85
Tongue River			
Bullion Butte	1.35	4.00	2.51
Medora	1.20	3.75	1.70
Beicegel Creek	1.10	3.80	2.00
Yellowstone	1.25	3.80	2.90
Snowden	1.60	?3.80	2.55
Donnybrook	1.50	3.75	2.25
Average	1.33	3.82	2.32

Valley into the following morphometric types: (1) point-bar deposits, (2) channel fillings, (3) natural levee deposits, (4) backswamp deposits, (5) braided stream deposits, and (6) deltaic plain deposits. Happ, and others (1940) presented a detailed morphogenetic classification of fluvial sediments which included: (1) channel-fill, (2) vertical accretion, (3) floodplain-splay, (4) colluvial, (5) lateral accretion, and (6) channel lag deposits. Vertical accretion deposits consist of levee and floodbasin sediment, flood-plain-splays (crevasse-splays) are wedges of sediment deposited from channels which breach the natural levee, and lateral accretion deposits are the result of point bar migration.

Allen (1965c) broadened the concept of lateral and vertical accretion deposits in a classification in which fluvial deposits are grouped into three major and eight subordinate categories. This classification is both genetic (environmental) and descriptive (stratigraphic). Allen's classification is reproduced as Table 11.

According to Allen (1965c, p. 127),

> Channel or substratum deposits form the lower part of the typical floodplain sequence. Included are point bar and channel bar deposits and channel lag deposits left after stream winnowing. Bed load materials dominate substratum sediments. In overbank or topstratum deposits suspended load materials are dominant. Included are bar swale-fill, levee, crevasse-splay, and floodbasin deposits. Deposits of these environments form the upper part of the typical floodplain sequence, overlying channel deposits. Transitional deposits, with channel-fill deposits as the only category, generally include bed and suspended load sediments. Stratigraphically they occupy positions through the substratum.

Proposed classification.--Recognition of the fluvial origin of Tongue River and Sentinel Butte deposits, as represented by their CM patterns, facilitates genetic classification. Of the several CM

TABLE 11.--Allen's (1965c) classification of alluvial sediments.

Environment of deposition	Deposit	Origin reflected in typical stratigraphic position
Channel floor	Channel-lag	Channel or substratum deposits
Point bar	Point bar	
Channel bar	Channel bar	
Point bar swale or in an abandoned braided stream channel	Swale-fill	Overbank or topstratum deposits
Levee	Levee	
Crevasse-splay	Crevasse-splay	
Floodbasin	Floodbasin	
Within abandoned or decaying channel	Channel-fill	Transitional deposits

patterns by Passega (1957, 1964), the composite pattern for fluvial deposits yields, perhaps, most easily to environmental interpretation because the modes of sediment transport are closely related to the type of environment in which material can be deposited.

Sediments are normally carried in graded suspension only in the lower part of the water column. The term "graded" refers specifically to the concentrations of suspended sediment, but the maximum particle size is also graded upward from coarse to fine. Deposition of material transported in graded suspension contributes to substratum[3] (point-bar, channel-bar) deposits.

The graded suspension passes upward into a uniform suspension

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[3]The terms substratum and topstratum are used in the context of Allen (1965c) and are essentially synonymous with lateral and vertical accretion deposits respectively.

in which both sediment concentration and maximum particle size are uniform throughout the water column. It is this unformly suspended material which is carried over the stream banks, onto the floodplain, and into floodbasins during periods of flood, resulting in vertical accretion or topstratum deposition. These deposits have coarser median diameters proximal to the channel and become progressively finer with increased distance from the channel. Values of maximum particle size, however, remain remarkably constant.

The term "pelagic"[4] suspension is applied to fine material which settles very slowly from suspension. In general, sufficient time has lapsed during transport for the coarsest particles to have settled from suspension, and resulting deposits are distinguished from those typical of the original uniform suspension by their smaller values of C. Material from pelagic suspensions contribute to topstratum deposits in the most remote reaches of the floodbasin.

The balance of evidence (which includes considerations of textural and stratigraphic relationships, and the distribution of sedimentary structures) appears to justify an environmental interpretation of CM patterns. Samples which form a graded-suspension pattern comprise substratum deposits and those constituting a uniform-suspension pattern are of topstratum origin. Likewise, pelagic transport types were deposited in protected backwater environments distant from active channels. Graded suspension is considered genetically related to the channel environment, uniform suspension to the proximal

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[4]The term pelagic literally means "of the open sea" and is a misnomer in the present context. Usage is retained in this paper to avoid coining a new term; it is used in the sense of Passega (1957).

overbank (floodplain) environment, and pelagic suspension to the floodbasin environment distal to active channels. A classification based on these relationships is given in Table 12.

The graphical limits of the depositional (transport) classes are determined from the composite CM plots of Figures 28 and 29. Class envelopes conform in general to the array of the point pattern, but their bounds are, in part, somewhat arbitrarily fixed. The critical parameters of the patterns (C_u, C_s, and I_m) are, however, well defined and strict definition of other limits is of minor consequence. As drawn, the envelopes approximate a 95 per cent confidence interval for limits of the depositional classes.

It is useful, in consideration of the relative abundance of depositional types, to distinguish points which plot within the area of overlap between uniform and pelagic types. The term "transitional" is informally applied to these sediments and should not be confused with Allen's (1965c) "transitional" origin of "channel-fill" deposits (Table 11). Consideration of other plots (e.g., sand-silt-clay, median vs. skewness, etc.) indicates that transitional overbank deposits are genetically more closely related to floodplain than to floodbasin deposits and in subsequent discussion they may be included with the former. As indicated in Table 13, Tongue River and Sentinel Butte strata are composed of nearly equal amounts of substratum and topstratum material, but the distribution of the topstratum deposits is significantly different for the two units. The Tongue River Formation contains relatively greater proportions of floodbasin and less transitional and floodplain deposits than does the Sentinel Butte Formation.

TABLE 12.—Classification of Tongue River-Sentinel Butte sediments (in part after Allen, 1963).

Textural types	Inferred transport	Geomorphic-environmental relationships	Sedimentary form and structures
Clay-ball gravel	Bed load	Substratum deposition: channel-lag	Lenses and pockets (local)
Sand to silt	Graded and uniform suspension	Substratum deposition: Channel-lag, point bar, channel bar	Thin to moderate flat-bedding, small-scale to large-scale (kappa, lambda, nu, ?xi) cross-bedding, large-scale channeling
Clayey silt and silt	Uniform suspension	Topstratum deposition: Levee, crevasse-splay, floodplain	Thin bedded, laminated small-scale cross-beds (kappa, lambda)
Silty clay and clayey silt	Pelagic suspension	Topstratum deposition: Floodbasin, channel-fill (clay-plug)	Blocky to laminated

TABLE 13.--Relative abundance of depositional types in stratigraphic samples from the Tongue River and Sentinel Butte Formations.

Stratigraphic sections	Floodbasin	Transitional	Floodplain	Channel
Sentinel Butte				
Bullion Butte	7	2	7	22
Sentinel Butte	14	9	11	35
Beicegel Creek	1	2	6	3
Long Cross	9	4	18	21
Lost Bridge	6	4	11	16
Total	37	21	53	97
Per cent	17.8	10.1	25.5	46.6
Tongue River				
Medora	11	1	10	14
Beicegel Creek	5	-	6	10
Yellowstone	10	1	8	11
Snowden	7	1	1	8
Bullion Butte	10	2	1	17
Donnybrook	1	-	3	3
Total	44	5	29	63
Per cent	31.2	5.5	20.6	44.7

Primary sedimentary structures, present in many of the units sampled, aid in delimiting depositional environments. Structures which were most commonly observed in the various depositional classes are included in Table 12.

Skewness and median grain diameter appear to be the most environmentally sensitive of the size statistics, and plots of skewness versus median diameter for samples of Tongue River and Sentinel Butte sediments show a high degree of inverse correlation. In Figures 30 and 31, samples are designated according to their depositional type as determined on the CM diagrams. The end-members, which are channel and floodbasin deposits, are well separated in the plots, but floodplain deposits (including the "transitional" type) overlap the end-members. Much of the overlap is the result of combining data from a number of stratigraphic sections; most plots for individual sections (Appendix II-C) show a better separation of the three depositional types. Despite the overlap in the scatter diagrams, plots of median vs. skewness appear to have auxiliary value in sediment classification. In addition, they demonstrate the environmental sensitivity of skewness and median diameter, a property not readily discernible in other size statistics.

Composition of sediments

General statement.--The textural types and their relative abundances within the Tongue River and Sentinel Butte Formations have been discussed. The bulk of the sediments in these units are clastic mixtures of sand, silt, and clay, but minor amounts of chemical and biogenic lithologies occur. The foremost of these are freshwater
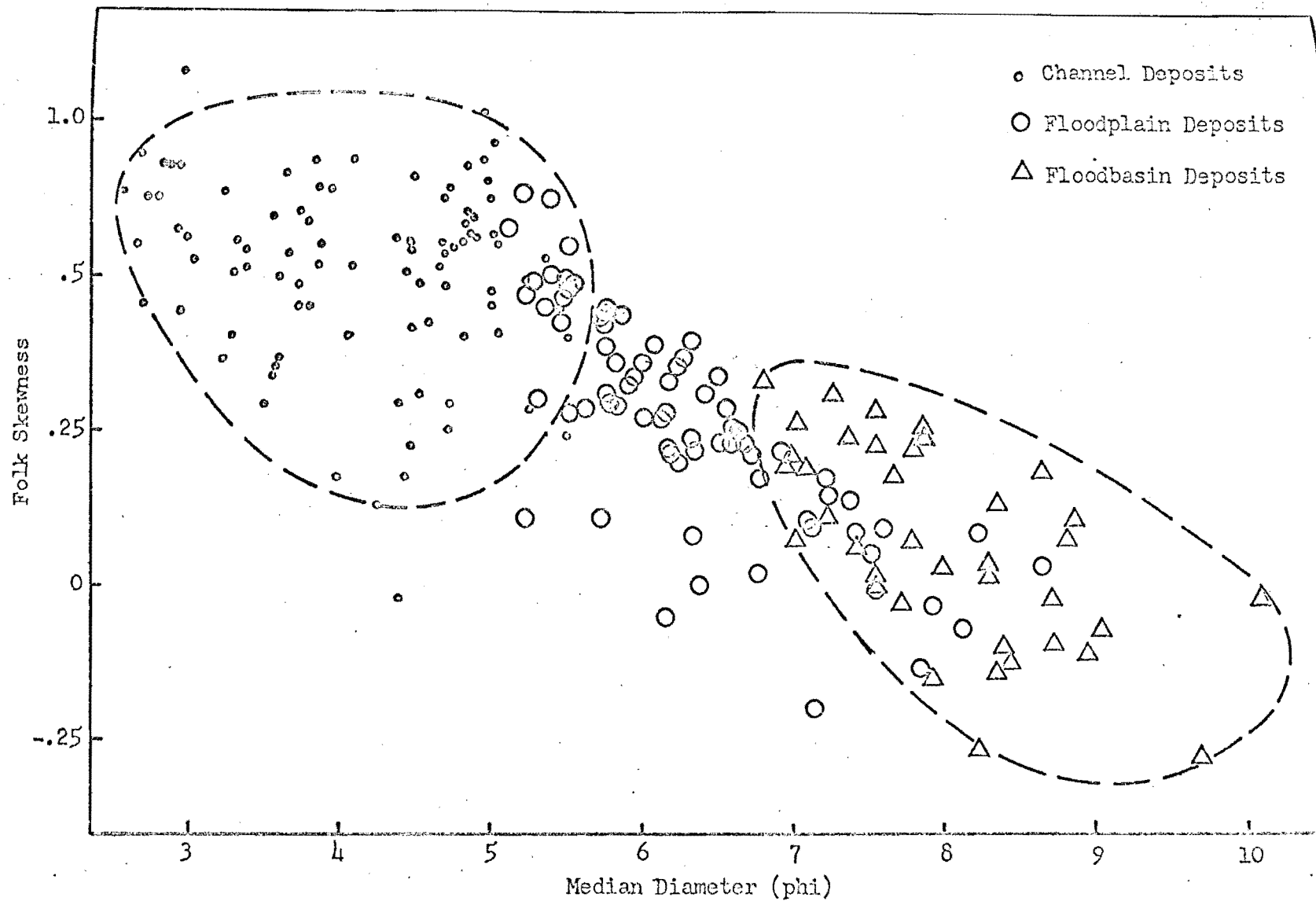
Figure 30.--Plot of Folk skewness vs. median for stratigraphic samples from the Sentinel Butte Formation.
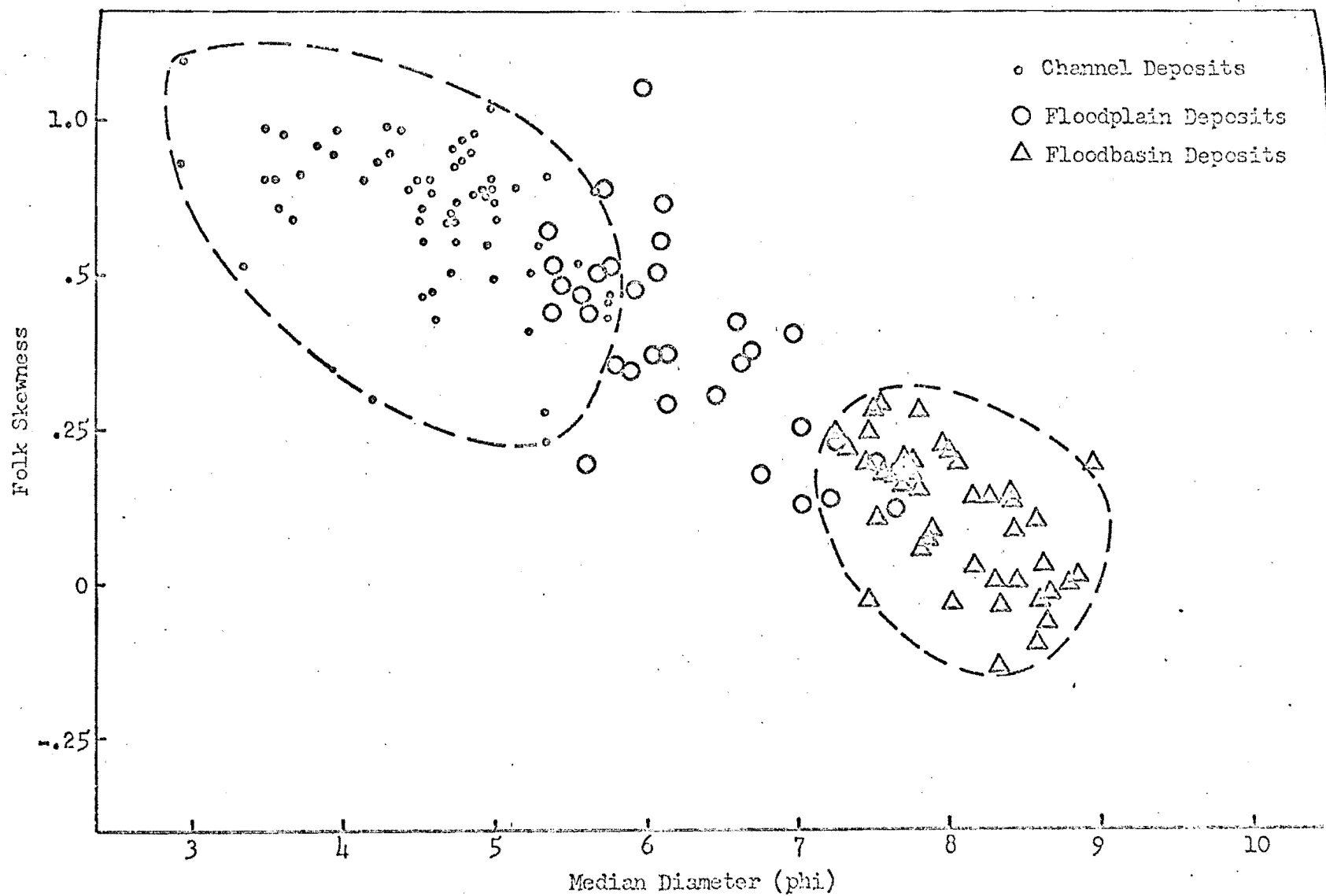
Figure 31.--Plot of Folk skewness vs. median diameter for stratigraphic samples from the Tongue River Formation.

limestone and lignite.

No comprehensive mineralogic or petrographic study of Paleocene units in North Dakota has been conducted. Although such study lies outside the scope of this report, sediment composition is a relevant factor in considerations of paleogeography, tectonics, erosion rates, sediment transport, rate of deposition, and similar factors. For this reason, it is important to establish the most pronounced similarities and differences between Tongue River and Sentinel Butte sediments. For this purpose, a brief review of previous studies and statements regarding sediment composition are given below, with added comments based on the writer's observations.

One of the best qualitative descriptions of Tongue River strata is given by Hares and, although the writer differs with several statements, it is useful to review it here. According to Hares (1928, p. 31-32):

> The rocks of the Tongue River member of the Fort Union are generally of lighter color than those of the Lance [= Hell Creek and Ludlow] and contain a larger percentage of sandstone, also thicker and more persistent beds of lignite, the best example being the Harmon lignite. The individual strata are also more persistent and regular. The sandstone is finer grained, cross-bedding is less abundant, and thin lentils of limestone are a distinctive feature. The cross-bedding of the sandstone in the basal Fort Union is of a peculiar swirly type [kappa type of Allen, 1963b] and quite different from that found in the Lance.
> The sandstone is mostly of light tints of tan, buff, cream, yellow, and white, with a lesser showing of brown, green, and gray. Some of it is so highly calcareous that it might well be called sandy limestone, but a few beds are apparently made up of grains of pure quartz. Some of the sandstone is spotted with small balls of limonite, which stain the surface a yellowish brown. Most of the beds are fine grained and massive, with few joints. Cross-bedding, except in the basal part, is not highly developed, and ripple marks are somewhat rare. Most of the shale

is of light colors, such as buff, grayish white, and greenish white, but some is gray, brown, drab, or black. Some of the shale is extremely sandy, some is limonitic, a little is gypsiferous, a small part is carbonaceous, and nearly all is calcareous. The member contains considerable very finely laminated cream-colored shale, the particles of which are so small as to remain in suspension in water for days. This shale closely resembles silt that collects in ponded water at flood times. Well-preserved fossil leaves are sometimes found in such material.

All the sandstone texted, except that composed of quartz grains, is calcareous, effervescing freely with weak hydrochloric acid. In thin section under the microscope the grains of sand are seen to be small and subangular and to make up less than one-half of the material, the remainder being chiefly dirty calcite. In some samples the calcite forms nine-tenths of the mass, and in many the quartz grains are not even in contact. Some of the samples contain small flakes of biotite and muscovite. Nearly all of them contain some fresh and altered feldspar, which is less in quantity than the quartz. As a whole, there is much less feldspar, much more calcium carbonate cement, and perhaps somewhat less quartz than in the Lance formation. In its regular bedding and smooth appearance the sandstone is in marked contrast to the knotty sandstone of the Lance. The sandstone of the Fort Union [Tongue River] may for that reason be easily trimmed into hand specimens. In general, the rocks of the Fort Union are much finer grained than those of the Lance, a difference indicating either that they were laid down farther from the source or that the land mass supplying the material was much lower. Possibly both of these conditions prevailed.

Thin lenses of dense, compact limestone occur in the lower 400 feet of the formation and were noted at several localities. . . . The limestone breaks with a conchoidal fracture and is of a slate-gray color, which becomes tan or brown upon weathering. The limestone lenses are sparingly fossiliferous . . .

Five lignite beds over 30 inches thick and many thinner ones were found in the Tongue River member and are both regular and persistent. Silicified tree trunks and stumps that have been washed out of clay and shale are common surface features of the member.

Hares' comment regarding the composition of Sentinel Butte beds are brief, probably because they are of minor extent in his map area. He states (p. 39) that:

The Sentinel Butte sandstone is fine grained and contains considerable dark mica (biotite). Even where the weak cement has gone, it has a peculiar compactness on a dry surface that resists the blow of a hammer, resembling the Hell

Creek member of the Lance in this respect as well as in general appearance. . . . The HT Butte lignite is the basal bed.

Lignite.--Observations of the writer indicate that lignite beds are both more abundant and better developed in Tongue River than in Sentinel Butte strata. This observation is necessarily a generalization, because the abundance of lignite in these units varies both stratigraphically and regionally. Tongue River strata contain the greatest number of thick lignites (the H, Hansen, and Harmon beds; Figure 2) in the basal third of the sequence, and this stratigraphic interval is exposed at the surface only in the southern portion of the study area (the Marmarth lignite field). The Garner Creek bed (bed C of Leonard and Smith, 1909), occurs somewhat below the middle of the sequence, and the Meyer bed near the top. The HT Butte bed marks the upper limit of the Tongue River interval. Lignite beds of lesser thicknesses are present at various horizons. None of the major Tongue River lignites below the Garner Creek bed crop out in the Little Missouri badlands north of Township 139 N., and the formation does not give as obvious an appearance in this area of being lignitic as it does farther south.

In the southern half of the badlands, in the Sentinel Butte and Marmarth lignite fields, the Sentinel Butte Formation contains few lignite beds greater than 3 feet thick. Leonard and Smith (1909, pl 2) include only two (undesignated) lignite beds above the F and G beds (which the writer designates as the HT Butte bed of the Tongue River Formation). The first of these is about 100 feet above the base of the unit and the second occurs near the top and is partially burned at Sentinel Butte. Hares (1928, p. 47) recognized only one

major lignite above the HT Butte bed, which he named the Bullion

Butte bed. The writer correlates the Bullion Butte bed with the

upper lignite of Leonard and Smith at Sentinel Butte. Crawford

(1967, pl. II) added a second lignite, which he indicated exceeds

20 feet in thickness, to the upper portion of the Sentinel Butte

sequence at Bullion Butte. That a 20 foot lignite bed was overlooked

by both Hares and the writer is possible, but the bed could be a slump

block containing the Bullion Butte stratum. Regardless, it can be

stated that the Sentinel Butte contains fewer thick lignites per

measured foot of section in this area than does the Tongue River.

Five lignites about 5 feet in thickness were reported by Clark

(1966, pl. II) from a partial section of the Sentinel Butte For-

mation in the North Unit of Roosevelt Park; these beds can also be

viewed along North Dakota Highway 85 as it ascends from the valley

of the Little Missouri River. By comparison with the Sentinel Butte

and Marmarth fields, lignite beds in the Sentinel Butte appear to

become more numerous northward but do not attain great thickness.

It should be recalled that the total Sentinel Butte interval also

thickens northward, being nearly twice as thick in the North Unit of

Roosevelt Park as at Bullion Butte.

In addition to the documentation of measured stratigraphic

sections, a number of comments regarding the relative abundance of

lignite in Tongue River and Sentinel Butte strata are found in the

literature. As quoted above, Hares (1928, p. 31) noted the thick

and persistent beds of lignite in the Tongue River Formation. Han-

son (1955) commented on the "sparse representation of lignites in the

Sentinel Butte member", noting, however, that it does contain numerous

carbonaceous shale beds, varying in thickness from a few inches to five feet.

A conflicting statement is given in a report on the geology of west-central McKenzie County by Fisher (1953) who stated,

> In the area mapped for this report, the base of the Sentinel Butte member is persistently marked by the prominent L scoria, and the member contains more lignites, scorias, and gray clays, a number of which are bentonitic, than does the regular Tongue River.

Fisher's generalized section faithfully records his observation. Thirteen lignites are indicated in the Sentinel Butte interval, two of which exceed 5 feet and none of which exceed 10 feet in thickness. A qualification is imposed on the statement, however, by the fact that only about the upper third of the total Tongue River sequence is exposed within the area of Fisher's report.

The writer feels justified in concluding that although both units are lignitic, thicker and more persistent lignites occur in the Tongue River than in the Sentinel Butte Formation.

Limestone.--Freshwater limestones occur as pods, lenses, lentils, and discontinuous beds in the Tongue River Formation. They are usually slate gray on a fresh surface, weather buff or yellow brown, and break with a conchoidal fracture or part along bedding planes. They are sparingly fossiliferous, containing fragments of indigenous plant debris and, rarely, enclose broad-leaf floras introduced from adjacent areas. Invertebrate fossils are rare, but molds of mollusks (both clams and snails) are occasionally found. With the exception of broad-leaves, preservation of fossils is poor. No micro-organisms have been observed in samples studied.

As discussed below, limestones are all argillaceous and

dolomitic. Mineral clasts are contained in an amorphous or crypto-crystalline matrix of carbonate and are frequently not in contact. Shrinkage, presumed to result from dolomitization, has created numerous vugs and cavities which are lined or filled with minute carbonate crystals. The insoluble fraction of samples consists largely of quartz and feldspar, feldspar being the minor component. Micas, clinopyroxenes, and unidentified organic debris constitute minor components. Mineral clasts vary from a maximum diameter of 0.01 to 0.10 millimeter with a mode in the range of medium-fine to medium coarse silt (0.01 to 0.03 millimeters). Particles are very angular, quartz appears shard-like and feldspars are freshly fractured. Feldspar composition, determined microscopically, is primarily orthoclase with subordinate amounts of plagioclase (?albite-andesine).

Primary structures consist largely of micro-laminae with occasional cross-bedding and minor disruptions. Light laminae are created by relative increased concentrations of quartz and feldspar, the matrix having an inherently darker color. Concentration of organic debris is also evident and contributes to the laminar structure. Field evidence of continuous bedding structures between the limestone and enclosing sediments has been obscured or obtitera-

dolomitic. Mineral clasts are contained in an amorphous or crypto-crystalline matrix of carbonate and are frequently not in contact. Shrinkage, presumed to result from dolomitization, has created numerous vugs and cavities which are lined or filled with minute carbonate crystals. The insoluble fraction of samples consists largely of quartz and feldspar, feldspar being the minor component. Micas, clinopyroxenes, and unidentified organic debris constitute minor components. Mineral clasts vary from a maximum diameter of 0.01 to 0.10 millimeter with a mode in the range of medium-fine to medium coarse silt (0.01 to 0.03 millimeters). Particles are very angular, quartz appears shard-like and feldspars are freshly fractured. Feldspar composition, determined microscopically, is primarily orthoclase with subordinate amounts of plagioclase (?albite-andesine).

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it is supported by evidence of primary sedimentary structures, textures, and indigenous fossils.

It is desirable to substantiate the writer's observation that, although carbonate lithologies are present in both the Tongue River and Sentinel Butte sequences, freshwater limestone is most abundant and best developed within the Tongue River Formation. Documentation of this observation is made more difficult because of the failure of many workers to distinguish clearly between "limestones" and "carbonate concretions", and by the failure of others to mention the lithology at all. Support is offered, however, by Hares (1928, p. 31, cited above) who noted thin lenses of dense, compact limestone at several horizons in the lower 400 feet of the Tongue River Formation and considered them a distinctive feature of the unit. It is significant that he included limestone in his lithologic description of the Tongue River "member" (pl. 14), but omitted it from that for the Sentinel Butte "member".

Crawford (1966, p. 30) independently arrived at the same conclusion as the writer, for he stated:

> Limestone, which is a rather unusual rock type for continental sediments, is found in lenses or pods throughout the lower member [Tongue River Formation] (Fig. 8), but was not observed in the Sentinel Butte Member. The lenses range in size from less than a foot in diameter to twenty feet long by six feet high; they are almost always wider than high.

Although the writer disagrees with Crawford's statement regarding occurrence in continental sediments, his observations on limestone in the Tongue River-Sentinel Butte sequence are accurate.

Mineralogy.--A review of reports on heavy mineral studies of

Tongue River and Sentinel Butte lithologies available[5] to the writer
are reviewed below.

Tisdale (1941, p. 28) found quartz and feldspar to be the most
abundant minerals in 18 samples from basal beds in the Tongue River
Formation. Quartz varieties were reported as crystalline, crypto-
crystalline chert, and fine aggregates (? quartzite). Wavy extinction
and quartzite fragments were considered suggestive of a metamorphic
source. Both orthoclase and plagioclase (andesine near labradorite)
are reported; orthoclase was turbid but plagioclase was clear, faintly
zoned, unaltered and angular. Sericitized muscovite grains consti-
tuted most of the remaining light mineral fraction.

Per cent weight of heavy minerals ranged from 0.13 to 2.22 per
cent, and the suite consisted of the following species:

apatite	leucoxene
andalucite	magnetite-ilmenite
biotite	muscovite
"carbonate" (dolomite)	sericite
chlorite	staurolite
epidote	tourmaline
garnet	tremolite
hornblende	zircon
kyanite	zoicite
	iron oxides (secondary)

Tisdale concluded that this suite represents a multiple source,

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[5]Attempts to obtain a U. S. Geol. Survey open-file report
(Denson and Gill, 1965a) on heavy minerals from formations in the
Williston basin were unsuccessful.

and contains some second cycle components, but it is characterized

by metamorphic species derived from a relatively near source. The

Black Hills are mentioned as a possible sedimentary province. No

samples from the Sentinel Butte were analyzed.

In a study of the Sentinel Butte Formation in the Sperati

Point Quadrangle, just west of the North Unit of Roosevelt Park,

Clark (1966, p. 15-22) found that,

> The lower 160 to 200 feet of the Sentinel Butte Member
> is dominantly grayish, fine to medium-grained graywacke
> sandstone, very fine to coarse-grained siltstone, and silty
> claystone. Most of the graywacke is lithic because it con-
> tains a greater abundance of dark minerals than feldspar;
> however, this is difficult to establish without detailed
> analyses. Quartz and chert are common constituents of the
> sandstones and siltstones. The upper part of the section
> is dominantly gray, yellow, and brownish graywacke sandstone,
> siltstone, claystone, bentonitic claystone, shale, and lignite.
> Heavy mineral analyses of graywacke sandstone from the
> lower part of each measured section reveal an abundance of
> the platy minerals with lesser amounts of amphibole, pyroxine,
> pyrite, tourmaline, epidote, garnet, barite and magnetite.
> . . . Microscopic studies reveal the presence of vol-
> canic ash in the form of glass shards throughout much of the
> Sentinel Butte Member. The shards are most abundant in silt-
> stones and sandstones, and especially bentonitic claystones.
> These shards range from acicular fibrous shapes to splinters,
> are 0.25 to 1.00 mm long, and colorless, greenish, brown and
> black.

Clark did not report the weight per cent of heavy mineral

fractions.

Crawford (1966, p. 22-23) compared the mineralogy of the sand

fraction of several samples from the Tongue River and Sentinel Butte

Formations at Bullion Butte. He found quartz, feldspar, and dolomite

to be the most abundant minerals in both units. In addition to

crystalline quartz and chert, similar to that cited by Tisdale, some

rose quartz was observed. Both orthoclase and plagioclase (assumed

to be andesine) were reported. Mica was found in both formations,

but muscovite and biotite were stated to be diagnostic of the Tongue River and biotite to be most abundant in the Sentinel Butte.

Heavy mineral separations were made by Crawford (1966) for comparison of 10 Tongue River and 10 Sentinel Butte samples; the heavy mineral suite reported consists of:

"carbonate" (dolomite)	hornblende
muscovite	pyroxene (? pigeonite)
biotite	zircon
magnetite	apatite
garnet	staurolite
chlorite	tourmaline
epidote	kyanite

The Tongue River Formation was found to contain more carbonate, chlorite, hornblende, and muscovite, whereas Sentinel Butte samples contained greater amounts of magnetite, zircon, biotite and apatite. Crawford agreed with Tisdale's conclusions regarding origin of the suite and the proximity of the sediment provenance. Crawford did not report the weight per cent composition of heavy mineral fractions, thus no comparison can be made of the relative abundance of heavy minerals in the two formations.

Sigsby (1966, p. 68) reported results of mineral analysis of 18 samples from the South Unit of Roosevelt Park. These were collected at 2.5-foot intervals above the HT Butte bed and thus (presumably) represent the basal Sentinel Butte sand. Quartz and feldspar are present in subequal amounts (about 20 to 50 per cent), the former being more abundant. Quartz is present in both crystalline and cryptocrystalline form. Oligoclase was determined to be the

most abundant (14 to 32 per cent) plagioclase; andesine was present in minor amounts. Orthoclase was present in amounts of 2 per cent or less. Carbonate (dolomite) values for these samples appear rather high and gypsum is reported to constitute between 15 and 50 per cent of all but one sample. These minerals are probably second-ary and their inclusion with the allogenic suite is somewhat mis-leading. Exclusion of values for carbonate, gypsum, and carbona-ceous material leaves a reported light mineral suite composed of quartz, two species of plagioclase, minor amounts of orthoclase, and trace amounts of sericite and microcline.

Sigsby separated heavy minerals from ten of the coarser samples cited above. The suite consisted of the following minerals.

biotite	hornblende
epidote	pyroxine
almandite	anhydrite
magnetite	siderite
apatite	chlorite
zircon	sphene
rutile	tourmaline

Traces of kyanite and leucoxene were also mentioned. Iron oxides were not removed prior to separation, and their presence results in high values of per cent weight for the heavy mineral fractions. Recal-culation of Sigsby's data, omitting iron oxides, is not possible because the total heavy mineral fraction is reported as weight per cent and mineral abundances are given as number per cent. An approx-imate correction, however, gives a range for per cent weight of

heavy minerals between 0.2 and 0.95.

Almandite and epidote are the most common heavy minerals, and are present in subequal amounts (5 to 30 and trace to 25 per cent, respectively). The almandite contains magnetite inclusions. Biotite was reported present in all samples and constitutes 5 to 15 per cent of the heavy fractions. Magnetite, apatite, and zircon were common, concentrations ranging from 2 to 15 per cent. Other reported minerals were present in minor amounts.

Sigsby (p. 70) agreed with Tisdale that the heavy mineral assemblage indicates a metamorphic source. Particular attention is directed to the presence of kyanite and tourmaline.

The writer differs with the interpretation of the investigators cited above who suggested a primary metamorphic source for even a portion of the Tongue River-Sentinel Butte sequence. An outstanding conclusion of the data reviewed is that the heavy mineral component of Tongue River and Sentinel Butte sediments is very minor, and the metamorphic minerals within this component are almost negligible. For example, Sigsby reported a trace of kyanite from only one sample (number 15) and traces of tourmaline in only two samples (numbers 10 and 12). Likewise, Tisdale (p. 29) found a "few angular grains" of andalusite in three samples and a "few grains" of kyanite in five samples. Both metamorphic suites are most probably residual. Tisdale's suite from the basal Tongue River is slightly more mature than that of Sigsby (and others) from the Sentinel Butte Formation, but the failure of each of these workers to present complete data on weight and number percentages (disregarding differences in analytical technique) makes quantitative comparison of their results impossible.

The best comparison of Tongue River and Sentinel Butte sediments can be made with their light mineral suites; the same limitations cited for comparison of heavy minerals applies to this suite. In the writer's opinion, it can be qualitatively stated that Tongue River sediments are more mature than Sentinel Butte sediments. Tongue River sandstones contain greater percentages of stable minerals (resistates) and fewer labile minerals. Many of the Tongue River sandstones would classify (Pettijohn, 1957, p. 291) as protoquartzitic and feldspathic; Sentinel Butte sandstones tend toward a lithic graywacke and feldspathic graywacke composition. These differences are apparent in field examination.

Reactive carbonate content.--Total reactive carbonate content, measured by the rapid titrametric method of Herrin, and others (1958; Appendix I), was determined for samples from stratigraphic sections in the Tongue River and Sentinel Butte Formations. The distribution of carbonate values for the two formations, reported as per cent weight CO_3, is shown in Figure 32; data for individual stratigraphic sections are given in Table 14.

Measured values of CO_3 range between 0 and 41 per cent in Tongue River and between 0 and 32 per cent in Sentinel Butte sediments; mean values are 12.1 and 6.5 per cent, respectively. The distribution of values for both formations are unimodal, but Tongue River samples have a broad, rather uniform distribution whereas nearly 85 per cent of the Sentinel Butte samples contain less than 10 per cent CO_3.

The distribution of CO_3 values as a function of mean grain size is shown in Figures 33 and 34. Sentinel Butte samples with mean diameters coraser than about 7 phi show a weak positive correlation
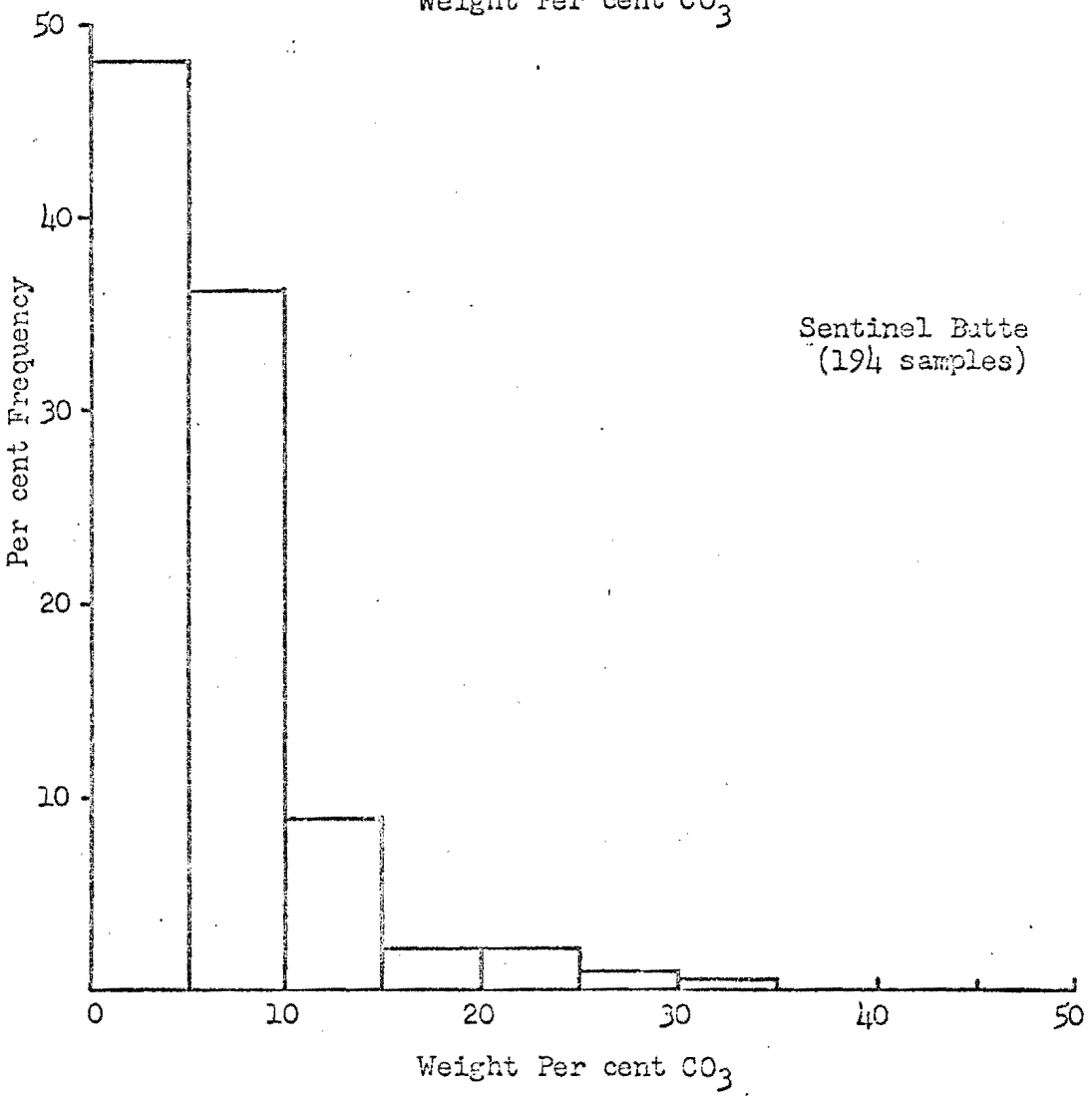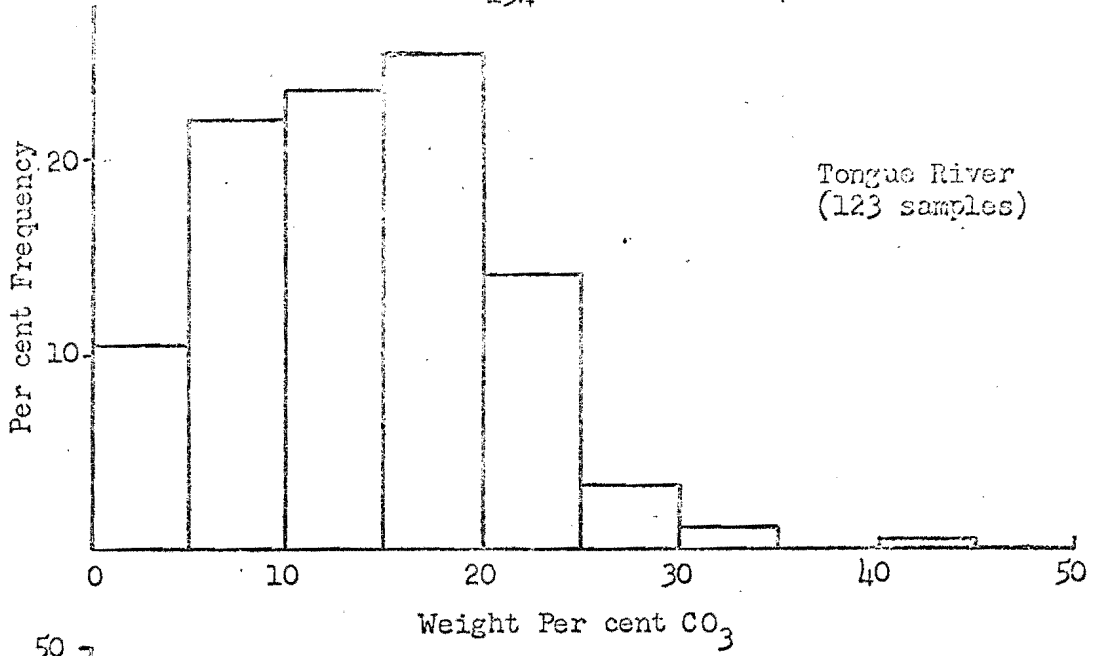
Figure 32.--Distribution of CO_3 in stratigraphic samples from the Tongue River and Sentinel Butte Formations.

TABLE 14.--Average carbonate values for stratigraphic samples from Tongue River and Sentinel Butte stratigraphic sections (nil measurements have been omitted).

Section	Number of samples	Weight CO_3 (%)	Weight $CaCO_3$ (%)
Sentinel Butte			
Bullion Butte	36	5.0	8.3
Sentinel Butte	64	7.8	12.9
Beicegel Creek	21	9.2	15.3
Long Cross	57	5.9	9.8
Lost Bridge	41	5.2	8.6
Total	219		
Weighted mean		6.5	10.8
Tongue River			
Bullion Butte	25	13.0	21.3
Medora	37	13.0	21.3
Beicegel Creek	19	10.6	17.6
Yellowstone	30	15.5	26.6
Snowden	18	14.3	23.7
Donnybrook	7	9.2	15.3
Total	136		
Weighted mean		12.1	20.1

Phi Median

Figure 33.--Plot of carbonate vs. median diameter for stratigraphic samples from the Sentinel Butte Formation.

Figure 34.--Plot of carbonate vs. median diameter for strati-
graphic samples from the Tongue River Formation.

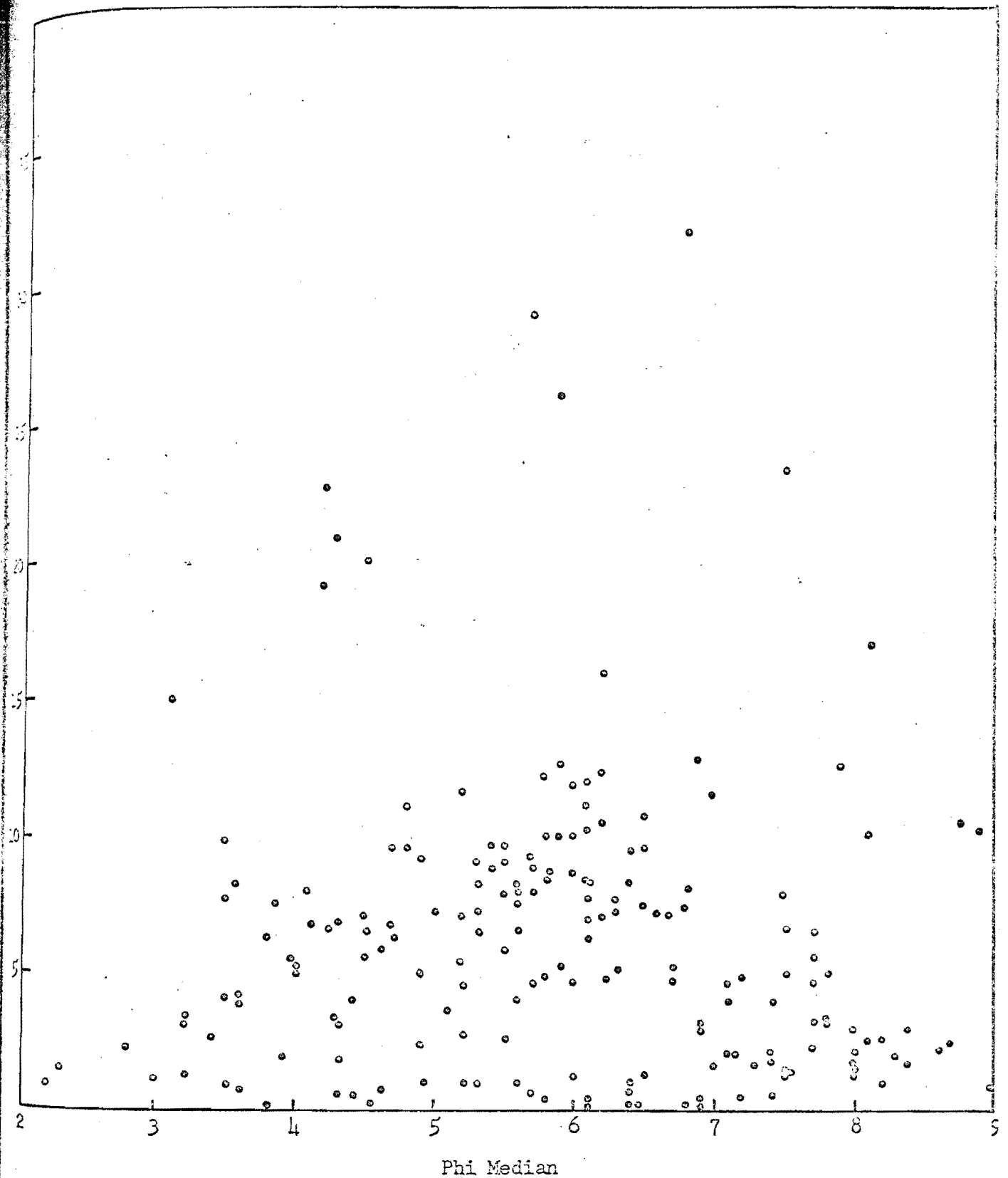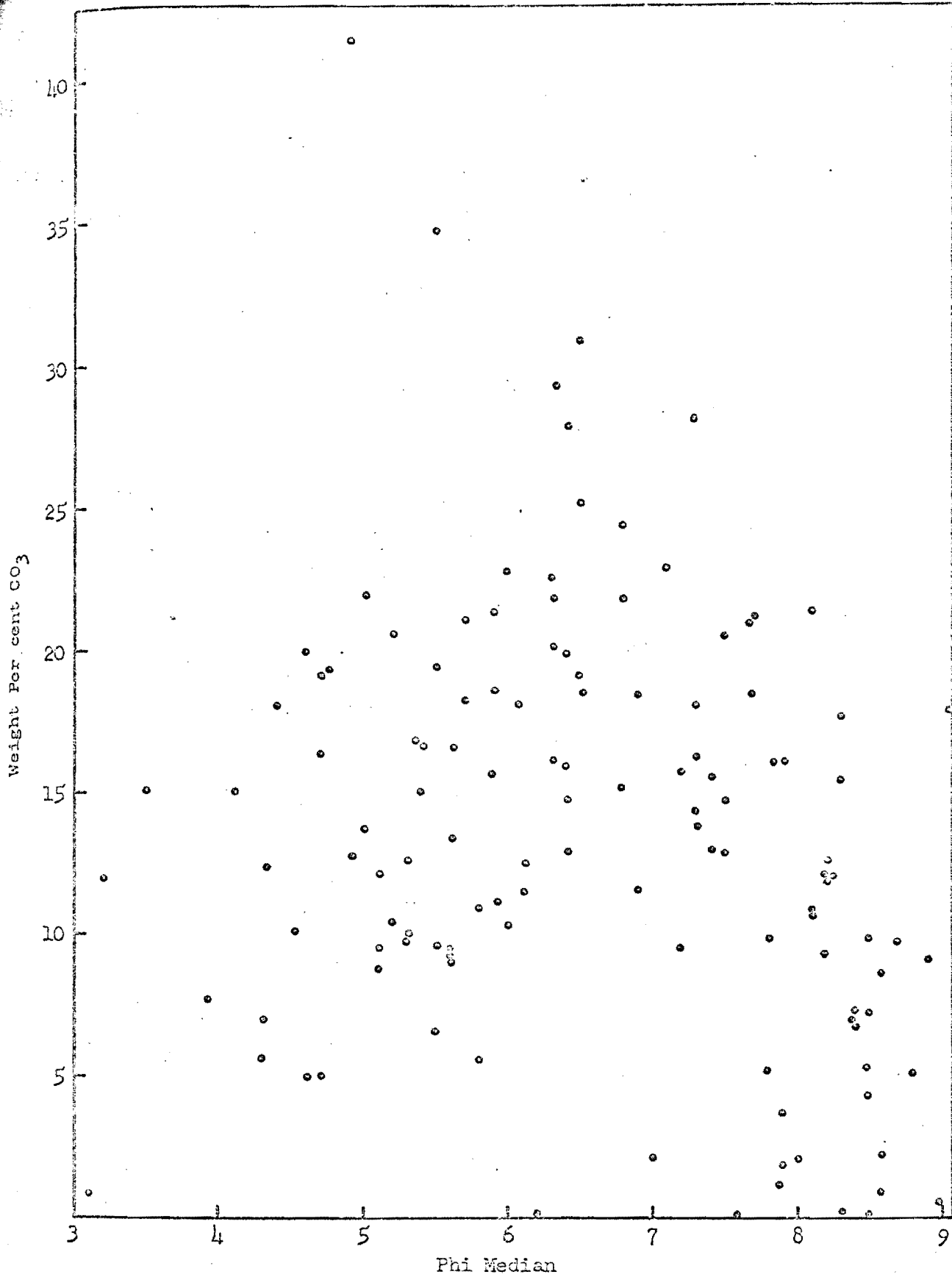with carbonate content, mean values greater than 7 phi show a marked decrease in carbonate content. The same trend is apparent in the Tongue River distribution, but the function is spread over a greater range of CO_3 values. These functions may lack significant linear correlation, but the weak trends and the tendency to group probably have interpretive value.

Carbonate values from the Sentinel Butte Formation greater than 20 per cent are all from the stratigraphic section at Sentinel Butte. Plots of carbonate content as a function of median grain size for the various stratigraphic sections are included in Appendix II-F.

Dolomite content.--Sediments of both the Tongue River and Sentinel Butte Formations contain significant amounts of dolomite. Dolomite content was investigated in sixty-one freshwater limestones collected from both the Tongue River and Sentinel Butte Formations, in 54 samples of the basal sand of the Sentinel Butte Formation, and in selected samples from the Medora, Snowden, and Sentinel Butte stratigraphic sections. Because dolomite is almost certainly of diagenetic (secondary) origin, it has less interpretive value in the present study than does total (primary) carbonate. Its presence was initially investigated in hopes that a regional dolomite gradient might be defined, which would contribute to an understanding of the source, transport, and implacement of metallic ions, including uranium. Although no success was achieved in this attempt, data of interest were obtained and these are presented below.

Weight per cent dolomite was determined from X-ray diffraction peak-height intensities according to the procedure of Weber and Smith (1961). As estimated from analysis of standard samples and comparison

of results with those obtained by analogous techniques (for example Gulbrandsen, 1960), the method has a relative accuracy within about three to four per cent of reported values. Although not highly precise, the method provides a good relative index to dolomite content.

Freshwater limestones were sampled for regional comparison of dolomite in the two formations because they are easily distinguished from a distance in the field, have fairly uniform texture, and may be presumed to have been equally susceptible (lithologically) to the post-depositional factors responsible for dolomitization. Also, they contain the greatest amounts of carbonate, which increases the relative accuracy of the dolomite determination. All limestones are argillaceous and average about 42 or 43 per cent CO_3 (70 per cent $CaCO_3$). Samples were collected from various stratigraphic positions, but the majority were taken from the upper third of the Tongue River and the lower third of the Sentinel Butte sequences.

As shown by the histograms (Figure 35), the distribution of dolomite in Sentinel Butte samples is markedly bimodal. As stated, no regional gradient can be detected, but a stratigraphic trend of increased dolomite content upward in the Sentinel Butte section is suggested. Of the seven samples containing greater than 90 per cent dolomite, three are from upper, three from middle, and only one from lower Sentinel Butte strata. Tongue River limestones are more consistent in dolomite content, over 70 per cent containing between 10 and 20 per cent dolomite.

Calcite-dolomite ratios for selected stratigraphic sediment samples (exclusive of limestones) from the Medora, Snowden, and
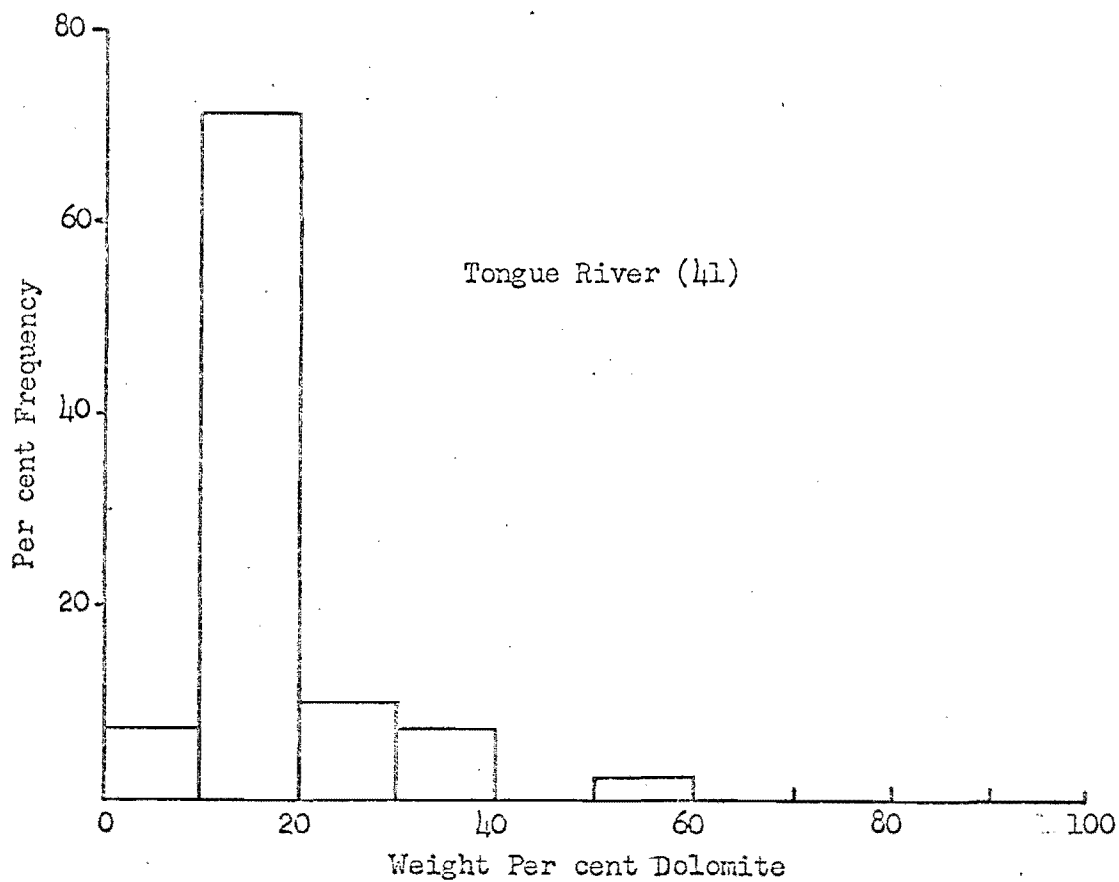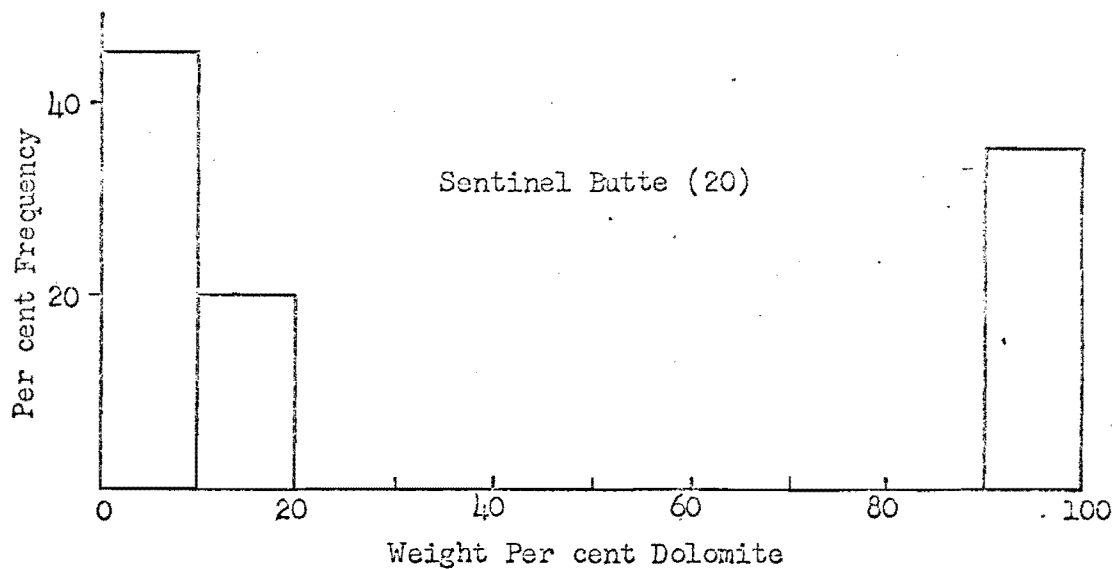
Figure 35.--Distribution of weight per cent dolomite content of limestone samples from the Tongue River and Sentinel Butte Formations.

Sentinel Butte sections were also inspected. These ranged between 0.2 and 10, and averaged 1.51 in the Snowden (17 samples) and 3.99 in the Medora (18 samples) sections. Six samples from the Sentinel Butte section ranged from 6.2 to 19.4 and had a mean value of 12.3. Stratigraphic data are sporadic, and highly dolomitic lithologies occur in both the Tongue River and Sentinel Butte Formations. The above data suggest that slightly greater amounts of dolomite occur in Tongue River sediments; however, this trend is countered by large dolomite values for the basal Sentinel Butte sand (presented in a subsequent section; see Figure 44), and more analyses are needed for a confident statement as to the relative degree of dolomitization of the Tongue River and Sentinel Butte Formations.

Fossil components.--Systematic paleontology is beyond the scope of this report, and elements of the fauna and flora of the Tongue River-Sentinel Butte interval are treated here as sediment components. It will suffice for the present to establish three factors regarding the fossils: (1) their general ecologic character, (2) their occurrence in various sediment types, and (3) their relative abundance in the Tongue River and Sentinel Butte Formations.

The megascopic fossil assemblage of the Tongue River-Sentinel Butte sequence consists of invertebrate, vertebrate, and plant remains. Plant remains are nearly ubiquitous throughout the Paleocene Series of the Rocky Mountains and Great Plains, and the flora (170 species) has been comprehensively reviewed by Brown (1962). All identifiable plant remains collected by the writer are included in the genera discussed by Brown, and no additional comments are warranted here.

Invertebrates consist primarily of mollusks, both clams and snails, of freshwater and terrestrial habit. The most recent accounts of this fauna are given by Yen (1946, 1947) and Tozer (1956). Yen described 22 species of mollusks from Wyoming and southern Montana, most of which were collected from Tongue River strata. The fauna appeared to be divisible into two assemblages at the horizon of the Wall coal bed, which occurs about a third of the way above the base of the Tongue River Formation. The general ecology of the fauna was stated by Yen (1947, p. 36) as follows:

> The abundant occurrence of viviparids and unios implies that the enclosing rocks were fluviatile deposits. These forms in the living fauna exist more commonly in rivers of various sizes.

Tozer (1956) has discussed the uppermost Cretaceous and Paleocene molluscan faunas of western Alberta and offered taxonomic revisions. This work is perhaps the best available guide for study of the Tongue River and Sentinel Butte invertebrate faunas.

It is important, for environmental considerations, to establish the lithologies in which the fossils occur and whether evidence of transport is apparent. That is, it is necessary to know whether or not fossils are indigenous within the depositional environment. It is not always possible to make this judgment, but fossil occurrences are most generally of one of several types. Coquina-like beds are found which contain many well preserved shells (dominantly snails) in a sandy matrix. Such beds are rare and have been noted only in Tongue River strata. Mollusks are found also in sand bodies as isolated clusters of well preserved individuals. Pelecypods are the most common component of such assemblages and are usually entire with

both valves present and closed. Such occurrences are not frequent, but the excellent preservation of these specimens and the ease with which they can be removed from the outcrop makes them outstanding. Shell-hash layers are also found but, although not rare, are actually less common than deposits of well preserved remains. Most commonly, mollusks are found in thin zones, several inches thick, of limited lateral extent, or as isolated individuals dispersed throughout fine-grained beds.

Conclusions regarding the relative abundance of mollusks in various sediment types is complicated by selective preservation. The writer is of the opinion that greater numbers of fossils are contained in the clayey silts and silty clays, but these are invariably compressed and fragmentation upon exposure is facilitated by swelling of clay minerals. Crawford (1967, p. 36) found fossils in varied lithologies and, although "shales" adjacent to lignite beds appeared to have more fossils than most beds, he concluded that little generalization could be made regarding fossil occurrence and lithology. Clark (1966), in his study of the Sentinel Butte strata of the Sperati Point Quadrangle, found (p. 25) mollusks to be confined to claystone or clayey siltstone beds. Mollusks were reported as absent from sandstone beds.

Detailed inspection of Tongue River and Sentinel Butte beds at many localities throughout western North Dakota has convinced the writer that invertebrate fossils are far more abundant in Tongue River than in Sentinel Butte strata. This conclusion is supported by Crawford (1967) who reported seven fossil localities in his

stratigraphic section of Tongue River strata, at Bullion Butte,
but found only a few scattered pelecypods, gastropods, plant fossils,
and fish scales in the overlying Sentinel Butte. Similarly, Clark
(1966, p. 25) found mollusks to be rare and poorly preserved in the
Sentinel Butte strata of the Sperati Point Quadrangle. It is in-
teresting to note that the lower "yellow" bed, which as previously
noted resembles Tongue River strata, was reported by Clark as the
most fossiliferous unit in the 570 feet of strata present in the
quadrangle. Hanson (1955) noted that, within the Elkhorn Ranch area,
fossil shells were not so abundant in the Sentinel Butte as in the
Tongue River. Hares (1928, p. 37-40) presented an extensive faunal
list for the Tongue River Formation which was composed from 14 col-
lecting localities. In contrast, mollusks were reported from only
one locality in the Sentinel Butte Formation.

Vertebrate fossils are quite rare in both Tongue River and
Sentinel Butte strata, but scattered remains were found in both for-
mations. These include fish scales (ganoid), vertebrae, teeth
(cf. Platacodon nanus Marsh, and others), assorted bone and spines;
crocodile and turtle scutes and bone; crocodile teeth (? Champosaurus);
amphibian tooth plates (cf. Habrosaurus dilatus); and mammalian bone
and teeth (cf. Tricentes and Claenodon). With the exception of one
locality near the base of the Tongue River Formation southwest of
Bullion Butte, most vertebrate material was collected from the Sen-
tinel Butte Formation. The basal Sentinel Butte sand contained
vertebrate material at several localities, but there is no indica-
tion that the interval is more productive than others in the for-
mation.

No firm conclusions regarding the distribution of verte-
brate remains in the Tongue River-Sentinel Butte interval can be
formulated on the basis of collections made during this study, but
the writer is left with the impression that the Sentinel Butte is
probably more productive than the Tongue River. More fossils have
been reported from the latter, but this probably reflects its
greater geographic distribution. It is also likely, based on
studies reported to date, that Paleocene strata farther west con-
tain more vertebrate remains than are present in North Dakota (see
for example, Simpson, 1928, 1929, 1936, 1937; and Jepsen, 1930,
1940).

It seems justifiable to conclude, at least qualitatively,
that the fauna and flora of the Tongue River-Sentinel Butte interval
reflect a fluvial origin for the strata which enclose them. Mollusks
are the predominant faunal component, are most common in finer-
grained sediments, and are far more abundant in Tongue River than
in Sentinel Butte strata. It appears probable to the writer that
taxonomic study of fossils, for which stratigraphic positions are
accurately known, will reveal that the molluscan fauna has biostrat-
igraphic utility.

The basal sand of the Sentinel Butte Formation

For comparison of texture and composition of uppermost Tongue
River and basal Sentinel Butte strata, samples were collected 6 to 8
feet above and below the formational contact at many localities
throughout the study area. An initial objective of sampling was to
determine whether a significant change in carbonate content occurs

across the contact; this objective was achieved. In addition, and perhaps more important, this sampling program resulted in recognition of a distinctive basal unit in the Sentinel Butte Formation. The value of this unit in recognizing the Tongue River-Sentinel Butte contact has been discussed, but the bed has additional significance because it records the first impulse of the change (whatever this may have been) from Tongue River to Sentinel Butte conditions of sedimentation.

Although the ranges of measured values for samples of basal Sentinel Butte sand lie within those for the formation in general (as established by analyses of stratigraphic samples), mean values are significantly different for many parameters. Because of its distinctive features and its interpretative value, the basal Sentinel Butte sand is described separately in this section.

CM relationships.--Figure 36 shows the CM pattern formed by samples of basal sand. Transport types representing floodbasin and fine-grained floodplain deposits are absent from the pattern, and the sediments are considered to be largely the product of substratum deposition (Table 12). This interpretation is consistent with the presence of large-scale primary sedimentary structures within the unit (Figures 3-A,B,C and 4-A).

The range of values of C are roughly the same as found for stratigraphic samples (Table 10), but the value of C_s is slightly greater (about 1.25 phi as compared with 1.5 phi). C_u for the basal sand does not differ significantly from that of stratigraphic samples. The sorting index, I_m, is intermediate among the range of values determined for stratigraphic samples. CM data for the basal
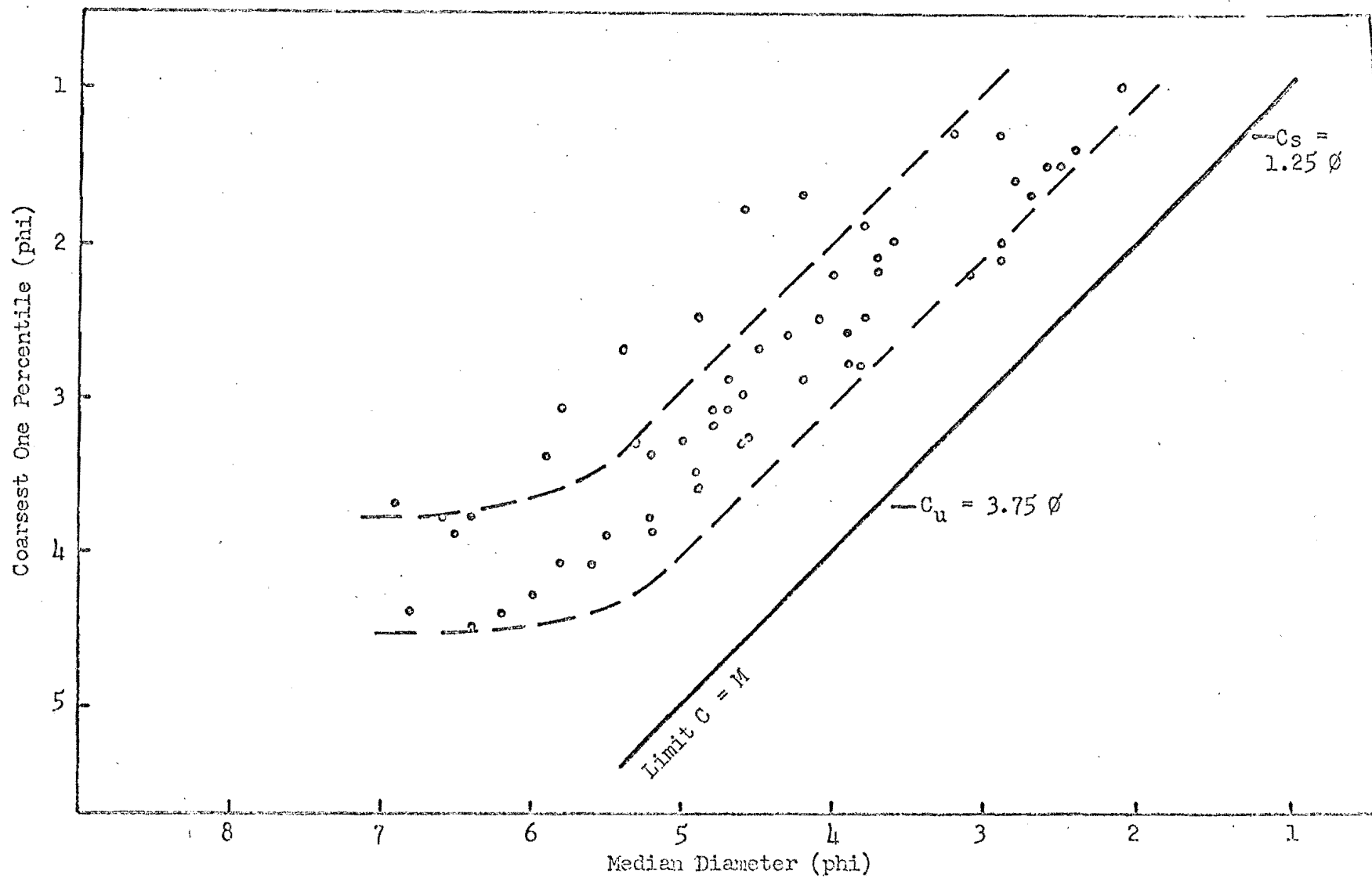
Figure 36.—CM pattern for basal Sentinel Butte sand samples.

sand are included in Table 10.

Sediment size statistics.--The distribution of mean and median particle diameters (average values = 5.01 and 4.53 phi, respectively) in the basal Sentinel Butte sand are shown in Figure 37. The distributions are similar, but the mean values tend to be finer than those for the median. Comparison with data for stratigraphic samples from the Sentinel Butte Formation (Figure 10) indicates that basal sand samples comprise a distribution similar to that of the coarser stratigraphic samples. Samples with means and medians finer than 7 phi are absent. These samples have been defined (Figure 28) as having been transported in "pelagic" suspension and are considered to represent floodbasin deposits; the distributions of mean and median values reflect the absence of this sediment type.

The distribution of sorting coefficients (mean value = 1.69 phi-units) for the basal sand (Figure 38) is similar to that of stratigraphic samples from the Sentinel Butte Formation (Figure 12). The modes and means of the two distributions are nearly identical, but the range of values is less for the basal sand. Comparison of Tables 6 and 15 shows that the major difference between the two lies in the greater percentage of very-poorly sorted, and lesser percentage of moderately and moderately-poorly sorted samples in the basal Sentinel Butte sand.

Folk skewness values (mean value = 0.52) for basal sand samples are all positive (Figure 39) and are dominantly very-fine skewed. The frequency distribution is markedly different from that of stratigraphic samples (Figure 15), the latter having a relatively
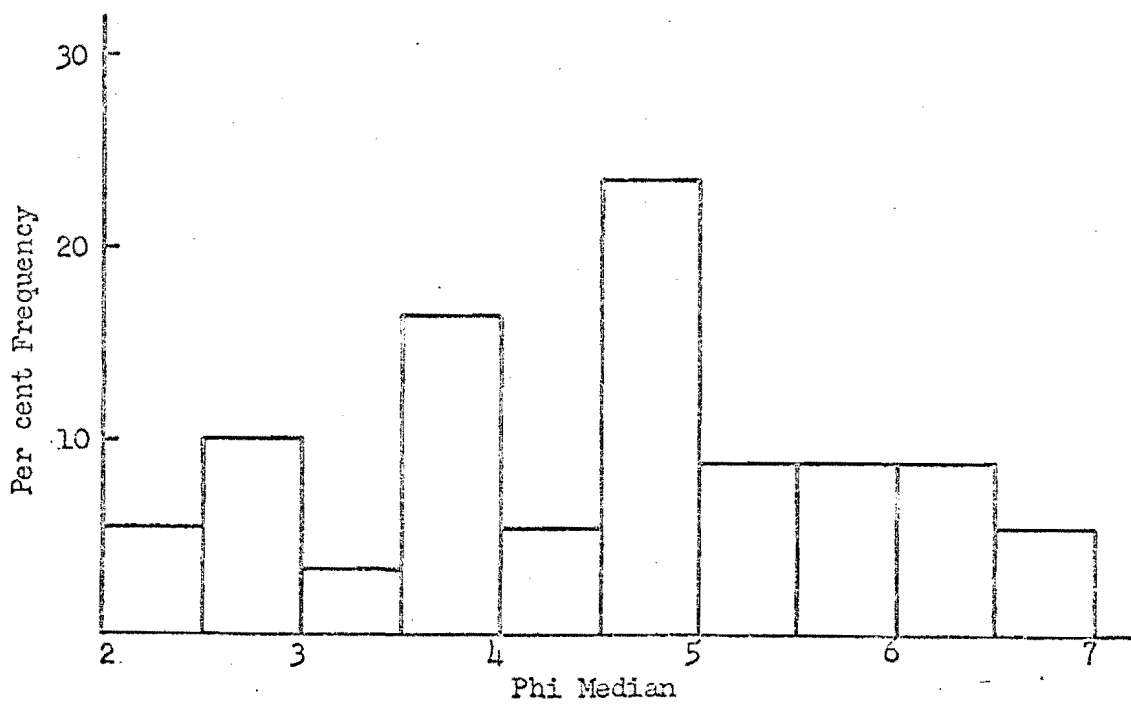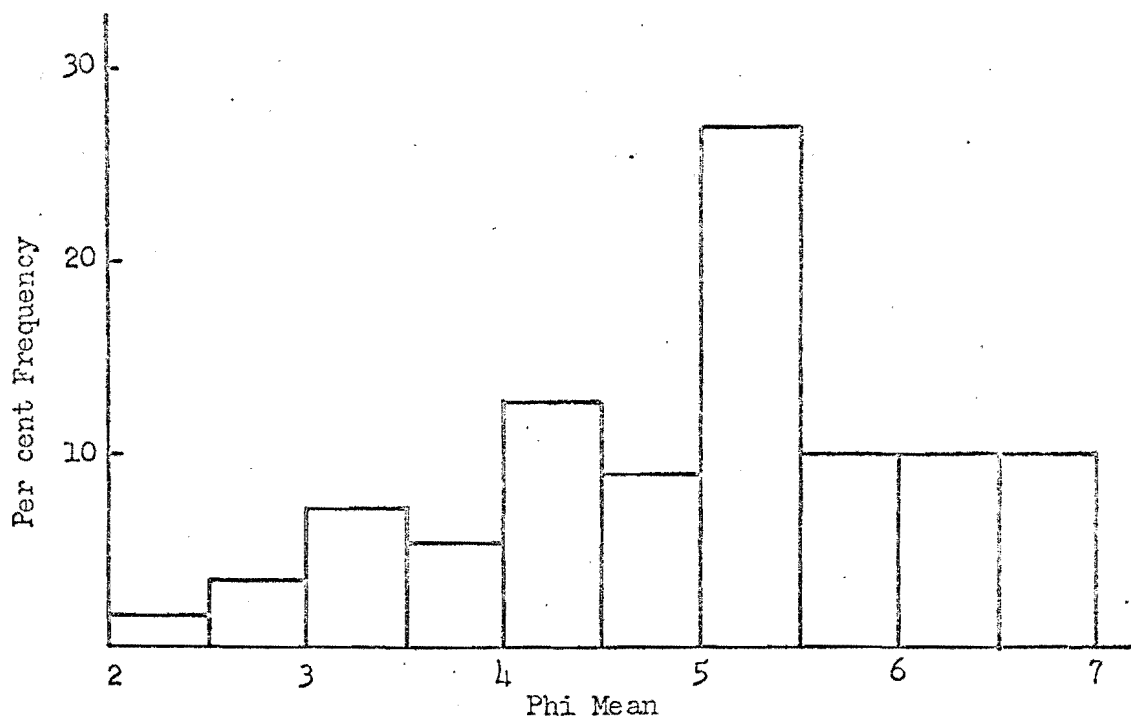
Figure 37.--Distribution of Folk mean and median diameters in basal Sentinel Butte sand samples.
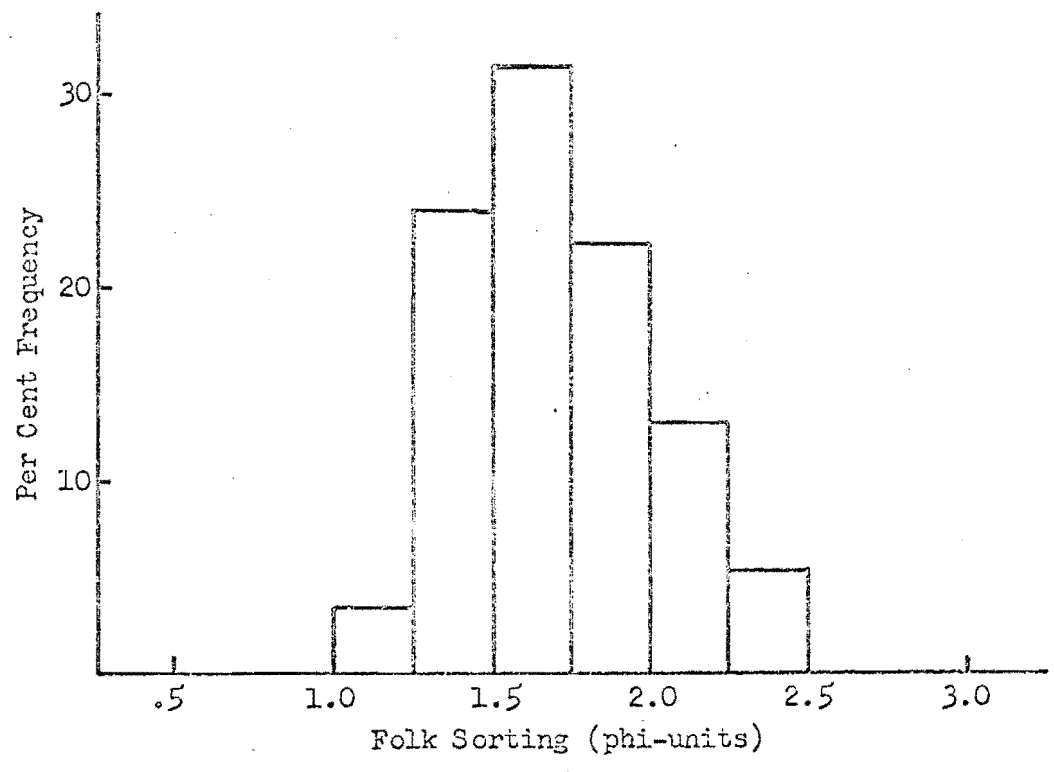
Figure 38.--Distribution of sorting coefficients in the basal Sentinel Butte sand.
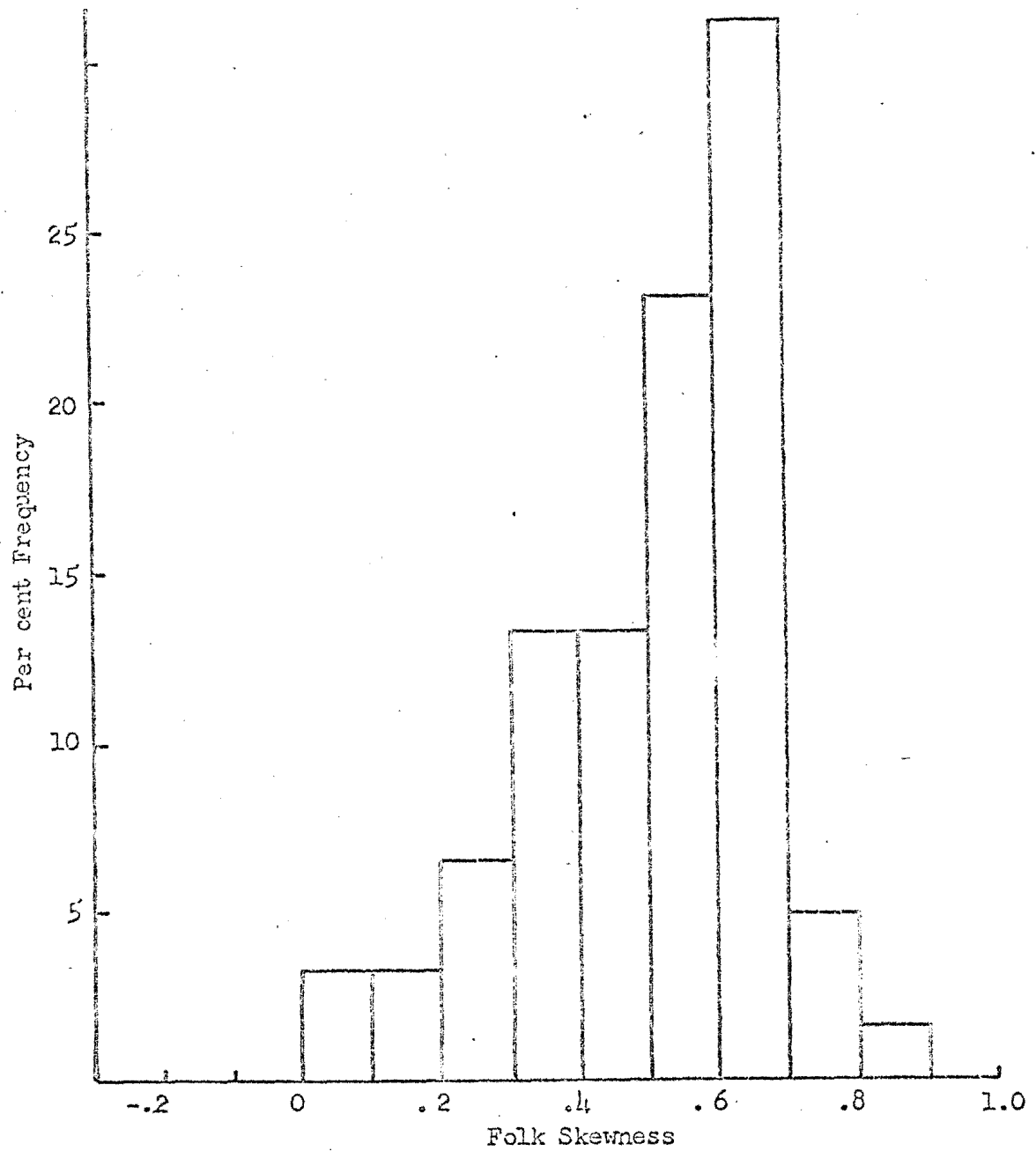
Figure 39.---Distribution of Folk skewness values in samples of basal Sentinel Butte sand.

TABLE 15.--Summary of relative frequency of Folk textural measures
for 57 samples of basal Sentinel Butte sand.

Measured Statistic	Frequency (%)
Sand	0.0
Silty Sand	36.8
Sandy Silt	31.6
Silt	31.6
Poorly Sorted	79.0
Very Poorly Sorted	21.0
Very Fine Skewed	86.0
Fine Skewed	10.5
Nearly Symmetrical	3.5
Very Leptokurtic	35.0
Leptokurtic	45.6
Mesokurtic	14.2
Platykurtic	5.2

greater percentage of samples with a low degree of skewness. These
samples are floodbasin deposits (Figure 30), and their absence in
the basal sand was noted above in the consideration of CM relation-
ships. The range of skewness values, their inverse correlation with
median diameter (coefficient = -0.75), and the absence of floodbasin
deposits are shown in Figure 40.

Kurtosis values for the basal sand (mean = 1.44) have a

Figure 40.--Plot of Folk skewness vs. median diameter for basal Sentinel Butte sand samples.
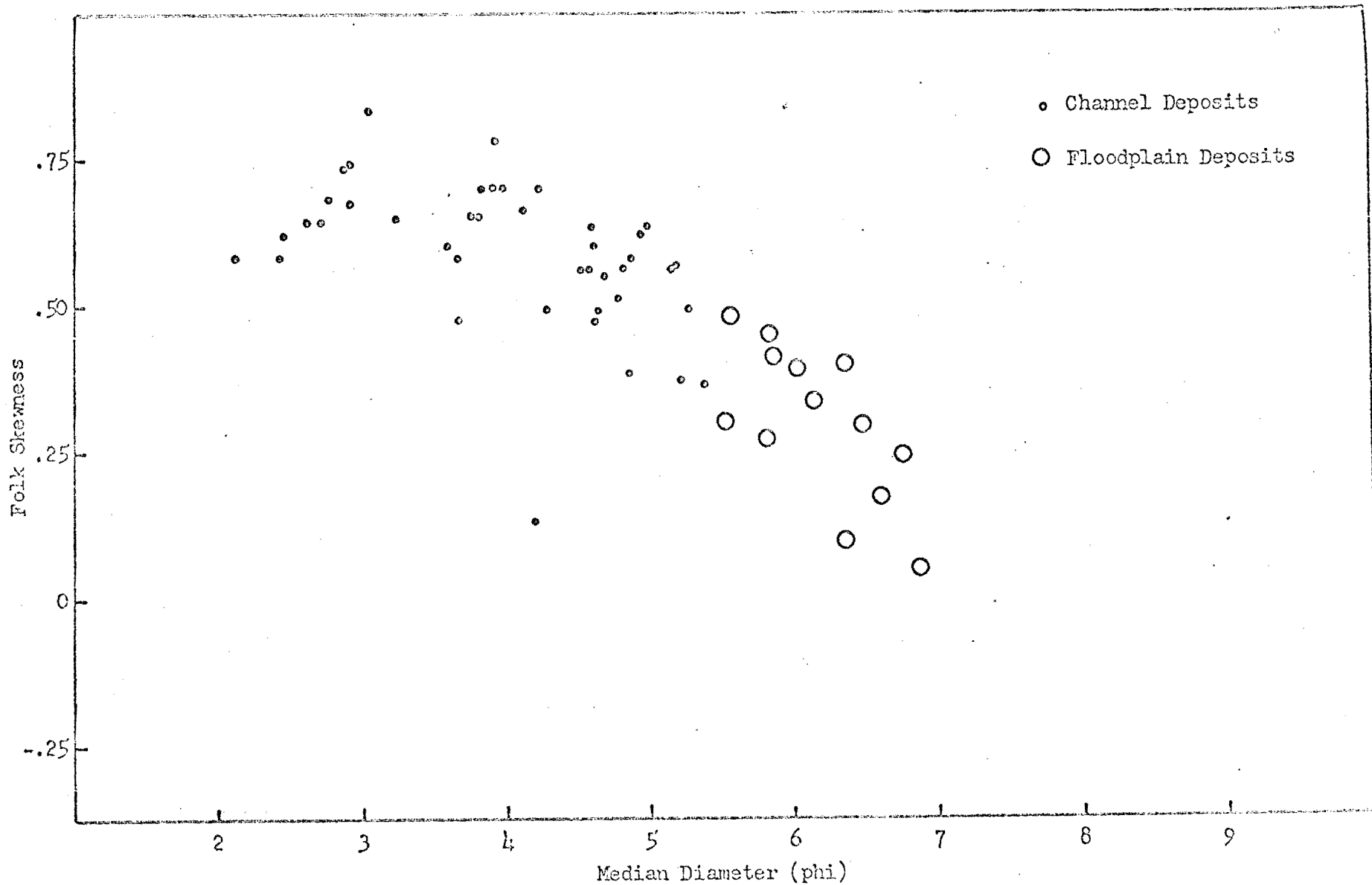
distribution similar to that of stratigraphic samples, but the basal sand contains a greater percentage of leptokuritc and very-leptokurtic samples (81 per cent compared to 64 per cent; Tables 6 and 15). Again, it appears that the greater proportion of mesokurtic and platykurtic samples found in stratigraphic samples represents floodbasin deposits, and this sediment type is not present in the basal Sentinel Butte sand.

Sediment size components.--The distribution of sand, silt, and clay components in samples of basal sand is shown in Figure 41. The absence of silty clay and the paucity of clayey silt sediment types, which are present in stratigraphic samples (Figure 17), reflects the absence of fine-grained overbank (topstratum) deposits in the basal Sentinel Butte bed. Conversely, comparison of Figures 36 and 41 indicates that samples plotting between the sand and silt limits of the triangular diagrams are largely products of graded-suspension transport; this realization aids in interpretation of the sand, silt, clay diagrams for stratigraphic samples (Figures 17 and 18).

Carbonate content.--Total reactive carbonate (Herrin, and others, 1958) was determined for 54 samples of basal Sentinel Butte sand collected 6 to 8 feet above the contact. These data are compared with those for samples collected 6 to 8 feet below the contact (at the same localities) Figure 42.

Basal sand samples have a narrow range of CO_3 values with a mean of 5.51 per cent and a standard deviation of 2.18; uppermost Tongue River samples have a much broader range of values with a mean of 11.0 per cent. The data for the two horizons are comparable to
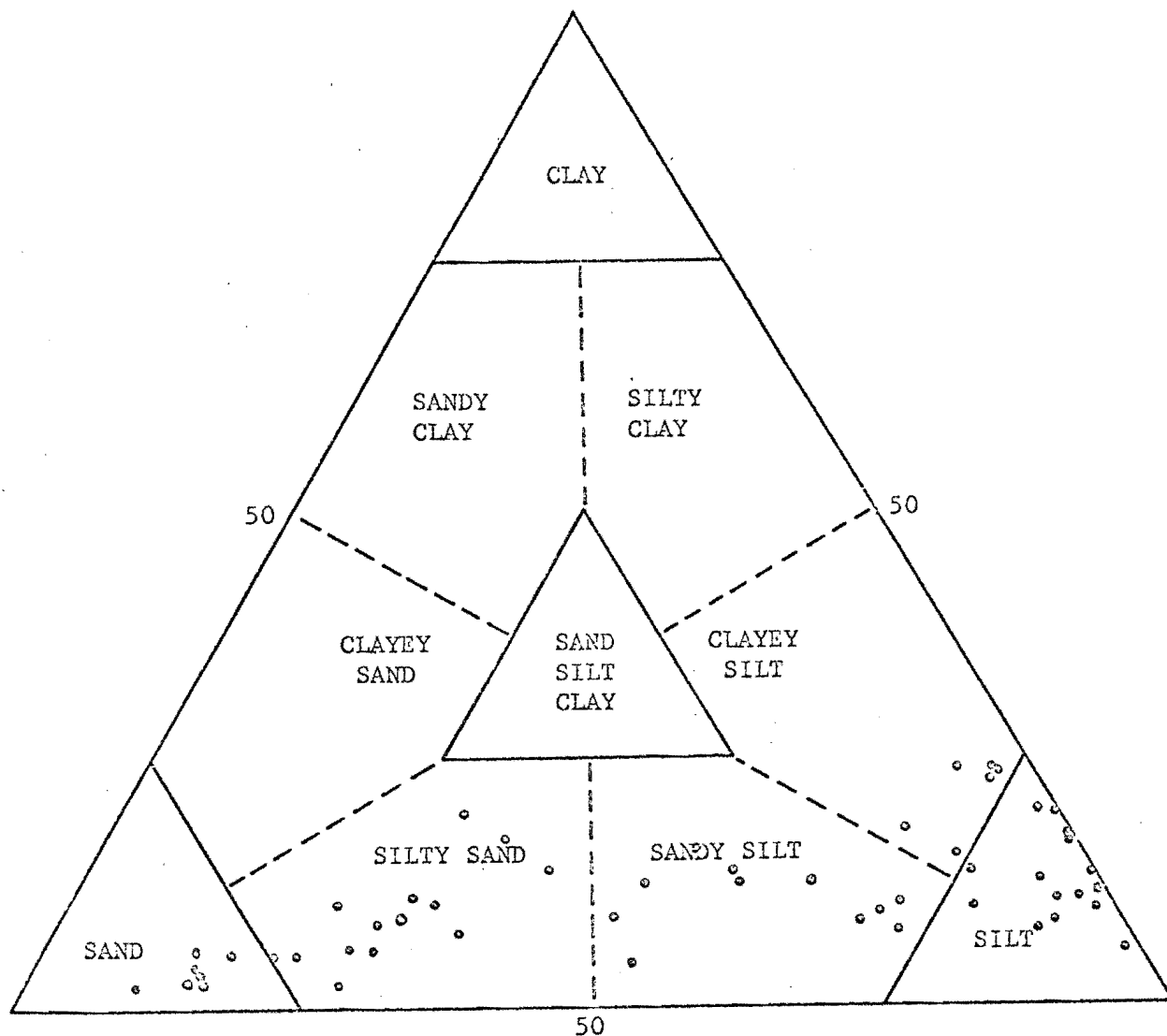
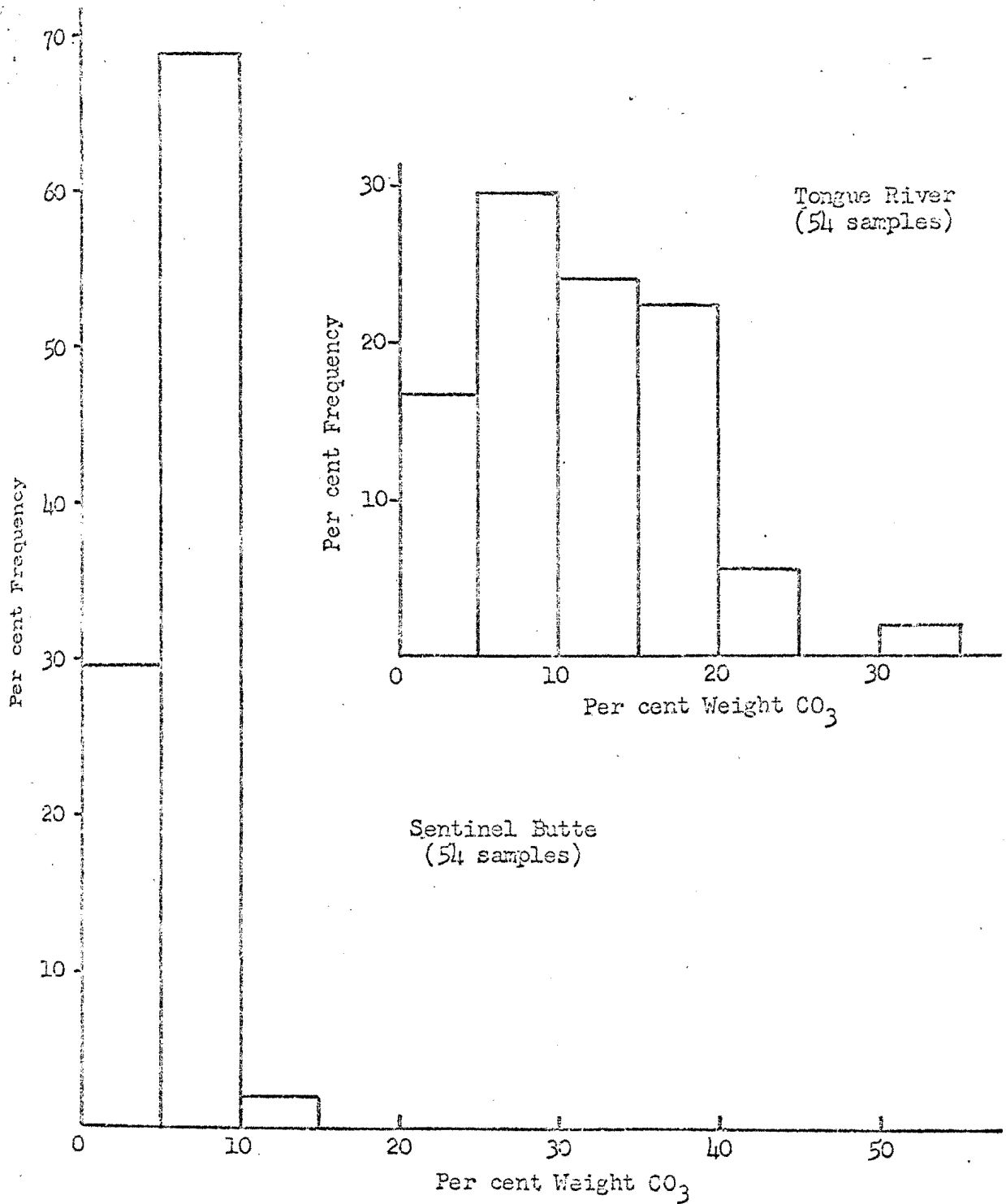Figure 41.—Sand, silt, clay relationships of samples from the basal Sentinel Butte sand.

Figure 42.--Distribution of CO_3 in samples above and below the Tongue River-Sentinel Butte contact.

those of stratigraphic samples from the two formations (Figure 32)
and illustrate the sharp change in carbonate content which occurs
across the Tongue River-Sentinel Butte contact.

A plot of median diameter and per cent CO_3 (Figure 43) shows
a high degree of correlation (coefficient = 0.73) between sediment
size and carbonate content of basal sand samples. The distribution
of points is similar to that noted for stratigraphic samples (Figure
33) with mean diameters coarser than 7 phi. This relationship tends
to confirm the suspicion that the median grain size of channel and
floodplain deposits is inversely related to carbonate content,
and that floodbasin deposits contain only minor amounts of carbon-
ate. The marked decrease in carbonate contents of stratigraphic
samples finer than about 7 phi supports the selection of this size
as a boundary between floodplain and floodbasin sediment types in
the CM diagram of Figure 28 and the plot of Folk skewness vs. median
diameter in Figure 30.

Dolomite content.--The weight per cent dolomite was determined
from X-ray diffractograms (Weber and Smith, 1961) for 52 basal sand
samples. Results (Figure 44) show a wide range of values and their
distribution is polymodal. No correlation exists between dolomite
content and per cent CO_3, but a weak correlation (coefficient = 0.13)
of higher dolomite content in coarser sediments is present (Figure 45).
The high degree of scatter in Figure 45 is partly due to a decrease
in precision of the analytical technique which results from low con-
centrations of total reactive carbonate in the basal Sentinel Butte
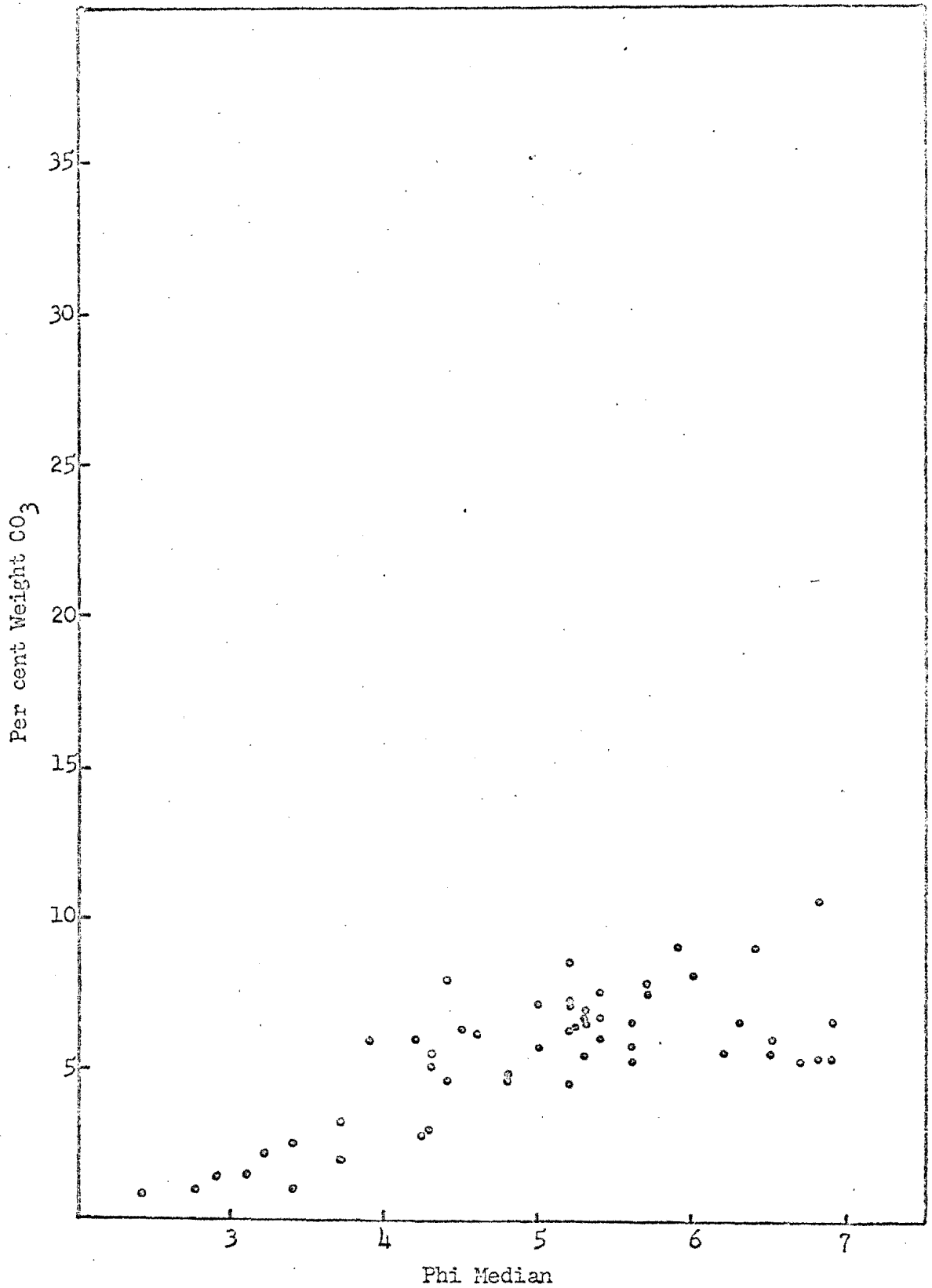sand. The correlation between dolomite and median diameter is

Figure 43.--Plot of per cent weight CO_3 vs. median diameter for basal Sentinel Butte sand samples.
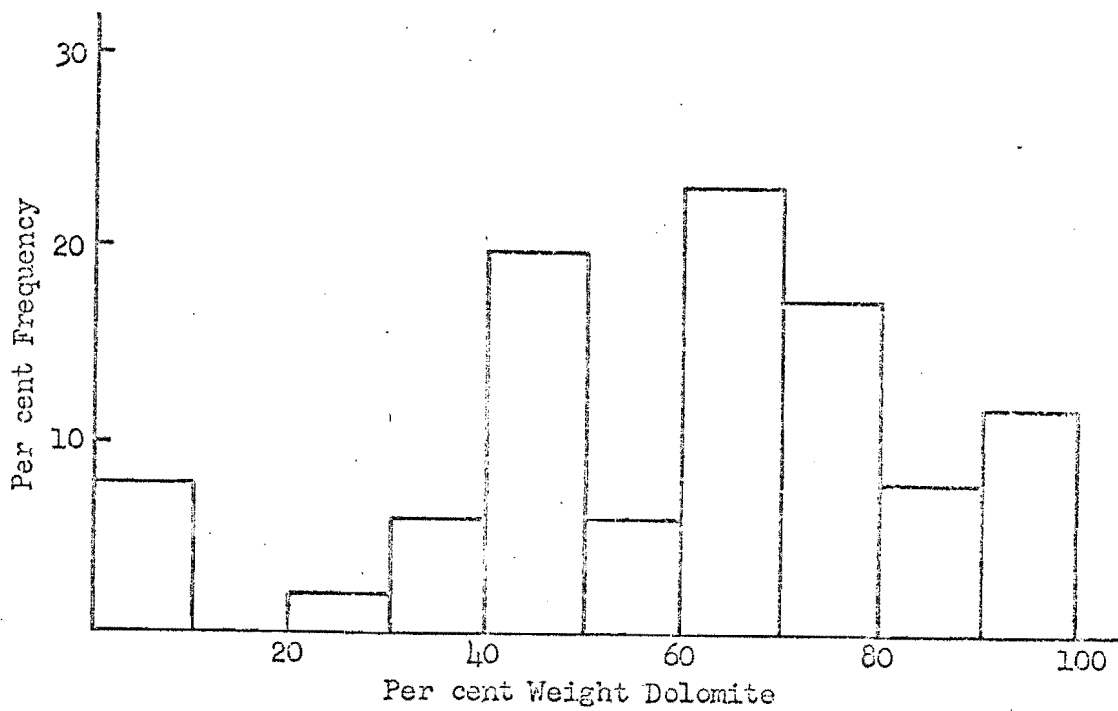
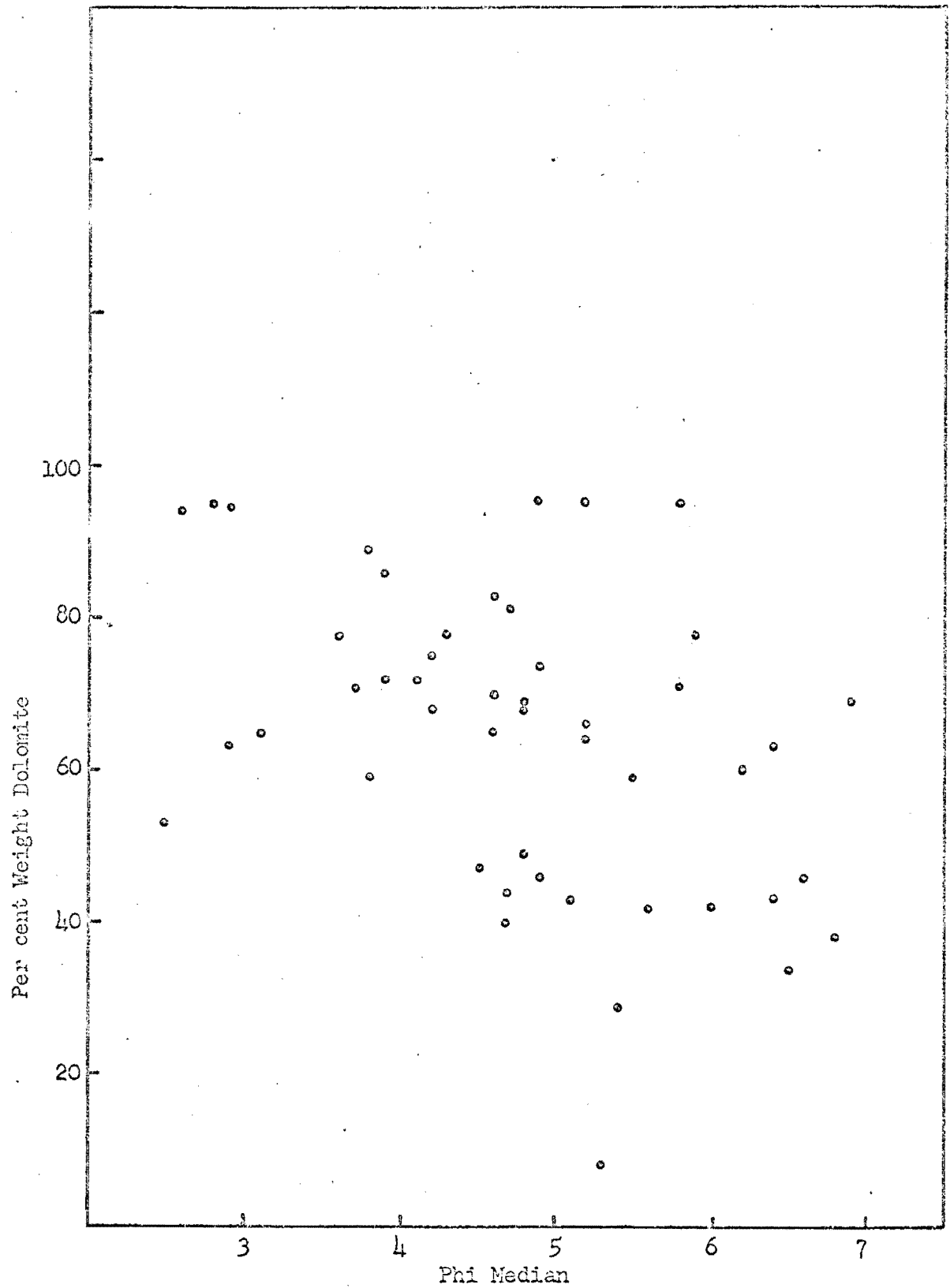Figure 44.--Distribution of weight per cent dolomite in basal Sentinel Butte sand samples.

Figure 45.--Plot of weight per cent dolomite vs. median diameter for basal Sentinel Butte sand samples.

significant because it is inverse to that of total reactive carbonate and median diameter (Figure 43); this suggests that dolomitization is of secondary origin and that its formation is controlled by sediment texture.

Regional distributions.--Basal Sentinel Butte sand samples provide the only sediment data from which regional trends can be established. These samples are not numerous and the lateral sampling interval is too great to reconstruct accurately the distribution of streams and interfluves which must have existed during earliest Sentinel Butte time. The sampling distribution of the basal sand has been smoothed by averaging data for samples (three or fewer) within a single township and shifting means to the northwest corner of the grid. The number of data points was thus reduced from about 54 to 35 and the distribution of variables is somewhat smoothed; the resulting maps indicating the distribution of sediment components are correspondingly generalized. This procedure will tend to mask local variability, but the validity of regional trends (if present) will be increased.

A per-cent-sand map was constructed (Figure 46) which shows the regional distribution of sand in the basal Sentinel Butte unit. Contour patterns of high and low sand content suggest areas of fluves and interfluves. Sediments in the north contain the largest percentages of sand, and low percentages are found along the western margin of the map area. The distribution of mean particle size (Figure 47) complements the per-cent-sand map.

The distribution of per cent total carbonate is shown in Figure 48. Per cent total carbonate is highest in the west and south,
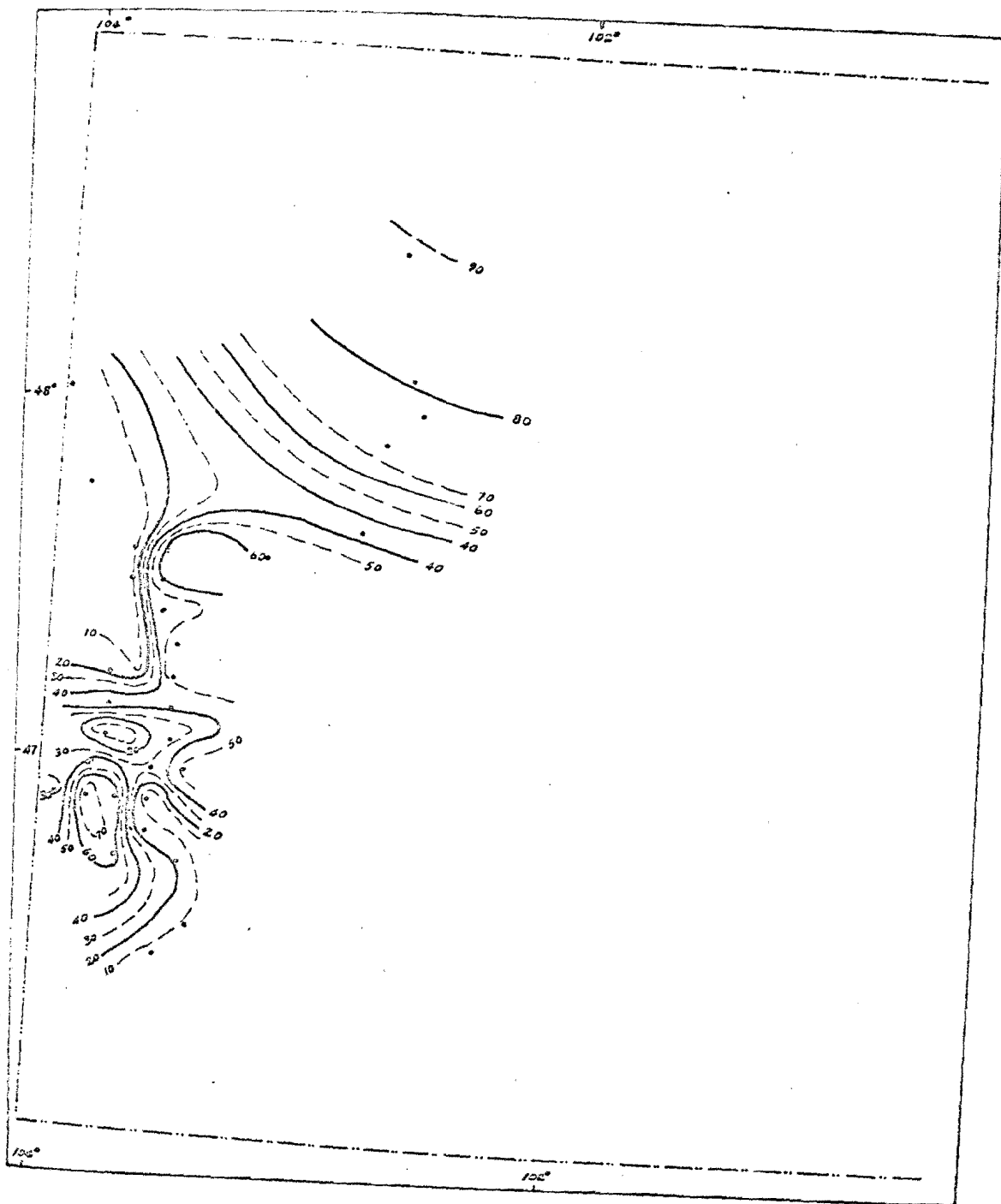
Figure 46.--Per cent sand map for the basal Sentinel Butte sand.
Broken line indicates boundary of western North Dakota.

Figure 47.—Areal distribution of median diameters (in phi) for basal Sentinel Butte sand samples. Broken line indicates boundary of western North Dakota.

Figure 48.--Areal distribution of per cent weight total reactive carbonate in basal Sentinel Butte sand samples. Broken line indicates boundary of western North Dakota.

and decreases northeastward. Comparison with the distributions of sand content and mean diameter shows that the finer-grained sediments in the west and south contain greater percentages of carbonate; this is a regional namifestation of the relationship established in Figure 43.

Per cent dolomite (Figure 49) shows a regional distribution pattern similar to that of sediment textural parameters. Areas of low dolomite content correspond roughly with areas of low per cent sand and fine median particle size. The tendency toward greater dolomite content in coarser-grained sediments inferred by Figure 45 is thus also apparent in the regional distribution of these components.

The combined regional relationship of per cent sand, mud (silt plus clay), and total carbonate are indicated in the triangle facies map of Figure 50. Despite the patchiness of the various facies (which is characteristic of triangular facies maps), the trends established above are apparent.

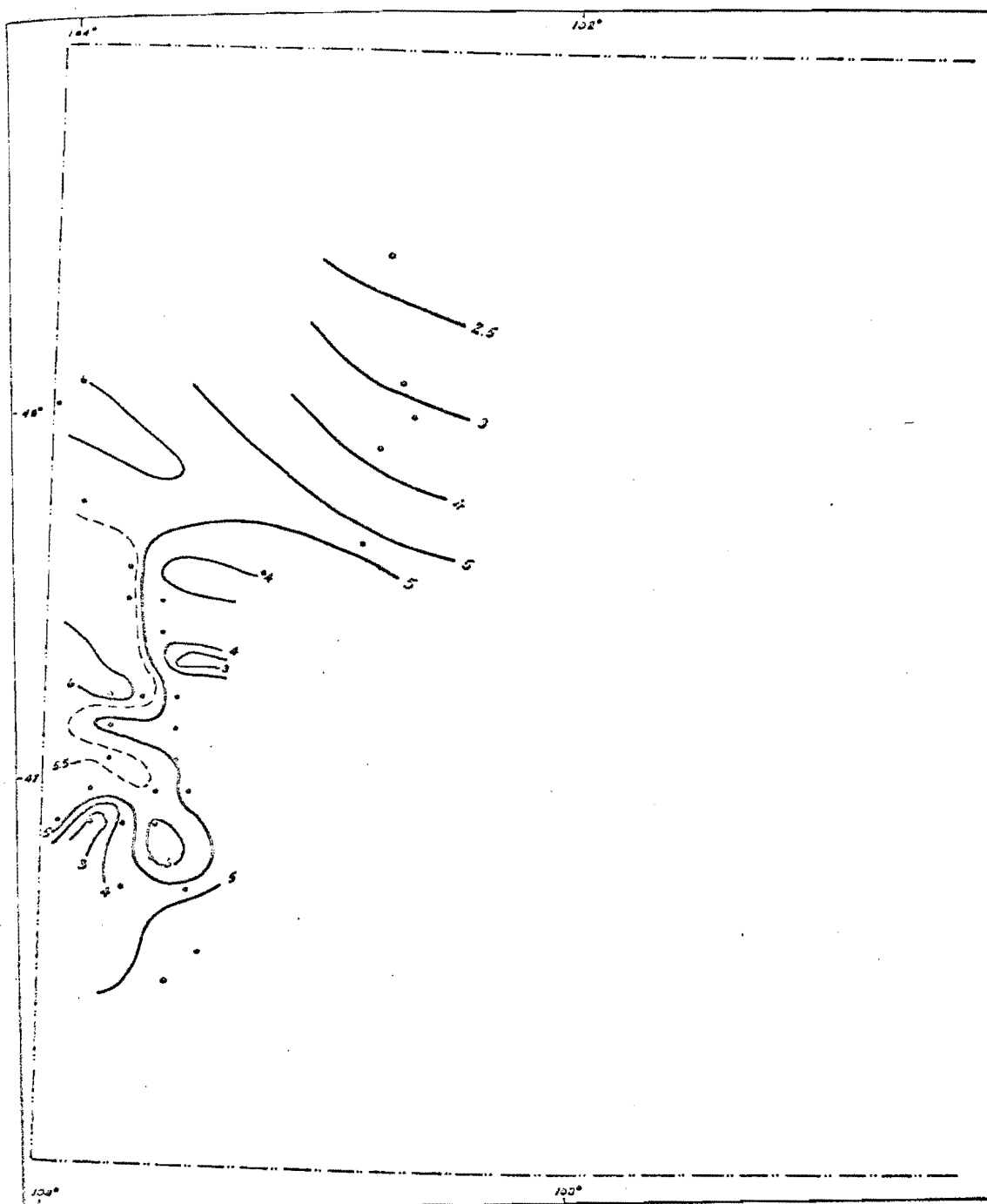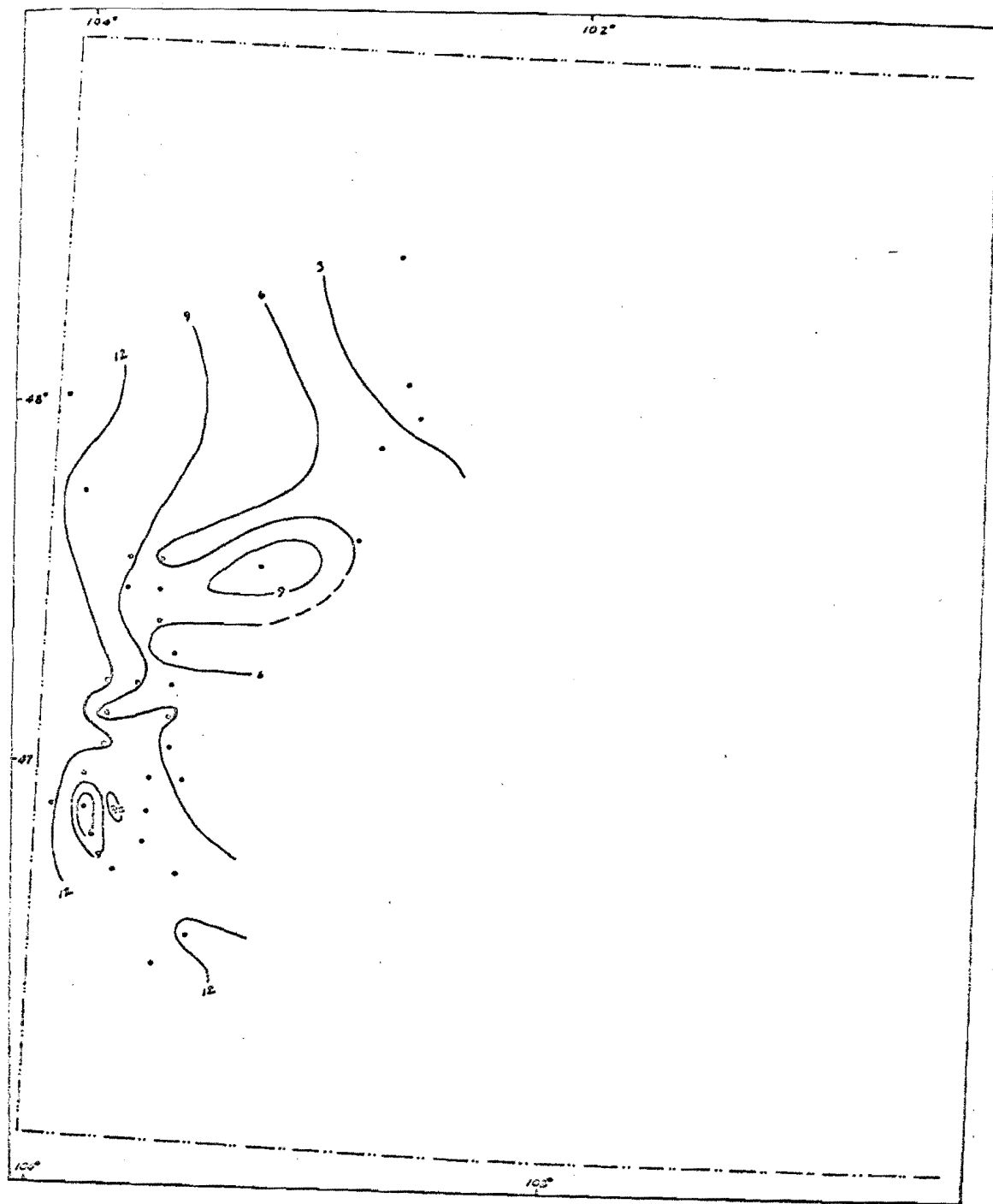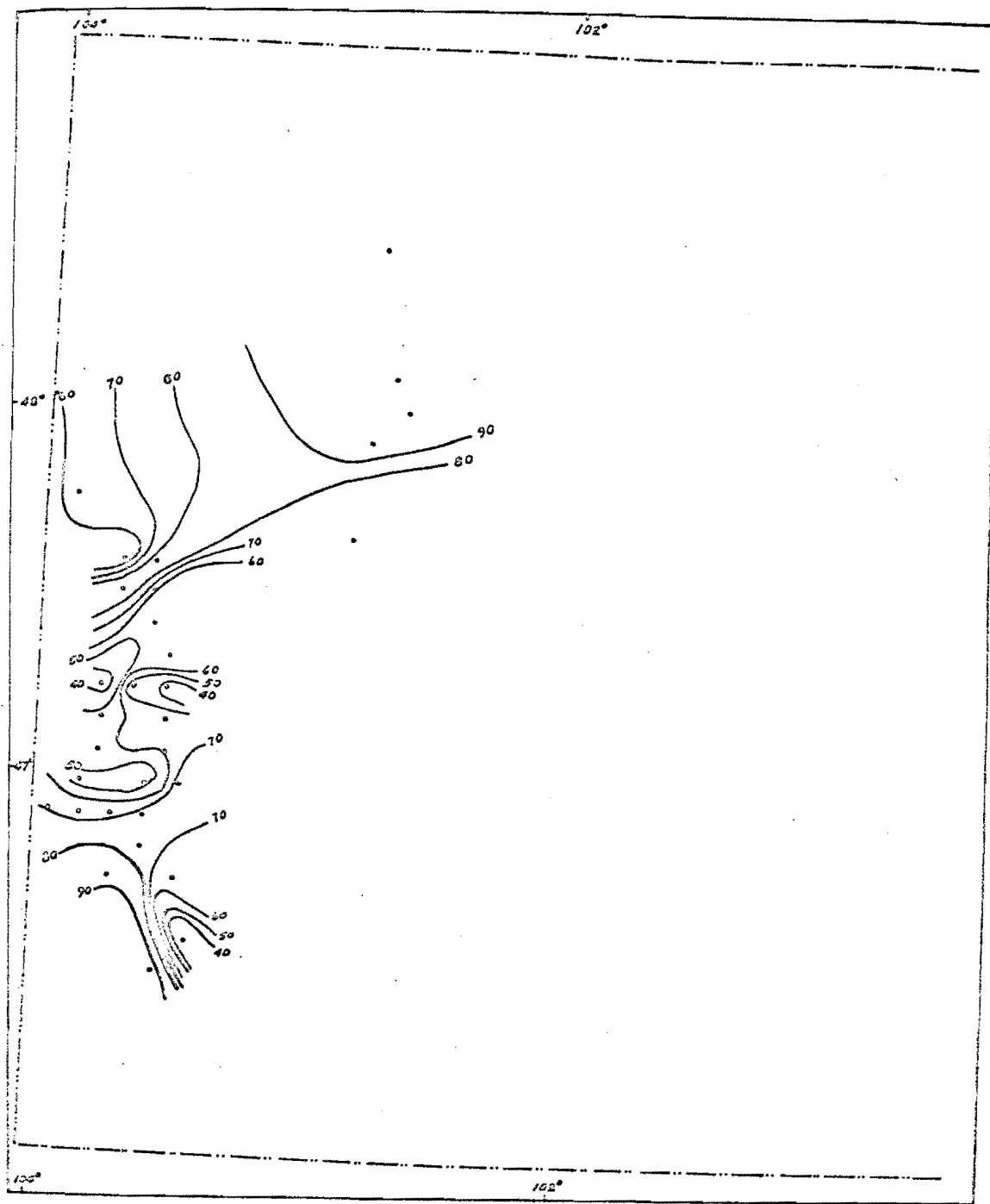Figure 49.--Areal distribution of per cent weight dolomite in basal Sentinel Butte sand samples. Broken line indicates boundary of western North Dakota.
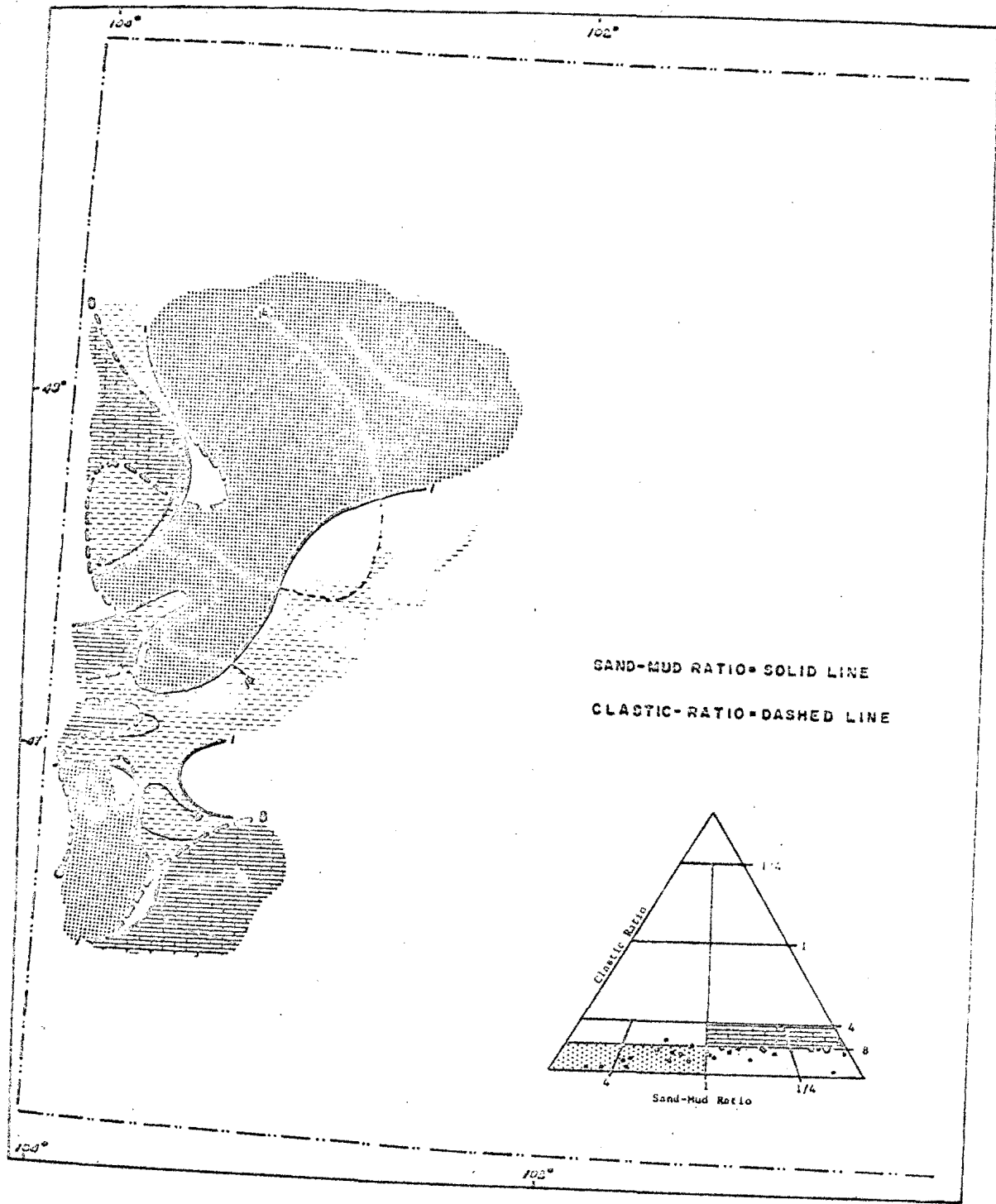
Figure 50.--Triangular facies map of the basal Sentinel Butte on a horizon 6 feet above the Tongue River-Sentinel Butte contact. Broken line indicates boundary of western North Dakota.

DISCUSSION AND INTERPRETATIONS

Paleocurrents and Fluvial Deposits

Paleostream velocities

Values of C_s, determined from the CM diagrams (Figures 28
and 29), can be used in conjunction with empirical curves for crit-
ical erosion velocity to determine a measure of paleocurrent velo-
city. Such curves have been presented and discussed by Hjulström
(1939, p. 10), Inman (1949, p. 56), Sundborg (1956, p. 218), Allen
(1965c, p. 109), and others. The critical erosion velocity may be
expressed in terms of several different parameters, including mean
stream velocity, stream velocity one meter above the bed, and the
friction velocity. The principle assumption involved in determining
stream velocity from CM data in the present study is that the particle
size C_s is equal not only to the coarsest particle in suspension,
but that it also represents the finest size in the bed load. As such,
C_s is a critical particle size, and the velocity required to place it
in suspension is the critical erosion velocity. If the critical
diameter (C_s) is known, a corresponding value of stream velocity
can be read from a "Hjulström-type" diagram (Figure 51). Average
values of C_s for Tongue River and Sentinel Butte samples (Table 10)
are nearly the same, 2.32 phi (0.20 mm) and 1.85 phi (0.28 mm) re-
spectively, and correspond to stream velocities one meter above the

188
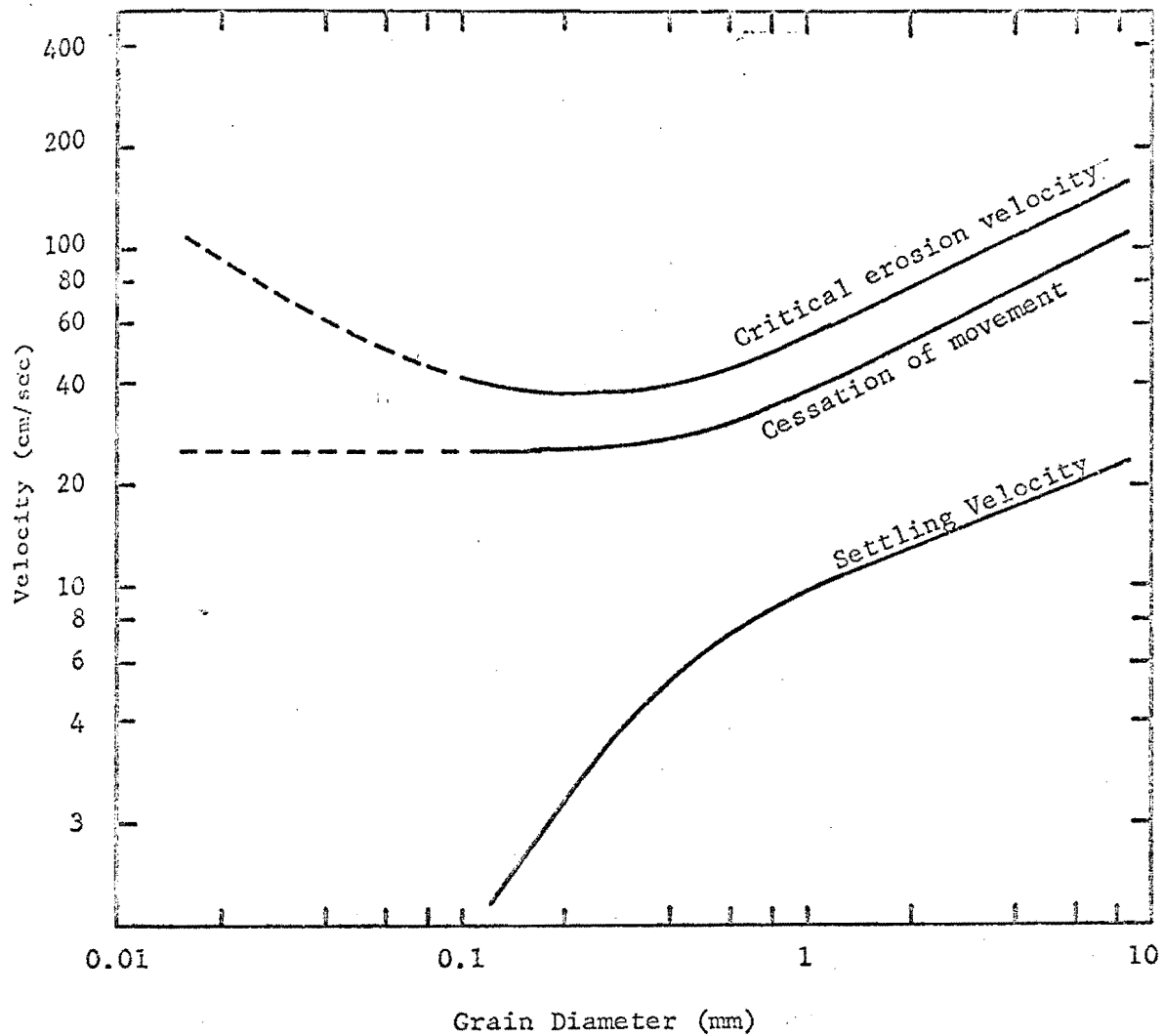
Figure 51.--Relation between flow velocity 1 meter above the stream bottom, and particle size of sediment of density 2.65 g/cm^3 (After Sundborg, 1956).

bed of about 38 to 40 centimeters per second. The corresponding velocity 10 meters above the bottom (which may approximate the mean stream velocity) is about 45 to 47 centimeters per second.

These values of stream velocity are only approximate and are subject to the relative error involved in formulating both the CM patterns and the critical erosion velocity curve. The fine size of Tongue River and Sentinel Butte sediments is a limiting factor in determining the relative difference in velocities of the streams which deposited them. Although their respective values of C_S differ by about 0.5 phi-unit, both diameters intercept the critical velocity curve near its point of inflection where the slope of the curve is very low. Thus velocity values, as interpolated from the curve of Figure 51, are nearly the same. The conclusion appears warranted, however, that velocities of Sentinel Butte streams were greater (on an average) than those of Tongue River streams.

A brief discussion is warranted regarding the type of stream velocities measured. Values of C are the finest diameters in the coarsest one per cent of sediment samples and represent what may be regarded as a "minimum stream competence". The greatest values of C determine C_S which is thus an upper limit of the minimum stream competence. If the coarsest particles a stream could carry are not available to it, values of C represent a lower limit of competence. In such instances, however, streams will generally adjust their "wash-load" so that stream capacity is satisfied and the system is in equilibrium. That is, if finer material is available for transport, dynamics are adjusted in such a way that stream competence is always satisfied by the coarsest material available to the system.

This process of exchange, in which the calibre of the stream load decreases but the total load remains constant, is common in streams extending from mountainous regions onto lowland plains and has been discussed by Mackin (1948). It appears probable that values of C_s for Tongue River and Sentinel Butte sediments give a fair approximation of the competence of streams which deposited them.

Most coarse sediment is transported and deposited by streams during flood stage when stream velocities are greatest, and the range of velocities associated with values of C_s are assumed to represent minimum flood velocities in or near stream channels. This range is quite low in comparison to present streams of sizes comparable to those postulated for Tongue River and Sentinel Butte streams. For example, the Mississippi River has mid-channel velocities of about 122 centimeters per second (4 ft/sec) one meter above the bottom and about 183 centimeters per second (6 ft/sec) 10 meters above the bottom near Mayersville, Mississippi (Passega, 1957, Figure 3). Thus the Paleocene streams in western North Dakota must have been extremely slow and sluggish.

Values of C_s for Tongue River samples are unique because they fall within a range of particle sizes for which the settling velocities and threshold velocities are nearly equal (Inman, 1949, p. 59). Such particle sizes, about 2.75 to 2.3 phi (0.15 to 0.20 mm) for spherical grains of specific gravities near 2.65, are easily placed in suspension and readily deposited with only slight variations in stream velocity. This property permits them to be easily transported at low velocities by processes of surface creep, saltation and suspension (Inman, 1949, p. 60). As stated by Sundborg (1956, p. 219)

this is the _finest_ particle size which may be transported as bed load.

In a discussion on sediment sorting and fluid mechanics, Inman
(1949) discussed the affect of progressive sorting on sediments. He
considered a hypothetical case of unidirectional flow in which ran-
dom fluctuations and the mean stream velocity decrease downstream. In
the upper stream reaches, the currents are capable of moving all
bottom material; downstream the threshold (critical erosion) velocity
decreases and there is a corresponding decrease in median diameter
of bottom samples. Near its source, the stream load would consist
predominantly of coarse material and would be poorly sorted and pos-
itively (fine) skewed. At a point farther downstream, where the
threshold velocity fluctuates between that for very coarse sand and
granules, the bed load would consist of very coarse sand with de-
creasing amounts of granules and pebbles. Fine sizes would also be
present in bottom samples, their amounts decreasing with decrease in
particle size. Such samples would be better sorted than those up-
stream, but the skewness would be nearly symmetrical. Bottom samples
collected from the Mississippi River by the U. S. Waterways Experiment
Station (1935) show that samples with median diameters near 0 phi
are predominantly negatively (coarse) skewed (Inman, 1949, Figure 4-B),
whereas those with median diameters between 0 phi (1 mm) and 2.5
phi (0.18 mm) are nearly symmetrical or slightly negatively skewed.
Farther downstream, where the average friction velocity fluctuates
between the threshold velocity for fine and coarse sand, bottom
roughness would be sufficient for suspension of material as coarse
as fine sand. The fine sand would be most easily transported, coarser
material would tend to lag behind, and bottom samples with median

diameters near 2.5 phi (0.18 mm) would result. Such samples would be well sorted and have symmetrical size distributions (Trask skewness equal to one; Inman, 1949, Figure 4-C).

As a final hypothetical case, and of greatest importance to this discussion, Inman (1949, p. 64) considered the character of a bottom sample at a point where the stream has a friction velocity near, but not exceeding, that of fine sand. Material coarser than fine sand is too large for transport and must therefore be absent. Bottom material transported by creep would consist predominantly of fine sand with lesser amounts of finer material. Fine sand would produce sufficient bottom turbulence to place finer material in suspension; however, the decrease in friction velocity would require a large percentage of fine sand per unit area of bottom surface to maintain a suspended load. Thus bottom deposits would consist predominantly of fine sand with decreasing amounts of finer material. Sediments would have median diameters less than 2.5 phi (0.18 mm), would be less well sorted than those immediately upstream, and would show a pronounced fine skewness. These characteristics are typical of samples reported from the Mississippi River (Inman, 1949, Figure 4-D) at "mile 1057 below Cairo, Illinois" (downstream from New Orleans). Channel samples from the Tongue River Formation are predominantly strongly-fine skewed and have mean diameters finer than 2.5 phi (0.18 mm). Sentinel Butte samples show a comparable range of skewness but have slightly coarser median values. If an analogy with the Mississippi River is desired, it can be stated that the texture of the Tongue River channel facies is similar to that of the Mississippi only in the general vicinity of New Orleans. The Sentinel

Butte channel facies is slightly coarser and is more similar to Mississippi sediments somewhat farther upstream.

Fluvial facies

The proposed sediment classification (Table 12) is useful in explaining the distribution of textural measures previously presented. The distributions of mean, median, and skewness (Figures 11 and 15) in Tongue River sediments are environmentally sensitive and their bimodality reflects the relative abundance of sediment types (Table 13). The modal classes correspond to channel and floodbasin deposits and the intervening range of lower frequency corresponds to the less abundant floodplain and transitional classes. Textural measures for Sentinel Butte samples (Figures 10 and 15) are more uniformly distributed and reflect a more equal distribution of depositional types within this unit (Table 13). The relative differences in abundance of sediment types in the Tongue River and Sentinel Butte Formations are significant, and their consideration is essential in evaluating Tongue River and Sentinel Butte fluvial regimes.

The present state of knowledge of the sedimentary characteristics of fluvial deposits is largely the result of studies of Wolman and Leopold (1957); of Sykes (1937) and McKee (1938, 1939) on the Colorado River and delta floodplain; of the U. S. Army Corps of Engineers (1935), Fisk (1944, 1947, 1951), and Frazier and Osanik (1961) on the Mississippi alluvial valley; of Grover and Mainland (1938), Happ, and others (1940), Jahns (1947), Lorens and Thronson (1955), Harms, and others (1962), and Bernard and Major

(1963) on other North American floodplains; and of Shantser (1951),
Kruit (1955), Sundborg (1956), NEDECO (1959), Anderson (1961), and
Doeglas (1962). Interpretation of ancient fluvial deposits has
been significantly advanced by the work of Allen (1962a,b,c,; 1963a,b,c;
1964a,b; 1965a,b,c) and by Allen and Narayan (1964) and Allen and
Tarlo (1963).

In order to interpret the depositional environment of ancient
fluvial deposits, the characteristics of modern floodplain deposits
must be reviewed (Allen, 1964c, 1965c). Recent fluvial deposits
may be classed among five genetic types: (1) vertical accretion
or topstratum deposits which extend from the natural levee to the
backswamp area; (2) channel-fill deposits; (3) crevasse-splay
deposits; (4) lateral accretion deposits, which include point-bars
and channel-bars; and (5) channel-lag deposits. Topstratum deposits
form as the result of overbank flow and contribute to sedimentary
deposits by vertical accretion of the natural levee, floodplain, and
floodbasin. Such deposits are fine-grained and consist predominantly
of suspended sediment, carried high in the water column. Levee de-
posits near the channel are coarser grained than those of distant
backswamps. Because levees are exposed much of the time, they
support vegetation and roots and plant debris are common in the
deposits. The high porosity and permeability promotes groundwater
circulation and oxidation halos around plant debris are common. In
drier localities, desiccation features may form, particularly in the
finer sediments. The vertical sequence commonly contains alternately
coarse and fine layers which are generally thin-bedded and show only

small-scale primary structures; invertebrate remains are usually sparse or absent.

Channel-fill deposits are the result of filling of channel segments abandoned by meander cutoff or avulsion. Most of the fill is introduced by overbank flow and the deposit is relatively fine-grained. Such deposits were termed "clay plugs" by Fisk (1947).

Crevasse-splay deposits are fan-like accumulations of material dispersed onto the floodplain through a breach in the natural levee. Channels incised in the levee may reach depths sufficient to tap the stream bed load; in such instances they may be quite coarse grained. In general, they are slightly coarser than the associated levee deposits.

Lateral accretion deposits form in meandering streams by point-bar migration or by down-current and lateral "foreset" accumulation of channel bars in braided streams. The deposits consist largely of bed load and coarse suspended load material and are formed below the general level of the levee and floodplain. Evidence of subaerial exposure is generally lacking except in the uppermost strata of lateral accretion deposits. Primary sedimentary structures may include both large- and small-sacle cross-bedding resulting from ripple migration, flat-bedding due to aggradation, scoured surfaces, and scour-fill. These structures imply transport on or near the stream-bed (Allen, 1963d; cited in Allen, 1964c). Drifted plant remains are the major component of lateral accretion deposits, but vertebrate bones and fragmented mollusk shells may also be present.

Channel-lag deposits represent the coarsest material available

to the stream and represent two sources of material: rocks from the
source area of the drainage basin, and cohesive sediments from the
alluvial plain itself. Lag deposits usually occur near the base of
a floodplain sequence and interfinger with lateral accretion deposits.
They may form planar deposits representing erosion pavements or len-
ticular pockets formed by accumulation in the deeper parts of the
stream bed.

The terminology of fluvial deposits is essentially morpholo-
gical, as is apparent in the terms channel, levee, crevasse-splay,
point-bar, floodbasin, etc. Lateral relationships are commonly
masked or concealed in outcrops of ancient sediments and the three-
dimensional form of individual deposits often cannot be determined.
For this reason, a major portion of the burden of environmental re-
construction is placed upon measurements of textural properties,
observations of primary sedimentary structures, bed forms, fossil
occurrences, and similar factors.

It is apparent that fluvial deposits are heterogeneous, but
collectively they form a depositional continuum from the stream
channel to the backwater swamp. This continuum is particularly well
established by the CM patterns of Figures 28 and 29. The trans-
itional character of the pattern, however, permits recognition of
only three basic depositional types: channel and channel-proximal
deposits, floodplain or floodplain-related deposits, and floodbasin
deposits. There is no sharp demarcation between these classes,
particularly between floodplain and floodbasin types (a transitional
class is indicated between these classes in Table 13). Detailed
field study of the morphology of strata from which samples for this

investigation were collected might aid in refining the general classes here recognized for Tongue River and Sentinel Butte sediments. For example, it might be possible to differentiate crevasse-splay, levee, point-bar, and channel-bar deposits on the basis of morphologic and stratigraphic relationships, whereas textural data alone permit recognition only of channel-related or channel-proximal deposits. The classification utilized in this study does, however, aid in establishing the fluvial regime of Tongue River and Sentinel Butte deposits.

Table 13 indicates that channel-type deposits compose nearly 50 per cent of the samples analyzed from both the Tongue River and Sentinel Butte Formations, but floodbasin deposits are more abundant in Tongue River strata. The reported percentages are subject to comment; they represent number frequencies of collected samples and are not precisely weighted to the volume frequencies of strata. However, in view of the fact that both formations were sampled in a similar fashion, the data should be acceptable for comparison. These data indicate that floodbasin deposition during Tongue River time prevailed over topstratum deposition on the floodplain. The converse is true of Sentinel Butte streams, the floodplain was the principle environment of topstratum deposition.

A necessary requisite for floodbasin development is stream stability. Stream channels must be confined to well established belts from which sediment escapes to protected backwater areas only during periodic episodes of flood. Such a system is indicated by Tongue River deposits, which are largely of channel and floodbasin types.

Stream channels achieve stability with increased maturity when marginal "clay plugs" and other fine-grained, cohesive deposits, which are resistent to erosion, restrict lateral channel migration. The process is somewhat paradoxical inasmuch as channel stability is partly dependent upon the presence of fine-grained deposits, and accumulation of fine-grained deposits depends in part upon stable stream channels. Such mutual dependence suggests that stability is approached slowly during stream evolution and, because it is a limiting condition, is indicative of a mature fluvial regime. Vertical accretion and overbank flow must be minimal to protect floodbasins from influxes of coarse material. The lower Mississippi River, where it approaches its deltaic plain, is characteristic of the mature system described; the effects of fine-grained sediments on the control of channel activity have been discussed by Fisk (1947).

The greater proportion of floodplain deposits in the Sentinel Butte sequence suggests the depositing streams were rapidly aggrading, laterally migrating, and less stable waterways than those of the preceding Tongue River episode. The sediments are slightly coarser grained and better sorted than those of the Tongue River Formation, and floodbasin deposits are minor components.

Supporting evidence for the difference in Tongue River and Sentinel Butte fluvial regimes, suggested by the relative abundance of sediment types, is indicated by the distribution and persistence of lignite beds. These are thicker and most persistent in the Tongue River sequence and appear to reflect stability of the backwater swamps in which they were deposited. Although a few thick lignites

are found in Sentinel Butte strata, the majority are thin, silty, carbonaceous beds of local extent and indicate frequent invasion of floodbasin areas by coarser material.

A near terminal fluvial environment of deposition for Tongue River sediments is also suggested by the abundance of floodplain deposits in the sequence. The size, shape, and relative position of floodbasins depends in part upon their proximity to the stream mouth. Floodbasins generally increase in area and thickness, relative to levees and channels, in a downstream direction. For example, Fisk (1947, p. 45-46) noted that backswamp deposits are absent along the present course of the Mississippi River between Cairo, Illinois, and Helena, Arkansas. Between Helena and Vicksburg, Mississippi, they are confined to patchy areas of restricted extent. South of Vicksburg, floodbasin deposits are more common, their area increasing downstream at the expense of channel and levee deposits (Fisk, 1947, Figure 7). Near Donaldsonville, Louisiana, fine-grained, floodbasin alluvium constitutes more than 25 per cent of the bank material at eroded river-bend poisitons. South of Donaldsonville, backswamp deposits are replaced by deltaic plain deposits. A similar distribution of floodbasin deposits has been shown by Anderson (1961; in Allen, 1965c, p. 124) for the Rufiji River alluvial valley, Tanganyika.

The thickness of Mississippi floodbasin deposits also increases downstream, although considerable local variations occur. Near the northern limit of these deposits, an average thickness of 40 feet has been recorded from borings. At Yellow Bend, Arkansas, thicknesses vary from 25 to 50 feet and at Millikens Bend, Louisiana, from

60 to 80 feet. The maximum thickness noted was at White Castle, Louisiana, where 140 feet of backswamp deposits have been penetrated in borings (Fisk, 1947). By analogy, the relative abundance of Tongue River sediment facies is similar to that of the lower reaches of the alluvial valley of the present Mississippi River.

Carbonate content

Carbonate occurs, both as interstitial filling and as freshwater limestones, in much greater abundance in Tongue River sediments than in those of the Sentinel Butte sequence (Figures 34 and 42). Limestones probably formed in restricted evaporite ponds on the floodplain and floodbasin and in abandoned or cut-off sections of stream channels. Dunbar and Rodgers (1963, p. 33) suggested abandoned channels and floodplain depressions as probable sites of limestone deposition in areas where the climate is sufficiently arid. The resulting deposits were described as lenticular bodies enclosed in fine-grained strata and containing molds of indigenous plants and sparse invertebrate remains.

Freshwater limestones have been widely reported from continental deposits; such beds occur in the Dunkard Group (Permian) of West Virginia and Ohio (Cross, and others, 1950), the Newark Group (Triassic) of Connecticut (Kyrnine, 1950, p. 101-111), the Morrison Formation (Jurassic) and related rocks of Colorado and Wyoming (Baker, and others, 1936, p. 195), the Eocene Wasatch (Eardley, 1932) and Wind River (Tourtelot, 1946) Formations, and the Oligocene White River Formation of the Dakotas and Nebraska (Wanless, 1922, p. 194-195; Hansen, 1953). Not all of these limestones are fluvial deposits and

only part of them are products of chemical precipitation. Some show algal and other plant structures which suggest biochemical processes of deposition. Together they demonstrate the frequent, although not necessarily abundant, occurrence of limestone in restricted terrestrial environments.

Interstitial carbonate is most abundant in Tongue River silts (about 4.5 to 7.5 phi; Figure 33) which largely represent floodplain deposits. Low carbonate content in fine-grained (finer than about 7.5 phi) floodbasin sediments indicates that penecontemporaneous carbonate was not formed extensively in this environment.

Due to repeated exposure, floodplain deposits are subject to desiccation and oxidation and, in drier regions, downward movement of the water table, coupled with high evaporation rates, may result in formation of calcretes and ferrocretes. Bernard and Major (1963, p. 350) have observed numerous soil zones and calcareous and ferruginous nodules from "floodbasin" deposits of the Brazos River in Texas, and Lorens and Thronson (1955), have reported concentrations of carbonates in the fine-grained alluvial sediments of the Sacramento Valley of California. Allen (1964c, p. 180), in the absence of more direct evidence, considered abundant carbonate ("race") as indirect evidence of subaerial exposure during deposition of vertical accretion deposits of the Dittonian cyclothem (Lower Devonian) in Glouchestershire, Great Britain.

It is suggested that interstitial carbonate was formed in Tongue River sediments as the result of evaporation of ground water brought to the surface by capillary action in the permeable sediments of the levee and floodplain. Such a mechanism appears feasible for,

as will be discussed, western North Dakota was a major lowland during
Paleocene time, and such lowlands are universally areas of ground-
water discharge. If the climate was subtropical or warm temperate
(Dorf, 1942; Brown, 1962; Hickey, 1966) net flow of ground water
would have been high and carbonate would constitute a principle
dissolved solid.

It is difficult to demonstrate that all carbonate in Tongue
River sediments formed penecontemporaneously with sediment accumu-
lation. A correlation of increasing carbonate content with decrease
in grain size of floodplain sediments might be predicted from the
mechanism of carbonate deposition suggested above. A weak corre-
lation of this type was noted in Figure 34 for sediments coarser than
about 7 phi. The high degree of scatter of plotted points may in-
dicate fluctuations in the degree of carbonate deposition in the
floodplains of various ages which are compiled in the composite
plot. A better test is offered by the basal sand samples, which in-
clude only channel and floodplain facies and which may be assumed
to represent a nearly isochronous surface of deposition. These
samples (Figure 43) show a remarkable inverse correlation between
carbonate concentration and sediment size. Interpreted in terms of
primary carbonate deposition, the inverse relationship suggests
that finer sediments distant from active channels (excluding back-
swamp deposits) were the most favorable host for carbonate accumu-
lation. If the carbonate originated secondarily by concentration
from migrating groundwater, it seems probable that the coarser, more
permeable sediments would contain the greatest concentrations of
carbonate and a direct correlation between carbonate concentration

and grain size would exist. Although the possibility that some
carbonate has been introduced or removed from sediments of the
Paloecene Series by post-depositional processes cannot be discounted,
distributions of Figures 33 and 34 indicate a probability that such
processes have had minor effect.

The greater limestone and interstitial carbonate content of
Tongue River sediments, compared with those of the Sentinel Butte
Formation, can be explained in terms of fluvial regime. The sta-
bility of Tongue River streams and the slow rate of topstratum depo-
sition allowed more time for carbonate accumulation. The much
greater vertical accretion rate of Sentinel Butte streams resulted
in lower carbonate concentrations in their deposits. Stability
may have been achieved several times during the Sentinel Butte
episode, as reflected in the presence of the upper and lower "yellow"
beds in the vicinity of the North Unit of Roosevelt Park. These
units are notably high in carbonate, resemble Tongue River strata,
and, as previously stated, appear to represent a brief return to
"Tongue River conditions".

Primary sedimentary structures

Both the types of sedimentary structures present and their
relative abundances in Tongue River and Sentinel Butte strata are
useful in paleoenvironmental reconstruction. Although the data are
qualitative, it was concluded that large-scale structures consist
predominantly of xi-cross-stratification (Figure 19-C) and are most
abundant in the Tongue River Formation. With the exception of the
basal and upper sands, large-scale cross-beds are rare in Sentinel

Butte strata. Omikron-cross-stratification (Figure 19-D and 20-A) is present in both formations and predominates in the upper Sentinel Butte sand.

The origins of xi-cross-stratification are not clearly understood and it is doubtful that studies to date permit the type to be defined completely. McKee (1957) demonstrated the presence of such structures in the backshore deposits of some beaches. Allen (1963b) suggested the structure results from sheets of sand of local extent being thrown up so as to partly overlap. He points to the work of Reiche (1938), McKee (1940), and Bagnold (1941) which suggests that xi-cross-stratification can be formed under wind action by migration of longitundinal dunes. Recent work by McKee (1967) on dunes in White Sands National Monument, New Mexico revealed no structures of xi-cross-stratification. A fluvial origin for this structure in Tongue River strata is considered beyond question. It is associated with channel sands and is presumed to be related to point-bar deposition. No observations of this structure in modern fluvial environments are know to this writer.

Omikron-cross-stratification, according to Allen (1963b, p. 110), is most probably the product of migrating trains of large-scale ripples. Hülsemann (1955) demonstrated that such ripples are internally stratified and Allen (1963a) demonstrated that omikron-cross-stratification results from the migration of large-scale asymmetrical ripples with essentially straight crests. This structure is found both in channels and in the open sea and cannot be used as an index to water depth. The criterion for sediment supply has been discussed by Allen (1963a), who found that, in advancing its own length, each

ripple must receive a volume of sediment less than the volume of the ripple body. Thus the ripple must undergo erosion on the stoss side, giving rise to an erosional surface between sets. The greater abundance of omikron-cross-stratification in Sentinel Butte strata might be used to infer that the erosional energies of those streams were greater than those which deposited Tongue River sediments.

Small-scale cross-stratification is found in both formations, and consists predominantly of kappa and lambda types (Figures 20-B and 20-C). The origins of these types appear to be similar, the first is formed by migration of asymmetrical linguoid ripples and the second by asymmetrical ripples with straight crests. Kappa-cross-stratification has been reported from the Colorado delta (McKee, 1939) and was discussed by Sorby (1908) who referred to it as ripple-drift bedding (Allen, 1963b). Allen (1963a) demonstrated that both types of ripples will form when sediment supply received from suspension during the time required for the ripple to advance its own length is greater than the volume of the ripple body. Under these conditions, the ripple bodies are not eroded, but are aided to on both the lee- and stoss-sides. Formation of these structures would require a copious supply of suspended material and low, uniform flow velocities. Such structures are common in topstratum deposits of the Tongue River and Sentinel Butte Formations, and were probably also produced in shoal, protected backwaters of major channels.

Nu-cross-stratification (Figure 20-C) is also formed by the migration of small-scale linguoid ripples (Hamblin, 1961). The correctness of this interpretation has been verified by Allen (1963a) who also demonstrated that the sediment supplied from suspension during

the interval of time required for a ripple to advance its own length must be substantially less than the volume of the ripple body. As each ripple advances, it erodes a trough on its concave side which is subsequently filled by ripples in the advancing train, the ripples being arranged in a scale-like pattern. According to Hamblin (1961, p. 440) such structures can conceivably form a number of environments but always indicate a low level of mechanical energy. In the upper Keeweenawan sediments studied by Hamblin, the structures were accompanied by rain imprints and mud cracks. The predominance of kappa- and lambda-cross-stratification types over nu-cross-stratification again suggests that Tongue River streams were well charged with material in suspension and that erosion, even on the scale of small ripples, was not prevalent. In this regard, it might be noted that the large-scale analogue of nu-cross-stratification, pi-cross-stratification (festoon bedding), was not observed in either Tongue River or Sentinel Butte strata.

Observation of primary sedimentary structures and bedding surfaces show no evidence that an upper (rapid or shooting) flow regime was ever achieved by Tongue River or Sentinel Butte streams. The structures discussed are all products of the lower (tranquil) flow regime and are formed at Froude numbers less than one. Flat bedded sandstones (Figure 19-A) are the only bedding type that might be suspected of plane-bed formation during transition between flow regimes, but the absence of current lineations on bedding planes and the presence of fine-grained sediment at bed boundaries discounts the possibility of such formation. They are probably products of vertical accretion on levees and point-bars.

Paleochannel form

The greater abundance of large-scale structures in Tongue River strata appears to be related to its fluvial regime. Large-scale structures are products of substratum deposition and, as in the case of point-bar deposits, cosets of cross-bedded or massive strata may attain thicknesses equivalent to the maximum water depth. Point-bar deposits in the Mississippi Valley are typically 40 to 60 feet thick (Fisk, 1944, 1947) and deposits up to 55 feet thick are recorded from the Brazos River (Bernard and Major, 1963). As emphasized by Allen (1965c) not all streams form vertical accretion deposits, but lateral accretion (substratum) deposits are common to all fluvial sequences. Because the combined activities of lateral migration and vertical accretion, perhaps accompanied by subsidence, produced the fluvial deposits of the Tongue River-Sentinel Butte sequence, the relative amounts of substratum material present in the sequence should reflect both the activity of the streams and the depth of their channels. Thick sands and coarse silts, portions of which are conspicuously cross bedded, are locally prominent in the Tongue River sequence. They attain thicknesses, as at Wind Canyon in the South Unit of Roosevelt Park, in excess of 100 feet. Similar bodies, with the exception of the upper and lower sands, are absent in Sentinel Butte strata. These relationships indicate that Tongue River streams flowed in deeper channels than those of Sentinel Butte time and that their lateral migration was restricted.

The magnitude of large-scale cross-stratification affords additional qualitative data on paleostream depth. Under steady flow conditions the height of large-scale ripples is directly proportional

to water depth, the height ranging from approximately 10 to 20 per cent of the depth (Allen, 1965c, p. 110). Large structures in the Tongue River Formation have maximum exposed thicknesses averaging about 2 feet; true maximum thickness should be greater. Thus, if at least a portion of the structures studied represent bed forms, minimum water depths of 10 to 20 feet are indicated. Maximum depths were probably much greater. The paucity of large-scale cross-stratification and thick sand bodies within the bulk of the Sentinel Butte sequence suggests shoal, perhaps more diffuse, channel systems.

The presence of thick sand bodies and large-scale cross-stratification suggests that Tongue River stream channels were deeper than those of Sentinel Butte streams, but their relative widths must also be considered in an evaluation of channel form. The texture of the Tongue River and Sentinel Butte channel facies support an inference that Tongue River streams had greater depth-width ratios than Sentinel Butte streams. Schumm (1960) demonstrated that the width-depth ratio of various stable streams is inversely proportional to the mean per cent silt-clay content (finer than 0.074 mm) in the bed and banks. That is, streams with high silt-clay content in sediments of their wetted perimeter are relatively narrow and deep; the converse is true of streams with sandy beds and banks. The explanation for this relationship is found largely in the cohesiveness of the sediments and their resistance to bank erosion and caving.

Inspection of the sand, silt, clay contents of Tongue River and Sentinel Butte samples (Figures 17 and 18) shows that the clay content is appreciably greater in the channel facies of the Tongue River Formation. Likewise, the Tongue River deposits are finer grained

(Figure 11), less well sorted (Figure 12), and contain a greater proportion of fine-grained, floodbasin deposits (Table 13), on an average, than Sentinel Butte deposits. These facts lead to the conclusion that the bed and bank materials of Tongue River streams, whether depositional or erosional, were finer-grained than those of Sentinel Butte streams, and that their width-depth ratio should have been considerably smaller.

Schumms's (1960, p. 18) "mean per cent silt-clay" value is weighted by factors of stream width and depth (i.e., a weighted mean for the wetted perimeter) and is impossible to compute for ancient sediments. If it could be computed, approximate width-depth values might be read directly from his plotted curve of width-depth ratio versus weighted mean per cent silt-clay. However, if it is assumed that stratigraphic sampling was sufficiently random to obtain a weighted average of channel floor and bank material, and that streams were alluviating (not eroding previously deposited material), an approximation of the relative width-depth ratios of Tongue River and Sentinel Butte streams can be made. Tongue River and Sentinel Butte channel samples average about 71 and 58 per cent silt plus clay (finer than .063 mm) respectively and, utilizing the data of Schumm (1960, Figure 8), represent width-depth ratios of about 2.5 and 3.3, respectively.

The similarity of these ratios is disappointing in view of the greater differences in Tongue River and Sentinel Butte channel forms indicated by primary sedimentary structures and sedimentary criteria. Considering the uncertainties involved in using unweighted values of per cent silt-clay and the assumptions regarding other variables,

both the absolute values and the relative difference of the ratios
cannot be regarded as more than gross indicators. As noted by Schumm
(1960, p. 17), aggrading streams generally have higher width-depth
ratios than are indicated by their silt-clay percentages, whereas
degrading streams have lower ratios. Because both Tongue River and
Sentinel Butte streams were undergoing significant aggradation, the
ratios obtained above are likely to be low. The lower silt-clay
content of Sentinel Butte sediments does, however, indicate that the
streams which deposited them constructed less resistant channels
than did Tongue River streams.

Basin Analysis

Sediment dispersion and paleoslope

Directional measurements of large-scale cross-stratification
provide information about sediment dispersion within the Paleocene
Williston basin. During Tongue River time, sediments entered the
basin from the west (Figure 23) and were dispersed uniformly in an
eastward direction. Sentinel Butte deposition was initiated by an
influx of sandy material from the northwest (Figure 24) which spread
southward and eastward across the basin. This trend of dispersal
was apparently maintained during the ensuing Sentinel Butte episode
(Figure 25). The dispersal pattern was modified near the close of
Sentinel Butte time by an influx of upper Sentinel Butte sand
(Figure 26) which was distributed from west to east in much the same
pattern as Tongue River sediments. The dispersal directions of
Tongue River and Sentinel Butte sediments, although not greatly

different, have statistical significance (Table 9).

The vectoral data of Figures 23 to 26 are not entirely ade-
quate for pin-pointing precisely the sources of Paleocene sediments,
but it can be confidently stated that they entered the Williston
basin from the west and northwest. This appears to exclude the
Black Hills (Tisdale, 1942; and others) and the Big Horn Mountains
of north-central Wyoming as probable source areas. The possibility
that uplift along the Cedar Creek anticline and Poplar dome, which
form the southwestern and western margins of the Williston basin in
western North Dakota, exerted primary control on sediment entry into
the basin cannot entirely be discounted. The Tongue River and
Sentinel Butte intervals thin on the flanks of these structures,
and post-Paleocene uplift and erosion on the Cedar Creek anticline
has exposed rocks of Cretaceous age. It is likely, however, that
Tongue River and Sentinel Butte deposition was continuous across
these structures and that they were not effective barriers to sedi-
ment dispersion during the Paleocene.

The degree of variability of cross-bedding may be (quali-
tatively) useful in making inferences about stream morphology, stream
gradient, paleoslope, and tectonic stability. The type of inter-
pretations possible are dependent upon the nature of the data. For
example, if data are from a single depositional unit in a small
locality, their dispersion may reflect the degree of sinuosity of
the depositing streams. The more complex the meander pattern, the
greater will be the deviation of local stream vectors to the mean
direction of flow. The degree of sinuosity in turn reflects the
general gradient of the stream. Hamblin (1958, Figure 28; in Potter

and Pettijohn, 1963, p. 87) found the standard deviation in several modern streams to vary from 20 degrees to as high as 83 degrees, depending on their amount of meandering and their gradient. By analogy, he concluded that the Jacobsville Sandstone, for which the standard deviation of directional data is low, was deposited from streams with fairly high gradients.

Directional data presented for the Tongue River and Sentinel Butte Formations are integrated over a large area and a thick stratigraphic interval. Such data are likely to reflect the complexity of the regional drainage net and changes in paleoslope caused by tectonism. If the regional slope is maintained, the current flow pattern should remain stable and directional data should show a lesser degree of variance. Tectonic fluctuations may disrupt or alter drainage, resulting in increased current vector deviation. The implications of paleocurrent variability are thus complex and subject to multiple interpretation; the most satisfactory interpretations will utilize other, independent sedimentological or basinal attributes.

A qualitative appraisal of cross-bed data and depositional environments (Potter and Pettijohn, 1963, p. 88) indicate that the most common variance of fluvial-deltaic deposits is in the range of 4000 to 6000 (standard deviations between 63 and 78 degrees). Marine samples tend to have higher deviations, commonly between 6000 and 8000 (standard deviations between 78 and 89 degrees). Variances of aeolian deposits are comparable to those of most fluvial-deltaic deposits. Standard deviations of directional data from the basal and upper Sentinel Butte sands (65 and 62 degrees; Table 7) are thus well within the predicted range for fluvial deposits. The standard

deviation of composite data for the Tongue River interval is somewhat higher (71 degrees), but still within the range common for fluvial and deltaic deposits. The composite data for the Sentinel Butte interval between the basal and upper sands, however, is greater (91 degrees) than would be expected in a fluvial system. Because it is so much greater than that of the basal and upper sands, which are discrete stratigraphic intervals within the Sentinel Butte Formation, it seems reasonable to assume that much of the large deviation for intervening strata results from shifting stream channels and changes in paleoslope.

Paleocene tectonics

Further consideration of Paleocene deposition within the Williston basin of western North Dakota requires brief consideration of its tectonic framework. The intracratonic Williston basin was initiated during the Ordovician and underwent slow deposition during most of Paleozoic time. It functioned as an autogeosyncline during much of this time (Sloss and Hamblin, 1942; Perry and Sloss, 1943), accumulating substantial thicknesses of carbonates and evaporites.

With the advent of the Laramide orogeny the basin developed an exogeosynclinal aspect (Sloss, 1956), accumulating and preserving a representative portion of the mass of clastic debris shed eastward from the Rocky Mountain arch. Late Cretaceous sediments form a transition from marine and brackish-water to continental deposits. The latest of the marine deposits were dispersed in the "relict" Cannonball sea during early Paleocene time. Streams transporting and depositing sediments of the transgressive Tongue River Formation

must have followed the path of the receding Cannonball sea. Direct documentation of this path has been lost by erosion of Tongue River and Cannonball sediments, but directional measurements from existing Tongue River strata (Figure 23) suggest it extended southeastward.

Discussions of basinal deposition invariably require consideration of three factors: (1) subsidence within the basin, (2) tectonism in the sedimentary province, and (3) changes in base level. For lack of evidence to the contrary, the Paleocene base level is considered to have been constant or undergone negligible change. A relatively slow and constant subsidence within the Williston basin is indicated by the continuity of the stratigraphic record of late Mesozoic and early Cenozoic rocks. Failure of basinal subsidence to keep pace with sedimentation is suggested by expulsion of the Cannonball sea. The Laramide orogeny was in progress to the west, and it is probable that its pulsations were responsible for the most profound changes recorded in the Paleocene stratigraphic sequence of the Williston basin.

The great thickness of the Tongue River-Sentinel Butte sequence (greater than 1000 feet) and the increase in total stratigraphic section toward the center of the North Dakota portion of the Williston basin indicate significant basinal subsidence. At many localities where it is in contact with the Ludlow Formation, the base of the Tongue River Formation is a scour surface, but throughout the remainder of the unit and in the overlying Sentinel Butte, no major erosional surfaces have been identified. Lignite beds are seldom truncated, even where overlain by channel deposits, and the indications are that deposition was continuous in response to basinal subsidence.

The Tongue River episode

Deposition of the Tongue River sequence began with an influx of basal sand over brackish-water sediments of the Ludlow and marine sediments of the Cannonball Formation. Local scour surfaces beneath the base of the Tongue River indicate a minor state of depositional non-equilibrium, presumably caused by tectonism which increased the paleoslope and sediment supply. The source of sediment lay to the west, but cannot be specifically identified. The relatively mature character of Tongue River sediments suggests that the source area may have been a low arch of older sedimentary rocks, and that little or no extrusive volcanism accompanied deformation. Dispersion across the basin was eastward, and the low variance of paleocurrent data is interpreted as indicating constancy of the paleoslope, and thus of the source of sediments and the system of streams which transported them seaward.

Depositional equilibrium was achieved early in Tongue River time through aggradation of the basal sand, and the remainder of the episode was characterized by a stable fluvial system. The streams of this system were confined to relatively deep channels with low gradients; their velocities were low and insufficient to transport sediment exclusively as bed load. Extensive backwater swamps formed between the waterways and were seldom invaded by overbank flows or by channel avulsion. Thick deposits of plant debris, derived primarily from local stands of vegetation on the levees and floodplains, accumulated in these swamps. Floodplains of restricted extent existed between the active stream channels and backwater swamps. Subaerial exposure of the floodplain deposits during extensive periods of low

stream-discharge, coupled with capillary rise of ground water and evaporation, resulted in carbonate enrichment of topstratum deposits. In isolated depressions, filled periodically with surface water, calcareous ooze was deposited which subsequently lithified to fresh-water limestone.

Floodbasins are a favorable habitat for freshwater inverte-brates (Allen, 1964, Table 1; Fisk, 1947, p. 57, Plate 66, Figure 14), and the great extent of this environment (and the associated stream stability) may account for the greater abundance of mollusks in Tongue River strata as compared to those of the Sentinel Butte For-mation.

The fine texture and relative abundance of the various sedi-ment facies suggest that western North Dakota was near the terminus of a regional drainage system, but the character of the baselevel is problematical. It is presumed that the paleoslope was contin-uous across the Williston basin and that streams continued in a general eastward and southeastward direction. Discharge into a remnant of the Cannonball sea during a significant portion of Tongue River time is possible, but such a relationship can only be inferred.

The accumulation of Tongue River sediments was relatively slow, as indicated by thick floodbasin deposits and freshwater limestones, and deposition was probably equal to basinal subsidence. Deposition waned near the close of the Tongue River episode (perhaps reflecting leveling of the source area), stream drainages deteriorated, and a vast swamp formed in response to continued basinal subsidence. With-in this swamp, organic debris of the HT Butte bed accumulated. Net accumulation was greater in some areas than others, but the requisite

conditions for ultimate formation of lignite or lignitic shale were

regionally persistent. Lignitic shales formed in areas where fine

sediment filtered into the swamp, as evidenced by the HT Butte bed

at Snowden and along the Garrison Reservoir (Figure 8-C). Thus,

ultimate Tongue River time was a period of minimal deposition and

widespread quiescence.

The Sentinel Butte episode

Deposition of the Sentinel Butte sequence began abruptly with

transgression of a sandy basal unit across the HT Butte swamps.

Streams of higher gradient than those of the Tongue River episode

carried sediment in from the northwest and dispersed it in a fan-like

pattern (Figure 24) across the swamp. Deposition into a body of

standing water is suggested by large-scale inclined beds (Figure 4-A),

which resemble delta foresets, and the unit probably transgressed

the swamp in deltaic fashion, sediment being supplied by a system of

distributary streams. This origin is in accord with the absence of

fine-grained floodplain and floodbasin sediments (Figures 36 and 40)

and explains why Sentinel Butte strata rest everywhere conformably

upon the HT Butte bed with no evidence of scour, channeling, or

erosion.

Although vertical accretion was great, and may have exceeded

basinal subsidence during much of the Sentinel Butte episode, a

degree of basinal control on sediment dispersion is indicated by

several scalar properties measured in the basal sand. Although the

trend is interrupted by a number of local reversals (presumed to

indicate distributary channels) the basal sand is coarsest in the

northern and eastern portion of the study area, near the axis of the Williston basin, and becomes finer westward and southward along the basin margin (Figures 46 and 47). Carbonate content shows an inverse relationship with grain size (Figure 43), being smallest in the north and increasing westward and southward (Figure 48). These relationships suggest that basinal subsidence influenced the location of major streams, and thus sediment dispersion, as well as the total accumulated thickness of deposits. Such influence can be demonstrated with certainty only during the initial phase of the Sentinel Butte episode.

A change in the source area of the basal sand is suggested by its less mature sedimentary composition and by the cross-bed readings from the unit, which differ with statistical significance (Table 9) from those of the Tongue River beds. The source area of Sentinel Butte deposits lay northwest of western North Dakota, and extrusive volcanism probably accompanied tectonism. The low degree of dispersion (Table 7) of directional measurements in the basal sand indicates that a single, dominant sediment source and a stable paleoslope direction prevailed during the initial phase of Sentinel Butte deposition.

Subsequent deposition of strata above the basal sand was more variable. The great variance and polymodality of cross-bed measurements (Figure 25) suggest shifting river courses and possibly changing or multiple areas of sediment supply. The drainage pattern was generally much less stable than that of Tongue River time but, as previously mentioned, the upper and lower "yellow" beds suggest that stability was attained several times during the Sentinel

Butte episode. Stream channels were probably shoal and diffuse but no direct evidence is available to indicate they were braided. The terminus of the fluvial system appears to have shifted eastward during Sentinel Butte time, but streams still transported sediment primarily as suspended load. Frequent overbank deposition can be postulated on the basis of sparse floodbasin deposits and low carbonate content of topstratum sediments. This system created a habitat less favorable to freshwater mollusks than that of the preceding Tongue River episode.

Late in Sentinel Butte time, increase of the paleoslope caused deposition of an upper sand throughout much of the basin. This sand is cleaner and coarser than any sediment previously introduced into the basin and apparently represents a significant rejuvenation to the west. Cross-bed measurements although available from only a portion of the study area, are unimodal and have a low standard deviation (Figure 26). The maximum extent of this unit has not been defined, but it is believed to be widespread. It is of particular economic significance where it overlies lignitic strata, as near Belfield and Gorham, for its high permeability has facilitated uranium enrichment of these beds. The absence of similar sands elsewhere in the Sentinel Butte Formation suggests that such enrichment is not likely to be prevalent throughout the entire Sentinel Butte sequence.

Sentinel Butte deposition terminated shortly after deposition of the upper sand, apparently in response to reduction of sediment supply. Non-deposition, and perhaps minor local erosion, appear to have ensued throughout much of western North Dakota. In the axial

portions of the Williston basin syncline, sediments of presumed lacustrine origin (Benson, 1952; Hickey, 1966) were deposited conformably upon Sentinel Butte strata; in basin marginal areas, Sentinel Butte strata are overlain (in erosional unconformity) by Oligocene sediments of the White River Formation. Thus, termination of the Sentinel Butte episode concluded a long-lived epoch of continuous fluvial sedimentation in the Williston basin of western North Dakota.

SUMMARY OF CONCLUSIONS

The stratigraphic and sedimentologic relationships presented
herein appear to justify the following conclusions.

1. The contact between the Tongue River and Sentinel Butte
units can be distinguished by three criteria; the presence of the HT
Butte bed at the top of the Tongue River sequence, a basal sandy unit
in the Sentinel Butte sequence, and a change in gross color from
buff-yellow below to somber gray above the contact.

2. The Tongue River-Sentinel Butte contact is the most distinc-
tive and persistent marker horizon in the Tongue River-Sentinel Butte
interval. It can be traced throughout the drainage of the Little
Missouri River and (where exposed) along the Missouri River from
the Montana-North Dakota state boundary to the mouth of the Little
Missouri. The eastward extent of the contact has not been defined,
but outcrops in Morton County indicate that it is persistent across
the Williston basin.

3. The Sentinel Butte sequence is a distinctive and mappable
lithostratigraphic unit in western North Dakota and should be regarded
as a formation. Use of the term "Tongue River" should be restricted
to its original definition; in western North Dakota this definition
includes the stratigraphic interval between the Ludlow and Sentinel
Butte Formations, and includes the HT Butte bed.

4. The Tongue River-Sentinel Butte sequence thickens toward

the center of the Williston basin, indicating that sediment accumulation was influenced by basinal subsidence.

5. Tongue River sediments are finer grained and less well sorted, on an average, than are those of the Sentinel Butte Formation. The range of skewness values for samples from the two units is similar, but the distribution of skewness for Tongue River samples is markedly bimodal. The distribution of kurtosis values is similar for both formations, but Tongue River samples display a narrower range and a stronger mode. The distributions of all size statistics reflect the relative abundance of sediment types, but median diameter and skewness appear to be most environmentally sensitive.

6. Silt is the most abundant sediment type in Sentinel Butte strata, followed by clayey silt and nearly equal amounts of sand, silty sand, sandy silt, and silty clay. Tongue River strata are composed predominantly of clayey silt, with decreasing (but subequal) amounts of silt, sandy silt, silty clay, and silty sand; sand and sand-silt-clay classes are sparsely represented. Tongue River samples contain greater percentages of clay, on an average, than do those of the Sentinel Butte Formation.

7. CM patterns for Tongue River and Sentinel Butte strata are very similar and illustrate the fluvial origin of units. They indicate a depositional continuum from stream channels to backwater swamps, but products of graded, uniform and "pelagic" suspension can be differentiated. As a first approximation, these transport types can be considered equivalent to channel, floodplain, and floodbasin environments.

8. The abundance of thick sands, large-scale cross-bedding, thick lignites and other floodbasin deposits, limestones, and the high carbonate content of Tongue River strata indicate a more stable fluvial regime than that which existed during Sentinel Butte time.

9. CM diagrams, used in conjunction with empirical curves for critical erosion velocities, can be used to approximate paleo-current velocities. Sentinel Butte streams had higher velocities than those of Tongue River time, but the magnitude of both was small and maximum mid-depth velocities of 40 to 50 centimeters per second are estimated. Sediments of both formations were transported primarily as suspended load, and all transport occurred in the lower flow regime.

10. Tongue River sediments were dispersed eastward across the North Dakota portion of the Paleocene Williston basin from a low source area postulated to have existed to the west. The paleoslope, down which streams flowed, appears to have been quite stable, and sedimentation gradually waned as the elevation of the source area was reduced by erosion. Continued basinal subsidence exceeded deposition, and a vast swamp developed in which the HT Butte bed accumulated.

11. Sentinel Butte deposition was heralded by an influx of sand which spread in deltaic fashion southeastward across the HT Butte swamp. Subsequent deposits came from the west and northwest, and the high variance of the dispersion pattern suggests variability of the paleoslope and possibly multiple sediment sources.

12. The Black Hills can probably be discounted as a source area of any significant portion of Tongue River or Sentinel Butte deposits.

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APPENDIX I

Analytical Procedures

Sediment size analysis

Sampling.--All samples were split by cone-and-quarter to obtain subsamples for; (1) chemical analyses, (2) size analysis, and (3) departmental reference collection. A quantity of sediment estimated to contain 12 to 15 grams (dry weight) of material finer than 4 phi was taken for size analysis, up to a maximum weight of about 28 to 30 grams. Twelve to 15 grams of sediment per liter was considered an optimal concentration for pipette analysis, and approximately the same weight is maximum for the 3-inch sieves used to size material coarser than 4 phi. About 100 grams of sediment was retained and ground to fineness for chemical analyses. A portion of the last quartered cone was retained and catalogued as a reference sample.

Pretreatment.--Many Tongue River and Sentinel Butte samples contain large amounts of reactive carbonate. Both field and laboratory observations indicate that the carbonate minerals are authigenic and diagenic, and were not part of the allogenic sediment transported into the Paleocene Williston basin. For this reason, all reactive carbonate was removed by acid leaching prior to size analysis.

Samples were placed in screw-top jars and permitted to react with an excess of dilute (0.5 to 0.75 N) sulfuric acid at room temperature until effervescence slowed. Samples were then heated to 70 to

80 degrees Celsius in a water bath, agitated frequently, removed from the bath, and allowed to equilibrate with room temperature. When cool, samples were centrifuged (10 minutes at 1600 rpm), decanted, twice rinsed with distilled water, centrifuged, and decanted. Centrifugation was extremely efficient, permitting removal of all supernatant liquid with negligible loss of lithogenous material.

Two hundred milliliters of Merasperse-N (sodiumlignosulfonate; stock solution 0.1 grams/200 milliliters) was added to each leached and washed sample, the sample was agitated thoroughly and allowed to stand overnight. Disaggregation was essentially completed for most samples during removal of carbonate, but some fine-grained, carbonate-free samples required additional agitation for complete disaggregation. This was accomplished by periodic agitation (10 to 15 minutes) in an automatic shaker; between these periods, samples were soaked for several hours. With the exception of lignitic shales and a few clays, a high degree of disaggregation was achieved for all samples.

Wet sieving.—Disaggregated samples were dispersed 8 to 10 minutes in a malt mixer and rinsed through a new, 4-phi sieve (U. S. Standard No. 230) into a one-liter cylinder. Sediment retained on the screen was thoroughly washed with distilled water until the liquid volume in the cylinder reached one liter. For samples which required more than one liter of water for complete washing, the excess liquid was removed from the cylinder (or other container), centrifuged, decanted, the sediment returned to the cylinder, and the volume brought to one liter with a working solution of Merasperse-N (0.1 grams/liter). Sediment retained on the screen (usually a small amount) was rinsed onto filter paper, dried, and set aside for sieving.

Dispersion efficiency was checked by thoroughly mixing the sediment in the cylinders and allowing them to sit overnight. Samples which flocculated (fewer than 10 per cent) were decanted into jars, centrifuged, decanted, rinsed back into their cylinders, and the fluid volume returned to one liter with fresh dispersing solution. This procedure effectively inhibited flocculation of most samples; those in which flocculation persisted were discarded and a new (smaller) sample was prepared.

Pipette analysis.--Particle-size analysis of the silt-clay fractions was made by removal of aliquots at times and depths selected according to the Wadell modification of Stokes' law for settling velocities. The schedule established for withdrawal of aliquots is shown in Table 16.

TABLE 16.--Time of settling computed according to Wadell's law.

Diameter ($\emptyset$) (mm)		Velocity (cm/sec)	h (cm)	Hours	Minutes	Seconds
4	1/16	0.223	20	0	1	
5	1/32	0.0558	10	0	2	59
6	1/64	0.0139	10	0	11	59
7	1/128	0.00349	10	0	47	51
8	1/256	0.00087	10	3	12	--
9	1/512	0.000217	7	8	58	--
10	1/1024	0.000054	5	25	43	--

Analyses were begun with homogenization of the material in the cylinders by mixing with a plunger for one minute. Cessation of mixing

was taken as time zero. One minute was allowed for reduction of tur-
bulence before removal of the first aliquot. Subsequent aliquots
were drawn at times and depths shown in Table 16. All aliquots were
taken with 20-milliliter pipettes with attached suction bulbs, drained
into tared beakers, and evaporated to dryness at 80 degrees Celsius.
The aid of three assistants in removal of initial aliquots permitted
analysis of 30 to 40 samples in a single run; one or two runs were
completed per week.

Precautions taken to increase the accuracy and reproducibility
of results included; (1) automatic maintenance of room temperature,
(2) consistent use of the same operators, (3) inducement of a simi-
lar state of turbulence in each cylinder at time zero, (4) slow (5
seconds) insertion and removal of pipettes, (5) uniform rate (20
seconds) of aliquot withdrawal, (6) maintenance of pipette depth
during withdrawal, and (7) delivery of exact aliquots.

Dried aliquots were cooled in a desiccator, weighed to the
nearest milligram, and the phi-class weights determined by successive
subtractions and multiplication of differences by a factor of fifty.
Results of duplicate analyses of samples with negligible coarse frac-
tions (i.e., those for which the entire size distribution was deter-
mined by pipette analysis) indicate that the phi mean and phi deviation
statistics have a minimum reproducibility of about 0.2 phi and 0.3
phi-units respectively. Reproducibility is, in large part, a function
of the particle-size distribution, and sediments with coarser means
and larger coarse fractions will have a higher degree of reproduci-
bility.

Sieve analysis.--Dry coarse fractions were sieved (15 minutes)

through new, calibrated, U. S. Standard sieves, arranged in a single phi-unit progression from 0 to 4 phi, in an automated Tyler Portable Sieve Shaker (220 cycles/minute, 6.8 centimeter displacement). Size fractions were weighed to the nearest 0.02 gram.

McManus (1965) showed that the maximum load for 3-inch sieves is related to the number of near-mesh particle sizes. This number decreases, for a fixed sample size, with decrease in the sieve class interval. For screens in a single-phi progression (not considered by McManus), the maximum sample size permissible for efficient sieving was estimated to be about 4, 3, and 1 gram respectively for the 2-, 3-, and 4-phi screens. If these weights were exceeded, the sample was split and sieved in two or more parts.

The effect of overloading the screens was considered for several samples. For example, sample 19 from the Yellowstone section initially retained 7.62 grams of sediment on the 4-phi screen. After splitting and resieving, an additional 0.54 grams of sediment passed through the screen. The error due to overloading in this sample amounted to 7 per cent of the fraction weight and 2 per cent of the total weight. The potential effect of such error on the size statistics is variable, but in all cases it is quite small.

Results of duplicate analysis indicate that sandy samples have phi mean and phi deviation measures reproducible within about 0.05 phi and 0.05 phi-units respectively.

Computation of size statistics.--Pipette analysis provided values for sediment weights in each size class from 5 to 10 phi. This range was sufficient to accumulate greater than 95 per cent of the total weight of most samples; however, a minor number of fine-grained samples

were too open-ended for direct measurement of the phi diameter at the
95 percentile. For these samples, the value was approximated by
straight-line interpolation between the last measured value (10 phi)
and 13 phi, the latter value being assumed a practical lower limit of
lithogenous particle sizes. Two factors lend strong support to this
procedure: (1) interpolated phi values at the 95 percentile usually
occurred between 10 and 11 phi, which means that the interpolation,
with its associated indeterminant error, was usually minor; and (2)
nearly all the sediments are markedly fine skewed, which justifies
use of a straight-line interpolation in the fine tail..

Particle-size statistics were computed by an IBM System/360
according to a revised version (Reinhold Fischer, University of North
Dakota Computer Center) of the University of Missouri Fortran program
for evaluation of size analyses (Kane and Hubert, 1963). Revision in-
volved; (1) modification of input form to accept any class interval
over any range of phi values, (2) a change from linear to exponential
interpolation (subroutine) of critical phi values, and (3) modifica-
tion of the print-out to include sand, silt, clay percentages and in-
terpolated phi values (Table 17). Sample input included only sample
identification and the sediment weight in each size class. The output
accuracy, in the size ranges measured, is consistent with that of the
input data.

Carbonate analysis

Carbonate contents of samples were determined by the method of
Herrin and others (1958) in which a known weight of sediment is allowed
to react with a measured quantity of standard H_2SO_4. The milliequiva--
lents of CO_3 liberated, which equal the milliequivalents of acid

TABLE 17.--Sample print-out of sediment-size data.

SAMPLE NO.   C-1   DATE _____

LOCATION SEC. ____ TWP. ____ RNG. ____ CO. _____

SAMPLE TYPE _____

MOMENT MEASURES NOT COMPUTED

CALCULATION OF FOLK STATISTICS   FOLK'S TEXTURAL DESCRIPTIONS
MZ = 6.359   SILT
SORTING = 1.619   POORLY SORTED
SKEWNESS = 0.377   PLATYKURTIC
KURTOSIS = 0.864   STRONGLY FINE SKEWED

CALCULATION OF INMAN STATISTICS
M PHI = 6.513
SIGMA PHI = 1.629
SKEWNESS = 0.272
KG (INMAN) = 0.629
ALPHA TWO PHI = 0.784

DATA FOR DRAWING A FREQUENCY DISTRIBUTION CURVE

PHI SIZE	FRACTION WEIGHT	FRACTION PER CENT	CUMULATED PER CENT
5.00	1.10	27.50	27.50
6.00	0.85	21.25	48.75
7.00	0.70	17.50	66.25
8.00	0.65	16.25	82.50
9.00	0.35	8.75	91.25
10.00	0.15	3.75	95.00
11.00	0.11	2.75	97.75
12.00	0.09	2.25	100.00

PHI SIZE AT PER CENT LEVEL OF

5	16	25	50	75	84	95
4.69	4.88	4.98	6.07	7.50	8.14	10.00

GRAVEL	SAND	SILT	CLAY	TOTAL
0.00	0.00	82.50	17.50	100.00

utilized, are measured by back titration with standard NaOH. The
procedure is outlined below.

Reagents.--Standard reagents are prepared as directed.

1. Standard sulfuric acid, 0.4 N.

   One liter - dilute 12 ml of pure concentrated
   H_2SO_4 (density = 1.84) to 500 ml with distilled
   water. Mix thoroughly, cool, and dilute to one
   liter. Mix again.

2. Standard sodium hydroxide, 0.45 N.

   One liter - dissolve 19 grams of sodium hydroxide
   in 500 ml of distilled water, cool, and dilute
   to one liter. Mix again.

The acid is relatively stable and need not be checked against
newly standardized base more than once a year, but the base reacts
slowly with glass and CO_2 and must be standardized at least one a
month.

Standardization.--Standardization of both acid and base were
made in triplicate. About 0.8 grams of potassium acid pthalate was
weighed to the nearest milligram, dissolved in a flask with 150 mill-
iliters of distilled and deionized water, and titrated with standard
base to a potentiometric end-point of 7.0. The normality of the
base was calculated by the equation:

$$\text{Normality (NaOH)} = \frac{\text{wt. KH pthalate}}{(0.2042)\ (\text{ml NaOH})}$$

The acid was standardized against the base. Twenty five milli-
liters of acid were added by volumetric pipette to about 100 milliliters
of distilled-deionized water and titrated with standard base to a pH

of 7.0. The normality of the acid was determined by the relationship:

$$\text{Normality } (H_2SO_4) = \frac{(\text{ml NaOH}) \ (\text{N NaOH})}{\text{ml } H_2SO_4}$$

The reagents were standardized to the same potentiometric end-point (pH = 7.0) used in the analysis (if phenopthalein is used as an indicator, reagents must be standardized to the phenopthalein end-point; pK = 8.3).

Procedure.--Each sample was ground to fineness with a mortar and pestle, dried to constant weight, homogenized, and one gram portions weighed to the nearest 0.02 gram for analysis. Fifty milliliters of standard H_2SO_4 was pipetted into each sample, reacted at room temperature until effervescence slowed, and heated in a water bath to 80 to 90° Celsius for twenty minutes. Samples were cooled and checked with indicator paper; if the pH exceeded 2 or 3, additional acid (25 milliliters) was added and the samples re-heated for 10 minutes. Samples were cooled, diluted with approximately 200 milliliters of newly distilled water, and titrated potentiometrically to a pH of 7 (caution: use glass-bead or plastic stopcock burette) with constant stirring with a magnetic mixer.

Calculation of results.--The number of milliequivalents of acid which reacted with one gram of sample is equivalent to the milliequivalents of CO_2 in the sample:

$$(\text{ml } H_2SO_4) \ (\text{N } H_2SO_4) - (\text{ml NaOH}) \ (\text{N NaOH}) = \text{meq. } CO_2$$

This difference multiplied by the milliequivalent weight of the carbonate compound times 100 gives the per cent weight of the compound per gram of sample:

of 7.0. The normality of the acid was determined by the relationship:

$$\text{Normality (H}_2\text{SO}_4) = \frac{(\text{ml NaOH}) \ (\text{N NaOH})}{\text{ml H}_2\text{SO}_4}$$

The reagents were standardized to the same potentiometric end-point (pH = 7.0) used in the analysis (if phenopthalein is used as an indicator, reagents must be standardized to the phenopthalein end-point; pK = 8.3).

Procedure.--Each sample was ground to fineness with a mortar and pestle, dried to constant weight, homogenized, and one gram portions weighed to the nearest 0.02 gram for analysis. Fifty milliliters of standard H_2SO_4 was pipetted into each sample, reacted at room temperature until effervescence slowed, and heated in a water bath to 80 to 90° Celsius for twenty minutes. Samples were cooled and checked with indicator paper; if the pH exceeded 2 or 3, additional acid (25 milliliters) was added and the samples re-heated for 10 minutes. Samples were cooled, diluted with approximately 200 milliliters of newly distilled water, and titrated potentiometrically to a pH of 7 (caution: use glass-bead or plastic stopcock burette) with constant stirring with a magnetic mixer.

Calculation of results.--The number of milliequivalents of acid which reacted with one gram of sample is equivalent to the milliequivalents of CO_2 in the sample:

$$(\text{ml H}_2\text{SO}_4) \ (\text{N H}_2\text{SO}_4) - (\text{ml NaOH}) \ (\text{N NaOH}) = \text{meq. CO}_2$$

This difference multiplied by the milliequivalent weight of the carbonate compound times 100 gives the per cent weight of the compound per gram of sample:

$$(\text{meq. } CO_2)\ (\text{meq. wt. of compound})\ (100) = \text{per cent weight of the compound in one gram of sample}$$

It is possible to express results as per cent CO_2 or CO_3 in any sample, but a decision as to the proper cation is necessary before the amount of carbonate mineral (calcite, dolomite, siderite, etc.) can be determined.

Use of sulfuric acid gives lower and more reproducible results than does hydrochloric acid. This is so because of the large number of components which can be put into solution by hydrochloric acid; these include oxides of iron, aluminum, manganese, titanium, and silicon. By this titration method, the only sediment components that will contribute to the results are those which will form volatile or insoluble products by reaction with dilute sulfuric acid. Except for carbonates, sulfides are the only common components of Tongue River and Sentinel Butte sediments which might occur and react in this fashion. The error caused by reaction of the transition metals, which are common in rocks and sediments, would be minor because, by back-titration to a pH of seven or greater, the sulfates formed by reaction with the acid would be precipitated by an equivalent amount of base.

Considerable controversy exists among sedimentologists concerning the relative accuracy of various methods of determination of carbonate in rocks and minerals. The titrametric method outlined above is subject to particular criticism because it measures hydrogen ion utilization rather than direct evolution of CO_2. Objections to the technique are based largely on the fact that some hydrogen ions may be adsorbed by or exchanged with clay minerals, or be utilized in decomposition of non-carbonate compounds. Gasometric methods, involving

entrainment of gases, scrubbing with a strong base, and measurement of the amount of CO_2 evolved are often considered superior to titrametric procedures. Because of the large number of samples to be analyzed, the rapid method of Herrin, and others (1958) was preferred, and a comparative study was made to determine its accuracy and precision relative to gasometric analysis.

Four samples of Tongue River sediment, with $CaCO_3$ contents ranging from 3 to 80 per cent, and standard samples of sodium carbonate were analyzed in triplicate both by the method outlined above and by the gasometric technique of Shapiro and Brannock (1962). Carbonate was evolved by hydrochloric, sulfuric, and phosphoric acids. Statistical comparison of results showed no significant difference between use of hydrochloric and sulfuric acid, but phosphoric acid gave an indistinct end-point and sporadic results. No difference, at the 99 per cent level of significance, was detected between the two methods, utilizing either hydrochloric or sulfuric acid, for samples with carbonate contents less than 50 per cent by weight; the gasometric technique gave higher results for samples with calcium carbonate contents greater than 50 per cent. Because, with the exception of freshwater limestones, nearly all Tongue River and Sentinel Butte samples contain less than 50 per cent $CaCO_3$ (31 per cent CO_3), the titrametric method should give the same results as those of gasometric analysis. The reproducibility and accuracy of the method employed in this study are within one per cent of reported values.

APPENDIX II

Supplementary Data for Stratigraphic Sections

Appendix II-A

Plots of sorting vs. mean for stratigraphic samples
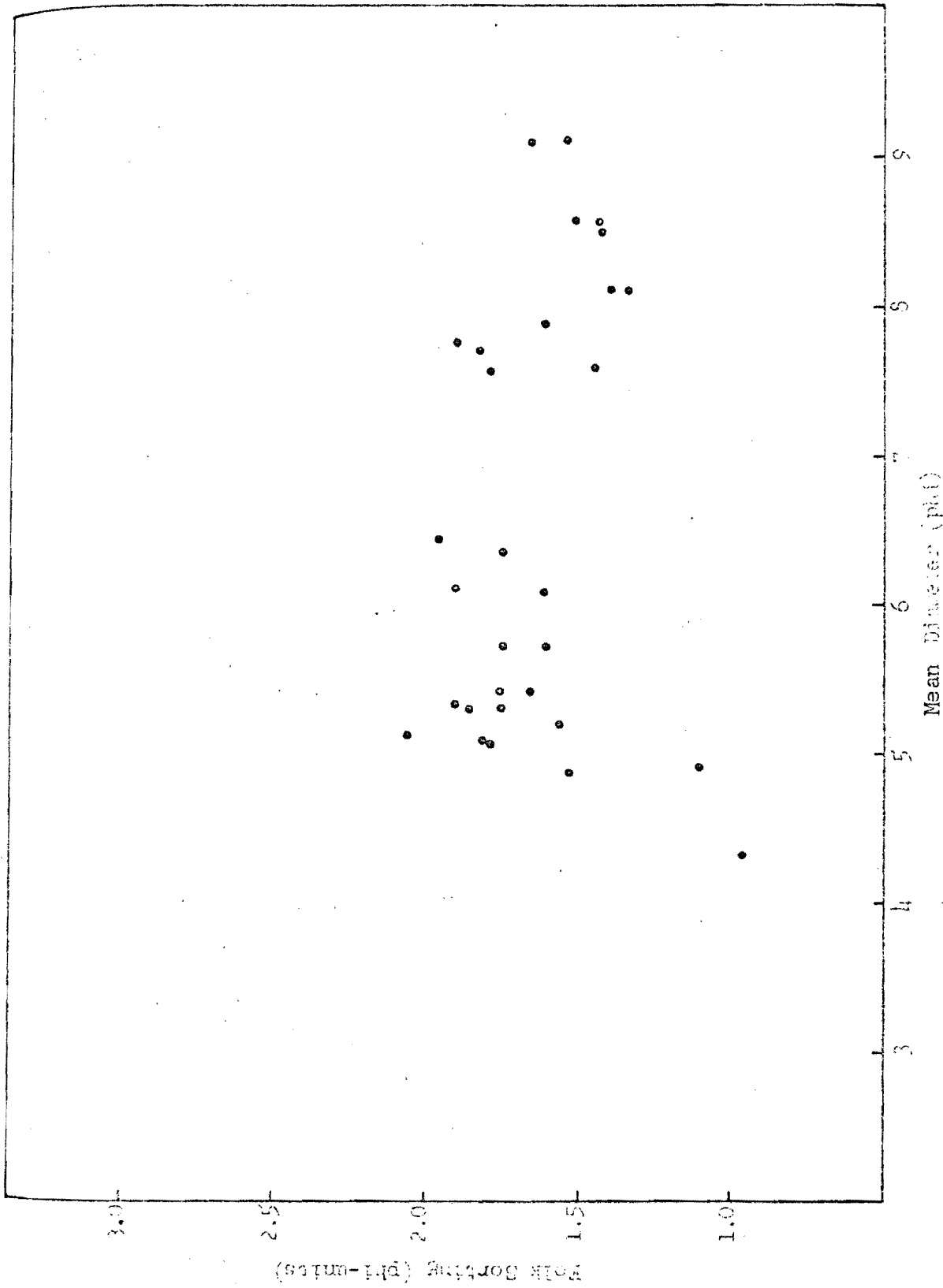
Figure 52.--Plot of Folk sorting vs. mean diameter for Tongue River samples from the Bullion Butte session.
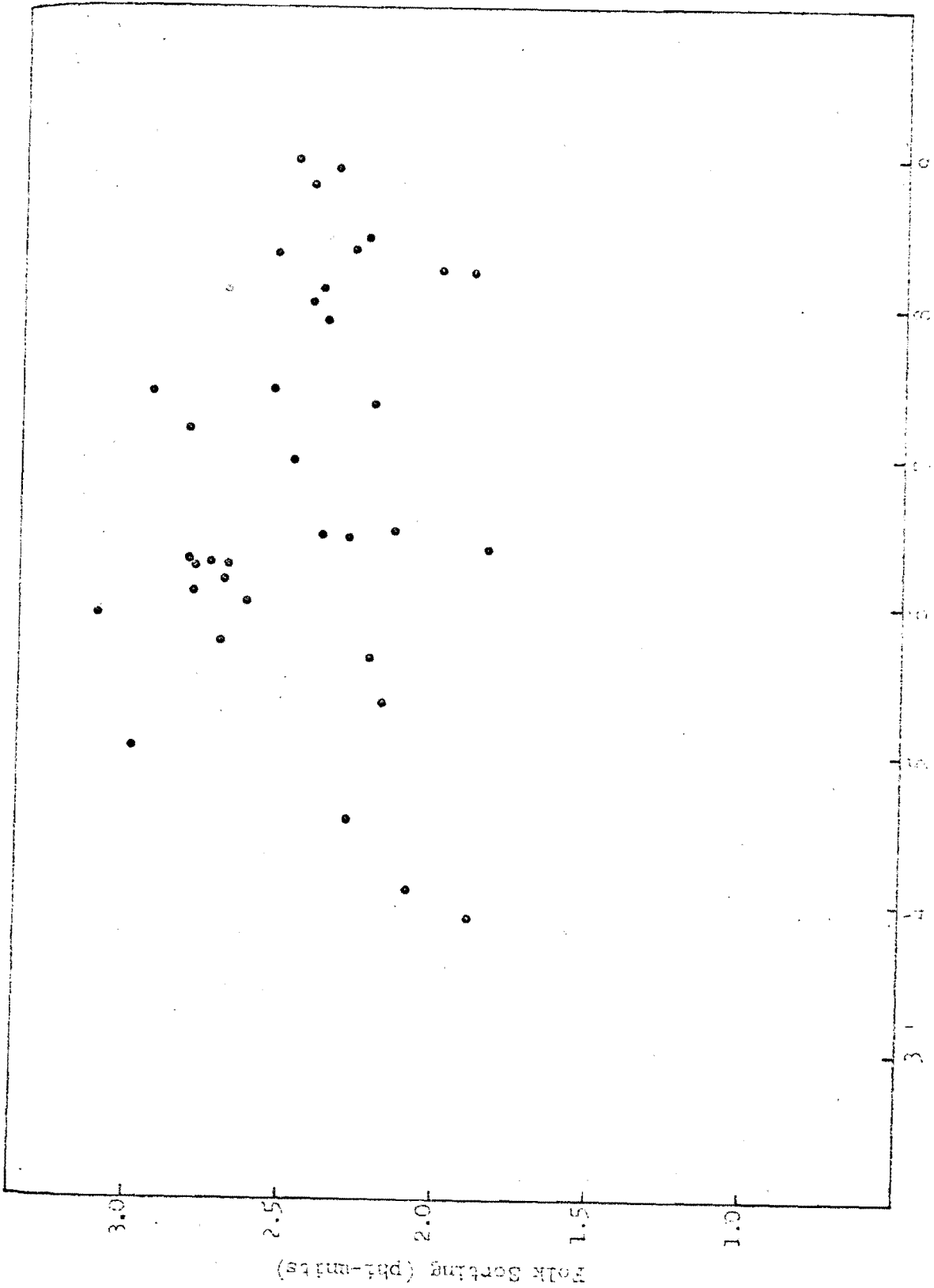
Figure 53.--Plot of Folk sorting vs. mean diameter for Tongue River samples from the Hadora section.
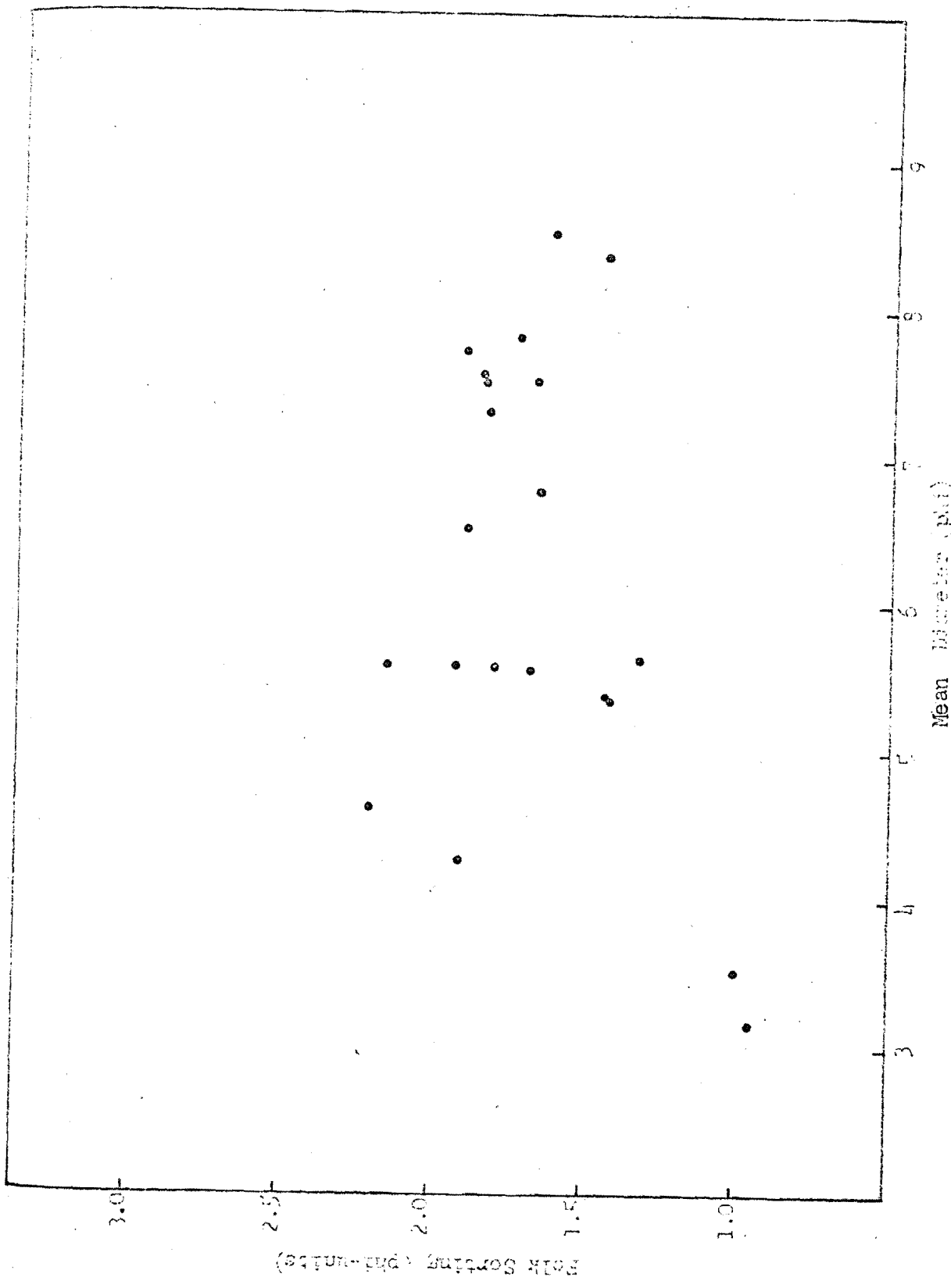
Figure 54.--Plot of Folk sorting vs. mean diameter for Tongue River samples from the Beicesel Creek section.
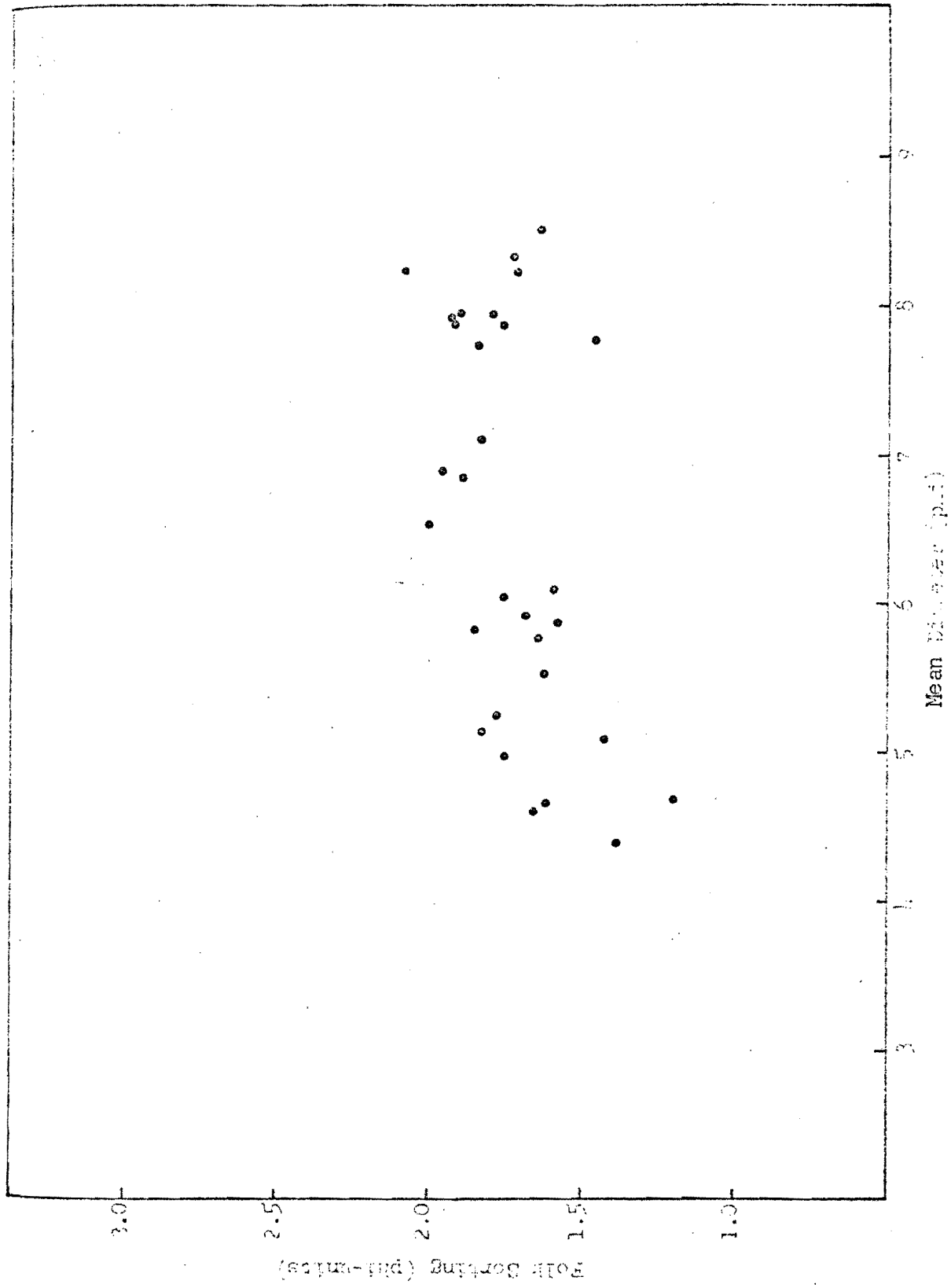
Figure 55.--Plot of Folk sorting vs. mean diameter for Tongue River samples from the Yellowstone section.
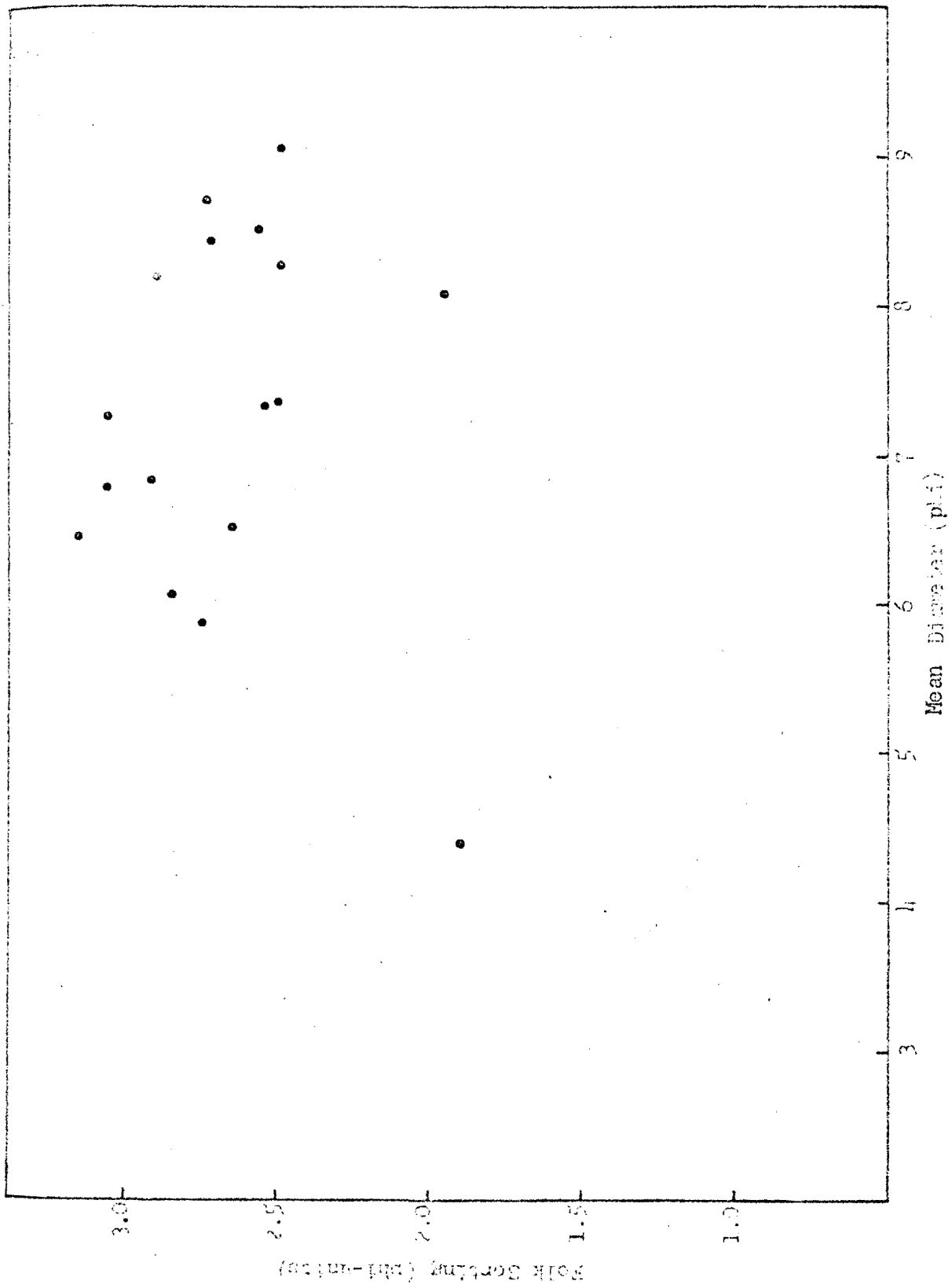
Figure 56.--Plot of Folk sorting vs. mean diameter for Tongue River samples from the Snowden section.
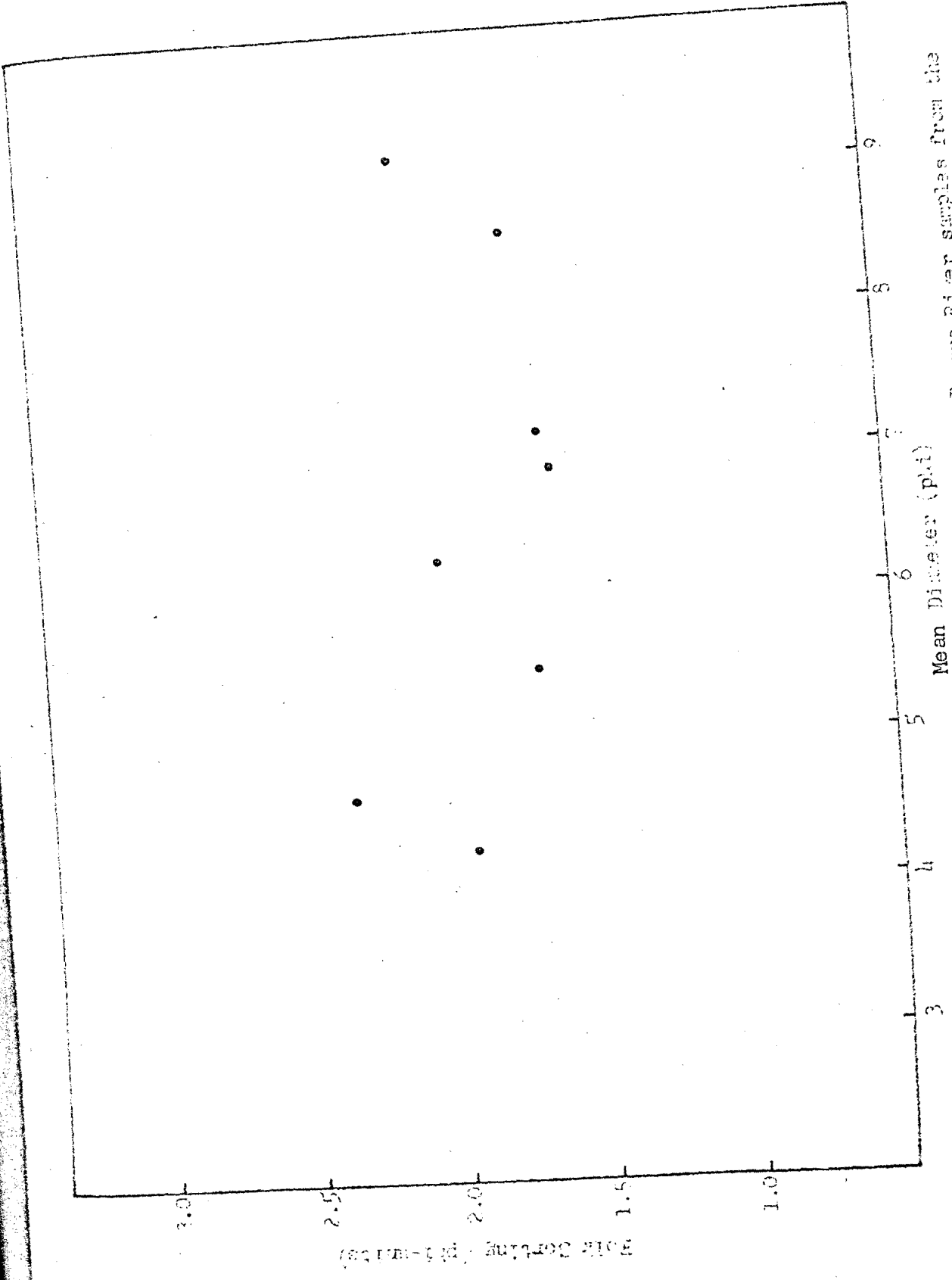
Figure 57.--Plot of Folk sorting vs. mean diameter for Tongue River samples from the Donnybrook section.
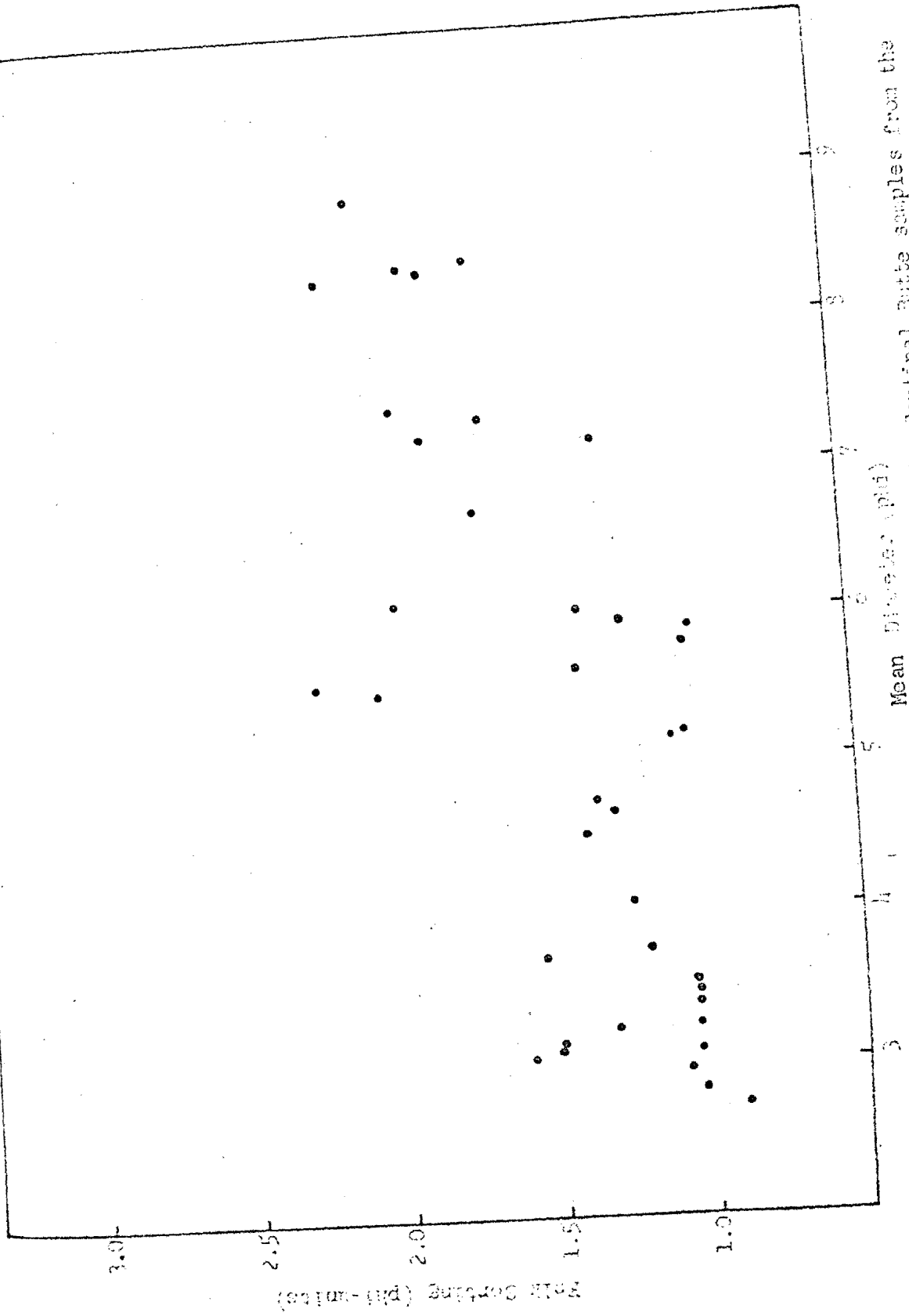
Figure 58.--Plot of Folk sorting vs. mean diameter for Sentinel Butte samples from the Bullion Butte section.
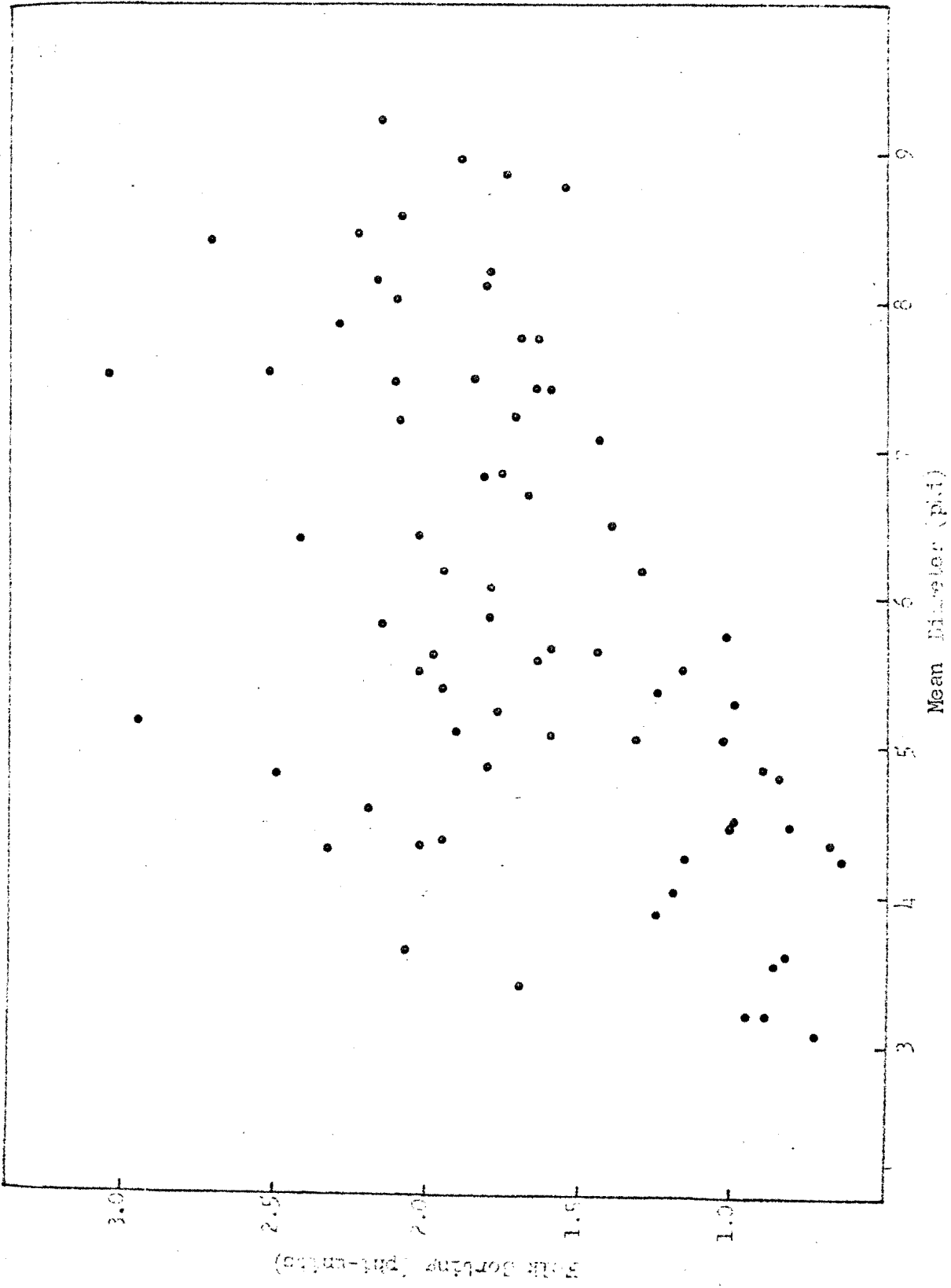
Figure 59.--Plot of Folk sorting vs. mean diameter for Sentinel Butte samples from the Sentinel Butte section.
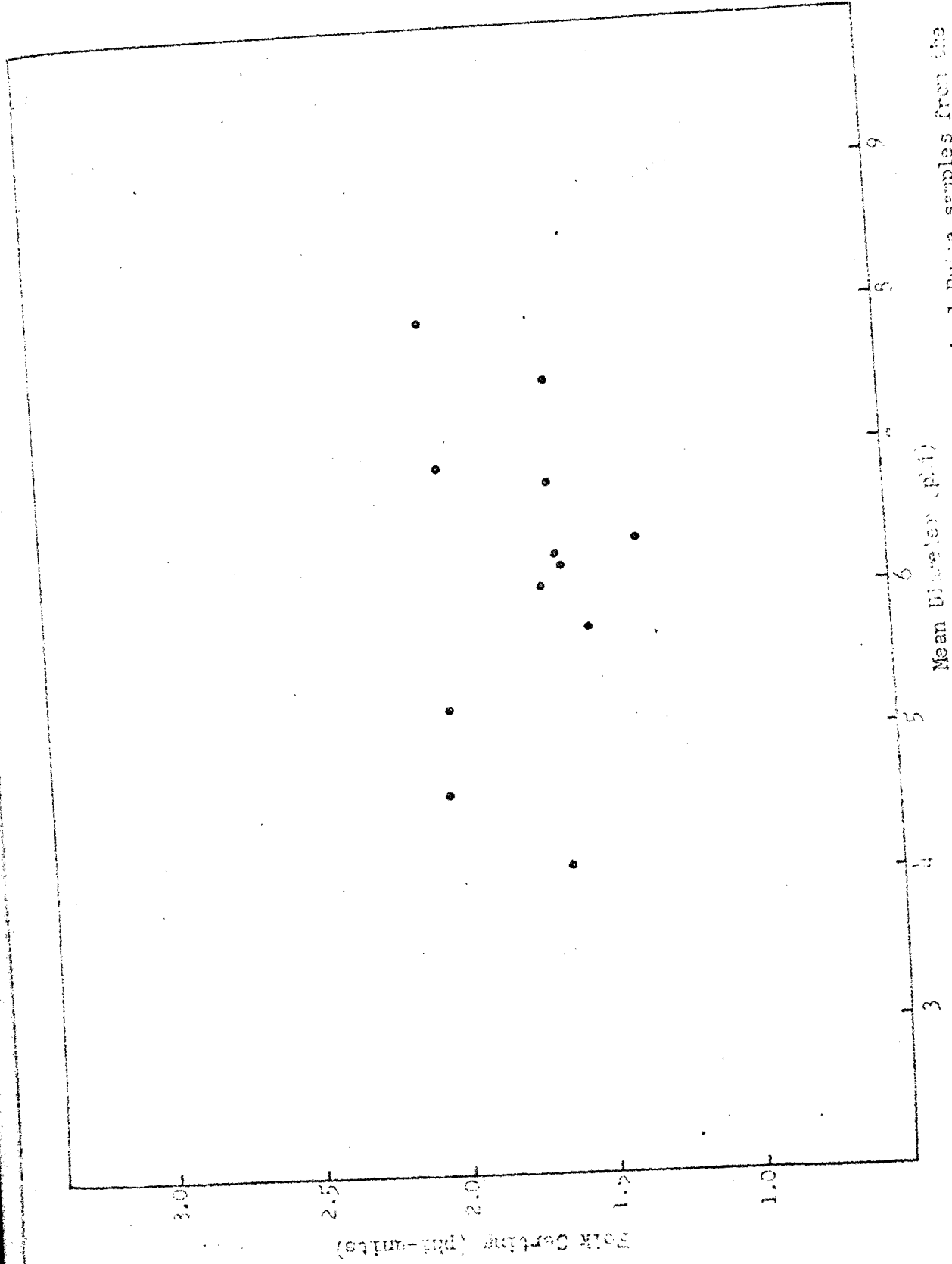
Figure 50.—Plot of Folk sorting vs. mean diameter for Sentinel Butte samples from the Beicegel Creek section.
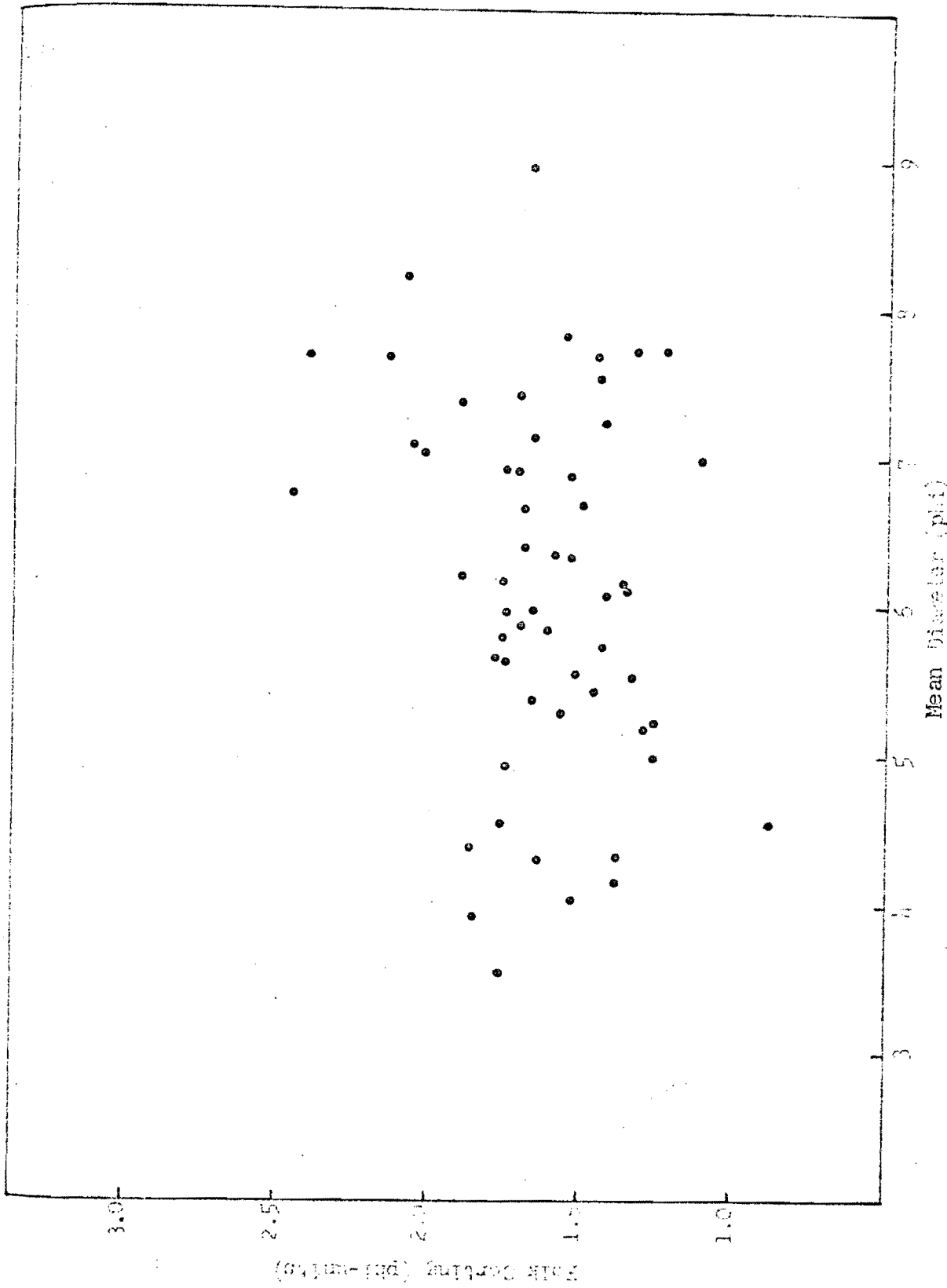
Figure 61.--Plot of Folk sorting vs. mean diameter for Sentinel Butte samples from the long cross section.
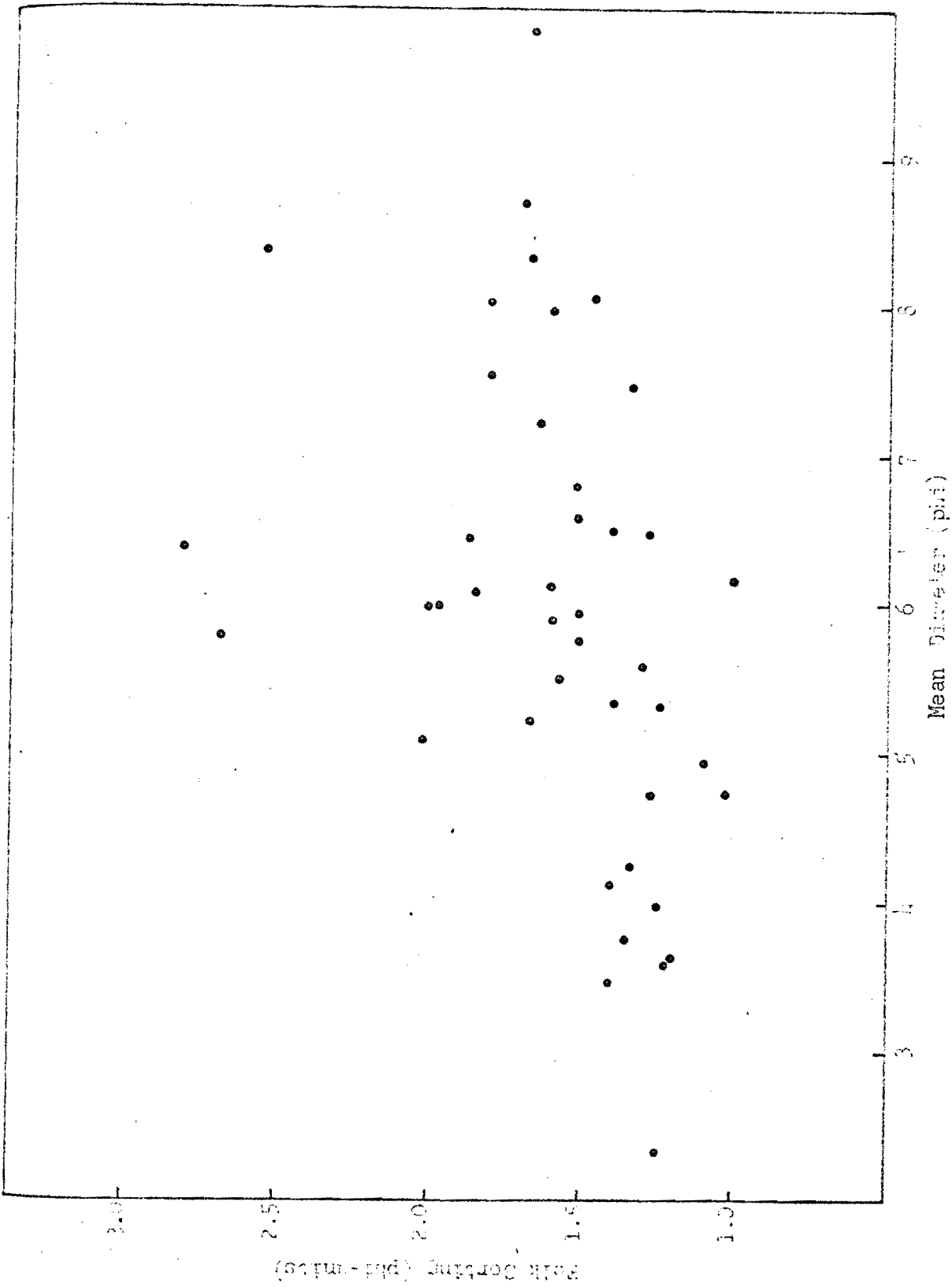
Figure 62.—Plot of Folk sorting vs. mean diameter for Seminal Buss samples from the Lost Bridge section.

Appendix II-B

Distribution of Folk skewness values in stratigraphic samples
from the Tongue River and Sentinel Butte Formations
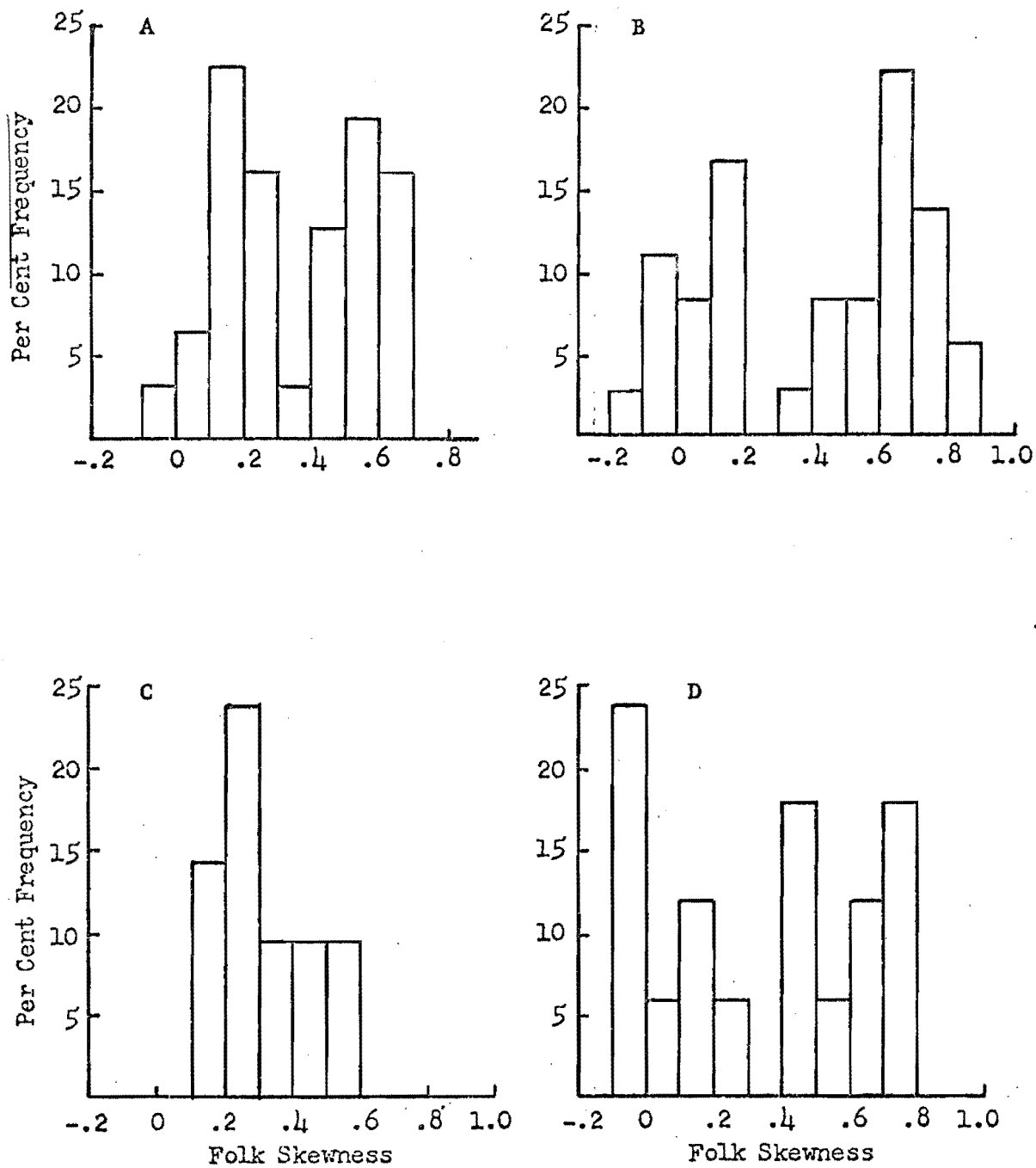
Figure 63.--Distribution of Folk skewness values in Tongue River samples from the Bullion Butte (A), Medora (B), Beicegel Creek (C), and Snowden (D) stratigraphic sections.
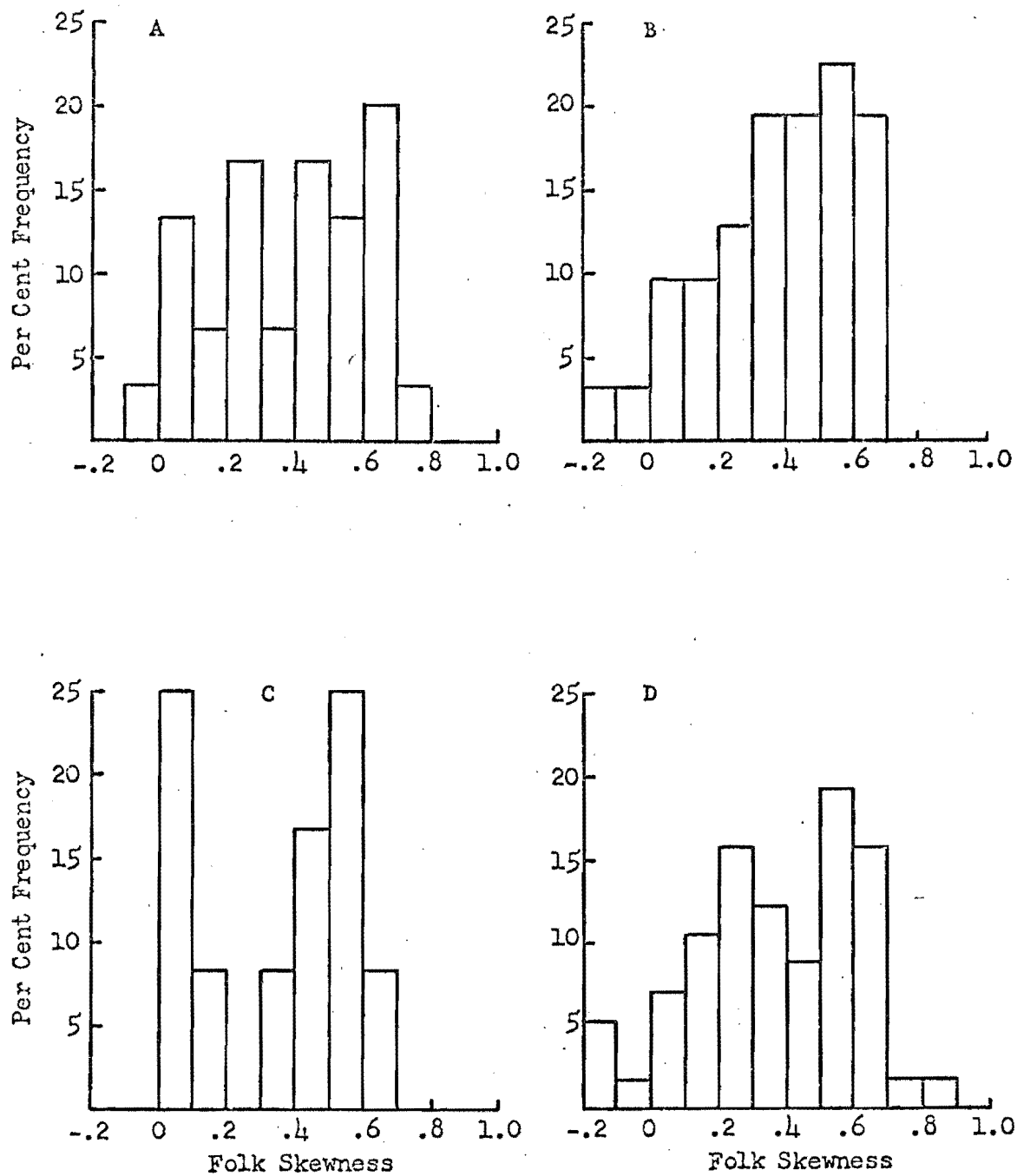
Figure 64.--Distribution of Folk skewness values in Tongue River samples from the Yellowstone (A), and Sentinel Butte samples from the Bullion Butte (B), Beicegel Creek (C), and Long Cross (D) stratigraphic sections.
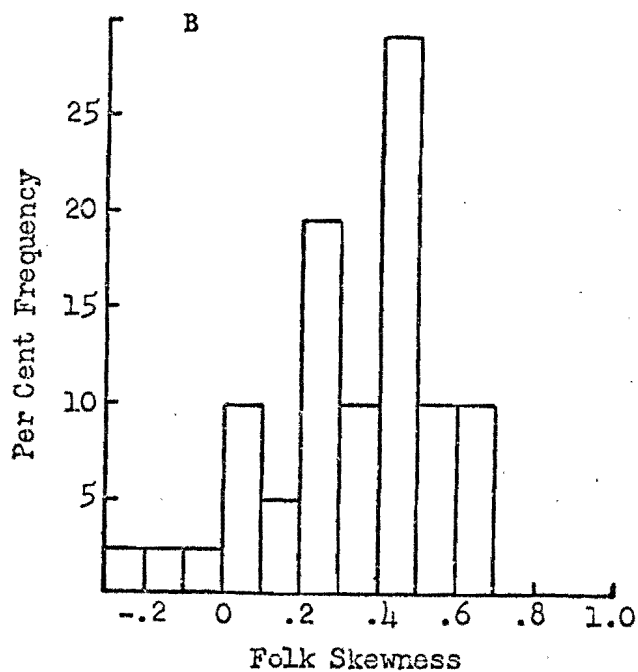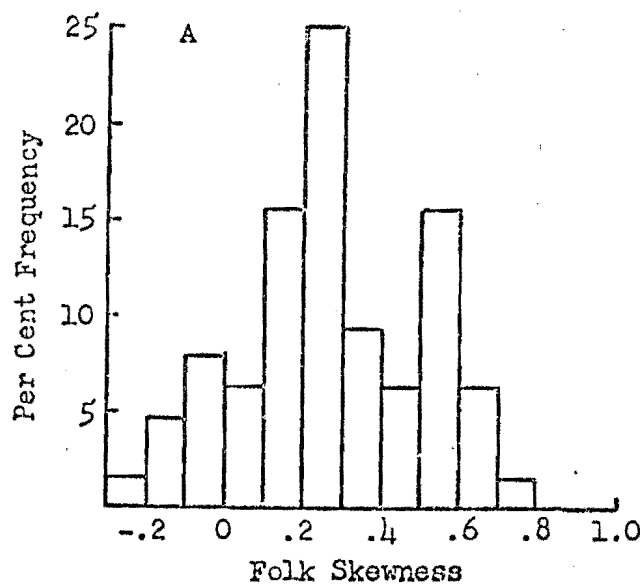
Figure 65.--Distribution of skewness values in Sentinel Butte samples from the Sentinel Butte (A) and Lost Bridge (B) stratigraphic sections.

Appendix II-C

Plots of skewness vs. median for stratigraphic samples
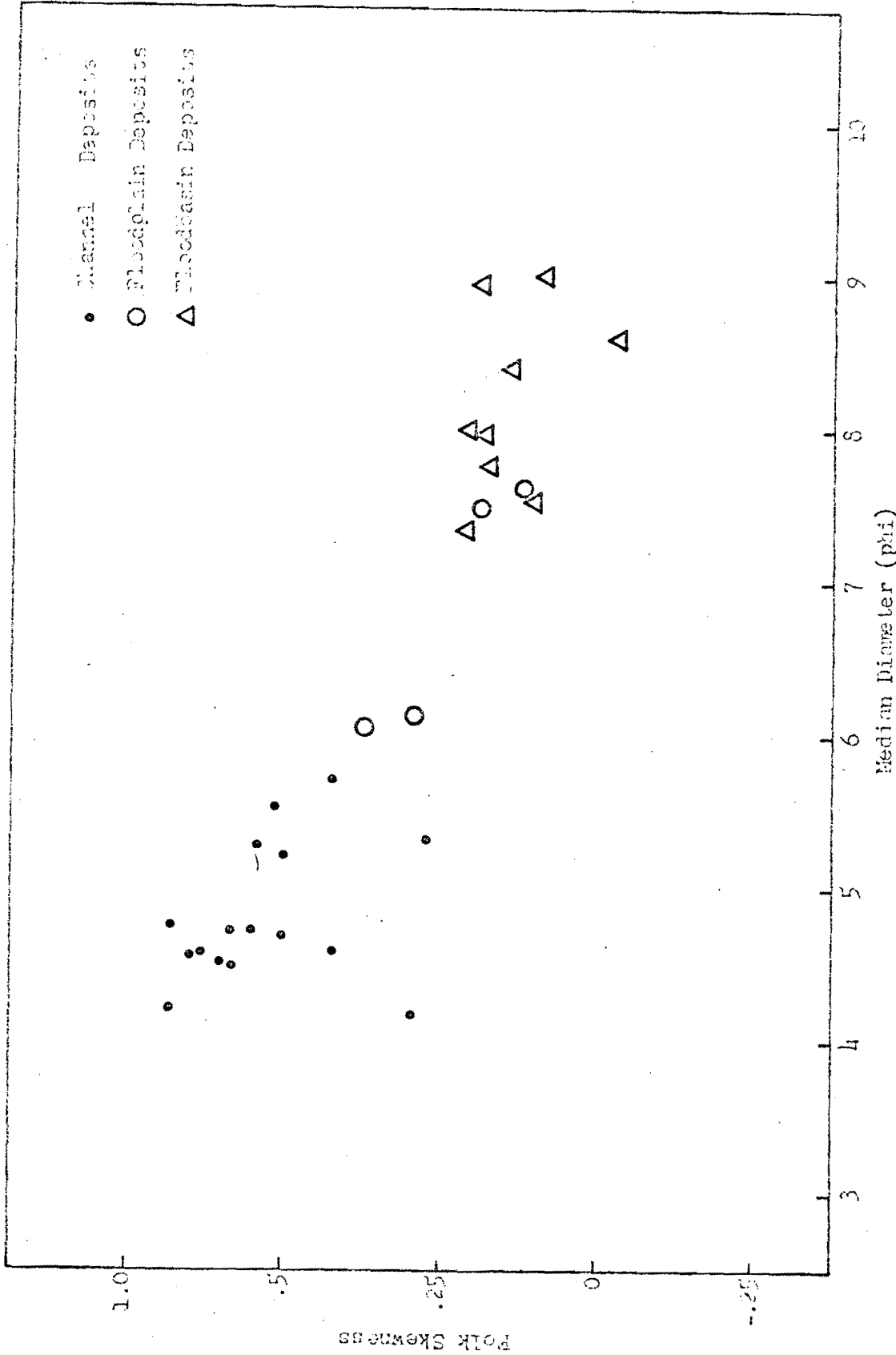
Figure 56.--Plot of Folk skewness vs. median diameter for Tongue River samples from the Bullion Butte section.
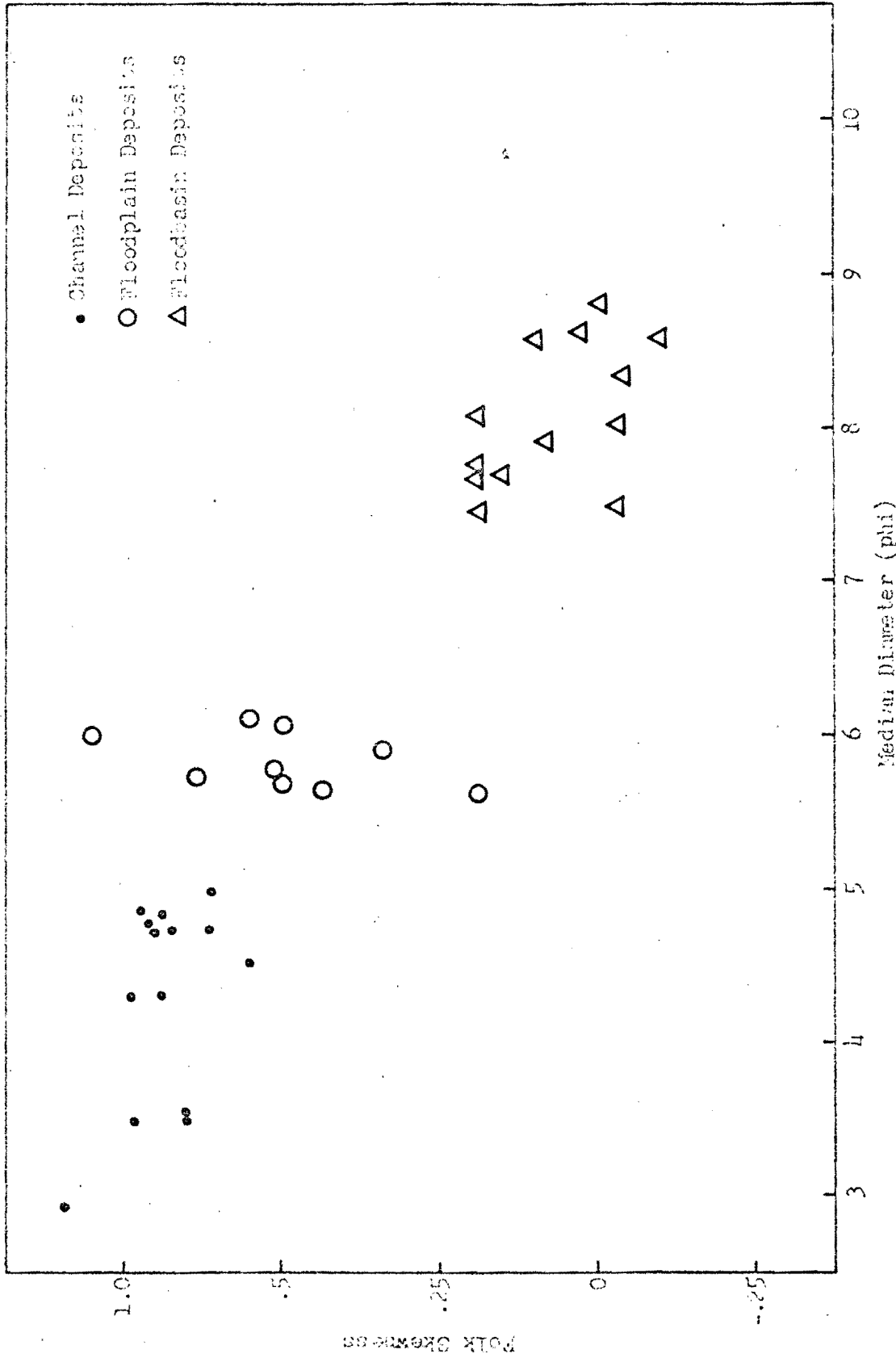
Figure 67.--Plot of Folk skewness vs. median diameter for Tongue River samples from the Medora section.
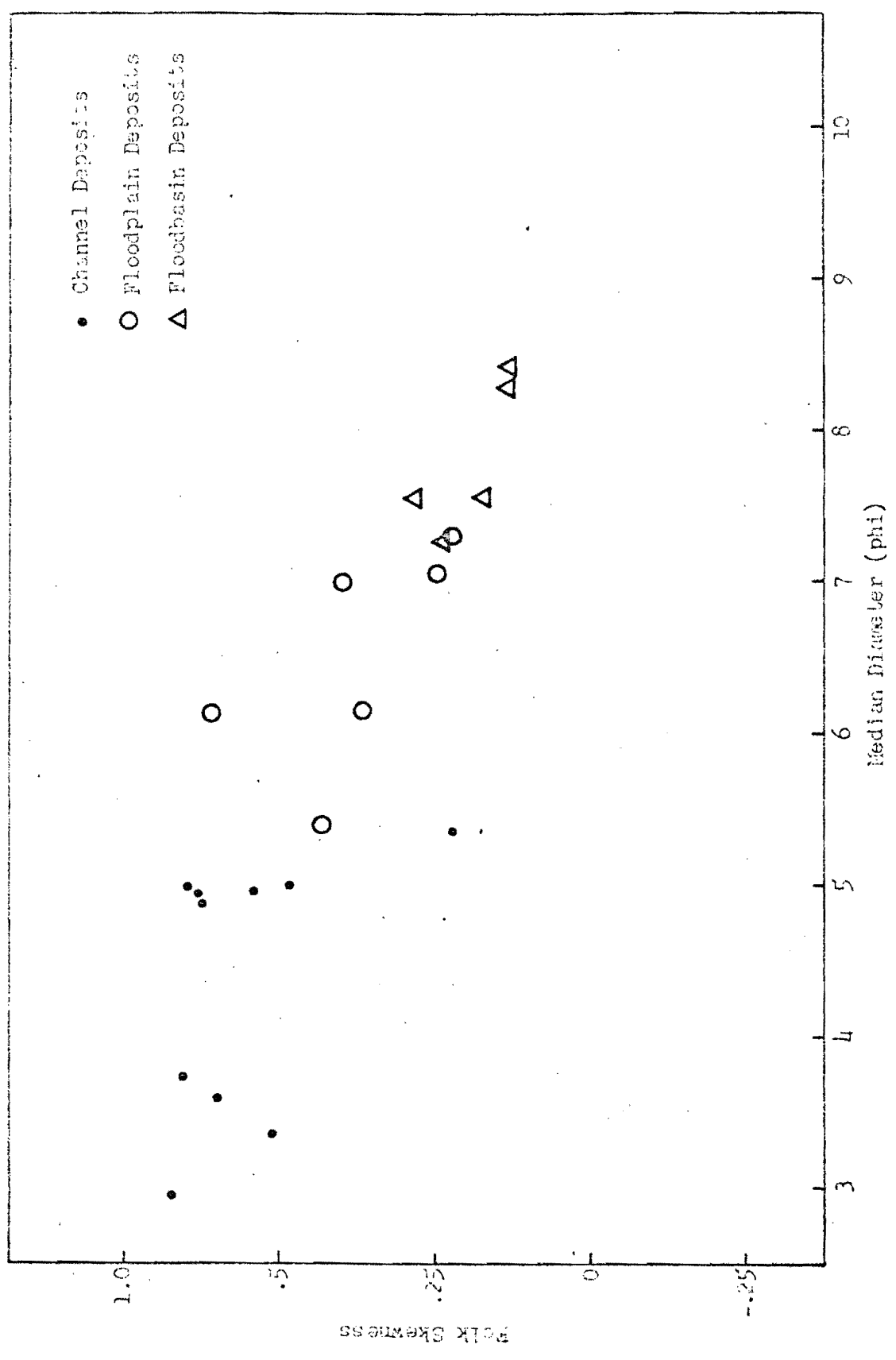
Figure 68.--Plot of Folk skewness vs. median diameter for Tongue River samples from the Beicegel Creek section.
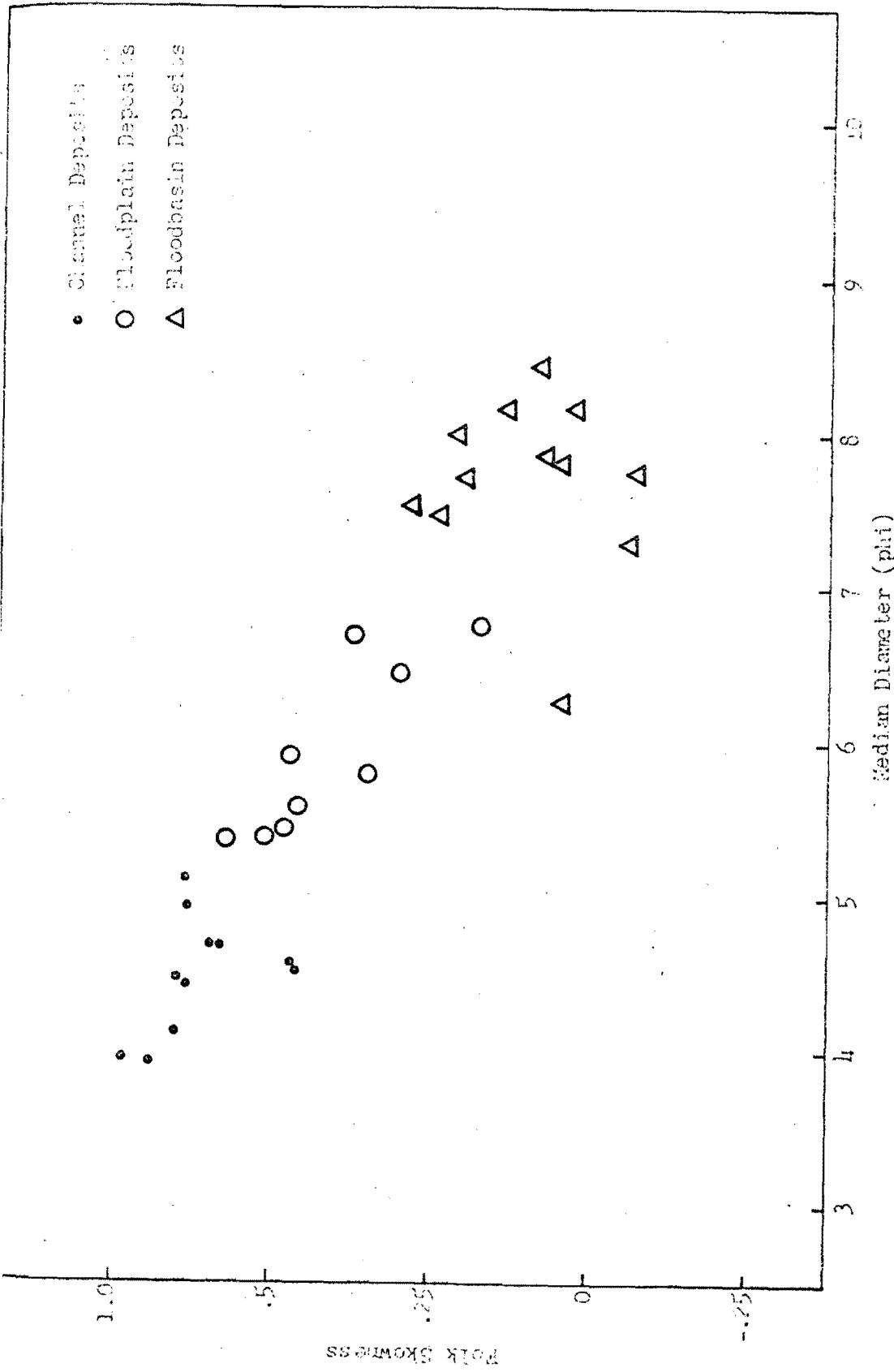
Figure 69.--Plot of Folk skewness vs. median diameter for Tongue River samples from the Yellowstone section.
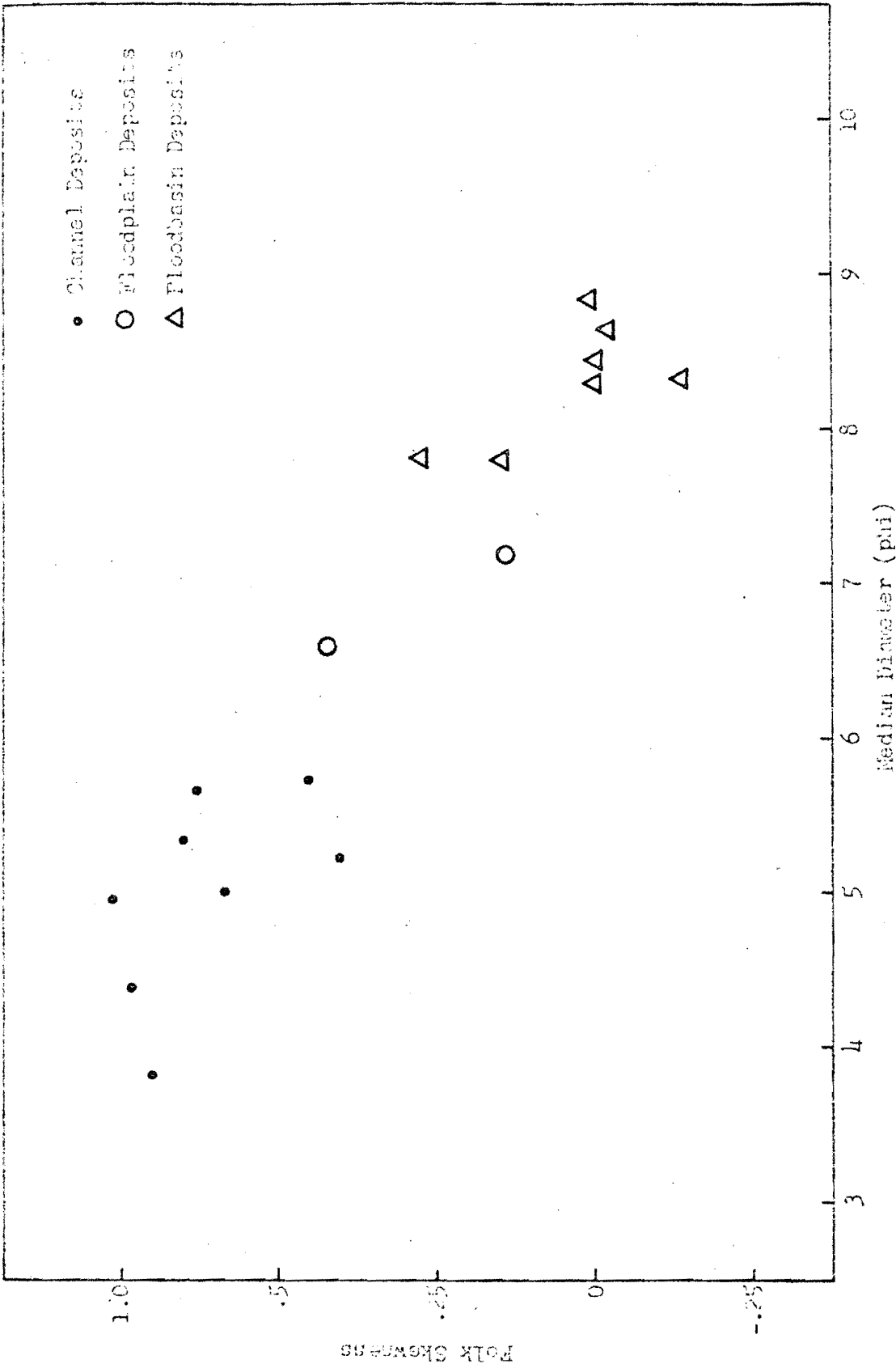
Figure 70.--Plot of Folk skewness vs. median diameter for Tongue River samples from the Snowden section.
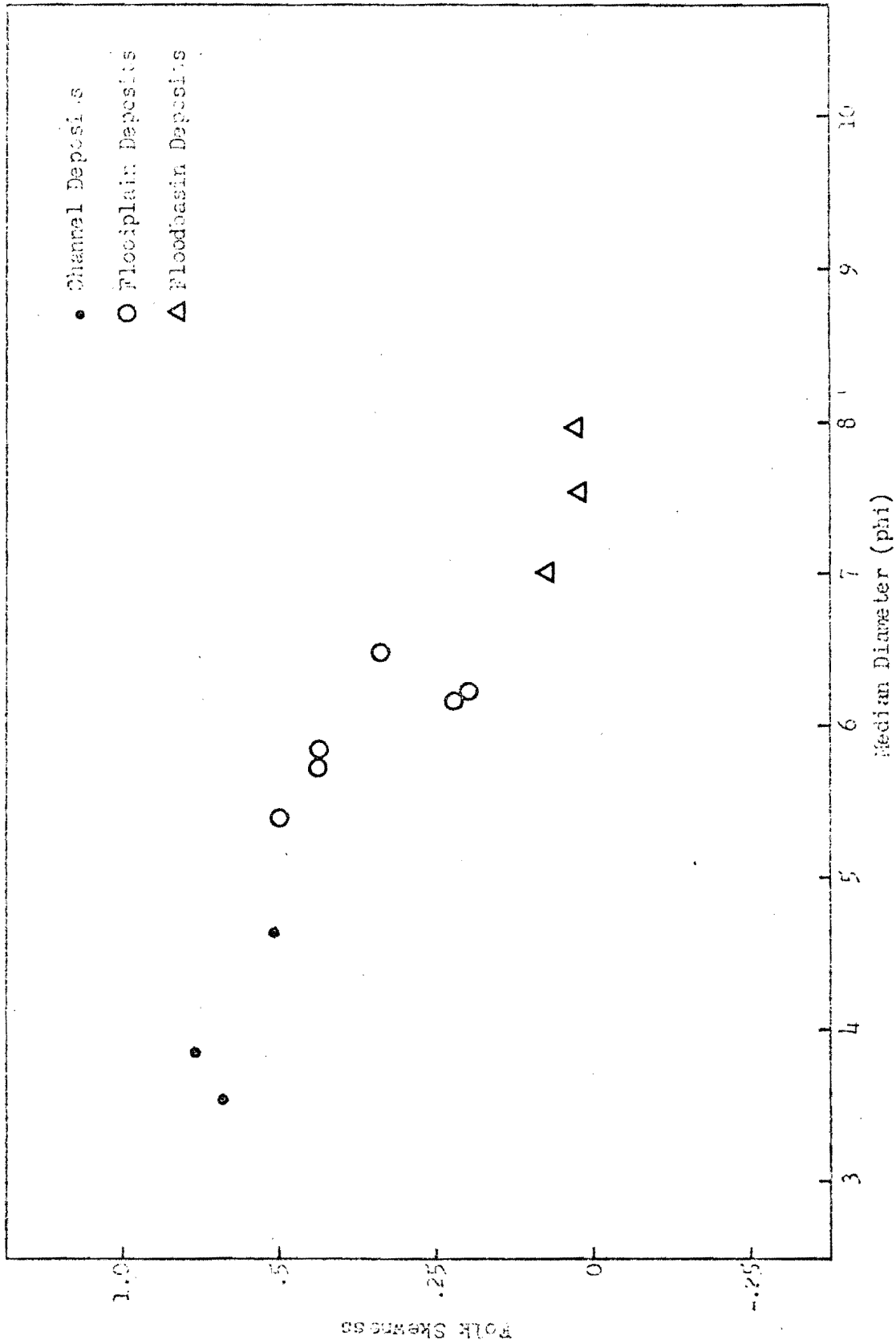
Figure 74.—Plot of Folk skewness vs. median diameter for Sentinel Butte samples from the Beicegel Creek section.
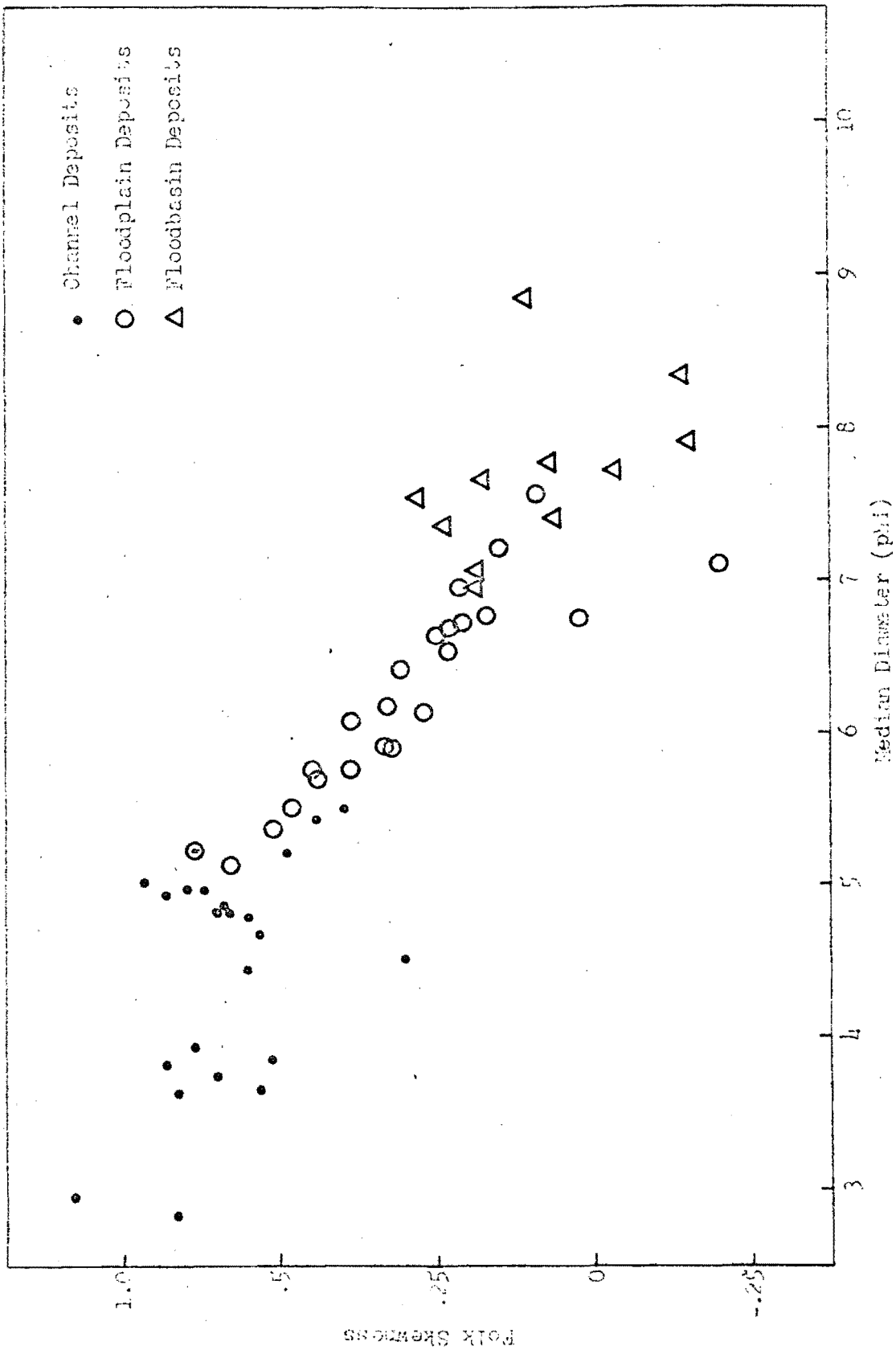
Figure 75.—Plot of Folk skewness vs. median diameter for Sentinel Butte samples from the Long Cross section.
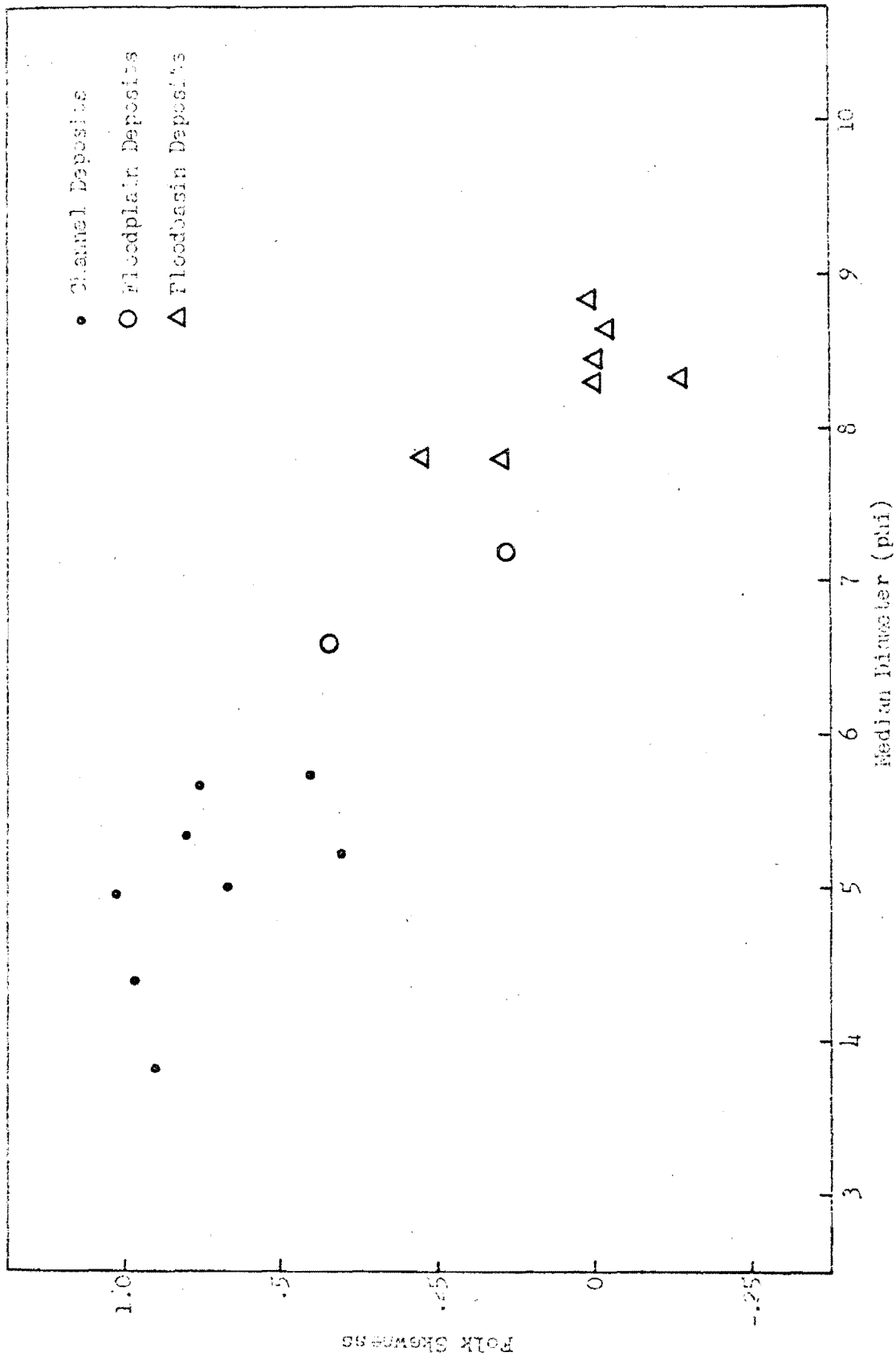
Figure 70.--Plot of Folk skewness vs. median diameter for Tongue River samples from the Snowden section.

Figure 76.--Plot of Folk skewness vs. median diameter for Sentinel Butte samples from the Lost Bridge section.

Appendix II-D

Sand, silt, clay relationships of stratigraphic samples
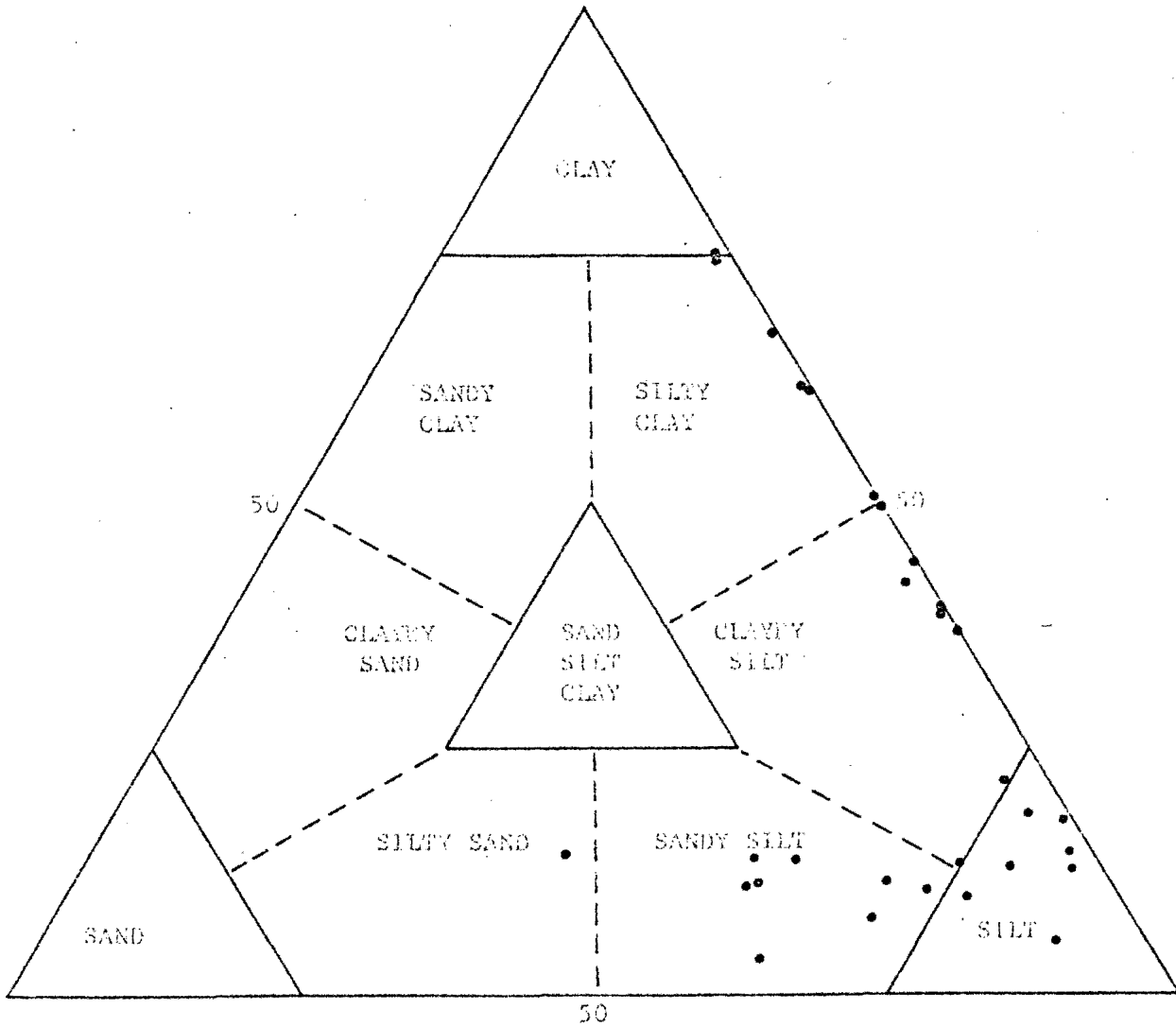
Figure 77.--Sand, silt, clay relationships of Tongue River samples from the Bullion Butte section.
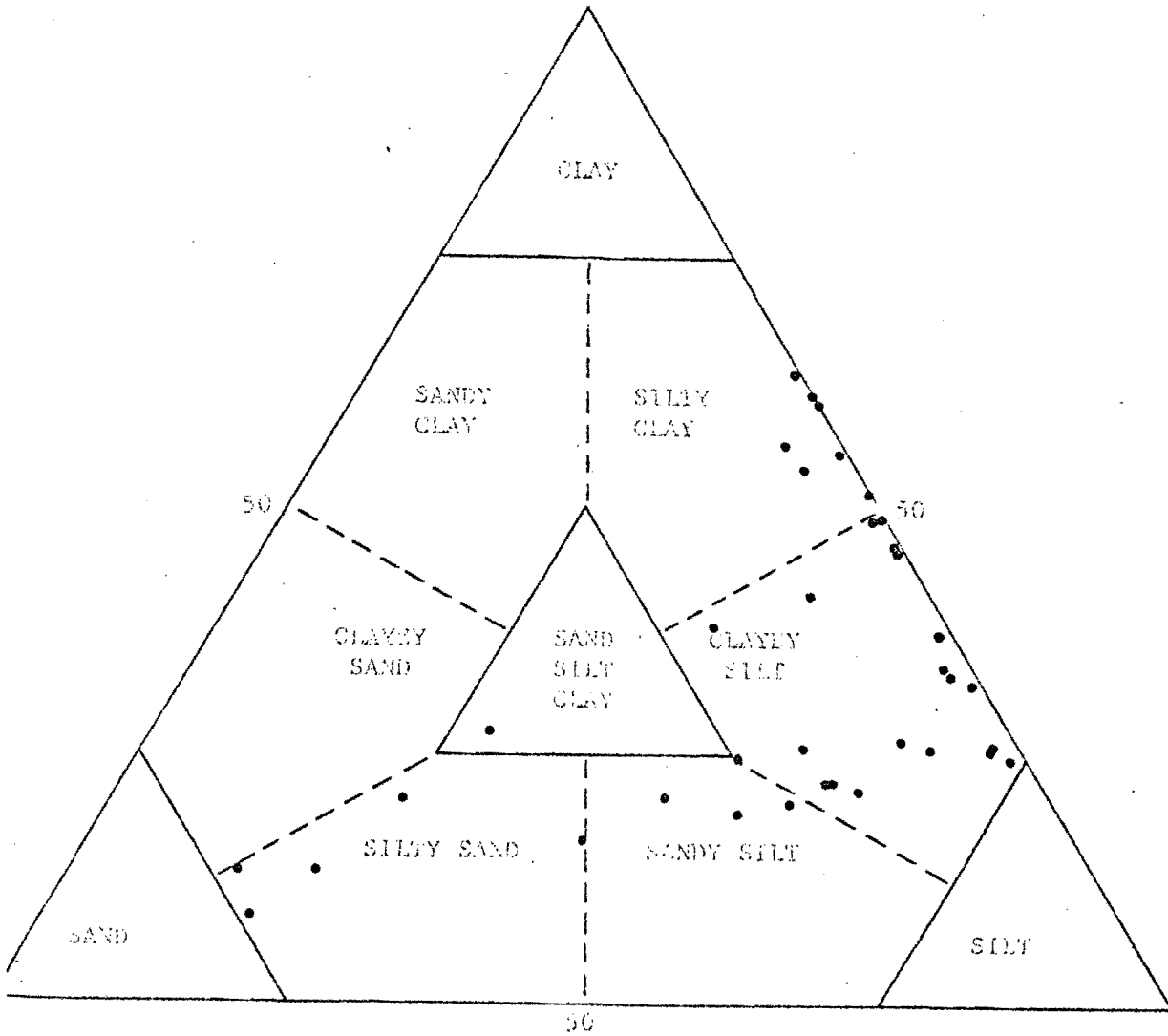
Figure 78.--Sand, silt, clay relationships of Tongue River samples from the Medora section.
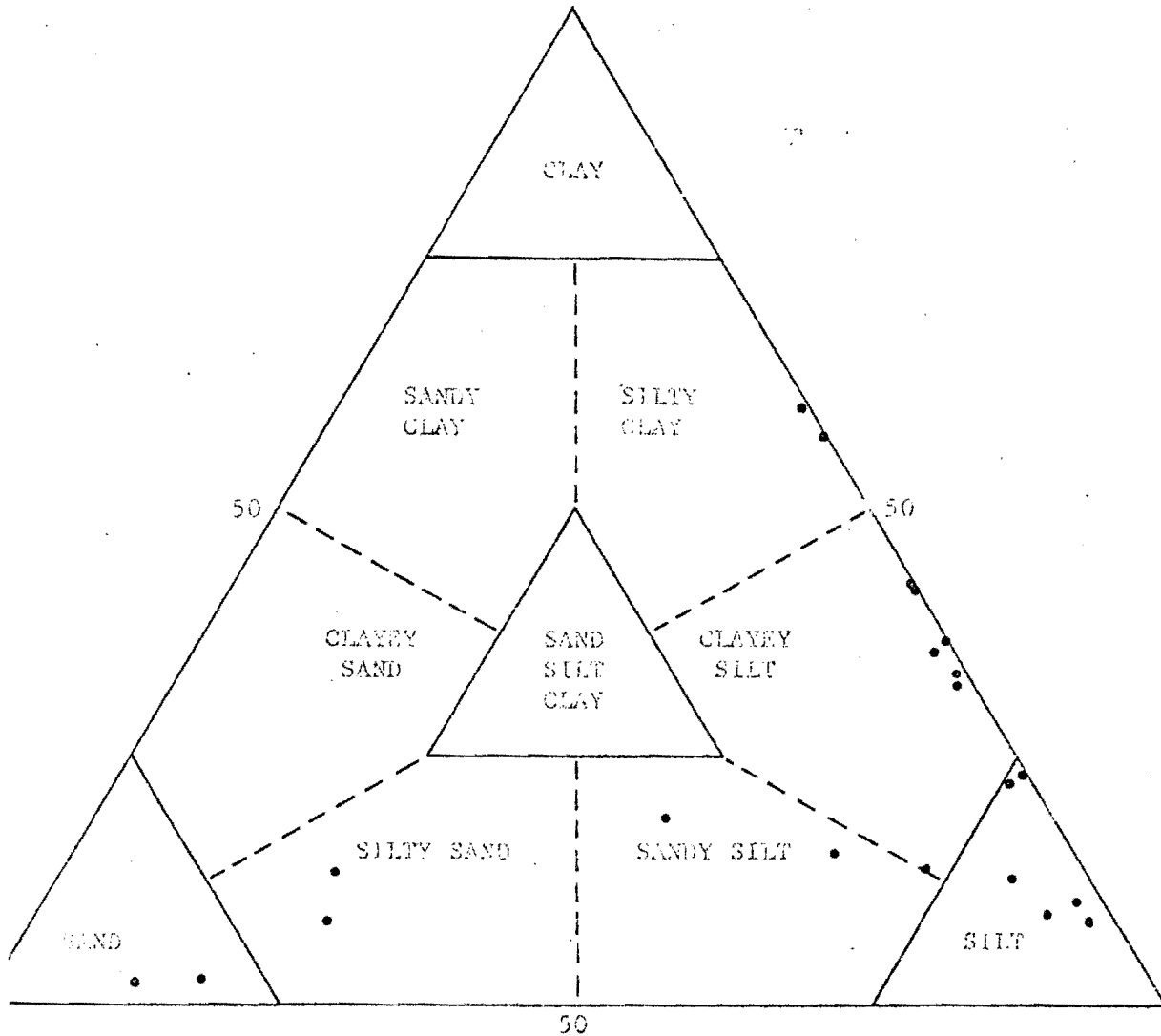
Figure 79.--Sand, silt, clay relationships of Tongue River samples from the Beicegel Creek section.
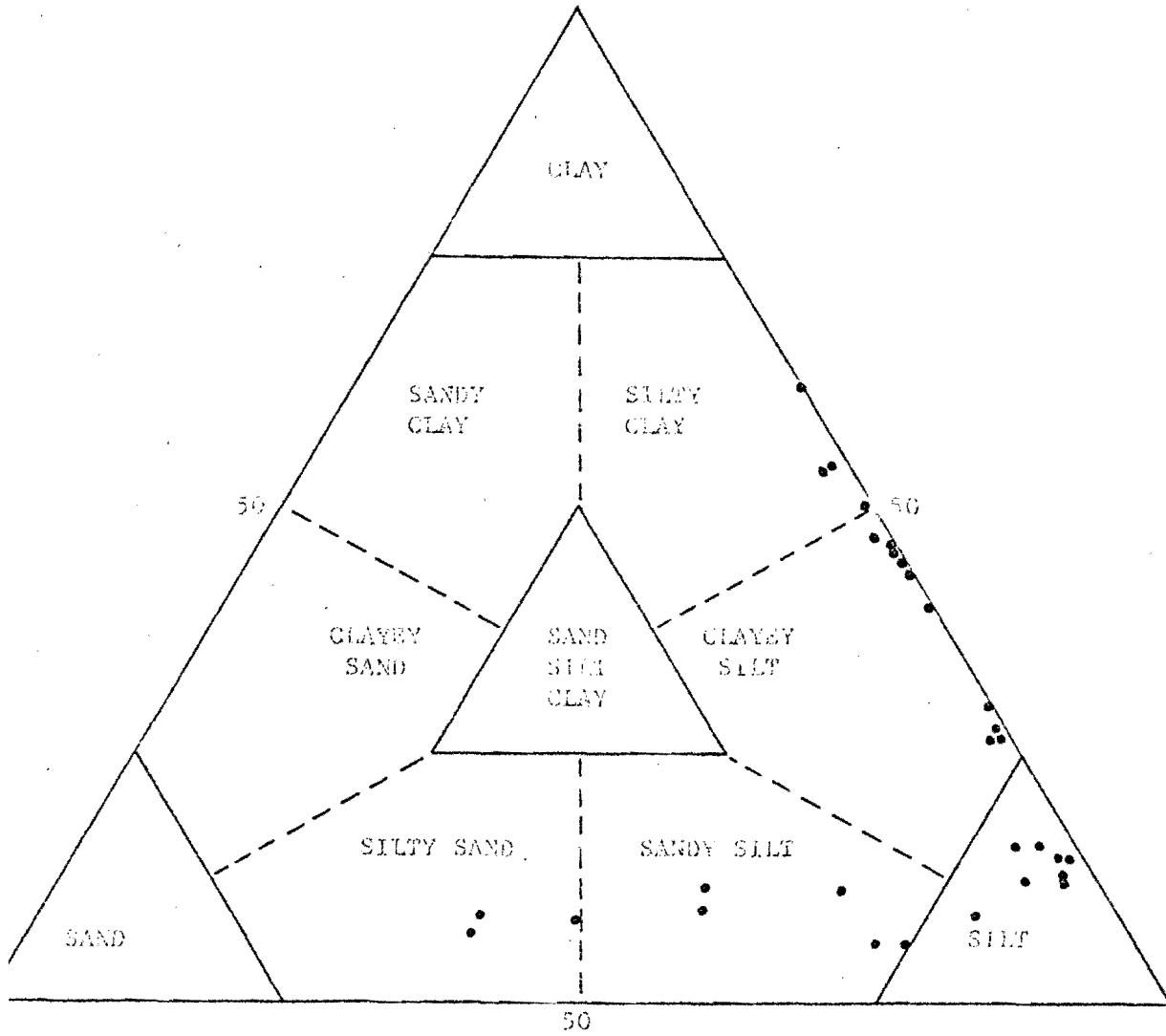
Figure 80.--Sand, silt, clay relationships of Tongue River samples from the Yellowstone section.
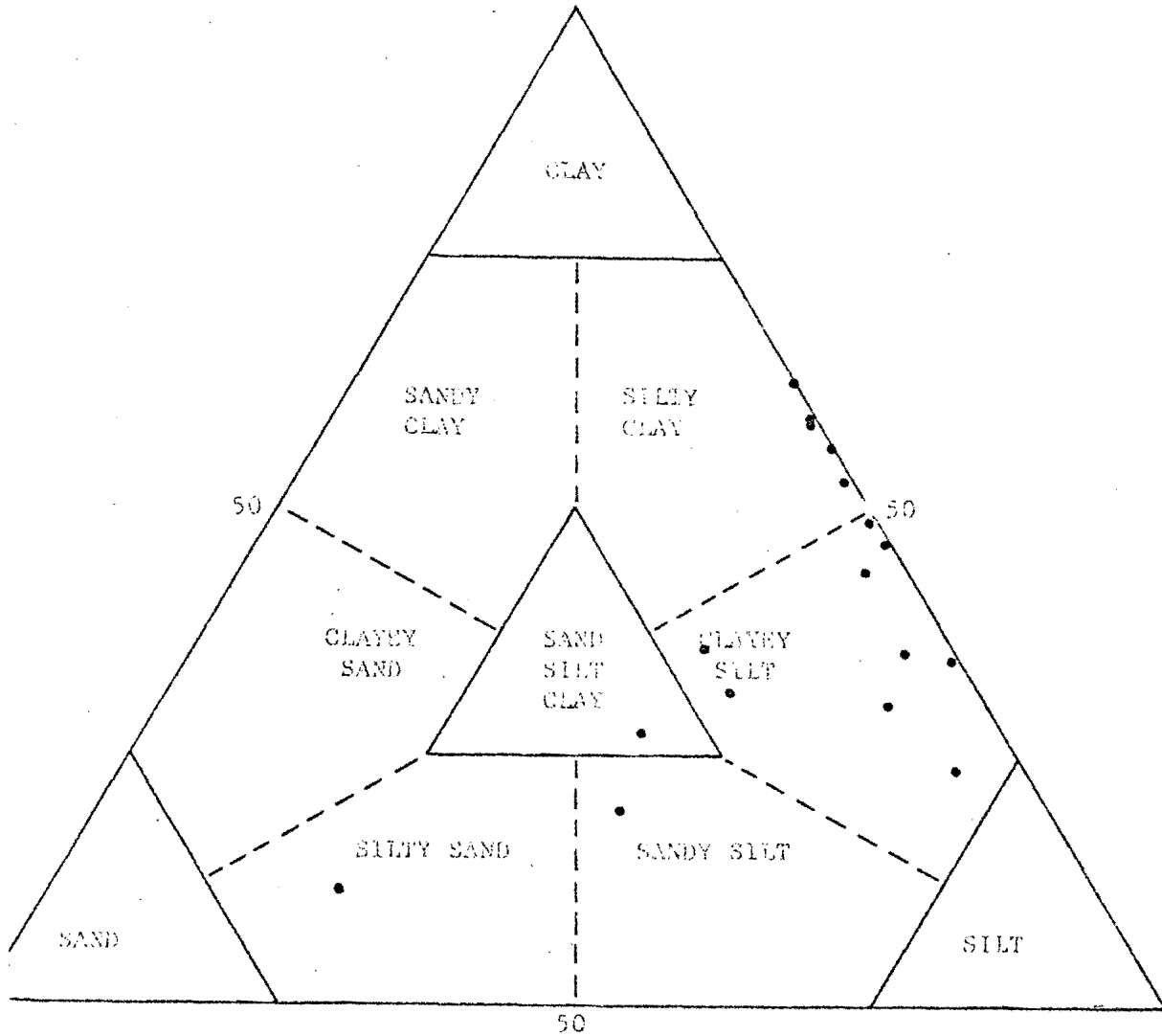
Figure 81.--Sand, silt, clay relationships of Tongue River samples from the Snowden section.
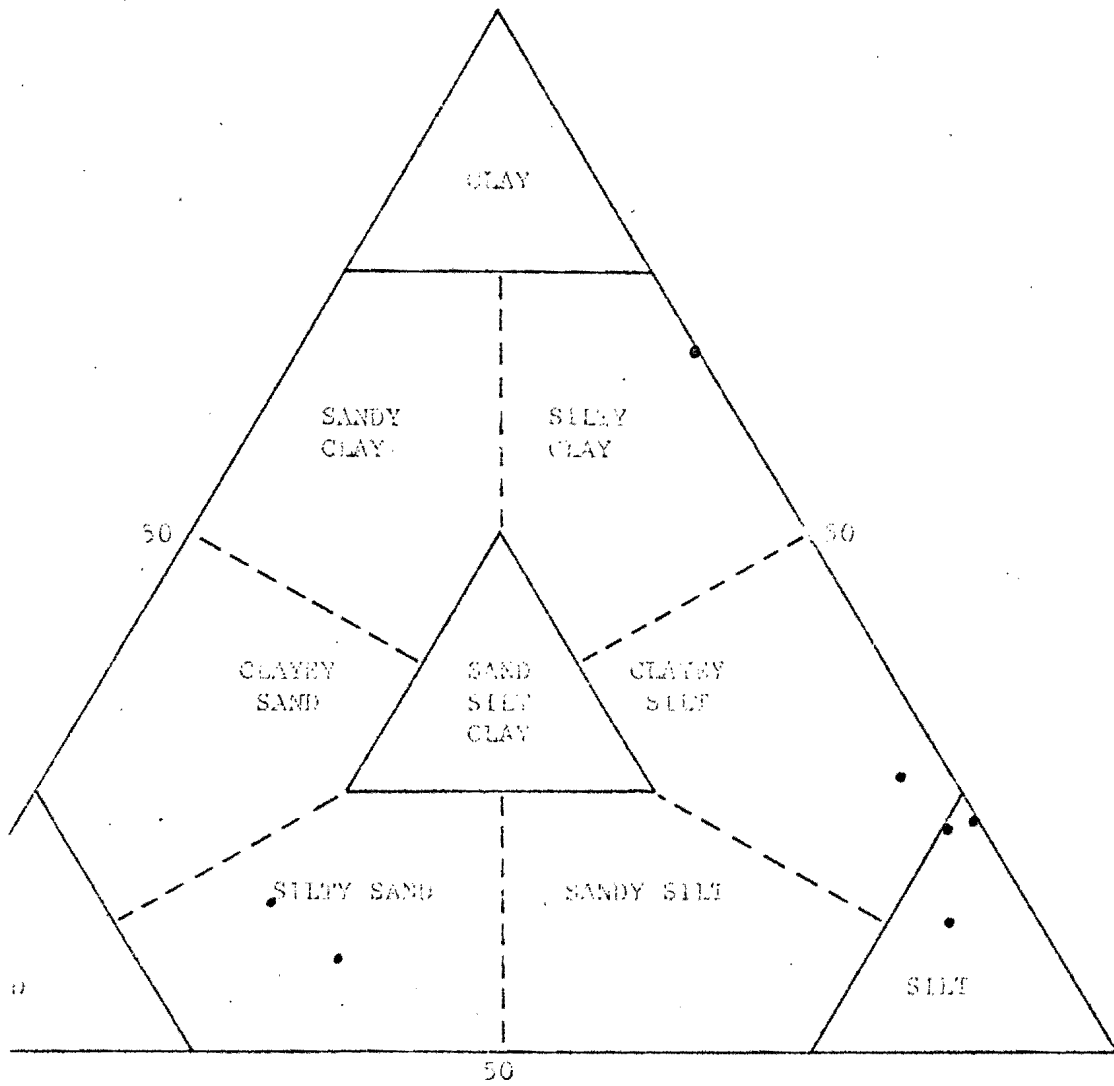
Figure 82.--Sand, silt, clay relationships of Tongue River samples
he Donnybrook section.
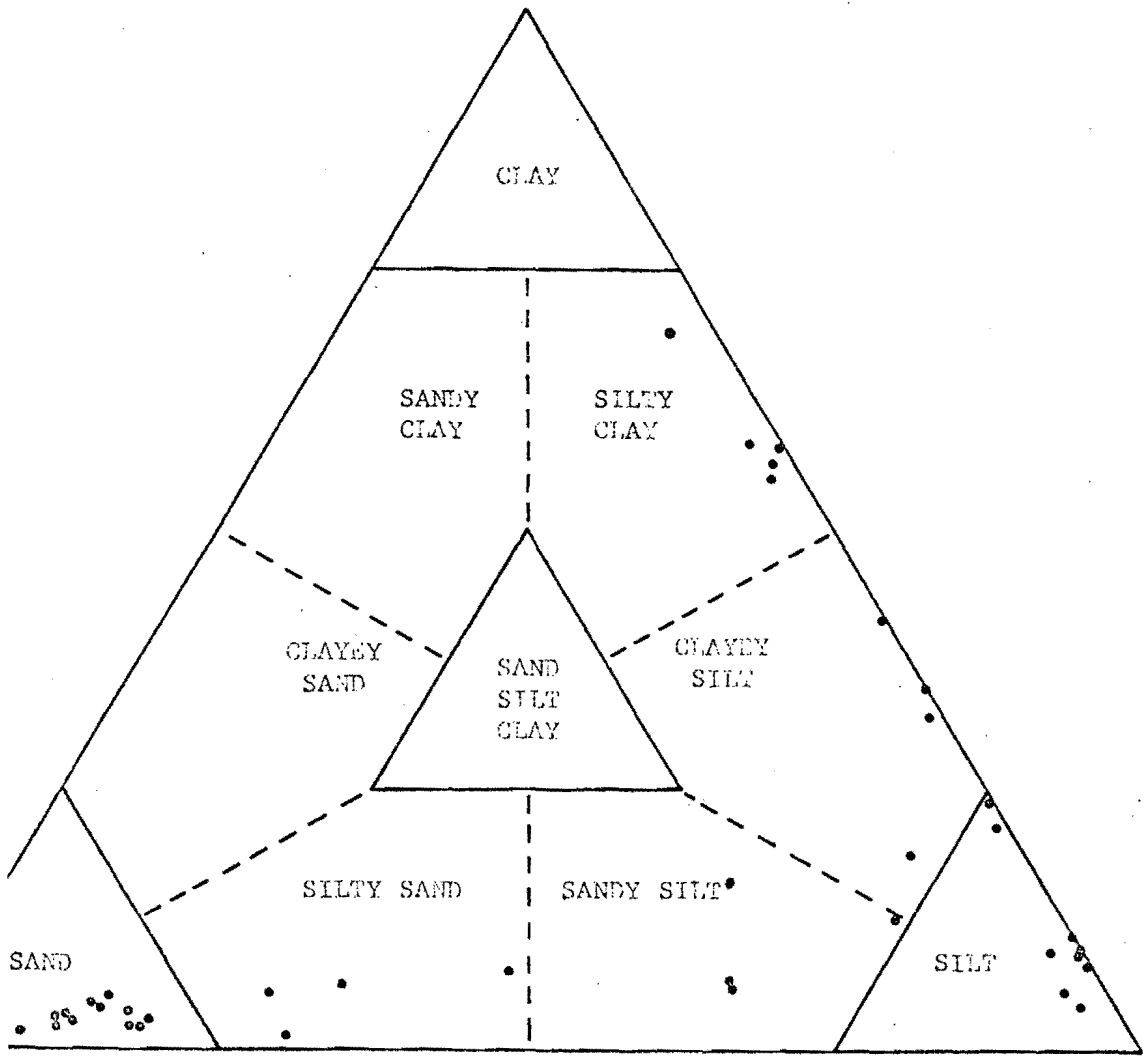
Figure 83.--Sand, silt, clay relationships of Sentinel Butte samples
the Bullion Butte section.
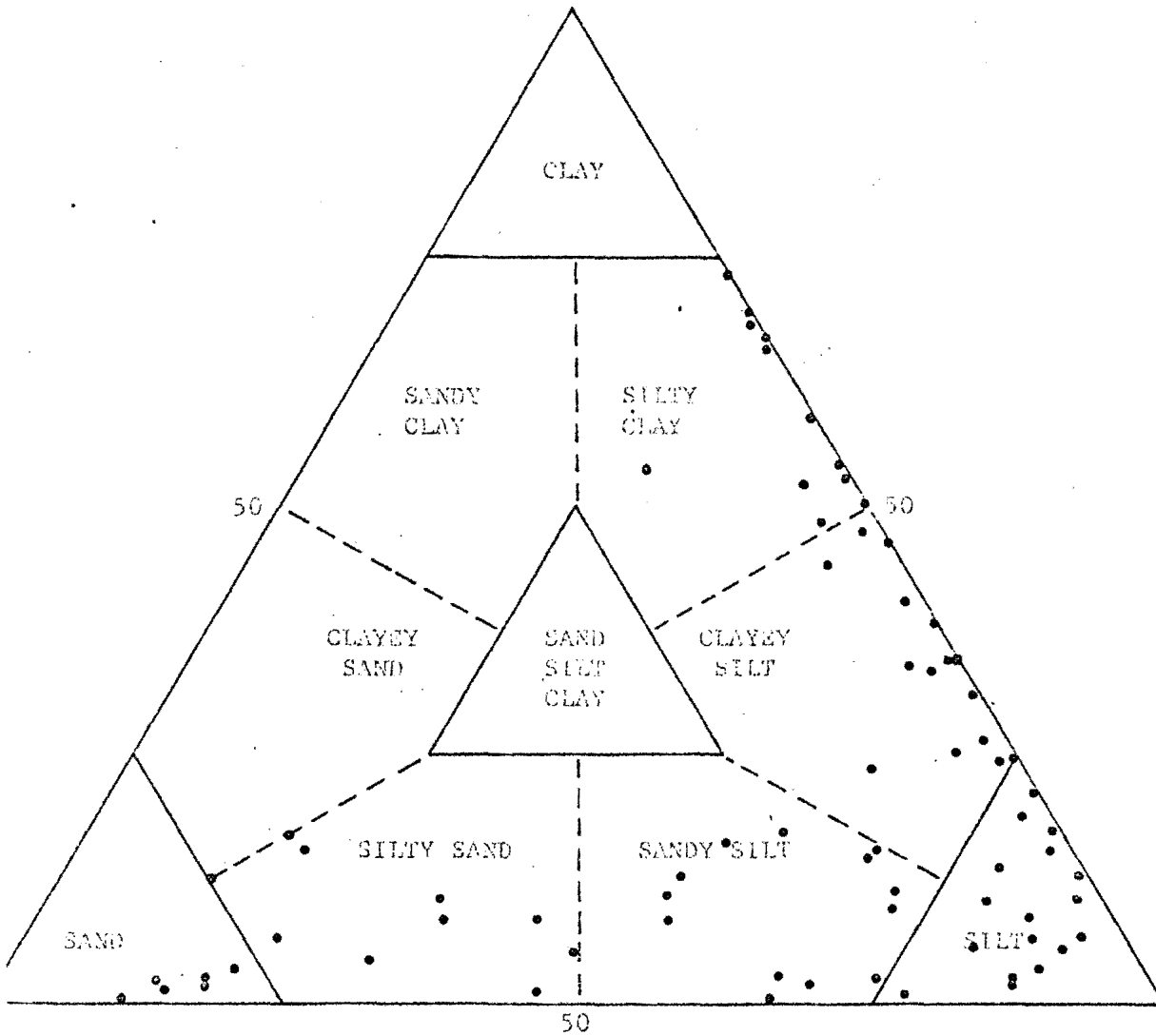
Figure 84.—Sand, silt, clay relationships of Sentinel Butte samples from the Sentinel Butte section.
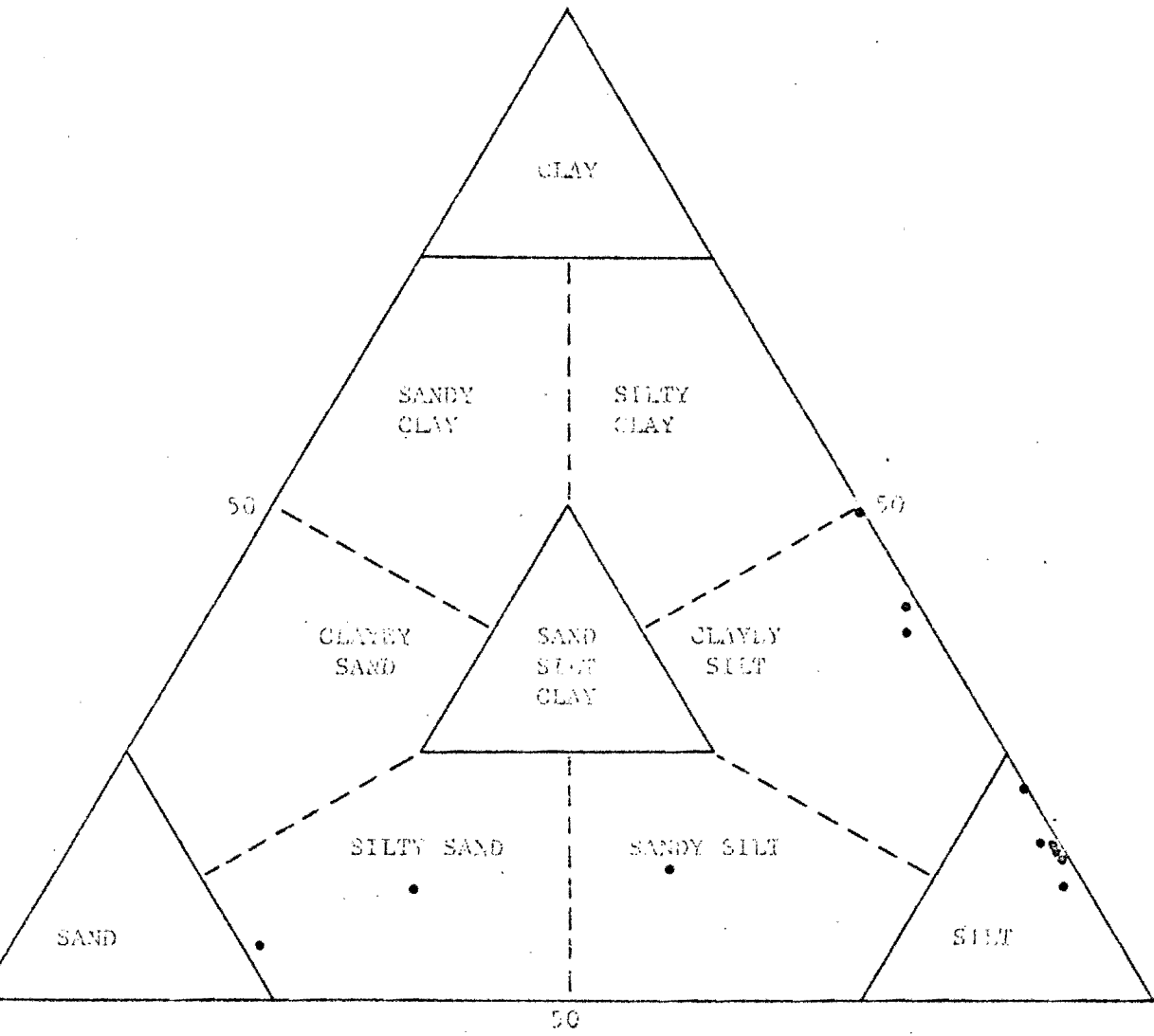
Figure 85.--Sand, silt, clay relationships of Centinel Butte samples from the Belcegel Creek section.
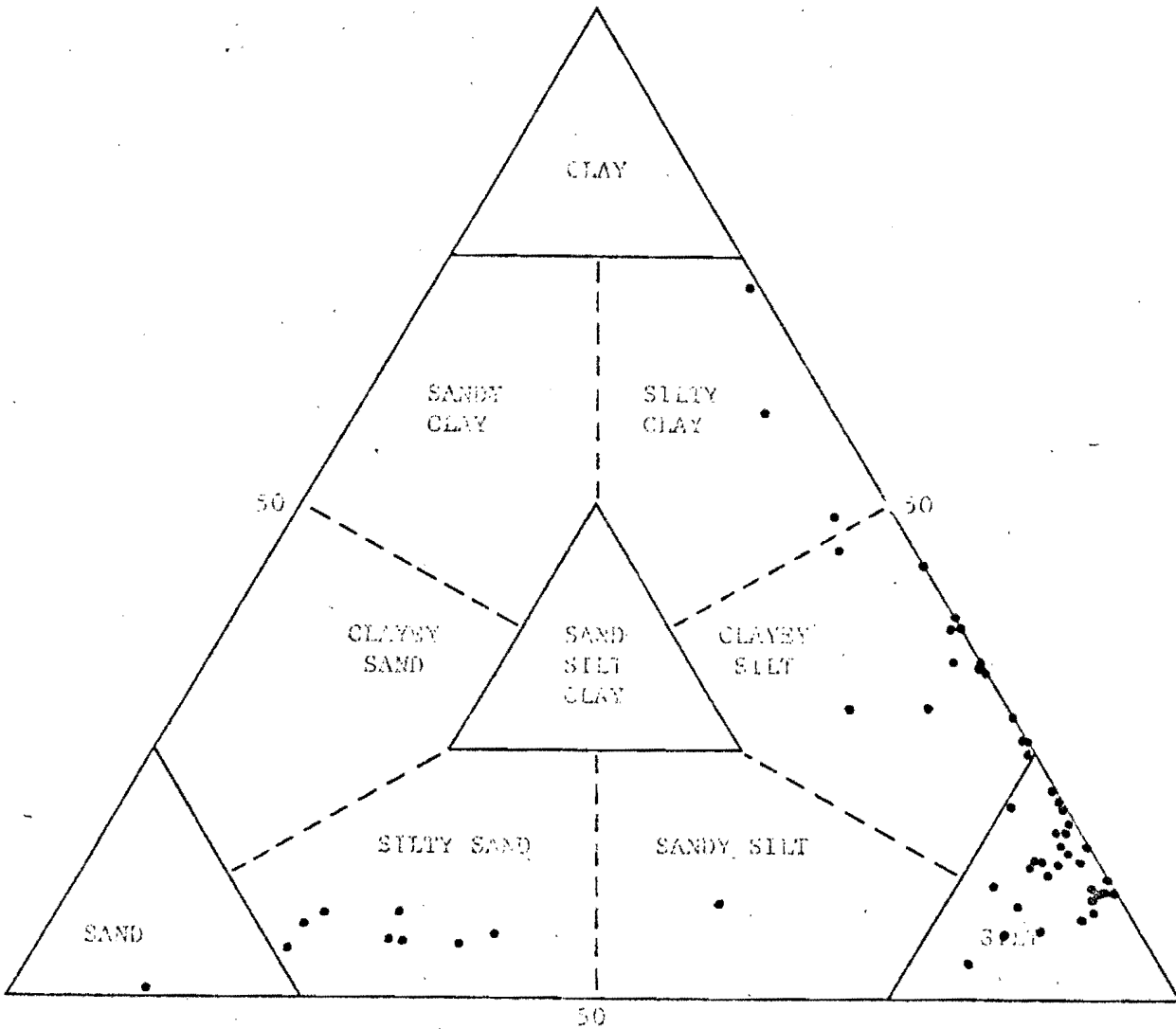
Figure 86.--Sand, silt, clay relationships of Sentinel Butte samples from the Long Cross section.
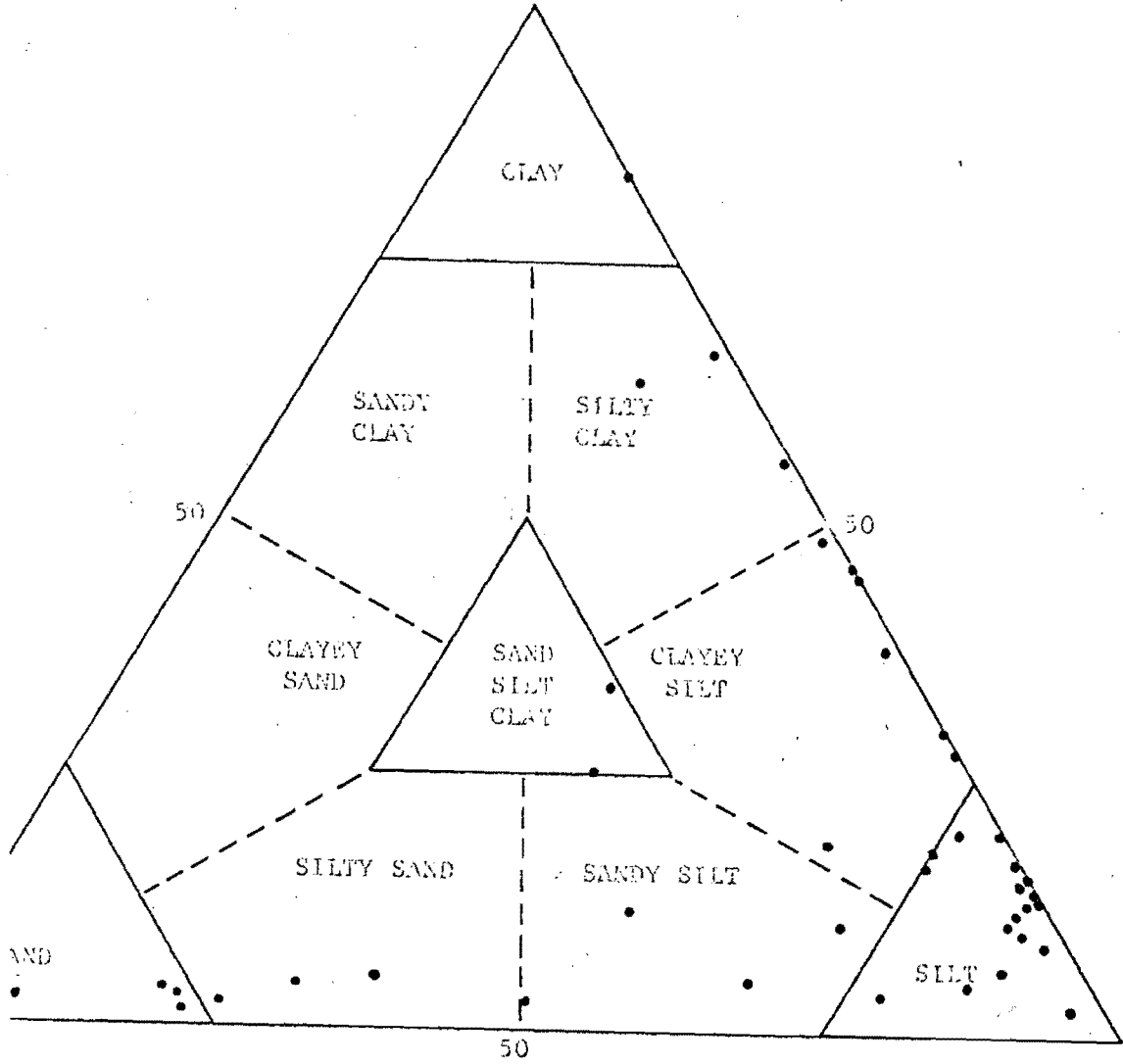
Figure 87.—Sand, silt, clay relationships of Sentinel Butte samples
the Lost Bridge section.

Appendix II-E

CM patterns for stratigraphic samples
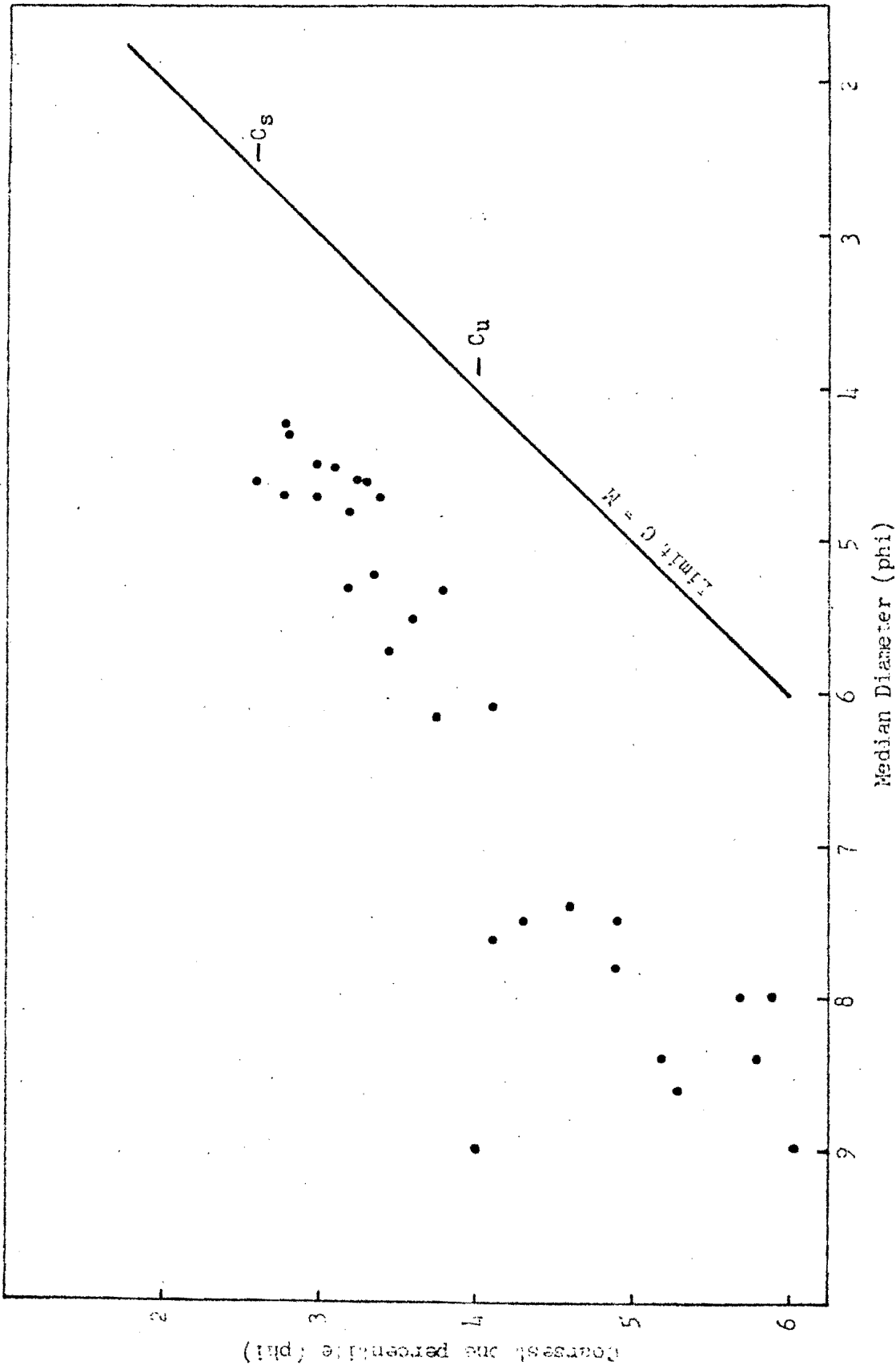
Figure 88.--CM pattern for Tongue River samples from the Bullion Butte section.

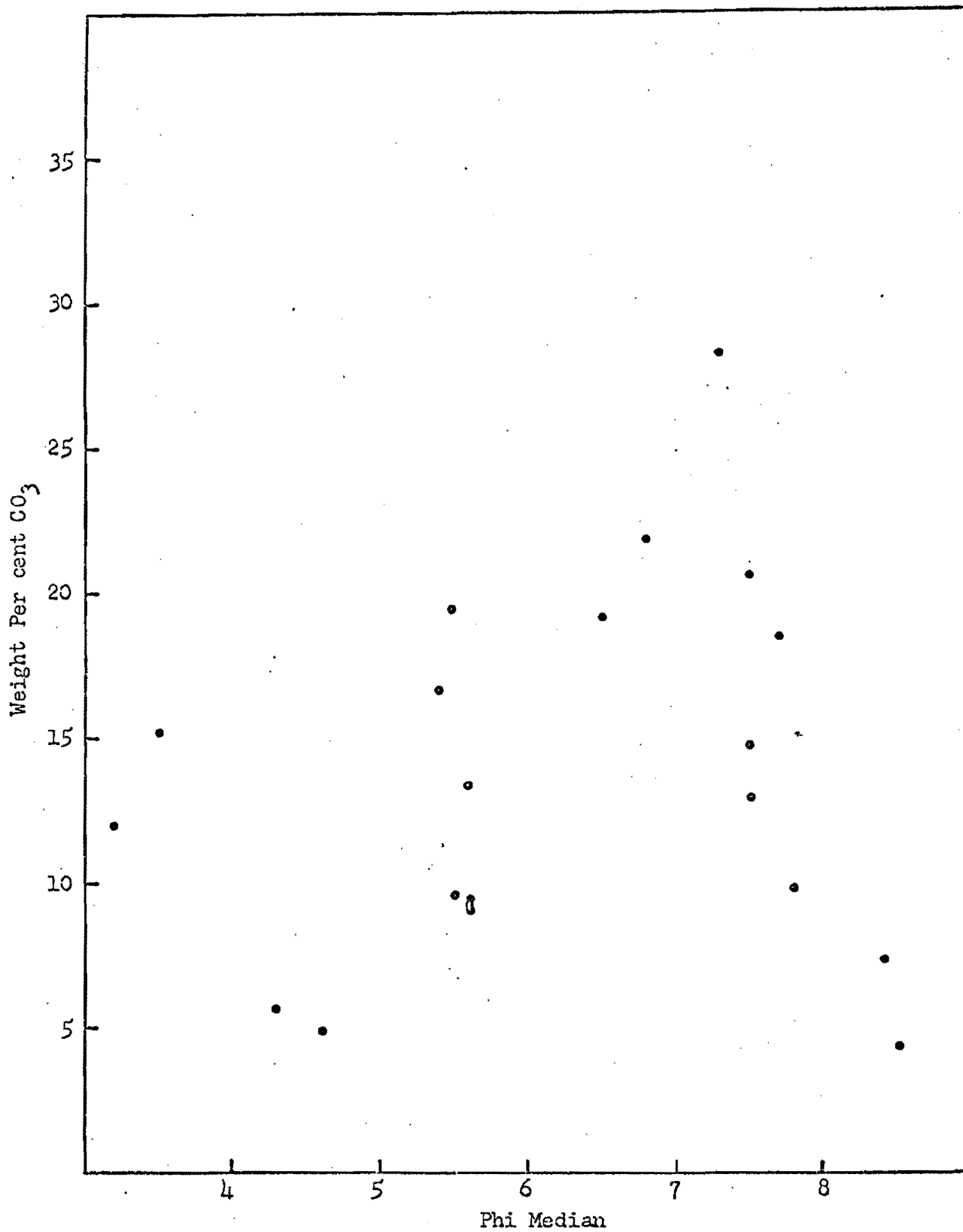Figure 89.--CM pattern for Tongue River samples from the Medora section.

Median Diameter (phi)

Coarsest one percentile (phi)

C_s

C_u

limit $C = M$
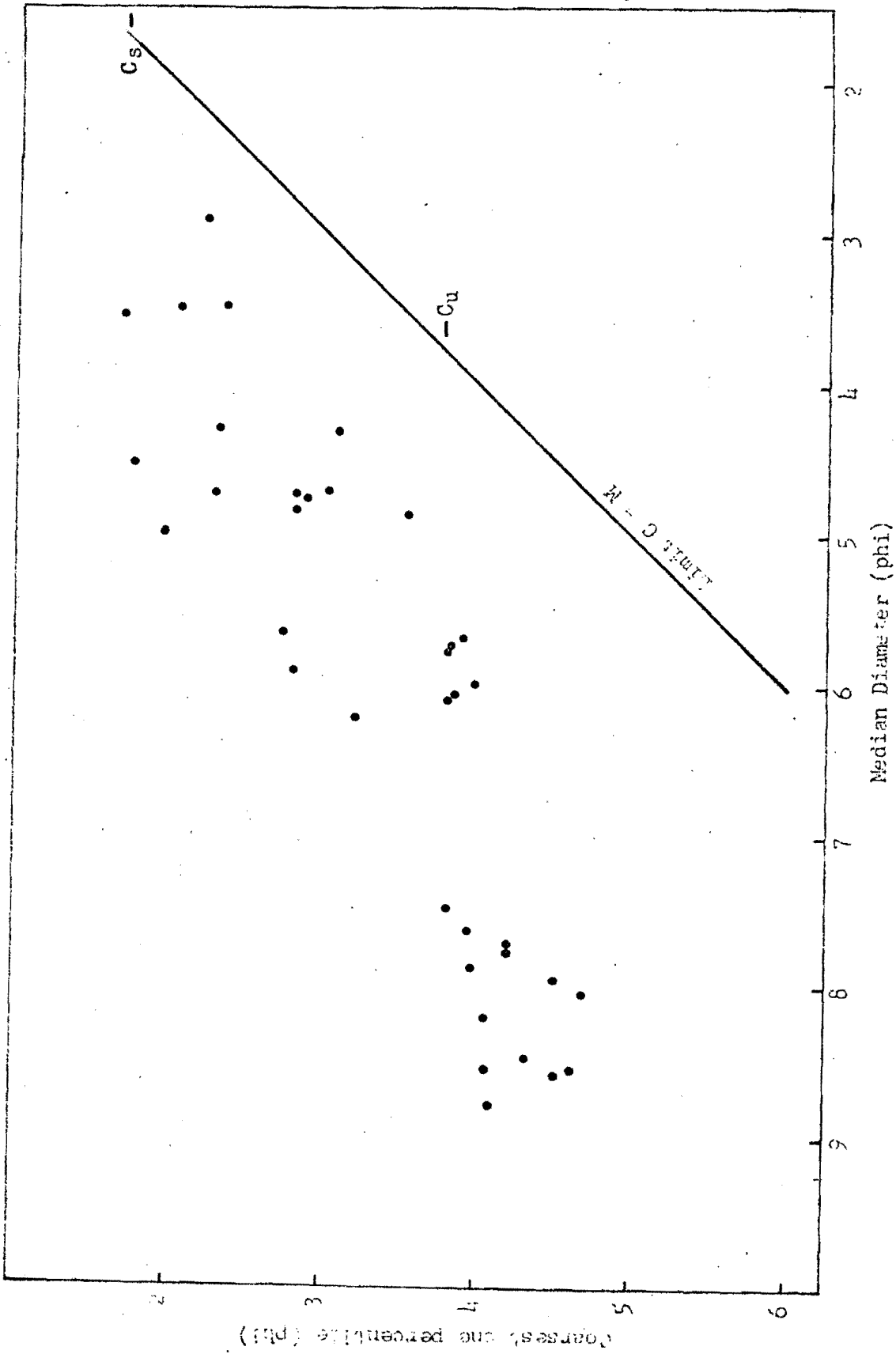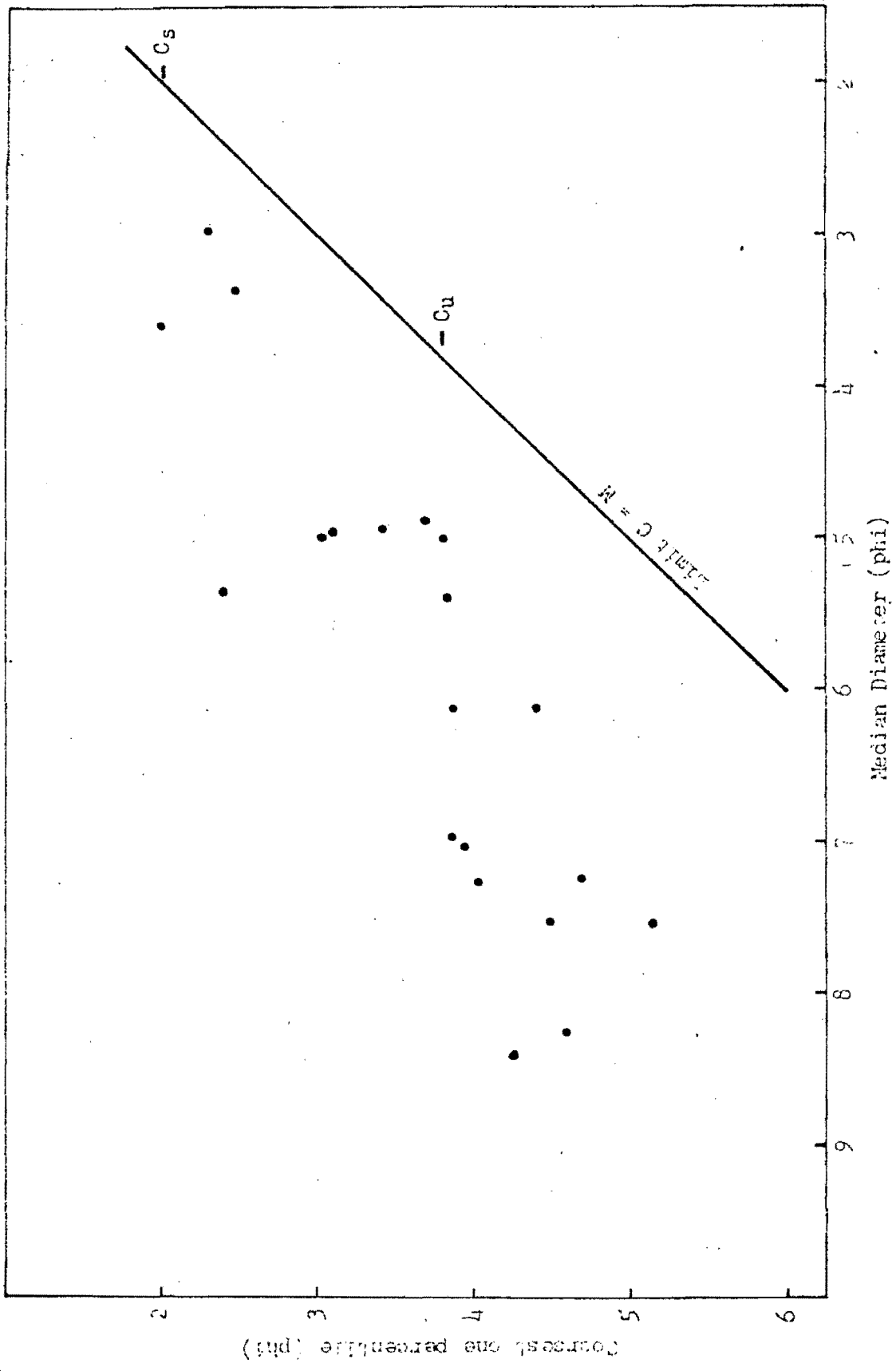
Figure 90.--CM pattern for Tongue River samples from the Baicegel Creek section.
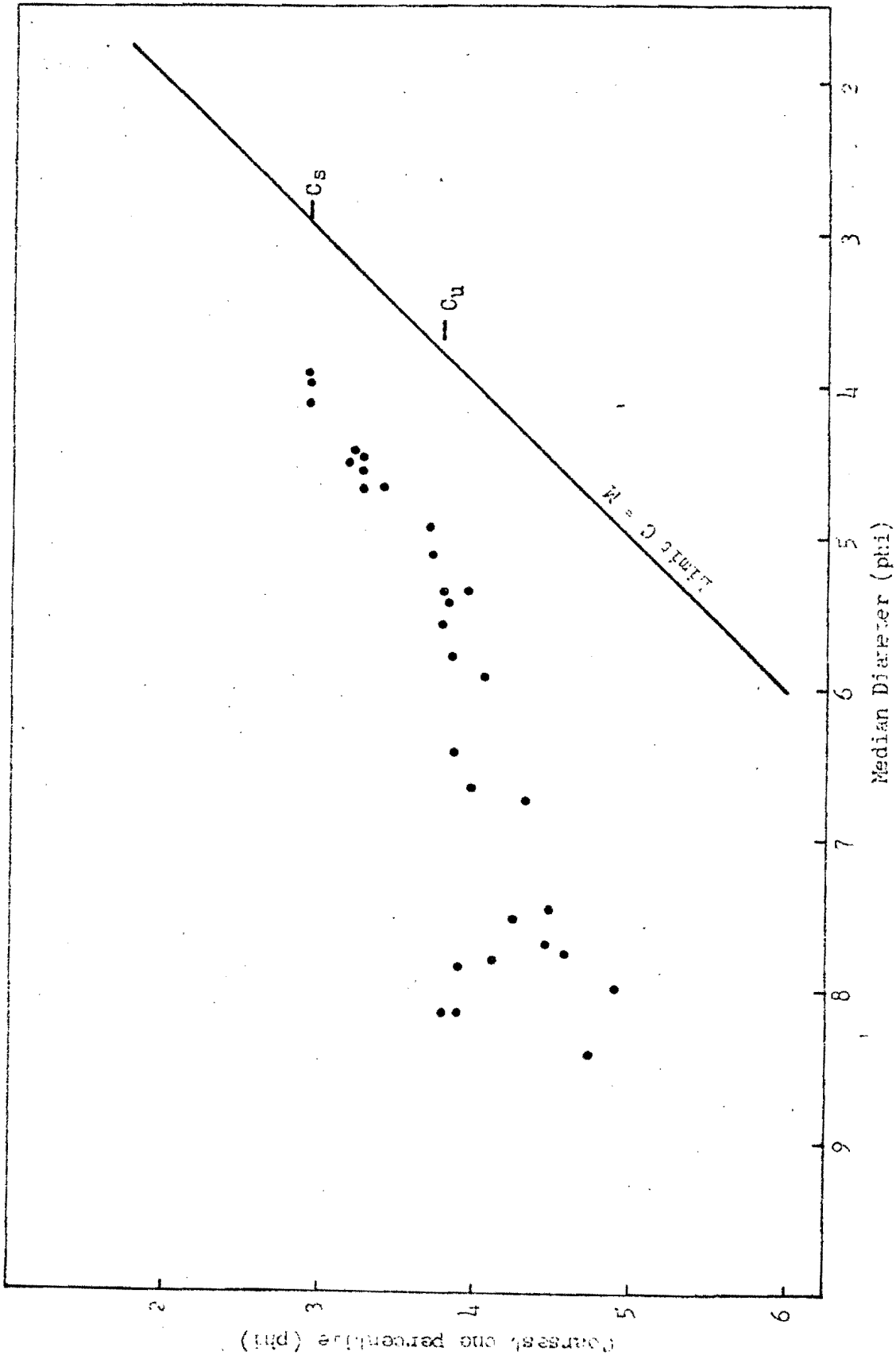
Figure 91.--CM pattern for Tongue River samples from the Yellowstone section.
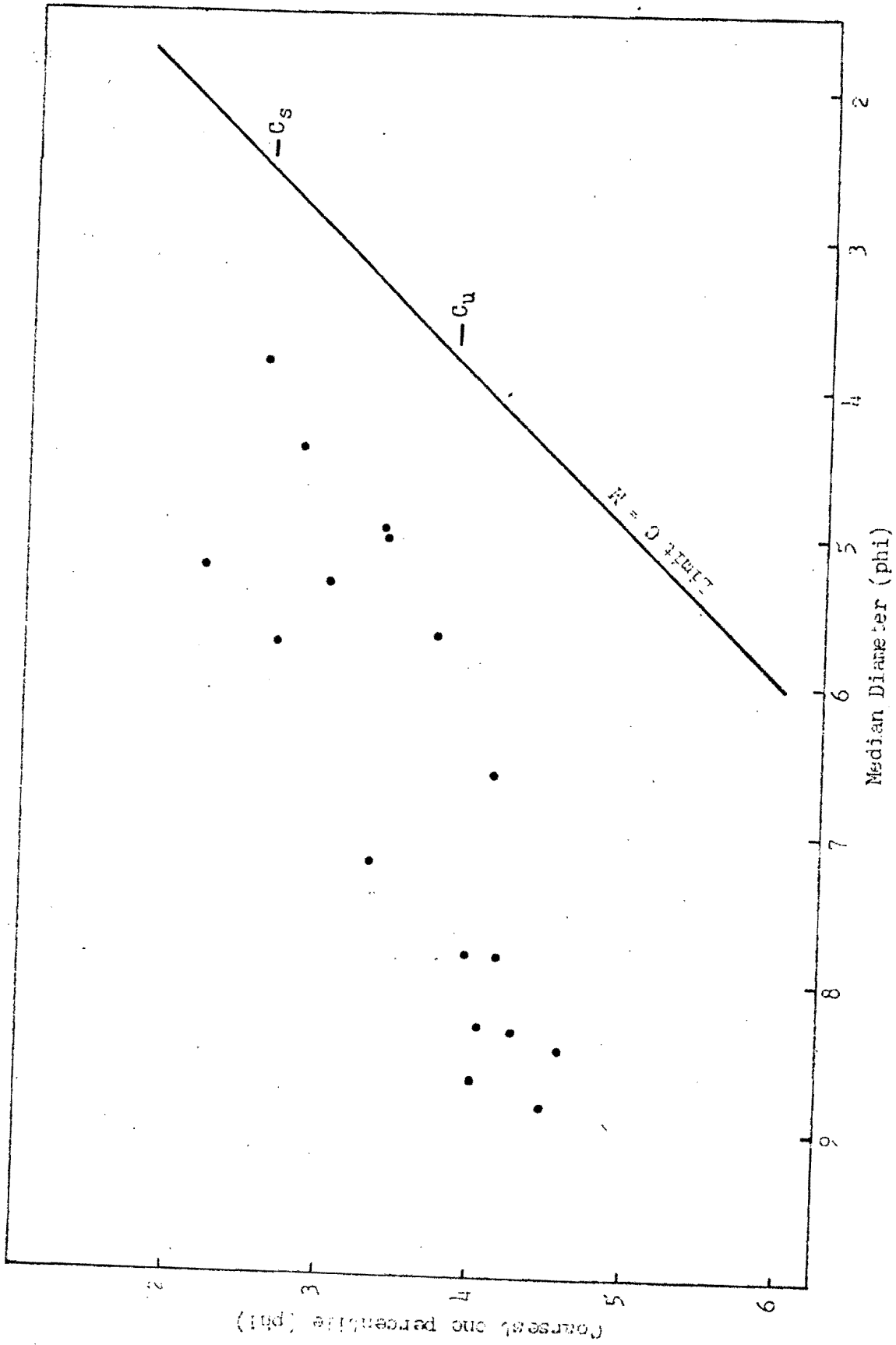
Figure 92.—CM pattern for Tongue River samples from the Snowden section.
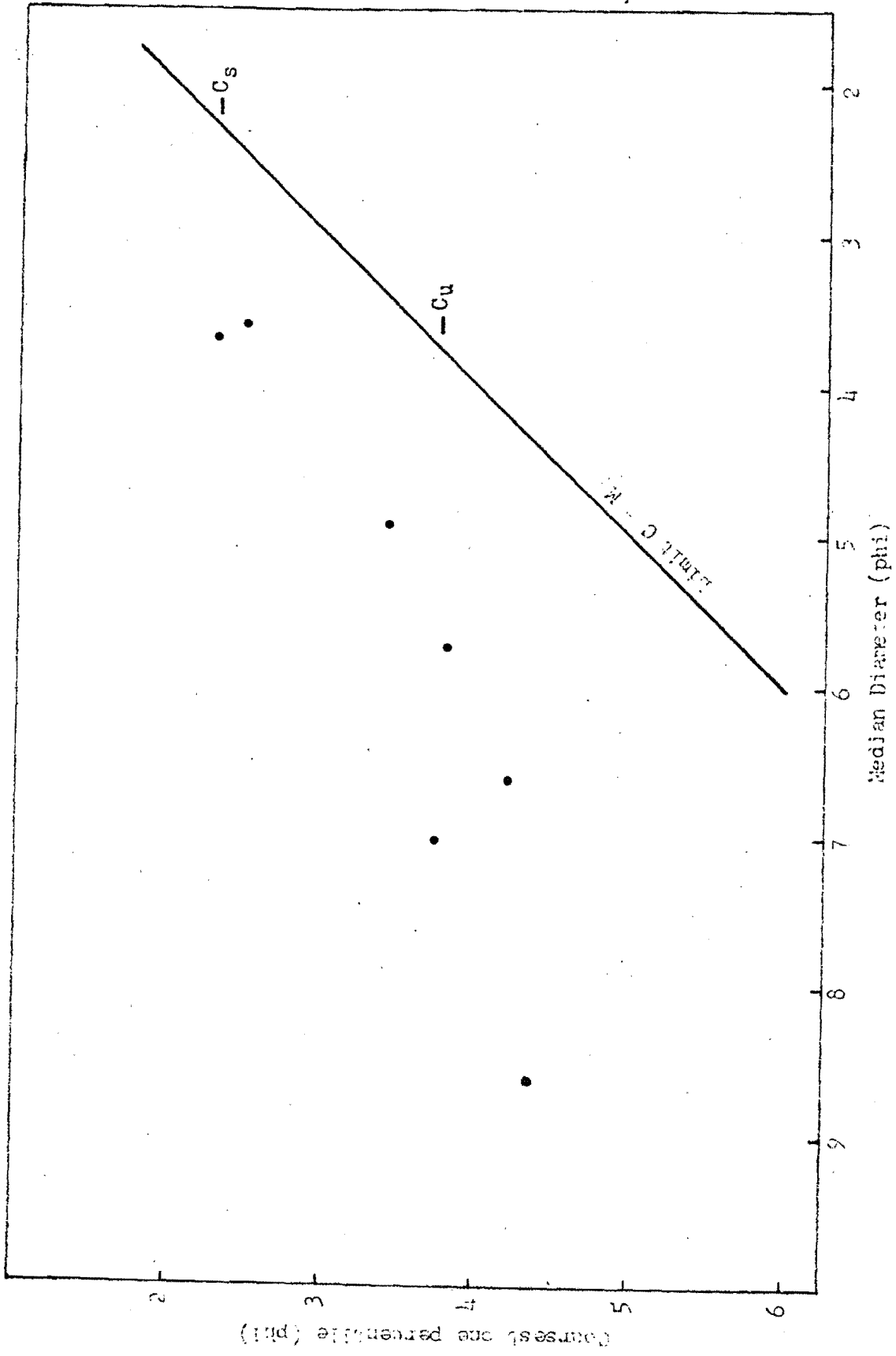
Figure 93.—Cu pattern for Tongue River samples from the Donnybrook section.
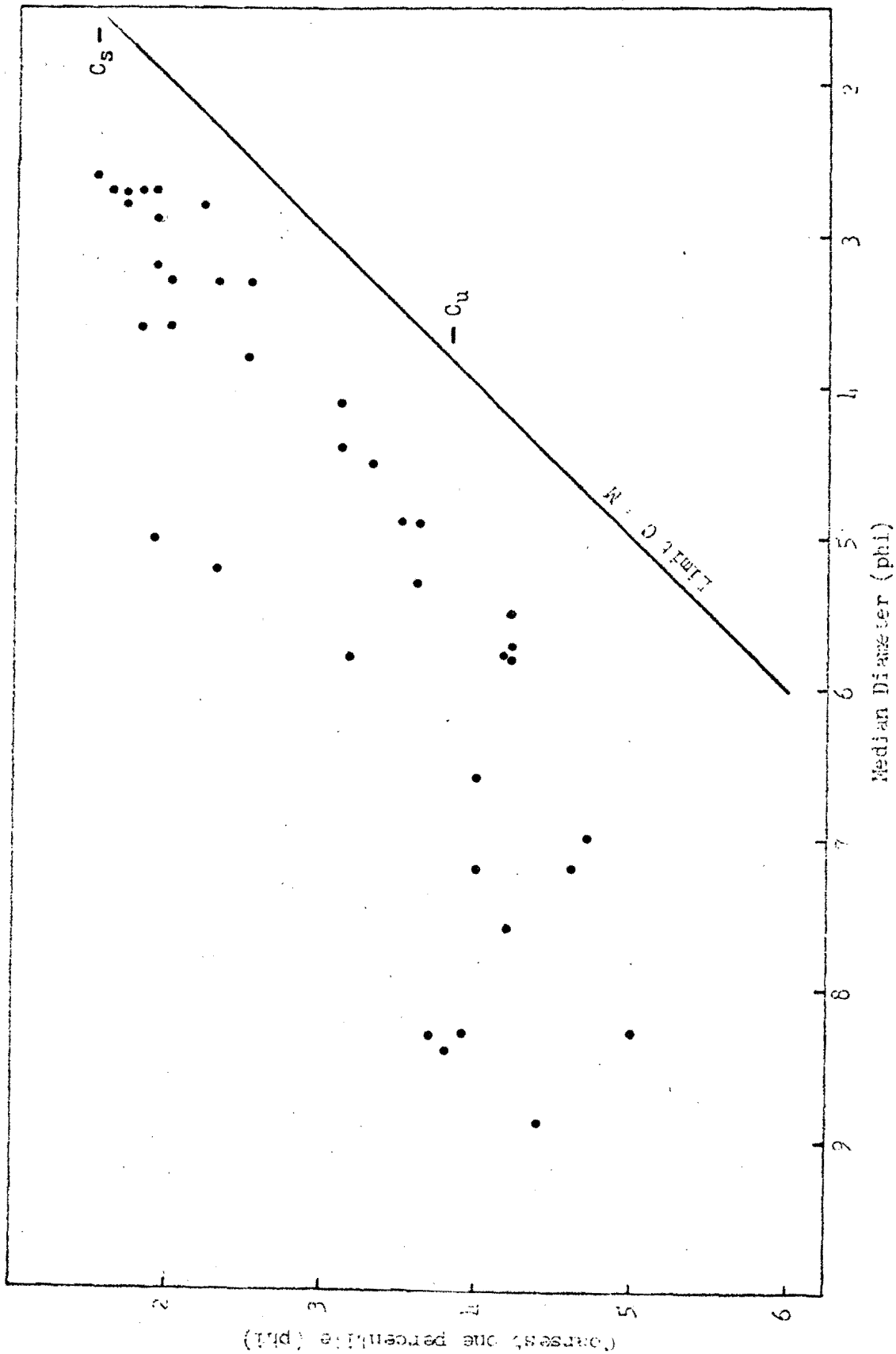
Figure 94.--CM pattern for Sentinel Butte samples from the Bullion Butte section.
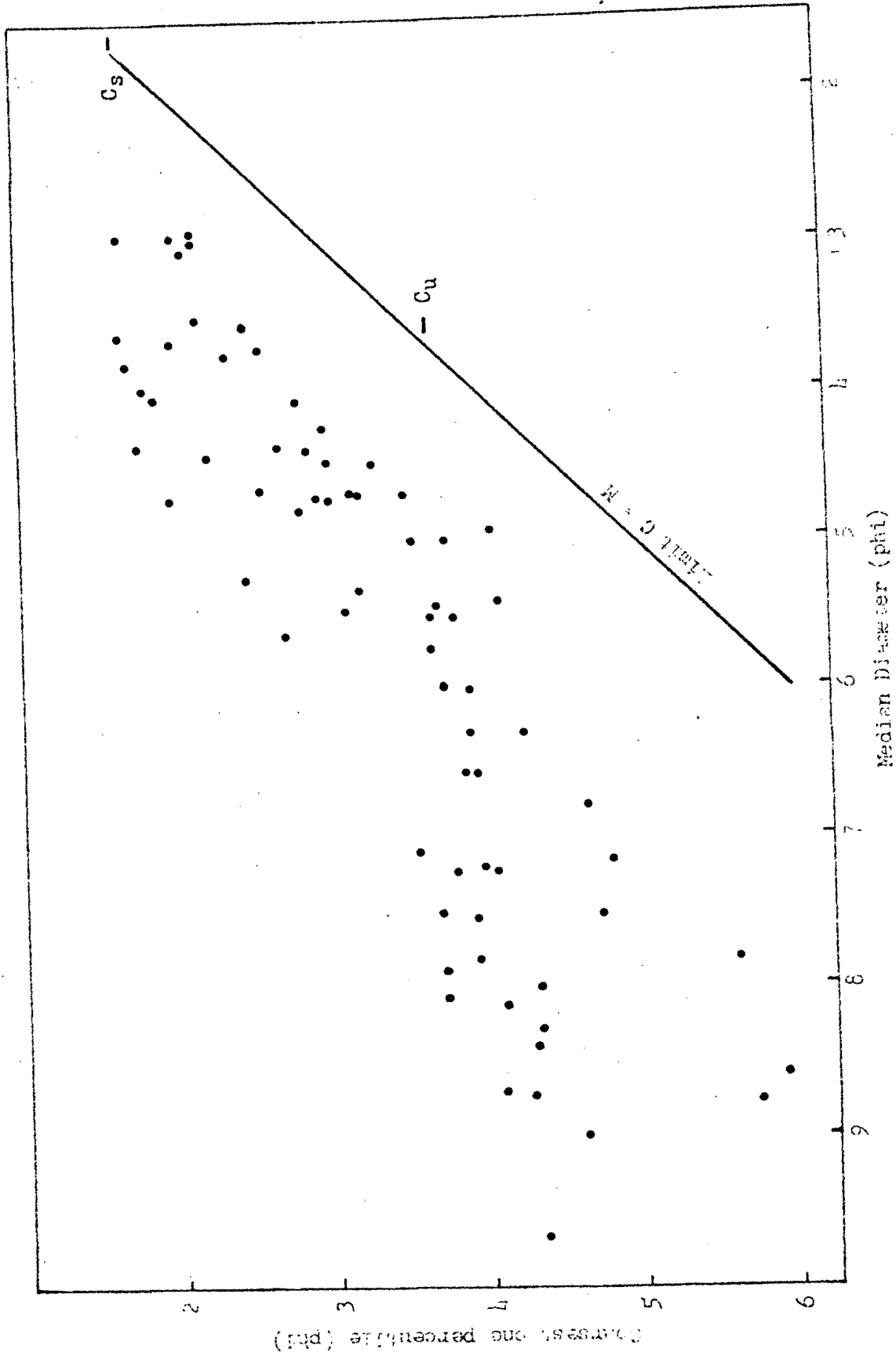
Figure 95.—CM pattern for Sentinel Butte samples from the Sentinel Butte section.
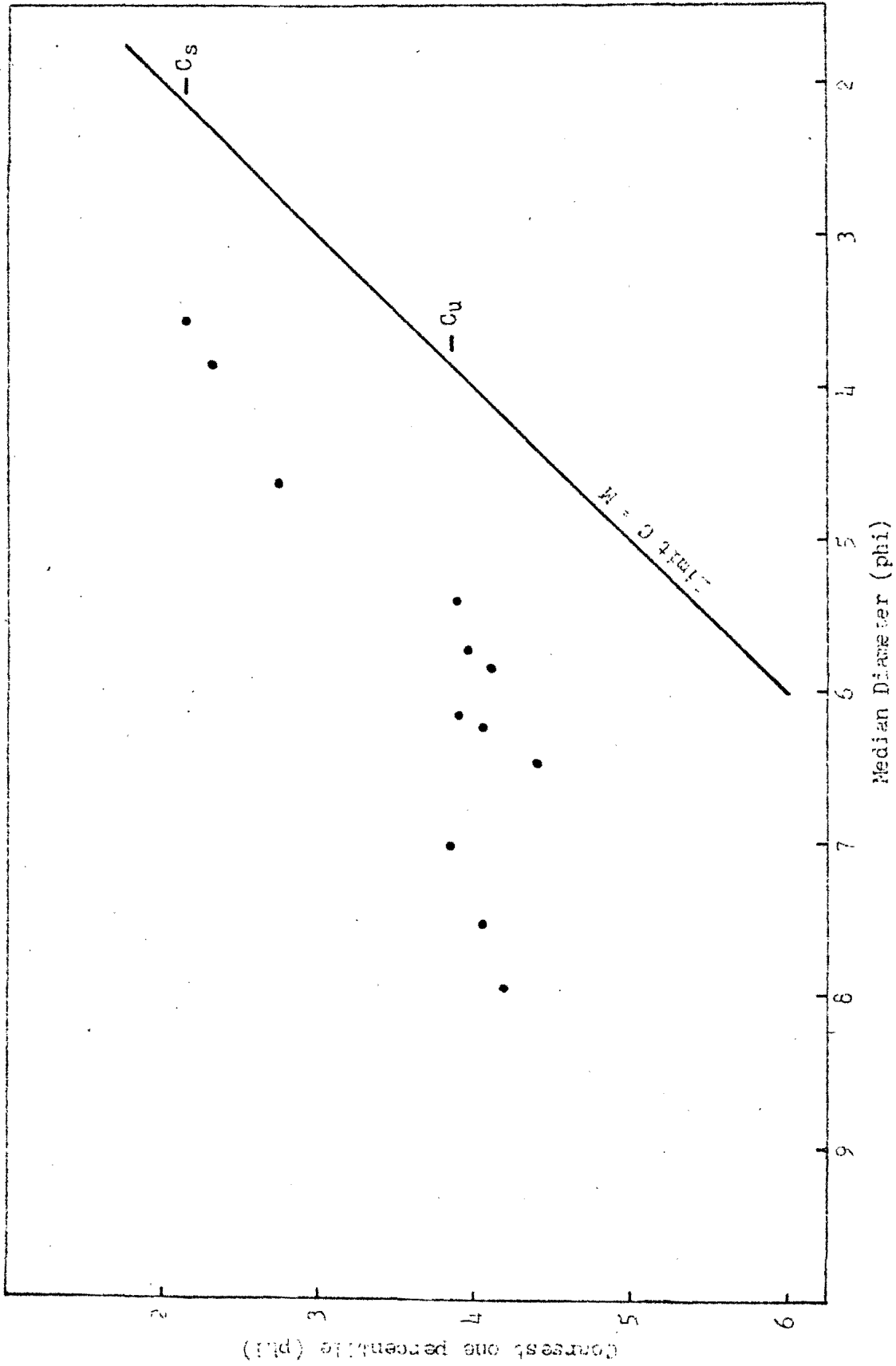
Figure 96.—CM pattern for Sentinel Butte samples from the Beicegel Creek section.
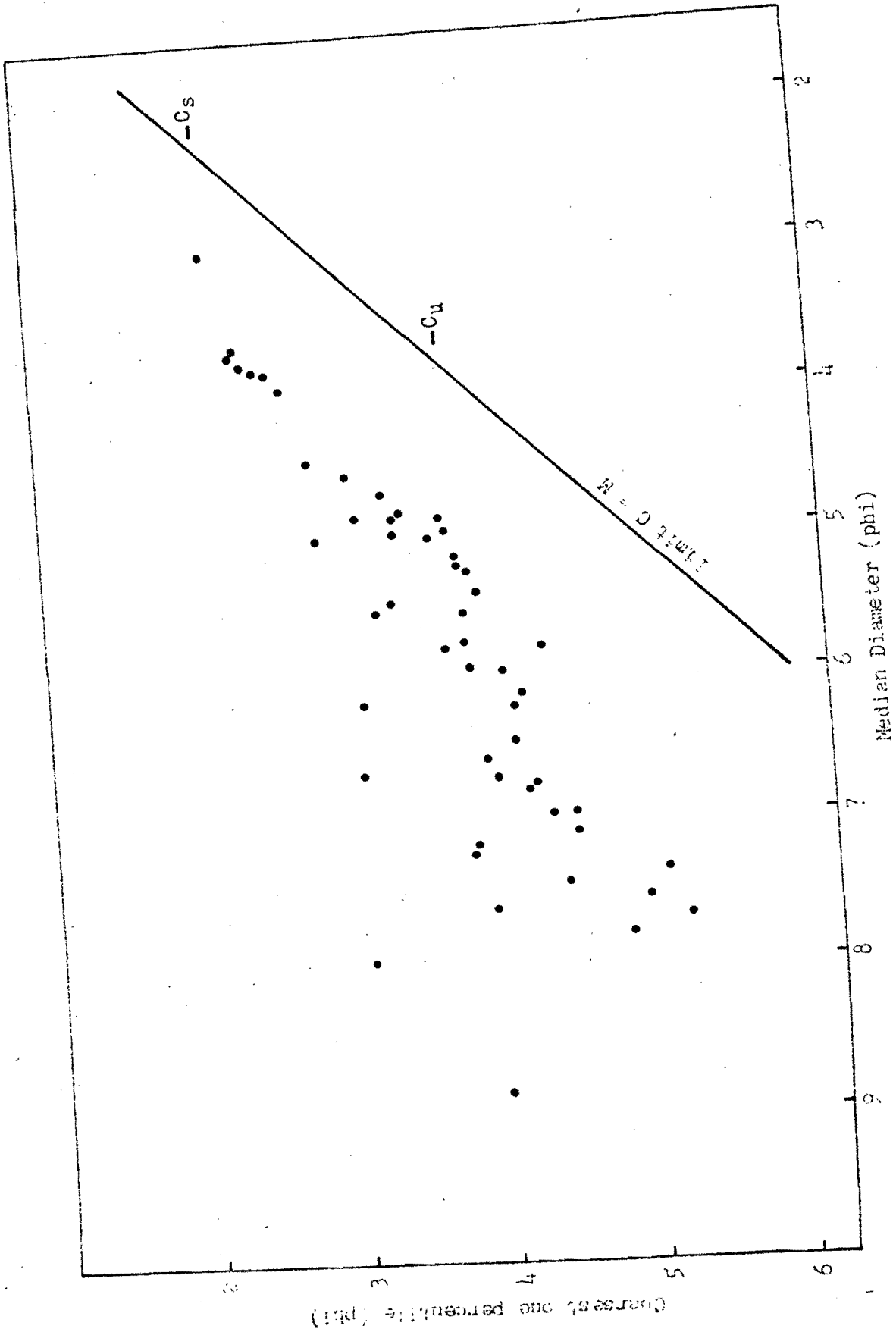
Figure 97.--CM pattern for Sentinel Butte samples from the Long Cross section.
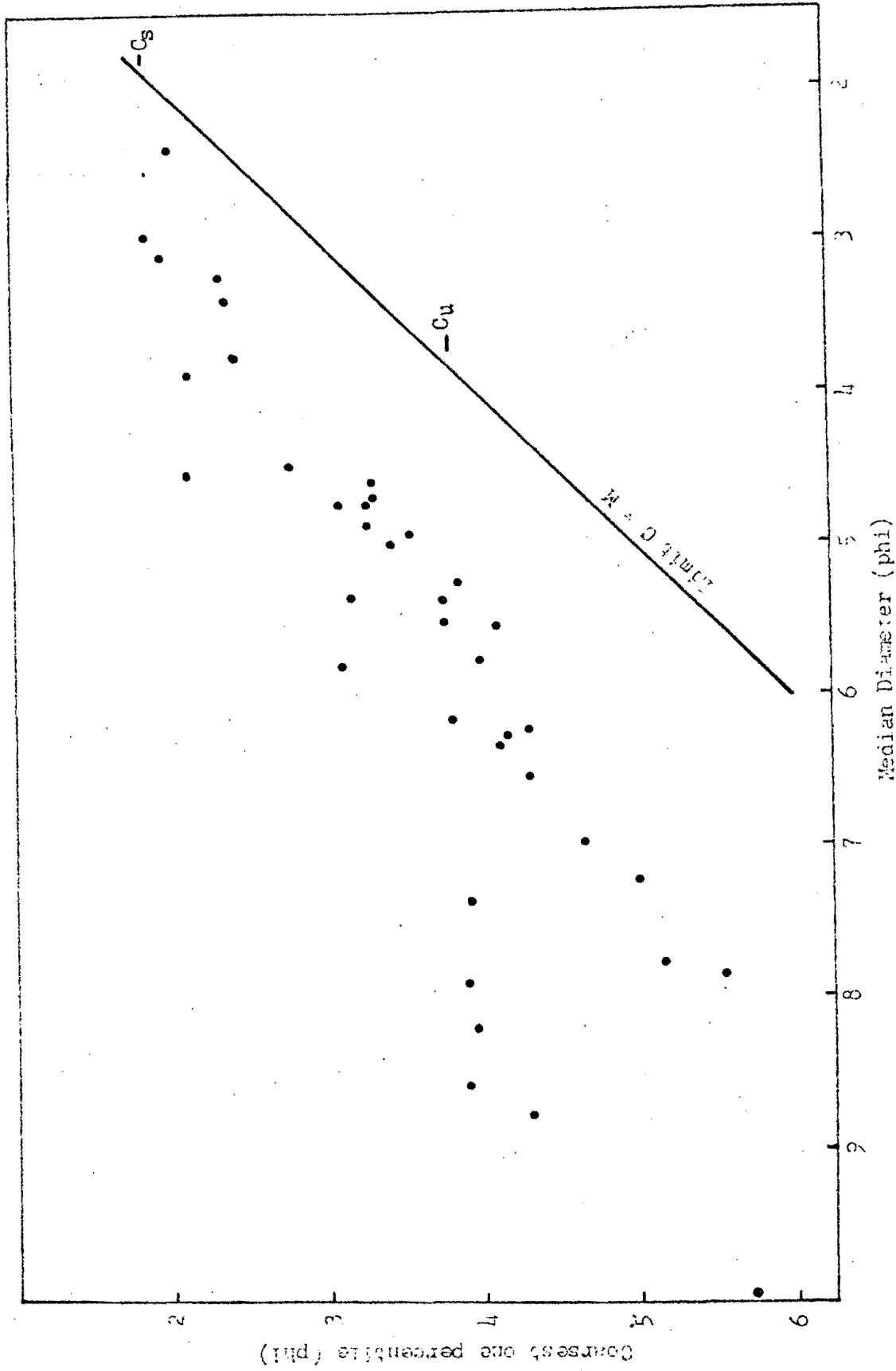
Figure 98.—CM pattern for Sentinel Butte samples from the Lost Bridge section.

Appendix II-F

Plots of carbonate vs. median for stratigraphic samples
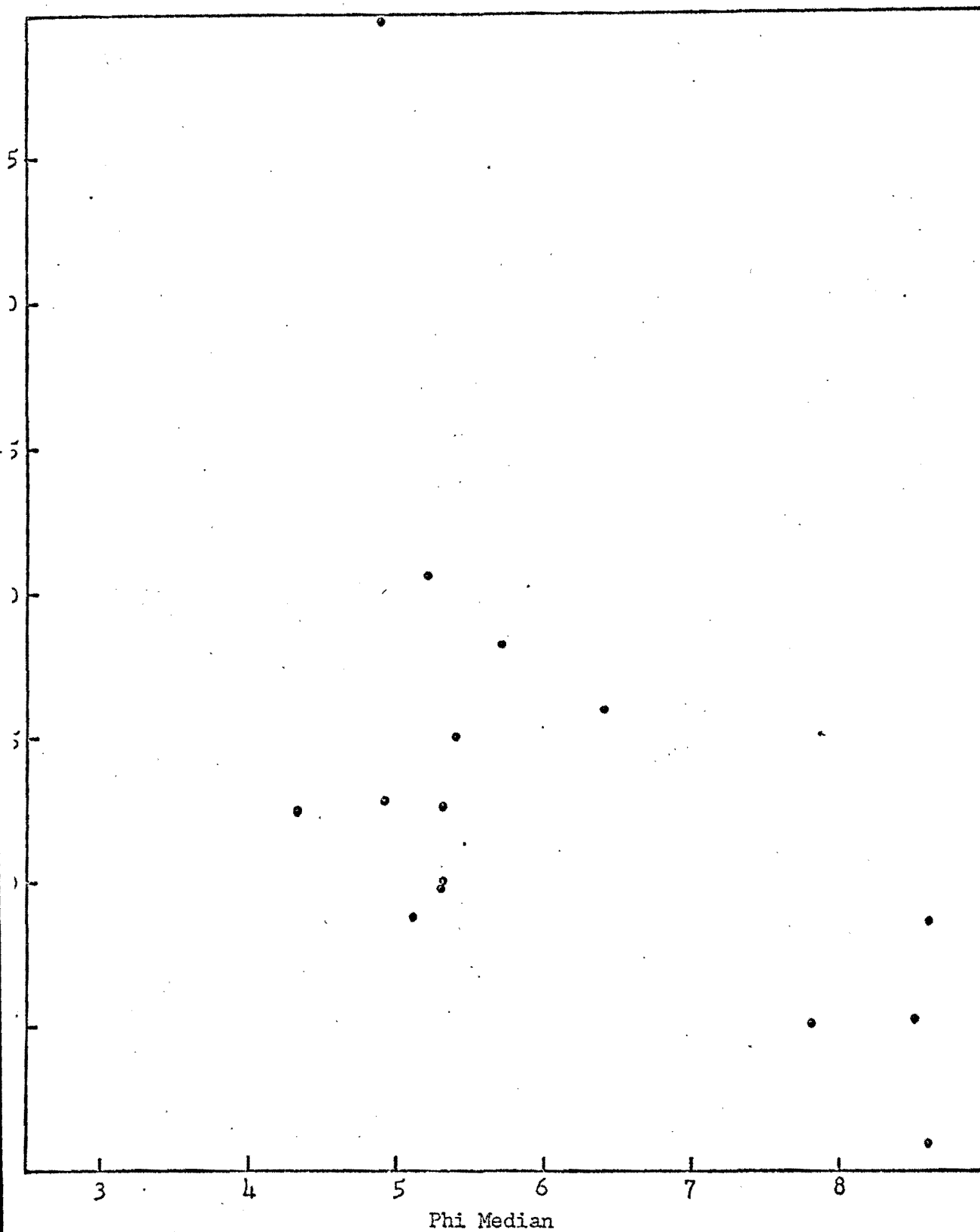
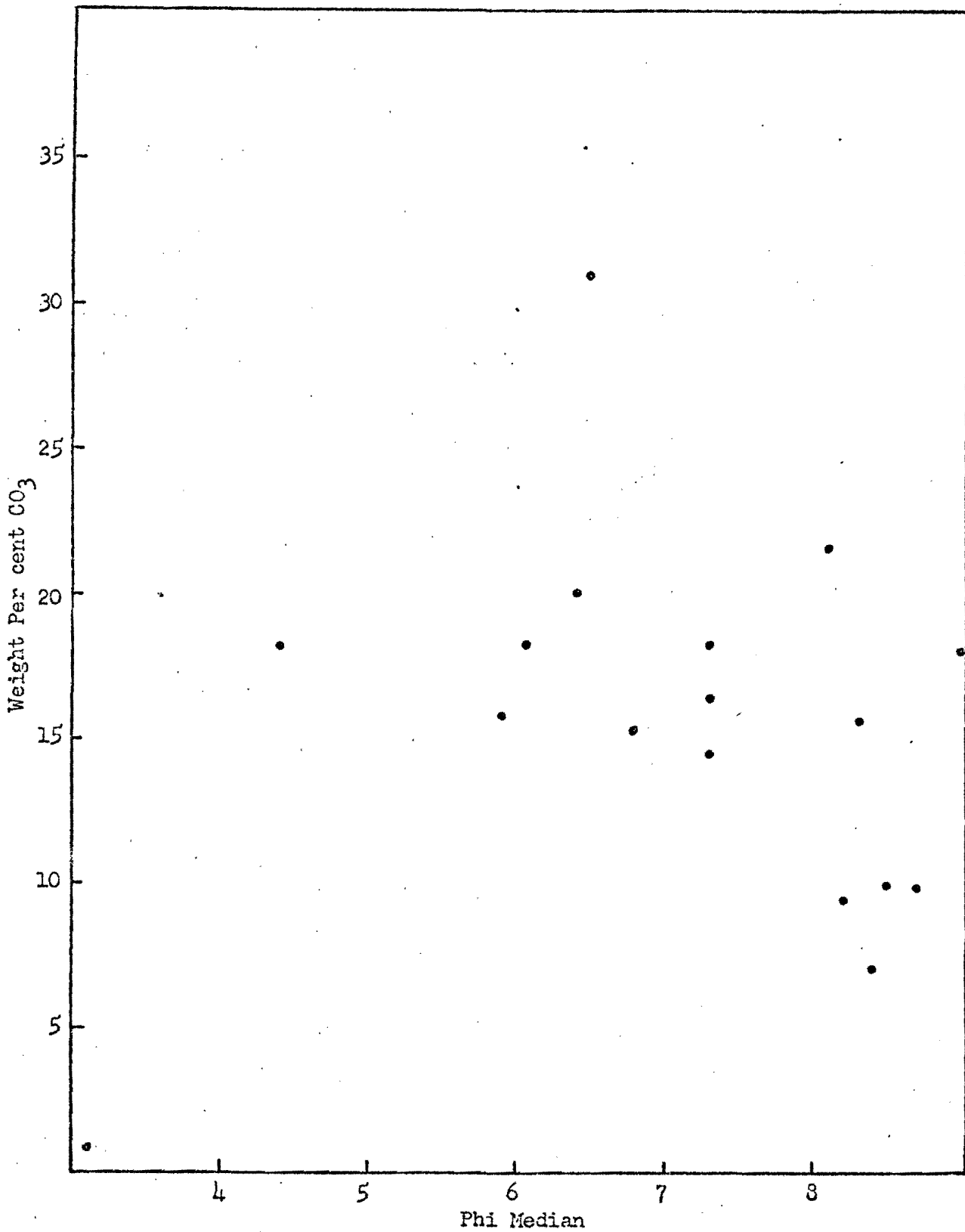Figure 99.—Plot of carbonate vs. median diameter for Tongue River samples from the Bullion Butte section.
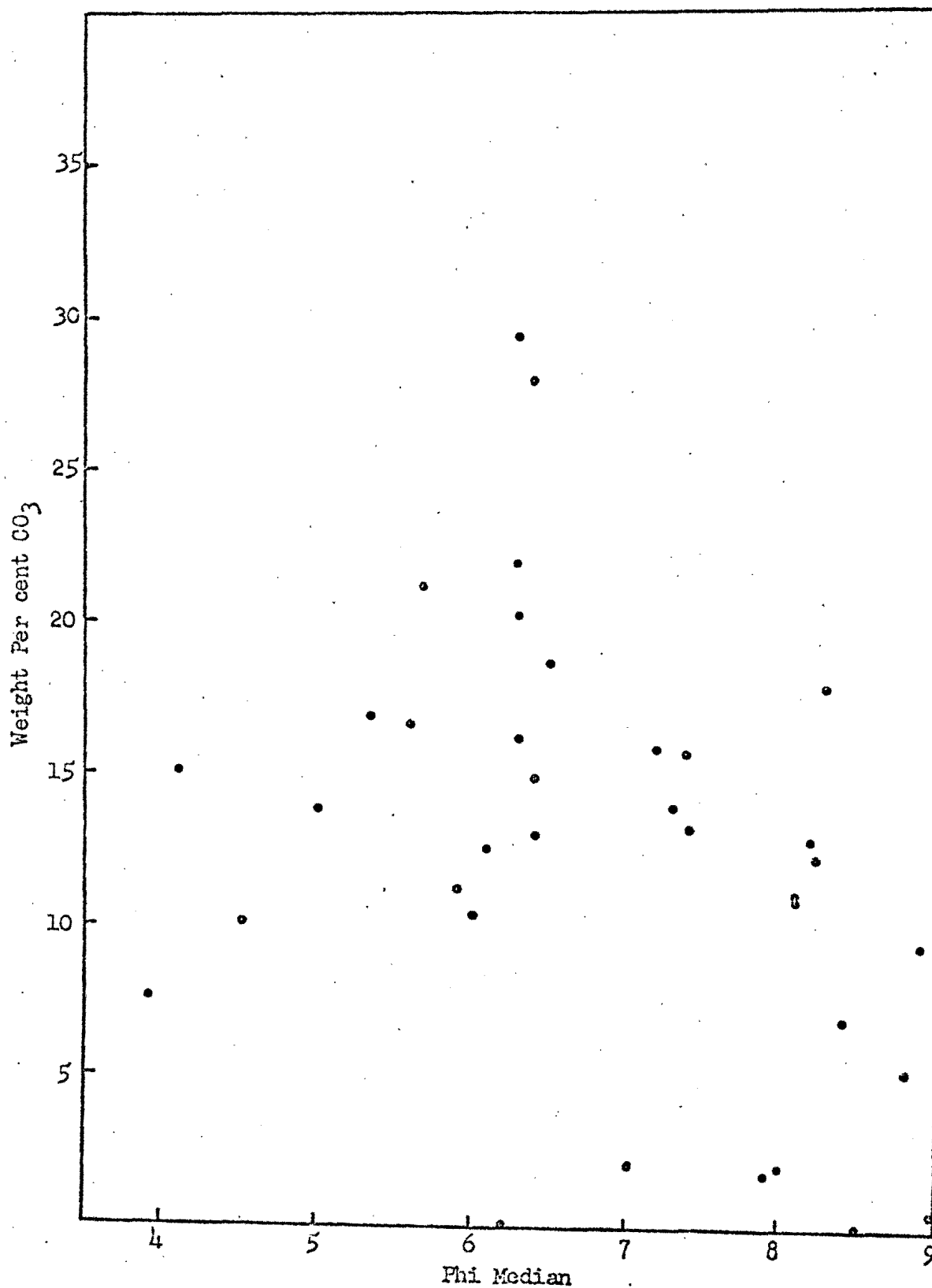
Figure 100.--Plot of carbonate vs. median diameter for Tongue River samples from the Medora section.

Figure 101.--Plot of carbonate vs. median diameter for Tongue River samples from the Deicegel Creek section
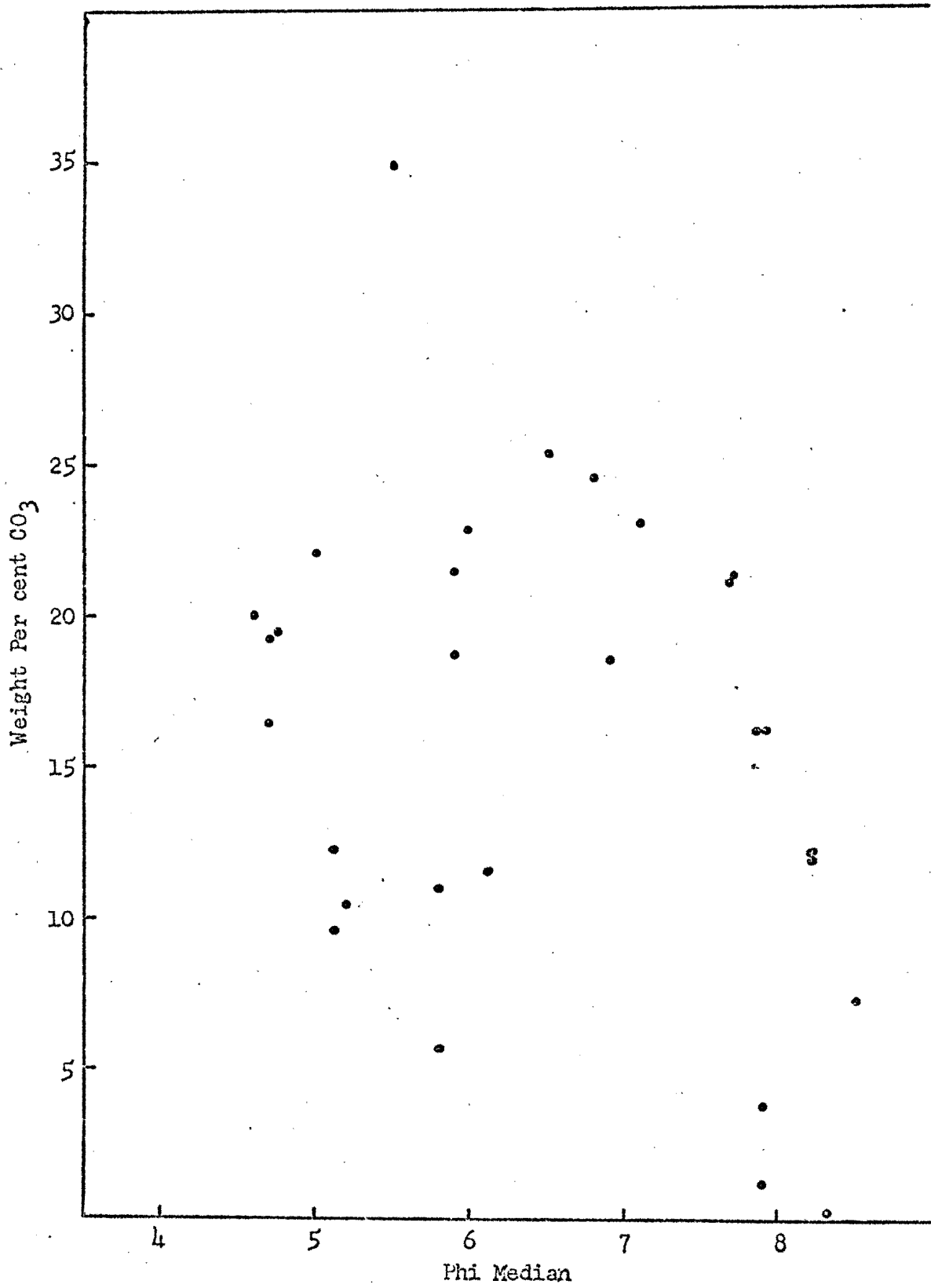
Figure 102.--Plot of carbonate vs. median diameter for Tongue River samples from the Yellowstone section.

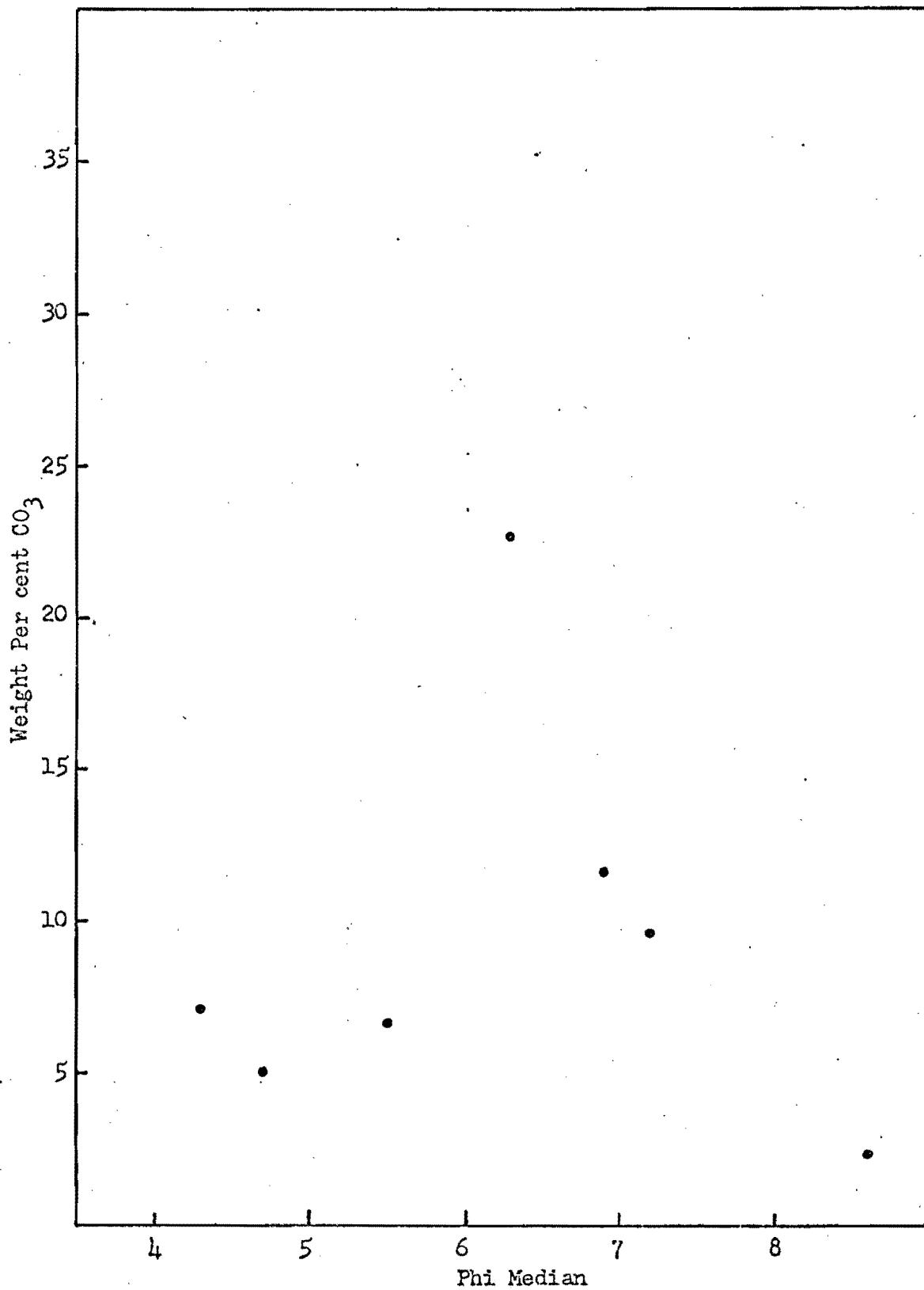Figure 103.--Plot of carbonate vs. median diameter for Tongue River samples from the Snowden section.

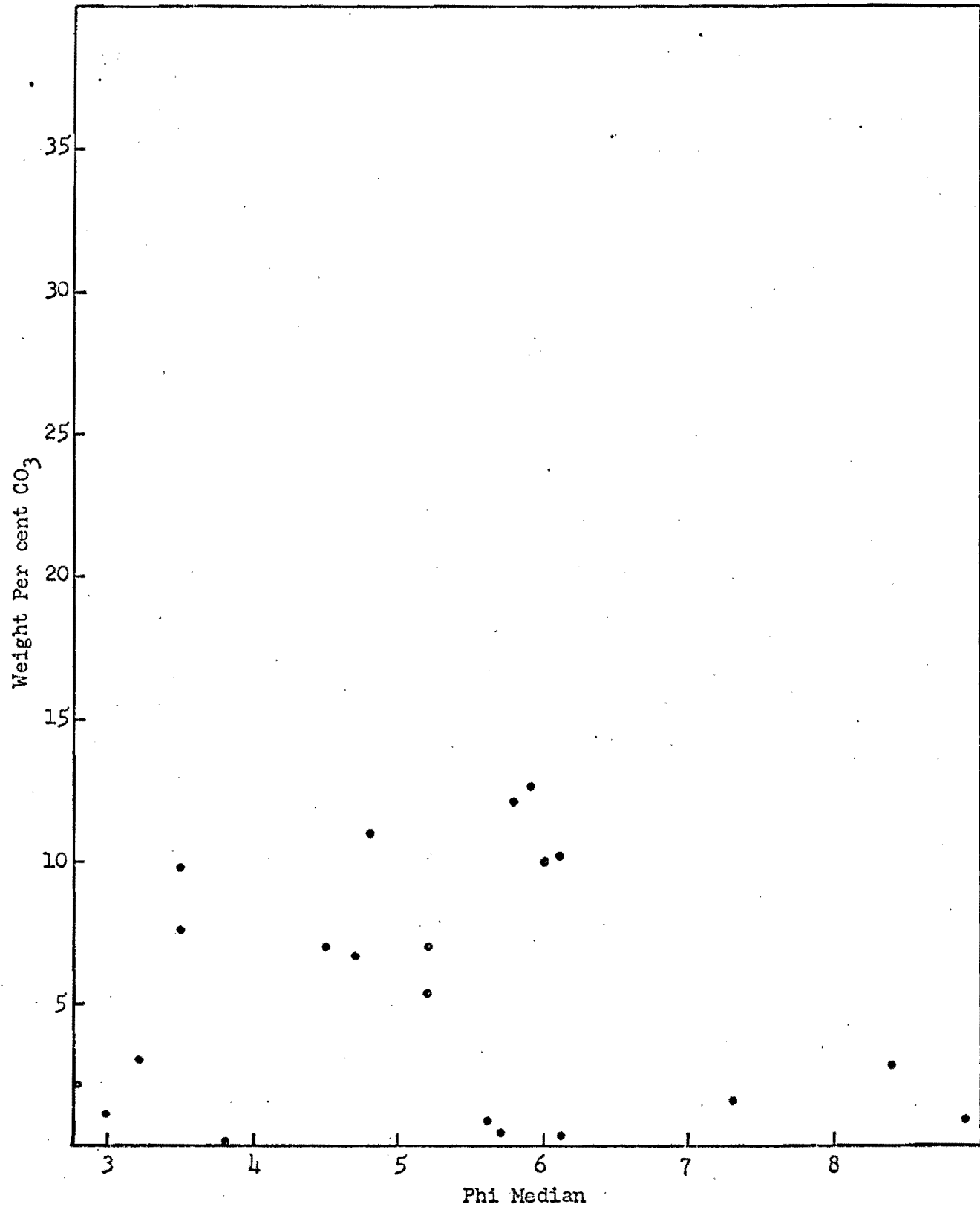Figure 104.--Plot of carbonate vs. median diameter for Tongue River samples from the Donnybrook section.

Figure 105.--Plot of carbonate vs. median diameter for Sentinel Butte samples from the Bullion Butte section.
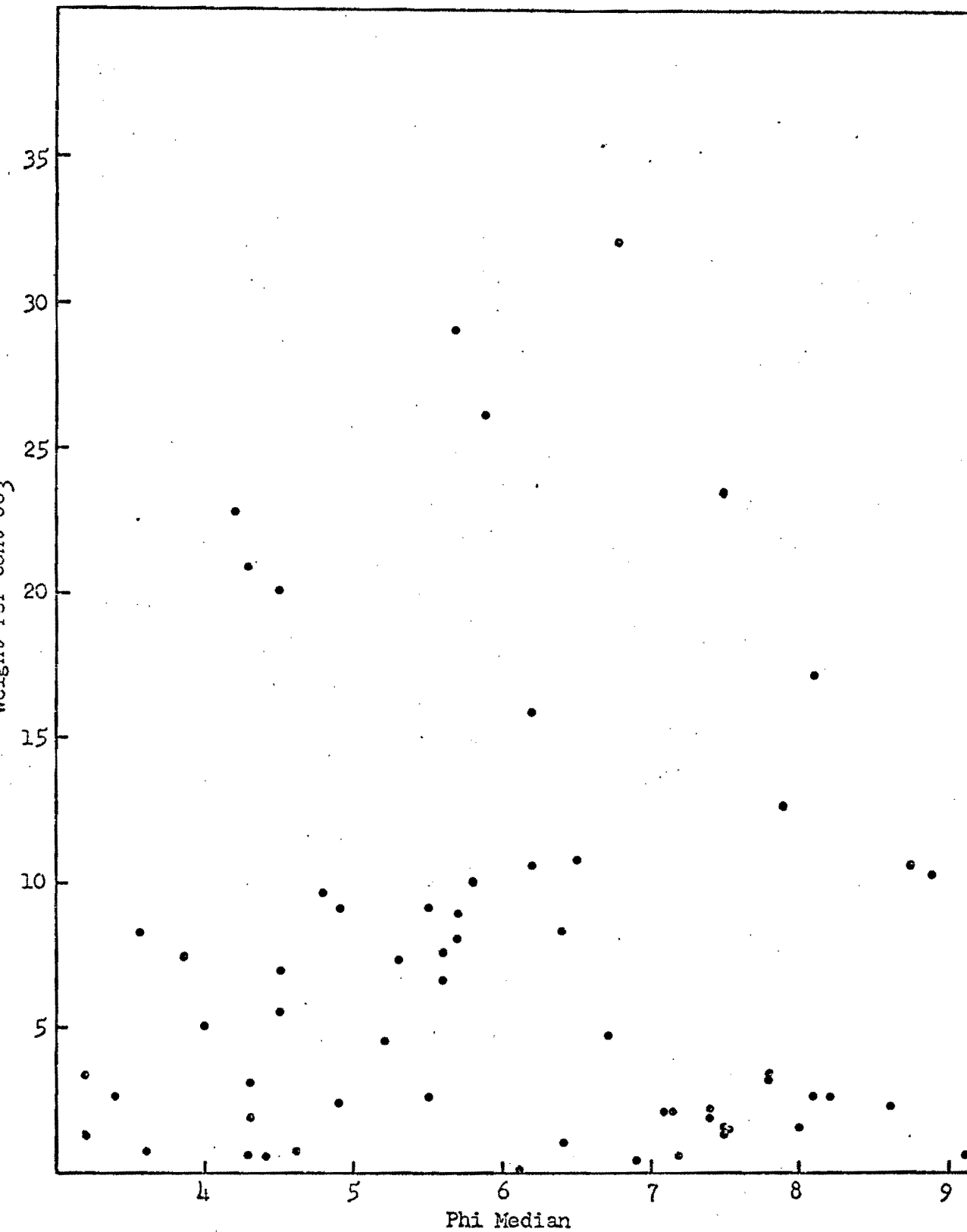
Figure 106.--Plot of carbonate vs. median diameter for Sentinel Butte samples from the Sentinel Butte section.
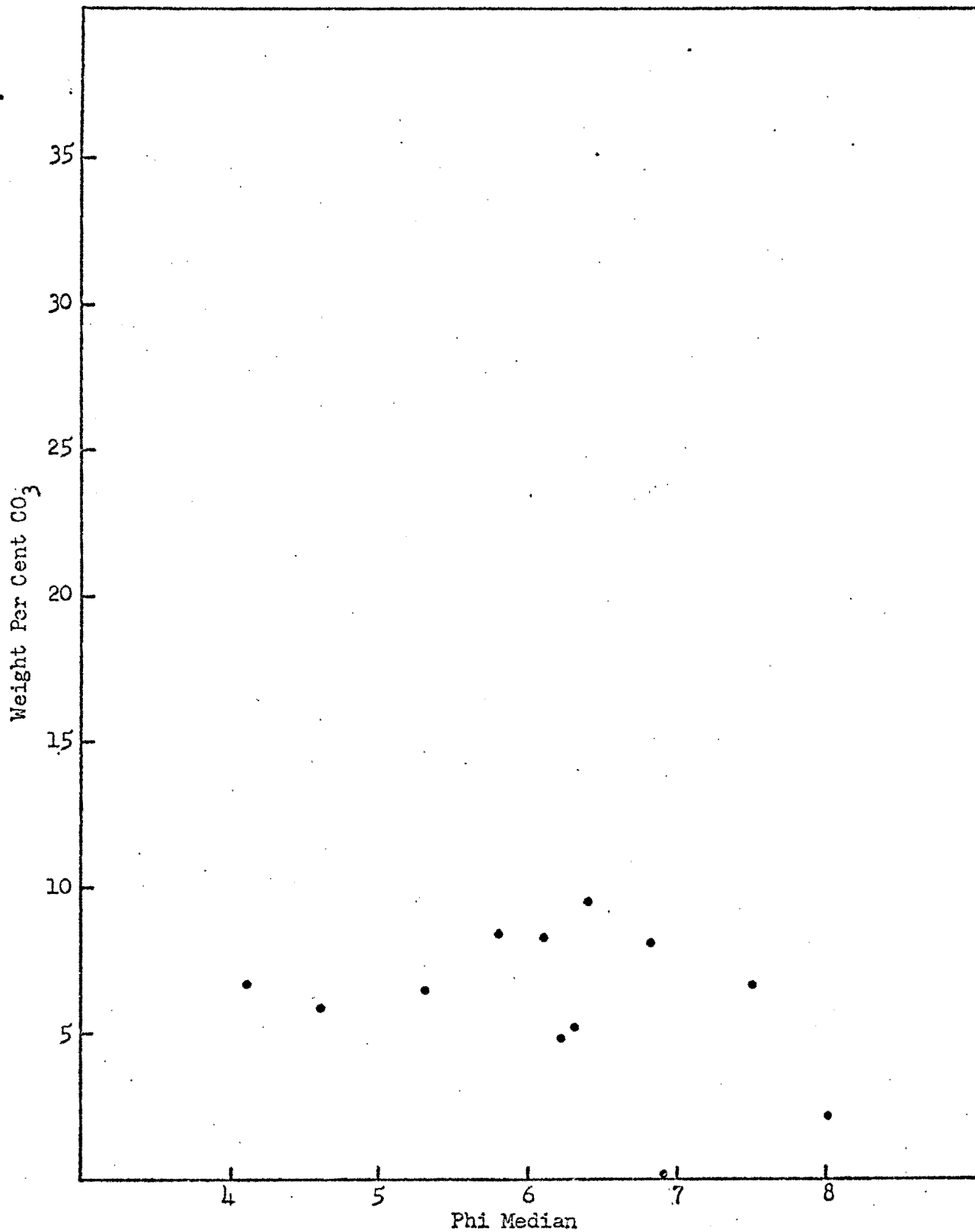
Figure 107.--Plot of carbonate vs. median diameter for Sentinel
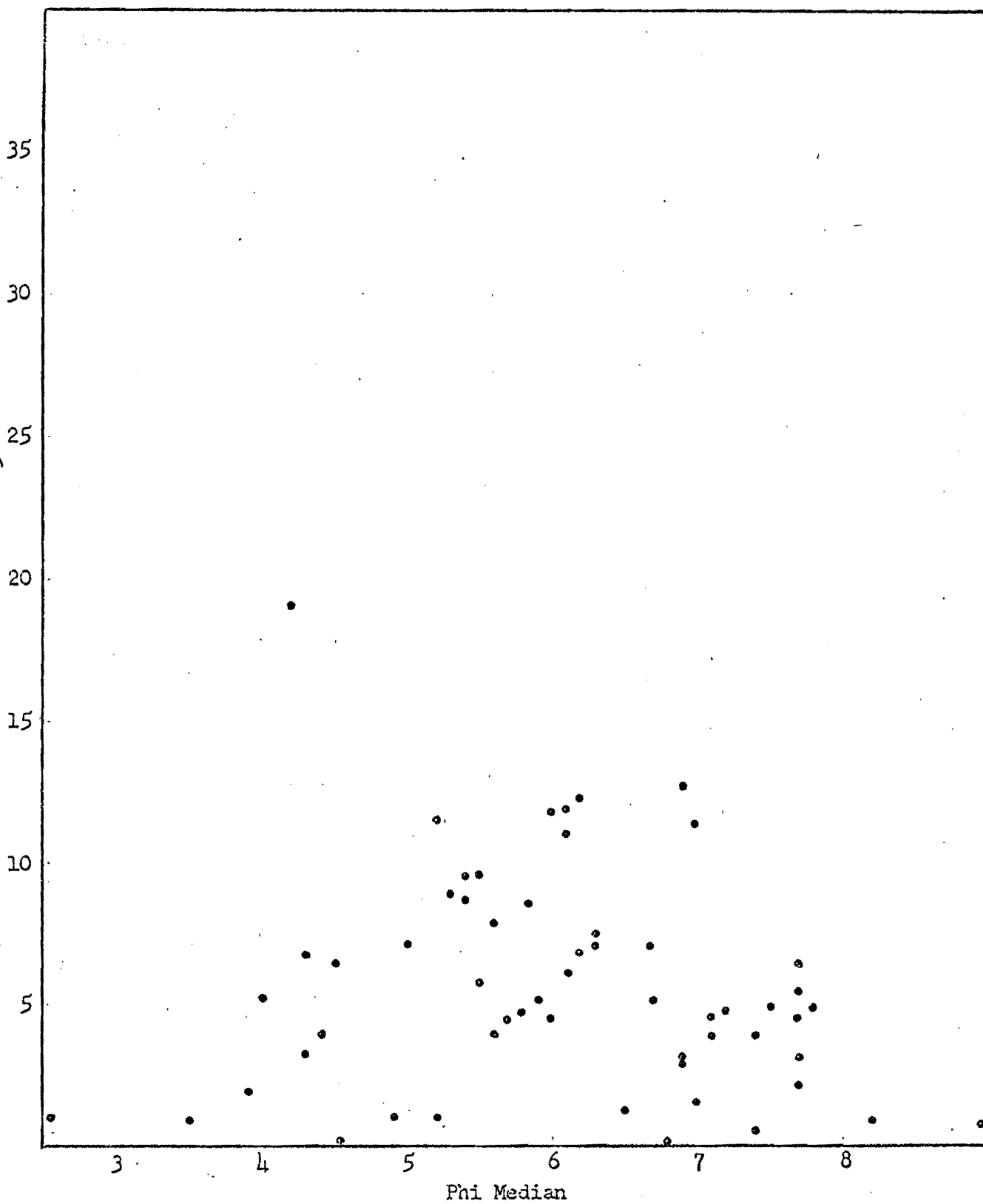Butte samples from the Beicegel Creek section.

Figure 108.--Plot of carbonate vs. median diameter for Sentinel Butte samples from the Long Cross section.
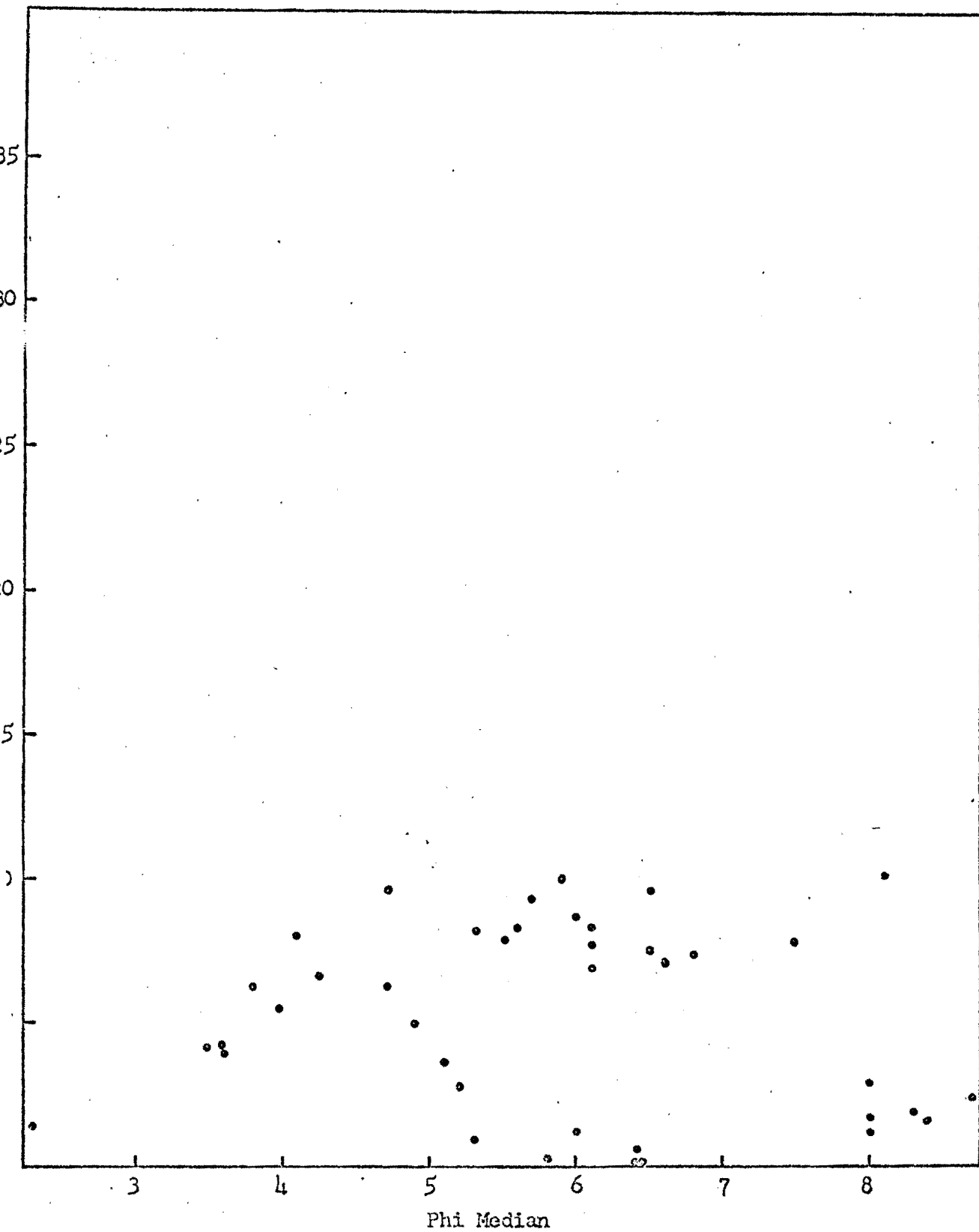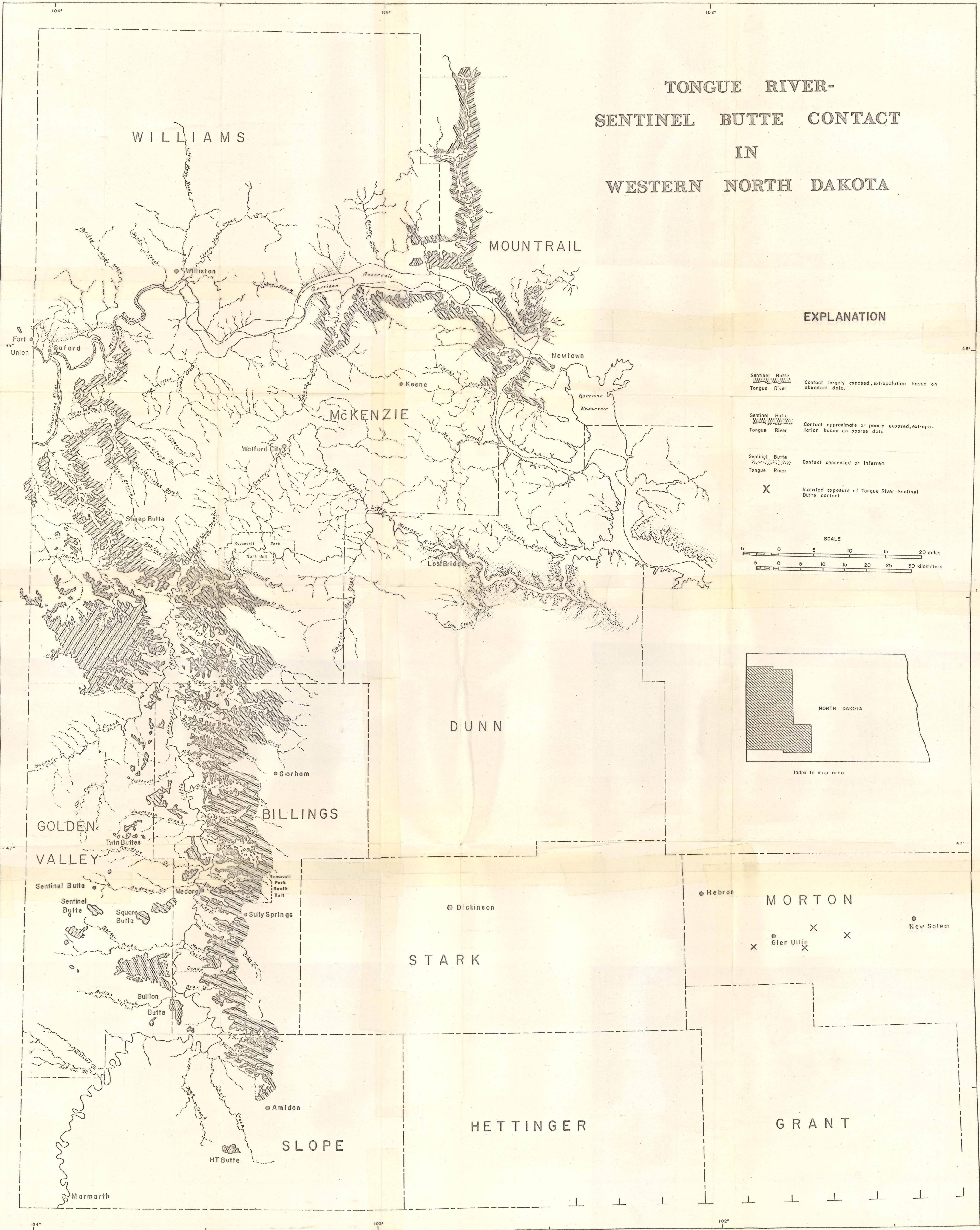
Figure 109.--Plot of carbonate vs. median diameter for Sentinel Butte samples from the Lost Bridge section.

TONGUE RIVER-SENTINEL BUTTE CONTACT IN WESTERN NORTH DAKOTA

WILLIAMS

MOUNTRAIL

McKENZIE

DUNN

BILLINGS

GOLDEN VALLEY

STARK

MORTON

SLOPE

HETTINGER

GRANT

Williston, Buford, Fort Union, Keene, Newtown, Watford City, Sheep Butte, Roosevelt Park North Unit, Lost Bridge, Gorham, Twin Buttes, Sentinel Butte, Square Butte, Medora, Roosevelt Park South Unit, Sully Springs, Dickinson, Hebron, Glen Ullin, New Salem, Bullion Butte, Amidon, H.T. Butte, Marmarth

Garrison Reservoir, Missouri River

EXPLANATION

Sentinel Butte / Tongue River — Contact largely exposed, extrapolation based on abundant data.

Sentinel Butte / Tongue River — Contact approximate or poorly exposed, extrapolation based on sparse data.

Sentinel Butte / Tongue River — Contact concealed or inferred.

X — Isolated exposure of Tongue River-Sentinel Butte contact.

SCALE

5   0   5   10   15   20 miles

5   0   5   10   15   20   25   30 kilometers

NORTH DAKOTA

Index to map area.