NORTH DAKOTA GEOLOGICAL SURVEY

Edwin A. Noble, State Geologist

Miscellaneous Series No. 43

A SEDIMENTOLOGIC ANALYSIS OF THE TONGUE RIVER-SENTINEL BUTTE INTERVAL (PALEOCENE) OF THE WILLISTON BASIN, WESTERN NORTH DAKOTA

by

CHESTER F. ROYSE, Jr.

Reprinted from
Sedimentary Geology, Vol. 4, 1970, pp. 19-80
Elsevier Publishing Company, Amsterdam

Grand Forks, North Dakota, 1971

Sedimentary Geology – Elsevier Publishing Company, Amsterdam – Printed in The Netherlands

A SEDIMENTOLOGIC ANALYSIS OF THE TONGUE RIVER–SENTINEL BUTTE INTERVAL (PALEOCENE) OF THE WILLISTON BASIN, WESTERN NORTH DAKOTA

CHESTER F. ROYSE JR.[1]
University of North Dakota, Grand Forks, N.D. (U.S.A.)

(Received November 15, 1968)

SUMMARY

Recognition of distinctive stratigraphic relationships at the Tongue River–Sentinel Butte contact, regarded by many as a vague color boundary, demonstrates that Sentinel Butte deposits are a mappable lithostratigraphic unit which merits formational rank. Granulometric analyses of approximately 500 sediment samples from nine stratigraphic sections amplify textural differences between the two units; Tongue River sediments are finer and less well sorted than those of the Sentinel Butte Formation. Median diameter and skewness are environmentally sensitive particle-size statistics. C–M patterns illustrate the fluvial origin of these deposits and are used to differentiate channel, floodplain, and backswamp facies. Differences in the relative abundances of facies types suggest significant differences in the regimes of fluvial systems which existed during Middle and Late Paleocene time.

Evaluation of primary sedimentary structures, lithologic composition, and stratigraphic abundance permits interpretation of paleostream velocities, paleochannel forms, suspended sediment concentrations, sediment dispersal patterns, paleoslope, and sedimentary provenances. Two sedimentation models have been formulated. 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. Paleoslope gradient was low and sediments were transported primarily in suspension. The fluvial system was stable and protected backswamps developed. Subsidence in the basin was uniform and controlled the rate of sedimentation during most of the episode; 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, subsidence exceeded sedimentation, and swamp conditions prevailed throughout much of western North Dakota.

Sentinel Butte deposition was initiated by an influx of coarse sediment

---

[1] Present address: Arizona State University, Tempe, Ariz. (U.S.A.).

Sediment. Geol., 4 (1970) 19–80

unit. As shown in Fig.4, these consist of: (*1*) a basal sand; (*2*) a "blue" bed; (*3*) a lower "yellow" bed; (*4*) an upper "yellow" bed; and (*5*) an upper sand. The first three of these are most useful because the lower beds of the Sentinel Butte are most widespread. Because it is the only non-lignitic unit which can be confidently recognized throughout the study area, the basal Sentinel Butte sand has particular significance in establishing regional trends of sedimentary parameters. As will be demonstrated, it also has unique lithogenetic significance and clarifies interpretation of sedimentologic data for the remainder of the Tongue River–Sentinel Butte interval. Details of field relationships and the areal extent of all key beds were given by ROYSE (1967b, pp.8–14).

The most widely exposed, distinctive, and useful key horizon is the contact between the Tongue River and Sentinel Butte Formations; it can be distinguished by three criteria. These are a marked change in gross color from buff yellow below to somber gray above the contact, the presence of the HT Butte lignite in the uppermost part of the Tongue River Formation, and the presence of a sandy basal Sentinel Butte unit. A single criterion may fail locally as a sole means of distinguishing the contact. The color contrast is largely a weathering phenomenon and may be subdued on fresh outcrops where strata are rapidly removed by slumping. The basal Sentinel Butte sand is a persistent facies but varies in texture and, in places, contains considerable fine silt. The HT Butte bed is predominantly lignite of variable thickness, but it becomes shaley locally and (apparently) toward the west and northwest. Additional attributes, defining characteristics, and persistence of these criteria have been discussed and illustrated (ROYSE, 1967a, pp.2–29).

Consideration of sediment dispersal and depositional history require general evaluation of formation thicknesses. Field experience and specific field checks indicate that a majority of the thicknesses reported for Paleocene units in North Dakota are unreliable. Discrepancies in values for Tongue River and Sentinel Butte thicknesses can be largely accounted for by three factors: (*1*) these strata are not constant in thickness; (*2*) the boundaries of stratigraphic intervals loosely designated as "Tongue River" and "Sentinel Butte" have not always been explicitly defined; and (*3*) stratigraphic thicknesses cited for a single locality have been indiscriminantly applied to other areas or to formations in general. The total thickness of Tongue River or Sentinel Butte strata can be accurately measured at few localities, because the base of the first is seldom exposed and the top of the second has been widely removed by erosion. ROYSE (1967b, pp.15–20) reviewed published thickness values (LEONARD and SMITH, 1909; THOM and DOBBIN, 1924; HARES, 1928; HENNEN, 1943; FISHER, 1953, 1954; CLARK, 1966; CRAWFORD, 1967) which, combined with his own data, indicate that both units are thin (200–300 ft.) along the flanks of the Williston Basin and thicken (600 ft.) toward its center. This relationship is more easily documented for the Sentinel Butte than for the Tongue River Formation, but suggests that the total accumulated thickness of both units was controlled by Williston Basin subsidence during Paleocene time.

The Sentinel Butte is conformable upon Tongue River strata and the character of their contact suggests that sedimentation, although retarded, was continuous across this boundary. Beds above the Sentinel Butte, however, are of Eocene and Oligocene age and their contact with the Sentinel Butte is locally disconformable, indicating post-Sentinel Butte erosion and non-deposition. This is particularly evident at the type locality of the Sentinel Butte where the uppermost Paleocene strata are leached and incised by channels filled with Oligocene sandstone. ROYSE (1967b), however, supports the argument that basin margin thinning is primary and that, although some erosion preceded and accompanied deposition of Eocene and Oligocene sediments, the magnitude of post-Sentinel Butte erosion was slight.

SEDIMENTOLOGY

Sediment-size statistics

Size analysis. All samples were pretreated to remove reactive carbonate and analyzed for particle size according to conventional sieve and pipette procedures. Size statistics of FOLK and WARD (1957)[1]; sand, silt, and clay percentages; and other values were obtained by computer program. Moment measures could not be obtained for all samples and Folk and Ward statistics have been adopted for presentation of size data in this report.

Tongue River and Sentinel Butte sediments are loosely consolidated, easily disaggregated and dispersed, have a relatively narrow range of sizes, and contain only minor amounts of non-lithogenous material. Carbonate is present as cement and is believed to be penecontemporaneous or early diagenetic in origin, as such it was removed from samples in which the size characteristics of the allogenic components were desired. Size analyses have good reproducibility and a high level of confidence can be placed on their results.

Mean and median diameters. The distributions of Folk mean and median diameters of stratigraphic samples from the Tongue River and Sentinel Butte Formations are shown in Fig.5 and Fig.6. Sentinel Butte sediments are coarser, on an average, than Tongue River sediments and have a slightly broader range of mean and median values. Measures of central tendency for Tongue River sediments are bimodally distributed with a slight negative skewness (i.e., a small tail of coarse values), those of the Sentinel Butte samples are more nearly symmetrically distributed. The

---

[1] Folk statistics are defined as: median $= \varphi 50$; mean $= \dfrac{\varphi 16 + \varphi 50 + \varphi 84}{3}$;

sorting $= \dfrac{\varphi 84 - \varphi 16}{4} + \dfrac{\varphi 95 - \varphi 5}{6.6}$; skewness $= \dfrac{\varphi 16 + \varphi 84 - 2\varphi 50}{2(\varphi 84 - \varphi 16)} + \dfrac{\varphi 5 + \varphi 95 - 2\varphi 50}{2(\varphi 95 - \varphi 5)}$;

kurtosis $= \dfrac{\varphi 95 - \varphi 5}{2.44(\varphi 75 - \varphi 25)}$.

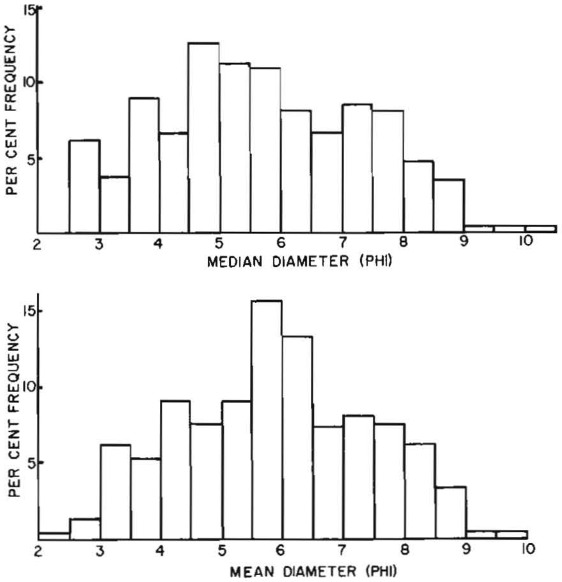


Fig.5. Distribution of median and mean diameters for 211 stratigraphic samples from the Sentinel Butte Formation.

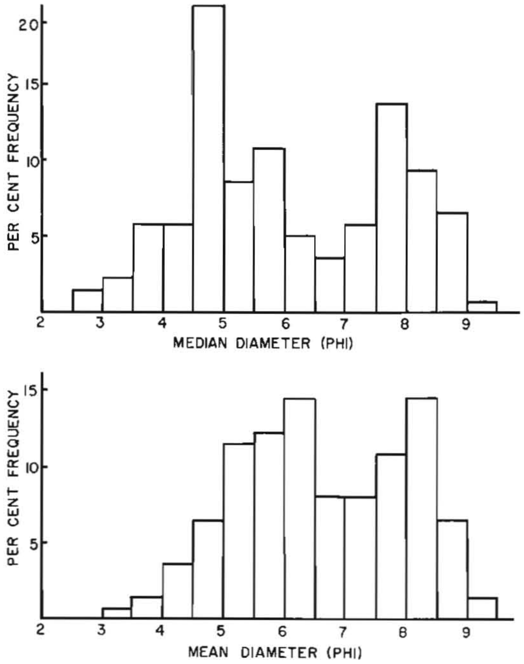


Fig.6. Distribution of median and mean diameters for 135 stratigraphic samples from the Tongue River Formation.

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 Fig.7. 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 (1.0–2.0 phi-units). The greatest difference in sorting values of the two units is the greater percentage of very poorly sorted (2.0–4.0 phi-units) Tongue River samples, which causes that distribution to be weakly bimodal. Plots of mean diameter versus sorting show only a slight tendency to group, and the comparison of these statistics appears to be of little value in differentiation of sediment types.

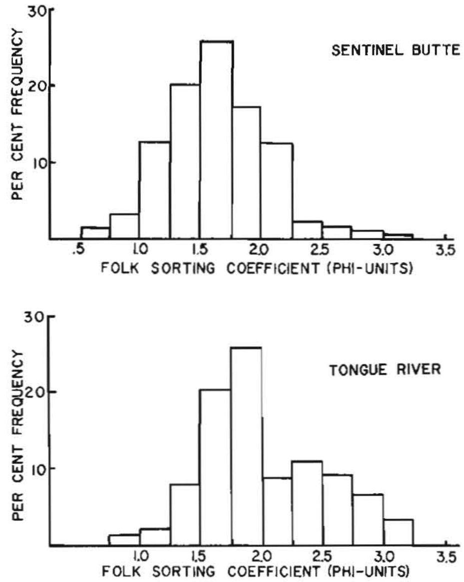


Fig.7. Distribution of Folk sorting in stratigraphic samples from the Sentinel Butte and Tongue River Formations.

The distribution of sorting values, according to the textural classification of Folk, for samples from the various stratigraphic sections is given in Table II.

Skewness. As shown in Fig.8, 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 values exists in Tongue River sediments, as is manifested by the

TABLE II

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
	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
	0.0%	2.1%	59.7%	38.1%

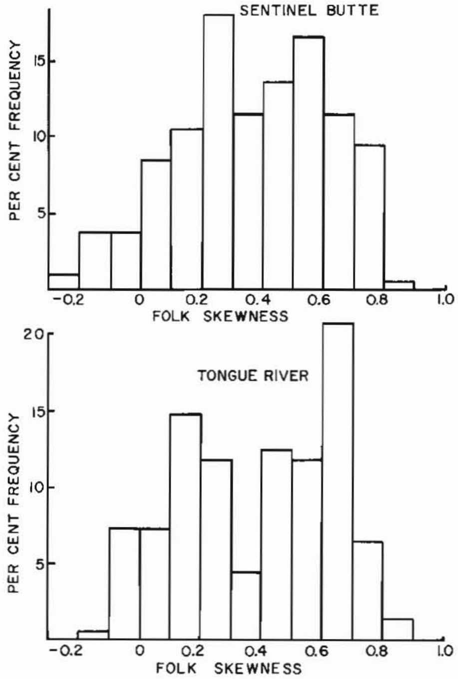


Fig.8. Distribution of Folk skewness values for stratigraphic samples from the Tongue River and Sentinel Butte Formations.

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% of the samples in both formations are very-fine skewed, and an additional 25% or more are fine skewed. The relative percentages of skewness types for samples from the two units are given in Table III.

TABLE III

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
	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	–
	57.5%	26.6%	14.3%	1.4%

Kurtosis. Fig.9 compares the relative distribution of kurtosis 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 skewed toward high kurtosis values but Sentinel Butte values show a fair 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 are given in Table IV.

Sediment-size components

Many ternary systems of classification have been proposed for sedimentary aggregates and little agreement exists regarding class limits; those of SHEPARD (1954) have been widely accepted and are used in this study. Plots of sand, silt, and clay (WENTWORTH, 1922) relationships are shown in Fig.10 and Fig.11. A summary of these data, expressed in FOLK's (1954) textural terms, is presented in Table V for the convenience of those more familiar with this nomenclature.

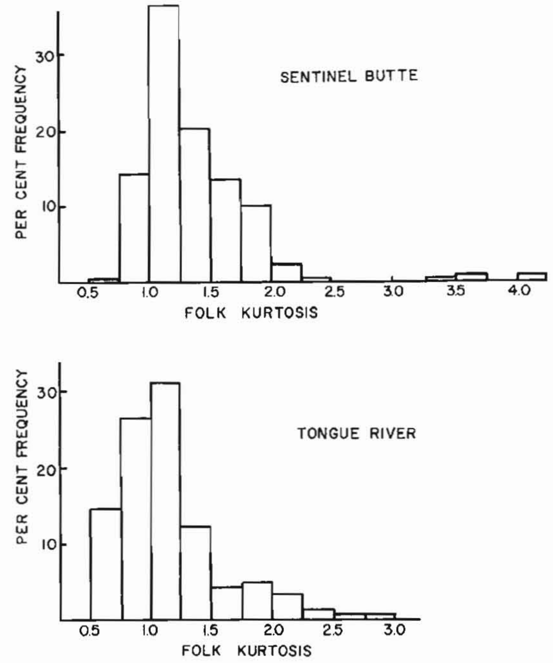


Fig.9. Summary of kurtosis values in stratigraphic samples from the Tongue River and Sentinel Butte Formations.

TABLE IV

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	–
	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	–	–
	0.0%	15.1%	28.7%	27.3%	23.0%	5.7%

TABLE V

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	–
	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
	0.0%	5.0%	22.3%	26.6%	35.9%	4.3%	2.8%	2.8%

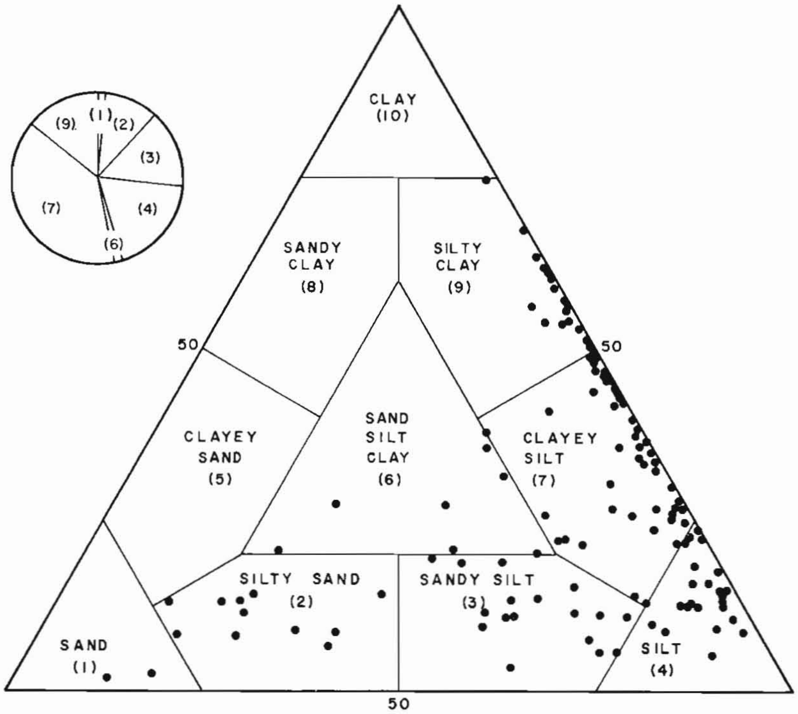


Fig.10. Sand, silt, clay contents of stratigraphic samples from the Tongue River Formation; the pie diagram indicates relative abundances in each textural class.

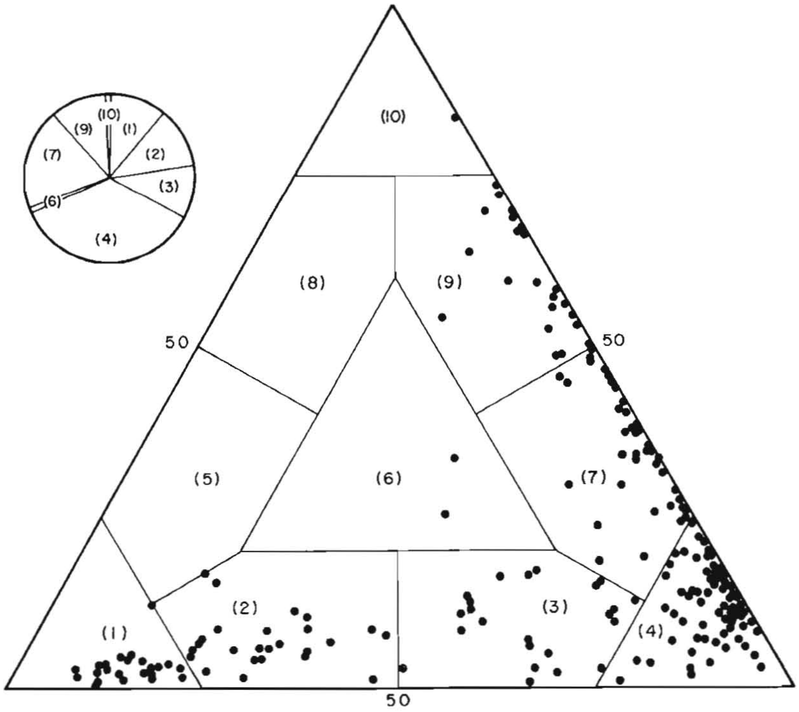


Fig.11. Sand, silt, clay contents of stratigraphic samples from the Sentinel Butte Formation; the pie diagram indicates relative abundances in each textural class as defined in Fig.10.

A comparison of Fig.10 and 11 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 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 relationships with the size classes are quantitatively summarized in the pie diagrams which accompany the triangular diagrams. Compared, the patterns illustrate the overall poorer sorting of Tongue River sediments relative to those of the Sentinel Butte.

Sedimentary structures

A major objective during field study was to obtain directional data from large-scale cross-stratified units. Both large- and small-scale primary bedding structures are abundant in Tongue River and Sentinel Butte strata, but priority is given here to consideration of large-scale structures. Genetic interpretation of small-scale structures are treated here only qualitatively. For convenience of discussion, sedimentary structures are grouped below into three categories; horizontal stratification, inclined stratification, and miscellaneous structures. The classification of ALLEN (1963b) for cross-stratified units and the nomenclature of McKEE and WEIR (1953) for bed-thickness are used; terminology applied to other structures is considered to be in common use and most terms are listed by PETTIJOHN (1957, pp.157–196).

Horizontal stratification. The bounding surfaces of major lithologic units of the Tongue River and Sentinel Butte Formations are usually planar and discordance is prominent 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 Fig.12A. Flat-bedded sandstones appear to be more abundant in the Tongue River Formation.

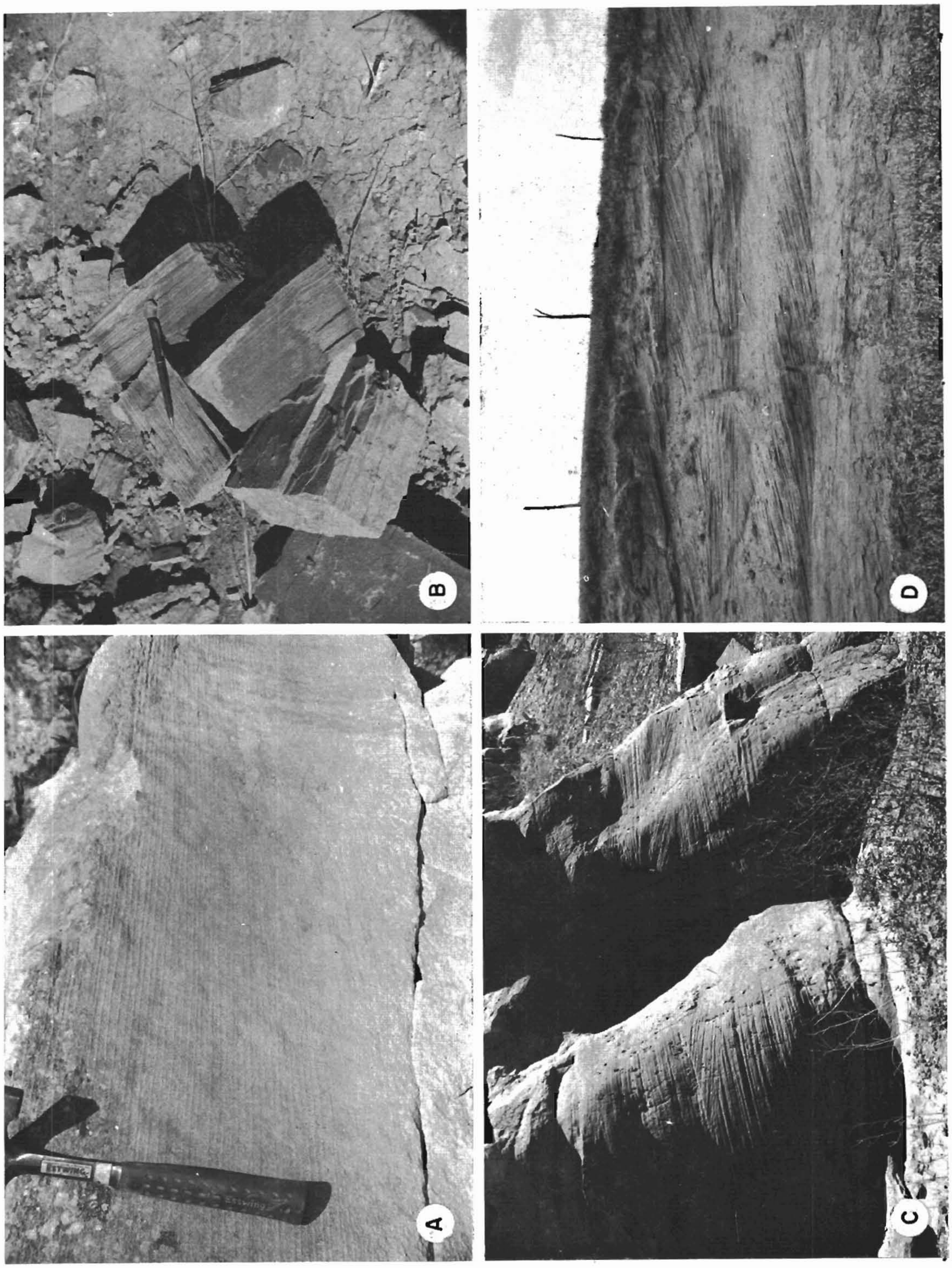
Laminated silt, silty clay, and clayey silt beds are nearly ubiquitous in outcrops of both formations and constitute the most common bedding type. Laminae vary in thickness but seldom exceed 0.5 cm; a very thin-laminated siltstone is illustrated in Fig.12B.

Inclined stratification. In terms of volume, cross-stratified units are not abundant, but because they are commonly better lithified, they are more prominent than other bedding types. 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 (Fig.12C). 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 (Fig.12D) 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 type of Allen. Kappa-cross-stratification predominates (Fig.13A,B). Nu-cross-stratification (festoon-bedding) is also found (Fig.13C), but is less common than either kappa or lambda types. Ripple-marked surfaces of asymmetrical transverse and linguoid (cuspate) ripples (Fig.13D) were observed, but sediment texture seldom favors preservation of these surfaces.

Large-scale cross-beds are found throughout the Tongue River Formation (Fig.12C), but within the Sentinel Butte they are largely confined to the basal and upper sands (ROYSE, 1967a, fig.2a, 2b, 2c, and 6b). 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


A
B
C
D
ESTWING

abundance of large scale structures is qualitatively reflected in the number of directional readings recorded from each unit (Table VI).

Inclined strata of large magnitude were noted at a number of localities in the basal Sentinel Butte sand (Fig.14A). 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.

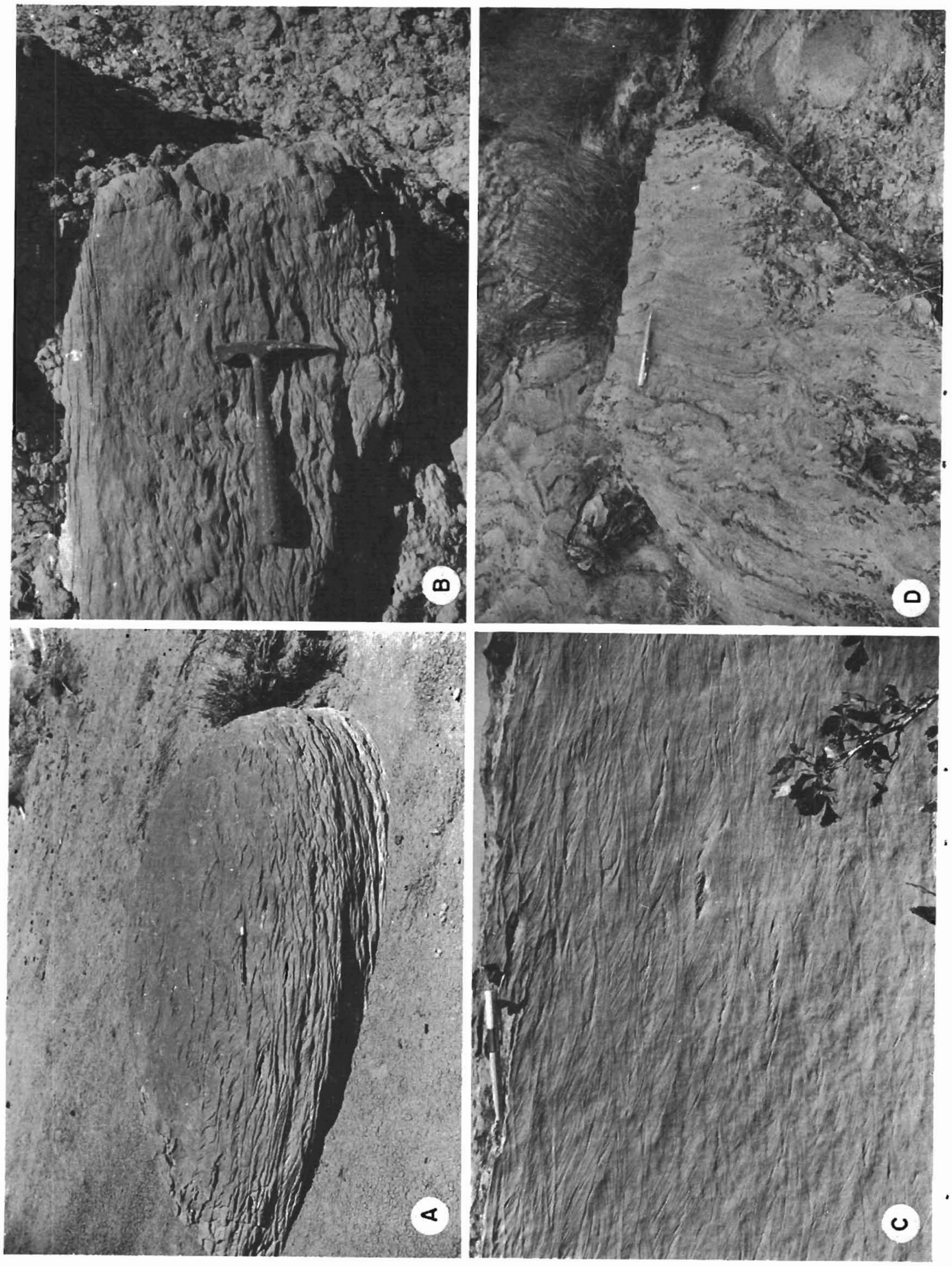
Occasionally, channel-lag or channel-fill deposits can be identified within the Tongue River–Sentinel Butte sequence. Rarely, channel structures truncate underlying strata, but such evidence of erosion (however local) is relatively uncommon. Fig.14B shows a small channel in the Sentinel Butte Formation which eroded underlying strata prior to being filled. Trough-sets are partly discordant and partly concordant with adjacent beds. Major channeling, such as that illustrated by HARES (1928, pl.5B), 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. Deformation due to loading and compaction is doubtful because of the lack of irregular boundaries (load casts) with adjacent units. 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 occur in limonitic 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 (Fig.14C). At one locality in the basal Sentinel Butte sand (Fig.14A), mud cracks were accompanied by small, conical structures with a pitted apex which resembles bubbles (Fig.14D). In vertical section, these structures display internal fractures (shrinkage cracks) and a flow structure from base to apex. The conical depression at the apex has been filled by sand from the superjacent bed. 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 such debris

---

Fig.12. Primary sedimentary structures. A. Thinly flat-bedded sandstone in Tongue River. B. Laminated siltstone in Sentinel Butte. C. Xi-cross-stratification in Tongue River. D. Omikron-cross-stratification in upper Sentinel Butte sand.


B
D
A
C

is documented by molds of leaves, seeds, and other vegetative material. The concretionary character of the zones themselves suggest quiescent interludes during which deposition of lithogeneous sediment was slow and organic material formed a significant sediment component. The fixation of iron, which has altered the bedding surfaces to thin indurated zones (Fig.14A, C), probably resulted from redox reaction involving anoxic decomposition of organic matter. Reduced iron was fixed as sulfides (or similar compounds) which was subsequently oxidized during weathering.

This mechanism probably accounts also for the origin of marcasite nodules which are common in Tongue River sands (Fig.15A). Large nodules commonly have plant molds passing through their axes and the writer found a marcasite replica of a small snail in one small nodule. 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 crystallization during replacement.

Large, cannonball-like, dolomitic carbonate concretions also occur and were noted principally in the Sentinal 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 Fig.15B. The origin of these structures is not known with certainty but, in the present instance, the volume reduction could be associated with dolomitization.

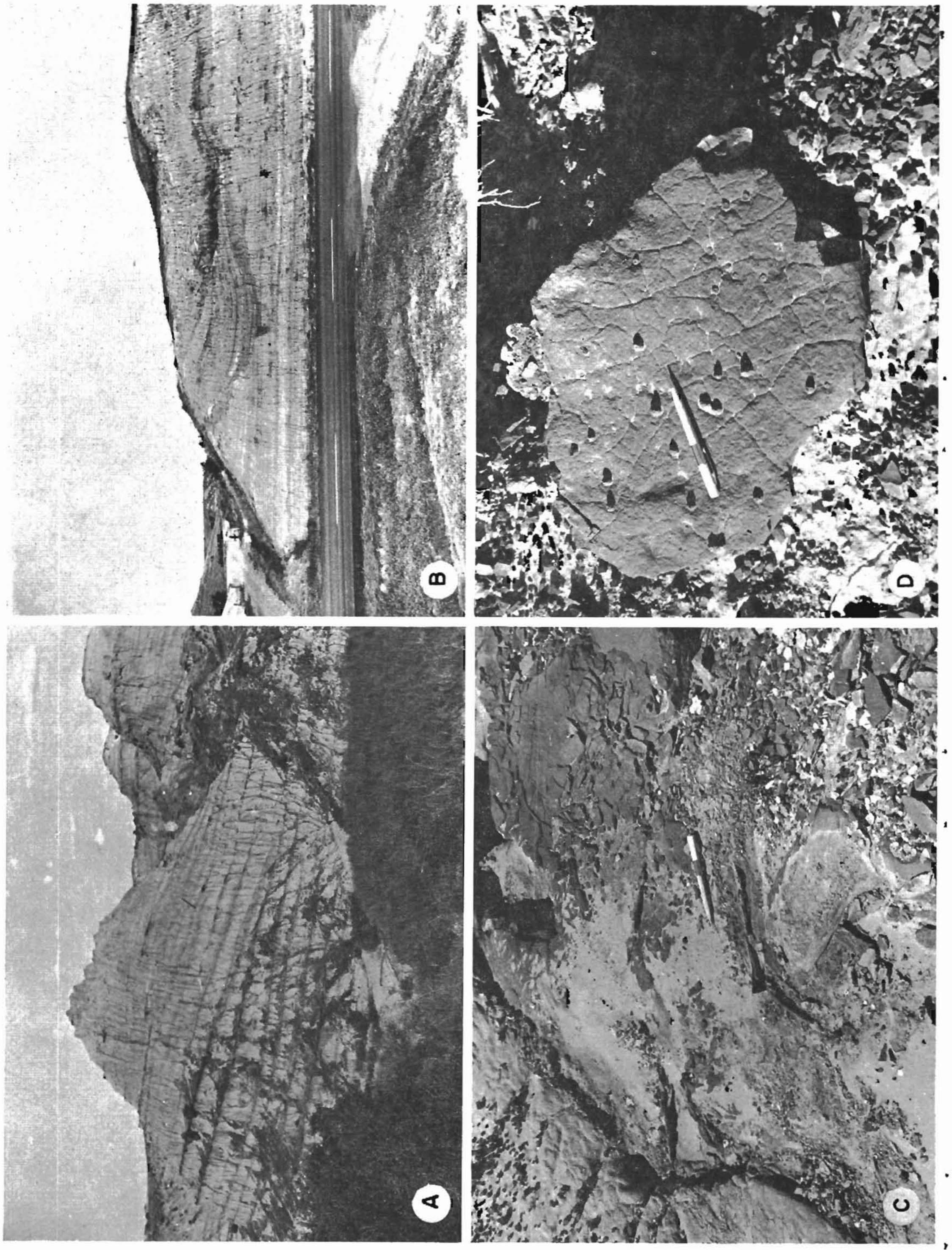
Log-like concretions (Fig.15C) are found in both Tongue River and Sentinel Butte strata, but were noted most frequently in the Tongue River Formation and in the basal Sentinel Butte sand. Their origin is not understood. A single occurrence of worm trails was observed (Fig.15D) on the base of a freshwater limestone slab from the Sentinel Butte section. To the writer's knowledge, such fossils have not previously been reported from the Sentinel Butte Formation and, although the biologic affinities of the organisms which formed them are not known, their presence has paleoecologic significance and merits documentation.

Paleocurrents

Field procedures. The strike, dip, maximum bed-thickness, stratigraphic position and location of large-scale cross-beds were systematically recorded for comparison of the sediment dispersal patterns in Tongue River and Sentinel Butte strata. One measurement of maximum dip and thickness was recorded per bed, in vertical succession, for 15–20 beds at each locality. The attitude of all major bedding planes

---

Fig.13. Primary sedimentary structures. A. Kappa-cross-stratification in a boulder of Sentinel Butte sandstone. B. Kappa-cross-stratification in Tongue River sandstone. C. Tangential section of nu-cross-stratification in silty sand of the Tongue River. D. Asymmetrical transverse ripple marks in silty sand of the Tongue River.


A
B
C
D

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° classes (Table VI). 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 of POTTER and PETTIJOHN (1963, p.256). Vector means for individual outcrops are shown, with rose diagrams and grand means, in Fig.16–19. The grand means, variance, and standard deviations calculated for all observations from the Tongue River, basal and upper sands, and intervening Sentinel Butte strata are included in Table VI.

A test to determine the level of significance of preferred orientation was made for the grand means. The ratio of the computed sample variance, s_o^2, to the variance of the uniform distribution, s_u^2, provides a test for the null hypothesis (H_0):

$$s_o^2 = s_u^2$$

The alternate hypothesis (H_a) must be:

$$s_o^2 < s_u^2$$

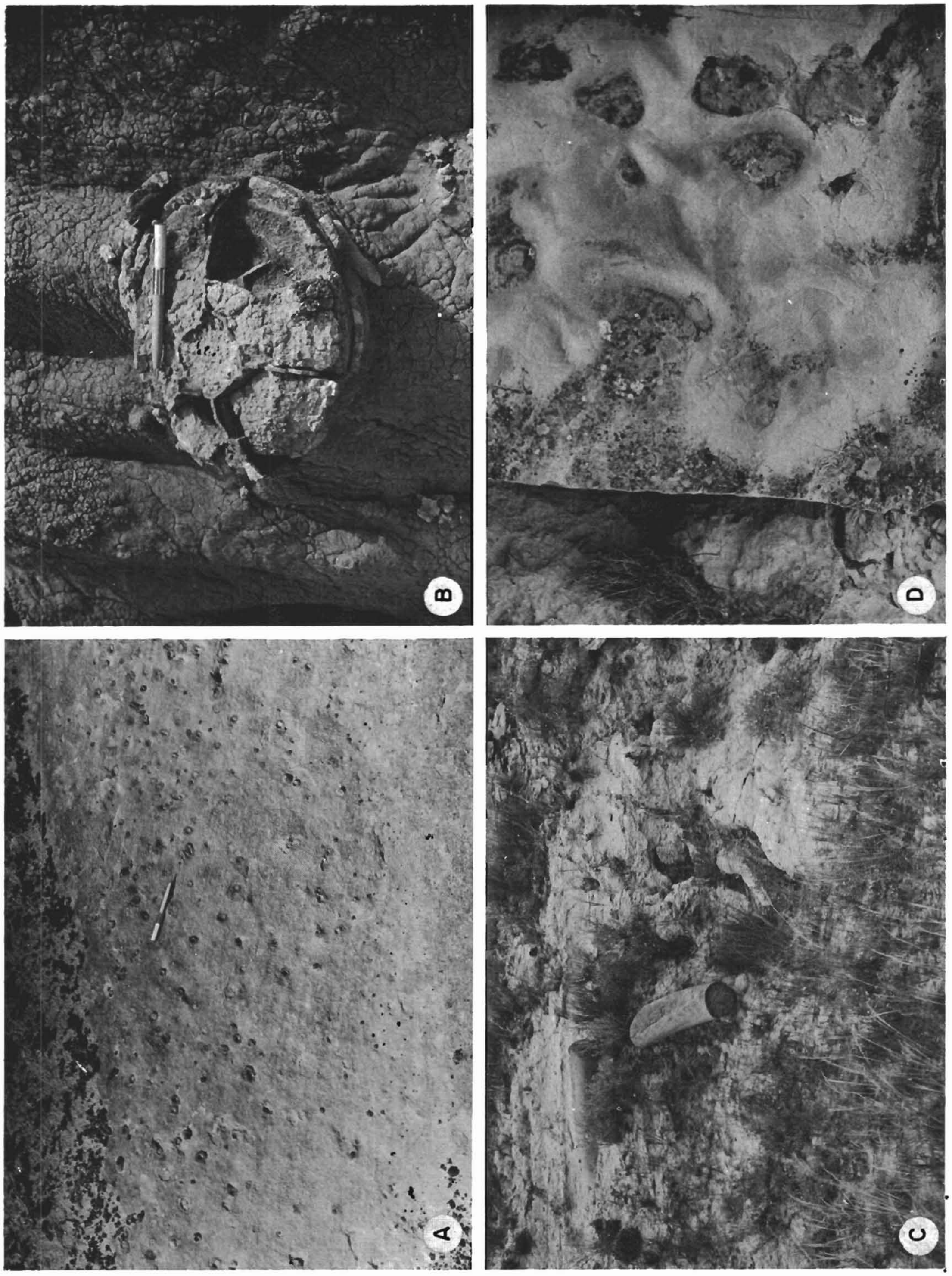
The value of s_u^2 is computed by the method of GRIFFITHS and ROSENFELD (1953, p.212):

$$s_u^2 = a^2/3$$

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% level

---

Fig.14. Sedimentary structures. A. Primary inclination in bedding of basal sand in the Sentinel Butte. B. Small channel-fill deposit in the Sentinel Butte. C. Desiccation-crack filling in concretionary bedding-plane material of the basal sand of the Sentinel Butte. D. Small pitted mounds presumed to be lithified gas bubbles.


A
B
C
D

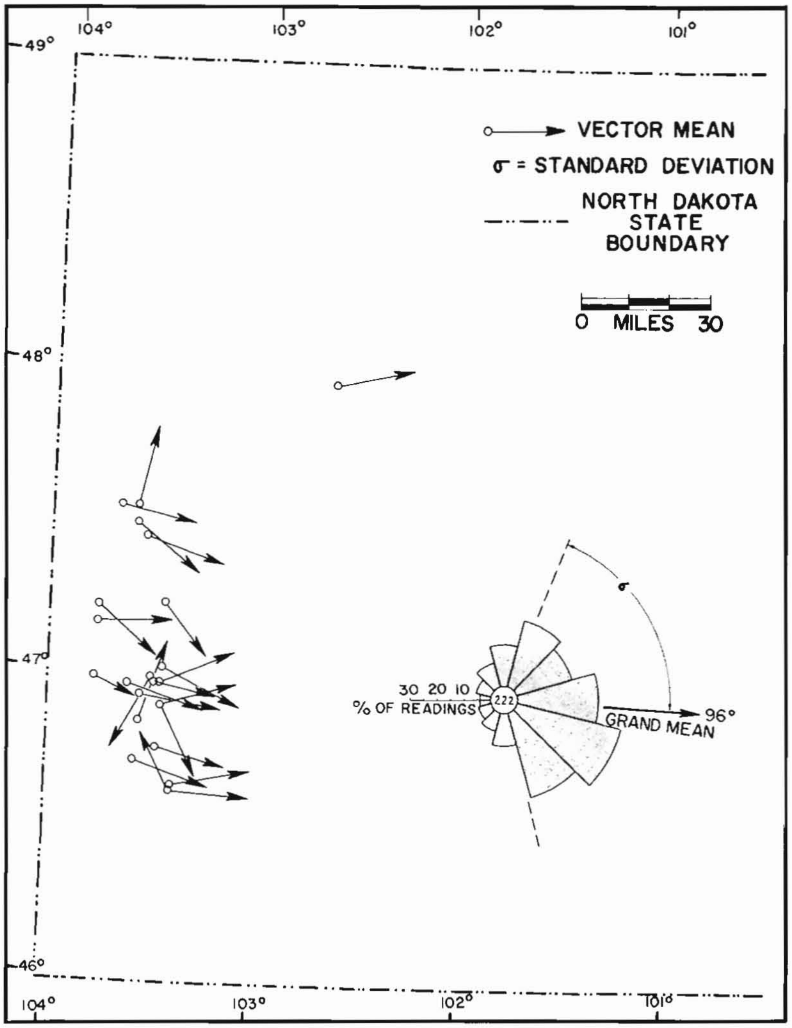


Fig.16. Vector means for cross-bed measurements from outcrops in the Tongue River Formation. Readings are summarized in the rose diagram.

of confidence, the Sentinel Butte is significant only at the 95.0 percentile. Results of orientation tests are summarized in Table VII.

A test for equality of means, using the Student's *t*-test (DIXON and MASSEY, 1957, p.123) indicate that data for the Tongue River Formation differ significantly (97.5% level) from those for the basal and upper sands and for the intervening

---

Fig.15. Sedimentary structures. A. Small nodules of weathered iron sulfide in the Tongue River. B. Boxwork (melikaria) structure in the Sentinel Butte. C. Log-like concretions in Tongue River strata. D. Molds of worm trails on the base of limestone from the Sentinel Butte.

TABLE VI

SUMMARY OF LARGE-SCALE CROSS-BED MEASUREMENTS FROM THE TONGUE RIVER AND SENTINEL BUTTE FORMATIONS

Stratigraphic unit	*Azimuth class*												*Total (n)*	*Grand mean (°)*	*Variance*	*Standard deviation*
	345–15	*15–45*	*45–75*	*75–105*	*105–135*	*135–165*	*165–195*	*195–225*	*225–255*	*255–285*	*285–315*	*315–345*				
Upper sand	7	12	16	19	17	23	11	8	4	–	–	–	117	111	3,835	61.9
Sentinel Butte[1]	3	4	9	7	7	10	9	2	5	2	5	5	68	120	8,285	91.0
Basal sand	12	19	27	55	46	43	23	14	4	3	3	8	257	109	4,176	64.6
Tongue River	16	27	23	33	43	35	13	7	5	4	6	10	222	96	5,136	71.7

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

TABLE VII

SUMMARY OF TEST DATA FOR PREFERRED ORIENTATION OF GRAND MEANS OF LARGE-SCALE CROSS-BED MEASUREMENTS

Stratigraphic unit	*Vector-mean (°)*	$s_u^2/s_o^2 = F$	*Degrees of freedom*	*Significance*
Upper sand	111	2.82	110	0.9995
Sentinel Butte[1]	120	1.50	67	0.950
Basal sand	109	2.59	256	0.9995
Tongue River	96	2.27	221	0.9995

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

TABLE VIII

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[1]	1.99	95	0.975
Tongue River vs. Basal sand	2.06	444	0.975
Tongue River vs. Upper sand	2.00	276	0.975
Sentinel Butte vs. Basal sand	0.94	88	0.800
Sentinel Butte vs. Upper sand	0.73	104	0.700
Basal sand vs. Upper sand	0.29	242	0.600

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

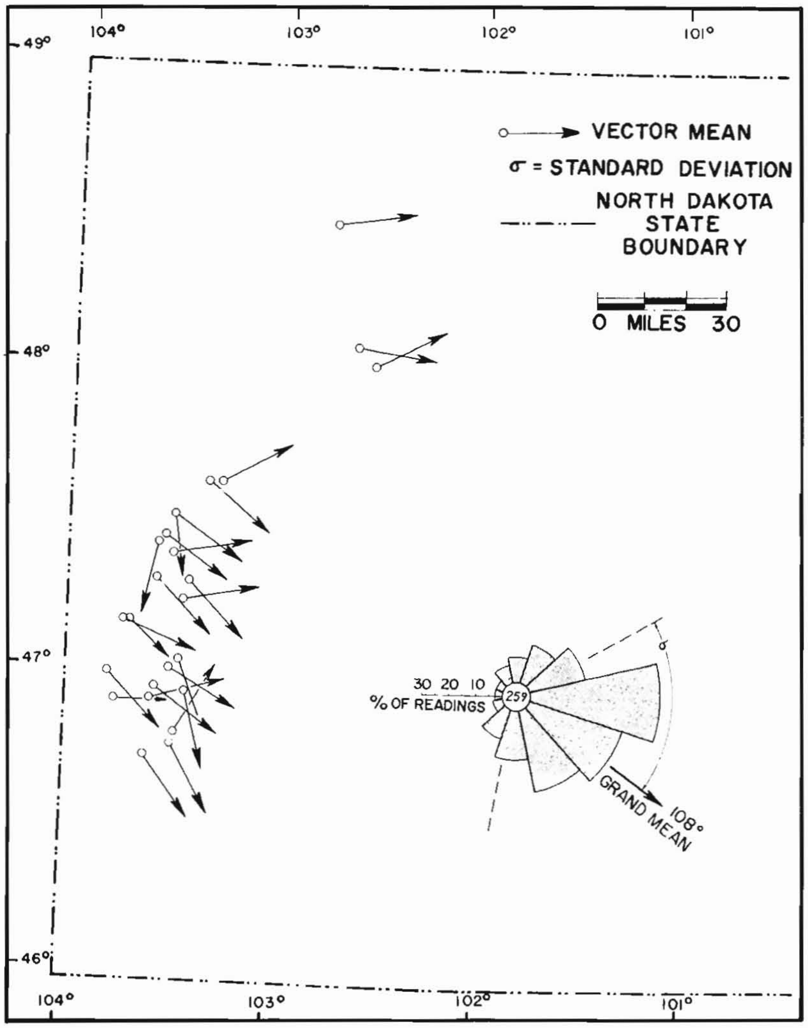


Fig.17. Vector means for cross-bed measurements from outcrops of the basal Sentinel Butte sand. Readings are summarized in the rose diagram.

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 60–80% confidence (Table VIII).

C–M RELATIONSHIPS

Theory and interpretation

PASSEGA (1957, 1964) presented plots of samples from known environments

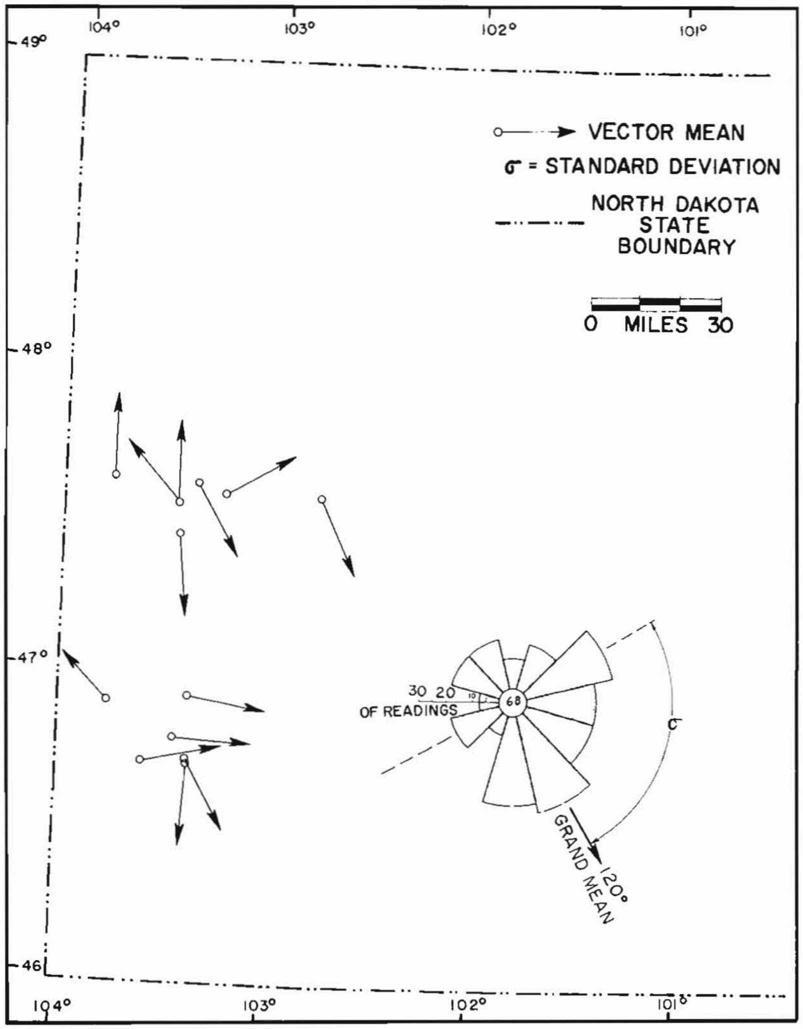


Fig.18. Vector means for cross-bed measurements from outcrops between the basal and upper Sentinel Butte sands. Readings are summarized in the rose diagram.

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 undergoing transport. 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

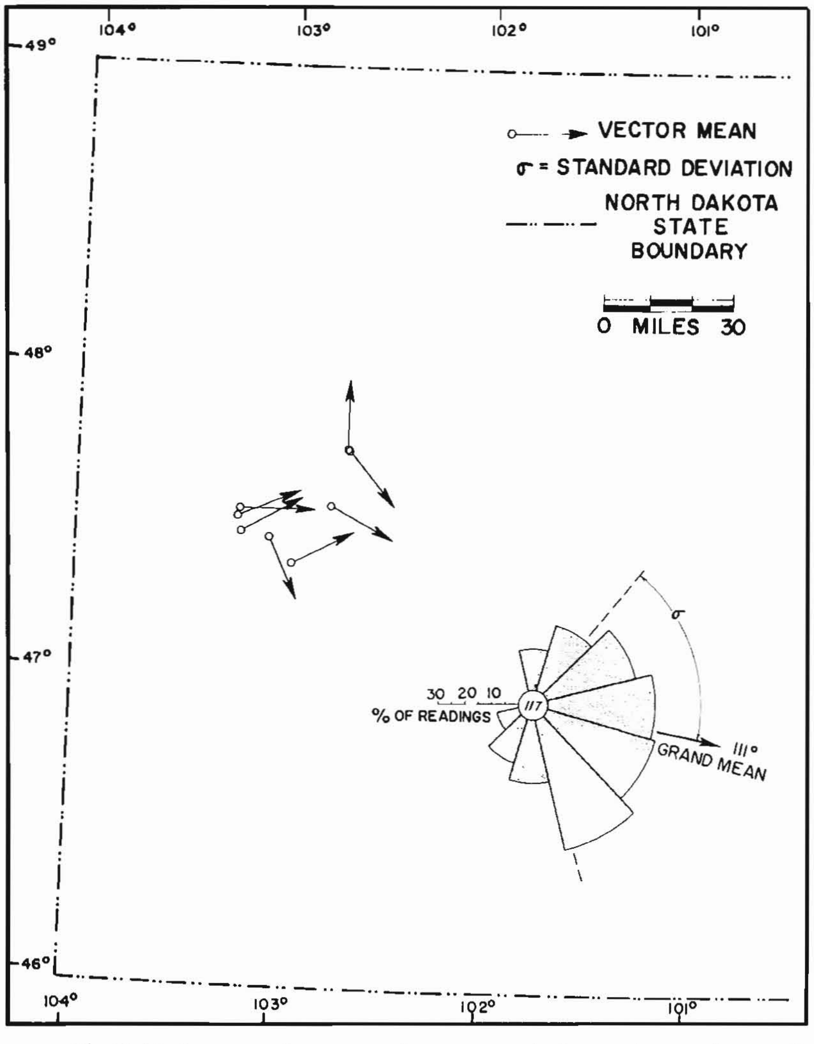


Fig.19. Vector means for cross-bed measurements from outcrops of upper Sentinel Butte sand. Readings are summarized in the rose diagram.

index to the sorting in the coarse half of sediment samples. For the segment of C–M diagrams representing sediments transported as graded suspension, PASSEGA (1964, p.834) has designated this displacement as an index of maximum sorting (Im). Basic types of C–M patterns are shown in Fig.20.

The interpretation of C–M patterns has been well documented by PASSEGA (1957, 1964) and their significance in recognizing depositional products in various fluvial environments was discussed by ROYSE (1968); details need not be reiterated here. Stratigraphic samples from the Tongue River and Sentinel Butte Formations form C–M patterns (Fig.21,22) characteristic of stream-transported materials.

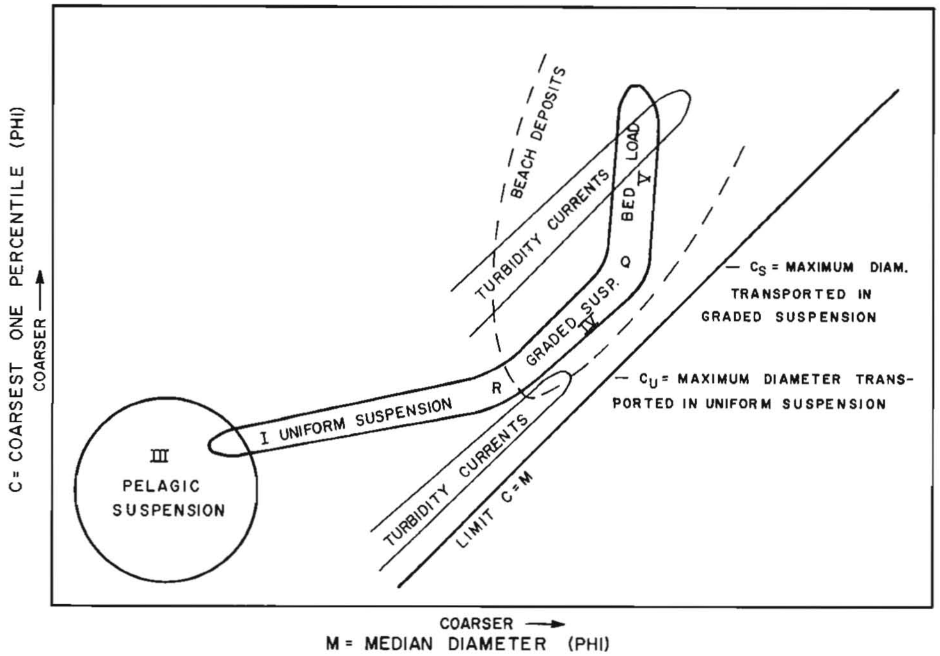


Fig.20. Basic C–M patterns (after PASSEGA, 1957).

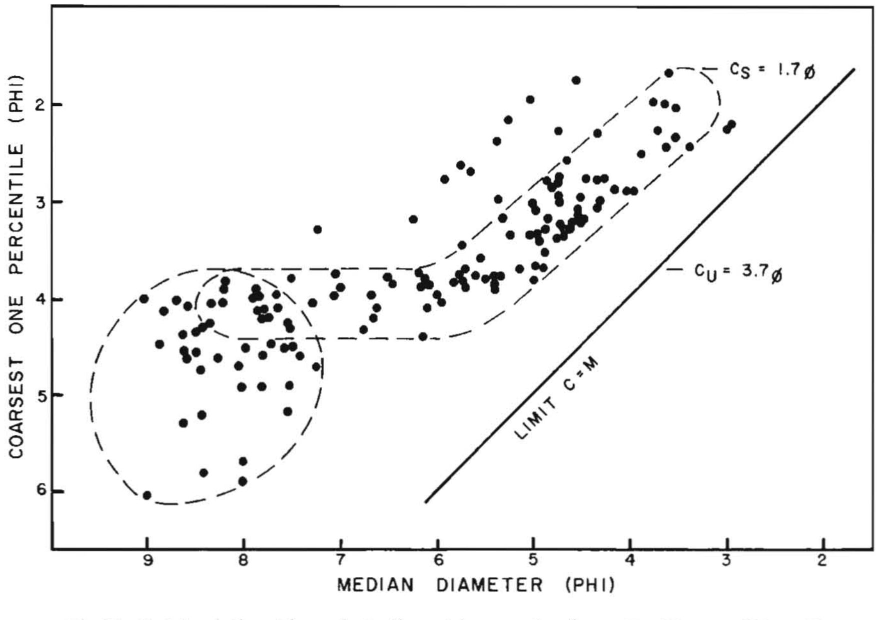


Fig.21. C–M relationships of stratigraphic samples from the Tongue River Formation.

These patterns are composite, and are assumed to represent "average" Tongue River and Sentinel Butte streams. Data are summarized in Table IX.

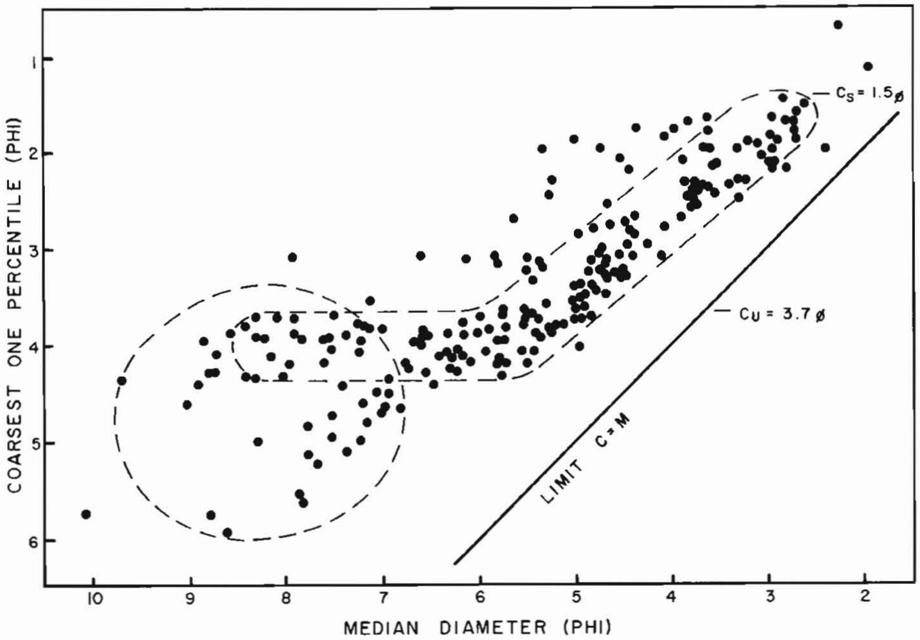


Fig.22. C–M relationships of stratigraphic samples from the Sentinel Butte Formation.

TABLE IX

SUMMARY OF C–M DATA FOR STRATIGRAPHIC SAMPLES FROM THE TONGUE RIVER AND SENTINEL BUTTE FORMATIONS

Station	I_m (φ-*units*)	C_u (φ)	C_s (φ)
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

Classification of fluvial sediments

Previous classifications. Fluvial sediments have been fundamentally differentiated into vertical and lateral accretion deposits (see ALLEN, 1965). These categories are subdivided into classes such as point-bar, channel-fill, natural levee, crevass-splay, channel lag, etc. Such classification is both genetic and descriptive and combines parameters which are morphometric, environmental, and stratigraphic. This nomenclature is not easily applied to ancient sediments for which the morphology and environment of deposition are uncertain. These factors frequently must be inferred from a few measureable physical and chemical properties of sediment samples.

ALLEN (1965, table 3, p.128) broadened the concept of vertical- and lateral-accretion deposits in a classification in which fluvial deposits are grouped into three major and eight subordinate categories. He uses the terms "topstratum" and "substratum" in the context of vertical — and lateral — accretion of previous workers. According to ALLEN (1965, p.127): "Channel or substratum deposits form the lower part of the typical floodplain sequence. Included are point and channel bar deposits and channel lag deposits left after stream bed 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 and topstratum." Although Allen has clearly differentiated the sediments from their environments of deposition and enunciated their relative stratigraphic relationships, his classification is also difficult to apply to sediments for which only sedimentological data are available.

Proposed classification. Recognition of the fluvial origin of Tongue River and Sentinel Butte deposits, as indicated by their C–M patterns, facilitates classification (ROYSE, 1968). Three fundamental sediment types can be defined, two of topstratum and one of substratum origin. These are backswamp, floodplain, and channel deposits and are essentially equivalent to Passega's "pelagic-", uniform-, and graded-suspension transport types[1] (Fig.20). The graphical limits of these depositional classes are determined from the *composite* C–M plots of Fig.21,22. Class envelopes conform in general to the array of the point pattern, but sediment types are gradational and their bounds are, in part, arbitrarily fixed. Plots for *individual* stratigraphic sections of Tongue River and Sentinel Butte strata showed

---

[1] The term "pelagic" literally means "of the open sea" and is a misnomer as applied to fluvial deposits. It is retained here in the sense of PASSEGA (1957) for reference to very-fine suspended sediment.

some "natural" breaks which aided in establishing class limits on the composite plot. As drawn, the class limits approximate a 95% confidence interval. The relationship between sediment texture, mode of transport, and depositional environment inferred from size analysis are indicated in Table X. The primary sedimentary structures most commonly observed in the various classes are included.

TABLE X

RELATIONSHIP BETWEEN SEDIMENT TEXTURE, STRUCTURE, MODE OF TRANSPORT, STRATIGRAPHIC POSITION AND DEPOSITIONAL ENVIRONMENT OF TONGUE RIVER AND SENTINEL BUTTE SEDIMENTS AS INFERRED FROM C–M RELATIONSHIPS AND FIELD OBSERVATIONS

Textural types	*Inferred transport*	*Stratigraphic-environmental relationship*	*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: backswamp, channel-fill (clay-plug)	blocky to laminated

In consideration of the relative abundance of depositional types, points which plot within the area of overlap between uniform and pelagic types are distinguished. The term "transitional" is informally applied to these sediments and should not be confused with ALLEN's (1965) "transitional" origin of "channel-fill" deposits. 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 backswamp deposits and in subsequent discussion they are included with the former.

As indicated in Table XI, 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 backswamp and less transitional and floodplain deposits than does the Sentinel Butte Formation.

The environmental sensitivity of other textural parameters was examined using the depositional criteria established by C–M relationships. Median (and mean) diameter and skewness are markedly affected by depositional environment

TABLE XI

RELATIVE ABUNDANCE OF DEPOSITIONAL TYPES IN STRATIGRAPHIC SAMPLES FROM THE TONGUE RIVER AND SENTINEL BUTTE FORMATIONS

Stratigraphic sections	*Backswamp*	*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

and plots of Folk skewness vs. median diameter show a high degree of inverse correlation. In Fig.23,24, samples are designated according to their depositional type as determined on the C–M diagrams (Fig.21,22). The end-members, which are channel and backswamp deposits, are well separated, but floodplain sediments (including the "transitional" type) overlap the end-members. Much of the overlap is the result of combining data from a number of stratigraphic sections; plots for individual sections give a better separation of the three depositional types.

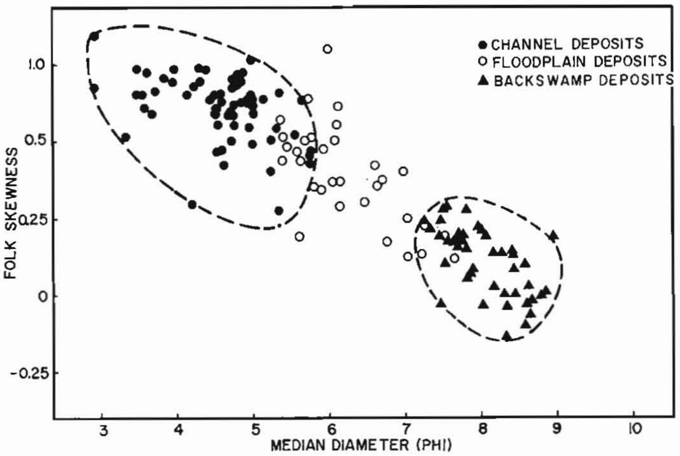


Fig.23. Composite plot of Folk skewness vs. median diameter for stratigraphic samples from the Tongue River Formation.

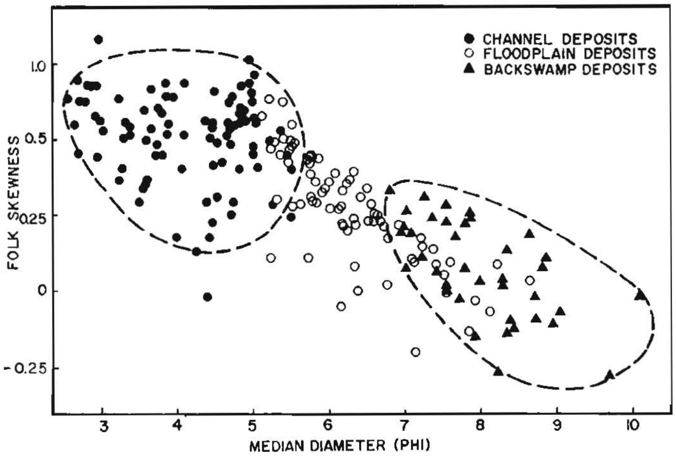


Fig.24. Composite plot of Folk skewness vs. median diameter for stratigraphic samples from the Sentinel Butte Formation.

COMPOSITION OF SEDIMENTS

No detailed mineralogic or petrographic studies of Paleocene units of North Dakota have been reported. Detailed petrographic considerations are outside the scope of this report and only the most pronounced lithologic relationships of Tongue River and Sentinel Butte lithologies will be established to facilitate paleogeographic and fluvial reconstruction.

Lignite

Lignite beds are thin, lack great lateral persistence, have high moisture and ash contents and contain large quantities of sulfate impurities. Their relationship to the fluvial sequence is documented by their proximity to beds of demonstrable fluvial origin. Fossils are rare in lignites, but shell-fragment deposits of freshwater mollusks were noted at the base of some thin beds and fossil bone was recovered from arenaceous lignite at one locality. With the exception of the HT Butte bed (previously discussed), outcrops are not sufficient to establish the areal attributes of lignite units.

Lignite beds are both more abundant and better developed in Tongue River than in Sentinel Butte strata. Tongue River strata contain the greatest number of thick lignites (Fig.4) 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). Due to regional dip, none of the major Tongue River lignites below the Garner Creek bed crop out in the Little Missouri badlands north of Medora (Fig.3), and the formation is less lignitic north of this area.

In the southern half of the study area (the Sentinel Butte and Marmarth lignite fields) the Sentinel Butte Formation contains few lignite beds greater than

3 ft. thick. A significant exception is the Bullion Butte lignite (Fig.4) named by HARES (1928, p.47). The writer correlates the Bullion Butte bed with the upper lignite of LEONARD and SMITH (1909, pl.2) at Sentinel Butte. Lignite beds in the Sentinel Butte appear to become more numerous northward but do not attain great thickness. It may be recalled that the total Sentinel Butte interval also thickens northward, being nearly twice as thick in the vicinity of the Long Cross and Lost Bridge sections as at Bullion Butte (Fig.3). ROYSE (1967b) has supported his generalizations regarding lignite abundances with local observations reported by HARES (1928), FISHER (1953), HANSON (1955) and others. The conclusion appears justified that, although both Tongue River and Sentinel Butte strata are lignitic, thicker and more persistent lignites occur in the Tongue River Formation.

Limestone

Argillaceous, dolomitic limestones occur as pods, lenses, lentils, and discontinuous beds in the Tongue River Formation. They are usually micritic, slate gray on a fresh surface, weather buff or yellow brown, break with a conchoidal fracture or part along bedding planes and occasionally show cross-lamination and minor disruption. They are sparingly fossiliferous, containing fragments of aquatic plant debris and, rarely, enclose broad-leaf floras introduced from adjacent areas. Invertebrate fossils are rare, but molds of mollusks are occasionally found. With the exception of broad-leaves, preservation of fossils is poor. No micro-organisms have been observed in thin sections studied.

Differential compaction, particularly in the smaller pods and lentils, causes the limestones to part the bedding planes of the enclosing sediment, a phenomenon which has apparently caused some workers to regard them as secondary features. The primary origin of Tongue River limestones is supported by evidence of primary sedimentary structures, textures, and indigenous fossils.

It is desirable to substantiate that freshwater limestone is more abundant in Tongue River than Sentinel Butte deposits. Documentation is made difficult because of the failure of many workers to distinguish clearly between "limestones" and "carbonate concretions", and by the failure of others to mention limestone at all. Support is offered, however, by HARES (1928, p.31) who noted thin lenses of dense, compact limestone at several horizons in the lower 400 ft. of the Tongue River Formation and considered them a distinctive lithology 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". In his study at Bullion Butte, CRAWFORD (1967, p.30) reported that "limestone... is found in lenses or pods throughout the lower member [Tongue River Formation] (Fig.8), but was not observed in the Sentinel Butte Member".

Mineralogy

With the exception of DENSON and GILL (1965a) and SATO and DENSON

(1967), previous petrographic studies of Fort Union strata are of limited scope and only their general conclusions merit consideration here. SIGSBY (1966) and CRAWFORD (1967) agreed with TISDALE's (1941) conclusion that the Fort Union heavy mineral suite is characterized by metamorphic species from a relatively near source; possibly the Black Hills.

SATO and DENSON (1967, fig.5) report volcanic minerals such as augite and hypersthene; greenish-brown, reddish-brown, and blue-green hornblende are extremely rare in Fort Union sediments. They concluded (p.55) that: "In most areas, such as the Bison Basin of central Wyoming, the Powder River Basin of eastern Wyoming, or the Williston basin in western North and South Dakota, fossiliferous rocks assigned to the Fort Union Formation were derived largely from the weathering of pre-existing sediments."

On the basis of a few analyses, the writer agrees with this conclusion. A basic conclusion of the data reviewed is that the heavy mineral component of Tongue River and Sentinel Butte sediments is small and the metamorphic minerals within this component are probably residual. The failure of most workers to present complete data on weight and number percentages makes quantitative comparison of their results difficult, but ROYSE (1967b) has qualitatively evaluated them.

Many of the Tongue River sandstones are protoquartzitic and feldspathic; Sentinel Butte sandstones tend toward a lithic graywacke and feldspathic graywacke composition (PETTIJOHN, 1957, p.291). A significant attribute of the Sentinel Butte is its greater abundance of thick silty clay beds, of which the "blue" bed (Fig.4) is an excellent example. Such beds are highly montmorillonitic, contain glass shards, and have been interpreted as devitrified volcanic ash. Similar strata are much less common in Tongue River deposits. These data indicate, at least qualitatively, that the Tongue River is mineralogically more mature than the Sentinel Butte.

Carbonate content

Total reactive (acid soluble) carbonate content, measured by the rapid titrametric method of HERRIN et al. (1958), in stratigraphic samples from the Tongue River and Sentinel Butte Formations is reported as per cent weight CO_3 in Fig.25; data for individual sections are given in Table XII.

Measured values of CO_3 range between 0 and 41% in Tongue River and between 0 and 32% in Sentinel Butte sediments (0–68 and 53% respectively computed as $CaCO_3$). The distribution of values for both formations are unimodal, but Tongue River samples have a broad, rather uniform distribution whereas nearly 85% of the Sentinel Butte samples contain less then 10% CO_3.

The distribution of CO_3 values as a function of median grain size is shown in Fig.26,27. Sentinel Butte samples with median diameters coarser than about 7 phi show a weak positive correlation with carbonate content, mean values greater then 7 phi show a marked decrease in carbonate content. The same trend

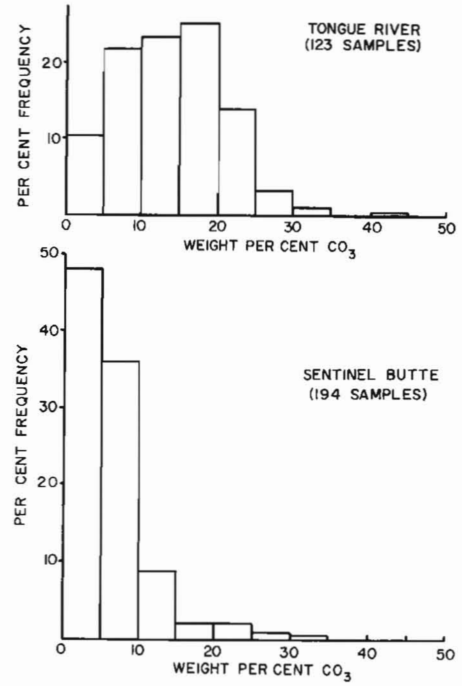


Fig.25. Distribution of CO_3 in stratigraphic samples from the Tongue River and Sentinel Butte Formations.

TABLE XII

AVERAGE CARBONATE VALUES FOR STRATIGRAPHIC SAMPLES FROM TONGUE RIVER AND SENTINEL BUTTE SECTIONS (NIL MEASUREMENTS 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

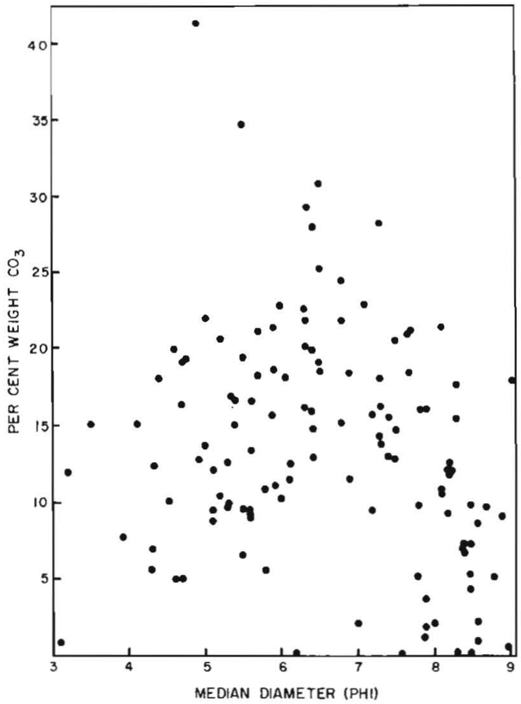


Fig.26. Plot of carbonate vs. median diameter for stratigraphic samples from the Tongue River Formation.

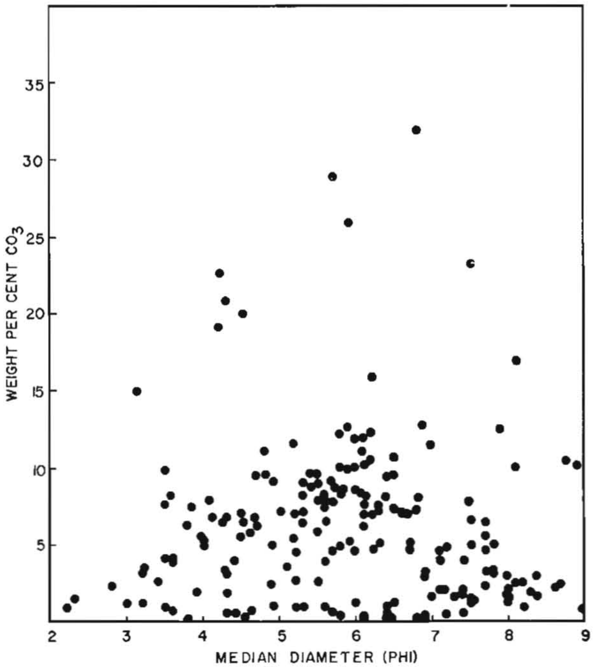


Fig.27. Plot of carbonate vs. median diameter for statigraphic samples from the Sentine Butte Formation.

is apparent in the Tongue River distribution, but the function is spread over a greater range of CO_3 values. Carbonate values from the Sentinel Butte are generally small and plotted values greater than 20% are all from the stratigraphic section at Sentinel Butte (Fig.3) and may reflect a local environment of high carbonate deposition.

Fossil components

Elements of the fauna and flora of the Tongue River–Sentinel Butte interval are treated here as sediment components. The megascopic assemblage 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 pelecypods and gastropods. The freshwater and terrestrial habit of the fauna has been established by YEN (1946, 1947), TOZER (1956), and TAYLOR (1969). Taxonomic revisions by Tozer and Taylor are particularly significant in interpretation of ecologic relationships. It is adequate to state here that the fauna implies that the enclosing rocks are of fluvial and lacustrine origin.

Although it is not always possible to judge, most fossils are indigenous to the enclosing sediment and indications of transport prior to deposition are minor. Coquina-like beds are occasionally 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 also found as isolated clusters of well preserved individuals in sand bodies. Bivalves are the most common component of such assemblages and are usually "entire" with both valves present and closed. Shell-hash layers are also found but, although not rare, are actually less frequent 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 are complicated by selective preservation. Greater numbers of fossils apparently 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.

The conclusion that invertebrate fossils are more abundant in Tongue River than in Sentinel Butte strata is supported by CRAWFORD (1967) who reported seven fossil localities in his Tongue River section 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 interesting to note that the lower "yellow" bed (Fig.4), which as previously noted resembles Tongue River strata, was reported by Clark as the most fossiliferous unit in the 570 ft. 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, pp.37–40) presented an extensive faunal list for the Tongue River Formation composed from fourteen collecting localities. In contrast, mollusks were reported from only one locality in the Sentinel Butte Formation.

It seems justifiable to conclude 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.

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 6–8 ft. above and below their contact at 52 localities. 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 (ROYSE, 1967a) but the bed has additional significance because it records the first impulse of the change 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 unique features, the basal Sentinel Butte sand aids in interpreting data for the rest of the stratigraphic interval under investigation. For this reason it is described separately in this section.

C–M relationships

Fig.28 shows the C–M pattern formed by samples of basal sand. Transport types representing backswamp and fine-grained floodplain deposits are absent from the pattern, and the sediments are considered to be largely the product of substratum deposition (Table X). This interpretation is consistent with the presence of large-scale primary sedimentary structures within the unit (Fig.14A).

The range of values of C are roughly the same as for stratigraphic samples (Table IX), but the value of C_s is slightly coarser. 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.

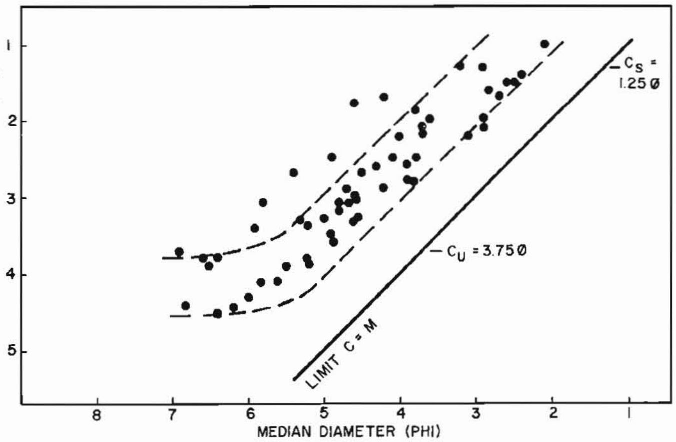


Fig.28. C-M pattern for basal Sentinel Butte sand samples.

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 Fig.29. The distributions are similar, but the mean values tend to be finer than those for the median. Comparison with data for stratigraphic samples (Fig.5) 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.

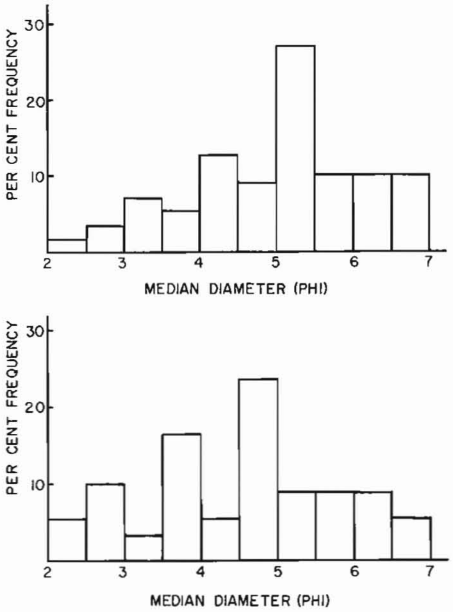


Fig.29. Distribution of Folk mean and median diameters in basal Sentinel Butte sand samples.

These samples have been defined (Fig.22) as having been transported in "pelagic" suspension and are interpreted as backswamp deposits; the distributions of mean and median values reflect the absence of this genetic type.

The distribution of sorting coefficients (mean value 1.69 phi-units) for the basal sand (Fig.30) is similar to that of stratigraphic samples (Fig.7). Comparison of Tables II and XIII shows that the major difference between the two lies in the greater percentage of poorly and very-poorly sorted, and an absence of moderately-poorly and moderately sorted samples in the basal Sentinel Butte sand.

Folk skewness values (mean value 0.52) for basal sand samples are all positive (Fig.31) and are dominantly very-fine skewed. The frequency distribution is markedly different from that of stratigraphic samples (Fig.8), the latter having

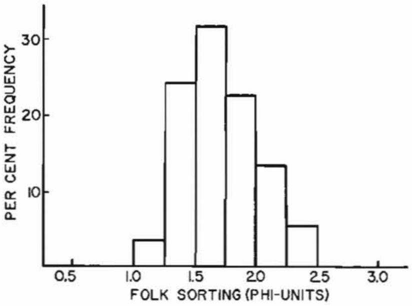


Fig.30. Distribution of sorting coefficients in the basal Sentinel Butte sand.

TABLE XIII

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

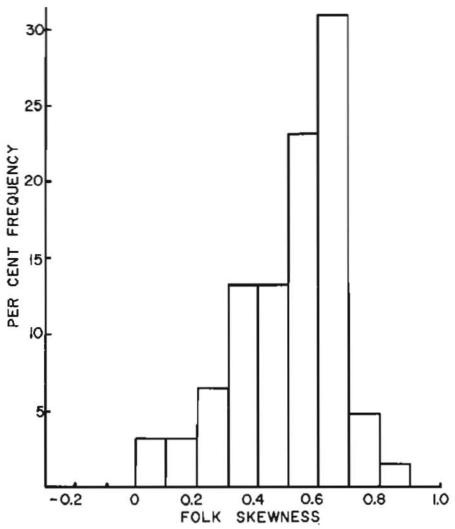


Fig.31. Distribution of Folk skewness values in samples of basal Sentinel Butte sand.

a relatively greater percentage of samples with a low degree of skewness. These samples are backswamp deposits (Fig.24), and their absence in the basal sand was noted above in the interpretation of C–M relationships. The range of skewness values, their inverse correlation with median diameter (coefficient — 0.75), and the absence of backswamp deposits are shown in Fig.32.

Kurtosis values for the basal sand (mean 1.44) have a distribution similar to that of stratigraphic samples, but the basal sand contains a greater percentage of leptokurtic and very-leptokurtic samples (81% compared to 64%; Table IV, XIII). Again it appears that the mesokurtic and platykurtic samples found in stratigraphic

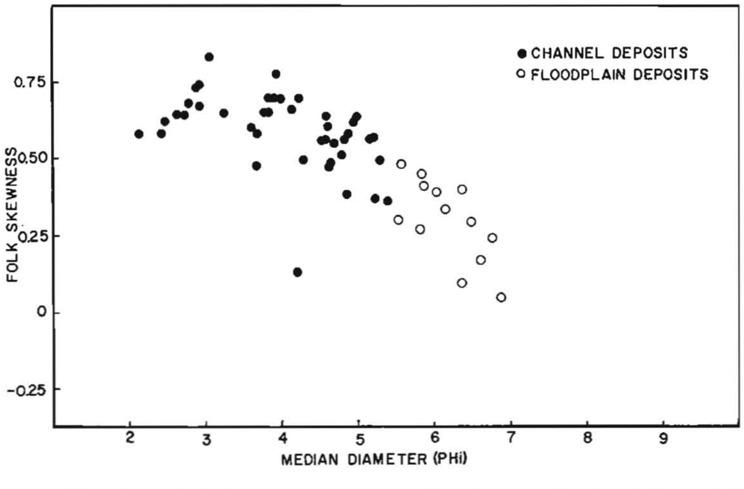


Fig.32. Plot of Folk skewness vs. median diameter for basal Sentinel Butte sand samples.

samples represent backswamp deposits, a sediment type 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 Fig.33. The absence of silty-clay and the paucity of clayey-silt sediment types, which are present in stratigraphic samples of the Sentinel Butte Formation (Fig.11), reflects the absence of fine-grained topstratum (backswamp) deposits in the basal Sentinel Butte bed. Also, comparison with Fig.10 and Fig.11 indicates that samples plotting between the sand and silt limits of the triangular diagrams are largely products of graded-suspension transport; the significance of this interpretation was discussed by ROYSE (1968).

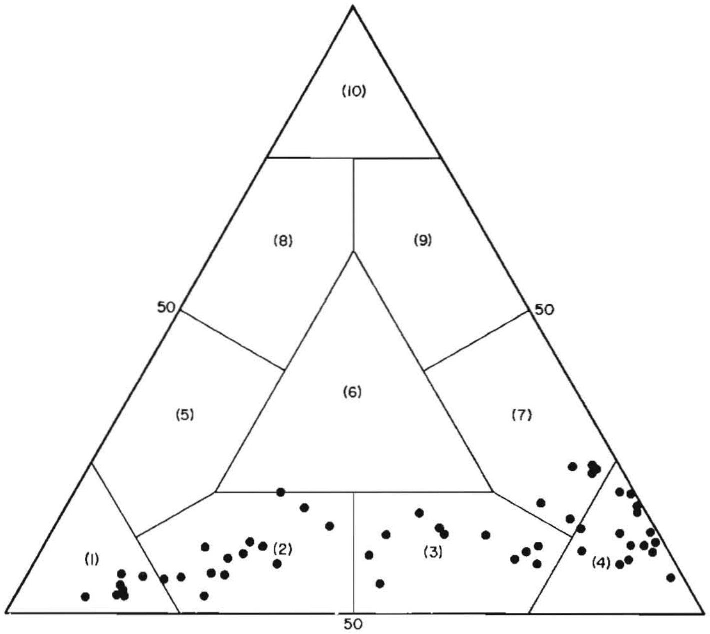


Fig.33. Sand – silt – clay relationships of samples from the basal Sentinel Butte sand (textural classes are the same as defined in Fig.10).

Carbonate content

Total reactive carbonate (HERRIN et al., 1958) was determined for all basal Sentinel Butte sand samples. These data are compared with those for samples collected 6–8 ft. below the contact (at the same localities) in Fig.34.

Basal sand samples have a narrow range of CO_3 values with a mean of 5.51% and a standard deviation of 2.18; uppermost Tongue River samples have a much broader range of values with a mean of 11.0%. The data for the two horizons are comparable to those of stratigraphic samples from the two formations (Fig.25) and

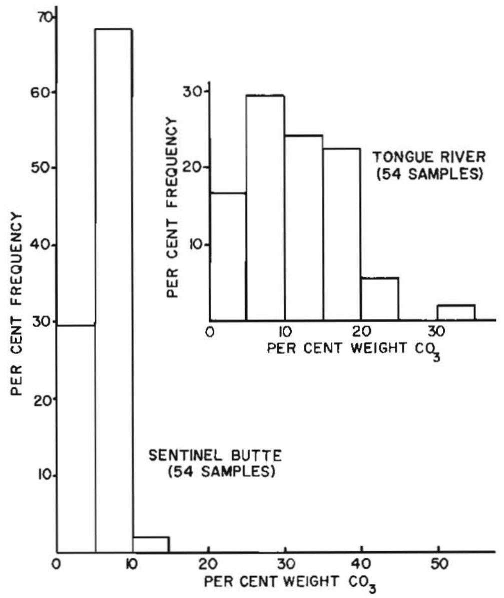


Fig.34. Distribution of CO_3 in samples above and below the Tongue River–Sentinel Butte contact.

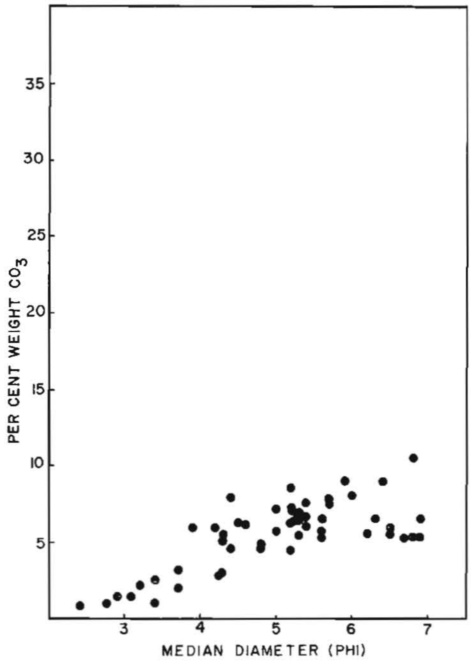


Fig.35. Plot of weight pei cent CO_3 vs. median diameter for basal Sentinel Butte sand samples.

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 (Fig.35) 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 (Fig.26, 27) with median diameters coarser than 7 phi and tends to confirm that two relationships exist between grain size and carbonate content in Tongue River and Sentinel Butte sediments. The median grain size of channel and floodplain deposits (coarser than 7 phi) is inversely proportional to carbonate content, and backswamp deposits (finer than 7 phi) contain only minor amounts of carbonate. The marked decrease in the carbonate component of stratigraphic samples finer than about 7 phi independently supports the selection of this size as a boundary between floodplain and backswamp sediment types in the C–M diagram of Fig.22.

Regional trends

The basal Sentinel Butte sand is the only persistent clastic unit recognized throughout the area of investigation, and thus provides the only data for which regional sedimentary trends can be determined. These samples are too few for accurate paleogeographic reconstruction, but they provide a fair approximation of the gross distribution of sedimentary components. The sampling distribution was smoothed by averaging data for samples (three or fewer) within a single township and shifting averages to the northwest corner of the grid. The number of data points was thus reduced from 54 to 35. This procedure tends to mask local variability, but regional trends, if present, should be accentuated.

Maps showing the areal distribution of per cent sand, mean particle size, and per cent total carbonate were constructed (ROYSE, 1967b, fig.46–48). Contour patterns of high and low sand content suggest areas of fluves and interfluves, but a regional trend of greater per cent sand in the north and low per cent sand in the west of the study area were evident. The distribution of mean particle size complimented the per-cent-sand map.

The per cent total reactive carbonate in basal sand samples was found to be highest in the west and south, and to decrease northeastward. Comparison with distributions of per cent sand and mean diameters showed that finer-grained sediments in the west and south contain greater percentages of carbonate; a regional manifestation of the relationship established in Fig.35.

The combined regional relationships of per cent sand, mud, and total carbonate are indicated in the facies map of Fig.36. Despite the patchiness of the various facies, the trends discussed above are apparent.

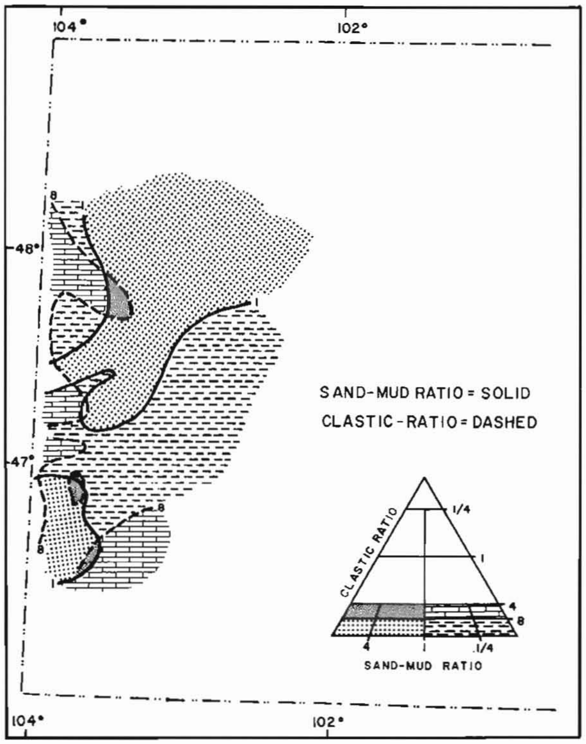


Fig.36. Triangular facies map of the basal Sentinel Butte sand on a horizon 6 ft. above the Tongue River–Sentinel Butte contact in western North Dakota.

DISCUSSION AND INTERPRETATIONS

Paleostreams and their deposits

Paleostream velocities. Values of C_s (Fig.21,22) can be used with empirical curves (see SUNDBORG, 1956, pp.177 and 218) to estimate minimum competent paleocurrent velocity. Such estimates are strictly valid only for materials of uniform texture. JOPLING (1966, pp.6–12) has comprehensively evaluated the subject of paleoflow reconstruction. He noted that the competency diagrams currently in use indicate that variation in competent velocity with particle size is small within the range of sand-sized material, and that the median grain size of a "not-too-poorly sorted" mix may be used in extrapolating competent velocity. For poorly sorted mixes, he recommends an arbitrary increase in competent velocity of about 20%.

Only the coarsest of the Tongue River and Sentinel Butte sediments represent channel facies and these are dominantly poorly sorted and extremely-fine skewed. Values of median diameter and C_s for coarse samples have corresponding flow velocities which differ by only about 2%, suggesting that the choice of a representative size in this instance is not critical. Average values of C_s for Tongue River and Sentinel Butte samples (Table IX) are nearly the same, 2.32 phi (0.20 mm) and 1.85 phi (0.28 mm), respectively, and correspond to stream velocities 1 m above the bed (SUNDBORG, 1956, p.177) of about 38–40 cm/sec. The corresponding velocity 10 m above the bottom (which may better approximate the mean stream velocity) is about 45–47 cm/sec. Applying JOPLING's (1966) empirical correction of 20%, to account for the poor sorting of sediments, increases these velocities to about 47 and 55 cm/sec, respectively.

C–M patterns indicate that no sediment in the Tongue River–Sentinel Butte interval was transported exclusively as bed load; that is, all particle sizes present were transported in uniform or graded suspension. As discussed by JOPLING (1966, pp.9–10), both empirical and theoretical data indicate that appreciable suspension transport becomes moderately well developed at velocities 2–2.5 times the competent velocity. Assuming that Tongue River and Sentinel Butte streams transported significant quantities of suspended sediment (which appears probable), the velocities cited above for transport 10 m above the bottom can be increased to about 94–118 and 110–138 cm/sec. The assumption of large suspension loads is corroborated by the predominant occurrence of kappa-cross-stratification, which forms only under conditions of high suspended-sediment concentration (ALLEN, 1963b, p.107), in Tongue River and Sentinel Butte strata and by the paucity of erosional features.

These values are probably representative of flow velocities of Paleocene streams which coursed eastward across western North Dakota, but they can be accepted only as approximations. The fine size of Tongue River and Sentinel Butte sediments is a limiting factor in determining the relative difference in velocities of streams which deposited them. Both have C_s diameters which intercept the critical velocity curve near its point of inflection, where the slope of the curve is very low, and the interpolated velocities 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.

Most coarse sediment is transported and deposited by streams during flood stage, 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 cm/sec 1 m above the bottom and about 183 cm/sec 10 m above the bottom near Mayersville, Mississippi (PASSEGA, 1957, fig.3). By comparison the Paleocene streams in western North Dakota must have been somewhat 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 2.75–2.3 phi (0.15–0.20 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 easy transport 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 exclusively as bed load, again suggesting that most Tongue River and Sentinel Butte deposits are products of suspension transport.

In a discussion on sediment sorting and fluid mechanics, INMAN (1949) demonstrated that progressive sorting in a fluvial system yields a symmetrical size distribution with a mean diameter near 2.5 phi (0.18 mm) at a point where the friction velocity fluctuates between fine and coarse sand. Farther downstream, where the friction velocity is near (but not exceeding) that for fine sand, bottom material is transported primarily by creep and sediments have median diameters finer than 2.5 phi, are less well sorted than those immediately upstream, and are markedly fine-skewed. These characteristics are cited (INMAN, 1949, fig.4D) as typical of samples from the Mississippi River at "mile 1057 below Cairo, Illinois" (downstream from New Orleans). Samples of channel facies from the Tongue River Formation are predominantly strongly-fine skewed and have median diameters finer than 2.5 phi. Sentinel Butte samples show a comparable range of skewness but have slightly coarser median values. In comparison with the Mississippi River, 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 facies classification (Table X) is useful in explaining the distribution of textural measures previously presented. The distributions of mean, median, skewness (Fig.6, 8) are environmentally sensitive and their bimodality in Tongue River sediments reflects the relative abundance of facies types (Table XI). The modal classes correspond to channel and backswamp deposits and the intervening range of lower frequency corresponds to the less abundant floodplain and transitional classes. Textural measures for Sentinel Butte samples (Fig.5, 8) are more uniformly distributed and reflect a more equal distribution of depositional types within this unit (Table XI). 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.

Fluvial deposits are heterogeneous, but collectively they form a depositional continuum from the stream channel to the backswamp. The transitional character of C–M patterns (Fig.21,22) permits recognition of only three basic depositional types; additional information on the morphology of strata might aid in refining these general classes. 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 reference only to channel-proximal deposits. Although the classification utilized in this study is general, it does aid in reconstruction of Tongue River and Sentinel Butte fluvial regimes.

Table XI indicates that channel-type deposits compose nearly 50% of the samples analyzed from both the Tongue River and Sentinel Butte Formations, but backswamp deposits are more abundant in Tongue River strata. These data indicate that backswamp 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 backswamp development is channel stability; 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 composed largely of channel and backswamp facies. Stream channels achieve stability when marginal "clay plugs" and other fine-grained deposits, which are resistent to erosion, restrict lateral channel migration. This condition is approached slowly during stream evolution and, because it is a limiting condition, is indicative of a mature fluvial regime. The lower Mississippi River, where it approaches its deltaic plain, is an example of the mature system suggested; the effects of fine-grained sediments on the control of channel activity have been discussed by FISK (1947). The greater proportion of floodplain (relative to backswamp) deposits in the Sentinel Butte sequence suggests the depositing streams were 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 backswamp deposits are a minor facies component. The relative abundance of thick and persistent lignite beds in the Tongue River sequence document the stability of the 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 backswamp areas by coarser material.

A near-terminal fluvial environment of deposition for Tongue River sediments is also suggested by the abundance of backswamp deposits in the sequence. Backswamps generally increase in area and thickness, relative to levees and channels, in a downstream direction. For example, FISK (1947, pp.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 their areas increase at the expense of channel and levee deposits (FISK, 1947, fig.7). Near Donaldsonville, Louisiana, fine-grained, backswamp alluvium constitutes more than 25% of the bank material at eroded river-bend positions. South of Donaldsonville, backswamp deposits are replaced by deltaic-plain deposits. A similar distribution of backswamp deposits has been shown by ANDERSON

(1961, in ALLEN, 1965, p.124) for the Rufiji River alluvial valley, Tanganyika. The thickness of Mississippi backswamp deposits also increases downstream, although considerable local variations occur. By analogy, the relative abundance of Tongue River sediment facies is similar to that of the lower reaches of the Mississippi alluvial valley.

Carbonate content. Carbonate occurs, both as cement and as dolomitic limestones, in much greater abundance in Tongue River sediments than in those of the Sentinel Butte sequence (Fig.25, 34). Within the facies recognized, carbonate cement is most abundant in Tongue River floodplain silts (about 4.5–7.5 phi; Fig.26). Low carbonate content of fine-grained (finer than about 7.5 phi) backswamp sediments indicates that penecontemporaneous carbonate was not formed extensively in this environment.

Carbonate in fluvial deposits may originate in several ways. In dry regions, downward movement of the water table coupled with high evaporation rates may result in the formation of "calcretes" and "ferrocretes" such as observed in deposits of the Brazos River, Texas (BERNARD and MAJOR, 1963, p.360) and in alluvial sediments of the Sacramento valley of California (LORENS and THRONSON, 1955, p.180). ALLEN (1964, p.180) has interpreted abundant carbonate "race" as indirect evidence of subaerial exposure during deposition of vertical accretion deposits of the Dittonian cyclothem (Lower Devonian) in Gloucestershire, Great Britain. It is suggested here that interstitial carbonate was formed in Tongue River sediments by saturation 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 western North Dakota was a major lowland during Paleocene time, and such lowlands are universally areas of goundwater 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. Evaporation need not have been (and probably was not) exceedingly great to facilitate such emplacement.

A correlation of increasing carbonate content with decrease in grain size of floodplain sediments might be expected from the penecontemporaneous mechanism of carbonate deposition suggested above. A weak correlation of this type was noted in Fig.26, 27 for sediments coarser than about 7 phi. The high degree of scatter of plotted points may indicate 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 Sentinel Butte sand samples which may be assumed to represent a nearly isochronous surface of deposition. These channel and floodplain samples (Fig.35) show a strong inverse correlation between carbonate concentration and sediment size. Interpreted in terms of primary carbonate deposition, the inverse relationship suggests that finer sediments far from active channels (excluding backswamp deposits) were the most favorable host for carbonate accumulation. 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 Paleocene Series by post-depositional processes cannot be discounted, distributions of Fig.26 and 27 indicate 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 stability of Tongue River streams and the slow rate of topstratum deposition allowed more time for carbonate accumulation. The somewhat 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 (Fig.4). These units are notably high in carbonate, resemble Tongue River strata in texture and appear to represent a brief return to "Tongue River conditions".

Primary sedimentary structures. Both the type and relative abundance of sedimentary structures are useful in paleoenvironmental reconstruction. In this regard it is significant that small-scale structures predominate over large-scale structures in both Tongue River and Sentinel Butte strata, and that the latter (xi- and omikron-cross-stratification) are most frequent in Tongue River strata. The origin of xi-cross-stratification is not clear, but postulated origins (backshore-beach and longitudinal-dune deposits) have been reviewed by ALLEN (1963b). A fluvial origin in Tongue River strata has been demonstrated and the structure is presumed to be related to point-bar deposition. Occurrences of this structure in modern fluvial deposits are not known by this writer to have been reported.

Omikron-cross-stratification, according to ALLEN (1963a, 1963b, p.110), is most probably the product of migration of large-scale asymmetrical ripples with essentially straight crests. The criterion for sediment supply (ALLEN, 1963a) is that, in advancing its own length, each ripple must receive a volume of sediment less than the volume of the ripple body. Thus ripples must undergo erosion on their stoss side, giving rise to an erosional surface between sets. The greater abundance of omikron-cross-stratification in Sentinel Butte strata suggests that the erosional energies of those streams were greater than ones which deposited Tongue River sediments.

Small-scale cross-stratification is found in both formations, and consists predominantly of kappa and lambda types (Fig.13A,B). The origin of each has been considered by ALLEN (1963b) who demonstrated (1963a) that both types 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 added to on both the lee- and stoss-sides. Formation of these structures would require (periodic) large suspended-sediment loads and low, uniform flow velocities. Such structures are common in Tongue River and Sentinel Butte topstratum deposits; they were probably also produced in shoal areas of major channels.

Nu-cross-stratification (Fig.13C) is also formed by the migration of small-scale linguoid ripples (HAMBLIN, 1961) but 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 (ALLEN, 1963a). 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. The predominance of kappa- and lambda-cross-stratification types over nu-cross-stratification suggests that Tongue River streams transported much 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 Tongue River or Sentinel Butte strata.

The structures discussed above are all products of the lower (tranquil) flow regime. Flat-bedded sandstones (Fig.12A) are the only deposits that might be suspected of plane-bed formation during transition between lower and upper 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 depths. The greater abundance of large-scale structures in Tongue River strata (Table X) 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 40–60 ft. thick (FISK, 1944, 1947) and deposits up to 55 ft. thick are recorded from the Brazos River (BERNARD and MAJOR, 1963). Thick sand and coarse-silt beds, portions of which are conspicuously cross-bedded, are locally prominent in the Tongue River sequence. They attain thicknesses, as at Wind Canyon (near Medora), in excess of 100 ft. Similar bodies, with the exception of the "upper" and "basal" 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 ranges from approximately 10 to 20% of the water depth (ALLEN, 1965, p.110). Individual sets of large structures in the Tongue River Formation have maximum exposed thicknesses averaging about 2 ft.; true maximum thickness should be greater. Thus, if at least a portion of the structures studied represent bed forms, minimum water depths of 10–20 ft. 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.

Basin analysis

Directional measurements of large-scale cross-stratification indicate that, during Tongue River time, sediments entered the Williston Basin from the west (Fig.16) and were dispersed uniformly in an eastward direction. Sentinel Butte deposition was initiated by an influx of sandy material from the northwest (Fig.17) which spread southward and eastward across the basin. This trend of dispersal was apparently maintained during the ensuing Sentinel Butte episode (Fig.18). The dispersal pattern was modified near the close of Sentinel Butte time by an influx of upper Sentinel Butte sand (Fig.19) 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 VIII).

The vectoral data of Fig.16–19 are not entirely adequate for defining 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 of South Dakota (TISDALE, 1941; and others) and the Big Horn Mountains of north-central Wyoming as probable source areas.

The degree of variability of cross-bedding may be (qualitatively) useful in making inferences about stream morphology, stream gradient, paleoslope, and tectonic stability. Directional data presented for the Tongue River and Sentinel Butte Formations are integrated over a large area and a thick stratigraphic interval and should reflect the complexity of the regional drainage net and the paleoslope. During tectonically quiescent periods, the regional slope should be maintained, the current flow pattern remain stable and directional data show a relatively low variance. Tectonic pulsations which disrupt or alter drainage should cause increased current-vector deviation.

A qualitative appraisal of cross-bed data and depositional environments (POTTER and PETTIJOHN, 1963, p.88) indicates that the most common variance of fluvial-deltaic deposits is in the range of 4,000–6,000 (standard deviations between 63°–78°). Marine samples tend to have higher deviations, commonly between 6,000–8,000 (standard deviations between 78°–89°). Standard deviations of directional data from the basal and upper Sentinel Butte sands (65° and 62°; Table VI) are thus within the predicted range for fluvial deposits. The standard deviation for the Tongue River interval is somewhat higher (71°), 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°) 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 combining data which record changes in paleoslope.

Late Cretaceous and Early Tertiary sediments in the Williston Basin form a transitional sequence from marine and brackish-water to continental deposits. The latest of the marine deposits were dispersed in a "relict" Cannonball sea during Early Paleocene time. Streams transporting and depositing prograding Tongue River sediments 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 data from existing Tongue River strata (Fig.16) suggest it extended southeastward. This appears to be in accord with the suggestion by Waage (DUNBAR, 1965, p.321) that the last connection of the great Cretaceous inundation of the continental interior was by way of the Mississippi Embayment.

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 increased sedimentation is suggested by expulsion of the Cannonball sea.

The thickness of the Tongue River–Sentinel Butte sequence (greater than 1,000 ft.) and its increase 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 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 Laramide orogeny was in progress to the west, and it is probable that the sedimentologic differences between major rock units, such as the Tongue River and Sentinel Butte Formations, reflect discrete tectonic pulsations.

Depositional episodes

The Tongue River episode. Tongue River deposition began with an influx of basal sand over continental sediments of the Ludlow and marine sediments of the Cannonball Formations. 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 extrusive volcanism (such as the Crazy Mountain-Livingston event) accompanied deformation of the sedimentary provenance. Dispersion across the basin was eastward, and the low variance of paleocurrent data indicates constancy of the paleoslope, 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 a 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 backswamps. 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 floodplain depressions, filled periodically with surface water, carbonate accumulated and subsequently lithified to freshwater limestone.

As noted by ALLEN (1964, table 1) and FISK (1947, p.57, pl.66, fig.14), backswamps are a favorable habitat for freshwater invertebrates. The greater development 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 Formation.

The fine texture and relative abundance of the various sediment facies suggest that western North Dakota was near the terminus of a regional drainage system during Tongue River time, but the character of the baselevel is problematical. It is presumed that the paleoslope was continuous 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 backswamp 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. Within 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, principally in northwestern North Dakota. Thus, final Tongue River time was a period of 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 greater competence than those of the Tongue River episode carried sediment in from the northwest and dispersed it in a fan-like pattern across the swamp. Deposition into a body of standing water is suggested by large-scale inclined beds 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 backswamp sediments in the basal sand 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 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. Carbonate content shows an inverse relationship with grain size, being smallest in the north and increasing westward and southward. These relationships suggest that basinal subsidence influenced the location of major streams, and thus sediment dispersal, 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 sedimentary provenance is suggested by cross-bed measurements from the unit, which differ with statistical significance from those of 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 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 suggest shifting river courses and possibly changing or multiple areas of sediment supply. The drainage pattern was generally much less stable than that ofTongue River time, but the upper and lower "yellow" beds, which resemble Tongue River strata, 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 across the Williston Basin primarily as suspended load. Frequent overbank deposition can be postulated on the basis of sparse backswamps 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 appears to represent 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 variance. The maximum extent of this unit has not been defined, but it is believed to have been widespread. It is of particular economic significance where it overlies lignitic strata, as in northern Billings county, 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 Sentinel Butte sequence.

Sentinel Butte sedimentation terminated shortly after deposition of the upper sand, apparently in response to reduction of sediment supply. Non-deposition and 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 disconformably overlain by Oligocene sediments of the White River Group. Thus, termination of the Sentinel Butte episode concluded a long-lived epoch of continuous fluvial sedimentation in the Williston Basin of western North Dakota.

ACKNOWLEDGEMENTS

The writer is indebted to Drs. W. M. Laird, E. A. Noble, F. D. Holland Jr., Lee Clayton, and A. M. Cvancara of the University of North Dakota for their advice and assistance during investigation and for reviewing a preliminary draft of this report. The present report has benefitted from critical comments by Dr. G. M. Friedman of Rensselaer Polytechnic Institute. My thanks are also extended to Messrs. Edward Callender, S. S. Harrison, Kent Johnson, R. G. Updike, and R. G. Wilson who assisted in laboratory routines, data reduction, and drafting. Samples from Bullion Butte were collected by Jack Crawford and Lee Clayton contributed unpublished field data from Mountrail County.

Various stages of investigation were supported by the National Science Foundation, the North Dakota Geological Survey, The University of North Dakota, and Arizona State University. My appreciation is extended to each of these organizations.

REFERENCES

Allen, J. R. L., 1963a. Asymmetrical ripple marks and the origin of waterlaid cosets of cross-strata. *Liverpool Manchester Geol. J.*, 3:187–236.

Allen, J. R. L., 1963b. The classification of cross-stratified units, with notes on their origin. *Sedimentology*, 2:93–114.

ALLEN, J. R. L., 1964. Studies in fluviatile sedimentation; six cyclothems from the lower Old Red Sandstone, Anglo–Welsh Basin. *Sedimentology*, 3:163–198.

ALLEN, J. R. L., 1965. A review of the origin and characteristics of recent alluvial sediments. *Sedimentology*, 5:89–195.

ANDERSON, B., 1961. The Rufigi Basin, Tanganyika, 7. Soils of the irrigable areas. *Rept. Govt. Tanganyika, Prelim. Reconstruction Surv. Rufigi Basin*, 125 pp.

BENSON, W. E., 1952. *Geology of the Knife River Area, North Dakota.* U.S. Geol. Surv., Washington, D.C. (open-file report).

BERNARD, H. A. and MAJOR, C. F., 1963. Recent meander belt deposits of the Brazos River; an alluvial "sand" model. *Am. Assoc. Petrol. Geologists, Bull.*, 47:350.

BROWN, R. W., 1948a. Correlation of the Sentinel Butte shale in western North Dakota. *Am. Assoc. Petrol. Geologists, Bull.*, 32:1265–1274.

BROWN, R. W., 1948b. Age of the Kingsbury conglomerate is Eocene. *Bull. Geol. Soc. Am.*, 59:1165–1172.

BROWN, R. W., 1952. Tertiary strata in eastern Montana and western North and South Dakota. *Billings Geol. Soc. Guidebook 3rd Ann. Field Conf., Sept. 1952*, 89–92.

BROWN, R. W., 1962. Paleocene flora of the Rocky Mountains and Great Plains. *U. S. Geol. Surv., Profess. Papers*, 375:119 pp.

CLARK, M. B., 1966. *The Stratigraphy of the Sperati Point Quadrangle, McKenzie County, North Dakota.* Thesis Univ. North Dakota, Grand Forks, N.D., 108 pp., unpublished.

CLAYTON, L., 1969. Geology of Mountrail County, North Dakota. *N. Dakota Geol. Surv. Bull.*, 20, in press.

CRAWFORD, J. W., 1967. *Stratigraphy and Sedimentology of the Tongue River Formation (Paleocene), Southeast Golden Valley County, North Dakota.* Thesis Univ. North Dakota, Grand Forks, N.D., 73 pp., unpublished.

DENSON, N. M. and GILL, J. R., 1965a. *Heavy Minerals in Grab Samples from Various Formations in the Williston Basin.* U.S. Geol. Surv., Washington, D.C. (open-file report).

DENSON, N. M. and GILL, J. R., 1965b. Uranium-bearing lignite and carbonaceous shale in the southwestern part of the Williston Basin—a regional study. *U.S. Geol. Surv. Profess. Papers*, 463: 75 pp.

DIXON, W. J. and MASSEY, F. J., 1957. *Introduction to Statistical Analysis.* McGraw-Hill, New York, N.Y., 488 pp.

DORF, E., 1942. Upper Cretaceous floras of the Rocky Mountain region, II. Flora of the Lance Formation at its type locality, Niobrara County, Wyoming. *Carnegie Inst. Wash. Publ.*, 580:79–159.

DUNBAR, C. O., 1965. *Historical Geology.* Wiley, New York, N.Y., 500 pp.

FISHER, S. P., 1953. Geology of west central McKenzie County, North Dakota. *N. Dakota Geol. Surv., Rept. Invest.*, 11.

FISHER, S. P., 1954. Structural geology of the Skaar-Trotters area, McKenzie and Golden Valley Counties, North Dakota. *N. Dakota Geol. Surv., Rept. Invest.*, 15.

FISK, H. N., 1944. Geological investigation of the alluvial valley of the lower Mississippi River. *U.S. Mississippi River Comm., Vicksburg, Miss.*, 78 pp.

FISK, H. N., 1947. Fine-grained alluvial deposits and their effects on Mississippi River activity. *U.S. Mississippi River Comm., Vicksburg, Miss.*, 1:1–82; 2:illus., maps.

FOLK, R. L., 1954. The distinction between grain size and mineral composition in sedimentary rock nomenclature. *J. Geol.*, 62:344–359.

FOLK, R. L. and WARD, W. C., 1957. Brazos River bar; a study in the significance of grain size parameters. *J. Sediment. Petrol.*, 27:3–26.

GRIFFITHS, J. C. and ROSENFELD, M. A., 1953. A further test of dimensional orientation of quartz grains in Bradford sand. *Am. J. Sci.*, 251:192–214.

HAMBLIN, W. K., 1961. Micro-cross-lamination in upper Keeweenawan sediments of northern Michigan. *J. Sediment. Petrol.*, 31:390–401.

HANSON, B. M., 1955. Geology of the Elkhorn Ranch area, Billings and Golden Valley Counties, North Dakota. *N. Dakota Geol. Surv., Rept. Invest.* 18.

HARES, C. J., 1928. Geology and lignite resources of the Marmarth field, southwestern North Dakota. *U.S. Geol. Surv. Bull.*, 775:110 pp.

HENNEN, R. V., 1943. Tertiary geology and oil and gas prospects in Dakota Basin, North Dakota. *Am. Assoc. Petrol. Geologists, Bull.*, 27:1567–1594.

HERRIN, E. T., HICKS, H. S. and ROBERTSON, H., 1958. A rapid volumetric analysis for carbonate in rocks. *Field Lab.*, 26:139–144.

HICKEY, L. J., 1966. *The Paleobotany and Stratigraphy of the Golden Valley Formation in Western North Dakota.* Thesis Princeton University, Princeton, N.J., 265 pp., unpublished.

INMAN, D. L., 1949. Sorting of sediments in the light of fluid mechanics. *J. Sediment. Petrol.*, 19:51–70.

JOPLING, A. V., 1966. Some principles and techniques used in reconstructing the hydraulic parameters of a paleo-flow regime. *J. Sediment. Petrol.*, 36:5–49.

KAY, M., 1951. North American geosynclines. *Geol. Soc. Am., Mem.*, 48:143 pp.

KLINE, V., 1942. Stratigraphy of North Dakota. *Am. Assoc. Petrol. Geologists, Bull.*, 26:336–379.

LEONARD, A. G. and SMITH, C. D., 1909. The Sentinel Butte lignite field, North Dakota and Montana. *U.S. Geol. Surv. Bull.*, 341:15–35.

LORENS, P. J. and THRONSON, R. C., 1955. Geology of the fine-grained alluvial deposits in Sacramento Valley and their relationship to seepage. In: H. O. BANKS (Editor), *Seepage Conditions in Sacramento Valley—Rept. Water Project Authority Calif.*, pp.1–26.

MAY, P. R., 1954. Strippable lignite deposits, Wibaux area, Montana and North Dakota. *U.S. Geol. Surv. Bull.*, 995-G: 267–268.

MCKEE, E. D. and WEIR, G. W., 1953. Terminology for stratification and cross-stratification in sedimentary rocks. *Geol. Soc. Am. Bull.*, 64:381–390.

PASSEGA, R., 1957. Texture as a characteristic of clastic deposition. *Am. Assoc. Petrol. Geologists Bull.*, 41:1952–1984.

PASSEGA, R., 1964. Grain-size representation by CM patterns as a geological tool. *J. Sediment. Petrol.*, 34:830–847.

PETTIJOHN, F. J., 1957. *Sedimentary Rocks.* Harper and Bros., New York, N.Y., 718 pp.

POTTER, P. E. and PETTIJOHN, F. J., 1963. *Paleocurrents and Basin Analysis.* Academic Press, New York, N.Y., 293 pp.

ROYSE JR., C. F., 1967a. The Tongue River–Sentinel Butte contact in western North Dakota. *N. Dakota Geol. Surv. Rept. Invest.*, 45:53 pp.

ROYSE JR., C. F., 1967b. *A Stratigraphic and Sedimentologic Analysis of the Tongue River and Sentinel Butte Formations (Paleocene), Western North Dakota.* Thesis Univ. North Dakota, Grand Forks, N.D., 312 pp., unpublished.

ROYSE JR., C. F., 1968. Recognition of fluvial environments by particle-size characteristics. *J. Sediment. Petrol.*, 38:1171–1178.

SATO, Y. and DENSON, N. M., 1967. Volcanism and tectonism as reflected by the distribution of nonopaque heavy minerals in some nonmarine Tertiary rocks of Wyoming and adjacent states. *U.S. Geol. Surv. Profess. Papers*, 575-C:42–54.

SEAGER, O. A., BLACKSTONE JR., D. L., COBBAN, W. A., DOWNS, G. R., LAIRD, W. M. and SLOSS, L. L., 1942. Stratigraphy in North Dakota. *Am. Assoc. Petrol. Geologists, Bull.*, 26:1414–1423.

SHEPARD, F. P., 1954. Nomenclature based on sand-silt-clay ratios. *J. Sediment. Petrol.*, 24:151–158.

SIGSBY, R. J., 1966. *"Scoria" of North Dakota.* Thesis Univ. North Dakota, Grand Forks, N.D., 218 pp., unpublished.

SUNDBORG, Å., 1956. The River Klarälven; a study of fluvial processes. *Geograph. Ann.*, 38:127–316.

TAYLOR, D. W., 1969. Early Tertiary mollusks from the Powder River Basin, Wyoming-Montana and adjacent regions. *U.S. Geol. Surv. Profess. Papers*, in press.

THOM JR., W. T. and DOBBIN, C. E., 1924. Stratigraphy of Cretaceous-Eocene transition beds in eastern Montana and the Dakotas. *Bull. Geol. Soc. Am.*, 35:481–505.

TISDALE, E. E., 1941. The geology of the Heart Butte Quadrangle, North Dakota. *N. Dakota Geol. Surv. Bull.* 13: 32 pp.

TOZER, E. T., 1956. Uppermost Cretaceous and Paleocene non-marine molluscan faunas of western Alberta. *Can. Geol. Surv. Mem.*, 280: 125 pp.

WENTWORTH, C. K., 1922. A scale of grade and class terms for clastic sediments. *J. Geology*, 30:377–392.

YEN, TENG-CHIEN, 1946. Paleocene fresh-water mollusks from Sheridan County, Wyoming. *Am. J. Sci.*, 224:41–48.

YEN, TENG-CHIEN, 1947. Paleocene fresh-water mollusks from southern Montana. *U.S. Geol. Surv. Profess. Papers*, 214-C:35–44.